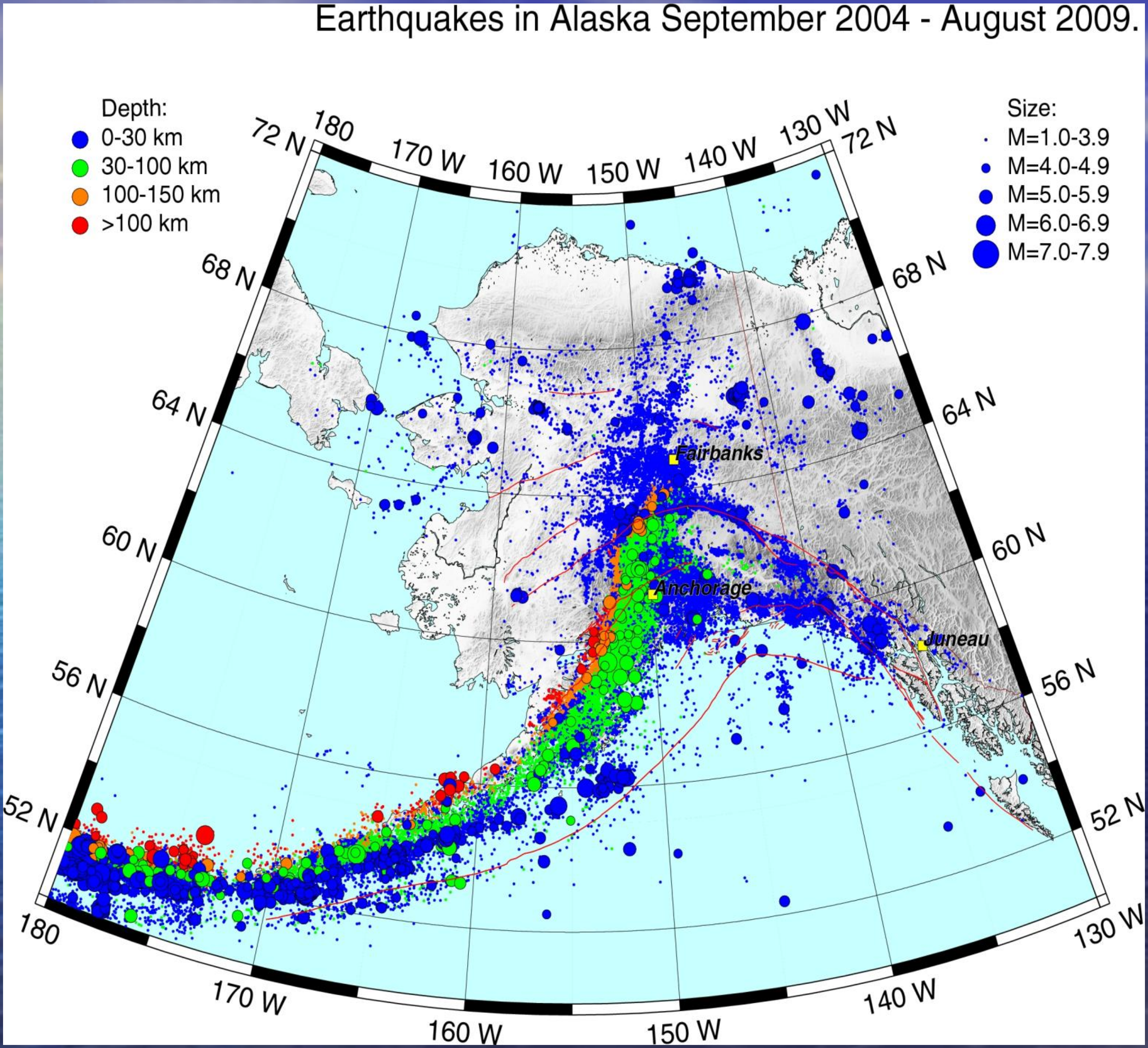
Tsunami Inundation Modeling in Alaska

Identifying The Threat

Roger Hansen, Dmitry Nicolsky, and Elena Suleimani

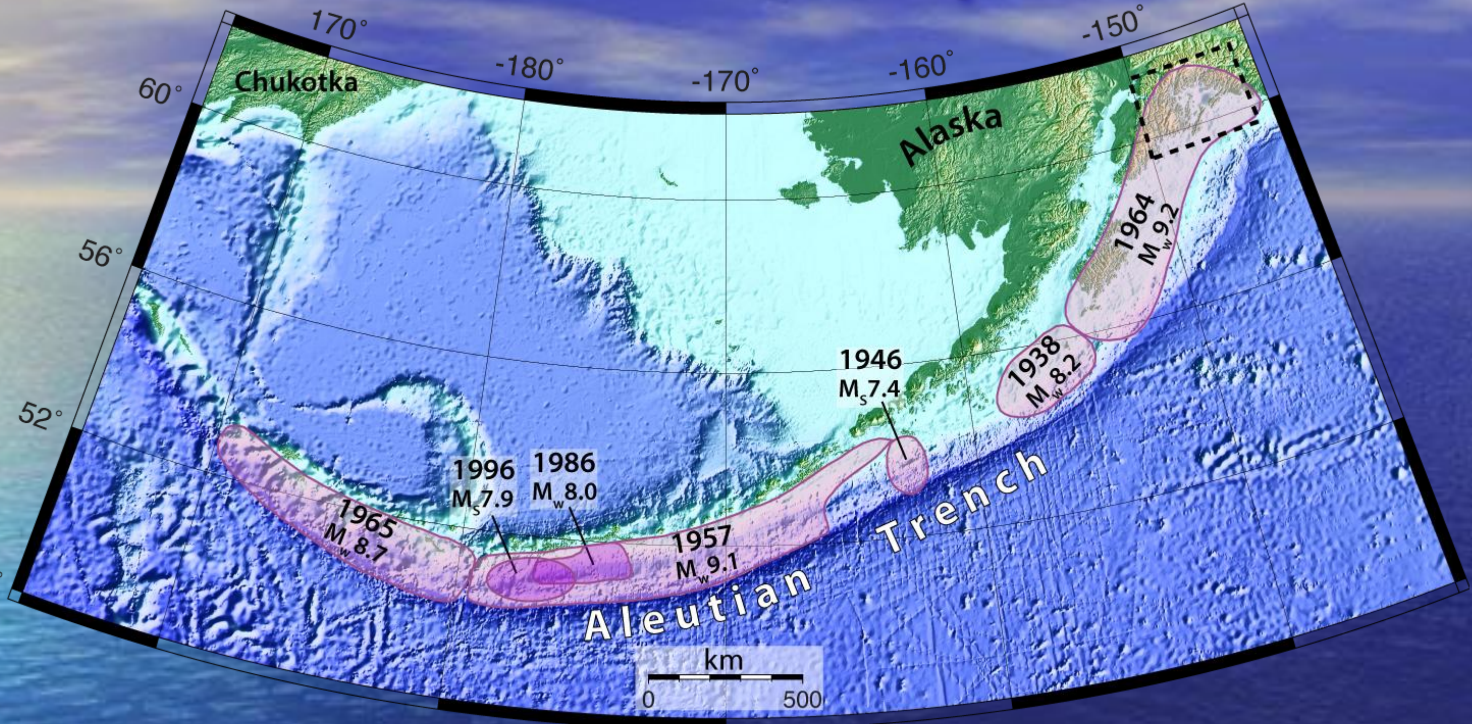
Alaska Earthquake Information Center

Geophysical Institute, University of Alaska Fairbanks



Earthquakes in Alaska September 2004 - August 2009.
Depth:
0-30 km
30-100 km
100-150 km
>100 km
Size:
M=1.0-3.9
M=4.0-4.9
M=5.0-5.9
M=6.0-6.9
M=7.0-7.9
Fairbanks
Anchorage
Juneau
180
170 W
160 W
150 W
140 W
130 W
72 N
68 N
64 N
60 N
56 N
52 N

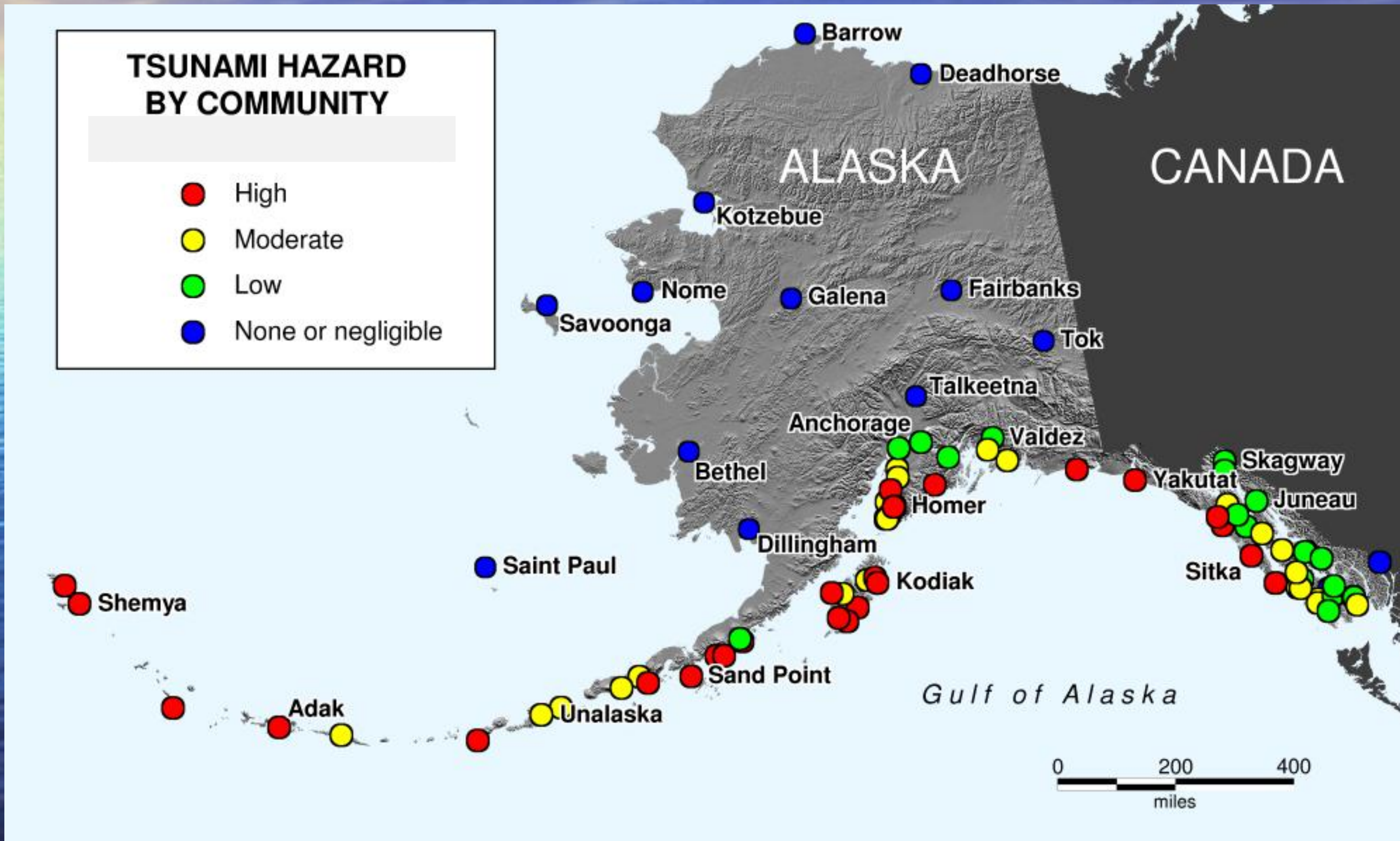
Tectonic tsunami potential



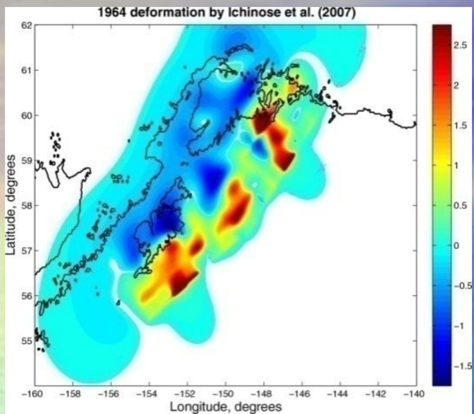
- Tectonics of Alaska is defined by the convergence of the Pacific and North American plates, which interact along the Aleutian Megathrust.
  - The Alaska-Aleutian subduction zone is a place where great tsunamigenic interplate earthquakes repeat. The subduction zone has a history of generating both local and Pacific-wide tsunamis.

State of Alaska
Department of Military and Veterans Affairs
Homeland Security & Emergency Management

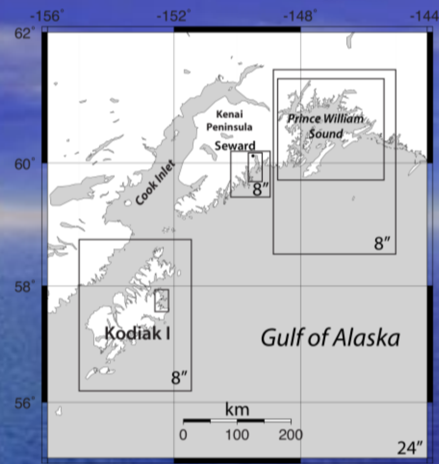
• Tsunami Threat



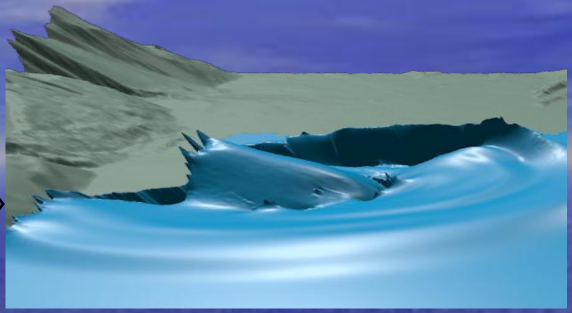
Inundation Mapping Process



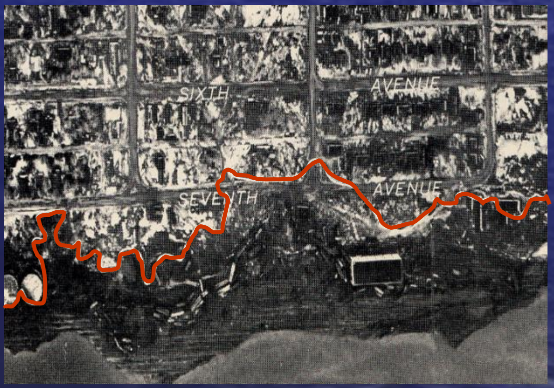
Tsunami Scenarios



Data preparation

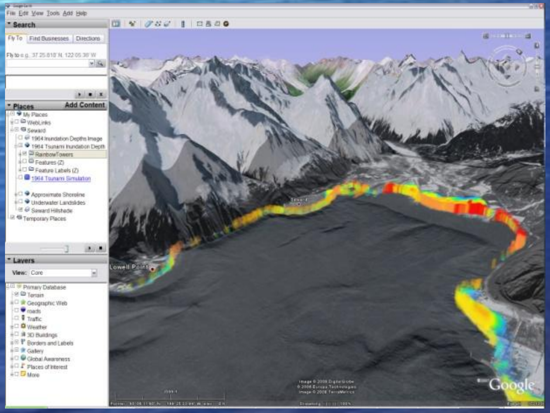


Numerical Modeling



Model verification with field observations (i.e. 1964 tsunami)

Inundation maps and report



Google Earth layers

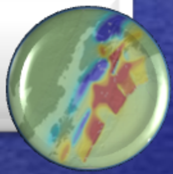
Community-based approach

- Community proposes areas for inundation mapping
- Community reviews maps and technical report
- Community is a resource for local data
- Education and outreach

Community involvement

- A set of scenarios is developed for every community
- 1964 tsunami is modeled if the community was affected by the event
- Landslide tsunamis

Sources



- Base map: high-resolution geo-referenced image
- Interface: ArcGIS
- Input : XYZ files
- Output: PDF, all image formats, KML for use in Google Earth

Projecting results

- Inundation limits
- Flow depth
- Flow velocity
- Drag force
- Historical and field data

Map layers

- Emergency officials, fire chiefs, city planners and engineers
- A base for developing the hazard and evacuation maps

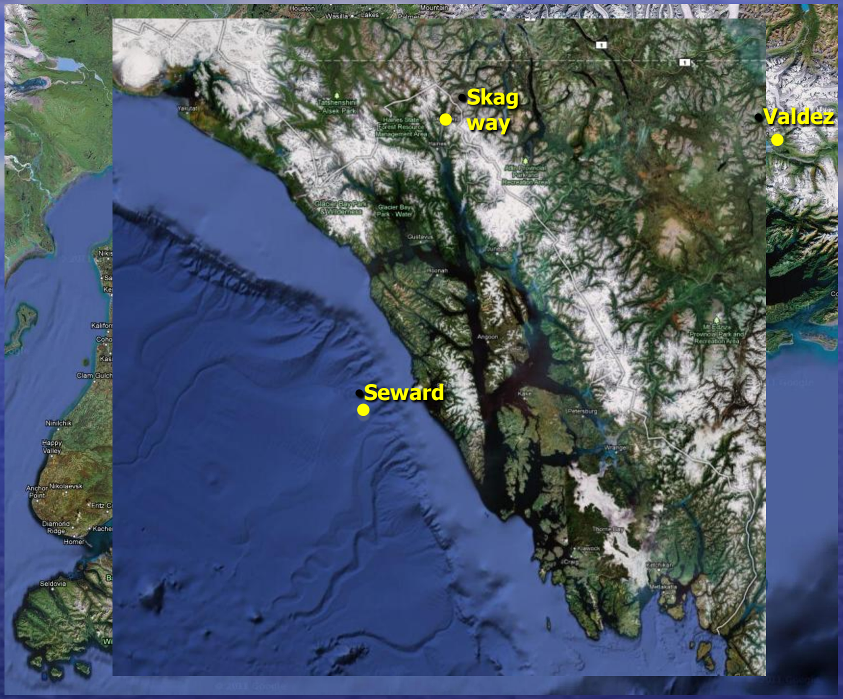
Use of maps

Complexities that contribute to Alaska tsunami modeling

- The Tectonic Tsunami Source:
  - Finite Fault models with Splay faults (1964)
  - Effects of horizontal motions
  - Need for plausible hypothetical sources
- Tsunamis caused by landslides
  - Important component to observed tsunamis in AK
- Comments on high resolution Bathymetry
  - Better understanding of potential landslide features

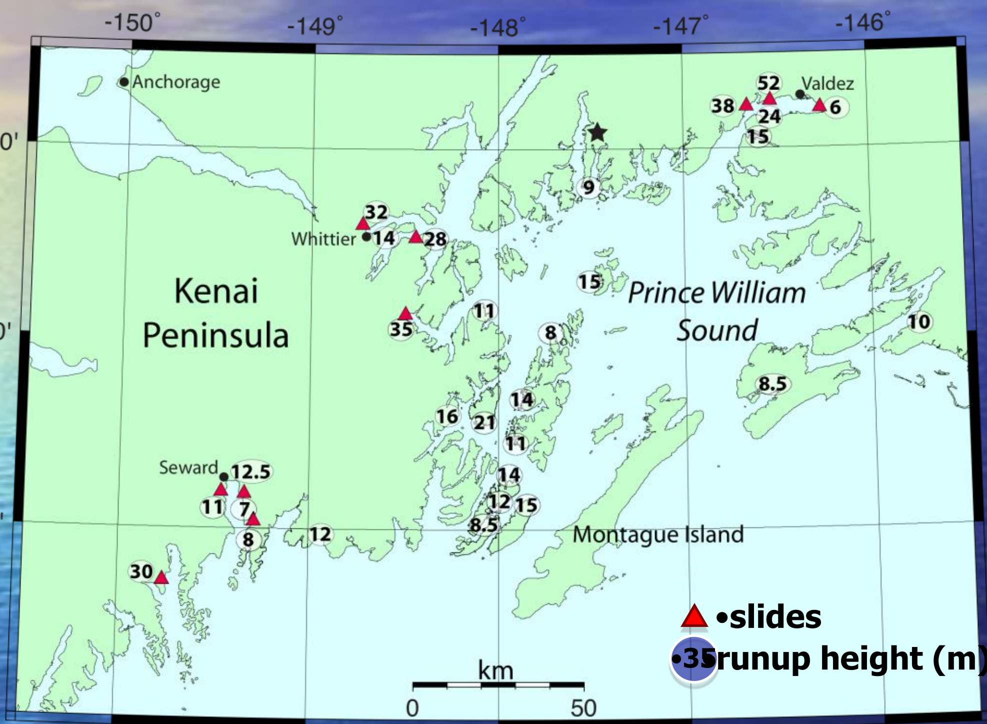
Landslide tsunami potential is high

- Tsunamis caused by submarine slope failures constitute a real hazard in glacial fjords of coastal Alaska, where sediment is deposited on steep fjord walls at a high rate.
- Factors contributing to initiation of submarine slope failures:
  - External events: earthquakes, extreme low tides, construction activities in ports
  - Material properties: overpressure due to rapid deposition, unconsolidated fine-grained materials.
- About 20 local landslide tsunamis of 1964 accounted for 76% of all tsunami fatalities.
- Seward and Valdez: core analysis shows sediment accumulation rate of about 2 cm/yr.



- **Landslide-generated wave in Skagway on 11/3/1994 killed one person and caused $21 million in damage. Triggering mechanism: extreme low tide.**

Sources of local waves in 1964



•Locations of known and probable large underwater slides triggered by the 1964 earthquake, and maximum observed runup heights in meters (from *Plafker et al., 1969*)

•Landslide tsunamis

Location	Max runup (m)	Deaths
Aialik Bay	30	
Blackstone Bay	24	
Homer	6	
Jack Bay	12	
Kenai Lake	10	
Chenega	21	23
Seward	12.5	12
Valdez	**52**	31
Whittier	32	13

•Total volume of slide material:

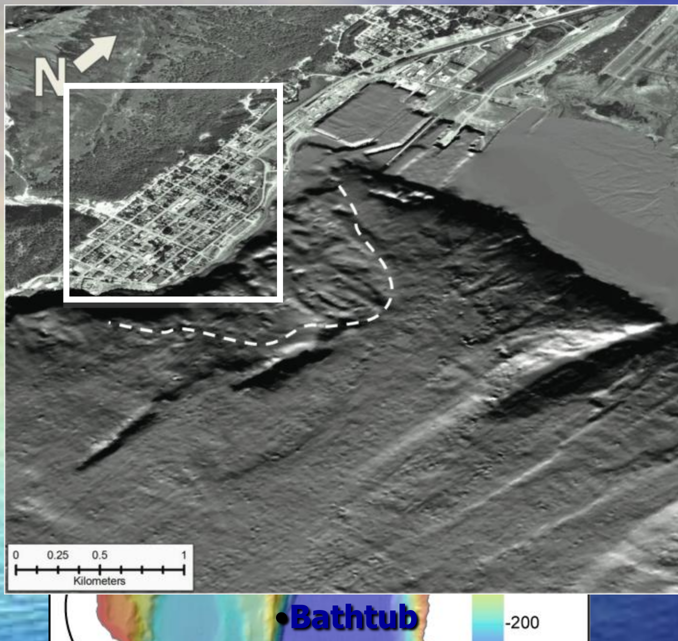
•Seward: 0.2 km^3

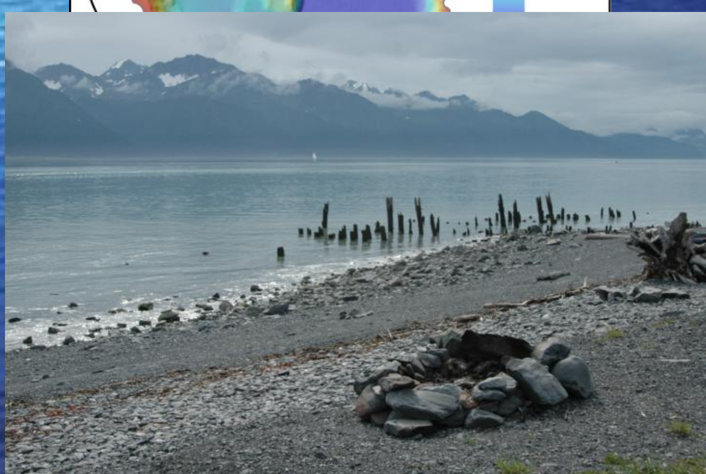
• Valdez: 1 km^3

Seward, Resurrection Bay on 3/27/64

- Seward was the only place hit by both tectonic and local landslide-generated waves during the earthquake.
- Strong ground motion lasted for 3-4 minutes.
- Seward waterfront slid into the bay within 30-45 seconds of the main shock.
- Fuel tanks ruptured, leaked and exploded, sliding into the bay.
- Sequence of waves:
  - Initial drawdown of water about 30 seconds after the main shock
  - The highest wave was observed about 1.5-2 minutes after shaking began. It was 6-8 meters high.
  - The tectonic wave came into the bay about 30 minutes after the main shock, was as high as the local wave.

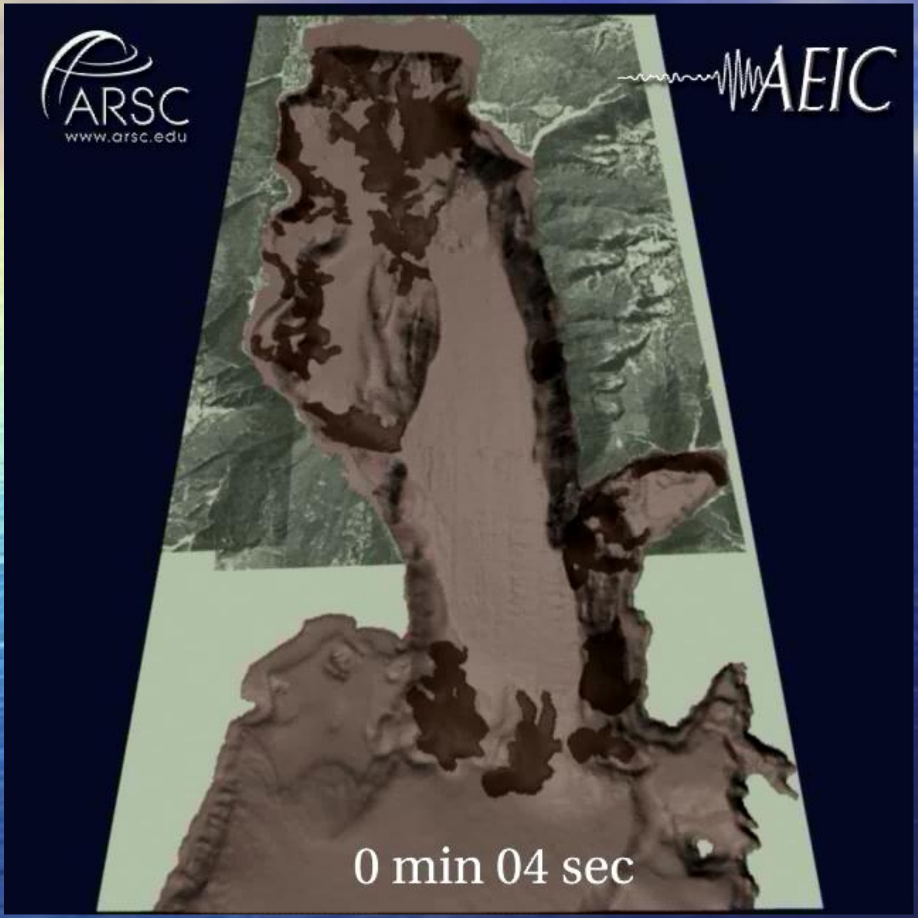
Geological setting

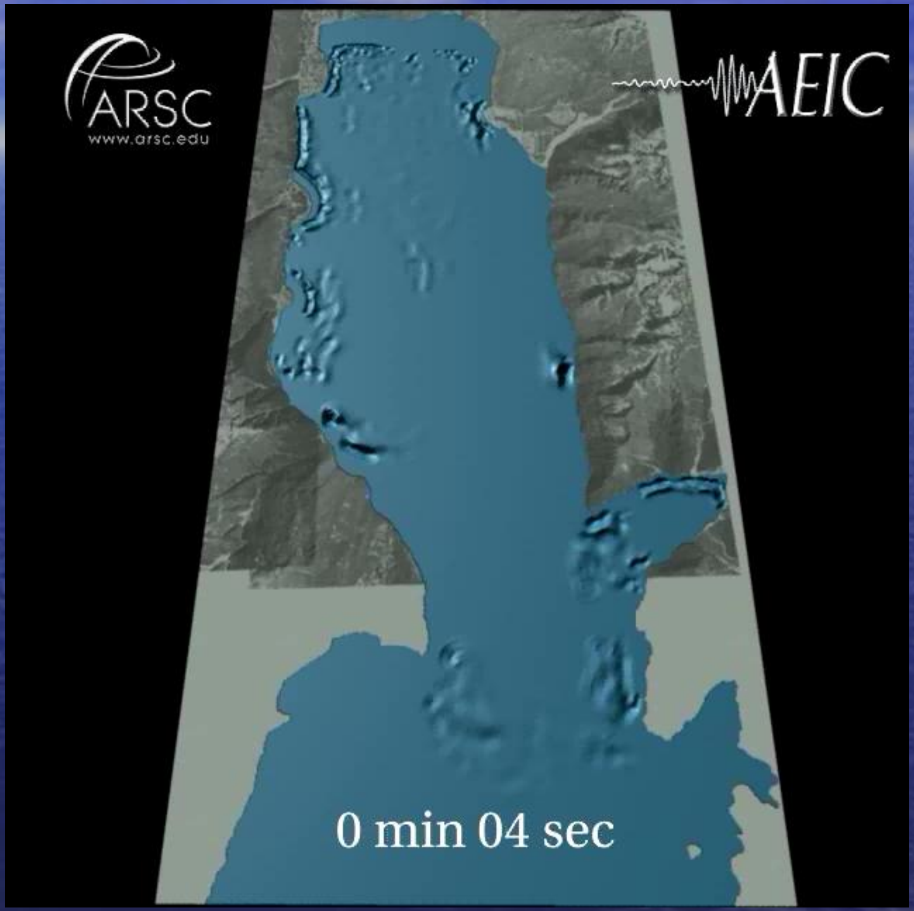




- Resurrection Bay is a deep glacial fjord with sediment deposition on the steep walls of the fjord.
- Major features: a fjord-head delta formed by Resurrection River, several alluvial fans, a deep depression called "bathtub", and a glacial sill.
- Seward is built mostly on the alluvial fan of Lowell Creek.
- The multi-beam survey of 2001 identified an area of blocky debris offshore Seward that is suggestive of submarine landslides.
- Factors that contributed to massive slope failures: intense and prolong ground motion, steep underwater slopes, type of sediments, low tide, artificial fill of the waterfront, rapid drawdown of water.
- Engineering and geotechnical studies concluded that slope failures have not improved slope stability of Seward waterfront, and landslides can be expected during another large earthquake

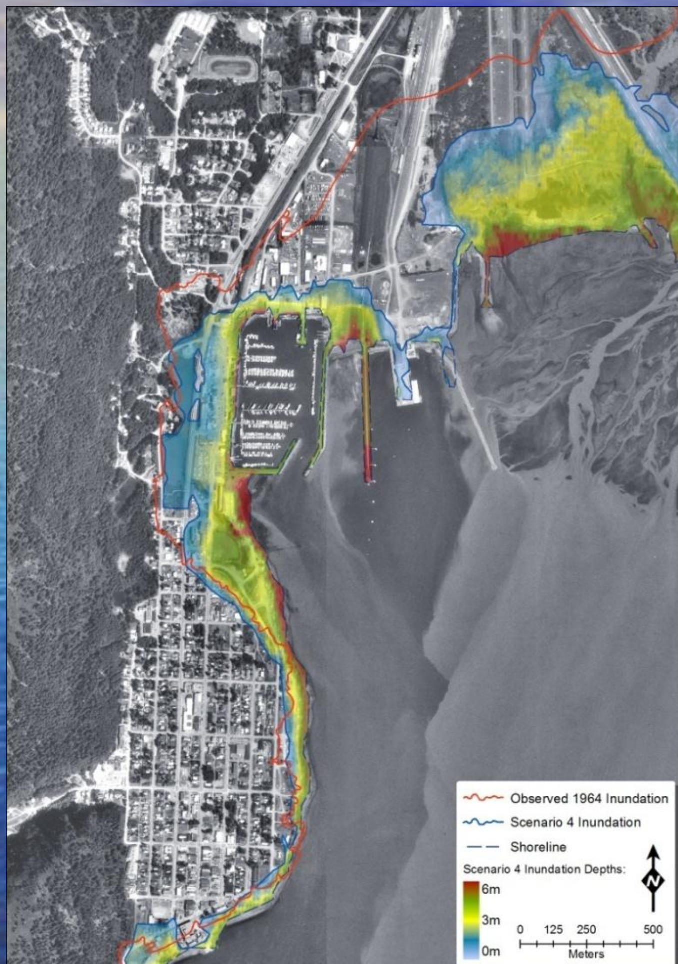
How far did the slides travel?



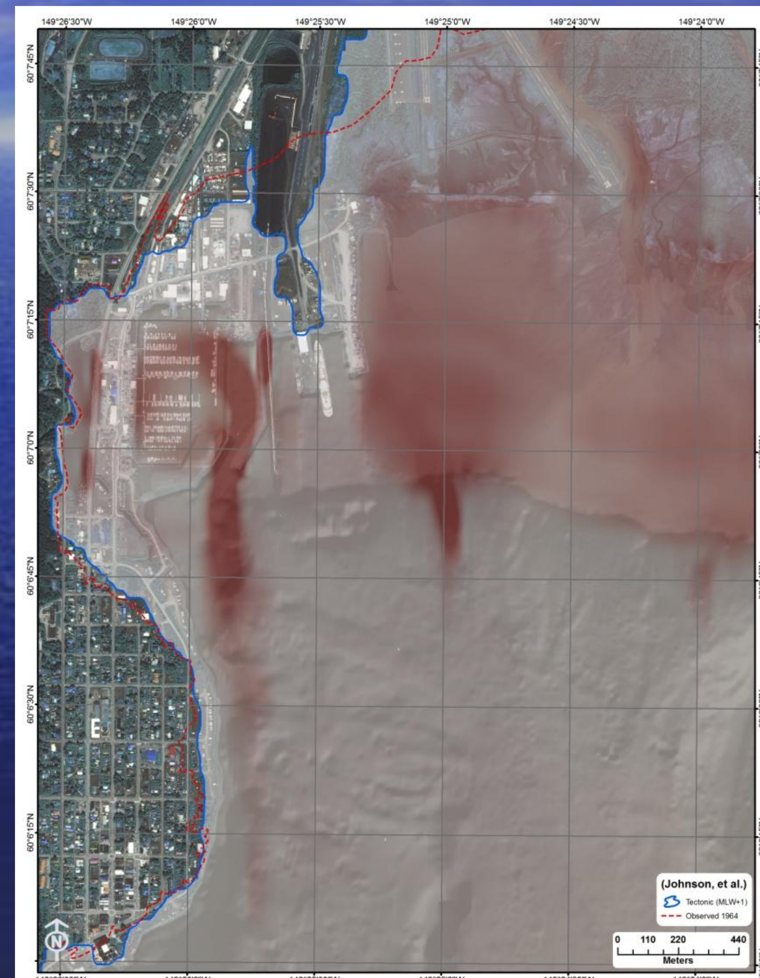


- **Space step: Δx=15 m 930,000 grid points**
- **Time step: Δt=0.01 sec 10 min of slide simulation, ≈ 5 CPU hours**

Model outputs



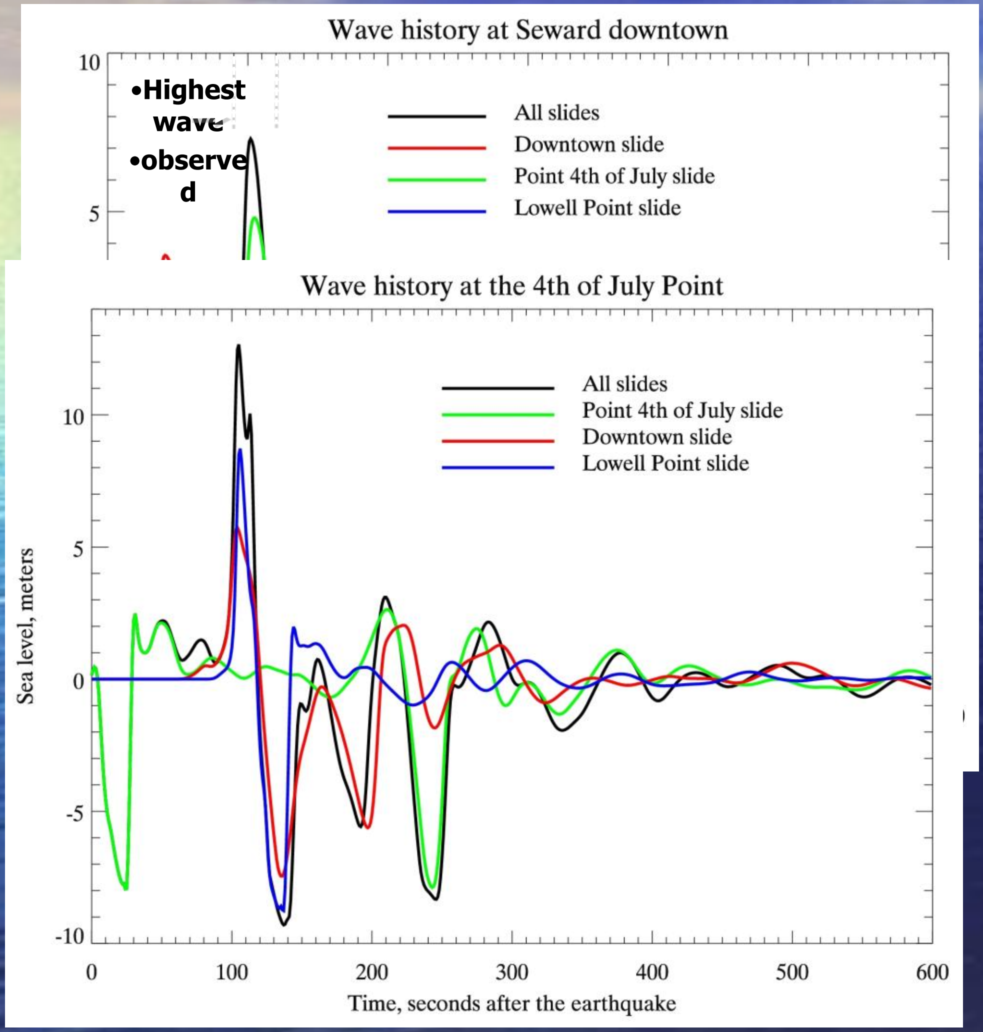
Flow depth

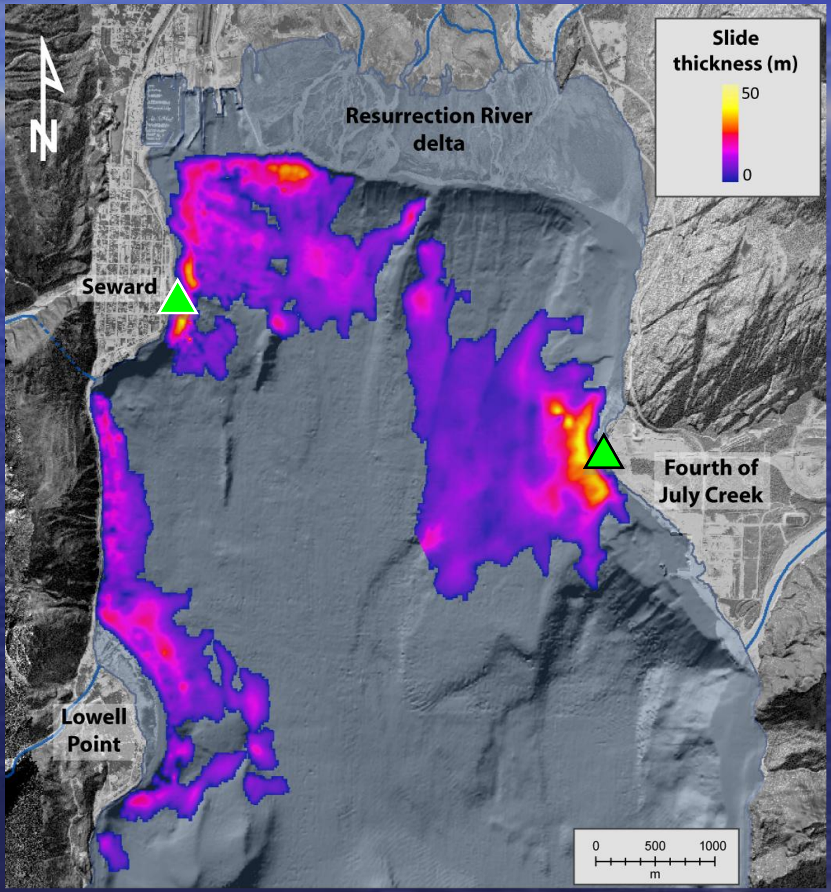


Drag force

Experiment: contributions of individual slides

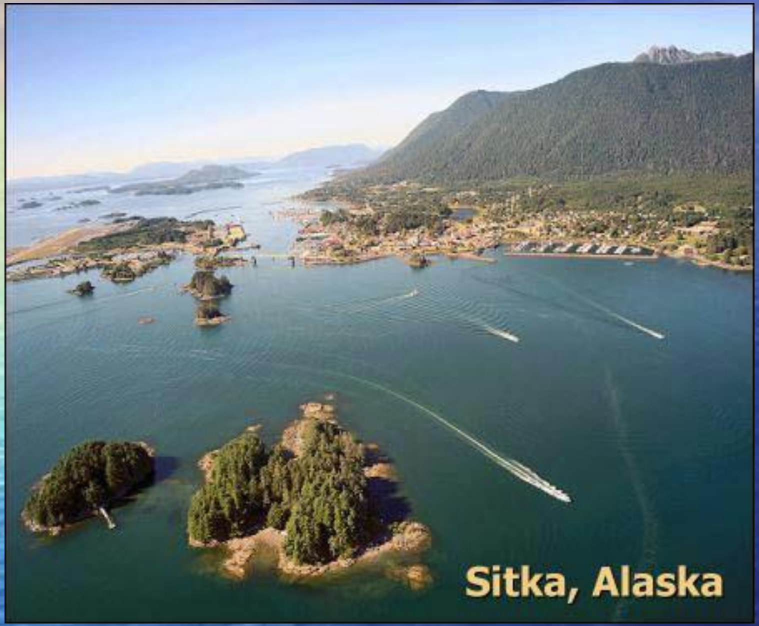
- Calculated sea level is decomposed into waveform contributions from each slid



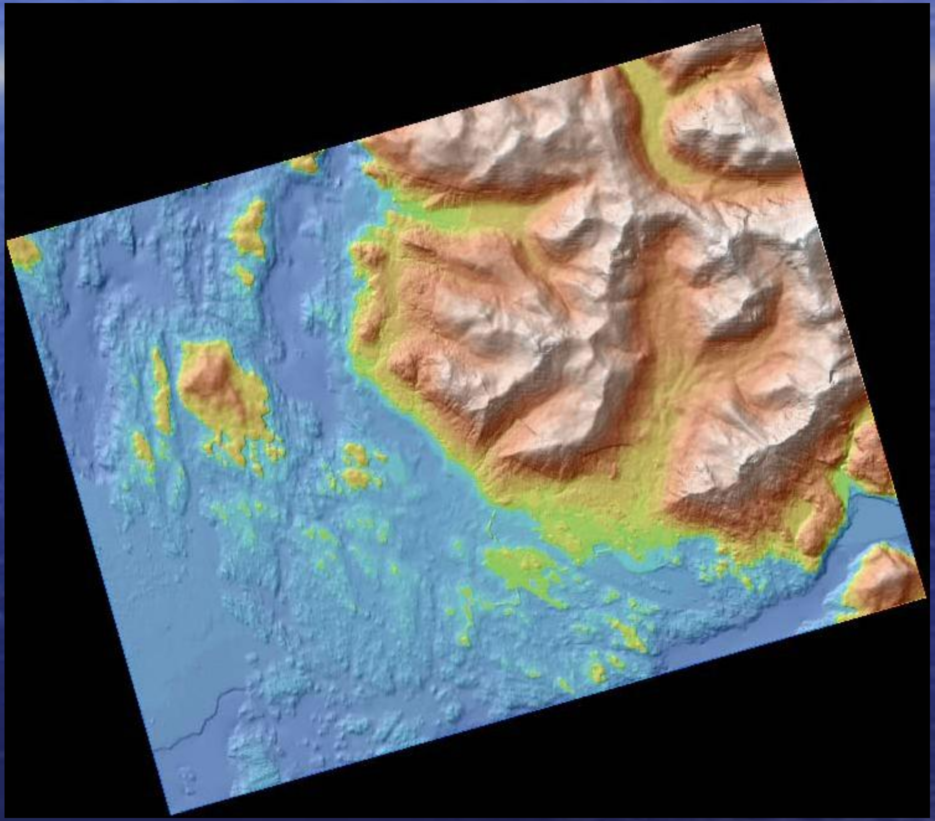


- Three major slides in the upper Resurrection Bay

Development of the Sitka DEM

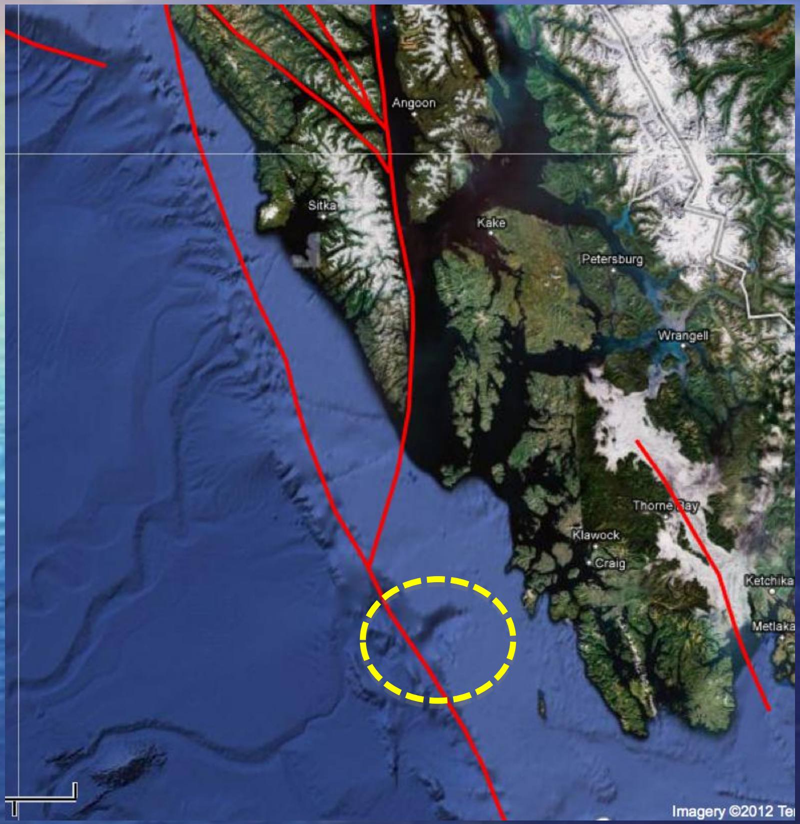


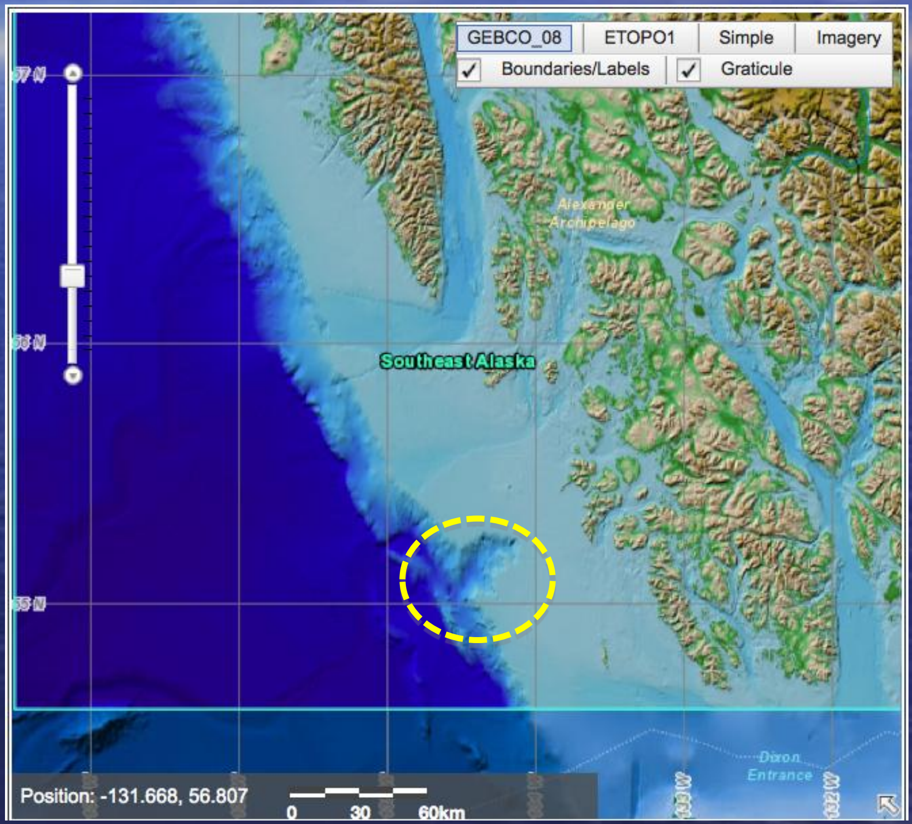
•P.J. Hickman, E.N. Suleimani and D.J. Nicolsky, "Digital Elevation Model of Sitka Harbor and the City of Sitka, Alaska: Procedures, Data Sources, and Quality Assessment" will be published this week by the Alaska Division of Geological and Geophysical Surveys.



•Shaded relief map of the seamless 8/15 arc-second bathymetry-topography DEM of Sitka.

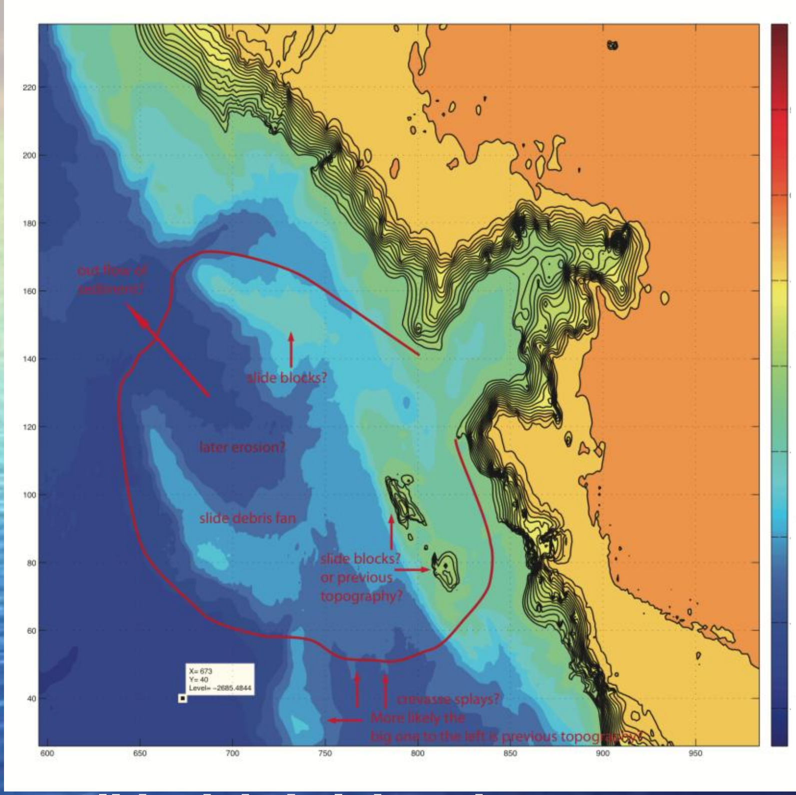
Probable slide on the Fairweather fault

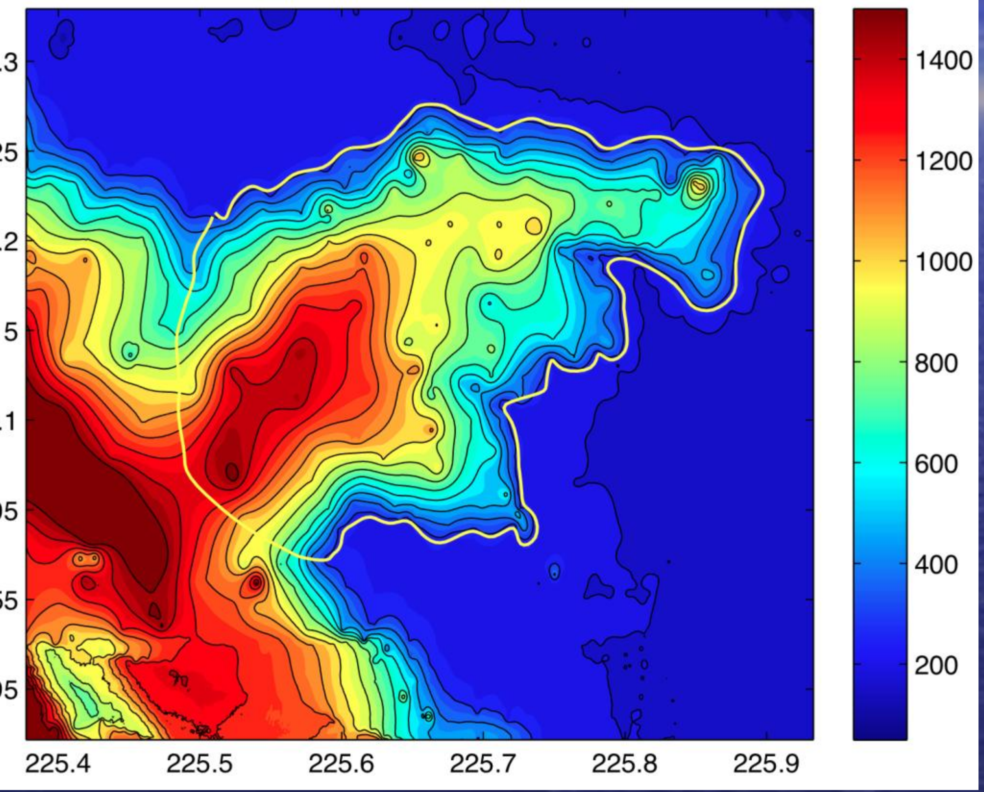




- **Google Maps imagery**
- **NGDC high-resolution bathymetry of Southeast Alaska**

•Probable slide on the Fairweather fault

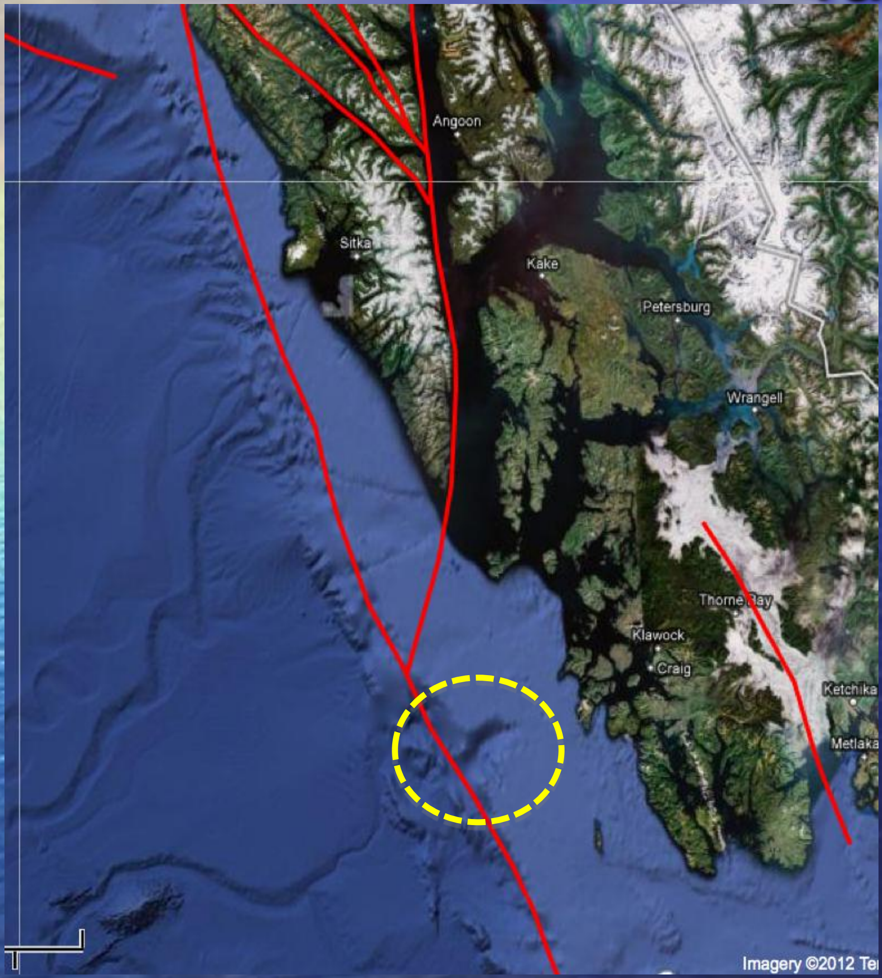




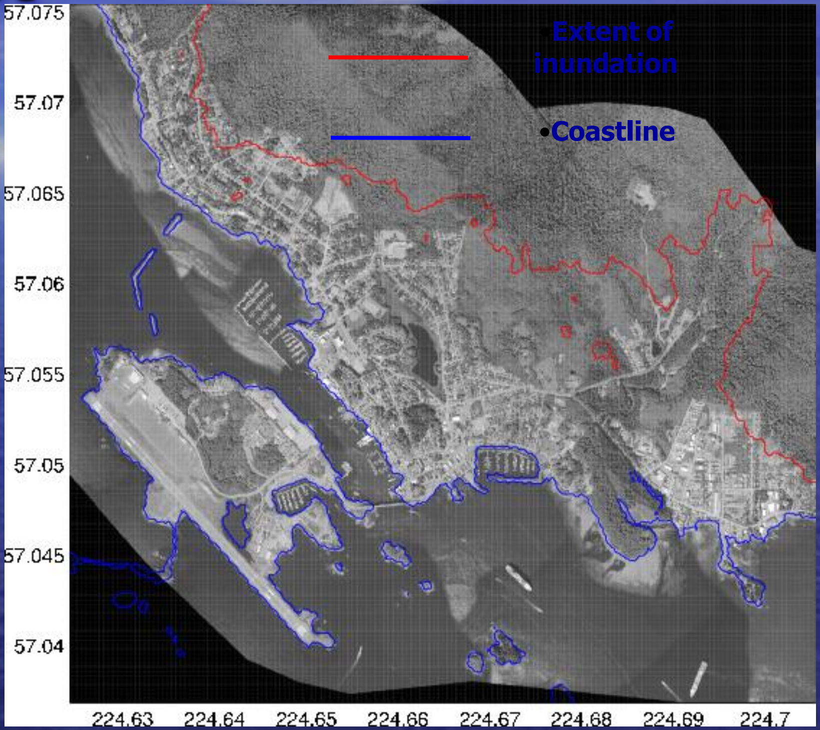
•Slide debris lobes do not appear to be offset on the fault, which indicates that the slide probably postdates LGM.

•Volume of the slide estimated at 200 cubic km (260 billion cubic yards)

Probable prehistoric slide on the Fairweather fault



- A location of the probable landslide
  - (according to Sue Karl, USGS)

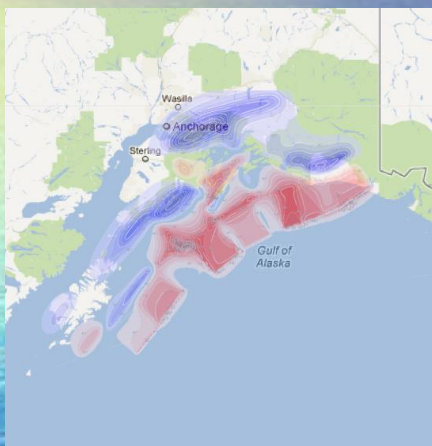


- We constructed a hypothetical slide offshore of the Kruzof Island with the same volume (≈200 km^3) as the prehistoric slide and then modeled a tsunami inundation in Sitka.
- *A computer experiment predicts a 30-meter wave arriving to Sitka!*

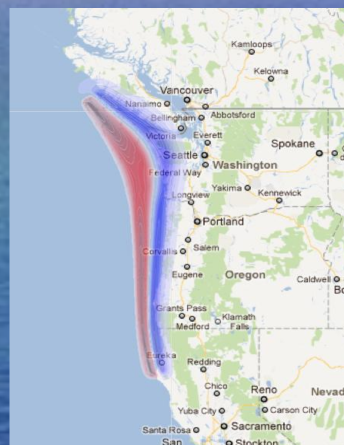
- What is the reasonable slide volume and its location on the continental shelf?

Hypothetical tectonic scenarios

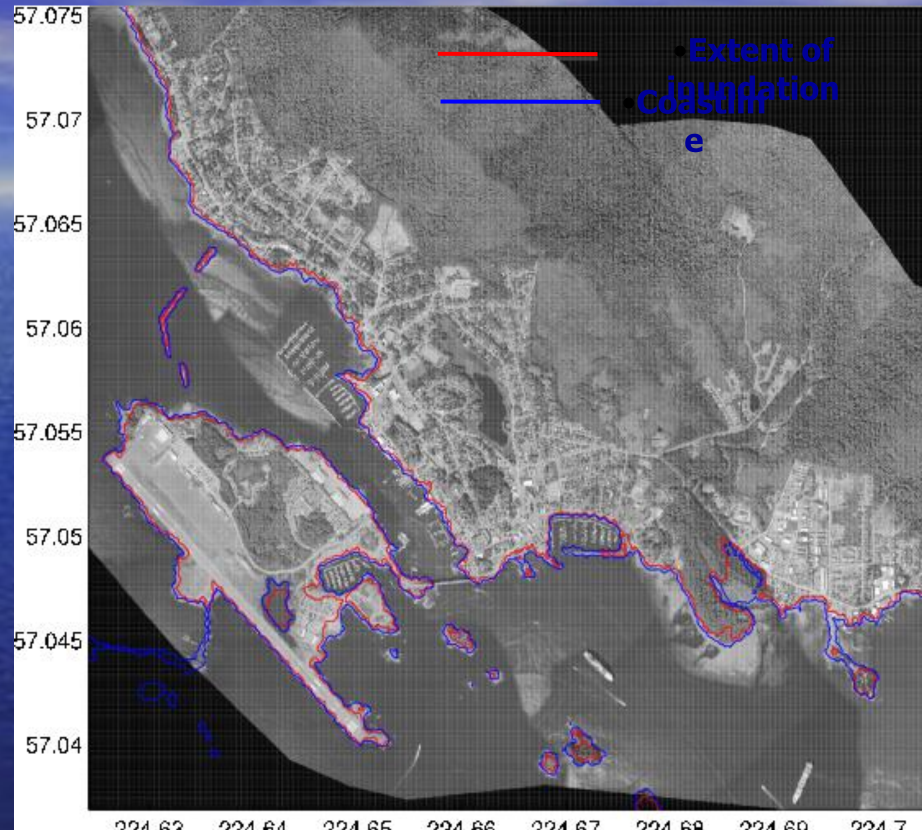
•**Vertical coseismic deformation**



•**Hypothetical 1964-type event**



•**Hypothetical Cascadia event**



•**Distant tsunami sources do not produce significant inundation in Sitka, which agrees with the effects of the 1964 tsunami in Sitka.**

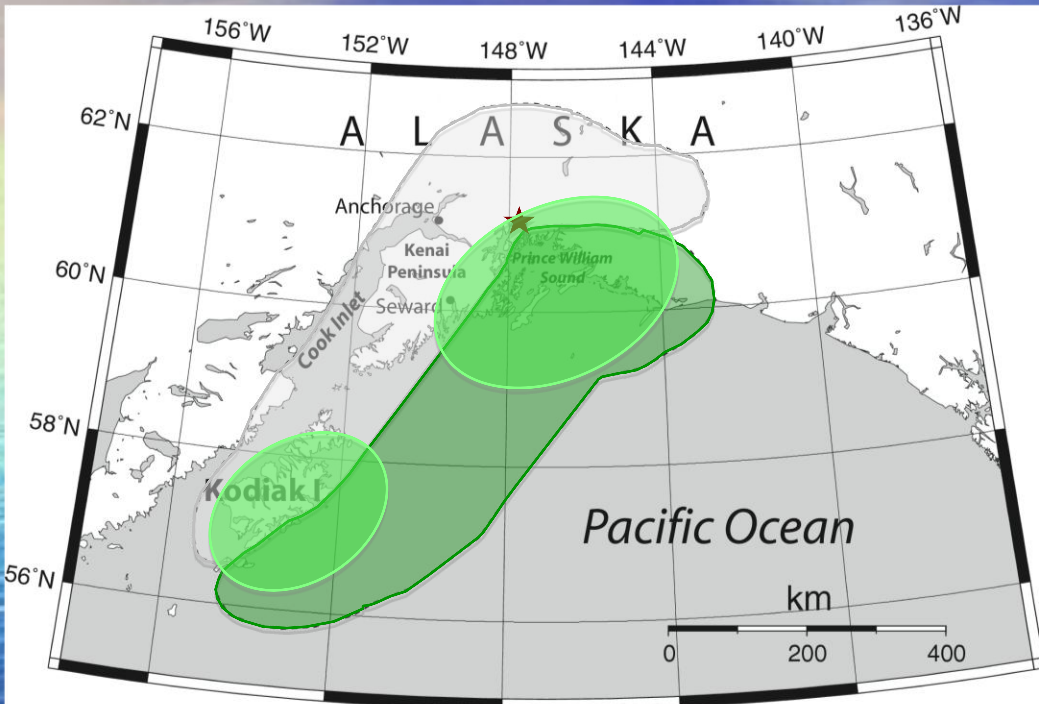
- ***Considered:***

- **10+ far-field tectonic scenarios,**
- **4-5 near-field tectonic scenarios.**

Complexities that contribute to Alaska tsunami modeling

- The Tectonic Tsunami Source:
  - Finite Fault models with Splay faults (1964)
  - Effects of horizontal motions
  - Need for plausible hypothetical sources
- Tsunamis caused by landslides
  - Important component to observed tsunamis in AK
- Comments on high resolution Bathymetry
  - Better understanding of potential landslide features

The 1964 Great Alaska earthquake

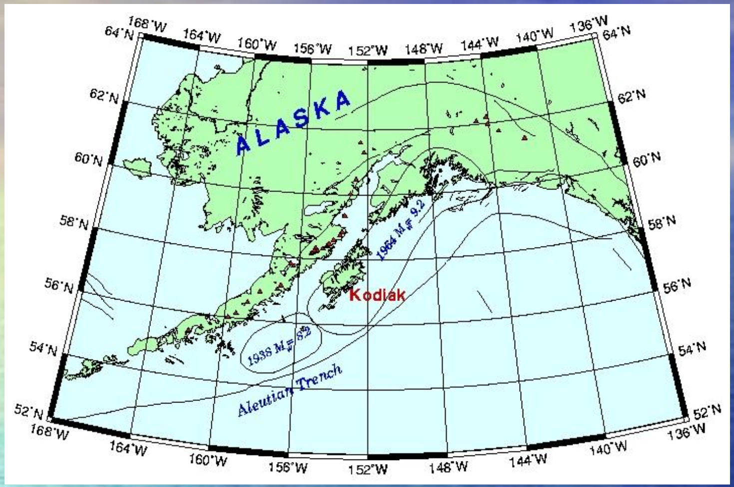


- ***Unique numerical setup of the problem*:**
  - **location of the tsunami source with respect to the coastal areas where tsunami effects are investigated.**

- The 1964 Alaska earthquake is the second-largest event ever recorded instrumentally:
  - Richter magnitudes: $M_S = 8.4 - 8.6$
  - Moment magnitude: $M_W = 9.2$
  - Area of crustal deformation:
    > 256,000 km²
- Vertical uplifts were 2 m in average, with a maximum of 11.5 m; maximum vertical subsidence was about 2 m Horizontal displacements of up to 20 m
- Two regions of concentrated moment release: the Prince William Sound asperity and the Kodiak asperity (*Christensen and Beck, 1994*)
- **Waves**: tectonic tsunami wave train, landslide tsunamis, seiches.

“Worst case scenario”

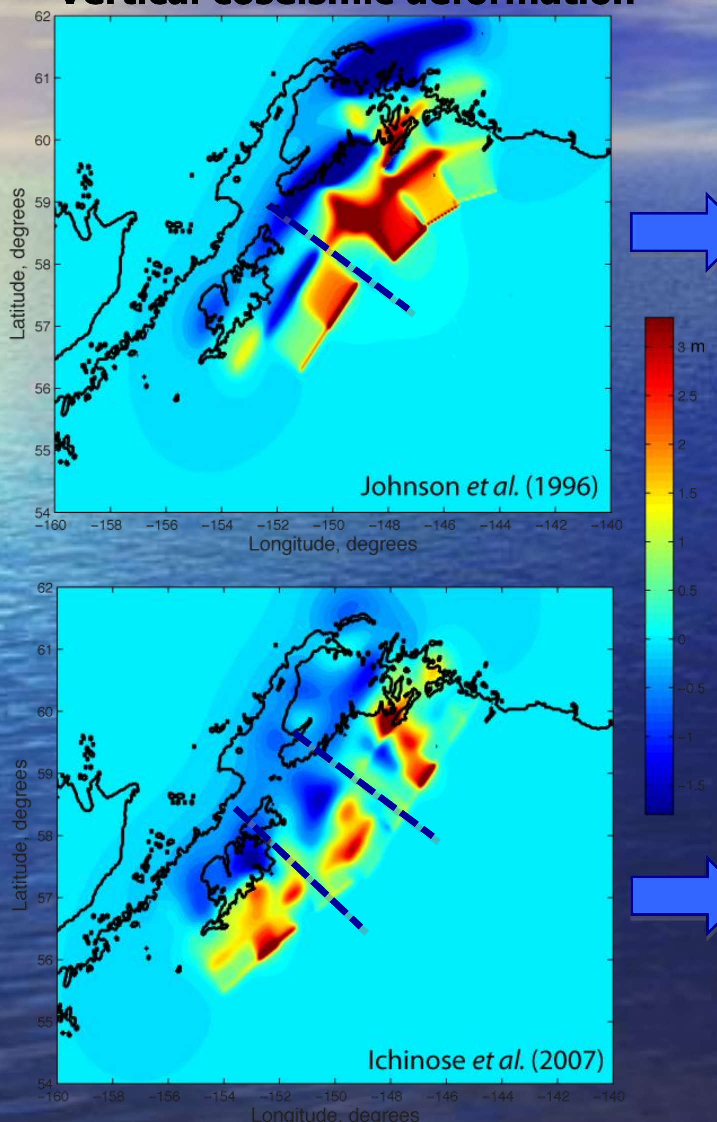
- The Great Alaska Earthquake was the second largest event ever recorded instrumentally:
  - $M_W = 9.2$
  - Area of crustal deformation: >256,000 km^2
- Tsunami damage:
  - Alaska: 106 deaths, $84 M
  - British Columbia: $10 M
  - OR: 4 deaths and $0.7 M
  - CA: 13 deaths and $10 M
- Historical observations exist.



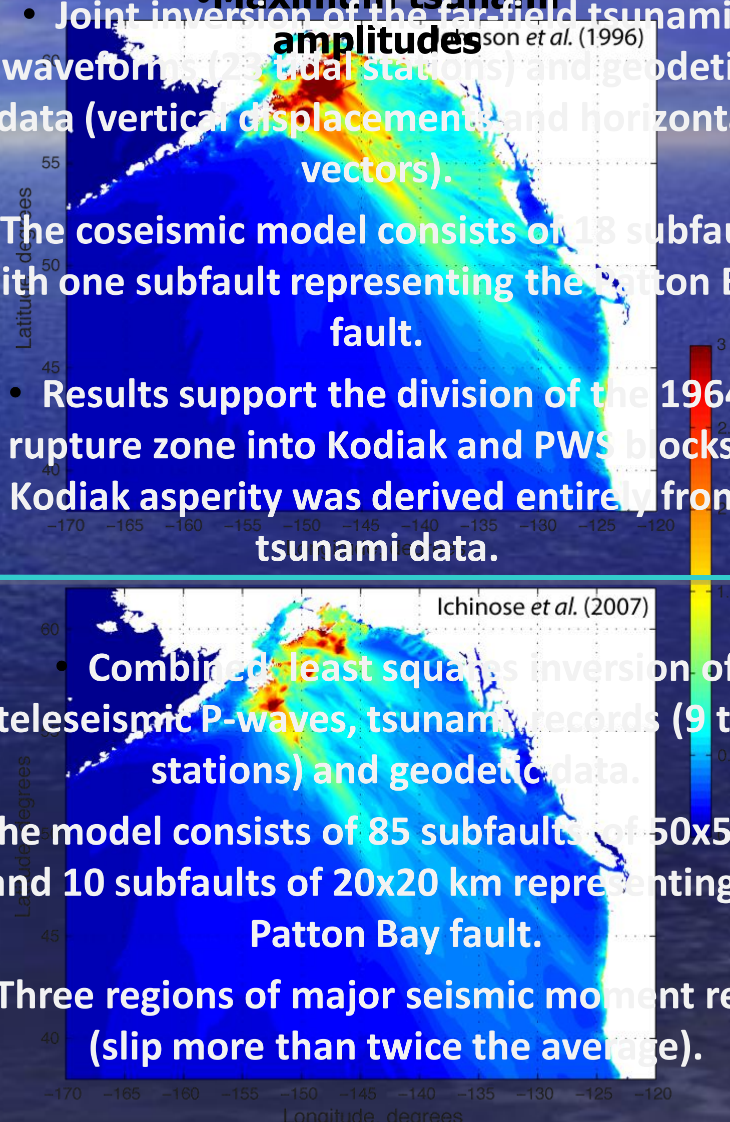
Damage in Seward. Photo credit: Department of Interior

Coseismic Deformation Models

•**Vertical coseismic deformation**



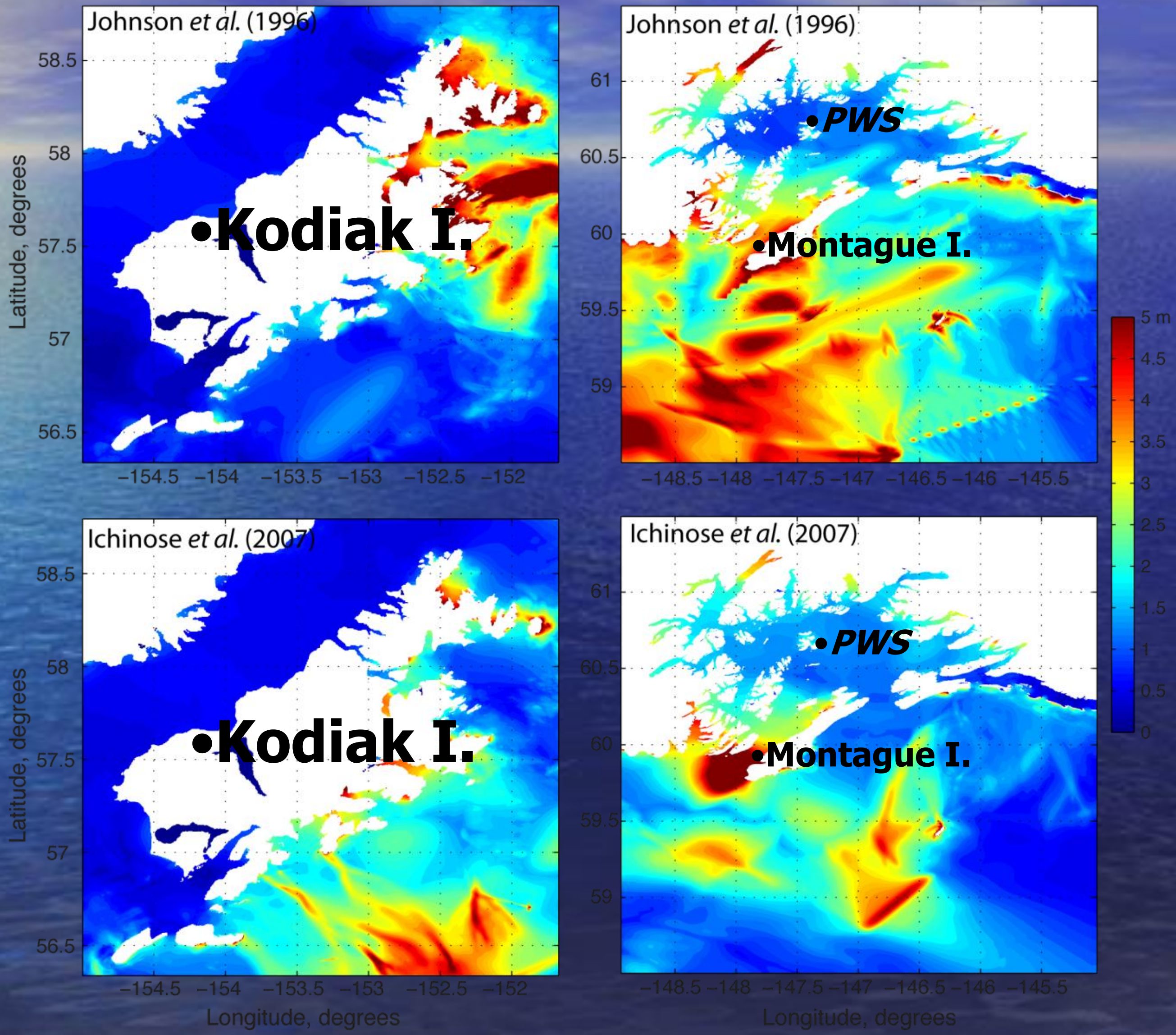
•**Maximum tsunami amplitudes**



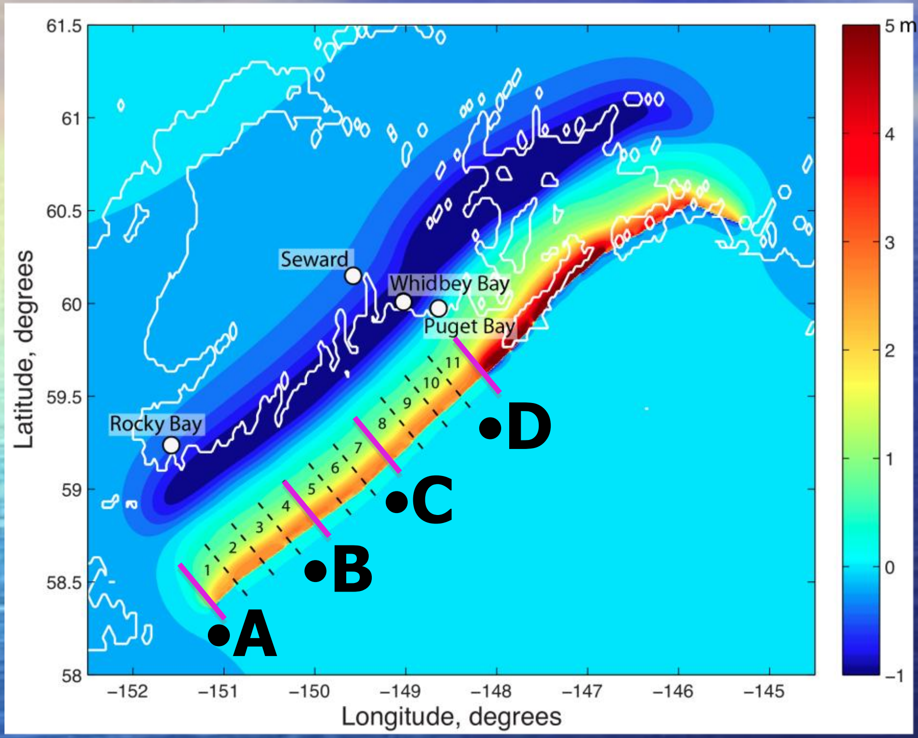
- Joint inversion of the far-field tsunami waveforms (23 tidal stations) and geodetic data (vertical displacements and horizontal vectors).
- The coseismic model consists of 18 subfaults with one subfault representing the Patton Bay fault.
- Results support the division of the 1964 rupture zone into Kodiak and PWS blocks. Kodiak asperity was derived entirely from tsunami data.

- Combined least squares inversion of teleseismic P-waves, tsunami records (9 tidal stations) and geodetic data.
- The model consists of 85 subfaults of 50x50 km, and 10 subfaults of 20x20 km representing the Patton Bay fault.
- Three regions of major seismic moment release (slip more than twice the average).

Near-field tsunami amplitudes differ



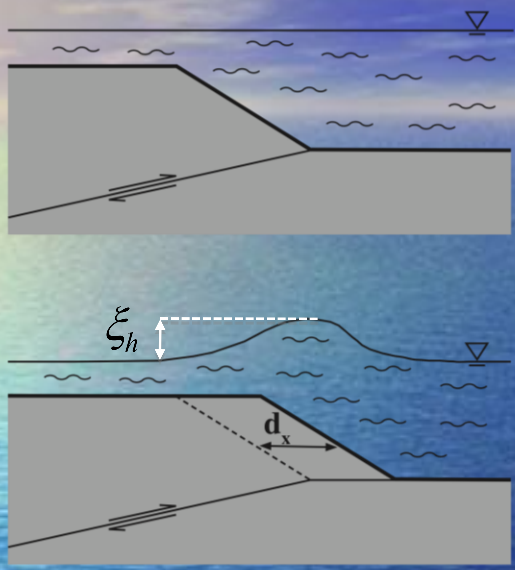
The splay fault: numerical experiment



•Calculated vertical coseismic deformations due to displacements on the splay fault.

- The extension of the fault is divided into 11 segments, and 11 source functions were constructed.
- Analysis of time series at Kenai Peninsula sites allowed to distinguish 4 major cases.
- Rocky Bay: source B fits observations best. Source A generates the wave amplitude that is too high compared to observations.
- Seward: all sources except for D provide a very good match to arrival time and wave amplitude.
- Conclusion: the splay fault probably extends as far as the boundary between 4th and 5th segment, but not as far as the western tip of the peninsula.

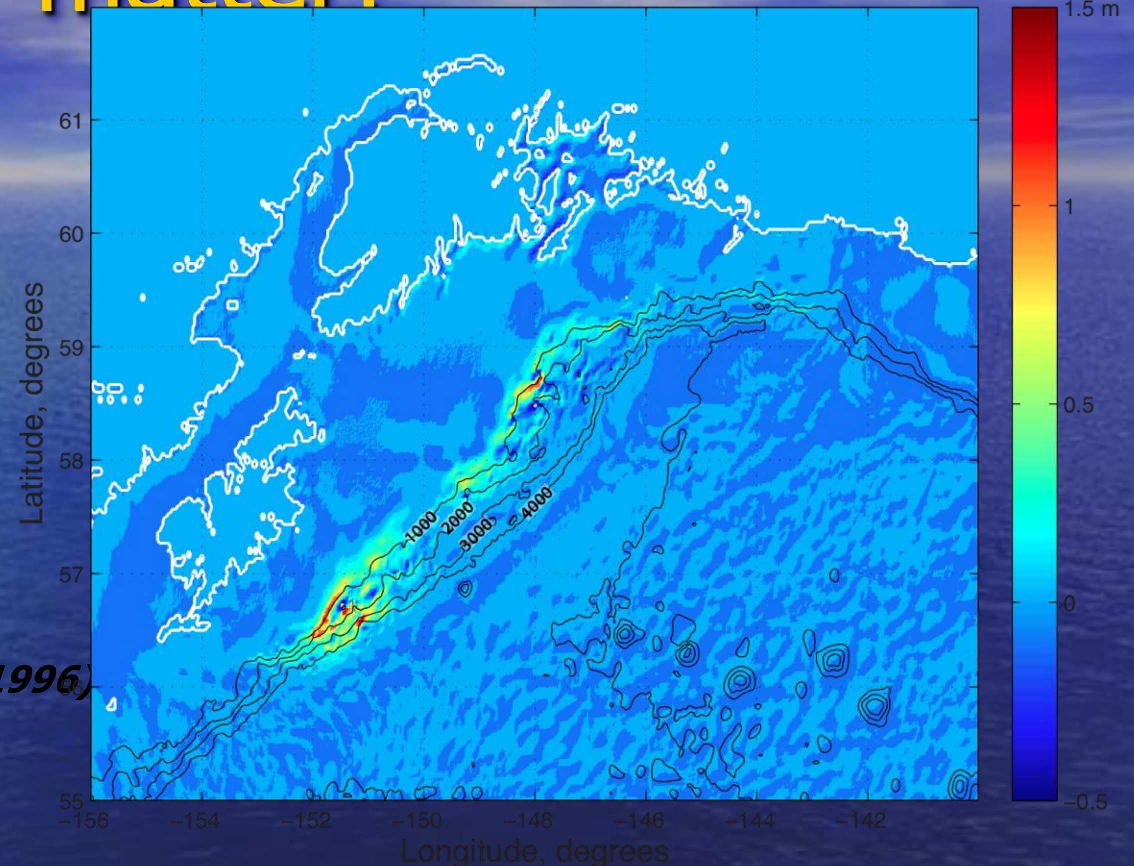
Do horizontal displacements matter?



•(Modified from *Tanioka and Satake, 1996*)

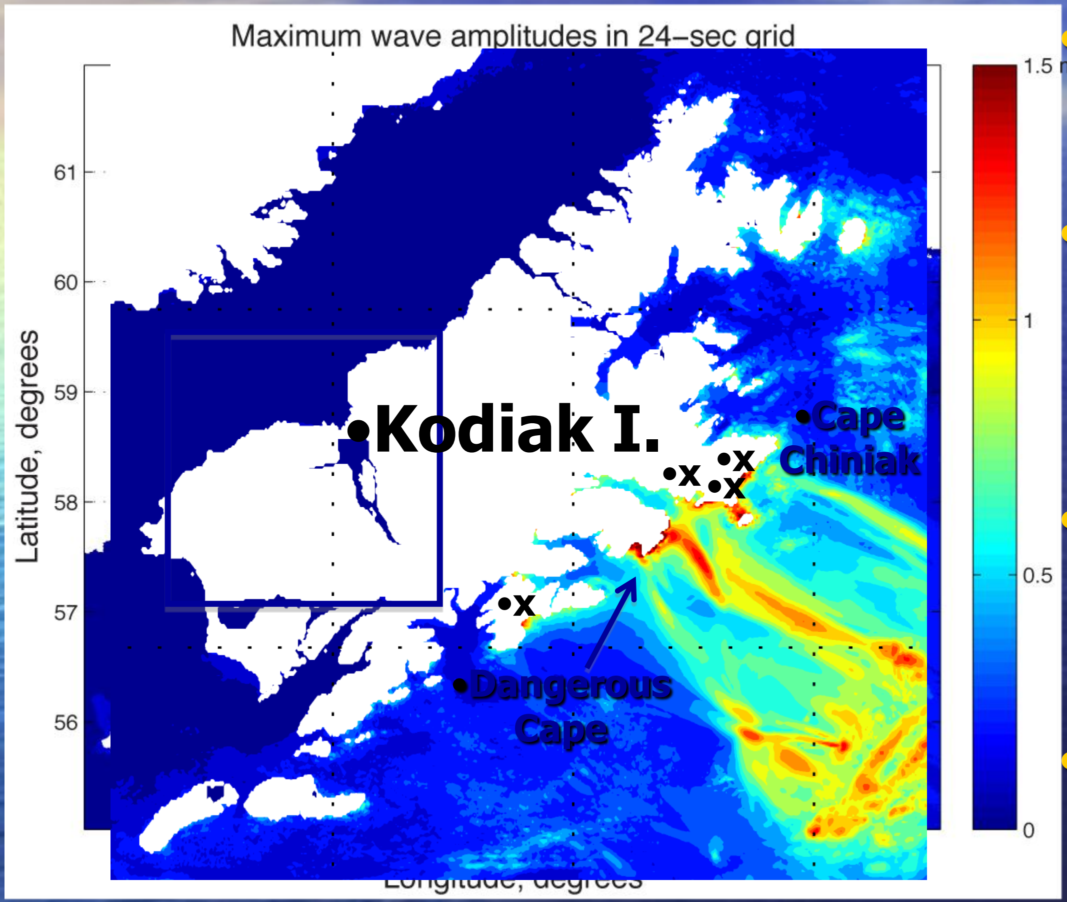
$$\xi_h = d_x \frac{\partial H}{\partial x} + d_y \frac{\partial H}{\partial y}$$

$$H(x,y) - bathymetry$$



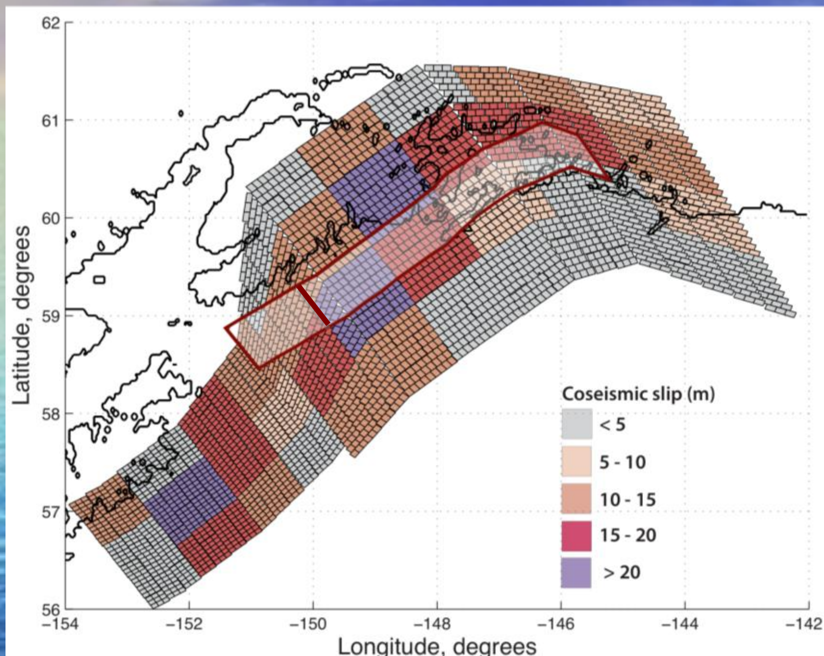
•**Calculated sea surface displacements due to horizontal motion of the sea floor during the 1964 earthquake.**

Horizontal displacements: near-field effects

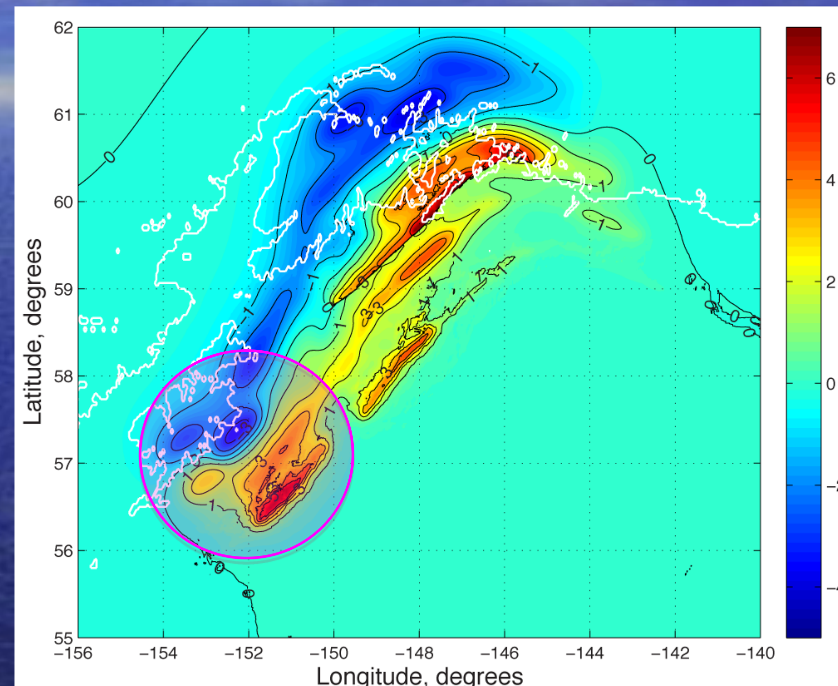


- There are two maxima of tsunami energy due to horizontal displacements: one in Kodiak asperity and one in PWS asperity.
- The deformation maximum in the PWS asperity generates waves whose energy is directed toward the coast of Kenai Peninsula (no measurements or observations in this area).
- The tsunami energy from the deformation maximum in the Kodiak asperity is directed toward the section of the Kodiak coast between Cape Chiniak and Dangerous Cape.
- This stretch of the coast is the area of the maximum measured runup.

The improved coseismic model



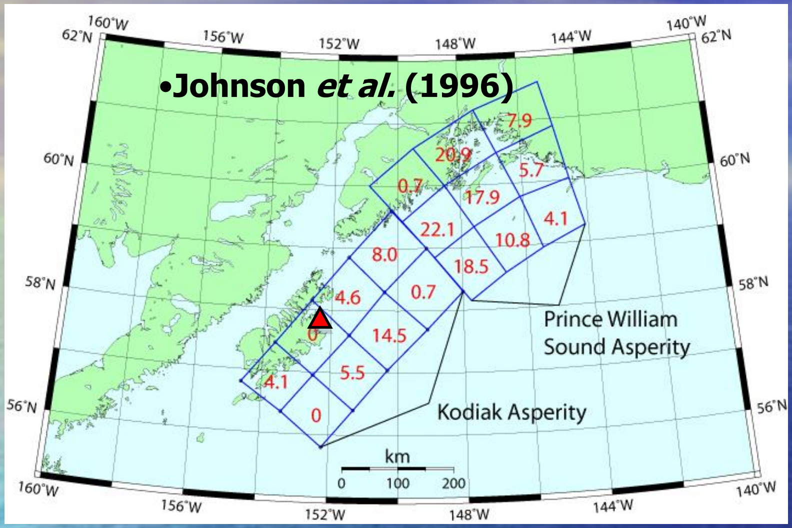
•Coseismic slip model of the 1964 rupture with the preferred length of the splay fault.

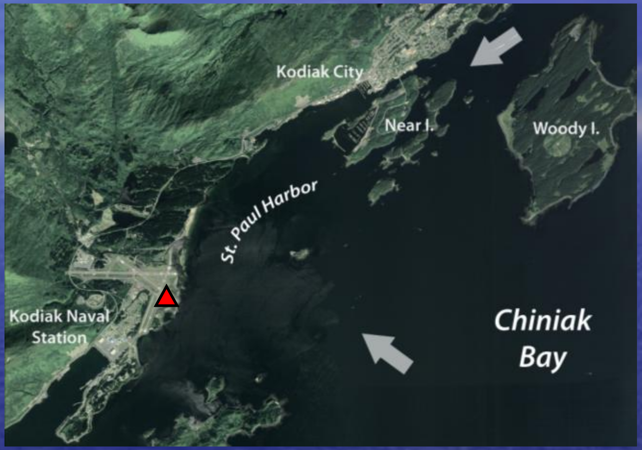


•The resulting vertical coseismic deformations in the 1964 rupture area, derived from superposition of:

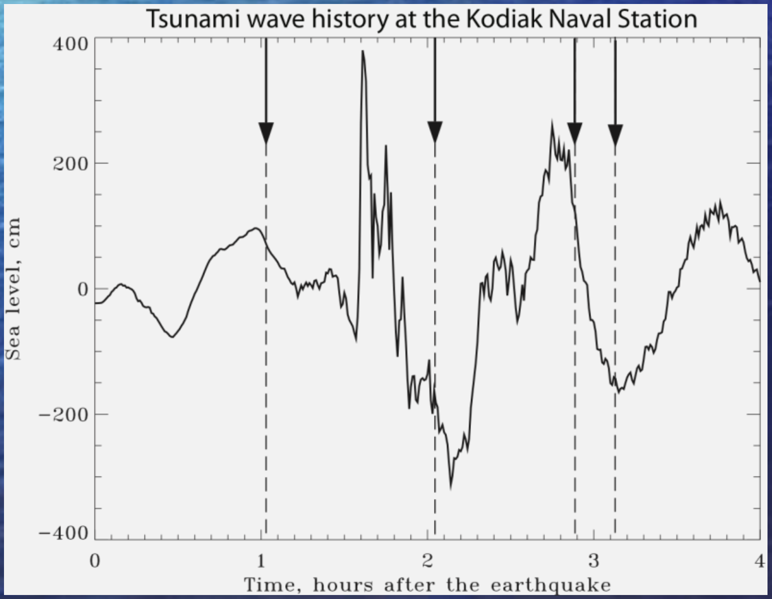
- vertical displacements on the megathrust
- horizontal displacements on the megathrust
- vertical displacements on the splay fault of the optimal extent.

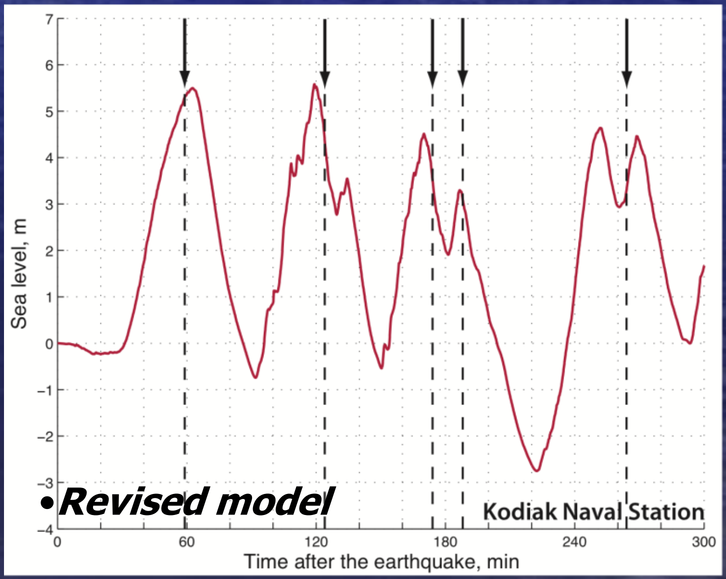
Time histories in Kodiak





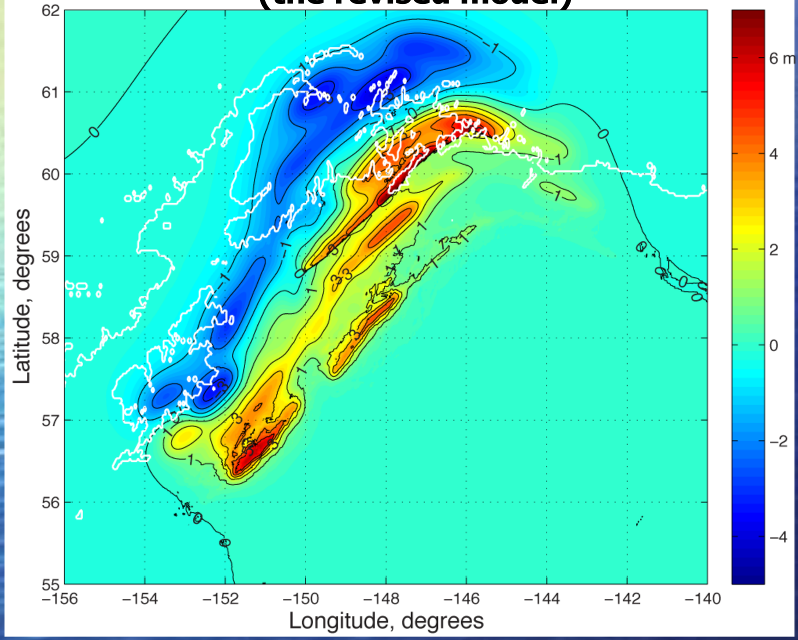
•Arrows indicate observed arrivals





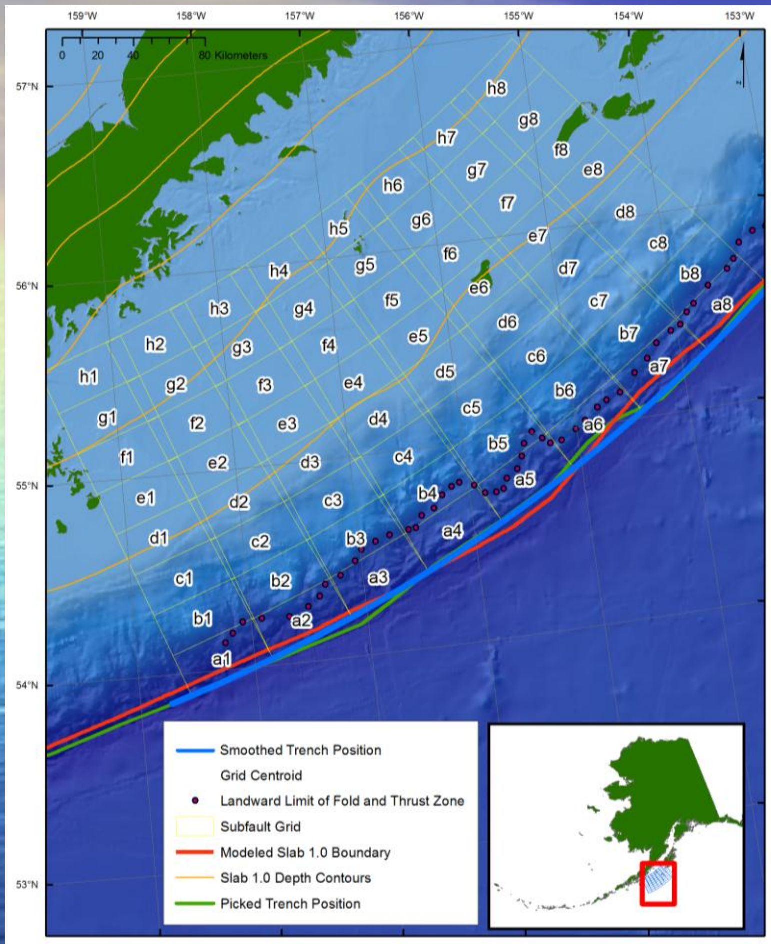
Results of the source function study

- **Vertical coseismic deformations of the 1964 earthquake**
- **(the revised model)**



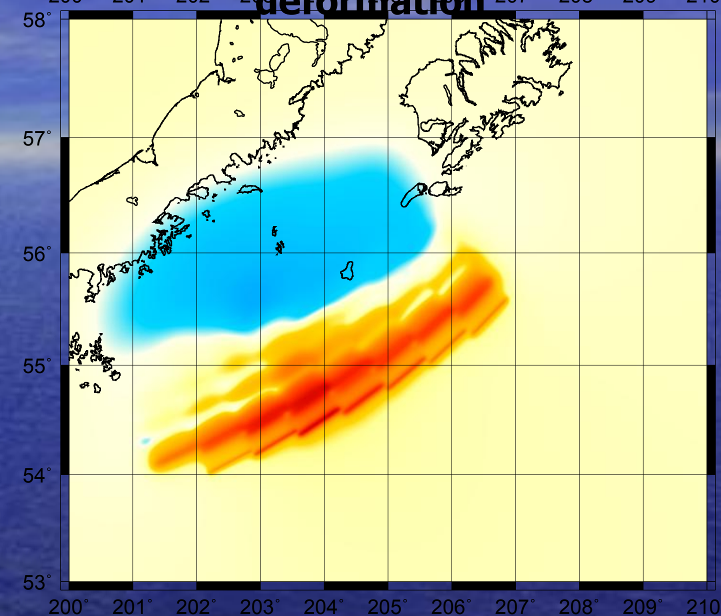
- Previously published coseismic models of the 1964 rupture generated tsunami arrival times and amplitudes that did not agree with the near-field tsunami observations.
- Numerical modeling results demonstrate that the Patton Bay fault needs to be extended as far as 150°W in order to fit the tsunami observations along the southern coast of Kenai Peninsula.
- The horizontal displacements had a pronounced effect on the far-field tsunami. In the near field, they had localized effect in the Kodiak asperity, adding to the maximum runup heights along the coast.
- Results of numerical modeling in the Kodiak Island region show that tsunami waves generated by displacements on megathrust in the Kodiak asperity produce arrival times and amplitudes that are in good agreement with observations.

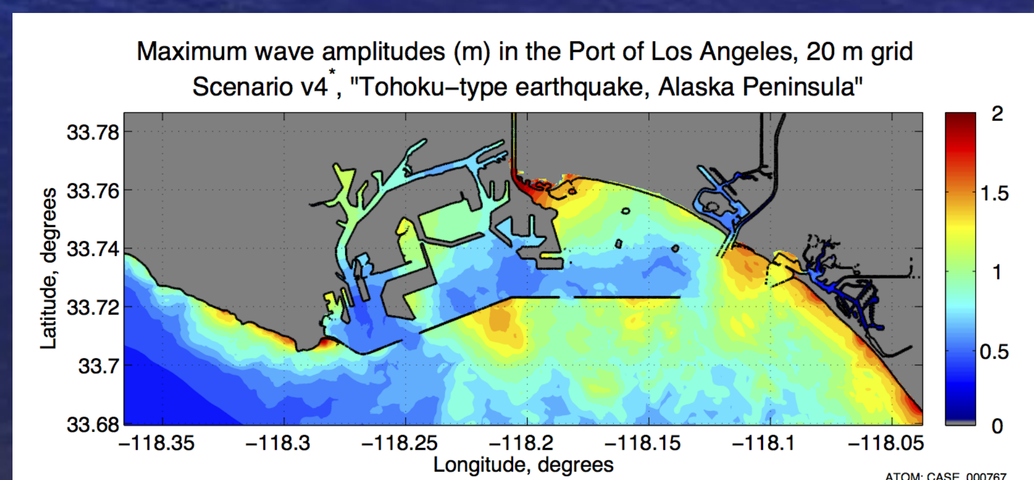
USGS multi-hazard demonstration project



- Proposed Subfault Geometry: M9.1 Tohoku Emulation V4.0* for the Southern California Tsunami Scenario. Slip distribution is similar to that of the Tohoku earthquake.

- Coseismic vertical deformation





•**Tentative assignment of slip (red-high, yellow-med, green-low) based on GPS, gravity lows and historic record (known patches of high moment release)**