The Many Potential Uses of a New Global Subduction Zone Interface Geometry Model - *Implications for Seismogenic Processes*

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Why do we need to understand subduction zones?

- Damage in and around Anchorage after the Good Friday M9.2 Earthquake, 1964

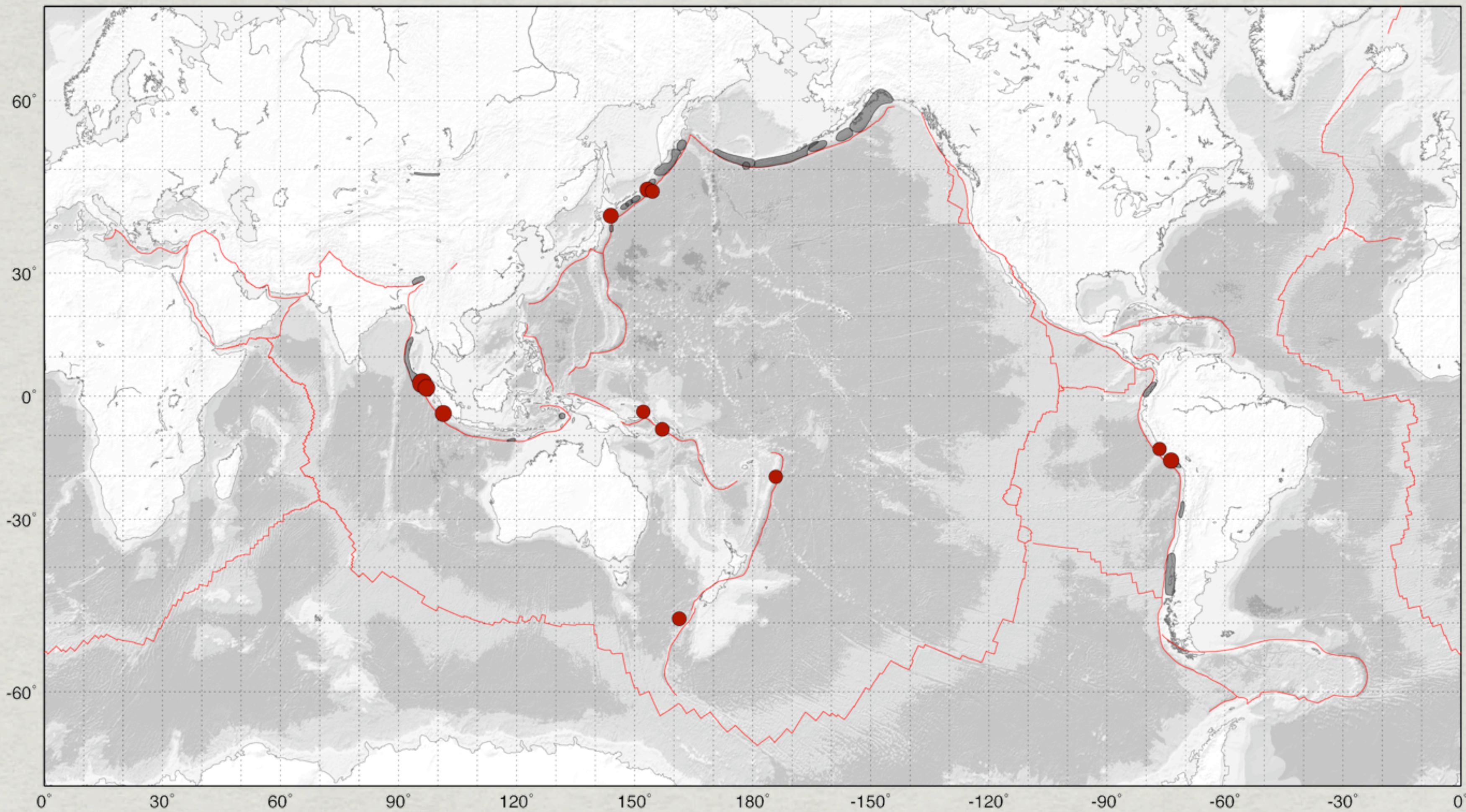
~33ft uplift on Montague Island, PWS

Subsidence trough at the head of the L Street landslide, Anchorage

Collapsed span of the One Million Dollar truss bridge, Copper River

Photos courtesy of USGS photographic library, USGS professional paper 541

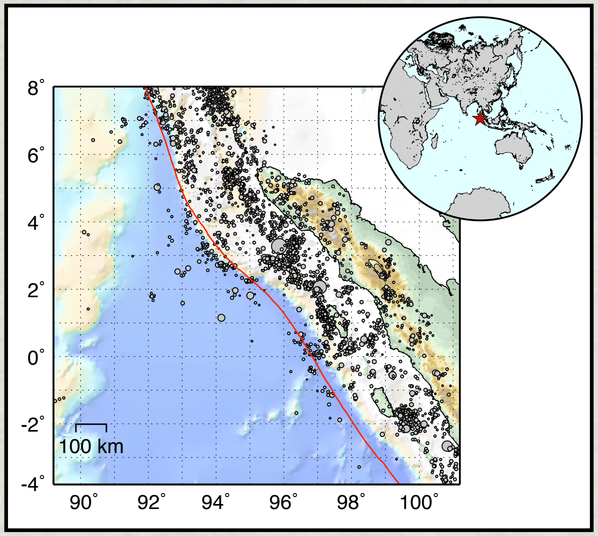
Why do we need to understand subduction zones?



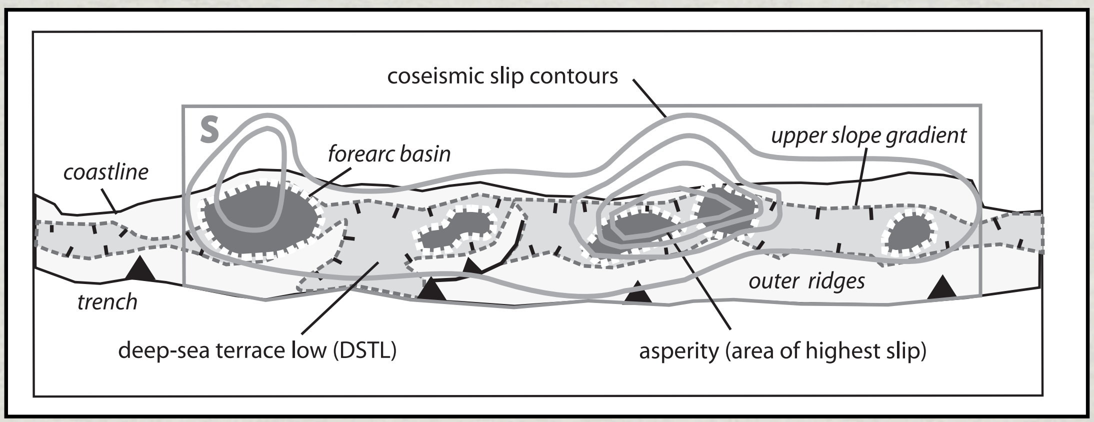
Red circles = Earthquakes of magnitude > 8 since 2000. Dark gray shading = rupture areas of earthquakes M > 8.3 since 1900 -- almost exclusively subduction zones.

How do we understand subduction zones?

In seismology, many ‘tools’ are available that allow the user to probe properties of subduction zones. From a hazards perspective, perhaps the most important of these are those from which we can infer where great earthquakes can (may) occur.



Earthquake Locations - What do uneven distributions of small/moderate EQs tell us about where very large EQs can occur?



Trench-Parallel Gravity - Correlations exist between the locations of forearc basins and rupture areas of very large earthquakes (figure from Wells et al., 2003).

How do we understand subduction zones?

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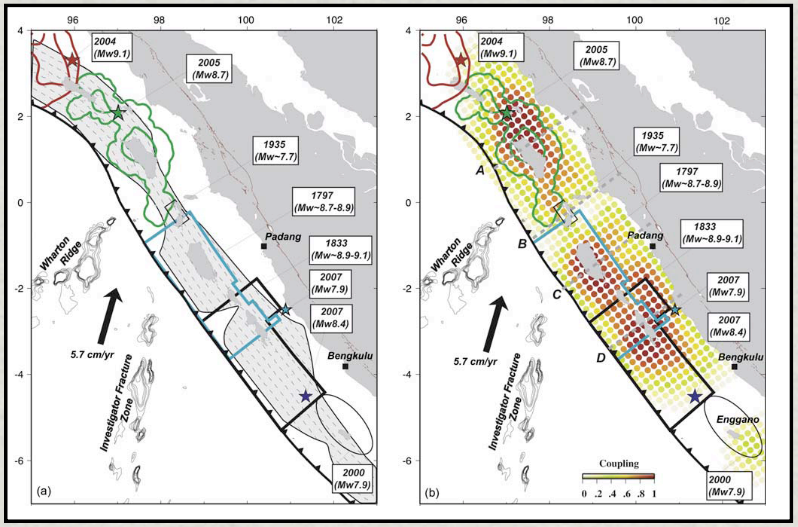
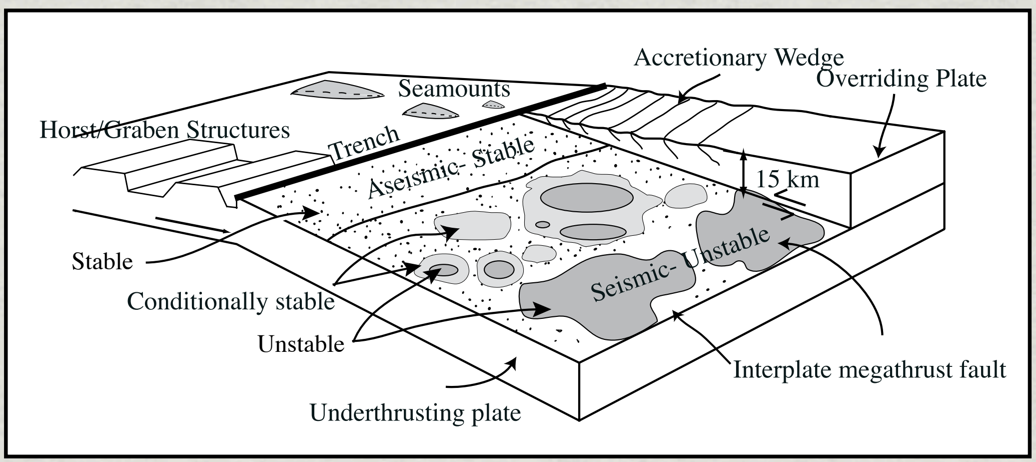


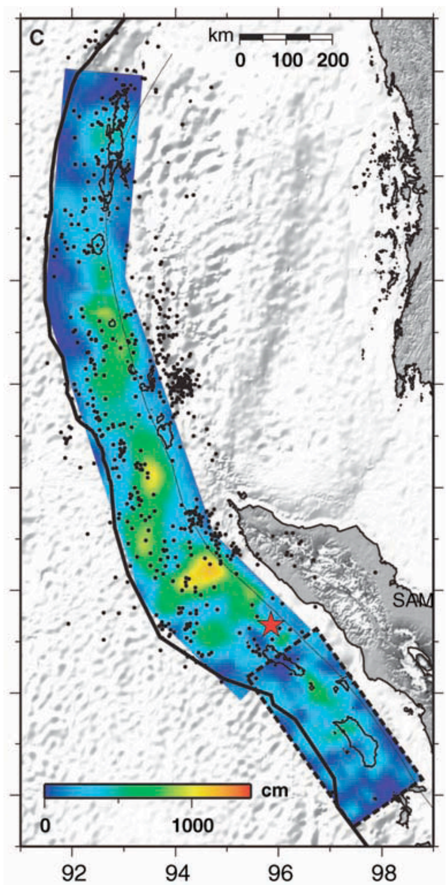
Geodesy - GPS data can help us delineate which areas of the subduction interface are locked and which are freely slipping (figure from Chlieh et al., 2008).



Sea-Floor Roughness - Correlations may exist between the locations of sea-mounts and other such topographic features, and rupture areas of large earthquakes (figure from Lay & Bilek, 2008).

How do we understand subduction zones?

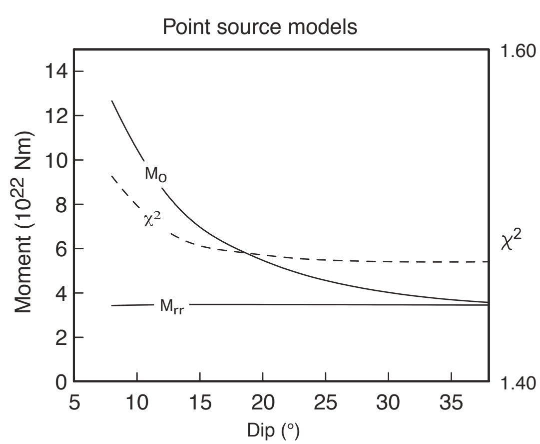
In real-time analyses and beyond, ***Finite Fault Modeling*** is a useful tool used to determine which parts of the subduction interface ruptured in past earthquakes - where did the slip occur?



Ammon et al. (2005)

For such models, the geometry of the source fault is very important:

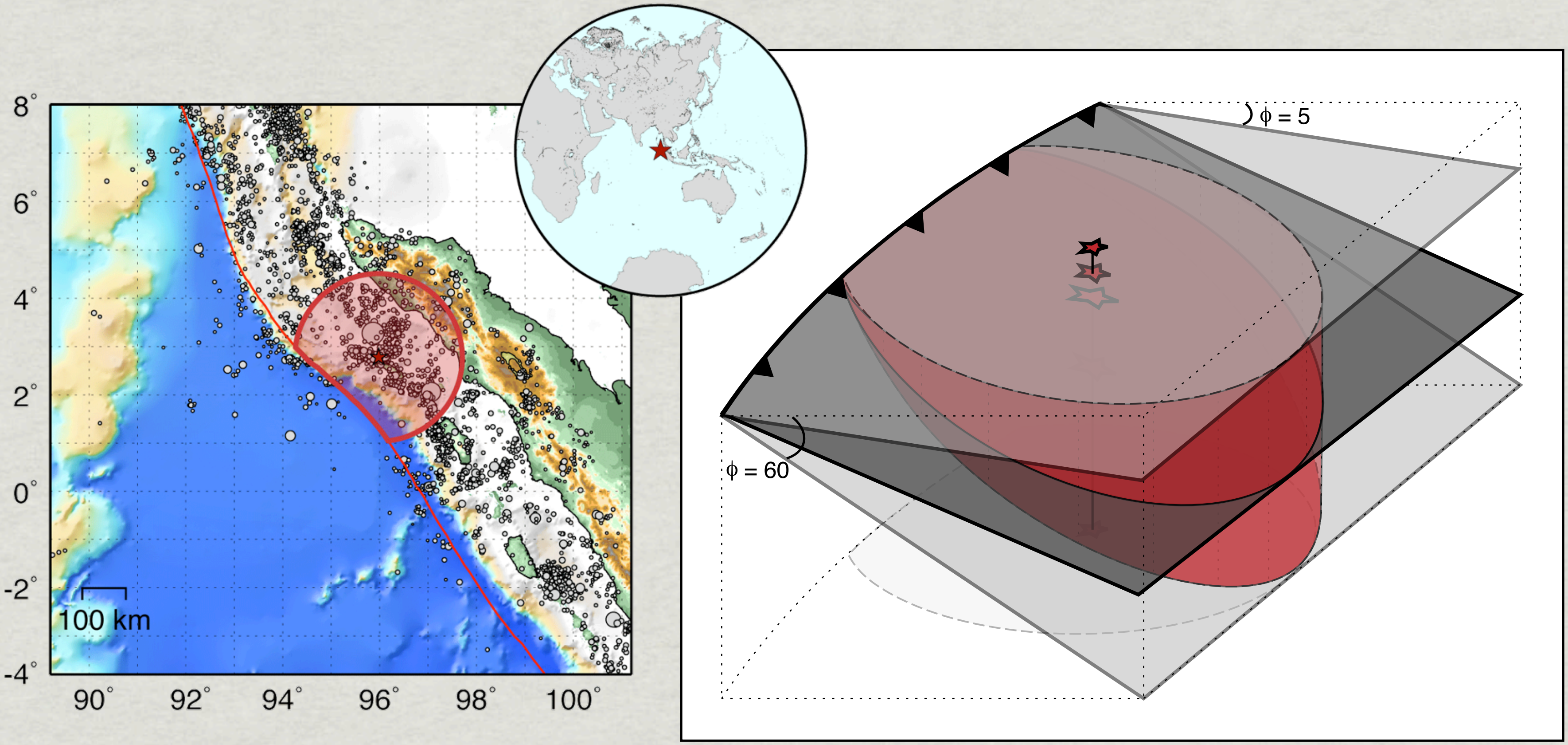
- for kinematic description of major slip
- for resolving the moment (energy) released



Banerjee et al. (2005)

At shallow depths, small changes in dip can result in a change in moment by as much as a factor of 2.

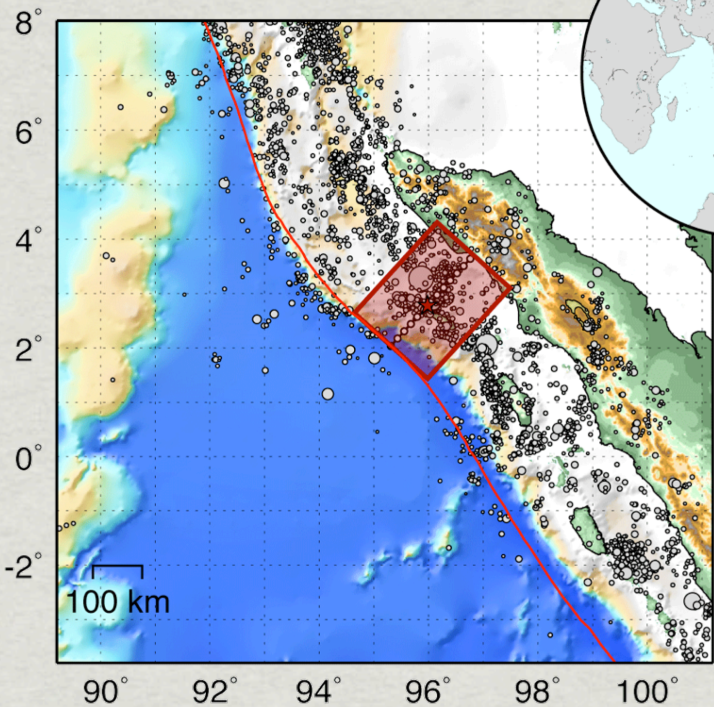
Methodology - Defining The Data Set

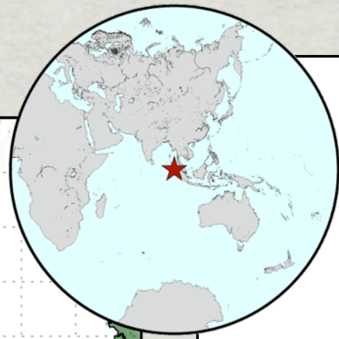


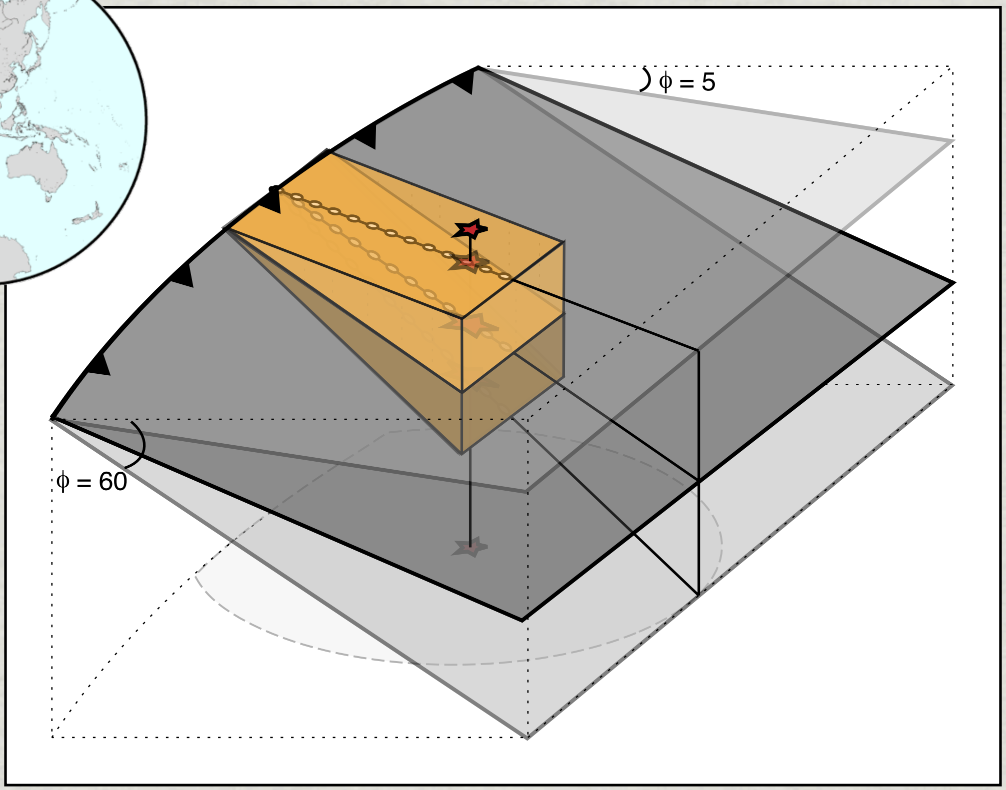
Select events within a broad radius of a location of interest.

Use these events to define the subduction direction; i.e. the strike of the interface.

Methodology - Defining The Data Set



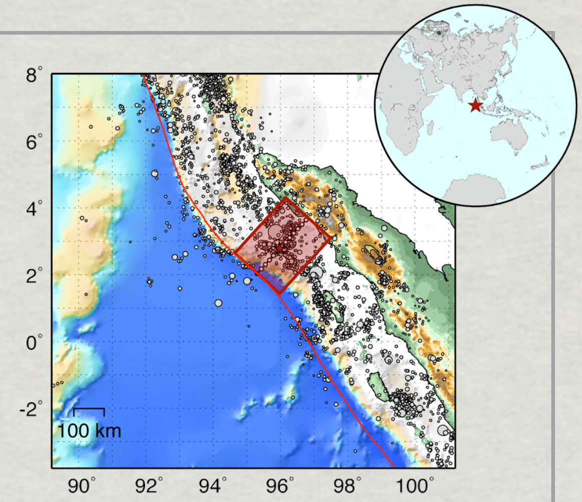


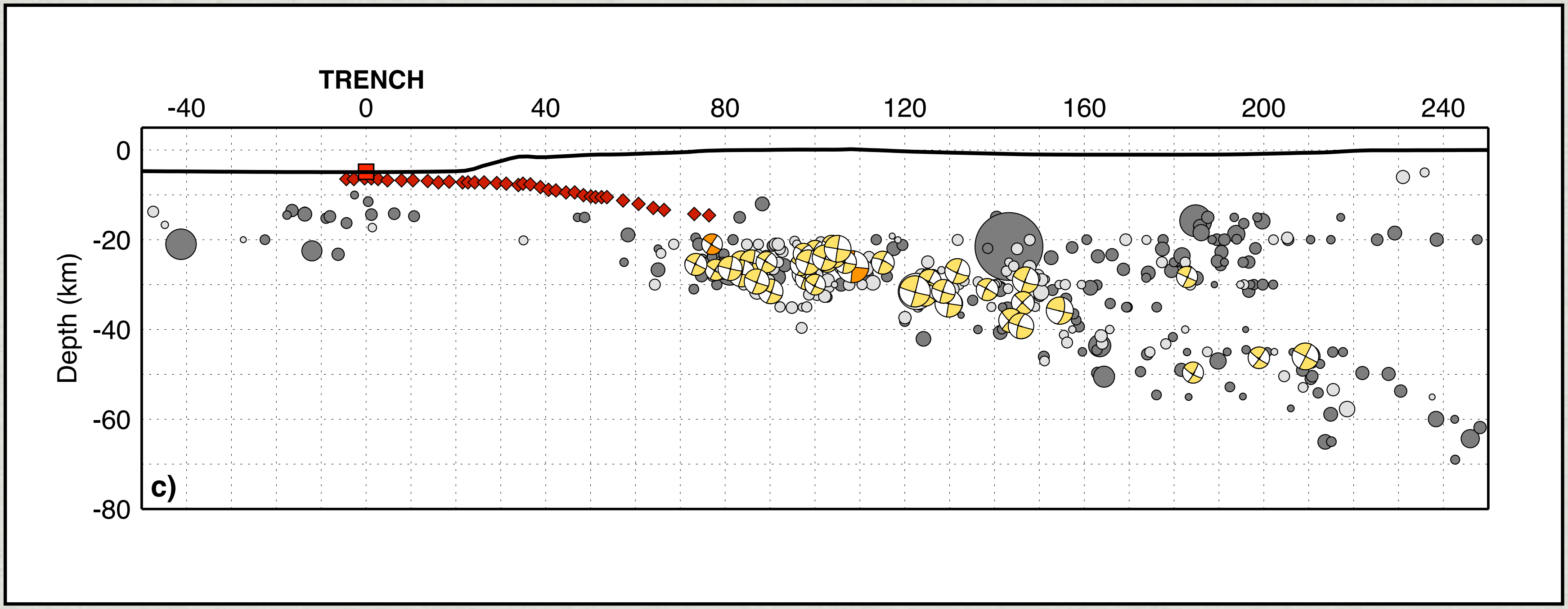


Using that strike, construct a reference profile from the trench (observed surface faulting location) to some point down dip (250 km).

Restrict data to those within some distance of the profile (100 km), to reduce effects of along-strike variation.

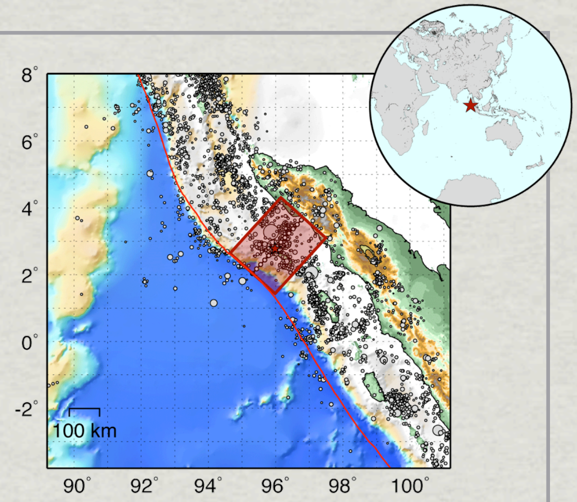
Example - Constraining Geometry in Two Dimensions

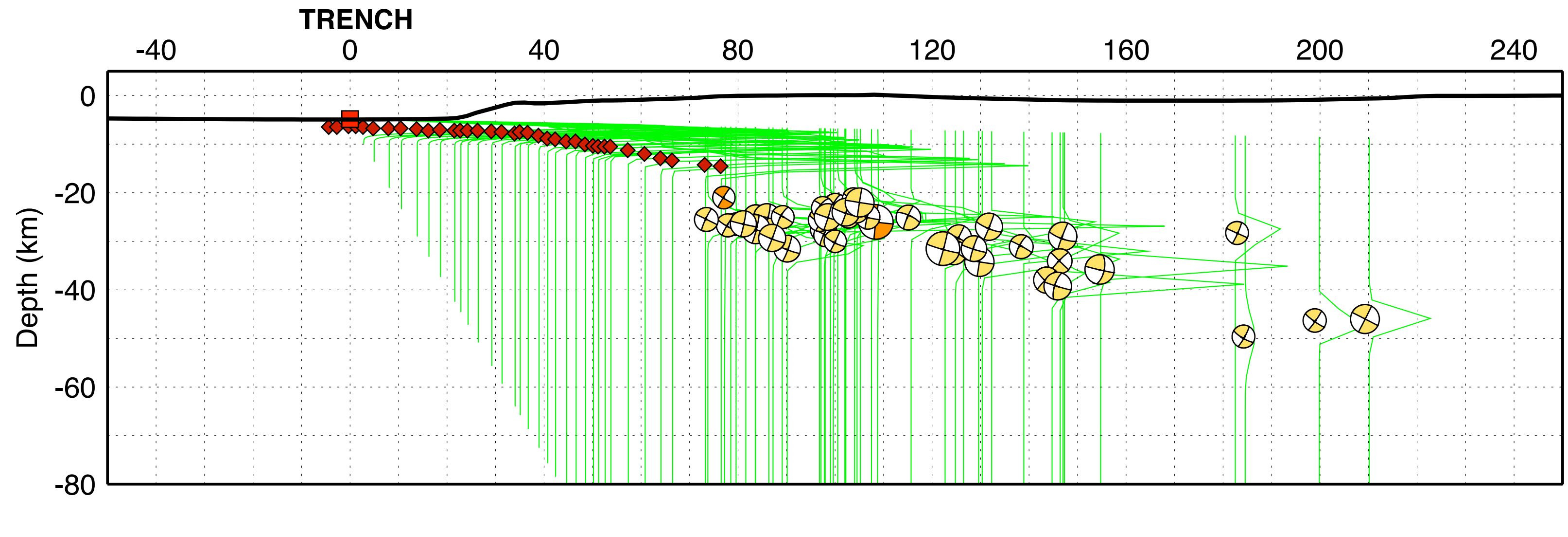




'Beachballs' = CMTs. We use these to constrain geometry, as we know these events are subduction related. Red diamonds = Data from local seismic reflection surveys (from collaborators at Menlo Park).

Example - Constraining Geometry in Two Dimensions





Each data point has some uncertainty associated with it - use these uncertainties to construct probability density functions around each point.

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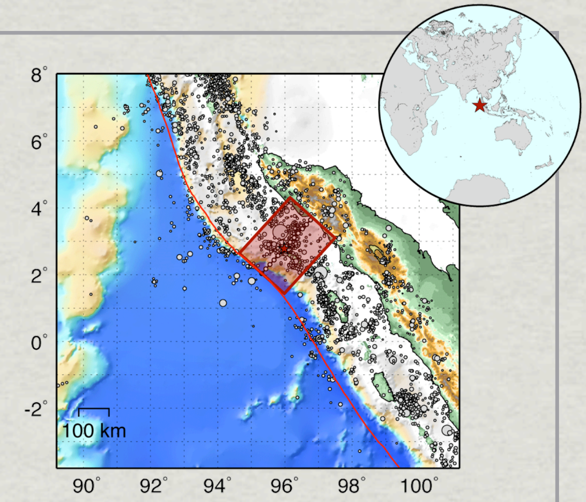

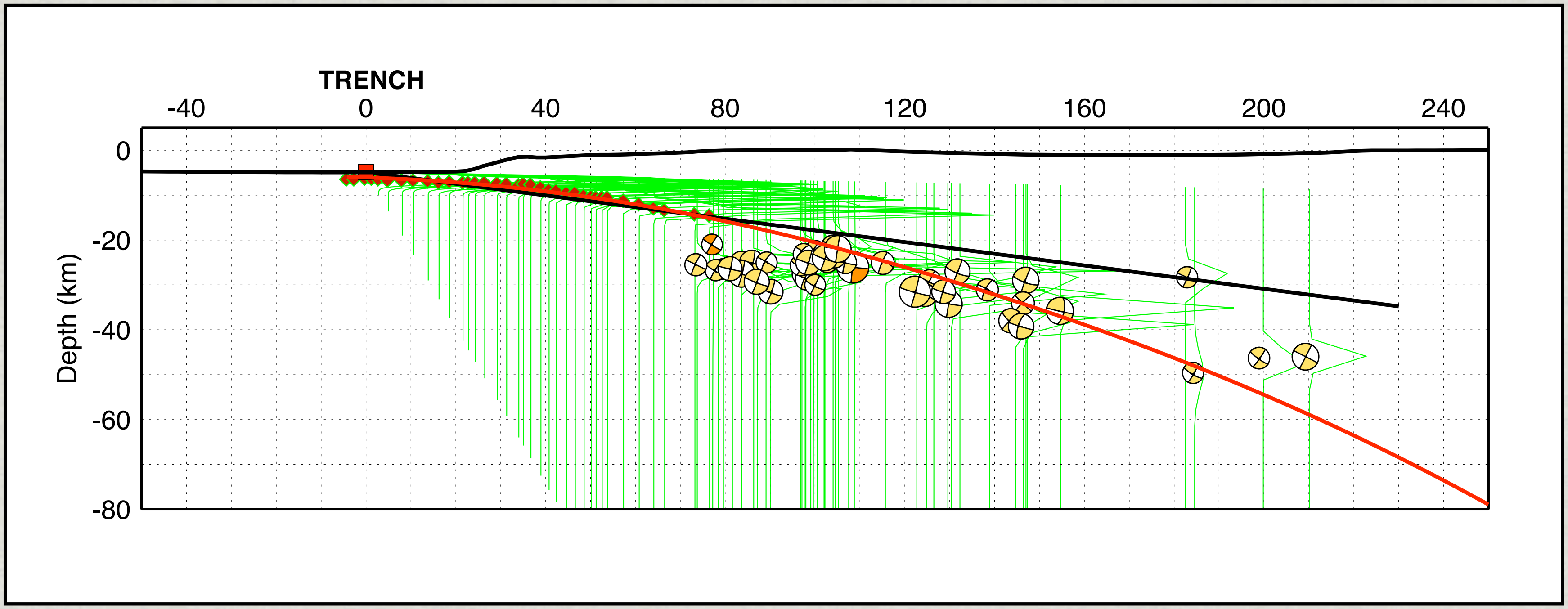

Map a best-fitting single plane (black) or polynomial (red) to these data ==> most likely subduction interface.

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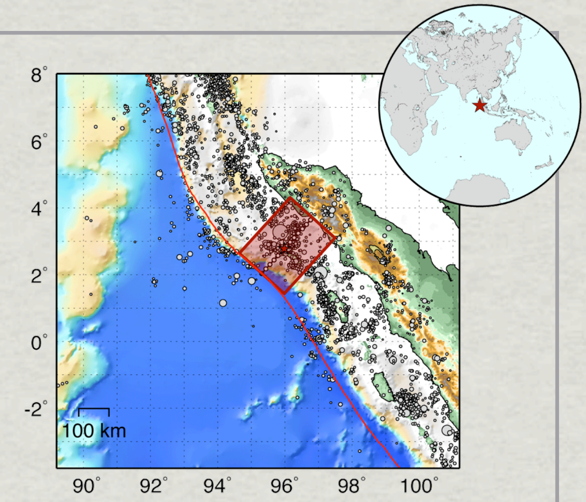
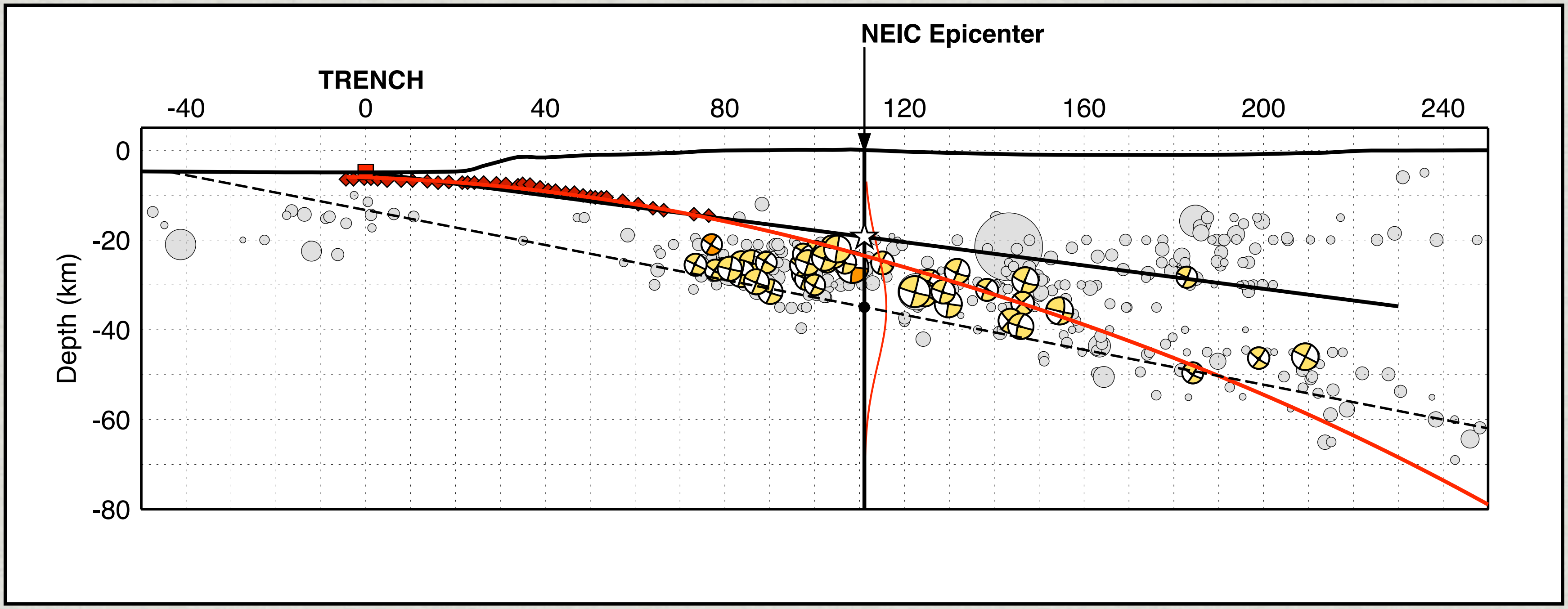
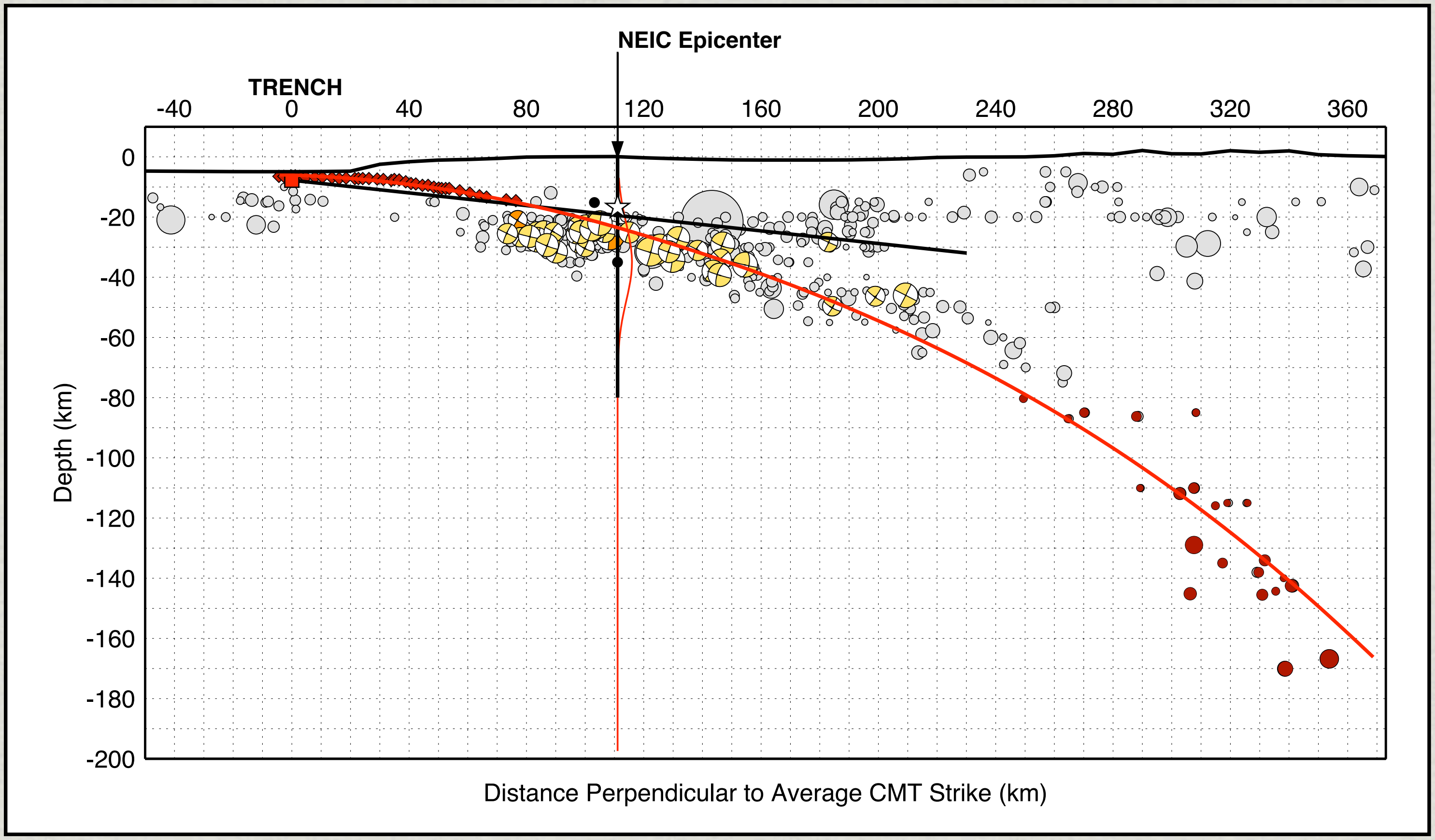




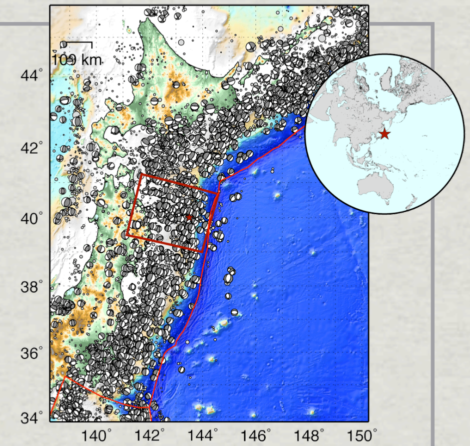
Compare to the single plane we would have chosen based on an individual CMT solution (dashed black) ==> Big difference in depth and dip ==> error.

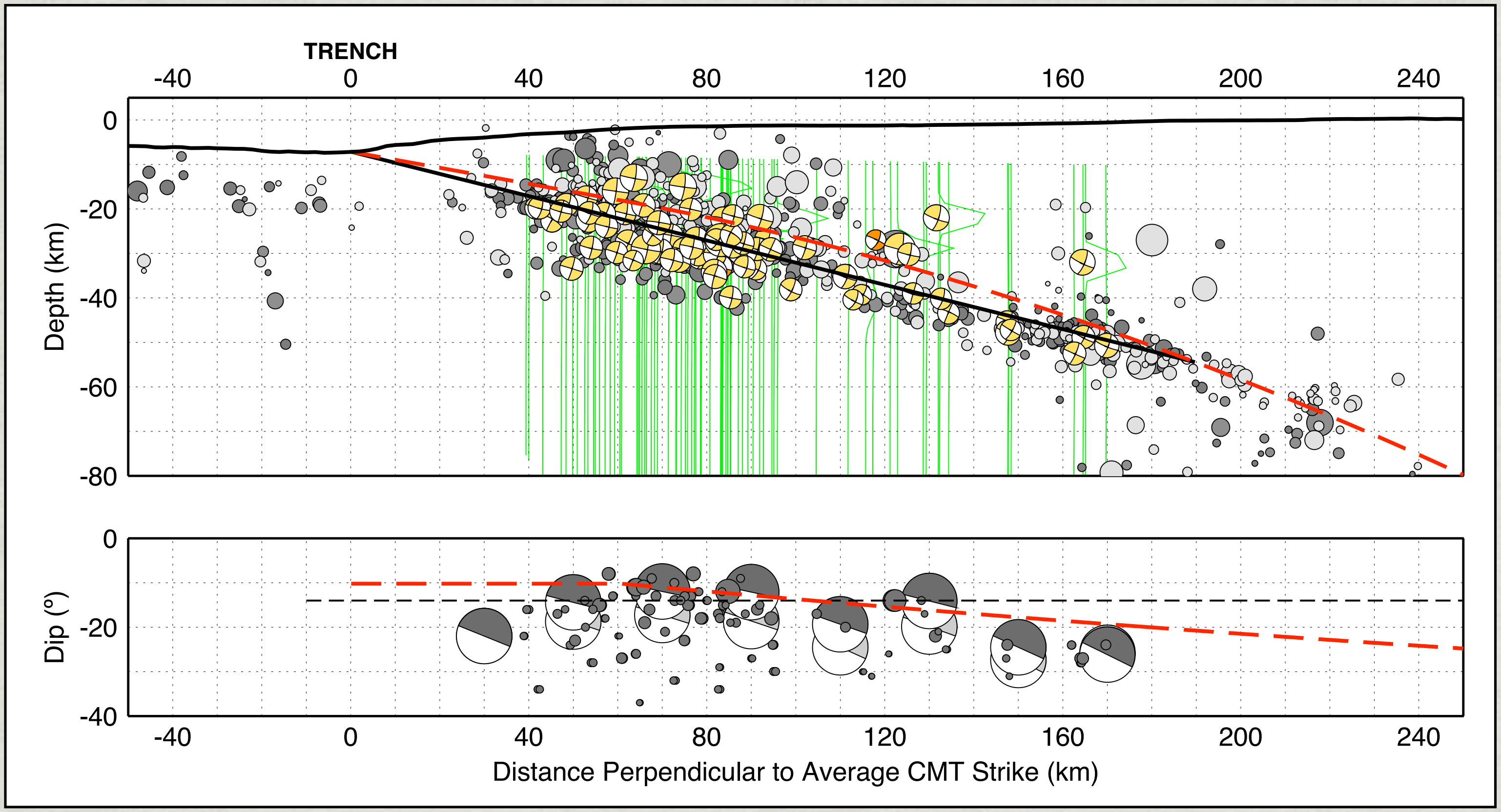
Example - Constraining Geometry in Two Dimensions - Using Deep EQs



Intermediate-depth earthquakes (~ 80-400 km) are all subduction related, occurring within the subducting oceanic plate. We can use these locations to inform us of the geometry of the subducting plate below the seismogenic zone.

Example - Japan Trench, Offshore Central Honshu





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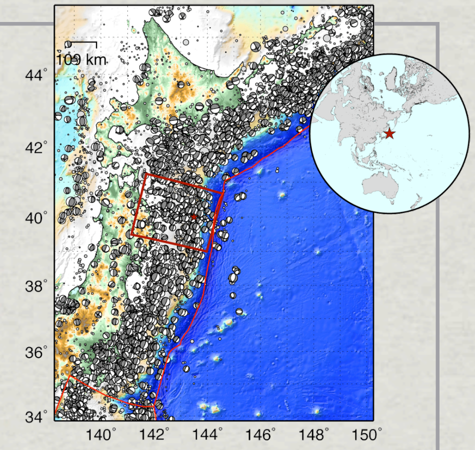
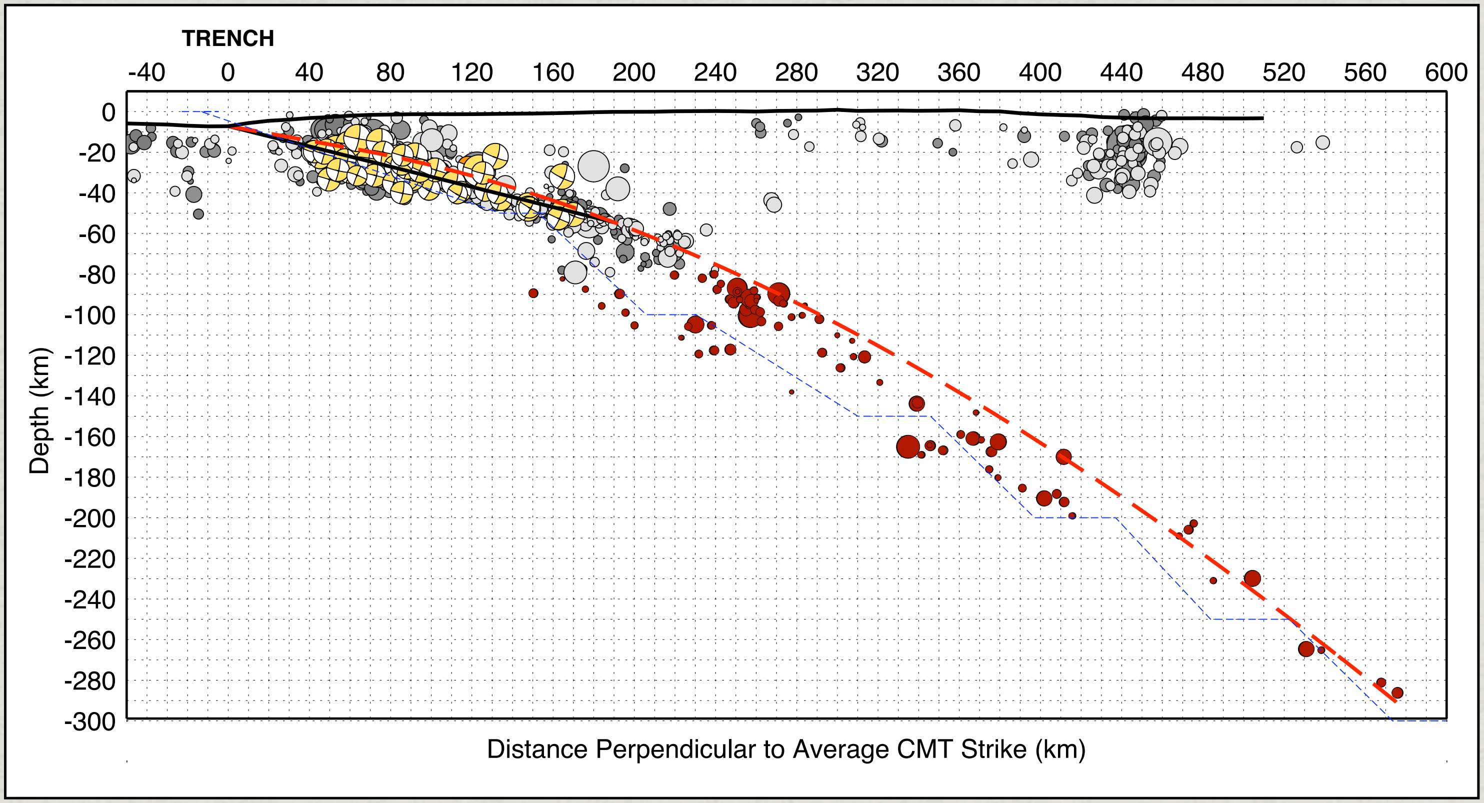
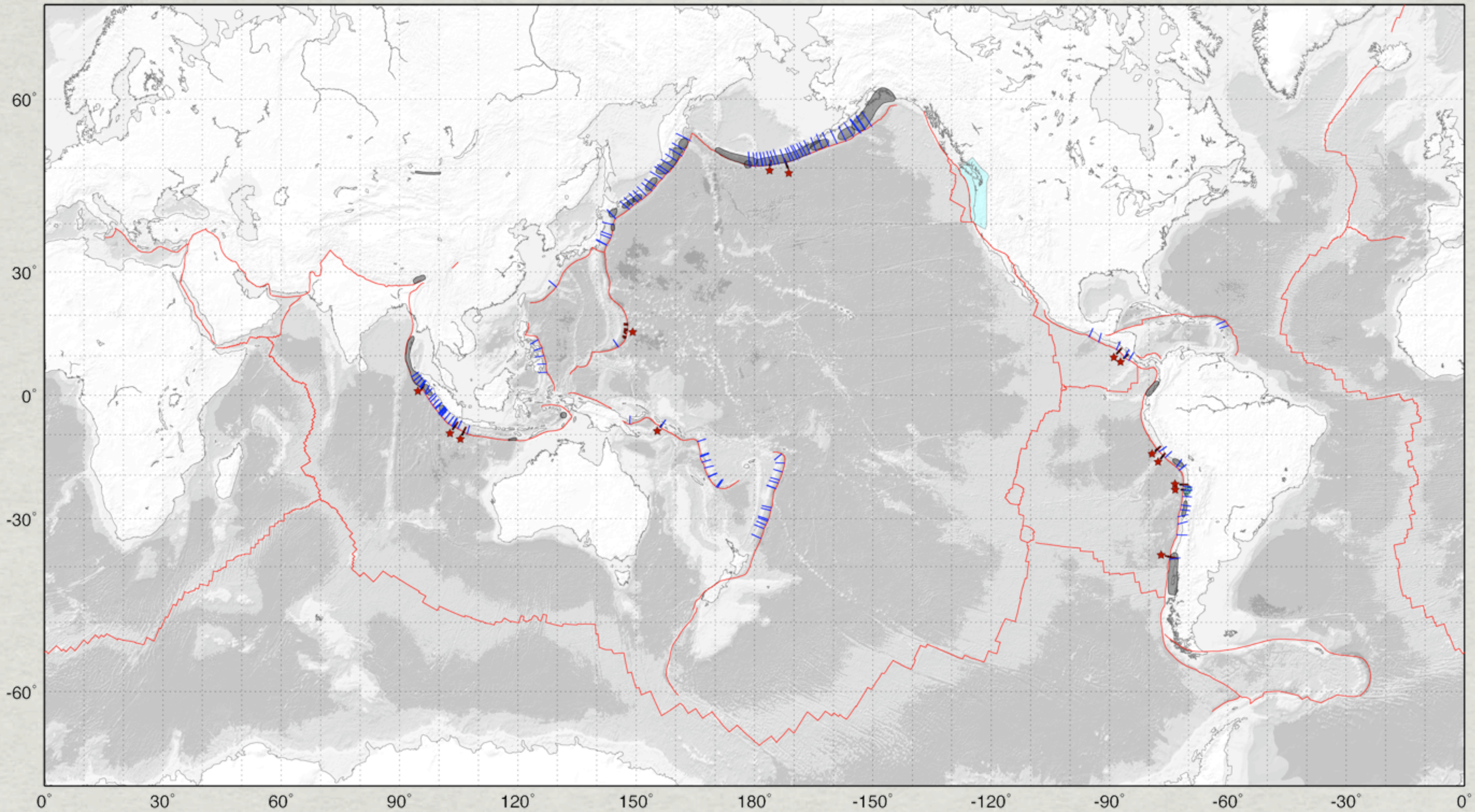




Constraining Geometry in Two Dimensions - Global Coverage



Constraining Geometry in Two Dimensions - Implications

New approach to constraining subduction zone interface geometry:

- Combines independent and complementary data sets
- Data limited to those data that represent subduction
- Additional uncertainty information incorporated

Data matched well for:

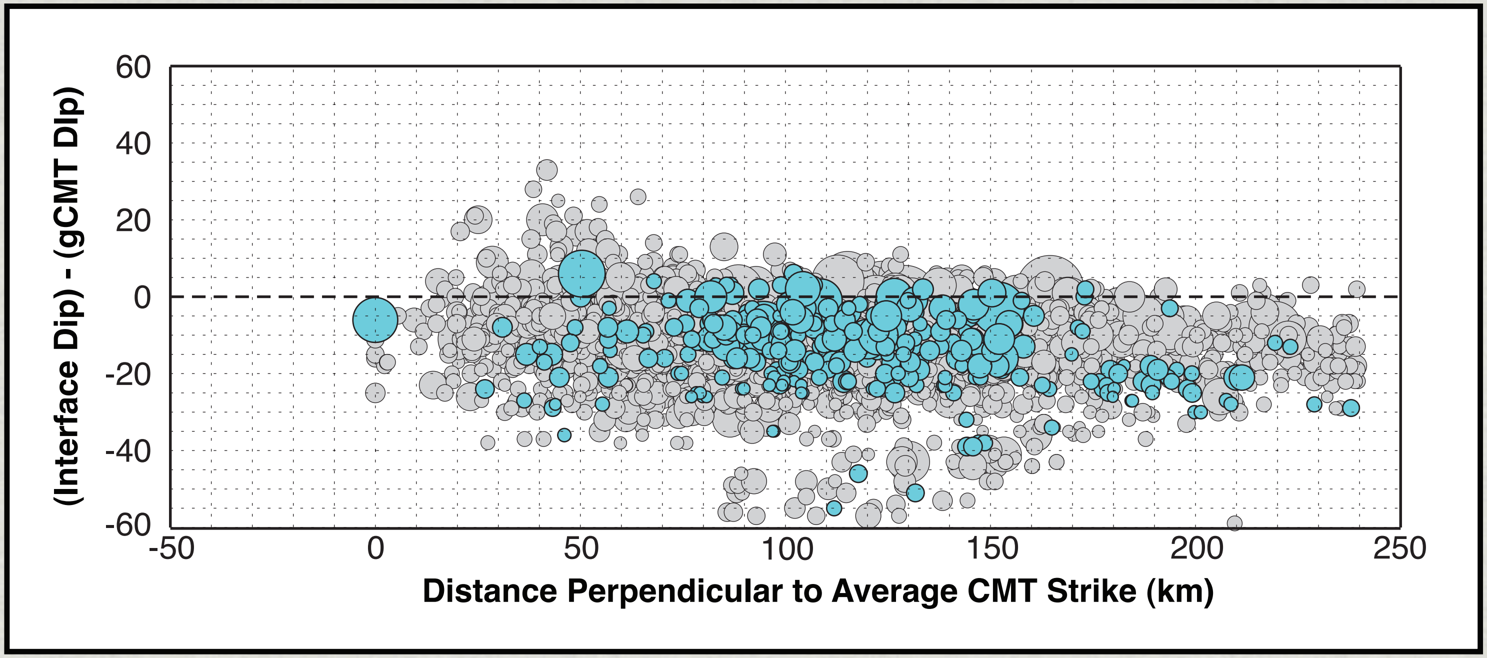
- Planar solutions (for the shallow seismogenic zone only)
- Non-planar solutions (extending to the deeper Benioff Zone)

==> Most-likely subduction geometries worldwide in a fully automated manner.

Complications arise when seismicity is diffuse (e.g. Cascadia).

Systematic differences exist between the dip of our most-likely slab interface(s) and the dips of best-fitting fault planes from individual CMT solutions on or near the subduction thrust in all subduction zones analyzed.

Dip Discrepancy? Interface Dip vs gCMT Dip - Planar Interfaces



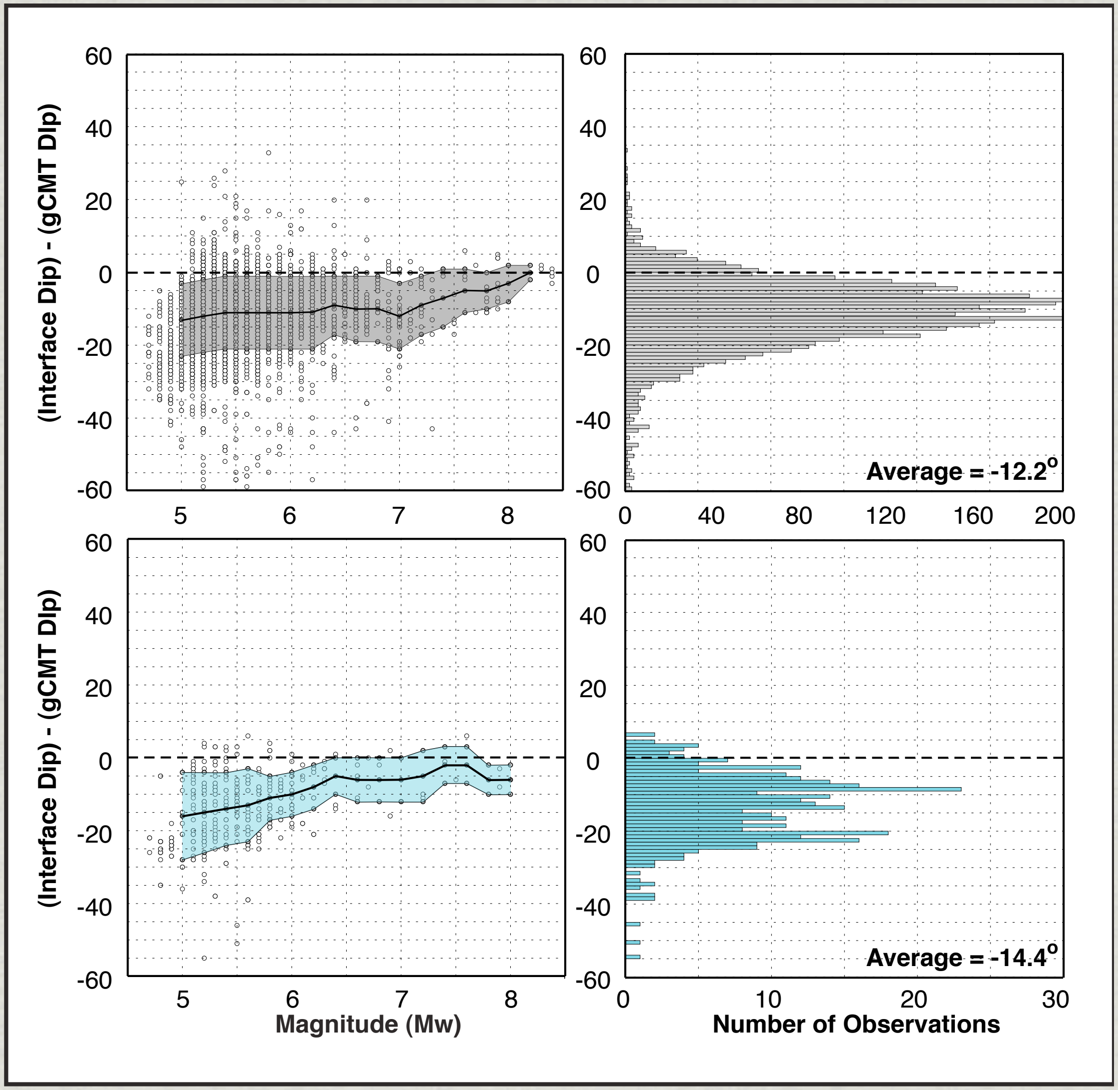
Gray circles = observations from all constrained locations.

Blue = Those profiles with additional constraint from shallow active source data.

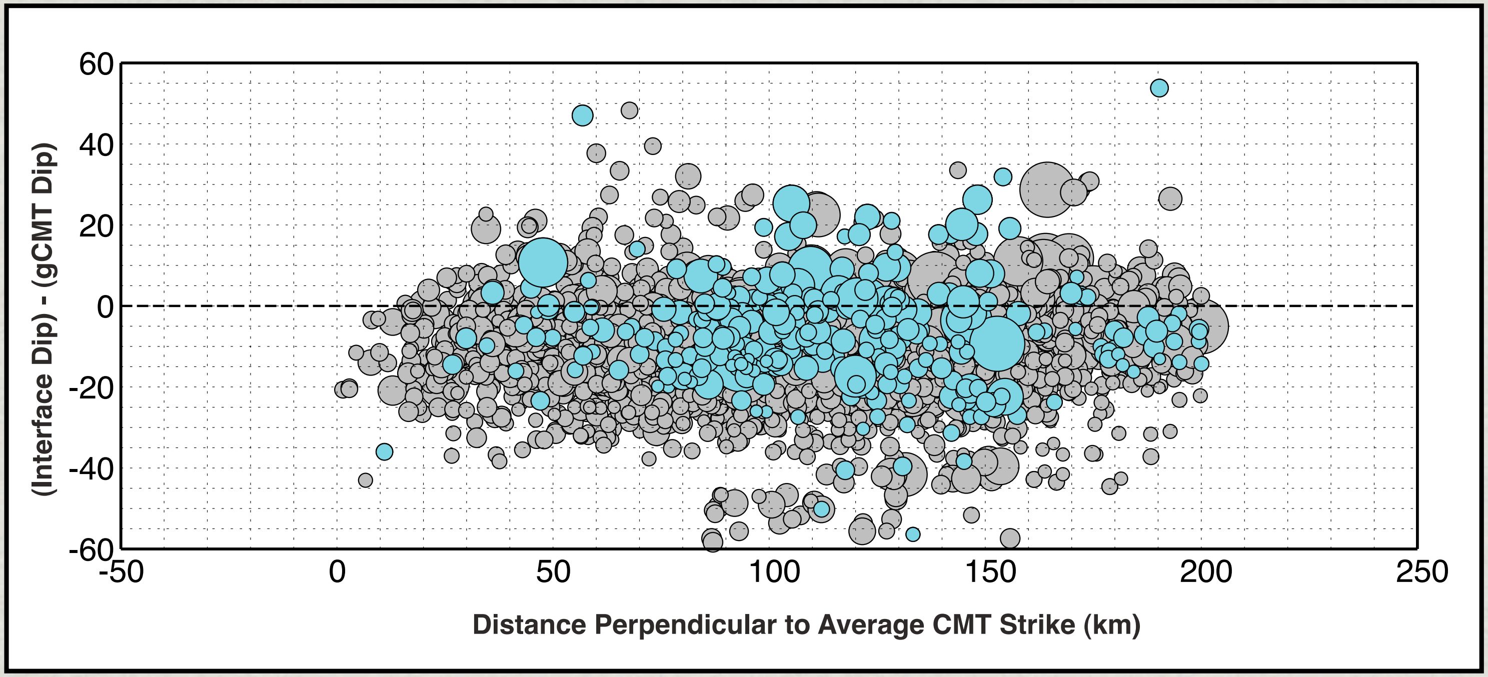
In general, CMT dips are steeper than is the subduction thrust.

This discrepancy may be magnitude-dependent, with bigger events aligning more closely with the main interface.

Dip Discrepancy? Interface Dip vs gCMT Dip - Planar Interfaces

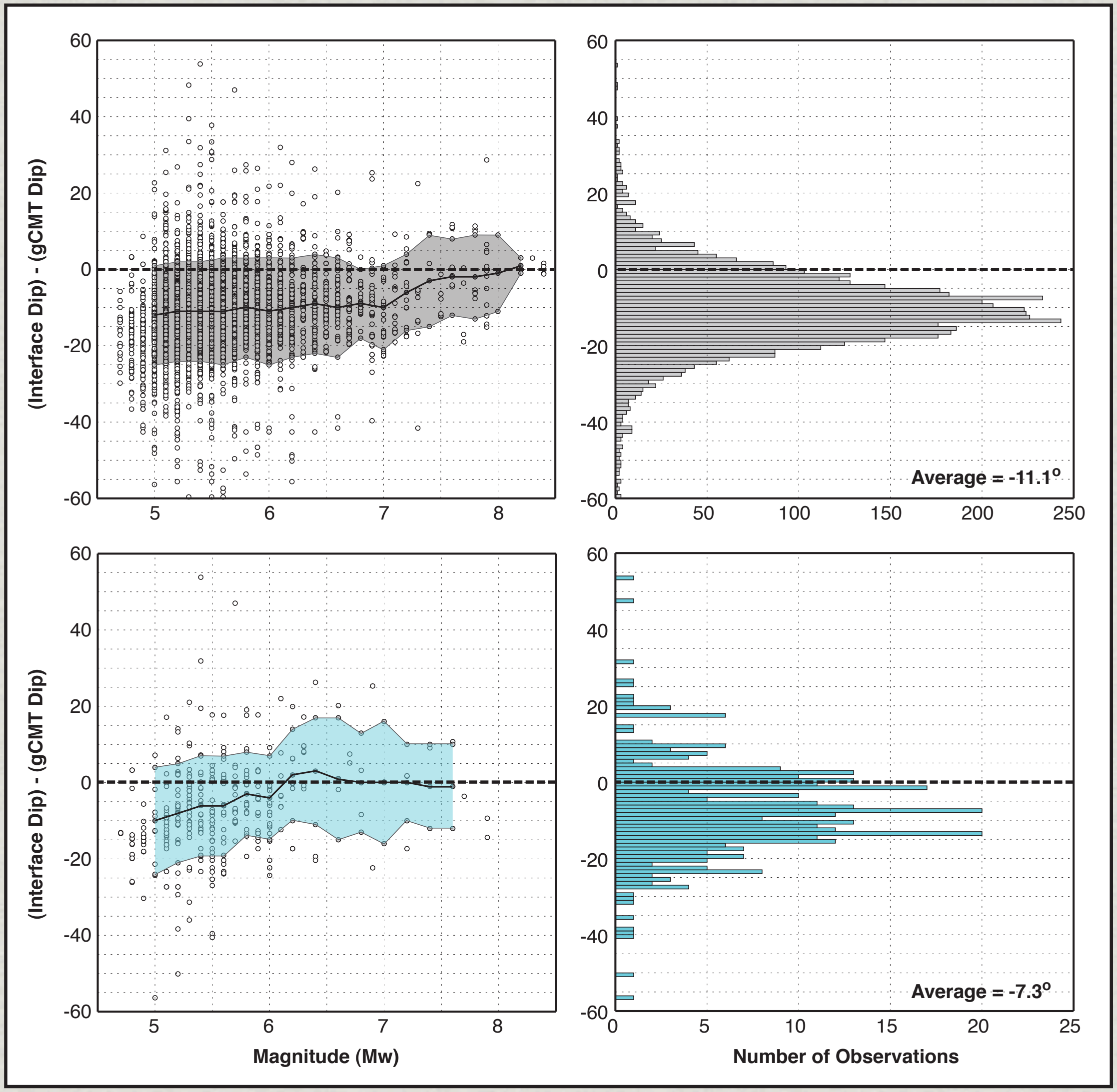


Dip Discrepancy? Interface Dip vs gCMT Dip - Non-Planar Interfaces



When compared to non-planar interfaces, the dip discrepancy is reduced, *but not removed* - i.e. not purely a result of matching non-planar surfaces with planar fits.

Dip Discrepancy? Interface Dip vs gCMT Dip - Non-Planar Interfaces



Constraining Geometry in Two Dimensions - Implications

Systematic differences exist between the dip of our most-likely slab interface(s) and the dips of best-fitting fault planes from individual CMT solutions on or near the subduction thrust in all subduction zones analyzed.

Evidence for uncertainties in CMT inversions?

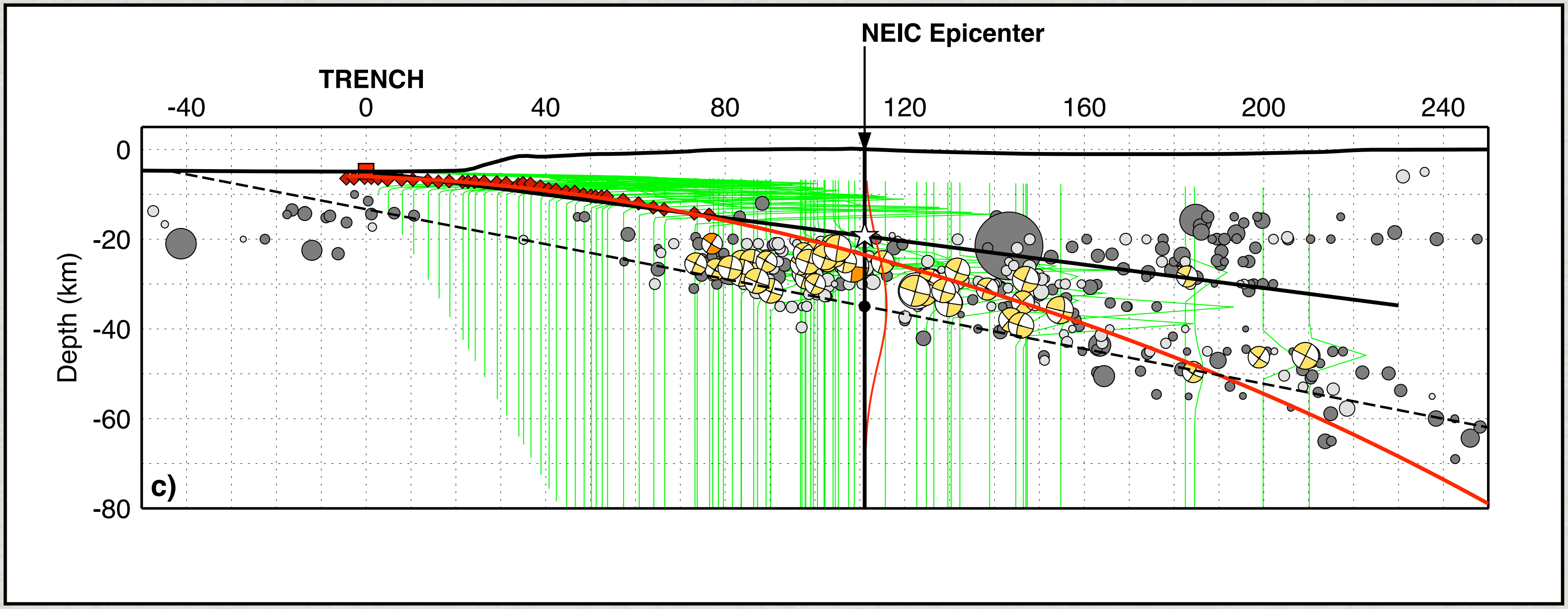
- Discrepancy exists for all depths, not just shallow earthquakes; moment-dip trade-off should not effect events below ~30km.
- Discrepancy exists when interfaces are compared to other CMT catalogs.

Uncertainties in best-fitting geometries?

- But present for both planar and non-planar fits, with and without local data...

Evidence for sub-parallel faulting about the main subduction thrust interface?

Constraining Geometry in Two Dimensions - Implications for Finite Faults

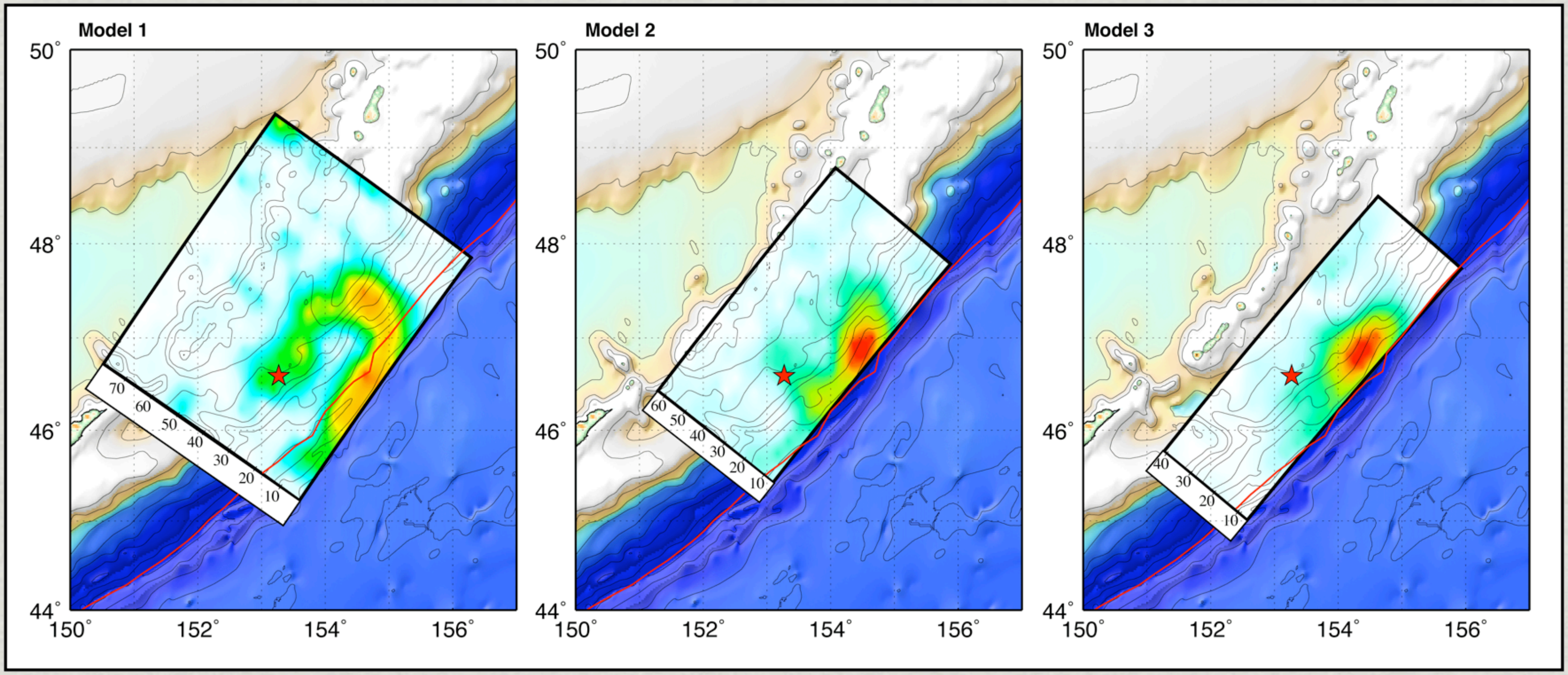


Depth difference between hypocenter and most-likely interface depth averages ~ 12 km.

Dip difference between gCMT and most-likely interface averages ~ 14^{o} (planar interfaces).

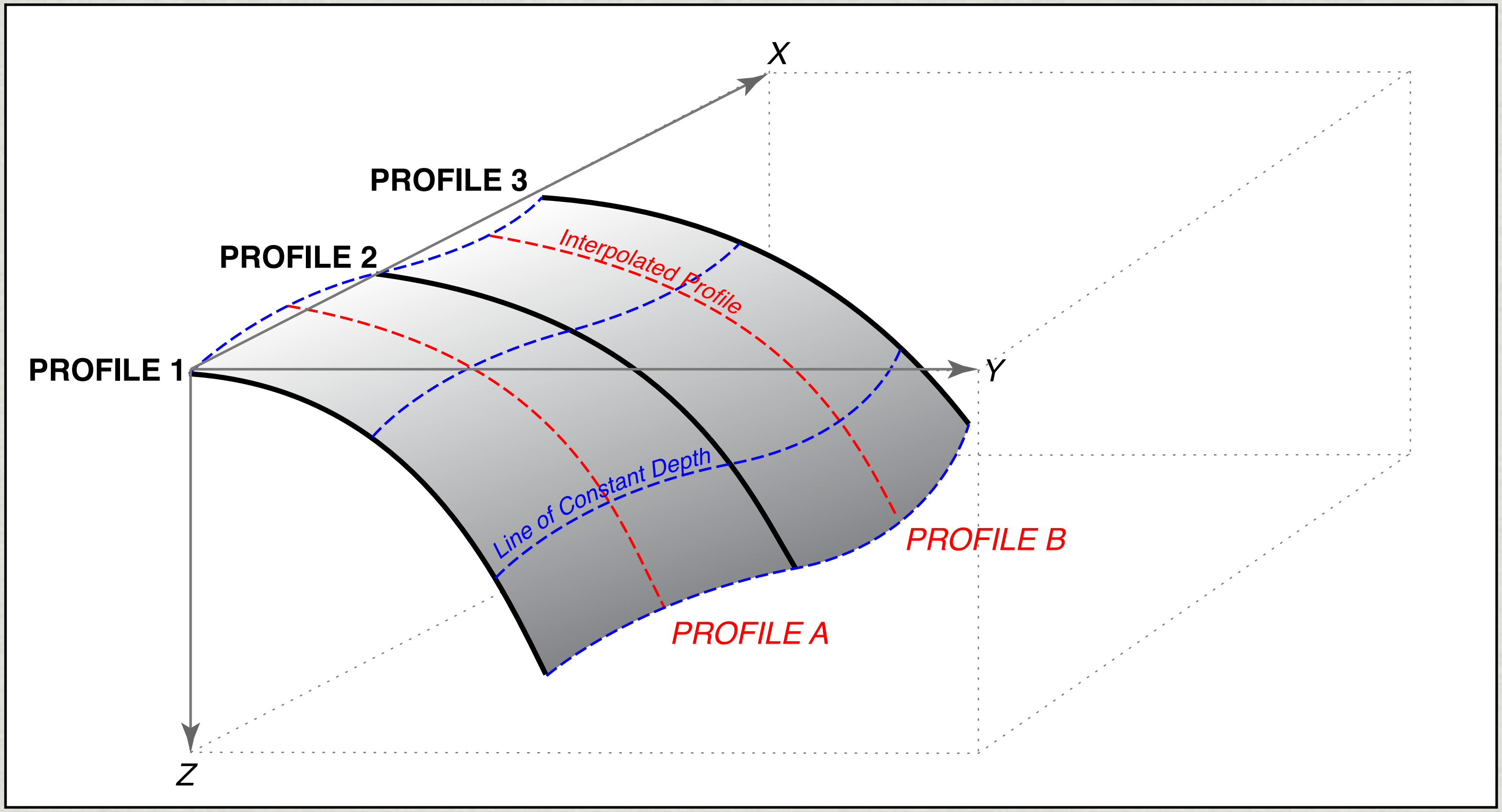
New geometries become inputs to subsequent finite-fault models. These inversions show significant differences in the temporal and spatial patterns of slip when compared to models produced using a best fitting CMT plane.

Finite Fault Model Slip Distributions - Kuril Islands 11/15/2006, Mw 8.3



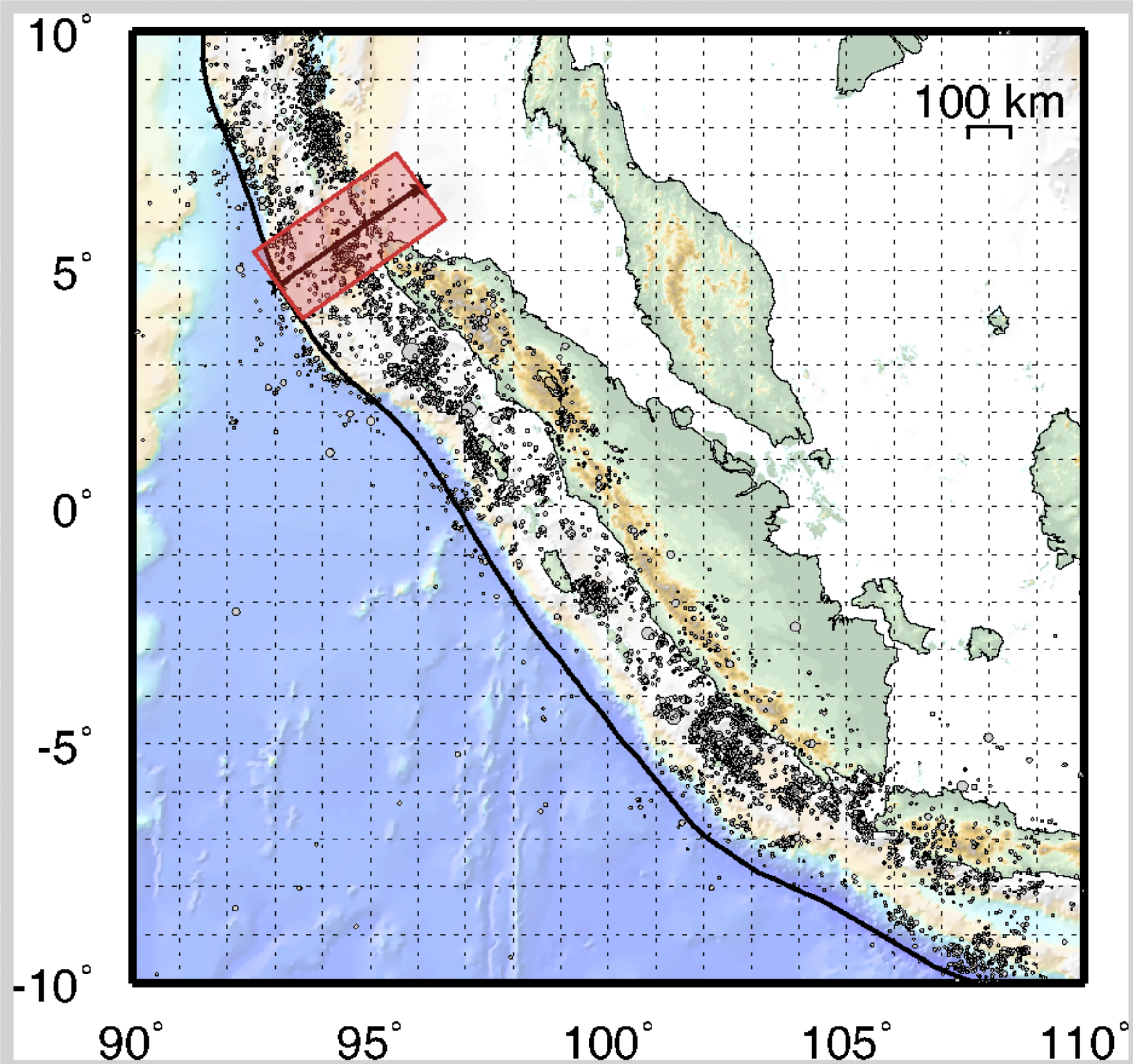
- Model 1: Quick FFM. CMT Dip = 15º, initial PDE Depth = 39km.
- Model 2: Adjusted FFM (days after event), made to fit trench geometry (Chen Ji).
- Model 3: SIGA Dip = 18º, Depth = 30km.

Moving to Three Dimensions

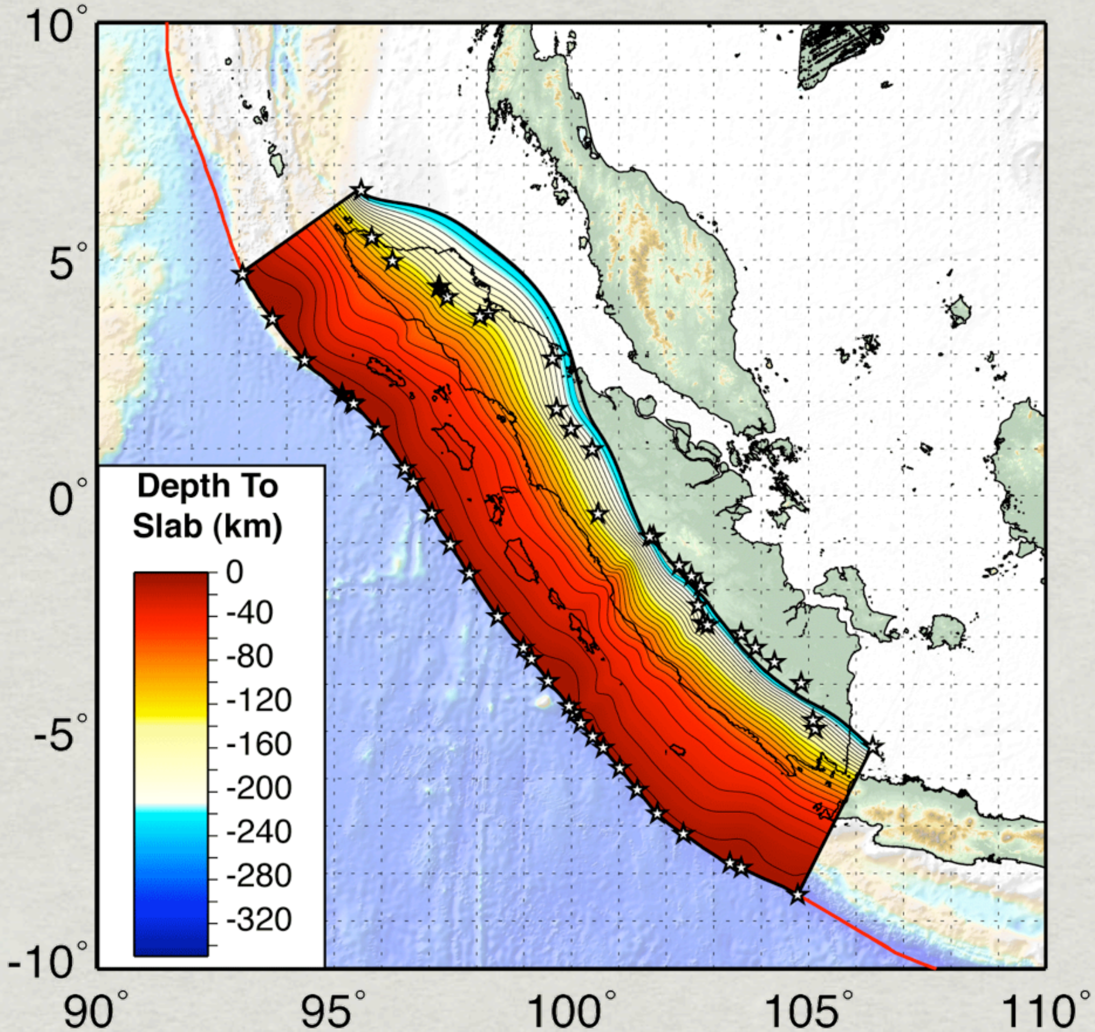


Our profiles will be explicitly merged with current Finite Fault Modeling algorithms, allowing us to invert over a ‘mesh’ geometry rather than one or more planar interfaces. Such a step facilitates finite fault models that more accurately model slip on the undulating subduction interface.

Example - Combining 2D Cross-Sections

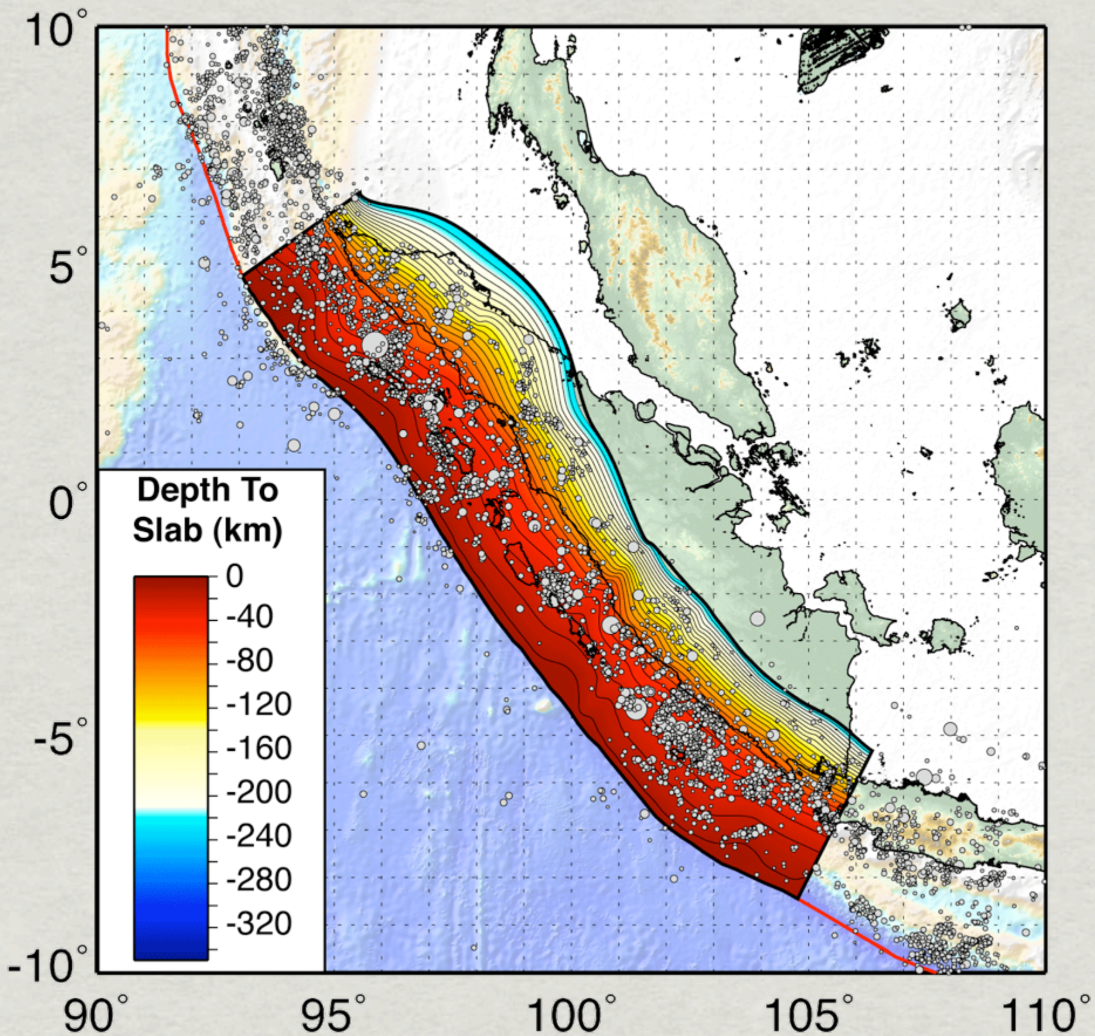


Example - Building a 3D Surface - SLAB1.0



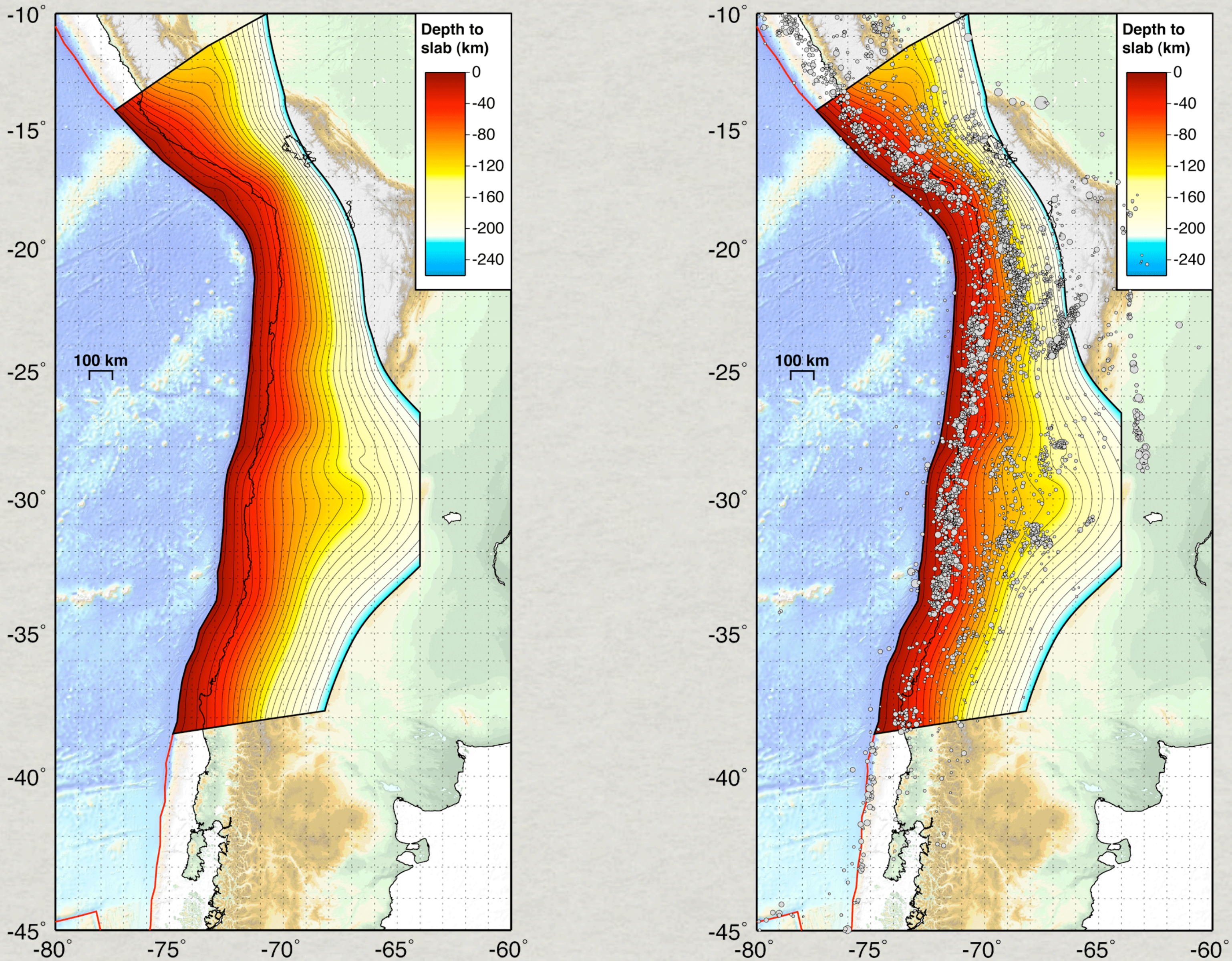
Color represents depth-to-subduction interface.

Example - Building a 3D Surface - SLAB1.0



Relation to earthquake locations can help identify patterns.

Example - Building a 3D Surface - SLAB1.0



Now What? How We Can Use SLAB1.0

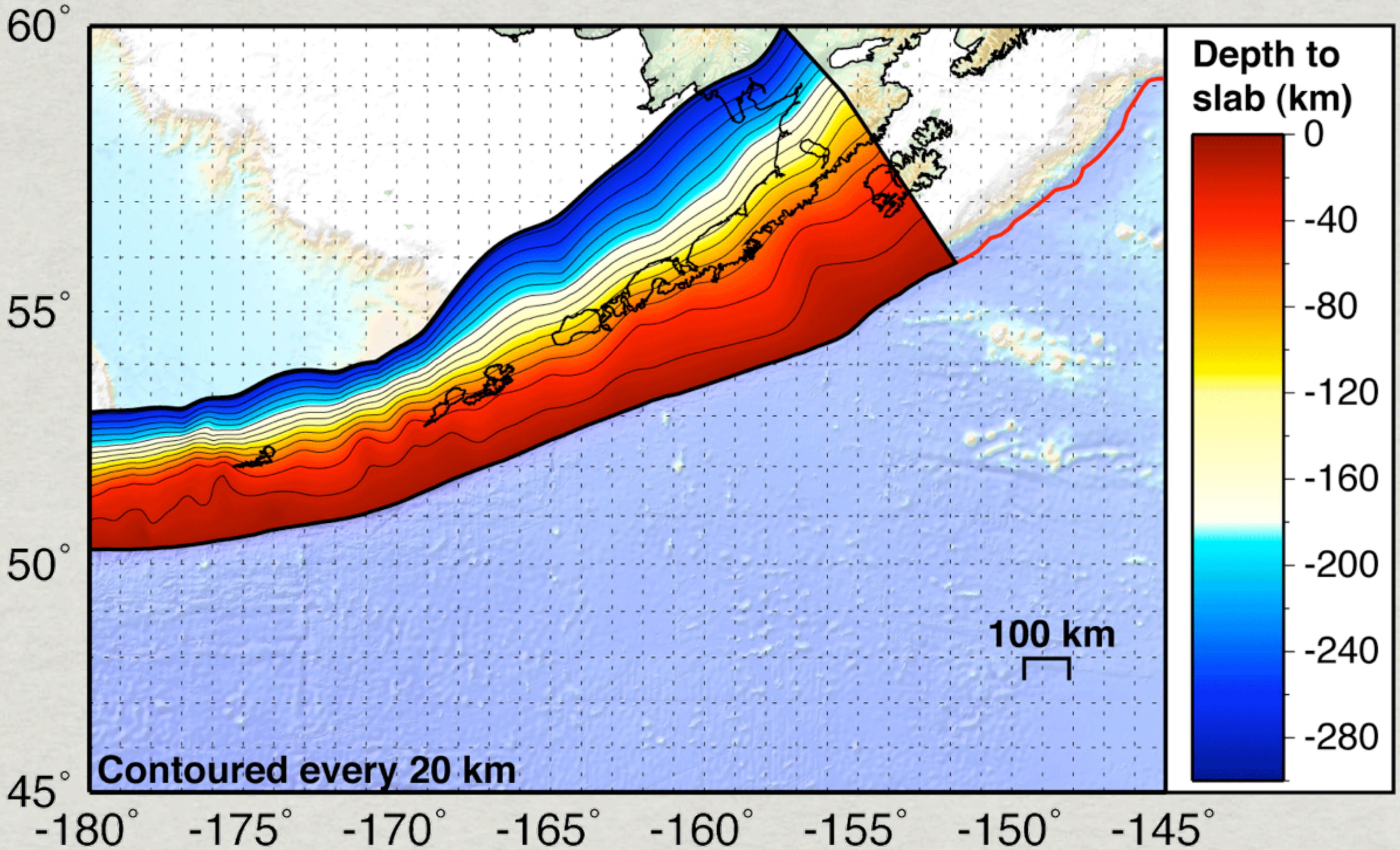
Aside from the application of this model for speeding up, improving constraint and reducing uncertainty in earthquake source inversions produced in realtime at the NEIC after large earthquakes, these 3D surfaces will have many other uses, including:

- **Hazard Modeling:** More accurate fault geometries ==> More accurate hazard analysis

- **Tsunami Modeling:** Suceptable to similar fault geometry issues as finite fault inversions

- **Earthquake Rupture Dynamics**: Correlate details of 3D structure with EQ distributions

Example - Building a 3D Surface - SLAB1.0



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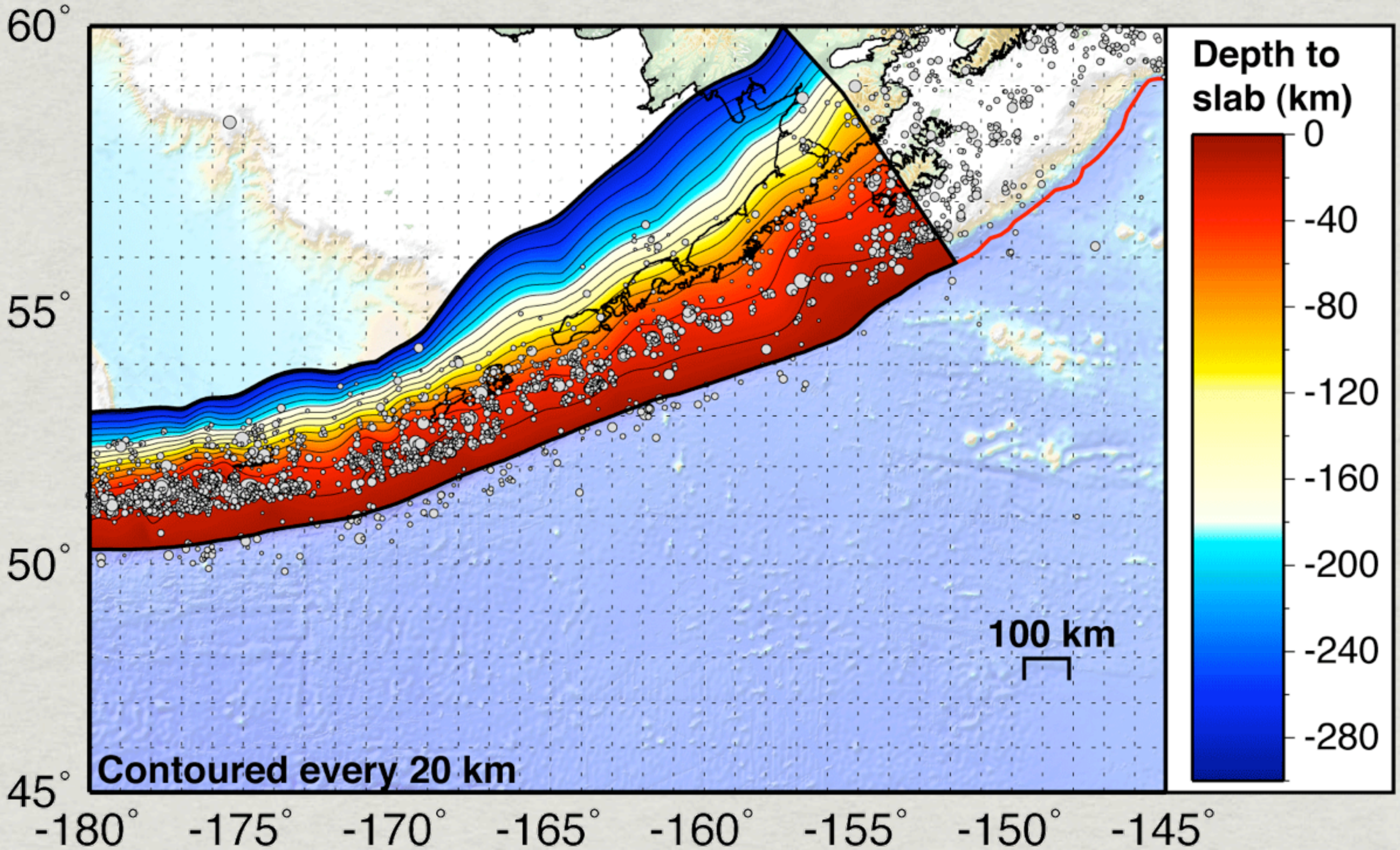
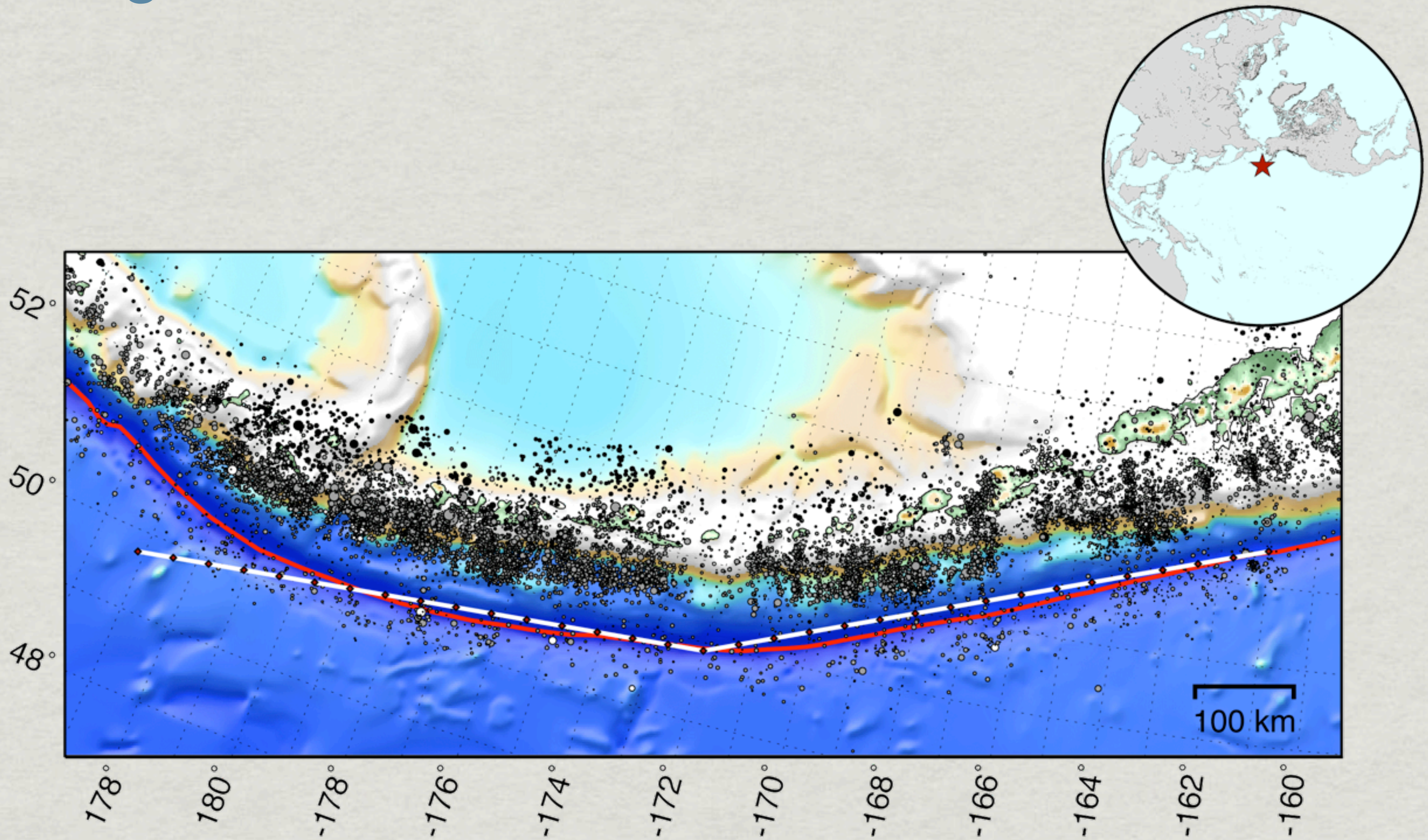
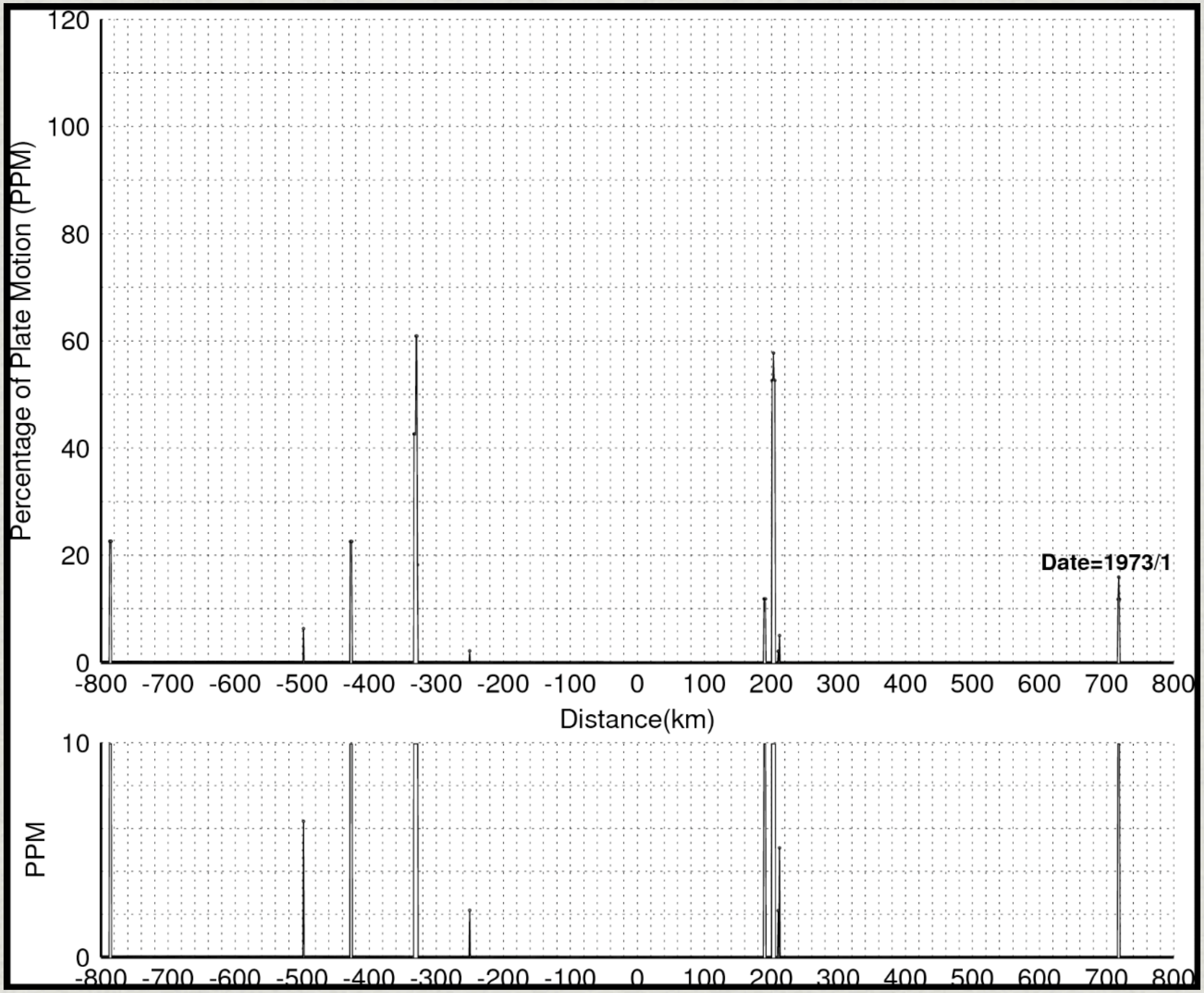


Using SLAB1.0: Moment-Rate Calculations



With a defined subduction interface location, we can begin to analyze how plate motions are accommodated along an entire arc - thereby identifying areas of potentially significant moment deficit.

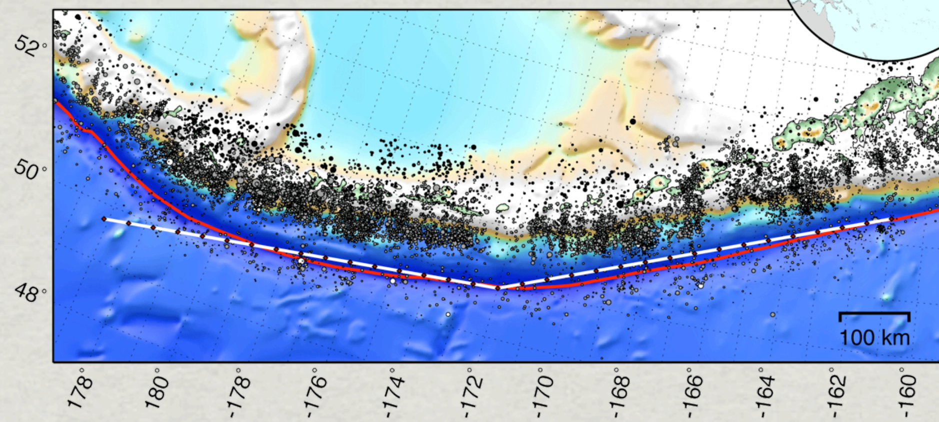
Using SLAB1.0: Moment-Rate Calculations



All earthquakes, 1973-current date. At each location, moment released by earthquakes is compared to moment 'accumulated' by plate motions.

Earthquakes with M < 7, 1973-current date (i.e. 'background' rate).

Using SLAB1.0: Moment-Rate Calculations

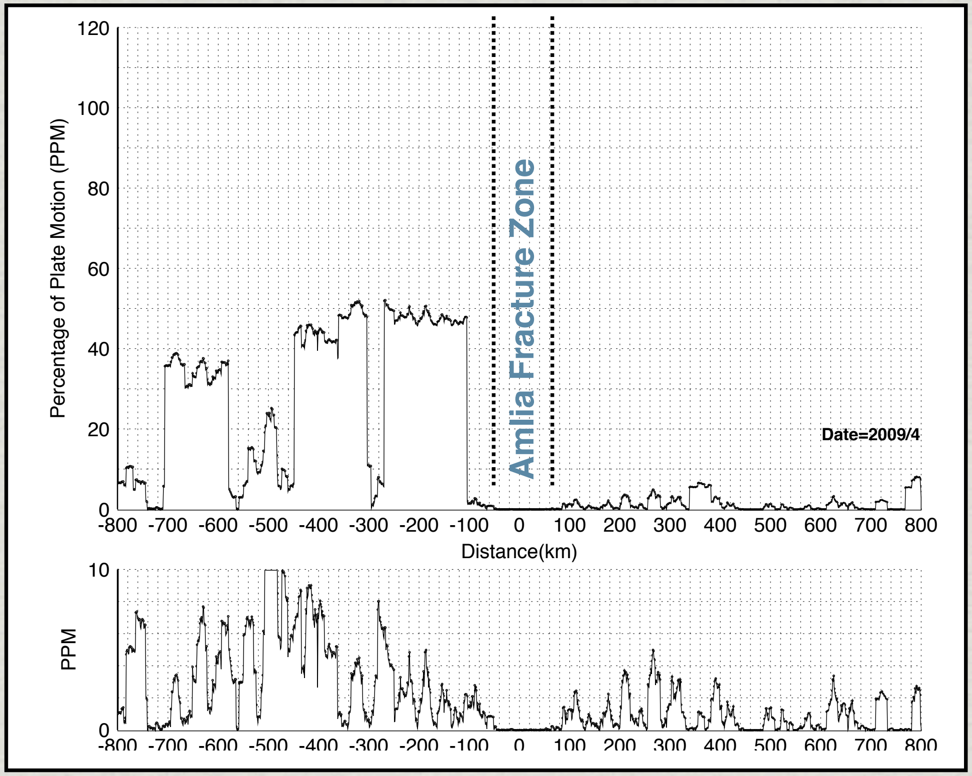


Analyzing patterns in moment release can tell is vital information about earthquake cycles.

Do background rates vary leading up to, or following mega-thrust earthquakes?

What do areas of low moment release mean? High hazard, or low?

Do moment release rates correlate with oceanic plate structure, upper plate structure, etc? What causes such along-strike variability?



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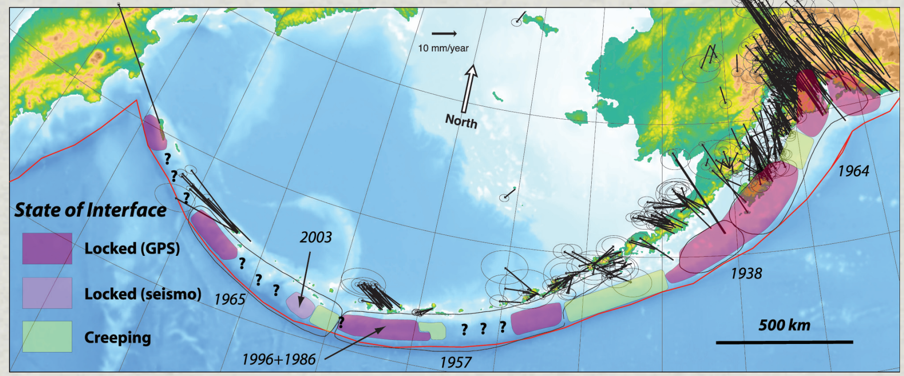
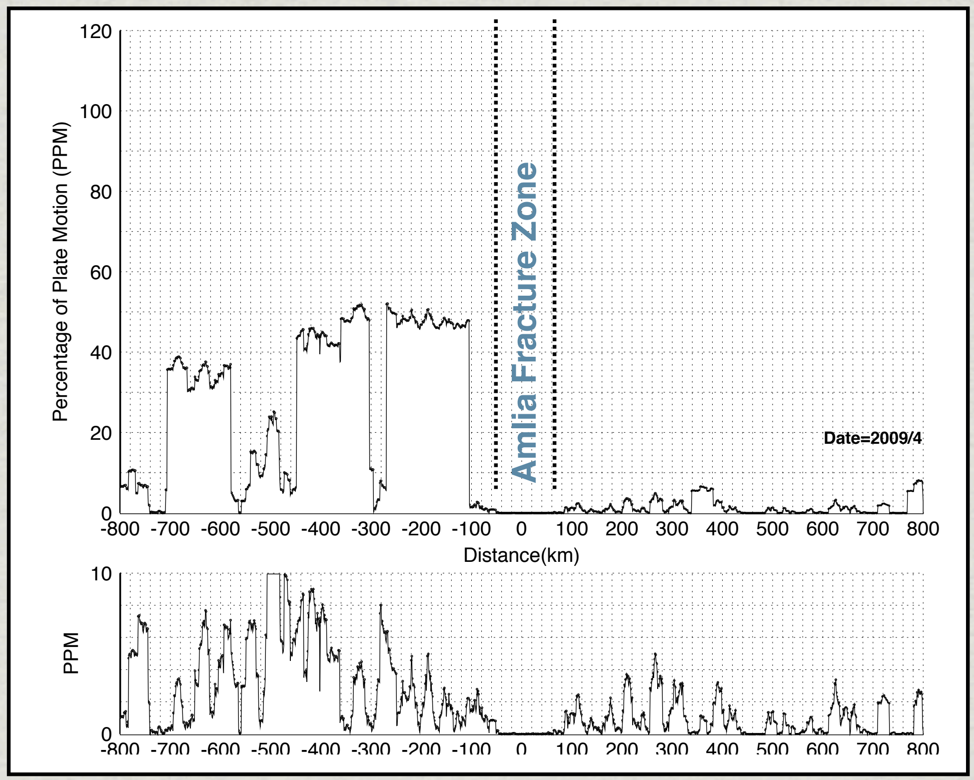


Freymueller, et al. 2008

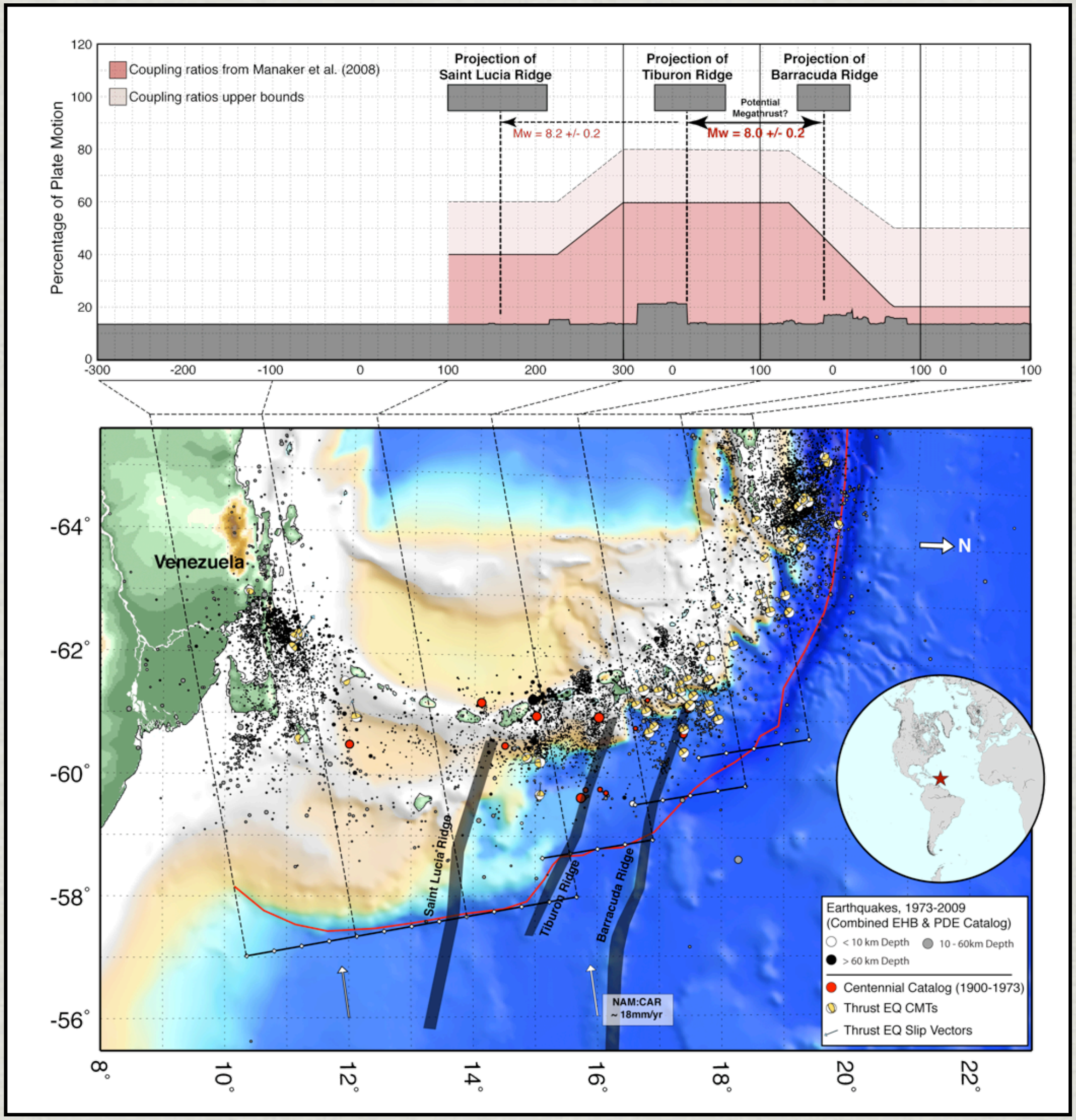


Using SLAB1.0: Moment-Rate Calculations

Comparing moment release rates to coupling ratios computed from independent analyses (e.g. GPS) can inform us of the earthquake potential for a subduction zone.

In the Caribbean, the section of the Lesser Antilles subduction zone has not ruptured in a large earthquake since the mid-19th century.

This area may be capable of hosting a M8+ event.



Conclusions - and More Questions

- ***A new approach*** to analyzing the geometry of subduction zones allows us to more clearly define both the subduction interfaces themselves, and the seismicity associated with the subduction process.

- ***Geometry models are not the last step!*** Rather these models facilitate a variety of more detailed studies.

WHERE WE ARE:

- What causes the discrepancy between dips of subduction interfaces and the dips of individual CMTs for earthquakes about those interfaces? What does this tell us about the subduction interface fault zone?

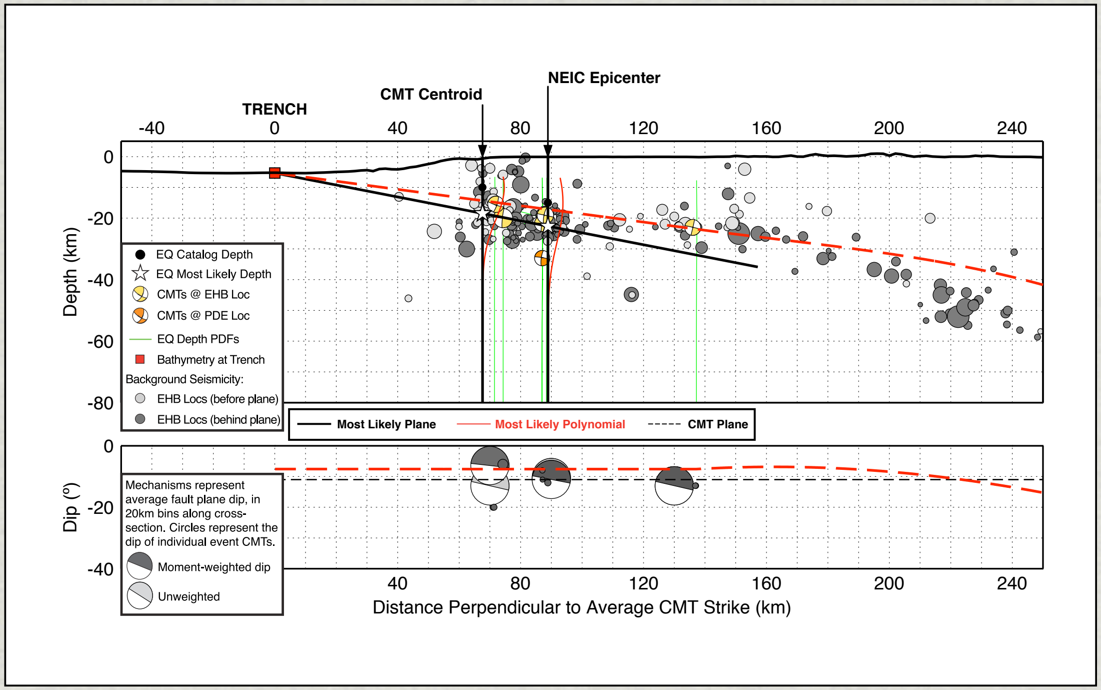
WHERE WE CAN GO:

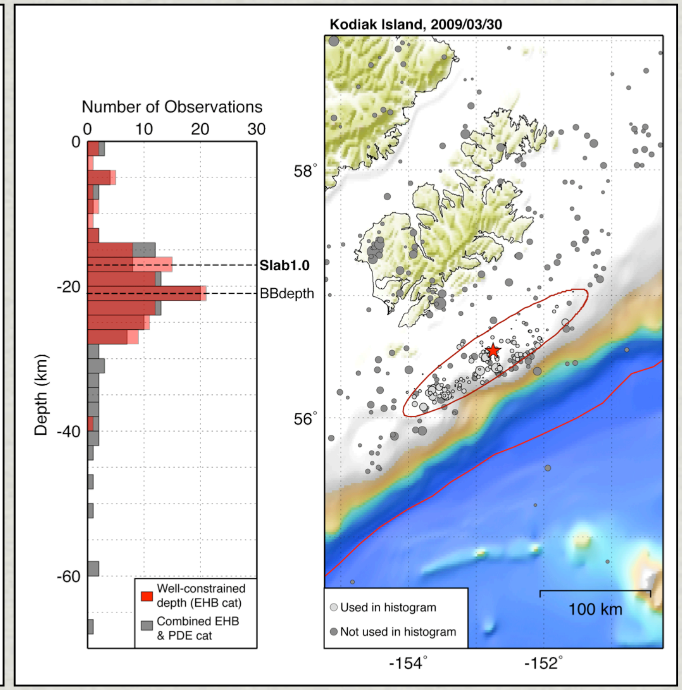
- What does the pattern of moment release in a subduction zone, and variations along strike, tell us about earthquake potential and seismic cycles?

- How do changes in detailed 3D subduction zone geometries (down-dip and along strike) effect rupture processes of earthquakes?

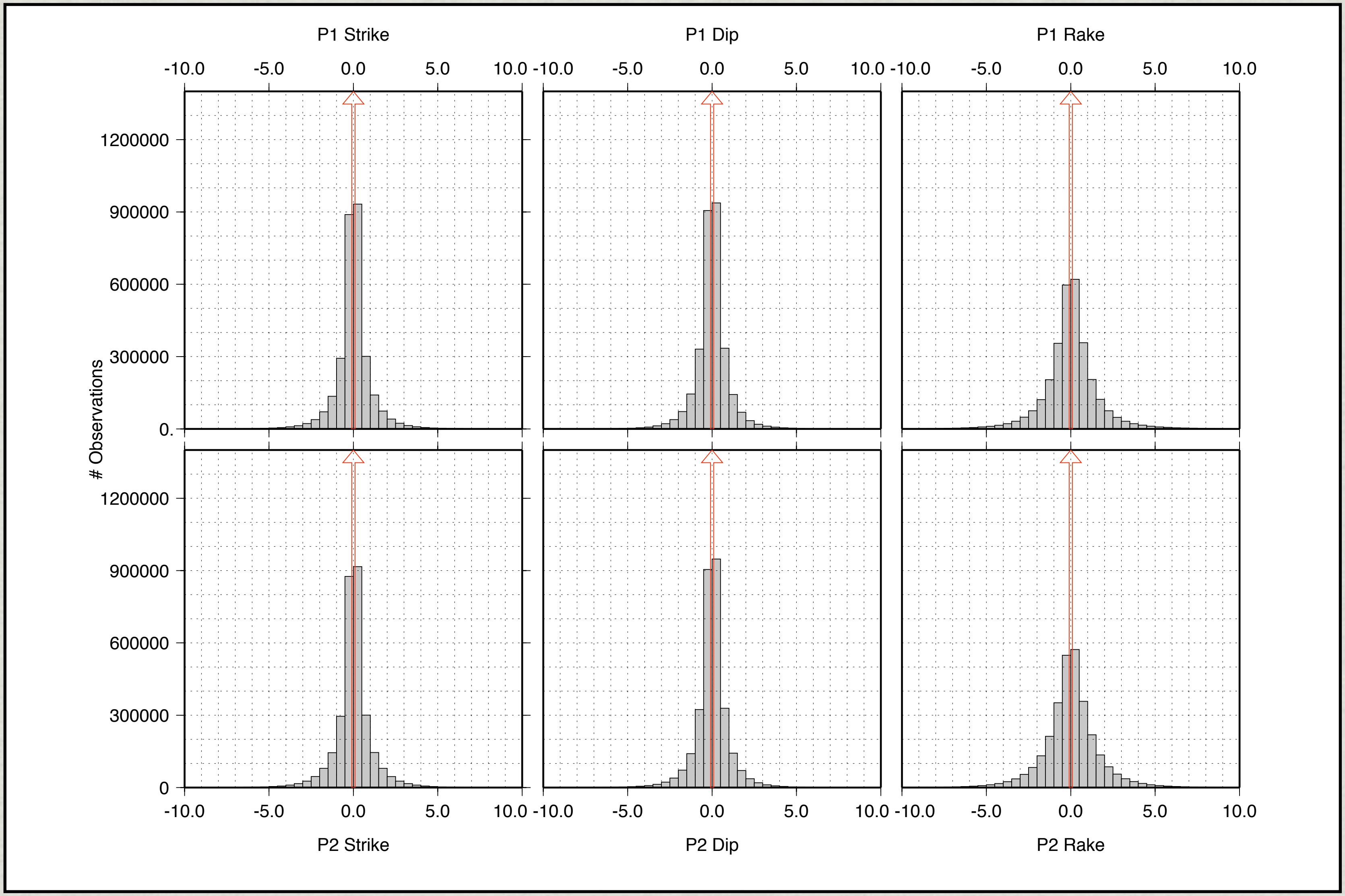
- *‘Intermission’* -

Using SLAB1.0: Constraining EQ Depth





gCMT Variance



Why we need to constrain subduction geometry

Geometries assumed in typical finite fault models (e.g. from focal mechanisms) often disagree with other data sets, such as historic EQ locations and surface fault break observations.

Fault geometry mislocation can cause significant errors in the final spatial and temporal slip patterns suggested by earthquake source inversions.

==> *Variations in slip distribution and moment release affect our understanding of where plate motions are accommodated (and where they aren't).*

Uncertain geometries also mean we do not know which earthquakes occur on the subduction interface, which are within the upper plate, and which are within the subducting plate.

==> *We do not fully understand the earthquake cycle(s) of a subduction zone.*

==> *We do not know which earthquakes release strain accumulated by plate motions, and thus how moment release has been distributed on and accommodated by a subduction interface in the past.*

Why we need to constrain subduction geometry - Real-time operations perspective

At the NEIC, our mission is to rapidly determine the location and size of all destructive earthquakes globally, and to disseminate this information to national and international agencies who play a role in responding to such disasters.

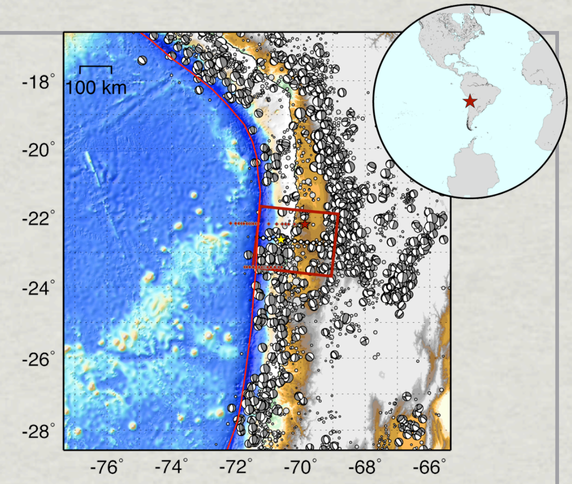
This means we must be able to understand what happened in any given event - where did slip occur? How much slip occurred, over how large an area? Such details inform us about the shaking felt at the surface, and thus the population exposed to the hazard.

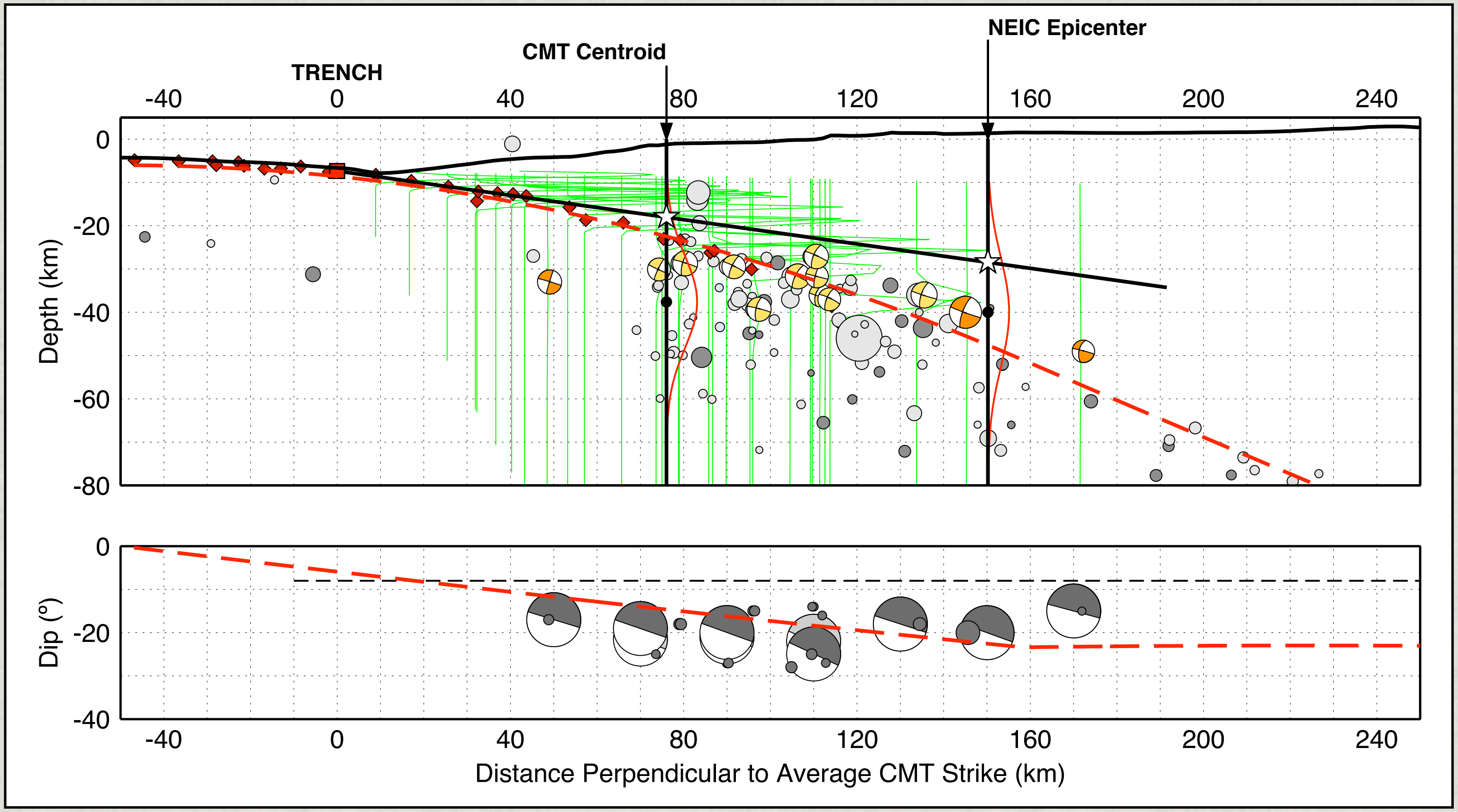
One of the tools we use for such analyses at the NEIC is Finite Fault Modeling.

To perform finite fault modeling inversions, we need to know the geometry of the fault the earthquake occurred on.

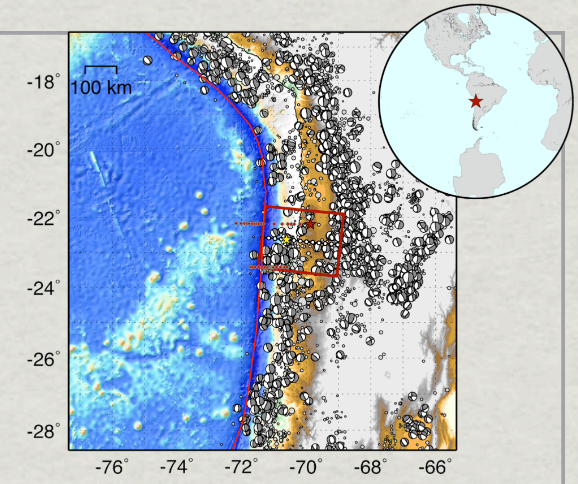
Rather than waiting for an event to occur and trying to piece all this information together in real time, why not use the wealth of information we have on past events to map out these highly hazardous earthquake zones now?

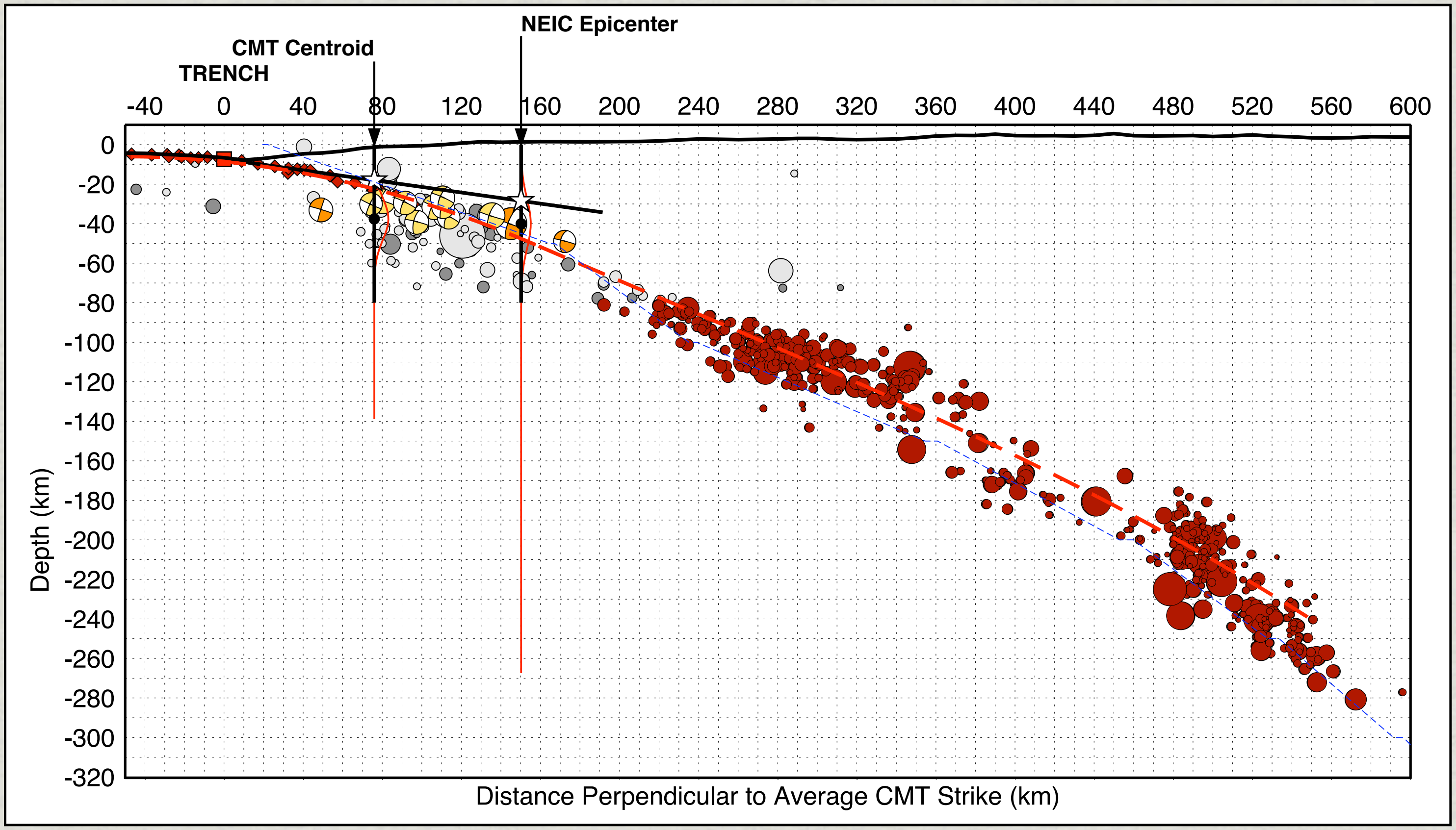
Example - South American Trench, Offshore Northern Chile



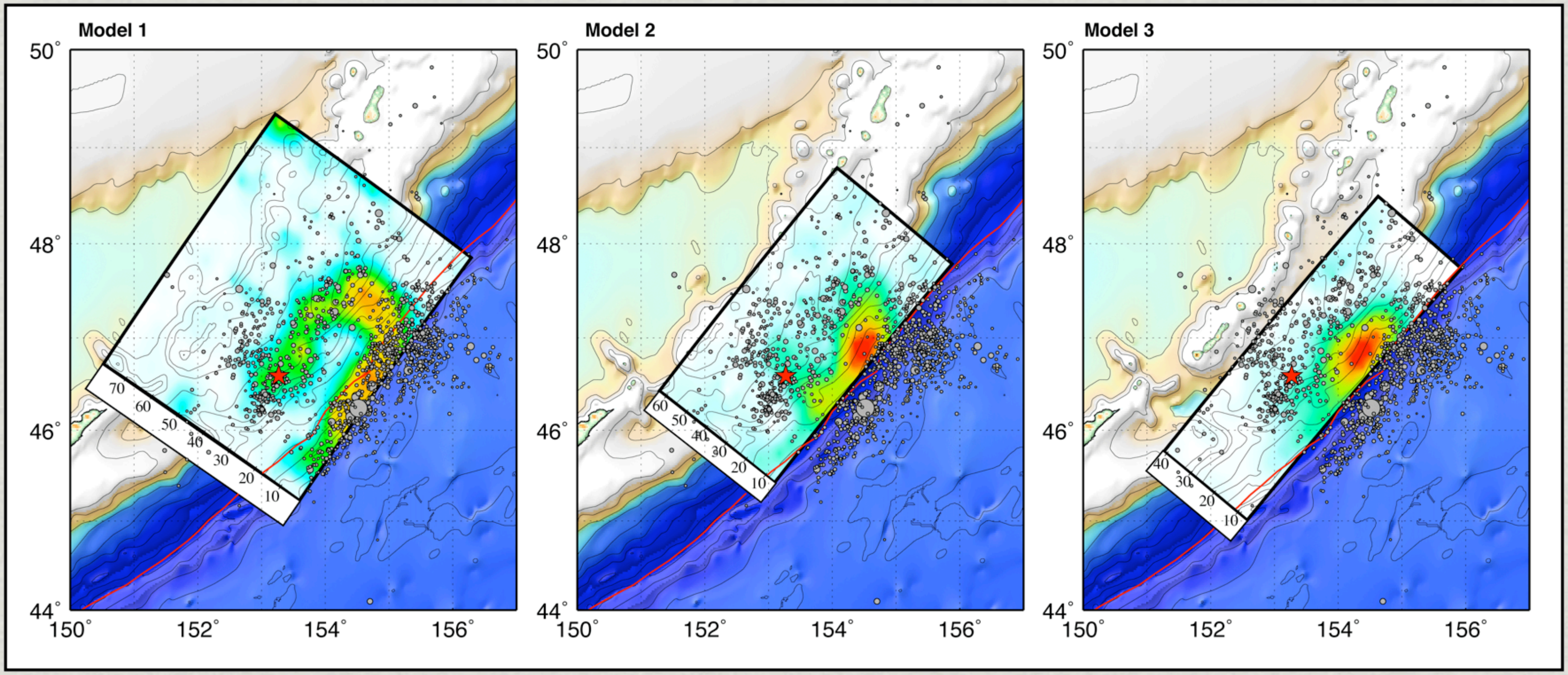


Example - South American Trench, Offshore Northern Chile





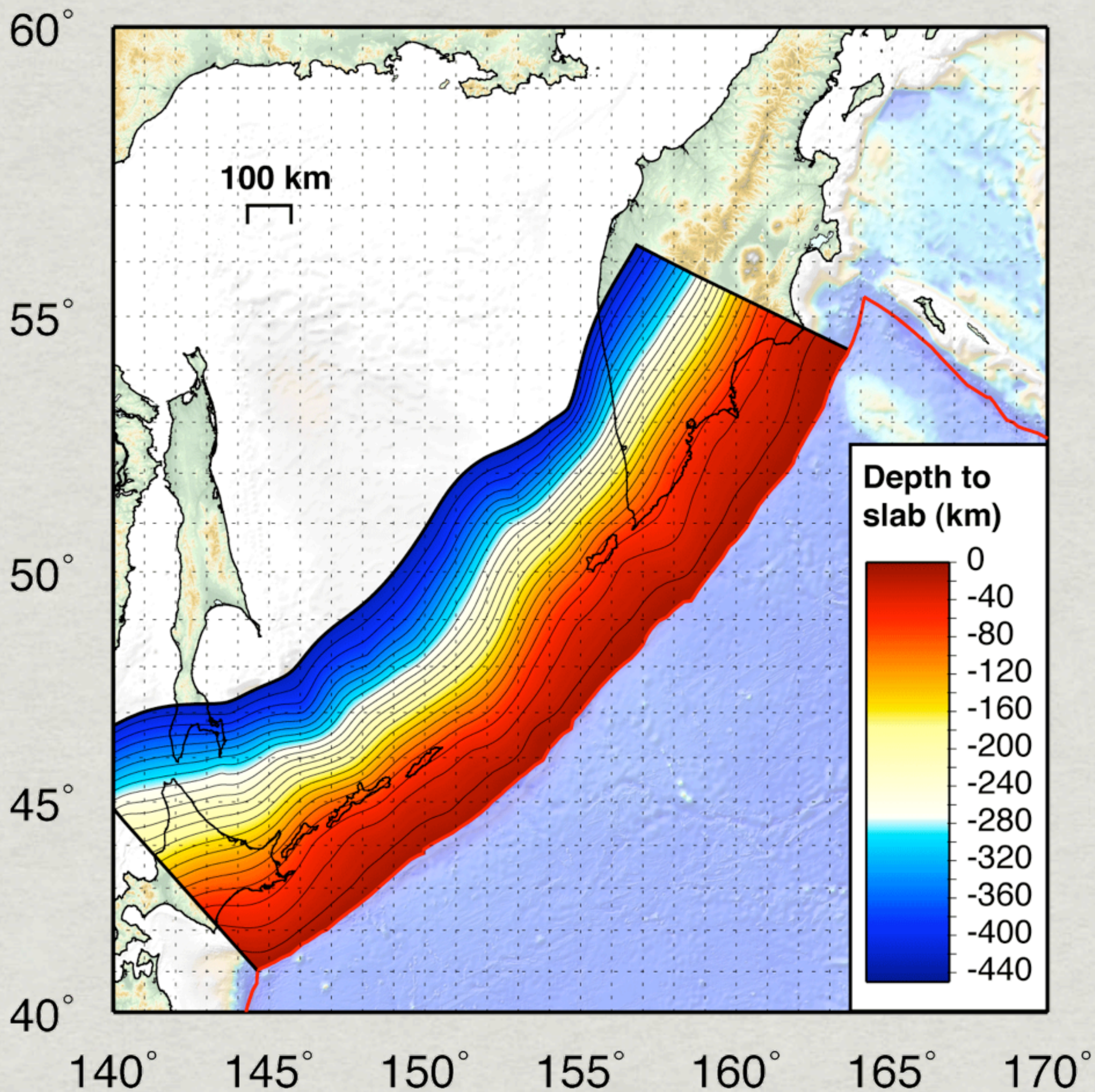
Finite Fault Model Slip Distributions - Kuril Islands 11/15/2006, Mw 8.3



Initial quick FFM does not match trench geometry and thus implies slip outboard of trench.

Independent SIGA model very similar to adjusted FFM, but can be derived much more quickly.

Example - Building a 3D Surface - SLAB1.0



Example - Building a 3D Surface - SLAB1.0