Improving Subduction Zone Hazards Assessments Using the Coastal Stratigraphic Record

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Abstract

Earthquake and tsunami records on centennial and millennial temporal scales are necessary to understanding subduction zone hazards and the occurrences of large, but infrequent events. Subduction zone paleoseismology combines the methods of coastal stratigraphy, sedimentology, micropaleontology, geophysical and sediment transport modeling, and sea-level research to produce some of the most detailed long-term histories of coseismic vertical deformation and tsunami inundation along subduction zone coastlines. Microfossil-based (e.g., diatoms, foraminifera) techniques that employ the relation between microfossils and salinity, tidal elevation, and life form to quantify coseismic land-level change across sharp stratigraphic contacts and identify anomalous sand beds deposited by tsunamis are particularly valuable to subduction zone paleoseismic studies. Microfossil-based techniques have been successfully employed in the reconstruction of earthquake and tsunami histories in Chile, the Indian Ocean, Japan, New Zealand, the North Sea, the Pacific Northwest of North America, and the South Pacific. In Alaska and Chile, microfossils have documented both uplift and subsidence at proposed subduction zone segment boundaries, expanding our knowledge of the variability of slip in megathrust ruptures. In tsunami studies in Alaska, Chile, and Japan allochthonous marine and brackish microfossils within anomalous sand deposits signaled previously undocumented high-energy marine incursions into coastal lowlands. At the Cascadia subduction zone, a marsh monitoring experiment emphasized the importance of studying the modern diatom response to changing environmental conditions to refine estimates of past coseismic deformation. Finally, paleoseismic studies have better informed our modeling of teleseismic tsunamis that pose a flooding hazard to near- and far-field coastlines. Forward modeling of teleseismic tsunamis originating along the Aleutian megathrust combined with probabilistic sea-level rise projections for southern California illustrate the increased flooding threat to highly populated areas from far-field tsunamis as sea level rise accelerates over the next 100 years, emphasizing the need for interdisciplinary approaches to future coastal hazards assessments.

References Cited


Presenter’s notes: This presentation will give an overview of the application of diatoms to subduction zone earthquake and tsunami studies. Diatoms can be applied to characterize modern earthquakes and tsunamis, and are a big component of paleoseismic studies. As we know, paleoseismic studies are very important to assessing subduction zone hazards because they allow us to extend earthquake and tsunami records beyond the historical period. I’ll use case studies from Chile, Alaska, and Cascadia to highlight some of the successes and challenges we’ve faced applying diatoms to earthquake and tsunami studies.
Presenter’s notes:

- Why is it important to extend earthquake and tsunami record?

- Temporally restricted historical and instrumental records limit our understanding of long-term subduction zone behavior
- Datasets on centennial and millennial temporal scales are necessary to capture the spatial variability of subduction zone ruptures
- Only then can the largest, but infrequent events be captured (e.g. 2004 Sumatra)
- Paleoseismic studies allow us to extend earthquake and tsunami records over multiple earthquake cycles
- This allows us to address fundamental questions about rupture mode variability and segmentation of subduction zones
Historical and instrumental records are **temporally restricted**

Short datasets may **miss largest earthquakes**

Japan 2011 ($M_w$ 9.0) earthquake **larger than expected**

Geologic datasets on **millennial** temporal scales are necessary

**Significance of work**

Sustainable coastal communities and infrastructure

How can we both take advantage of the opportunities for development at the coast, but also do it in a safe and sustainable way?

“Utilize and Protect”

Credit: Miyako city official
Presenter’s notes: Coastal marshes, lagoons, estuaries that are sensitive to RSL changes are the best places to preserve earthquake and tsunami records.
Need **accommodation space**: low-energy depositional environments

**Sharp contacts** (1-3 mm), **juxtaposition of environments, laterally continuous, correlated between regional sites**, sometimes with **tsunami deposits**
Tsunami deposit characteristics: anomalous marine sediment, landward thinning and fining, upward fining, rip-up clasts, sharp or eroded lower contact, coincident with land-level change.
Photosynthetic, unicellular algae that inhabit **freshwater, brackish and marine** environments.

Valuable in reconstructing paleoenvironmental changes due to their **preferences to a number of environmental factors**

**Salinity and substrate** for EQ and tsunami studies

Independent test of stratigraphic interpretations

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Presenter’s notes:

Photosynthetic, unicellular algae that inhabit **freshwater, brackish and marine** environments.

Valuable in reconstructing paleoenvironmental changes due to their **preferences to a number of environmental factors**.

Preferences for **salinity and life form** are particularly valuable for earthquake and tsunami studies.
Photosynthetic, unicellular algae that inhabit **freshwater, brackish and marine** environments

Valuable in reconstructing paleoenvironmental changes due to their **preferences to a number of environmental factors**

**Salinity and substrate** for EQ and tsunami studies

Independent test of stratigraphic interpretations
Presenter’s notes: Diatom diagram is a cycle.

• Low-energy depositional environments with a strong environmental gradient are most likely to archive evidence of coseismic RSL changes.
• RSL changes are recorded by changes in lithology.
• Sharp (1-3 mm) contacts, laterally continuous, sometimes with tsunami deposits.
• Coastal stratigraphic records at Cascadia contain records > 6000 years.
Diatoms in tsunami deposits:

- **Anomalous marine diatoms** - provenance
- **Low concentration** - provenance
- **High fragmentation** - energy
- **Normal grading** - transport
The application of diatoms to reconstruct the history of subduction zone earthquakes and tsunamis

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**Map Sections**

- **a** Sumatra
  - Dura et al., 2011
  - Dura et al., 2016b

- **b** Japan
  - Pilarczyk et al., 2019
  - Pilarczyk et al., 2014

- **c** Alaska
  - Briggs et al., 2014
  - Nelson et al., 2015

- **d** Chile
  - Dura et al., 2019
  - Horton et al., 2017

- **e** Pacific Northwest
  - Dura et al., 2015

- **f** New Zealand
  - Dura et al., 2016a

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*References*

- Pilarczyk et al., 2019
- Briggs et al., 2014
- Nelson et al., 2015
- Horton et al., 2017
- Ely et al., 2014
- Hong et al., 2017
- Cisternas et al., 2017
- Dura et al., 2017
- Dura et al., 2016a
- Dura et al., 2011
- Dura et al., 2016b
- Dura et al., 2015
- Dura et al., 2014
Alaska-Aleutian subduction zone

Nine investigations from 2010–2016

- Umnak Island
- Sedanka Island
- Sanak Island
- Unga Island
- Simeonof Island
- Chirikof Island
- Sitkinak Island
- Sitkalidak Island
- Kenai Fjords
Active subduction zone
One “great” EQ (>M8) every ~13 years
One M7-8 EQ per year
Six M6-M7 EQ per year
Subduction zone highly coupled between eastern Kodiak Island and the Shumagin Islands
Of particular concern: Semidi segment

Orientation directs tsunamis to CA coast
Alaska-Aleutian subduction zone

Of particular concern: **Semidi segment**

Orientation **directs tsunamis to CA coast**

Last EQ was in **1938 (Mw8.3)** - did not reset

1964 was to the east on the **Kodiak segment**
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**SAFFR** scenario (USGS)
Of particular concern: **Semidi segment**

Orientation **directs tsunamis to CA coast**

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**SAFFR** scenario (USGS)

Need to consider **multi-segment EQ’s? RSL rise?**
Assemble team.
Determine an area that we can learn a lot from.
Get there somehow.
Choose a site for coring etc.
Core.
Describe core.
Correlate and Survey.
Sample key sections.
Send samples home and process.
Everyone does their part to put the story together.
Presenter’s notes: Position cores, cut banks, and pits over coast-parallel and coast-perpendicular transects (hundreds of meters)
Sitkinak Island: characterizing modern environments

- Tidal flat
- Low marsh
- High marsh
- Modern beach
Sitkinak Island: sampling and analysis
Sitkinak Island: results

a) Core lithologies and correlations, transects 1-3, Sitkinak Island, Alaska

Legend

- Simplified lithology
- Ages
- Troels-Smith lithology
  - Clast or sand: 35%
  - Matrix: 30%
  - Sandy or silty layers: 7%
  - Residual till or diamicton: 7%
  - Deposited till or diamicton: 7%
  - Nodular or laminated diamicton: 7%

- Contacts
  - Sharp (0-3 mm)
  - Gradational (3-6 mm)

- Inferrred spilithofacies

- Transect 3

Figure S2

Core WS-09b, Sitkinak Island, Alaska

Legend

- Simplified lithology
- Ages
- Troels-Smith lithology
- Contacts

- Inferrred spilithofacies

- Transect 2
Sitkinak Island: results

Freshwater and fresh-brackish
- Pinnularia lagerstedtii
- Pinnularia ignobilis
- Cosmioneis pusilla
- Eunotia fallax

Brackish-fresh and brackish
- Navicula meniscus
- Nitzschia levidensis
- Diploneis interrupta
- Navicula cincta
- Navicula peregrina

Brackish-marine and marine
- Actinocyclus sp.
- Surirella ovalis
- Paralia sulcata
- Cocconeis scutellum
- Hyalodiscus scoticus
- Actinoptychus senarius
- Synedra tabulata

Upland
- Highest tide
- Mean tide level
- Lowest tide

High marsh

Low marsh

Tidal flat
Sitkinak Island: results

Optical CT

Diatoms

Land-level relative to present (m)

0 0.5 1 1.5

1964

C1

1788

C2

C3

C4

C5

Tidal flat

Low marsh

High marsh

Low marsh

Tidal flat

Tidal flat

Tidal flat

Tidal flat
When ruptures **stop at Sitkinak** you get **coseismic subsidence**

When ruptures **propagate through Sitkinak** you get **coseismic uplift**

*This suggests that the segment boundary is not persistent*
Next steps:
Take results and incorporate them into seismic hazard maps
Use results to inform earthquake and tsunami modeling to learn more about potential impacts of future events
Consider compounding hazards
**Presenter’s notes:**

*K14 projections* based on estimates of thermal expansion/ocean dynamics, glacier melt, ice sheet of Bamber and Aspinall (2013), land water storage, non-climatic local sea-level change, and gravitational, elastic, and rotational effects on local sea-level change from geophysical modeling.

*K17 projections* include an enhanced contribution from the Antarctic Ice Sheet (AIS).
Compounding impacts of tsunamis and relative sea-level rise

Highest historical...

- **a** Flood height = 0.5 m

Similar to SAFRR...

- **b** Flood height = 1.0 m

- **c** Flood height = 1.5 m

EQ magnitude that has a **50/50 chance of exceeding a certain flood height**, as a function of time
Collaborators

Bob Kopp
Sea-level projections

Kelin Wang
Earthquake modeling

Robert Weiss
Tsunami modeling

Ben Horton
Sea level reconstructions

Geomorphology/bear protection
Microfossils/sedimentology
Geomorphology/surveying
Microfossils/tidal monitoring
Geomorphology/big picture guy
Goals:
1. **Reconstruct land-level change and tsunami inundation**
2. **Characterize slip during past ruptures**
3. **Evaluate the persistence of a proposed segment boundary**
4. **Update hazards maps if needed**
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Sitkinak Island: research summary