SUSITNA-WATANA HYDRO

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April 2014
Board of Consultants Meeting (#4)

Seismic Hazard Update

ALASKA ENERGY AUTHORITY

Focus of Discussions

- Lineament Mapping and Evaluation
- Slab Geometry and Updated Rates
- Global Intraslab Mmax Assessment
- PSHA Sensitivity to New Slab Model

Lineament Mapping and Evaluation

- Primary Objectives
  - Synthesize new methods and new information (e.g. Susitna Glacier fault, 2002)
  - Look for potentially unrecognized seismic sources of engineering significance
  - Evaluate potential dam site fault rupture hazards
- Implications
  - Framework formed basis for 2013 geologic investigations

Lineament Mapping and Evaluation

- Geologic Compilation Strip Maps
- Detailed Lineament Summary Descriptions
- Evaluation Synthesizes Previous Mapping and Reports to Judge Level of Effort for Further Study in Field.

Lineament Group Example

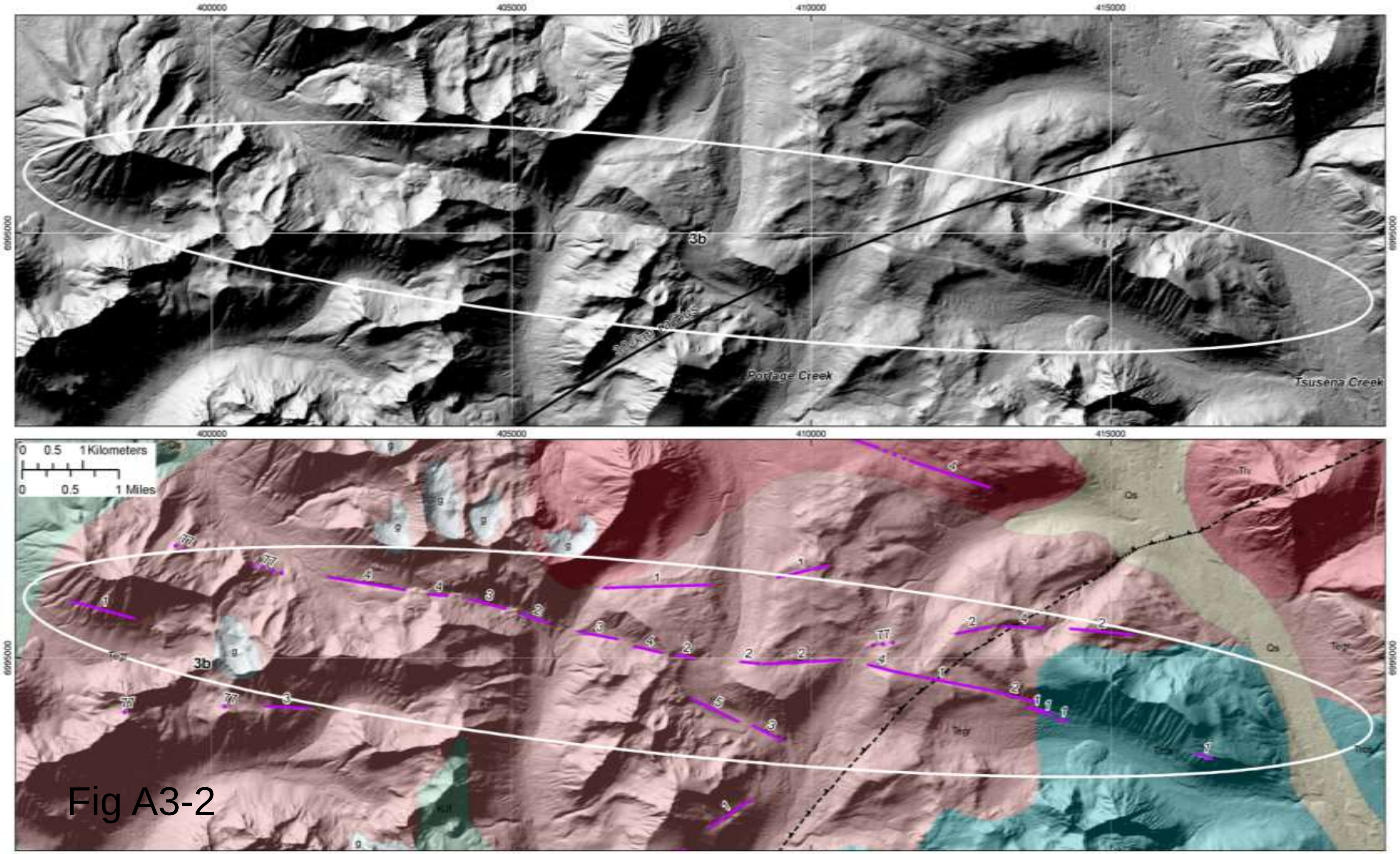


Fig A3-2

Lineament Mapping and Evaluation Summary

- Multi-Genetic Origin to Lineaments
  - Glacial or fluvial erosion,
  - Lithologic [jointing or structure],
  - Geomorphologic [glacial features or shorelines]
- 32 Lineament Aggregate Groups and 4 Areas of Lineaments Were Identified
- A Screening Process Reduced to 22 Lineament Groups and 3 Areas (desktop, spring 2013)

Criteria for Delineating Lineament Groups

Criterion	Reasoning
Lineaments that are expressed in Quaternary deposits, that collectively aggregate to greater than about 6 miles (10 km) in length.	Quaternary lineaments may strongly represent neotectonism.
Lineaments that appear to represent potential extensions or continuations of known Quaternary faults.	These lineaments may contribute to additional fault source length in ground motion calculations.
Lineaments with possible tectonic geomorphology that are spatially associated with previously mapped faults or lineaments.	Suggestive, but not conclusive, of neotectonism. Association with previously mapped faults or lineaments supports inference of structure.
Lineaments with possible tectonic geomorphology that are not spatially associated with previously mapped faults/lineaments.	Suggestive, but not conclusive, of neotectonism.
Lineaments that aggregate to greater than 10 km length.	Length criterion is based on an approximately minimal structural length for a seismogenic source capable of ground rupture.
Lineaments that are within 30 km from the proposed site and reservoir, and are greater than 20 km in aggregated length.	Seismogenic features within 30 km of the site may contribute non-trivially to the ground motion calculations.

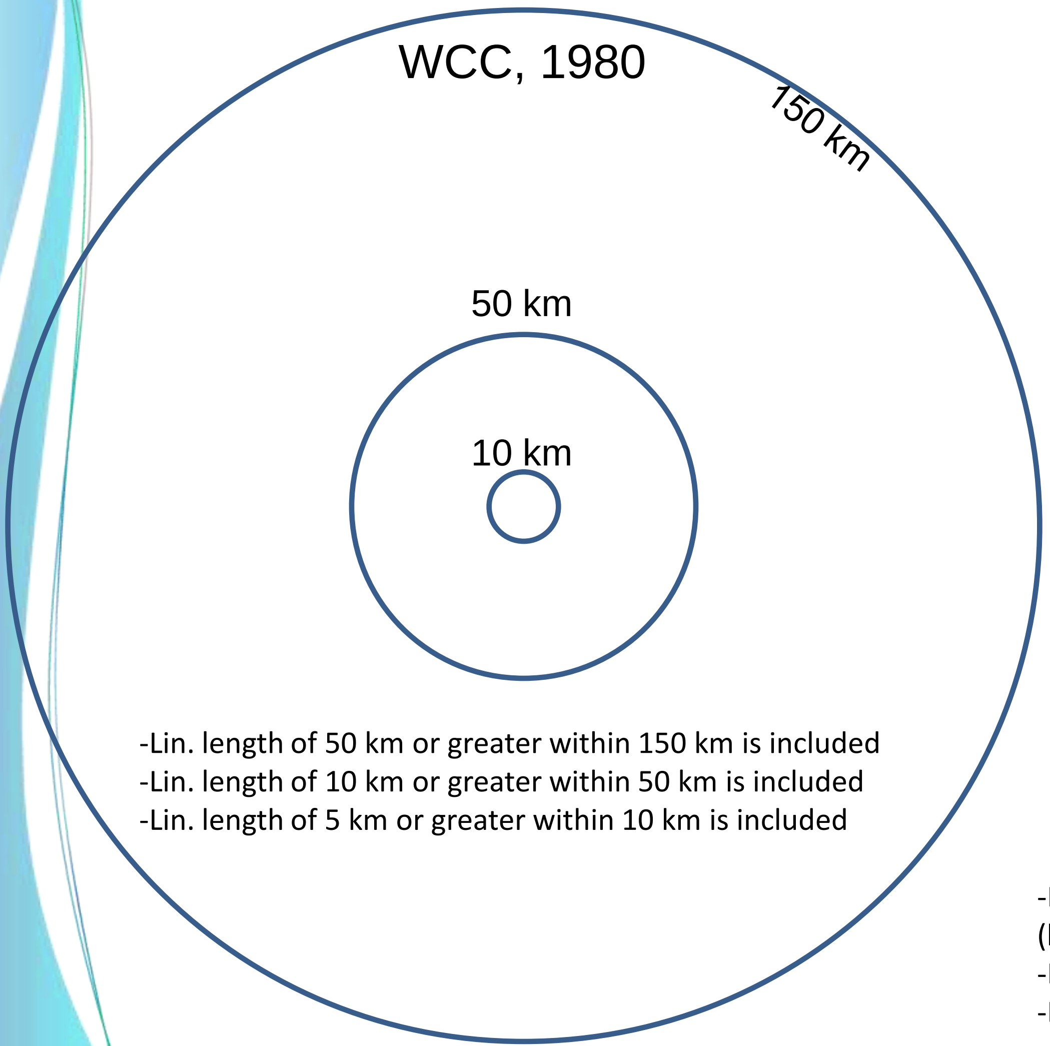
Need to meet at least one

Desktop Evaluation Exclusionary Criteria

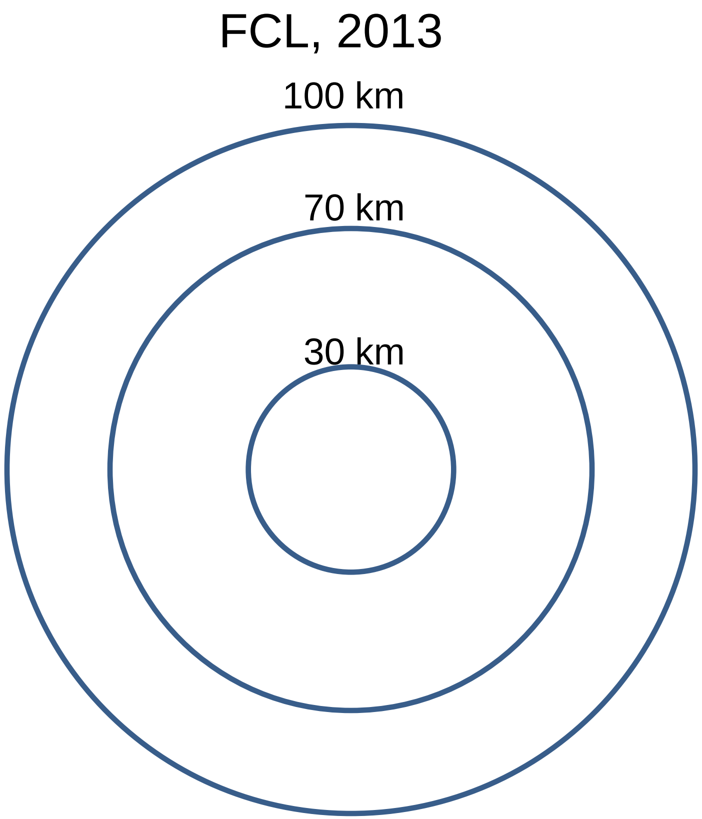
Criterion	Reasoning
Lineament groups that are greater than 100 km distance from the proposed dam site, excepting potential extensions of the Castle Mountain fault	Lineaments over 100 km distant would have no contribution in hazard calculations. Potential extensions of the Castle Mountain fault may contribute to hazard calculations.
Lineament groups that are greater than 70 km distance from the proposed site and less than 40 km aggregate length and with no apparent association to previously mapped structures	These lineament groups likely would not appreciably contribute to the hazard calculations, based on the Sonona Creek seismic source contribution in the initial (2011) PSHA.
Lineament groups that are greater than 30 km from the proposed dam site and less than 20 km in length are excluded from further analysis, where the group cannot be linked to an adjacent group	Based on the results of the initial (2011) PSHA, it is likely that these lineament groups (if seismic sources) will not appreciably contribute to the hazard calculations.
Lineament groups whose individual features are dominantly erosional and/or depositional with no apparent association with previously mapped faults or lineaments	Such lineaments are non-tectonic in origin and not considered further.
Lineament groups with inconsistent expression of kinematics along strike	Inconsistent, contrasting, or discrepant lineament kinematics indicates low likelihood as a potential seismic source.

Need to meet at least one

Comparison of Length-Distance Criteria



-Lin. length of 50 km or greater within 150 km is included
-Lin. length of 10 km or greater within 50 km is included
-Lin. length of 5 km or greater within 10 km is included



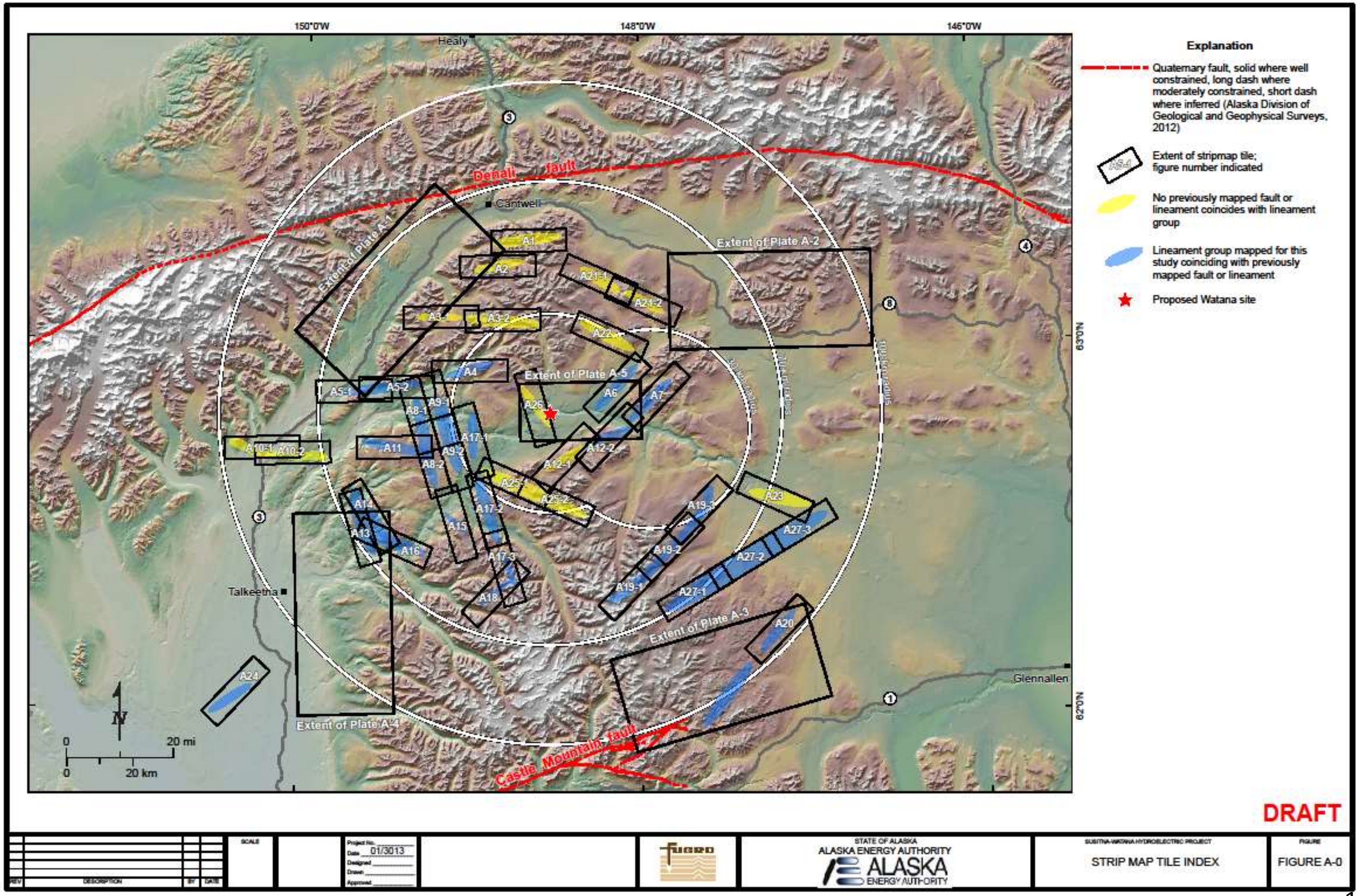
-Excluded outside of 100 km unless extension of Q fault (bounded by Denali and Castle Mountain faults)
-Lin. length of 40 km or greater within 70 km is included
-Lin. length of 20 km or greater within 30 km is included

Geologic Evaluation Criteria

Criterion	Reasoning
Lineaments within groups that appear to have expression in Quaternary units or Quaternary landforms proceed to further analysis	Quaternary-age lineaments may strongly represent neotectonism.
Lineament groups that transect or cut across different geologic units proceed to further analysis	Lineaments that are traceable across different geologic units implies crustal structure exists, as opposed to lineament genesis from lithology, bedding, or jointing.
Lineaments within groups that may be tested for positive evidence of inactivity (e.g., overlain by Tertiary volcanic units) proceed to further analysis	Determining inactivity via positive evidence will remove lineament group from further study.
Lineament groups that demonstrate relative consistency of geomorphic expression and anticipated structural kinematics along strike proceed to further analysis	Consistent expression and structural style suggests a common genesis such as neotectonism because many other processes of formation change along the length of their occurrence.
Lineament groups that are explainable in the context of the tectonic model proceed to further analysis	The tectonic model serves as a guide for anticipating orientation and sense of motion with respect to crustal stresses.

Need to meet at least one

Lineament Mapping and Evaluation Summary



Lineament Mapping and Evaluation Summary

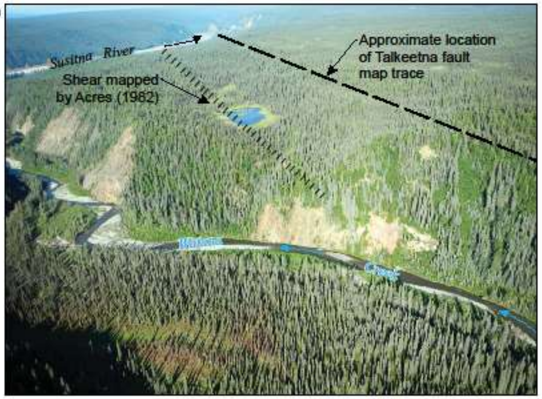
- Summer 2013 field investigation on accessible areas

Field Team Geologic Data Collection Guidance

Field Data	Reasoning/Comments
Is a previously mapped bedrock fault structure coincident with or near the lineament group?	Spatial proximity to or association with a previously mapped fault may support the lineament group having a tectonic origin.
Was field evidence of fault structure observed (either directly or indirectly)?	Direct evidence: exposure of shear zone or fault contacts observed. Indirect evidence: apparent rock type juxtapositions, alteration zones, color changes.
What does the trend of the lineament across the topography imply about the geometry of the potential structure?	Topographic expression provides a basis for defining the potential 3D geometry and potential style of faulting or constraints on potential non-tectonic origins.
What types of deposits or geomorphic surfaces is the lineament expressed in?	Quaternary glacial, lacustrine, alluvial, and colluvial deposits or bedrock units? Are the geomorphic surfaces constructional or erosional?
What is the oldest deposit in which the lineament occurs?	Age of deposit may constrain age of activity or limit of reasonable hypotheses of origin.
What is the youngest deposit in which the lineament occurs?	Age of deposit may constrain age of activity or limit of reasonable hypotheses of origin.
Do the mapped lineaments transect or cut across different geologic units or landforms?	Expression of lineament across multiple units or landforms may indicate continuity of geologic process.
What is the scale (magnitude) of expression of the lineaments along strike?	Expression that is proportionally consistent across different age portions of the landscape suggests continuity of process.
Is the lineament discordant with glacial ice flow directions?	Discordance with ice flow direction suggests origins other than ice flow.
Is there field evidence that linear strain markers (such as moraine or ridge crests, esker ridges, terrace risers or treads, lake shorelines, drumlins or other ice scour-generated striae) are cross-cut, deformed or displaced? If deformed, what is the amount?	Disruption of Quaternary strain markers may suggest a recent tectonic origin.
What does the morphology of the lineament imply about the kinematics of a potential fault? What are the apparent structural kinematics needed to produce the morphology of the lineament?	Kinematics need to be consistent along strike.

Examples of Field Geologic Data

A)



View looking west along oblique to projection of Talkeetna fault

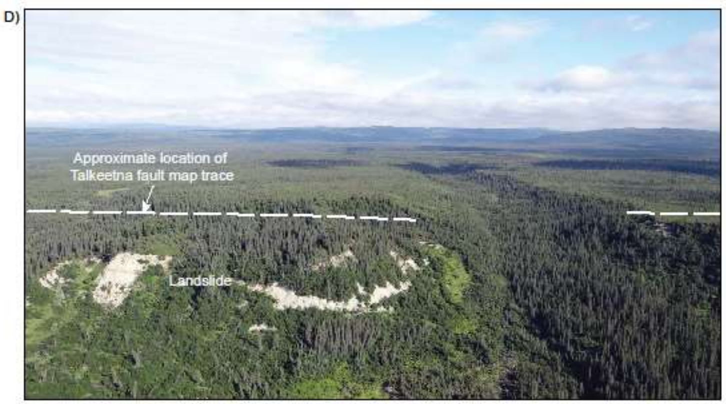
B)

View looking east along lower river bank at apparent alternation zone distinguished by color contrast, possible juxtaposition of Triassic metabasalts and undifferentiated Tertiary sediments. This location is east of the mapped projections of the Talkeetna fault.

C)

View looking east at apparent flat-lying contact between Quaternary lake sediments (above) and Quaternary till (below). Arrows point to contact.

D)



View looking west at projected trace of Talkeetna fault whose ground expression is absent in Quaternary surface.

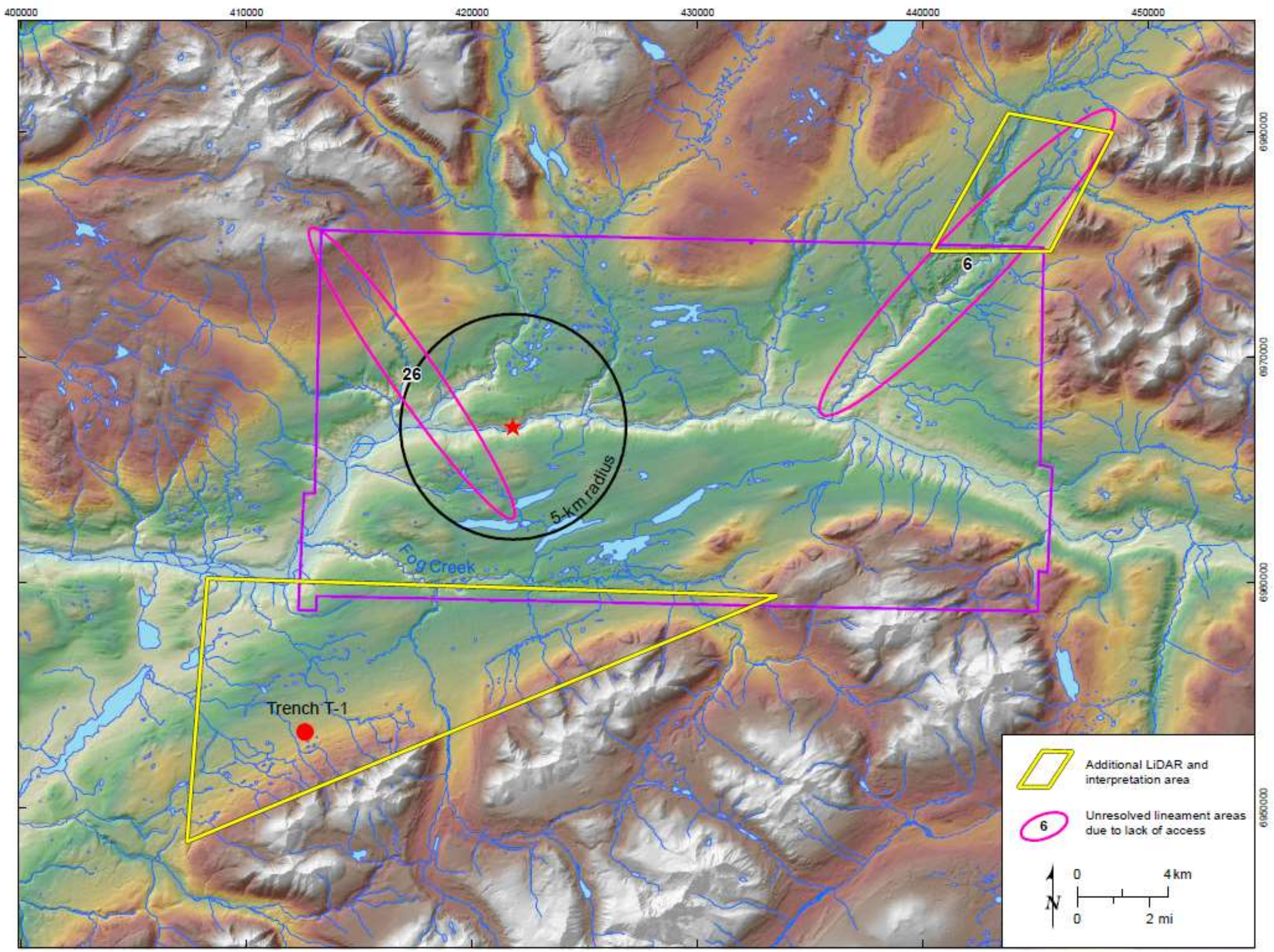
DRAFT

10/18/13	STATE OF ALASKA ALASKA ENERGY AUTHORITY	LINEAMENT GROUP 6 PHOTOGRAPHS	FIGURE A6.2

Lineament Mapping and Evaluation Summary

Category	Category Description	Lineament Groups
I	Lineament groups that were not advanced for field investigation in 2013 based on FCL (2013) desktop evaluations. Most were not inspected during 2013 field activities.	4, 10, 11, 13, 14, 15, 16, 18, 24, 25, North-South Features near Talkeetna River-Susitna River Confluence
IIa	Lineament groups evaluated during 2013 field studies, and judged to be non-tectonic (dominantly erosional, depositional, or jointing/bedding in origin). No further work is recommended for evaluation as potential crustal seismic sources.	1, 2, 3a, 3b, 5, 12a, 17a, 21a, 21b, 22, 23, select Reger et al. (1990) features
IIb	Lineament groups evaluated during 2013 field studies, and also judged to be of non-tectonic origin, but which appear to be spatially associated with previously mapped bedrock faults. No evidence of Quaternary faulting was observed, and no further work is recommended for evaluation as potential crustal seismic sources	7, 8, 9, 12b, 17b, 17c, 19, 20, Broad Pass area, Clearwater Mountains area, select Reger et al. (1990) features
III	Lineament groups or other areas unresolved due to unavailable ground access in 2013. Field activities and further evaluation are deferred.	6, 26, WCC T-1 area, Fog Creek area, dam site and reservoir vicinities
IV	Lineament groups that have defensible justification for consideration or inclusion as crustal seismic sources in an updated seismic source model.	27 (Sonona Creek fault), Castle Mountain extension

Lineament Mapping and Evaluation: 2014



Lineament Mapping and Evaluation

- Conclusions
  - Results generally consistent with WCC (1982), contingent on additional data
  - Quaternary faults or folds mapped by State of Alaska (Koehler, 2013) are consistent with those recognized by this study
    - No mapped Quaternary faults within Talkeetna Block near dam site
  - Little evidence for unrecognized late Quaternary tectonic geomorphology, suggestive of high slip rates, based on mapping and 2013 field investigation
    - Future studies are relatively unlikely to create significant changes in PSHA or deterministic ground motions
  - However, uncertainty of some previously mapped faults as recognizable features in the landscape suggests some need for additional evaluation in the field.
    - e.g. WCC T-1 and Talkeetna feature

Slab Geometry
and
Updated Rates

Catalog Development and Update

- 2 catalogs developed
- Slab Geometry Catalog
  - Used to characterize geometry of down going slab
  - AEC seismicity since 1988
  - All magnitudes
- PSHA/Recurrence Catalog
  - Used to develop smooth seismicity grids used in PSHA
  - (Update of USGS (2007) catalog)
  - Historic catalog: 1898-2012
  - M4+

Slab Geometry

- Rectangles are regions where slab appears to define a plane

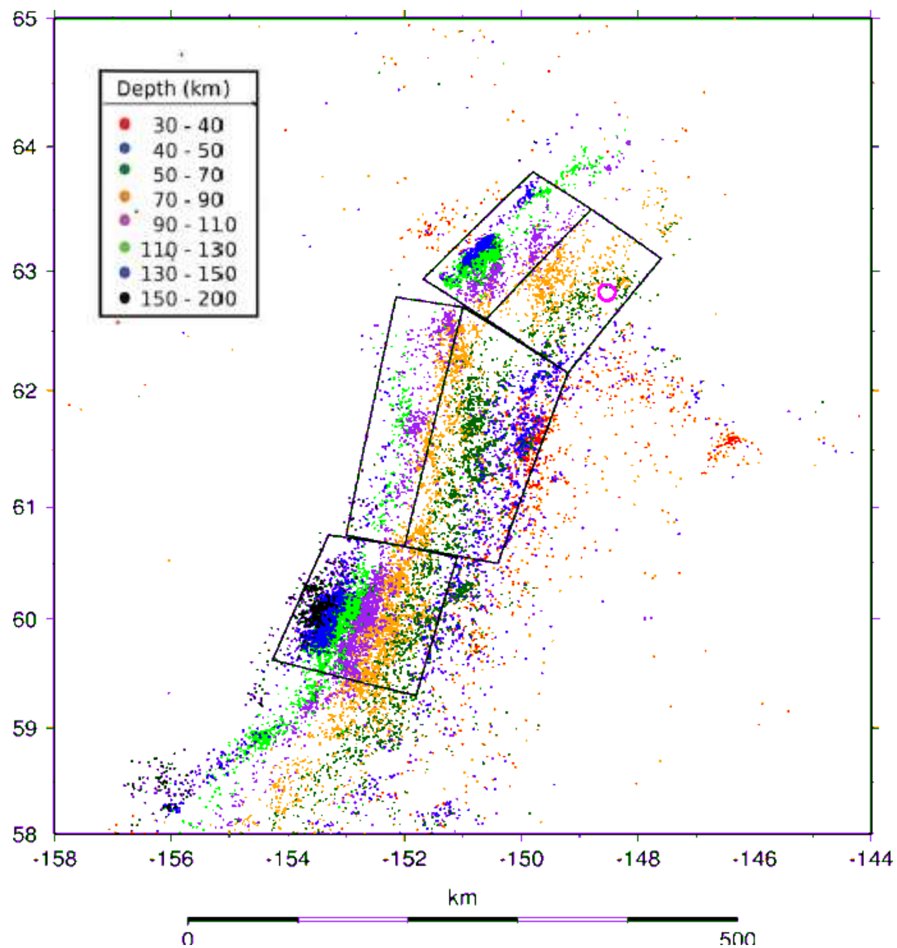


Figure 1. AEIC seismicity, July 1988 – January 2013. Color coding listed in Table 1. Rectangles are boxes used for identification of slab planes. Magenta circle is Watana site.

Slab Geometry

Planes fit to McKinley block

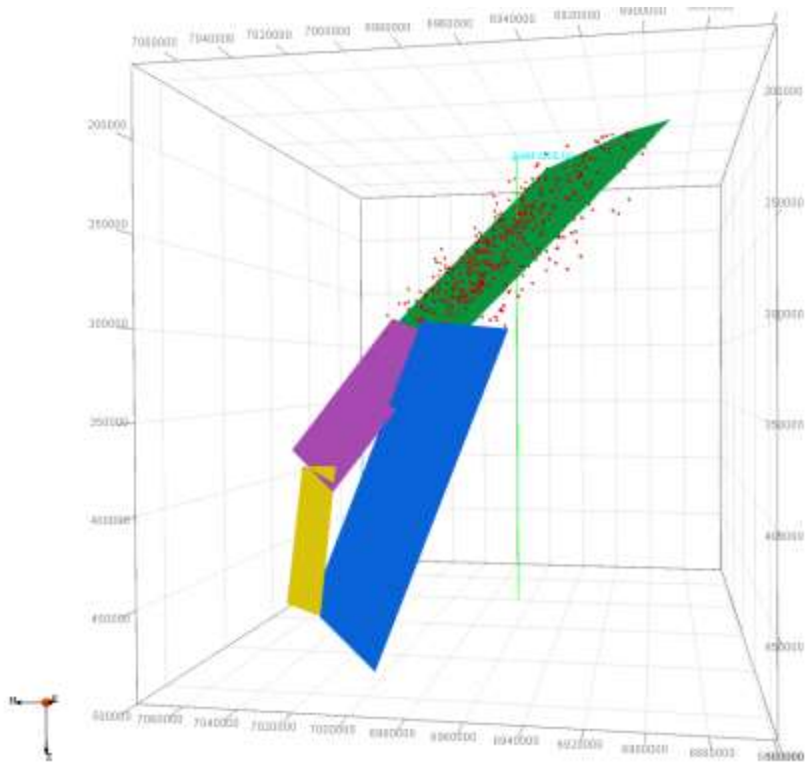


Figure 4. 3-d depiction of slab planes defined in northernmost box of Figure 1 (Planes 1-4). View looking NNE.

Slab Geometry

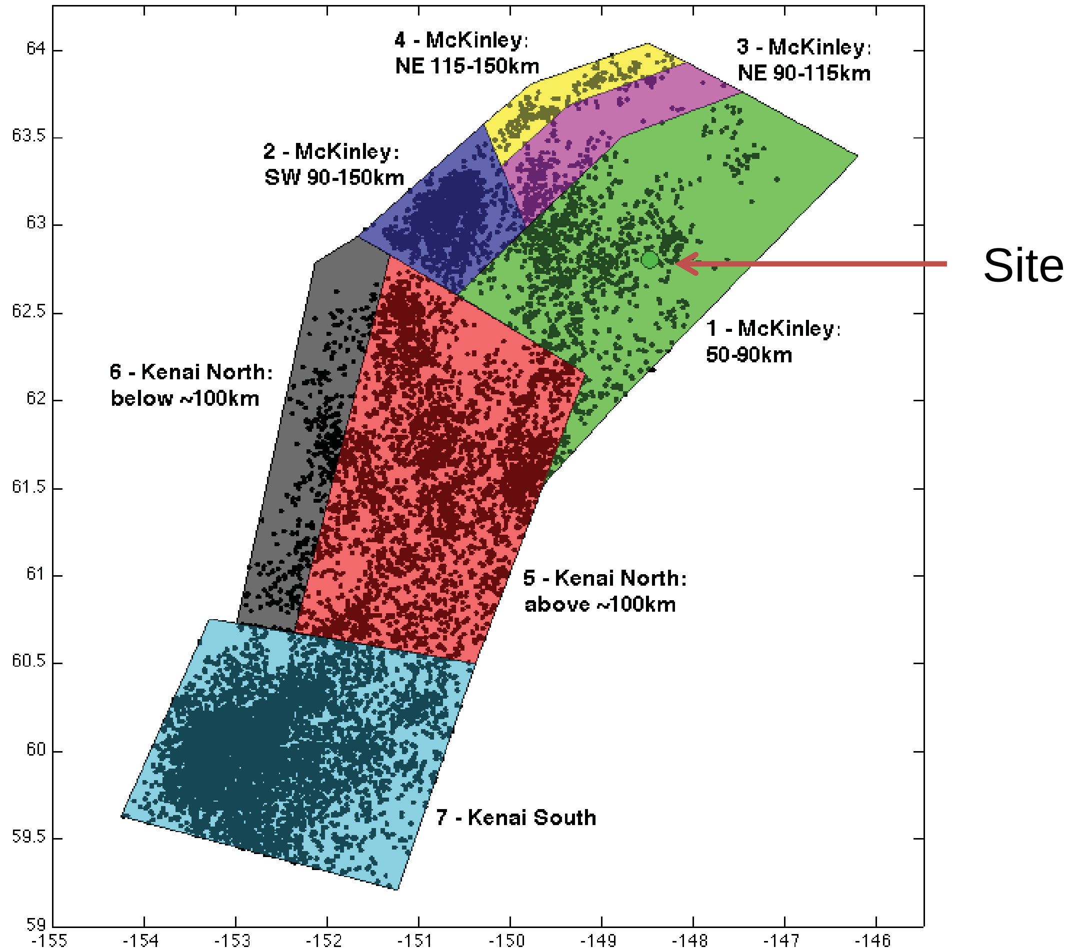


Figure 8. Map view of slab planes. Numbers referenced in Table 2.

Slab Geometry

1. Calculated Slab Plane Parameters
2. Thickness sigma assumes normal distribution

Plane Number	Location	Depth Range (km)	Strike	Dip	Seismicity Thickness: 1σ(km)	Seismicity Thickness: 2σ(km)
1	McKinley Block (AEIC)	35-90	58	25	4.5	9.0
1	McKinley Block (WSN)	35-90	63	21	6.2	12.3
2	McKinley Block	90-150	52	50	5.5	10.9
3	McKinley Block	90-115	50	32	3.6	7.2
4	McKinley Block	115-150	50	64	4.0	7.9
5	Kenai Block North	40-100	17	27	7.8	15.6
6	Kenai Block North	100-150	11	52	9.2	18.4
7	Kenai Block South	50-200	26	46	9.2	18.3

Grid Models

- Recurrence Calculation
  - PSHA/Recurrence catalog used, mag completeness periods used in FCL (2012), gaussian smoothed seismicity grids generated (Frankel et al. (1996)) for correlation distances of 15, 25, and 35 km
  - Maximum-likelihood recurrence calc (Weichert, 1980) done on PSHA/Recurrence catalog for events with depths $\geq$ 40 km, computed b-value of 0.903

Grid Models

10a incremental rate,
.1 deg cells,
Correlation distance (sigma) = 15 km

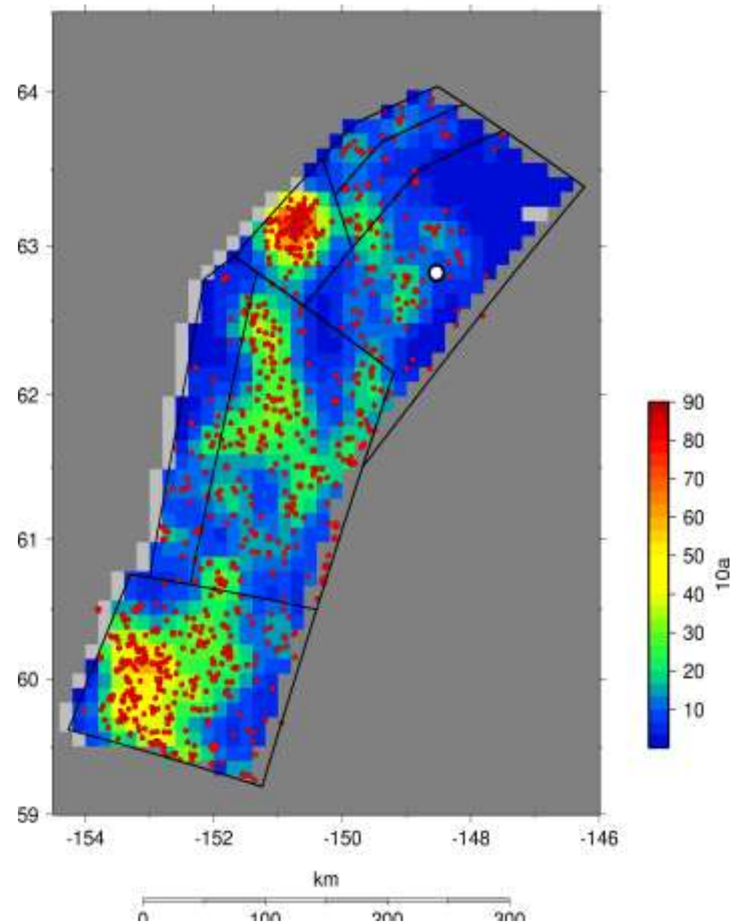


Figure 9. Grid with correlation distance = 15 km. Red dots are earthquakes used to generate the grid. White circle is Watana site.

Grid Models

10a incremental rate,
.1 deg cells,
Correlation distance (sigma) =
35 km

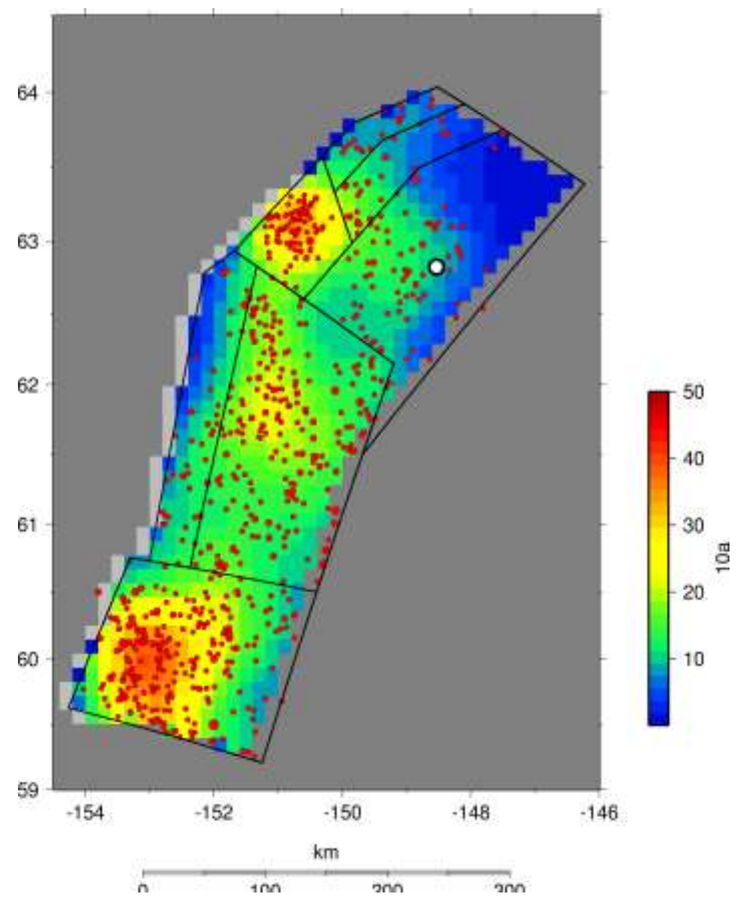
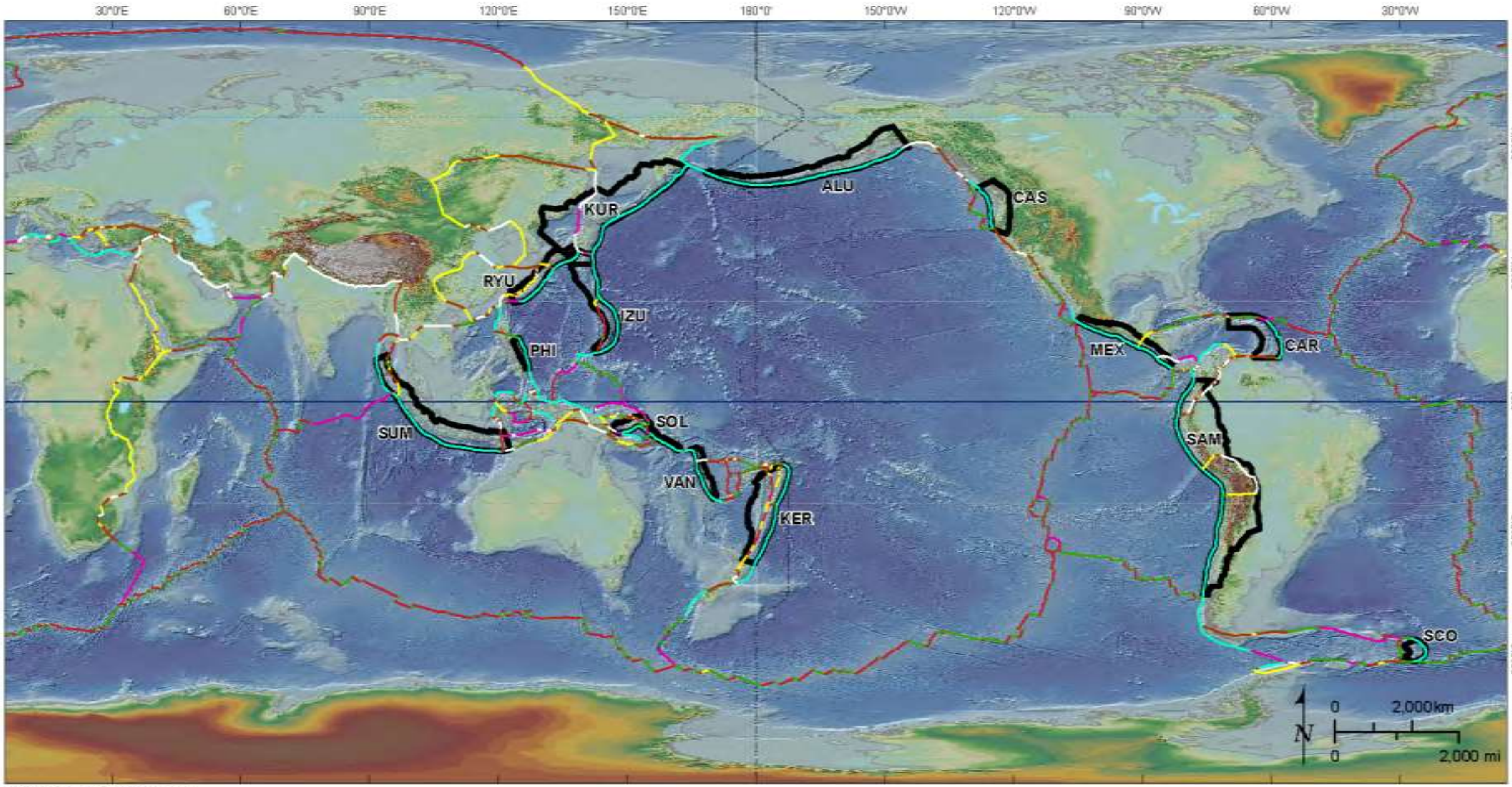


Figure 11. Grid with correlation distance = 35 km. Red dots are earthquakes used to generate the grid. White circle is Watana site.

Global Intraslab Mmax Assessment

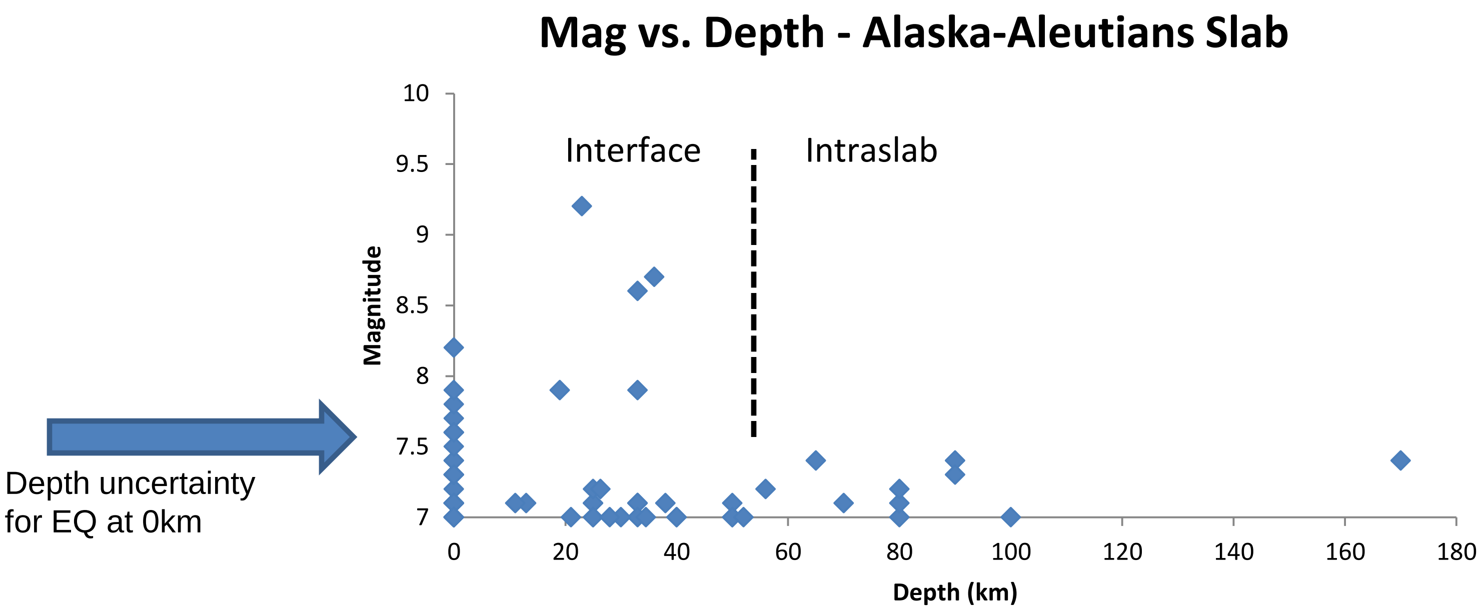
Subduction Zones Examined Worldwide



Elevation data from NGDC, 2001

Mmax of Intraslab Earthquakes

- Seismicity Data for Subduction Zones
  - Download seismicity data for each zone from ISC Bulletin and EHB Catalog, M7+, EHB authoritative
- Mag vs. Depth Plots for Subduction Zones
  - Modeled after Frohlich (1998), visualization of magnitude ranges with depth



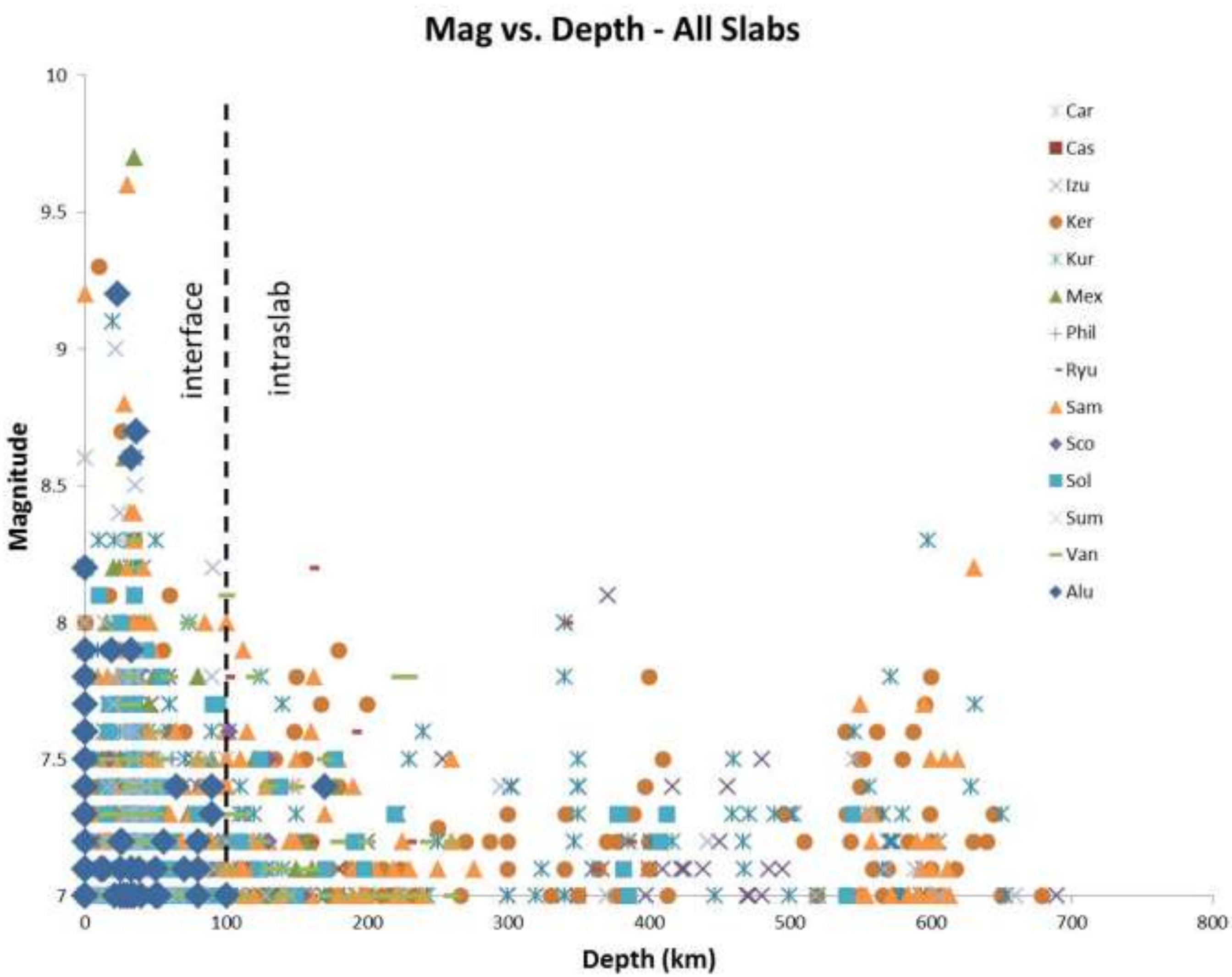
Mmax of Intraslab Earthquakes

- Pinpoint Data
  - Intraslab events (100 – 400 km in depth), also look at deep (400 km+)
- Largest Mmax in Each Subduction Zone (100 km+)

Region	Mmax (100 to 400 km)	Mmax > 400 km
Alaska-Aleutians	7.4	N/A
Caribbean-Lesser Antilles	7.5	N/A
Central America	7.4	N/A
Cascadia	N/A*	N/A
Izu-Bonin	**8.1**	7.5
Kermadec-Tonga	7.9	7.8
Kamchatka/Kuriles/Japan	**8.3****	**8.3**
Philippines	N/A*	N/A
Ryukyu	**8.2**	N/A
Santa Cruz Islands/Vanuatu/Loyalty Islands	**8.1**	N/A
Scotia	7.6	N/A
Solomon Islands	7.5	7.3
South America	7.8	**8.2**
Sumatra-Java	7.4	7.5

* All events occurring in Cascadia and Philippines are less than 100 km in depth
** 10/4/1994 event occurred at 50 km depth, but was identified by Tanioka et al. (1995) as an intraslab event that tore the upper part of the subducting plate.

Mmax of Intraslab Earthquakes



Mmax of Intraslab Earthquakes

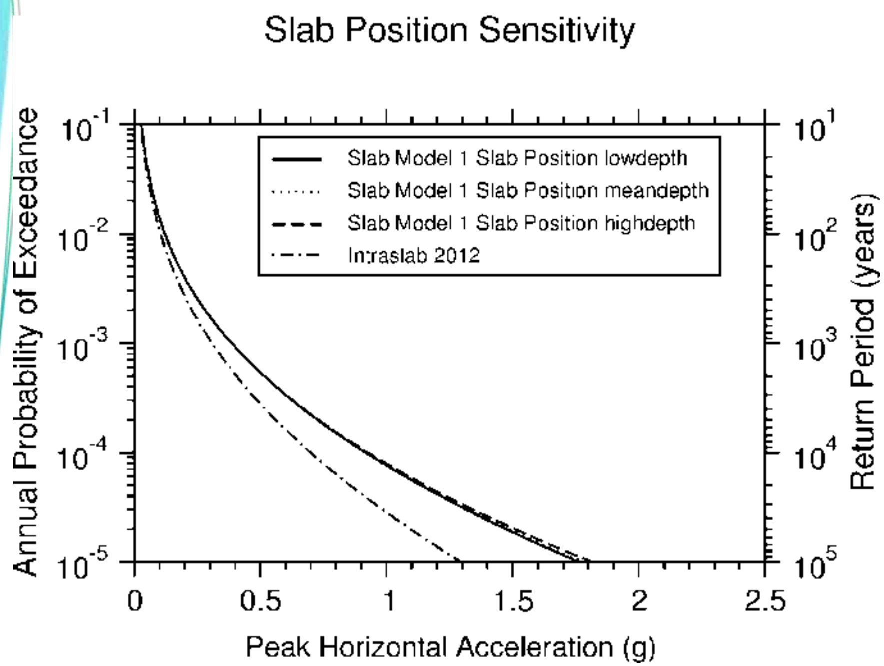
- Results
  - Mmax of earthquakes from 100 – 400 km decreases with depth, but from 400 – 600 km, Mmax increases (same pattern seen by Frohlich (1998, 2006))
- Reliability of Data
  - Many of the Mmax events in each zone occurred before 1964, attempt made to verify events in other published sources but have to question reliability of locations, depths, and magnitudes
- Conclusions
  - Reliability of data, can larger (M8 – 8.5) events in the 400-700 depth range occur in the 100-400 km depth range? ASZ down going slab terminates at 150 km beneath the Project site
- PSHA Sensitivity Mmax Distribution (October, 2013)
  - 7.5, 7.8, and 8.1

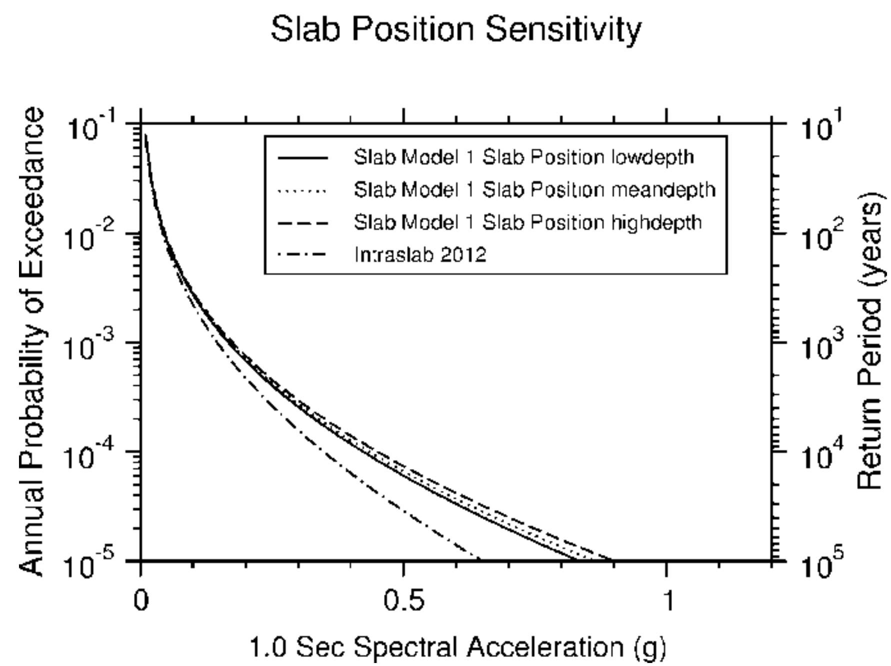
PSHA Sensitivity to New Slab Model

PSHA Sensitivity Calculation

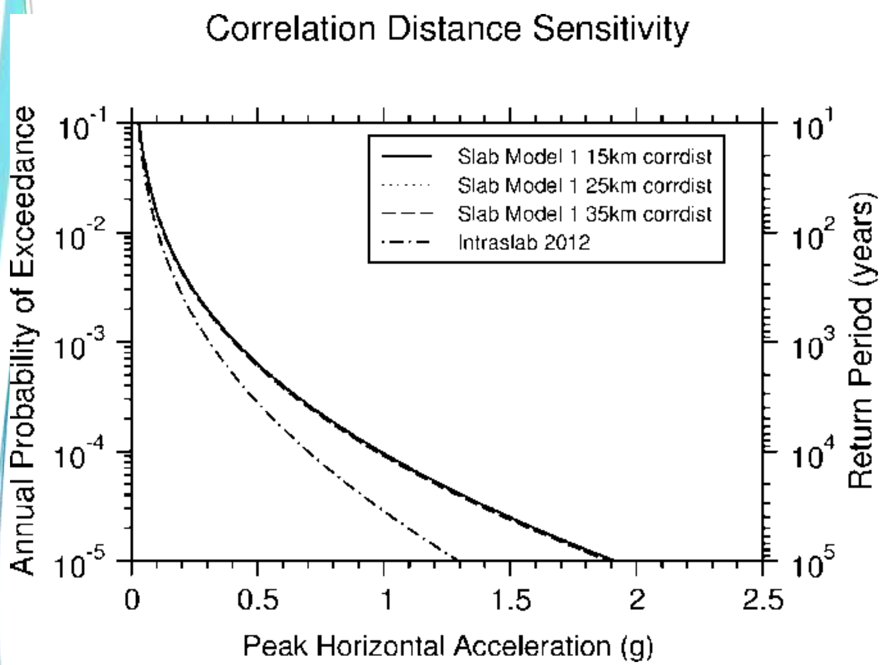
- Calculation Parameters
  - Calculation using source model in FCL (2012) but with calculated b-value, slab geometry, and Mmax, 3 correlation distances, 3 slab positions, and 3 Mmax values (27 results), PHA and 1.0 sec, 5% damping, updated Vs30 values (1080 m/s)
  - Same mix of GMPEs as FCL(2012) (.5 BCH, .25 Zhao et al, .25 AB2003
  - Grid points projected onto slab (median, +/- 2s depths)
- Results
  - Hazard curves close to 2012 results
  - Little/no sensitivity to slab position uncertainty
  - Little/no sensitivity to correlation distance
  - Some sensitivity to VS30
  - <u>VERY</u> sensitive to Mmax

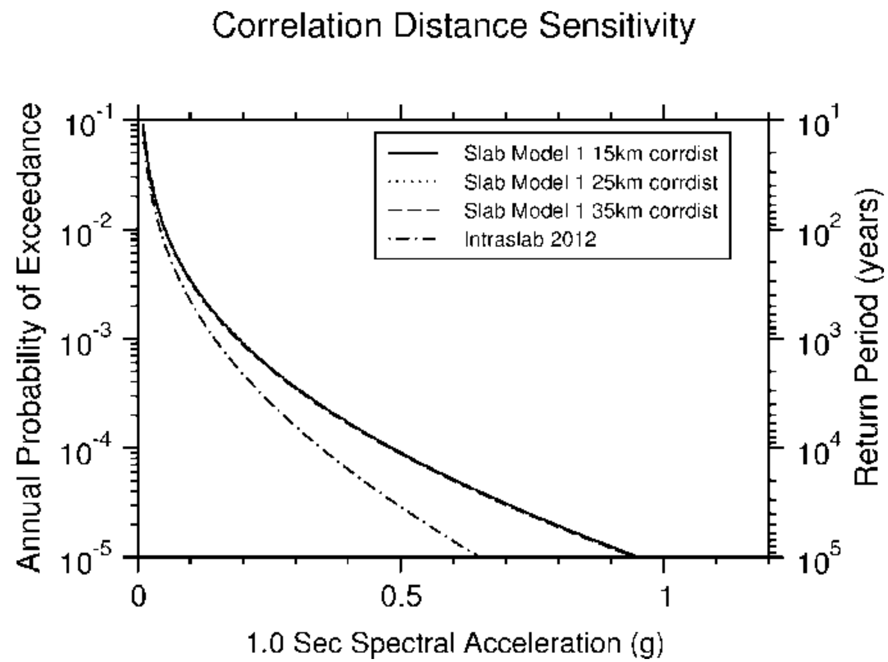
PSHA Sensitivity Calculation



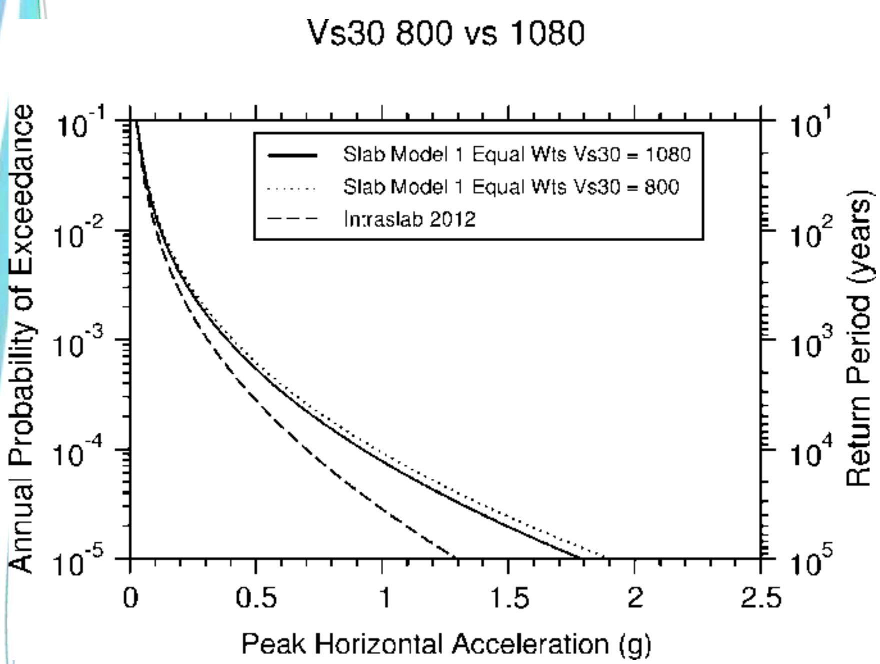


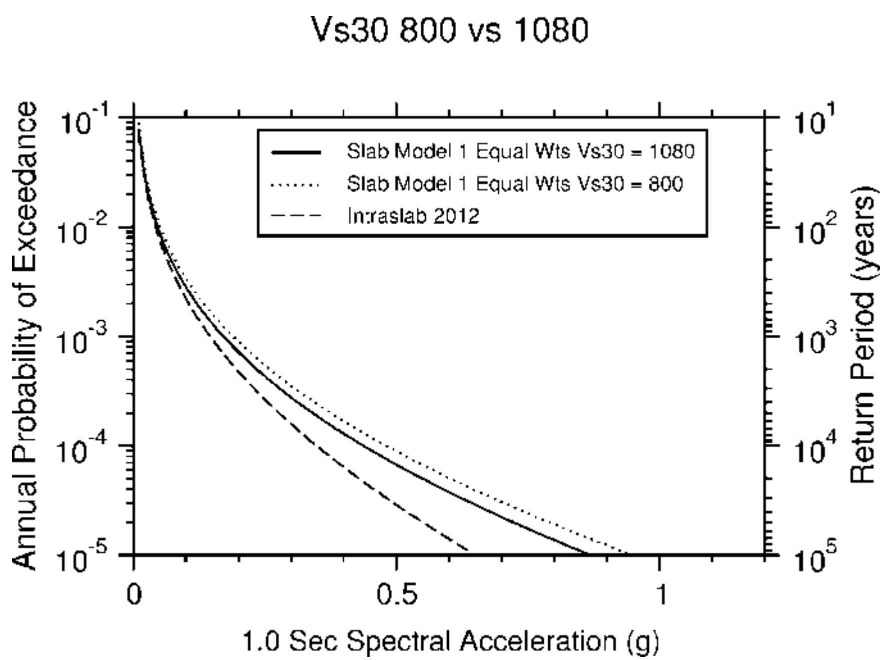
PSHA Sensitivity Calculation





PSHA Sensitivity Calculation





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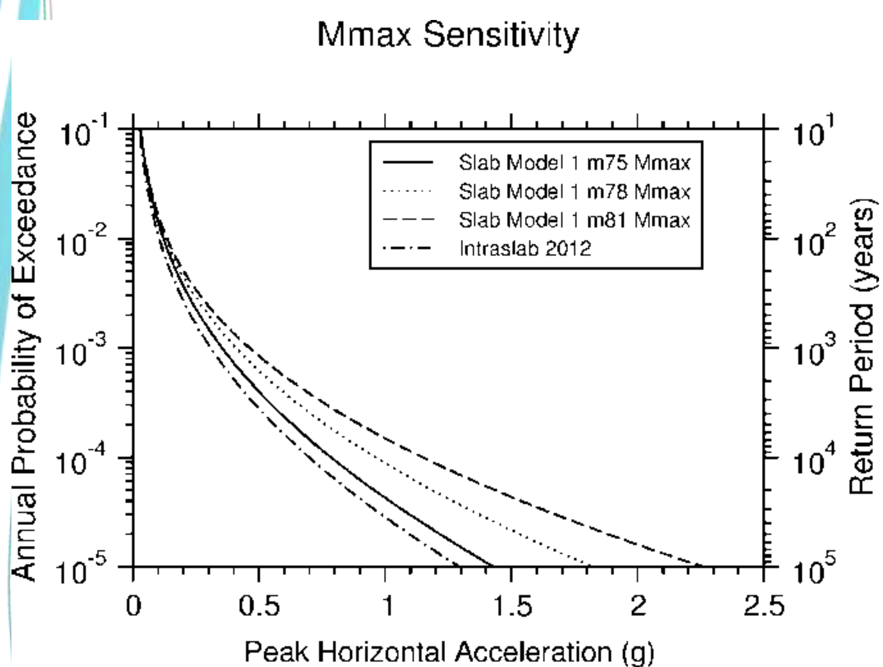

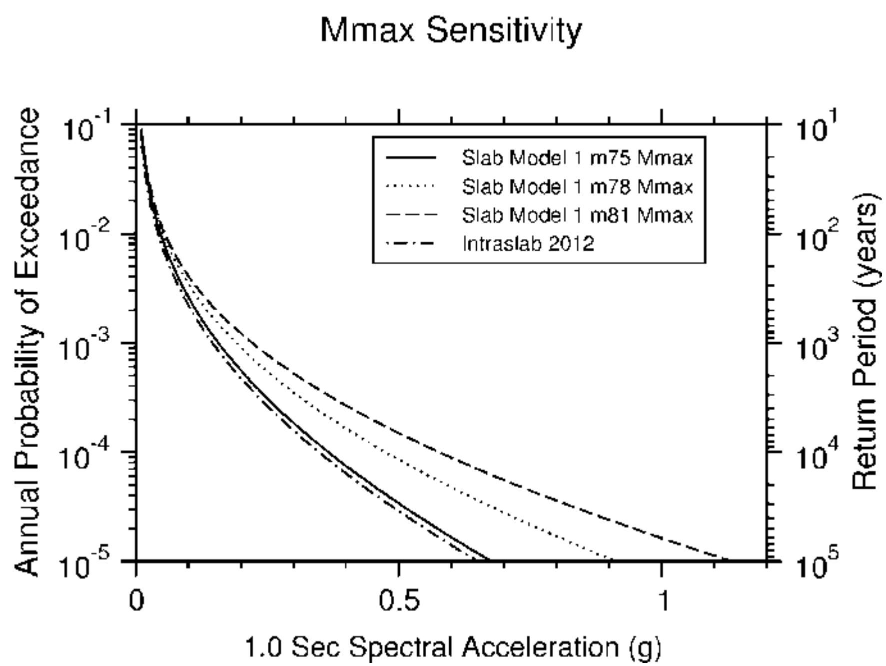

Conclusions

- Final assessment of crustal sources pending resolution of site access restrictions
- Dam Site Vs30 likely to be greater than 2000 m/s
- New slab model gives more realistic geometric representation
  - Segmented slab may provide rationale for limited Mmax
- Global subduction zone seismicity record suggests Intraslab Mmax probably larger than 7.5
- PSHA very sensitive to intraslab Mmax
- Future PSHA needs to develop intraslab Mmax distribution
- Need to assess intraslab GMPE applicability and uncertainty at M > 7.5