T23F-0678: Linkages Between the Megathrust and Upper-plate Deformation: Lessons From the Deformational Dichotomy of the 2016 Kaikoura, New Zealand Earthquake

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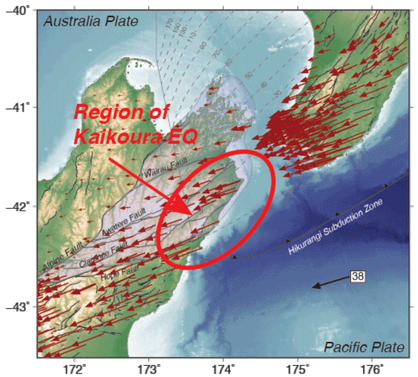


Inter-EQ GPS indicates a transition from Pacific to Australia motions in epicentral region - reflecting some combination of megathrust and crustal fault coupling.

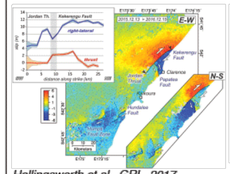
Following the 2016 Mw 7.8 Kaikoura earthquake, uncertainty over the nature of the coseismic rupture developed. Seismological evidence pointed to significant involvement of the subduction megathrust, while geodetic and field observations pointed to a shallow set of intra-crustal faults as the main participants during the earthquake. The addition of tsunami observations and modeling placed additional constraints on the specific location of co-seismic slip, which when combined with other observations indicates the simultaneous occurrence of shallow slip on the subduction interface and slip on overlying, upper-crustal fault structures.

This Kaikoura-style earthquake, involving synchronous ruptures on multiple components of the plate boundary, including extreme displacements on shallow faults, is an important mode of plate boundary deformation potentially affecting seismic hazard along subduction zones. Why the rupture proceeded in this manner remains uncertain.

Crustal vs Megathrust Faulting?

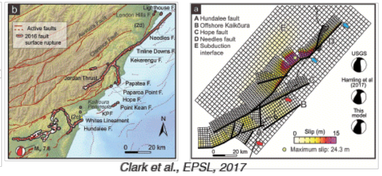
Evidence (conflicting?) on the nature of primary faulting during the Kaikoura event includes satellite and land based geologic and geodetic observations, which support a model with substantial shallow crustal faulting; while seismologic and tsunami observations and models indicate substantial moment release (and slip) along the southern segment of the Hikurangi megathrust.

Evidence for Crustal Faulting



Hollingsworth et al., GRL, 2017

Landsat8 Optical Image Correlation showing regions of major crustal displacements

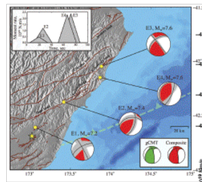


Clark et al., EPSL, 2017

(Left) Faults with significant co-seismic rupture; (right) kinematic model of fault slip on mapped faults with majority of slip on upper-crustal faults

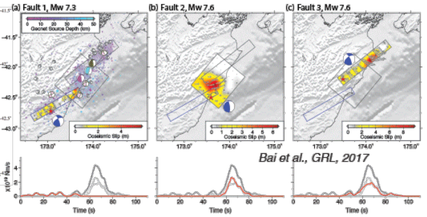
Surface faulting with significant slip (5-10+ meters) on multiple faults along the coastal region of northern South Island mapped by satellite, land-based, and geodetic observations (with assumptions of substantial deep slip on faults) can generate a focal mechanism similar to observed GMT solutions

Evidence for Megathrust Faulting



Duputel and Rivera, PEPI, 2017

Composite seismological rupture model involving both shallow strike slip and deeper thrust faulting

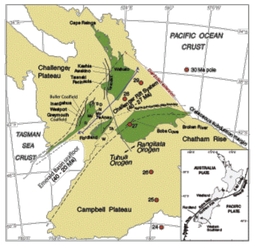


Bai et al., GRL, 2017

Tsunami signals indicate sizeable seafloor displacements in addition to onshore surface ruptures. Coupled seismological and tsunami models indicate 3 primary moment-release events

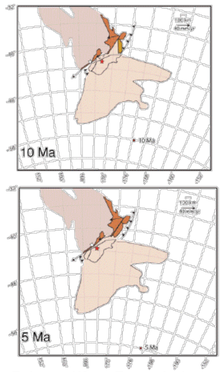
Seismologic and tsunami observations and models indicate a composite set of rupture planes that include shallow oblique/strike-slip motions and deeper dip-slip motion on an assumed plate interface. Tsunami model results indicate slip to shallow levels near the trench. According to the Bai et al. model, approximately 40% of the total moment release occurs on the megathrust (Fault 2 in model at left), similar to the Duputel and Rivera model

Plate Tectonic Evolution of the Kaikoura EQ Region



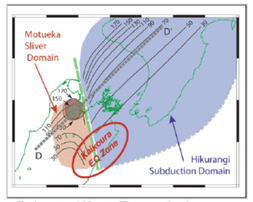
Furlong and Kamp, Tectonophysics, 2013

The current configuration of the New Zealand continent (Zealandia) has been produced over the past ~ 30 Ma as a plate boundary developed between the Australia and Pacific plates. As the Pacific side of the plate boundary translates south-westward, the Hikurangi subduction zone has developed; its southern edge is tied to the north-east corner of the South Island.



Furlong and Kamp, Tectonophysics, 2009

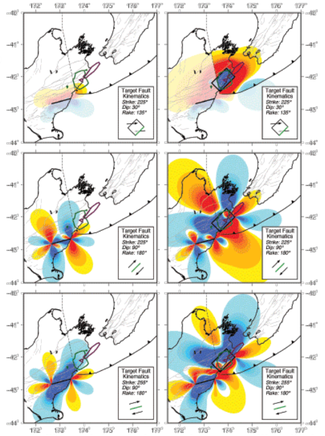
The Kaikoura earthquake sequence straddles this southern edge of the subducting slab, with its initiation south of the slab edge and propagation into the subduction zone



Furlong and Kamp, Tectonophysics, 2009

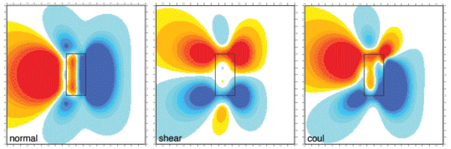
Co-seismic Stress Triggering, Decoupling and Extreme Fault Displacements

Seismological analyses indicate that the earthquake initiated as a crustal strike-slip fault in the south; the subsequent rupture of the megathrust and the major upper-plate faults was nearly simultaneous.

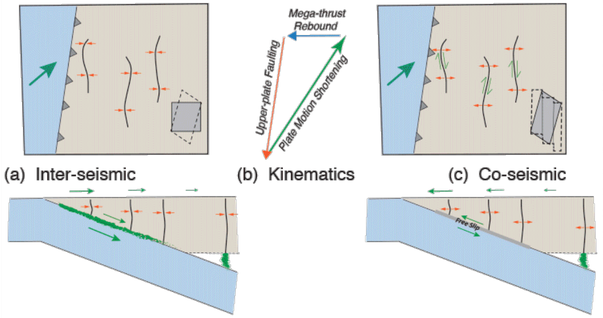


(left) models of stress changes with initial trigger event; (right) combined effect of initial trigger and megathrust

Stress modeling indicates that the initial strike-slip sub-event would positively load the megathrust interface (but not the surface faults). Rupture of the megathrust significantly loads the upper plate faults.



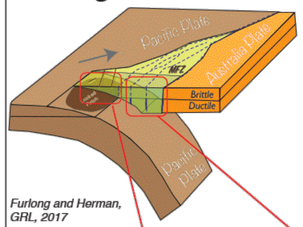
The principal effect of the megathrust rupture on the coulomb stress conditions in the overriding plate is to substantially reduce the normal stresses acting on those structures. Little change in the shear stress occurs on these faults.



During interseismic intervals, strain accumulates as a result of coupling between the obliquely subducting Pacific and overriding Australia plates. (left)

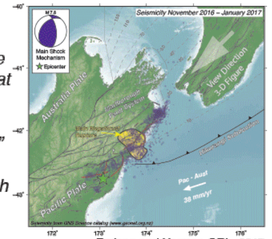
During megathrust rupture, the upper-plate faults above the rupture are decoupled at their base and unclamped (reduction in normal stresses) allowing nearly complete strain release along those structures and extreme fault slip. Once rupture ends they are again coupled at their base.(right)

Faulting and EQ Sources in the Kaikoura Region

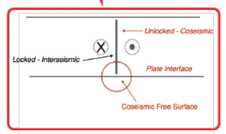


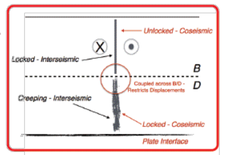
Furlong and Herman, GRL, 2017

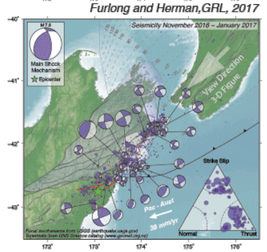
Surface faults activated during the Kaikoura earthquake generally overlie the subducting Pacific slab (which is at a depth of less than ~ 25 km). As a result, these faults terminate at the plate interface while still in the "brittle" deformation regime. The slab is deeper beneath the main Marlborough Faults (west of the Kaikoura faults), which likely include a ductile shear zone at their base.



Furlong and Herman,GRL, 2017

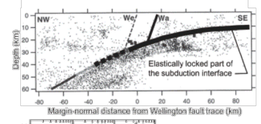


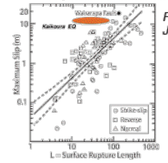




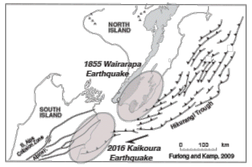
During megathrust rupture, the Kaikoura faults will be decoupled at their base from the subducting slab. Marlborough Faults include deeper ductile shear zones that behave as locked features co-seismically.

Implications for Subduction Zone EQs





Rodgers and Little, JGR, 2006



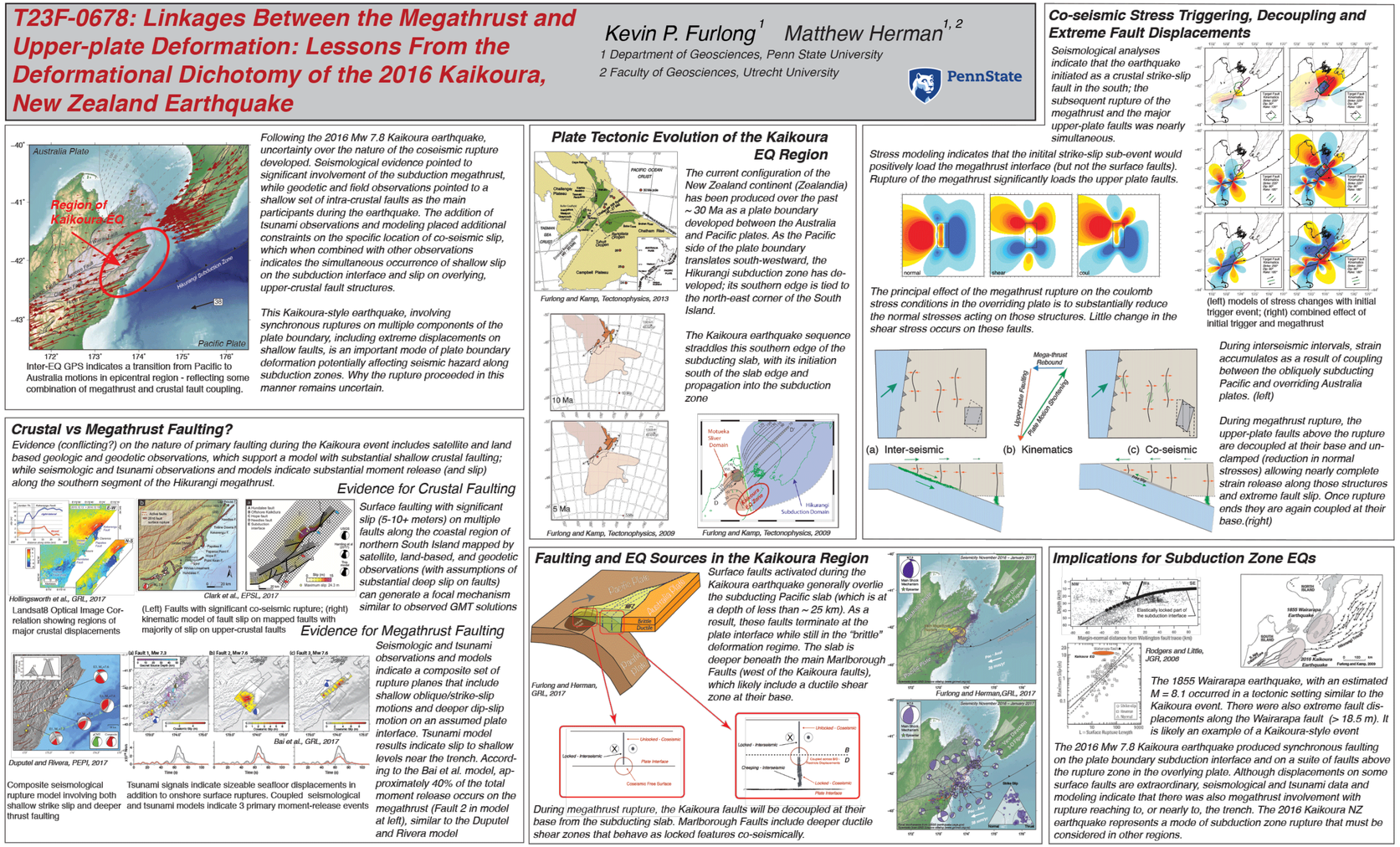
Furlong and Kamp, 2009

The 1855 Wairarapa earthquake, with an estimated M = 8.1 occurred in a tectonic setting similar to the Kaikoura event. There were also extreme fault displacements along the Wairarapa fault (> 18.5 m). It is likely an example of a Kaikoura-style event

The 2016 Mw 7.8 Kaikoura earthquake produced synchronous faulting on the plate boundary subduction interface and on a suite of faults above the rupture zone in the overlying plate. Although displacements on some surface faults are extraordinary, seismological and tsunami data and modeling indicate that there was also megathrust involvement with rupture reaching to, or nearly to, the trench. The 2016 Kaikoura NZ earthquake represents a mode of subduction zone rupture that must be considered in other regions.

Mechanics of Poster Presentations

- Poster Presentation
  - Organization
  - Text
  - Layout
  - Imagery
- Oral Presentation



Poster Organization - Have a Strategy!

Not the time to be 'cute'

- Short Title
- Author(s), Department

- State the Problem and its Significance to Discipline, Society, etc. - you need to "grab" your audience
- Objectives, Background - should be short but use to provide **Context**

- Methods
- Results/Findings
- Interpretation/Conclusions

- Future Directions - Primarily for Posters on "early-stage" projects - Projects with strong conclusions do not need this
- Acknowledgements and Funding Sources

Systematic Organization make it easier for your audience to follow your arguments

Things to Keep in Mind

1. What is the “take home” message? You should have this squarely in mind when you design your poster.
2. Keep things simple and accessible - You are presenting to a broad (but geoscience-focused) audience
3. Don’t use too many words – keep the font size large
4. Have a logical (and clear) pathway through your poster - viewers should be able to read it without your presence
5. Pay attention to maximum/reasonable poster size

Don’t forget about the details

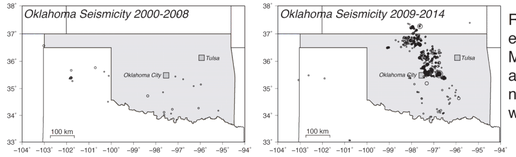
- 1. Use color/**bold**/*italic* effectively
- Use large font sizes – the poster should be able to be read from a distance (~ 6ft or 2m)
- Choose simple and clear font(s). Don't use too **many** different *fonts* on the poster - but simple **VARIATIONS** that help the reader are useful
- ***Highlight*** your key points - make it easy for the reader to know what matters
- Graphics are on the poster to help you tell your story - ***USE THEM!***

Do Small Earthquakes Lead to the Big One? Triggering Great Earthquakes

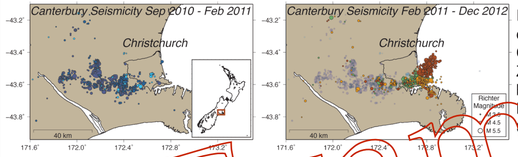
Matthew Herman, Department of Geosciences
Adviser: Kevin Furlong
PENNSTATE GEODYNAMICS

Earthquake Triggering – Small to Large

Precursory events have been invoked as triggers for earthquakes of all sizes, from nearly imperceptible tremors to the largest and most devastating great events.



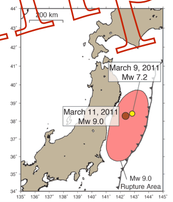
Relatively small earthquakes (up to Mw 5.0) in Oklahoma are correlated with nearby large volume wastewater injection.



In 2011, four Mw 6.0 earthquakes near Christchurch, New Zealand, may have been triggered by an Mw 7.0 earthquake in September 2010.

These are examples of potential triggering of relatively small earthquakes. Can extremely large earthquakes also be triggered?

This may be the case in Japan in 2011, when an Mw 7.2 earthquake occurred on March 9 near the epicenter of the March 11 Mw 9.0 Tohoku earthquake, possibly triggering the great earthquake.



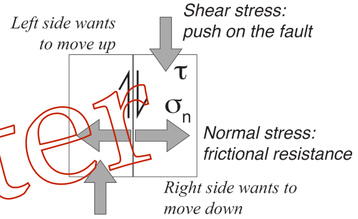
How to Tell if an Earthquake was Triggered

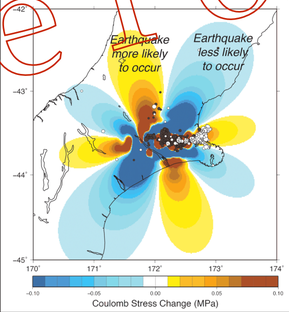
Events like earthquakes or wastewater injection change the state of stress on nearby faults.

If this stress change pushes harder in the direction the fault moves, or reduces the frictional resistance to sliding, then the fault is more likely to slip in an earthquake. These effects are combined into a quantity called Coulomb stress:

$$\Delta CS = \tau - \mu\sigma_n$$

Coulomb stress — Shear stress — Friction — Normal stress





Coulomb Stress Example: 2010 Mw 7.0 Christchurch Earthquake

Warm colors are where faults with the same geometry as the initial event are more likely to slip. Blue areas are where the same faults are less likely to slip. The color palette is based on research that shows increased seismicity associated with Coulomb stress changes above 0.01 MPa (yellow and darker).

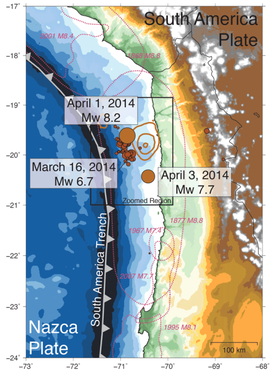
Subsequent earthquakes (white dots) that occur in the red zones were "loaded" by the initial event, and might be considered triggered.

2014 Iquique earthquake and foreshock sequence

On April 1, an Mw 8.2 earthquake struck offshore of northern Chile at 8:45 pm local time, severely shaking towns along the coast and generating a tsunami that reached 2-3 meters. Although there were few direct casualties, the earthquake led to massive evacuations and widespread damage in northern Chile and southern Peru.

Tsunami damage in Iquique port

Shaking damage in Iquique



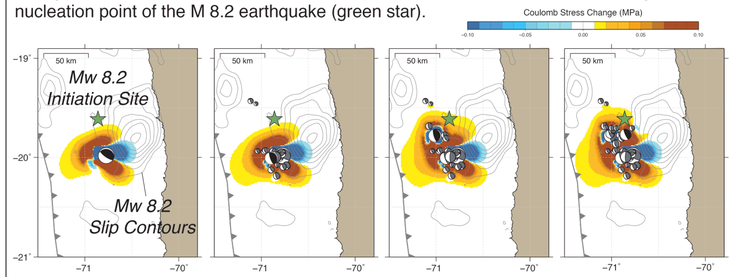
The earthquake occurred in the South America subduction zone, where the Nazca plate dives eastward beneath the South America plate at about 70 mm/yr. This subduction zone has hosted many great earthquakes throughout recorded history, and in particular, the 2014 event occurred in region that had not experienced a great earthquake since 1877.

The Iquique earthquake was preceded by a sequence of foreshocks, starting on March 16 with an Mw 6.7 event and including 3 more Mw 6.0 earthquakes. The question is:

Did the March foreshocks make the April main shock more likely to occur, i.e. did they trigger the main shock?

Coulomb Stress from the Iquique Foreshock Sequence

We compute the stress change around each earthquake, and resolve the Coulomb stress change on the subduction fault. In particular, pay attention to how the stress changes at the nucleation point of the M 8.2 earthquake (green star).



March 16
The first event (Mw 6.7) creates a footprint of increased Coulomb stress that does not quite reach the initiation site.

March 17
An Mw 6.2 earthquake to the west of the first foreshock enhances the positive stress footprint.

March 22
An Mw 6.0 earthquake to the north of the initial cluster pushes the yellow loading region to the initiation site of the Mw 8.2.

March 23
The final Mw 6.0 earthuake before April 1 puts the initiation site squarely in the positively stressed region.

Conclusions

- The March 16 - March 31 foreshocks combined to positively load the location where the April 1 Mw 8.2 main shock began.
- This suggests that the beginning of the Mw 8.2 earthquake may have been triggered by stress changes resulting from the foreshock seismicity.
- This is one of the best observed examples of an extremely large earthquake apparently being triggered by much smaller events.
- One caveat: this analysis does not account for how the earthquake grew from a small, triggered event into a great earthquake.

Example Poster

Do Small Earthquakes Lead to the Big One? Triggering Great Earthquakes

Matthew Herman, Department of Geosciences
Adviser: Kevin Furlong
PENNSTATE GEODYNAMICS

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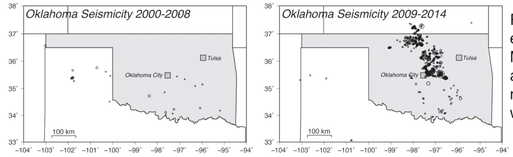

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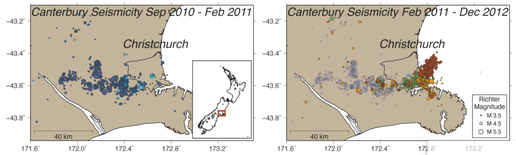

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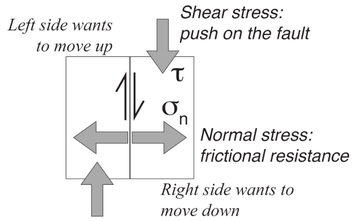

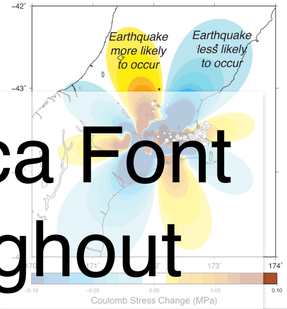

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36 pt

Helvetica Font Throughout

All are Large Sizes

48 pt (bold)

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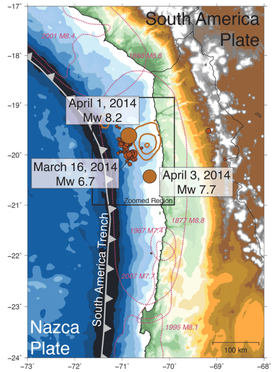

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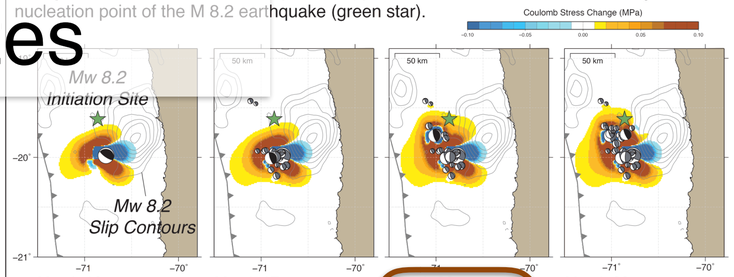

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32 pt

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Do Small Earthquakes Lead to the Big One? Triggering Great Earthquakes

Matthew Herman, Department of Geosciences
Adviser: Kevin Furlong
PENNSTATE GEODYNAMICS

Clear Title (short)

Presenter and Advisor

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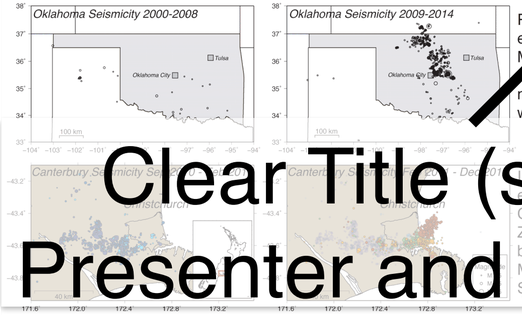

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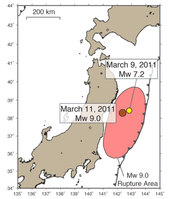

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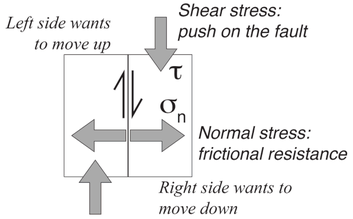

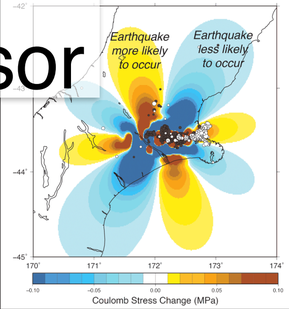

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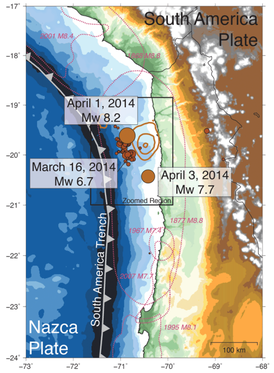

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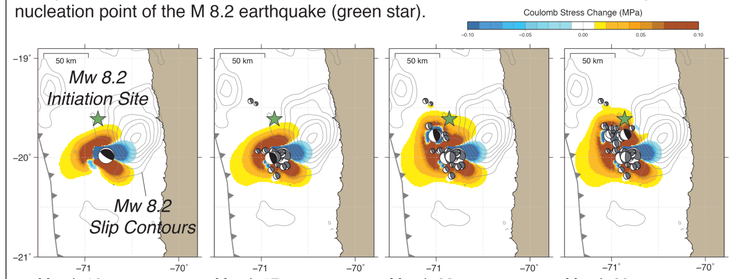

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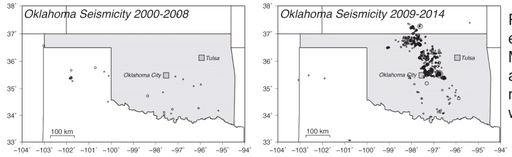

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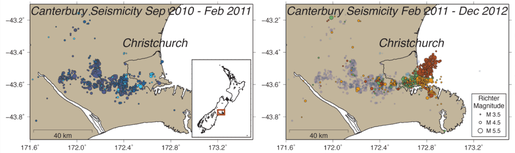

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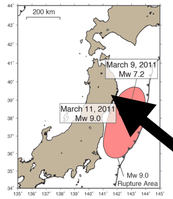

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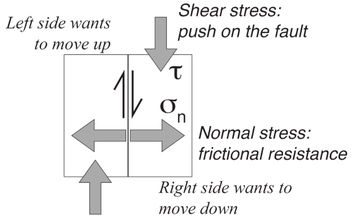

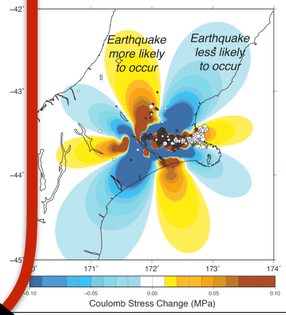

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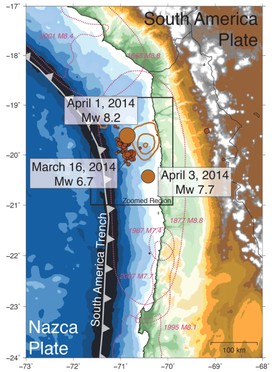

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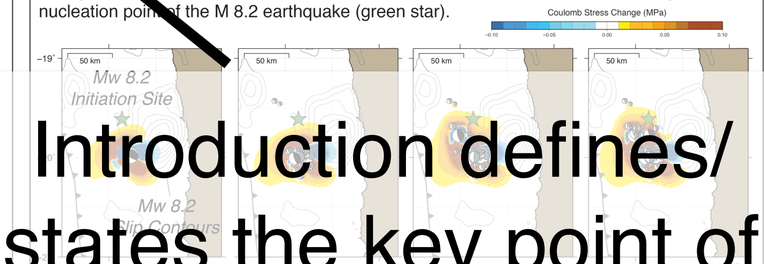

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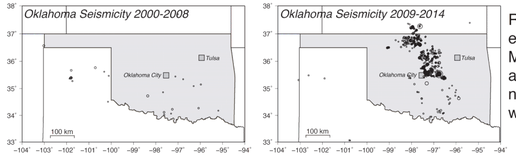

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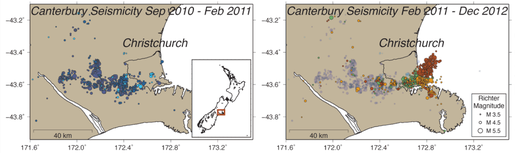

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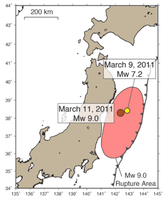

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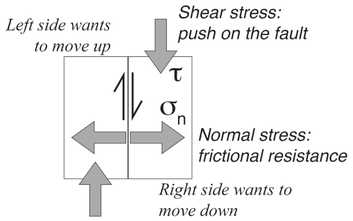

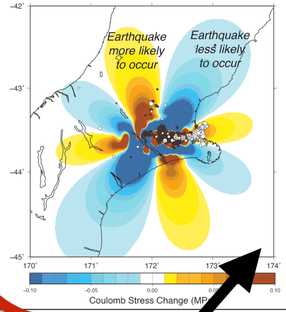

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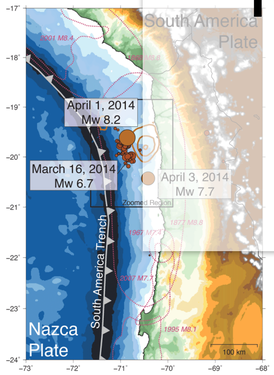

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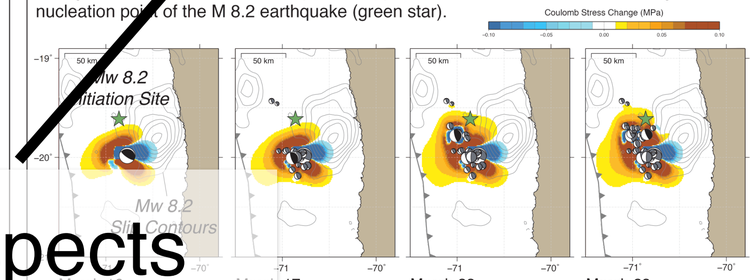

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Technical aspects presented in an accessible way

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Logical Pathway through presentation

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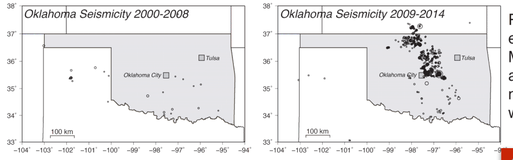

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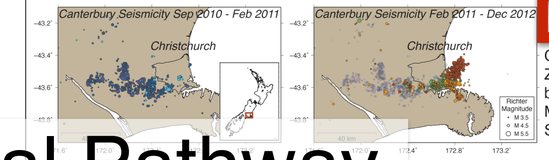

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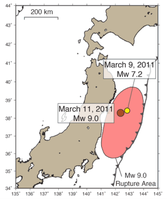

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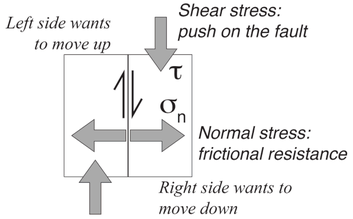

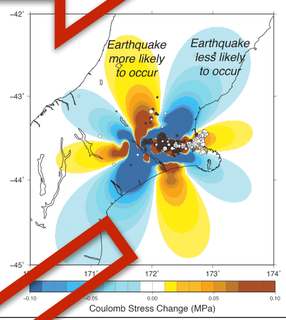

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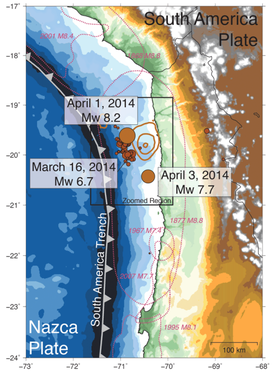

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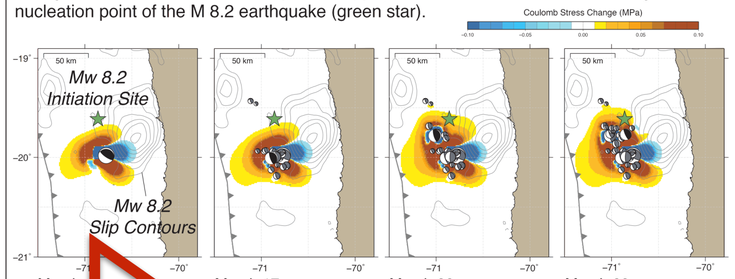

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March 17
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March 23
The final Mw 6.0 earthuake before April 1 puts the initiation site squarely in the positively stressed region.

Conclusions

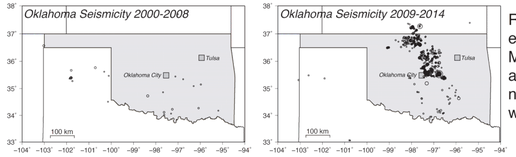
- The March 16 - March 31 foreshocks combined to positively load the location where the April 1 Mw 8.2 main shock began.
- This suggests that the beginning of the Mw 8.2 earthquake may have been triggered by stress changes resulting from the foreshock seismicity.
- This is one of the best observed examples of an extremely large earthquake apparently being triggered by much smaller events.
- One caveat: this analysis does not account for how the earthquake grew from a small, triggered event into a great earthquake.

Do Small Earthquakes Lead to the Big One? Triggering Great Earthquakes

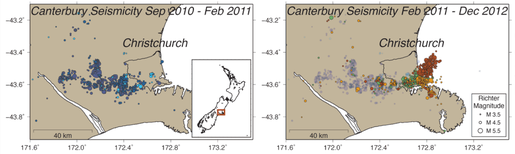
Matthew Herman, Department of Geosciences
Adviser: Kevin Furlong
PENNSTATE GEODYNAMICS

Earthquake Triggering – Small to Large

Precursory events have been invoked as triggers for earthquakes of all sizes, from nearly imperceptible tremors to the largest and most devastating great events.



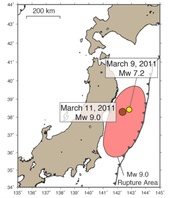
Relatively small earthquakes (up to Mw 5.0) in Oklahoma are correlated with nearby large volume wastewater injection.



In 2011, four Mw 6.0 earthquakes near Christchurch, New Zealand, may have been triggered by an Mw 7.0 earthquake in September 2010.

These are examples of potential triggering of relatively small earthquakes. Can extremely large earthquakes also be triggered?

This may be the case in Japan in 2011, when an Mw 7.2 earthquake occurred on March 9 near the epicenter of the March 11 Mw 9.0 Tohoku earthquake, possibly triggering the great earthquake.



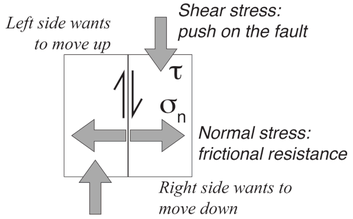
How to Tell if an Earthquake was Triggered

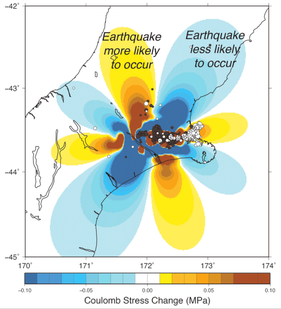
Events like earthquakes or wastewater injection change the state of stress on nearby faults.

If this stress change pushes harder in the direction the fault moves, or reduces the frictional resistance to sliding, then the fault is more likely to slip in an earthquake. These effects are combined into a quantity called Coulomb stress:

$$\Delta CS = \tau - \mu\sigma_n$$

Coulomb stress — Shear stress — Friction — Normal stress





Coulomb Stress Example: 2010 Mw 7.0 Christchurch Earthquake

Warm colors are where faults with the same geometry as the initial event are more likely to slip. Blue areas are where the same faults are less likely to slip. The color palette is based on research that shows increased seismicity associated with Coulomb stress changes above 0.01 MPa (yellow and darker).

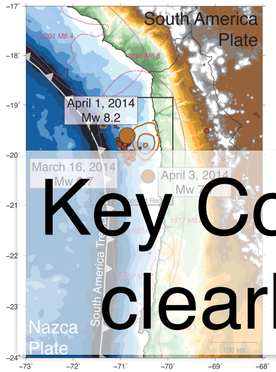
Subsequent earthquakes (white dots) that occur in the red zones were "loaded" by the initial event, and might be considered triggered.

2014 Iquique earthquake and foreshock sequence

On April 1, an Mw 8.2 earthquake struck offshore of northern Chile at 8:45 pm local time, severely shaking towns along the coast and generating a tsunami that reached 2-3 meters. Although there were few direct casualties, the earthquake led to massive evacuations and widespread damage in northern Chile and southern Peru.

Tsunami damage in Iquique port

Shaking damage in Iquique



The earthquake occurred in the South America subduction zone, where the Nazca plate dives eastward beneath the South America plate at about 70 mm/yr. This subduction zone has hosted many great earthquakes throughout recorded history, and in particular, the 2014 event occurred in region that had not experienced a great earthquake since 1877.

[illegible] with an Mw 6.7 event and including 3 more Mw 6.0 earthquakes. The question is:

[illegible] the April main shock more likely to occur, i.e. did they trigger the main shock?

Coulomb Stress from the Iquique Foreshock Sequence

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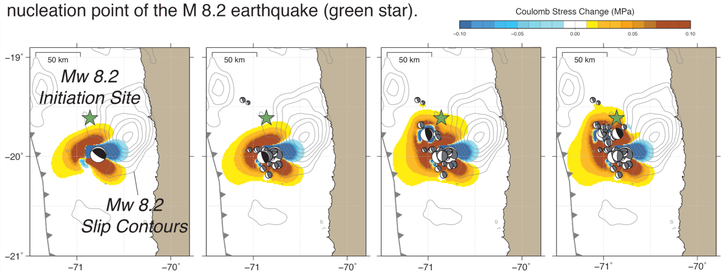

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- This is one of the best observed examples of an extremely large earthquake apparently being triggered by much smaller events.
- One caveat: this analysis does not account for how the earthquake grew from a small, triggered event into a great earthquake.

Key Conclusions clearly stated

Poster Text - Size

- making a good impression
- *making a good impression*
- **making a good impression**

Equal Font Size, Not Equal Look

- Calibri, Arial, Verdana

Poster Text - Review

- Sans Sarif Font - simple fonts
- Up to 3 Font Style Types

- Avoid *Italics (except in isolation)*
- Font Size Range Sample

88 – 14 (in Arial)

- Avoid Jargon
- Correct Spelling and Grammar

Poster Text - Readable from 4’ to 6’ Away!

Using Poster for More Than One Conference or Exhibition?

- ***Keep In Mind The Following .....***

Goals

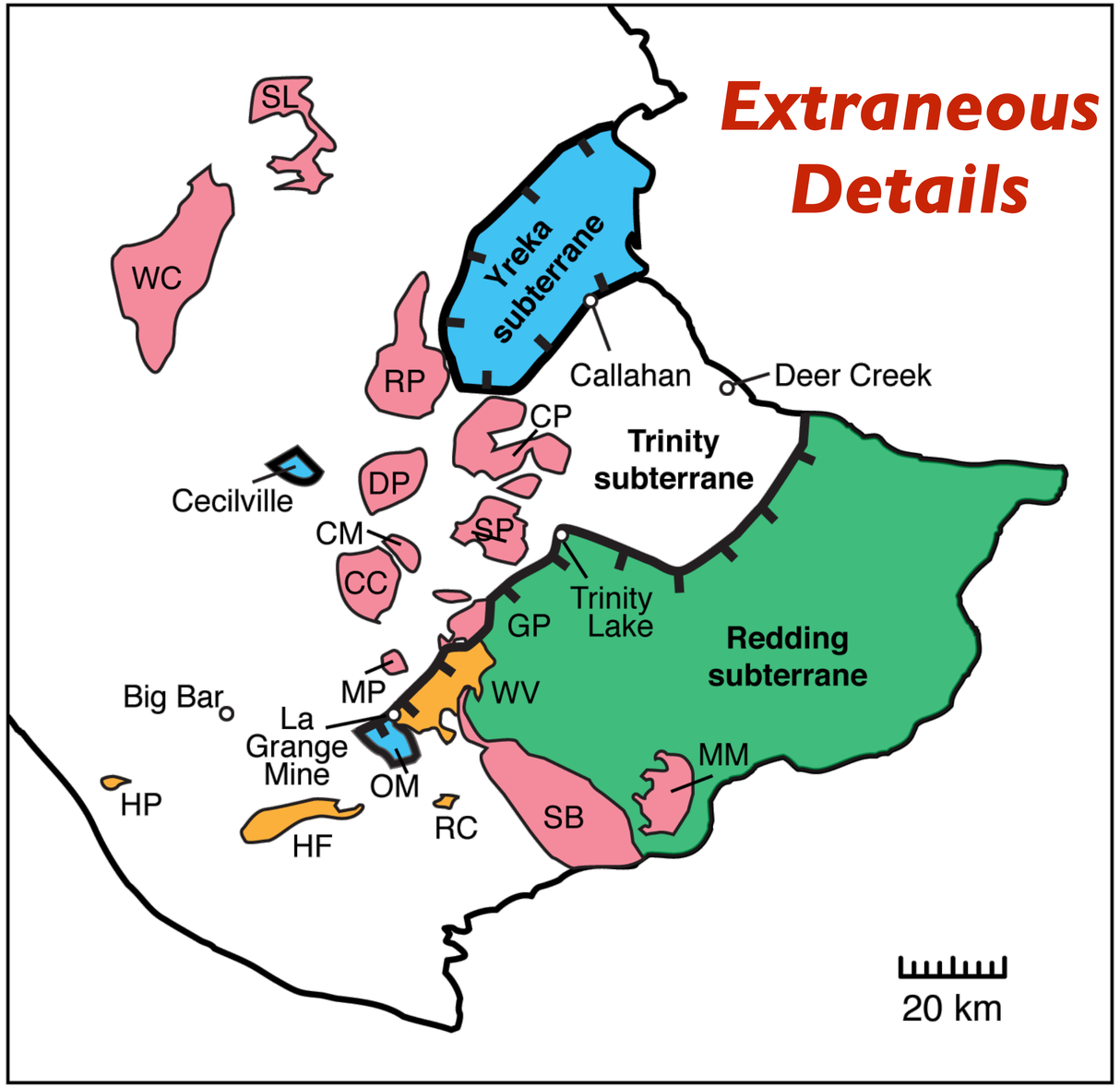
- Celebrate Research Accomplishments
- Enhance Presentation Skills
- Learn from/Collaborate with Colleagues
- Inform Geoscience Community of Research Significance

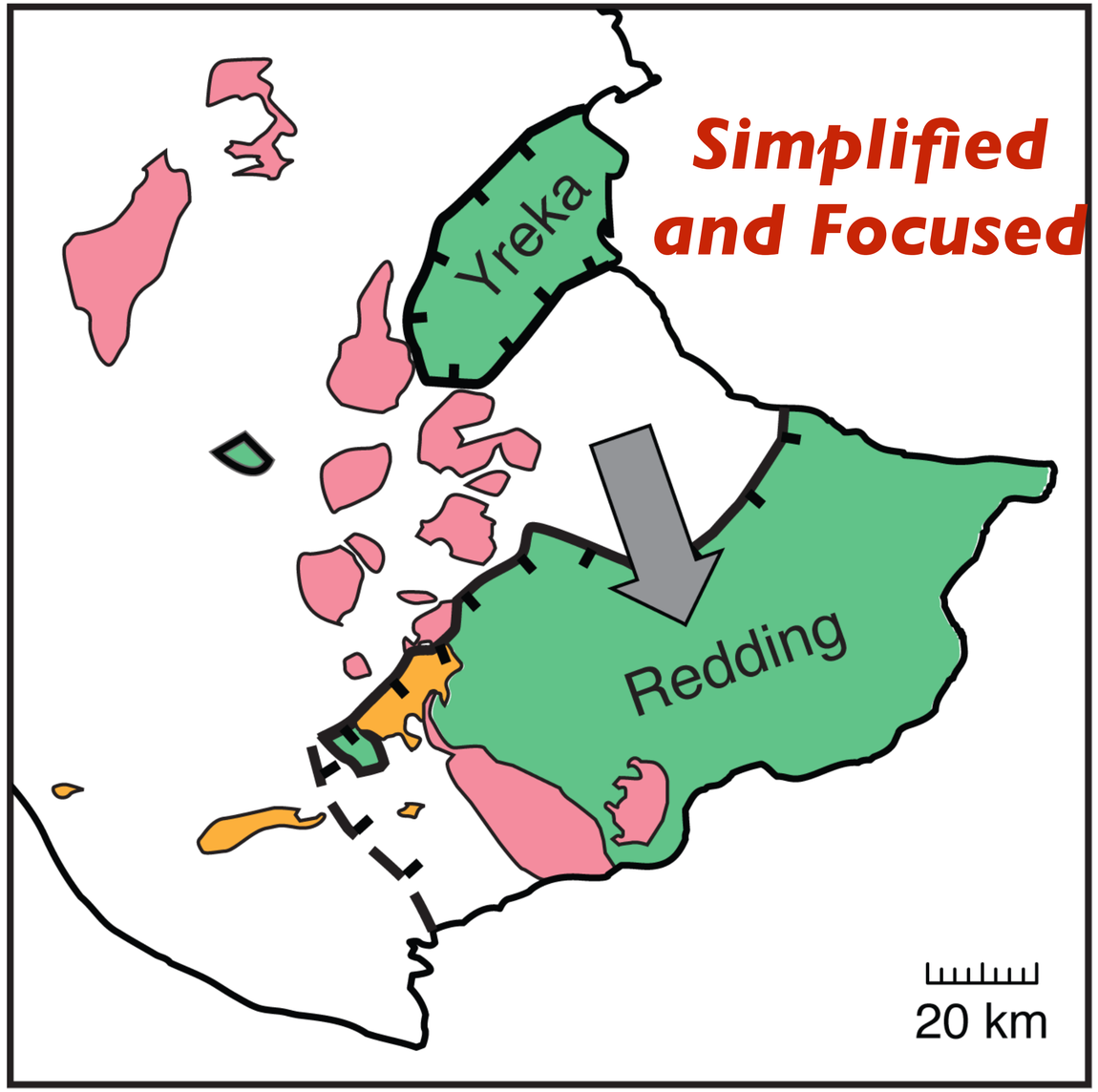
Audience

- Department Wide
  - Faculty
  - Graduate Students
  - Post-doctoral Scholars
  - Undergraduate Students
  - Staff in Department

Does your poster help you meet these goals?

Poster Imagery - Maps





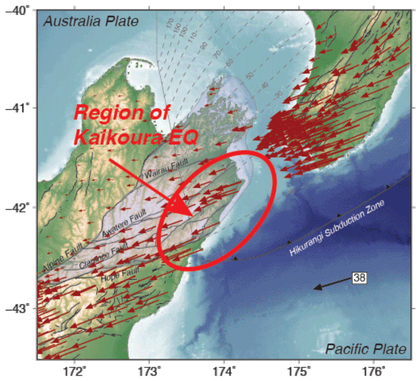
T23F-0678: Linkages Between the Megathrust and Upper-plate Deformation: Lessons From the Deformational Dichotomy of the 2016 Kaikoura, New Zealand Earthquake

Kevin P. Furlong[1] Matthew Herman[1, 2]

1 Department of Geosciences, Penn State University

2 Faculty of Geosciences, Utrecht University

PennState



Inter-EQ GPS indicates a transition from Pacific to Australia motions in epicentral region - reflecting some combination of megathrust and crustal fault coupling.

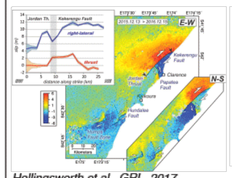
Following the 2016 Mw 7.8 Kaikoura earthquake, uncertainty over the nature of the coseismic rupture developed. Seismological evidence pointed to significant involvement of the subduction megathrust, while geodetic and field observations pointed to a shallow set of intra-crustal faults as the main participants during the earthquake. The addition of tsunami observations and modeling placed additional constraints on the specific location of co-seismic slip, which when combined with other observations indicates the simultaneous occurrence of shallow slip on the subduction interface and slip on overlying, upper-crustal fault structures.

This Kaikoura-style earthquake, involving synchronous ruptures on multiple components of the plate boundary, including extreme displacements on shallow faults, is an important mode of plate boundary deformation potentially affecting seismic hazard along subduction zones. Why the rupture proceeded in this manner remains uncertain.

Crustal vs Megathrust Faulting?

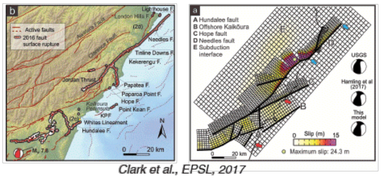
Evidence (conflicting?) on the nature of primary faulting during the Kaikoura event includes satellite and land based geologic and geodetic observations, which support a model with substantial shallow crustal faulting; while seismologic and tsunami observations and models indicate substantial moment release (and slip) along the southern segment of the Hikurangi megathrust.

Evidence for Crustal Faulting



Hollingsworth et al., GRL, 2017

Landsat8 Optical Image Correlation showing regions of major crustal displacements

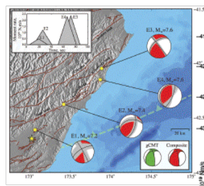


Clark et al., EPSL, 2017

(Left) Faults with significant co-seismic rupture; (right) kinematic model of fault slip on mapped faults with majority of slip on upper-crustal faults

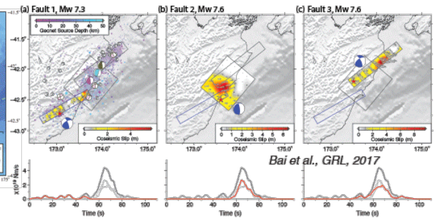
Surface faulting with significant slip (5-10+ meters) on multiple faults along the coastal region of northern South Island mapped by satellite, land-based, and geodetic observations (with assumptions of substantial deep slip on faults) can generate a focal mechanism similar to observed GMT solutions

Evidence for Megathrust Faulting



Duputel and Rivera, PEPI, 2017

Composite seismological rupture model involving both shallow strike slip and deeper thrust faulting

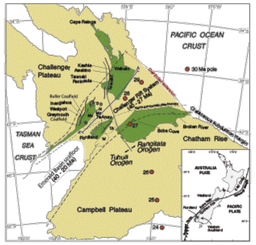


Bai et al., GRL, 2017

Tsunami signals indicate sizeable seafloor displacements in addition to onshore surface ruptures. Coupled seismological and tsunami models indicate 3 primary moment-release events

Seismologic and tsunami observations and models indicate a composite set of rupture planes that include shallow oblique/strike-slip motions and deeper dip-slip motion on an assumed plate interface. Tsunami model results indicate slip to shallow levels near the trench. According to the Bai et al. model, approximately 40% of the total moment release occurs on the megathrust (Fault 2 in model at left), similar to the Duputel and Rivera model

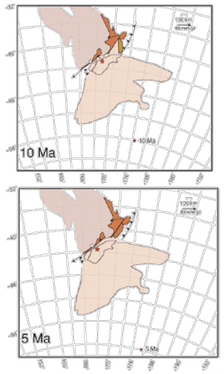
Plate Tectonic Evolution of the Kaikoura EQ Region



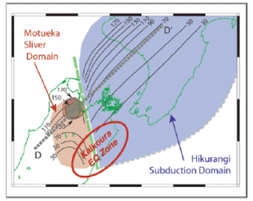
Furlong and Kamp, Tectonophysics, 2013

The current configuration of the New Zealand continent (Zealandia) has been produced over the past ~ 30 Ma as a plate boundary developed between the Australia and Pacific plates. As the Pacific side of the plate boundary translates south-westward, the Hikurangi subduction zone has developed; its southern edge is tied to the north-east corner of the South Island.

The Kaikoura earthquake sequence straddles this southern edge of the subducting slab, with its initiation south of the slab edge and propagation into the subduction zone



Furlong and Kamp, Tectonophysics, 2009

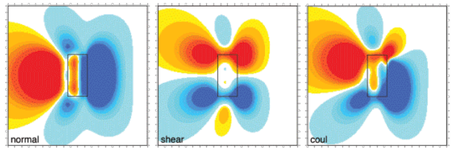


Furlong and Kamp, Tectonophysics, 2009

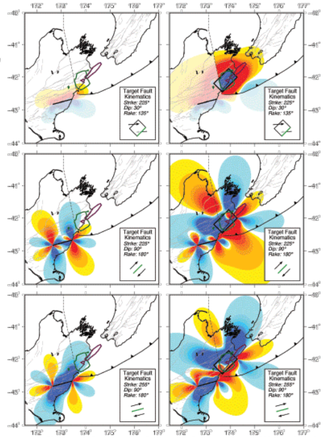
Co-seismic Stress Triggering, Decoupling and Extreme Fault Displacements

Seismological analyses indicate that the earthquake initiated as a crustal strike-slip fault in the south; the subsequent rupture of the megathrust and the major upper-plate faults was nearly simultaneous.

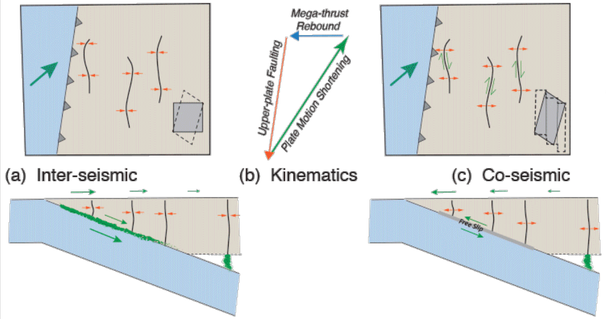
Stress modeling indicates that the initital strike-slip sub-event would positively load the megathrust interface (but not the surface faults). Rupture of the megathrust significantly loads the upper plate faults.



The principal effect of the megathrust rupture on the coulomb stress conditions in the overriding plate is to substantially reduce the normal stresses acting on those structures. Little change in the shear stress occurs on these faults.



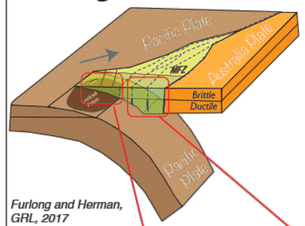
(left) models of stress changes with initial trigger event; (right) combined effect of initial trigger and megathrust



During interseismic intervals, strain accumulates as a result of coupling between the obliquely subducting Pacific and overriding Australia plates. (left)

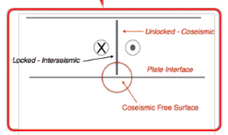
During megathrust rupture, the upper-plate faults above the rupture are decoupled at their base and unclamped (reduction in normal stresses) allowing nearly complete strain release along those structures and extreme fault slip. Once rupture ends they are again coupled at their base.(right)

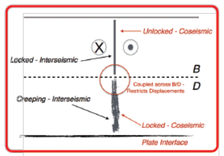
Faulting and EQ Sources in the Kaikoura Region

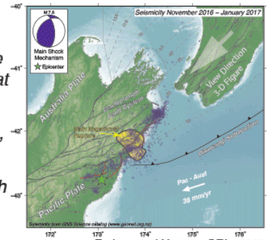


Furlong and Herman, GRL, 2017

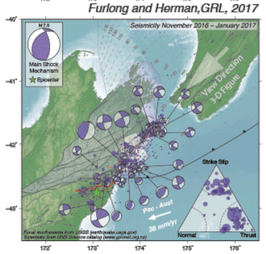
Surface faults activated during the Kaikoura earthquake generally overlie the subducting Pacific slab (which is at a depth of less than ~ 25 km). As a result, these faults terminate at the plate interface while still in the "brittle" deformation regime. The slab is deeper beneath the main Marlborough Faults (west of the Kaikoura faults), which likely include a ductile shear zone at their base.





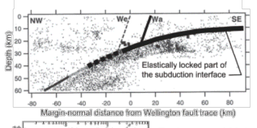


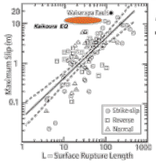
Furlong and Herman,GRL, 2017



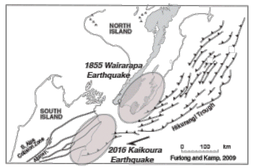
During megathrust rupture, the Kaikoura faults will be decoupled at their base from the subducting slab. Marlborough Faults include deeper ductile shear zones that behave as locked features co-seismically.

Implications for Subduction Zone EQs





Rodgers and Little, JGR, 2006



The 1855 Wairarapa earthquake, with an estimated M = 8.1 occurred in a tectonic setting similar to the Kaikoura event. There were also extreme fault displacements along the Wairarapa fault (> 18.5 m). It is likely an example of a Kaikoura-style event

The 2016 Mw 7.8 Kaikoura earthquake produced synchronous faulting on the plate boundary subduction interface and on a suite of faults above the rupture zone in the overlying plate. Although displacements on some surface faults are extraordinary, seismological and tsunami data and modeling indicate that there was also megathrust involvement with rupture reaching to, or nearly to, the trench. The 2016 Kaikoura NZ earthquake represents a mode of subduction zone rupture that must be considered in other regions.

What About the Oral Presentation and Discussion?

- You should prepare an oral “opening” discussion of your exhibit, tailored specifically to make the work understandable to a broad audience - and explain its importance.
- This discussion should be clear and concise, and should include the major points presented on the poster. Systematically lead the viewer through your poster; use your visual aids!
- It must not exceed 3-5 minutes; judges have many posters to visit
- If this work is part of a larger collaborative project, your intro presentation should clearly describe your role in the overall project.

This is NOT a 15 minute Presentation!!!

Getting Started

- Then What
- Free-ranging discussion with questions from the viewer
- An opportunity to provide further details on your work, where it is headed, and your goals
- Discussions will vary based on viewers background, interest, familiarity with your branch of geoscience - Be Prepared to adjust for depth of details etc.

Oral Presentation

- Business Casual - this is a *Professional Event*, treat it accordingly
- 3-5 Minute Intro Conversation – to get things started! Stand up Straight, Smile, Initiate Greeting; Speak Clearly and Slowly (noisy environment)
- Engage Visitor
- Ask Questions – Helps to know your audience
- Ask If Any Questions After Each Section, as appropriate - but DON’T Belabor this
- Leave a note if you need to leave your poster for a quick break
- Stay until end of exhibition period (even if you have seen all of your judges) - it is not only about the Judges

Oral Presentation - Recap

- Refer between Poster and Visitor
- Generate Interest - Have You, Did You Know, Why Care, How, What Worked, What Next
- Eye Contact, Point to Poster When Explaining
- Practice
- 3-5 MINUTE “intro”!

T21D-2844: Time-varying Upper-plate Deformation During the Megathrust Subduction Earthquake Cycle

Kevin P. Furlong[1] Rob Govers[2] Matthew Herman[1]

1 Department of Geosciences, Penn State University

2 Faculty of Geosciences, Utrecht University

Introduction/Motivation

Although the deformation behavior of subduction zones through the earthquake cycle roughly matches an elastic-rebound model, recent observations of deformation from the pre-, co-, and post-seismic periods along major subduction boundaries shows significant (and systematic) spatial and temporal variations.

This variable behavior has led to propositions for a wide range of rheological and mechanical processes at work to produce these signals. Here we explore the role of a relatively simple elastic/visco-elastic subduction system rheology as the underlying cause of much of the apparent complexity in the deformational response during the earthquake cycle.

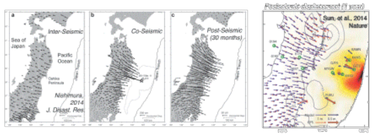
Key Points:

1. Pattern of co- and post-seismic deformation controlled by interplay between elastic and viscous processes.

2. Inferred afterslip largely a result of relaxation processes within the upper plate.

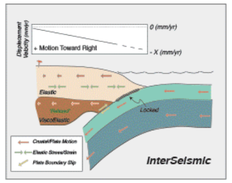
3. Coupling values vary through the EQ cycle and reflect influence of viscous relaxation and NOT actual fault coupling or locking.

Observed Deformation Through The Earthquake Cycle

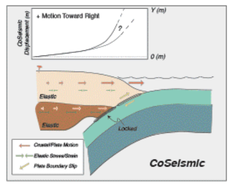


Densely instrumented subduction systems show direct evidence of the deformational response to plate interactions. The 2010 Tohoku earthquake provides insight into the late-stage inter-seismic, co-seismic, and early post-seismic response of the upper plate to slip deficit accumulation on the plate boundary interface.

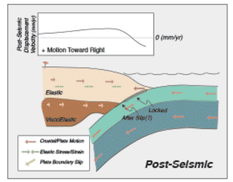
Here we explore the following conceptual model. We consider the system to be described by a lithosphere with an elastic overlying a visco-elastic rheology. At the characteristic time scale of strain accumulation (constrained by plate motions), the visco-elastic regions can relax stresses as they develop. During co-seismic elastic strain recovery, these visco-elastic regions hinder relaxation in the adjacent elastic layer.



Late in the cycle, the signature is dominated by elastic shortening of the upper-plate and subducting slab.

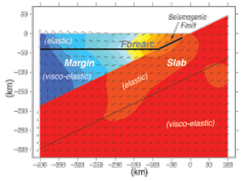


During the co-seismic interval, the seismogenic section of the plate boundary (locked during the inter-seismic period) slips. Down-dip the plate boundary is effectively locked during the co-seismic interval. Displacements (toward the trench) in the upper plate are partly inhibited by its coupling to the underlying low-stress visco-elastic layer, except in the region of the seismogenic fault.



During the initial post-seismic interval, the seismogenic fault re-locks, but the upper plate continues to relax (i.e. move trenchward). Over time, the transition from toward-trench (relaxation) to arc-ward (strain accumulation) motions migrates away from the trench. The observed signal varies through time.

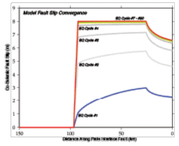
Modeling Approach



Finite-element model - Rheological layering reflecting thermal-mechanical structure of lithosphere.

Constant velocities on slab lateral sides, so that the slab itself can deform during the earthquake cycle.

Earthquakes result from stress buildup: shear stresses are allowed to relax periodically. The frequency of these (large) earthquakes is imposed, the co-seismic slip is not.



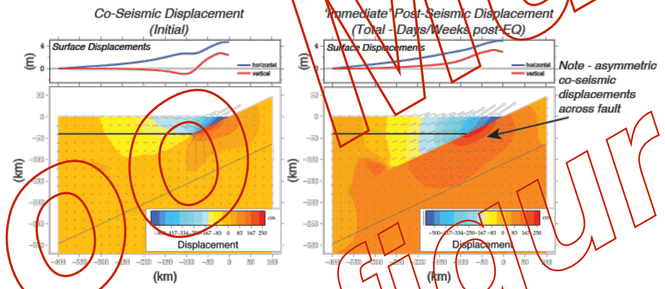
Inter-play between relaxation time of system (viscosity) and time scale of the earthquake cycle.

Numerous EQ cycles are run to reach dynamic steady state - after ~ 10 cycles (dependent on EQ cycle time and viscosity). We evaluate response during cycle 19/20.

This utilization of multiple EQ cycles allows us to explore the tectono-seismic process of partial co-seismic relaxation, and continued relaxation concurrent with the subsequent acquiring of slip deficit in the post-seismic time interval. This produces results that differ from using the proxy of co-seismic loading and its relaxation, typical of single cycle models.

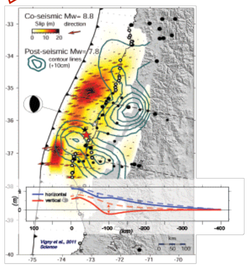
Results shown here are for EQ cycles of 200 years between events, and plate motions of 4 cm/yr - 8 m slip per EQ

The Co-seismic Interval



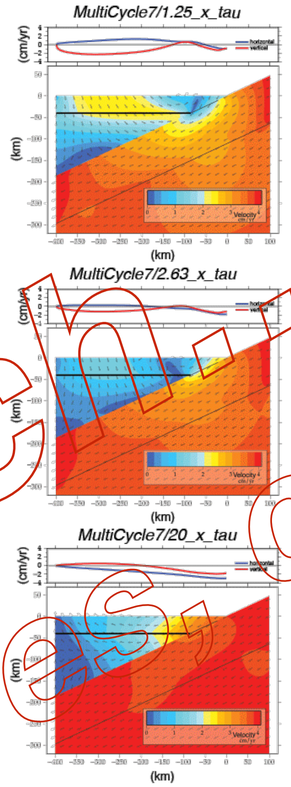
During the co-seismic interval, the seismogenic fault is unlocked and allowed to slip. A complex pattern of surface displacements results (above left). In the immediate post-seismic interval (after the fault is re-locked) there is additional displacement associated with displacements adjacent to the plate boundary down-dip of the locked zone (after slip?) (above right).

Observations from the 2010 Maule, Chile EQ show a pattern of co-seismic vertical motions consistent with model results. (left)



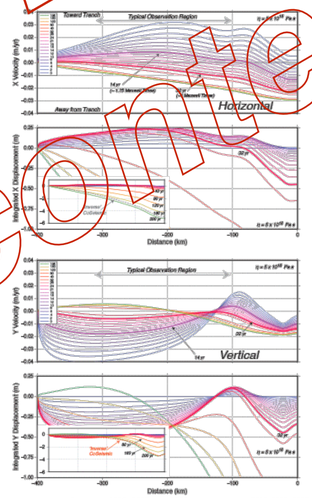
The immediate post-EQ equilibration produces a pattern of surface displacements that will map to the plate boundary fault down-dip of the co-seismic slip patch (compare solid and dashed curves in figure on right), as seen in the results from the Maule EQ. (right)

Modeling Results

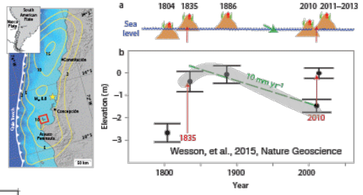


Results through the EQ cycle. Convergence rate is 4 cm/yr and EQs occur every 200 years. Maxwell relaxation time (tau) is ~ 8 years for results shown here (unless noted). In each panel at left, upper curves show surface velocity (e.g. GPS derived observations), lower panel shows displacement rates within the model.

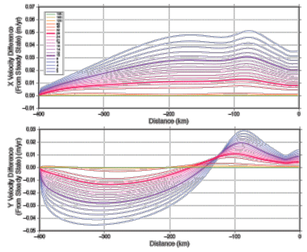
In panels below, surface displacements at time steps through cycle are shown. Upper curves are surface velocity, lower curves are cumulative displacement. Inset shows post-EQ displacements compared to co-seismic displacement (inverted). Note - migration away from trench of the transition from trenchward to arcward motions during the cycle



Pattern of uplift/subsidence in vicinity of the 2010 Maule EQ produce by the model is consistent with observations over the entire 200 year EQ cycle (grey curve superimposed on figure from Wesson et al., 2015)



Transient vs Steady State

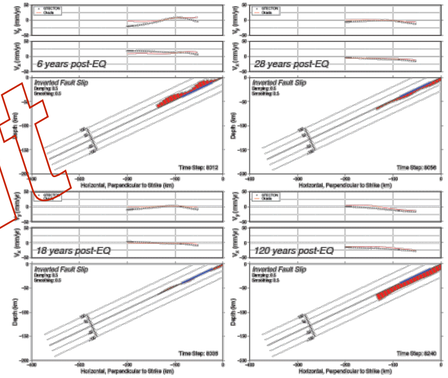


Observed inter-seismic surface displacements are the result of two simultaneous processes - the elastic shortening that occurs whenever the fault interface is locked, and displacements associated with viscous relaxation.

Figure at left shows the viscous component - the long-term, steady-state elastic component has been removed. EQ slip deficit is associated with the 'steady-state' process, which occurs throughout the EQ cycle.

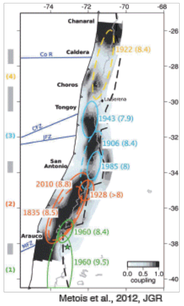
Coupling

Observed surface displacements are often used to infer patterns of fault coupling or locking. Most such models assume elastic half-space conditions (Okada solution), and map surface displacements onto equivalent back-slip conditions on the fault plane. Here we replicate that analysis using our model results as observations in the inversions for fault coupling. In all cases, the actual model is full locking on the seismogenic fault and zero coupling elsewhere. (Positive is fault slip, negative is locking)

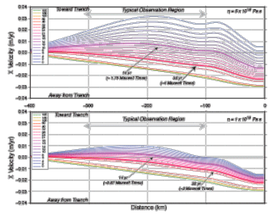


Early in cycle (6 years post-EQ), observations (in realistic observing zone) show trenchward motions which will be mapped into afterslip. By 18 years post-EQ (Maxwell time of 8 years), there is little surface displacement as elastic strain is balanced by viscous relaxation - this maps to near-zero coupling. For the initial 50-75 years of this cycle (for modeled viscosity), inferred coupling values are 50% or less of actual conditions. It is only in the later stages of the EQ cycle that an elastic inversion replicates the actual coupling conditions.

These model results imply that many cases of inferred low-coupling may rather reflect being in an intermediate stage in the EQ cycle. This hypothesis is generally consistent with the results shown at right for the central Chile subduction zone - highest coupling zones have longest time since last major EQ.



Metois et al., 2012, JGR



Viscosity

Role of Viscosity in observed signal. (right) Overall patterns are similar (and steady-state signal is the same), but amplitude of viscous response is damped at higher viscosity values. Overall patterns scales with viscosity - when EQ cycle duration is scaled to Maxwell time.

Summary

1. Afterslip appears to be a combination of actual near-fault slip immediately down dip of seismogenic patch (immediate) and toward trench displacements in upper-plate mapped into fault slip (longer lived).

2. Interplay of viscosity structure and earthquake cycle times produce varied responses that scale with Maxwell relaxation time.

3. Subduction zones with low apparent coupling likely reflect combination of processes including lithospheric strength, viscosity, and spatial-temporal history of major earthquakes - but not actual slip deficit conditions.

Too Much Text Figures Content