Real-time Offshore Geophysical Monitoring of the Cascadia Subduction Zone: Applications to Earthquake and Tsunami Early Warning and Scientific Research

William Wilcock

with contributions from Deborah Kelley, John Delaney, David Schmidt, Michael Harrington, Paul Bodin, Frank Gonzalez, Randy LeVeque, Emily Roland,John Vidale, Dana Manalang, Chuck McGuire, Geoff Cram, James Tilley, Martin Heeseman, Tania Lado Insua

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Outline

- Introduction to the Ocean Observatories Initiative Cabled Array
- Motivation for Sustained Offshore Observations in Cascadia
  - Science
  - Earthquake Early Warning
  - Tsunami Early Warning
- An Offshore Monitoring System for Early Warning and Hazards Research
- Next Steps

Ocean Observatories Initiative

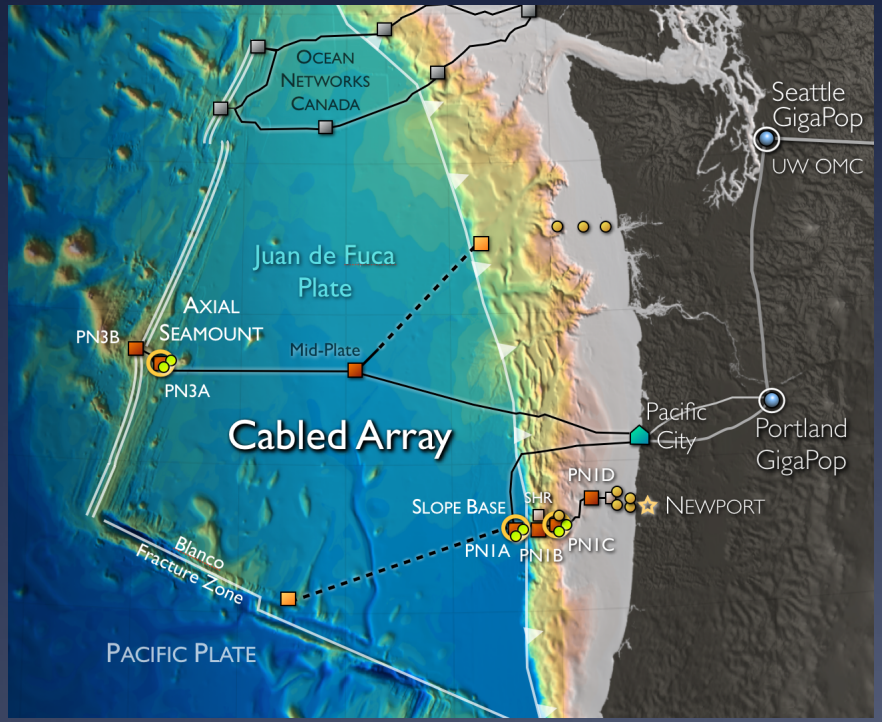
NSF MREFC in 2009 - $386M

4 components

- Global Moorings (now just Northern Hemisphere)
- Pioneer Array – East Coast
- Endurance Array – West Coast
- Cabled Array (NEPTUNE, RSN)
  - $126M to install
  - The only component supporting solid earth studies

Annual O&M - $44M

NSFs' Ocean Observatories Initiative Cabled Array



Built on time and under budget

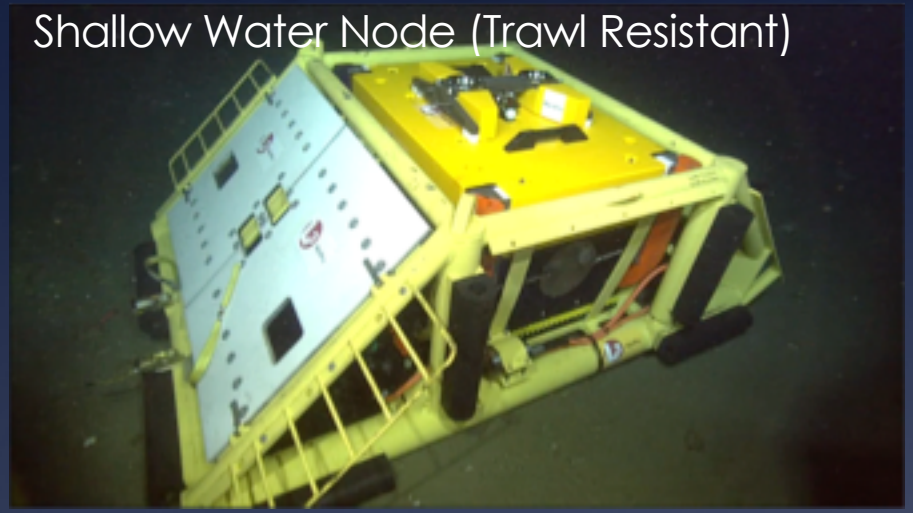
- The most technologically-advanced community facility in the world's ocean
- Five years of construction
  - Completed in 2014
  - Commissioned in 2016
- 25 year design life
- Instruments fully operational 83% of the time, installed in some of the most extreme environments on Earth
- Geophysical instruments – no failures yet.

Cabled Array: West Coast Perspective

Imagine

- 525 km of high power cable stretching across Cascades, Columbia River flood basalts, desert
- Single nick in armor kills the system
- All installations done at night from 10,000 ft up
- Power, communications, data flow

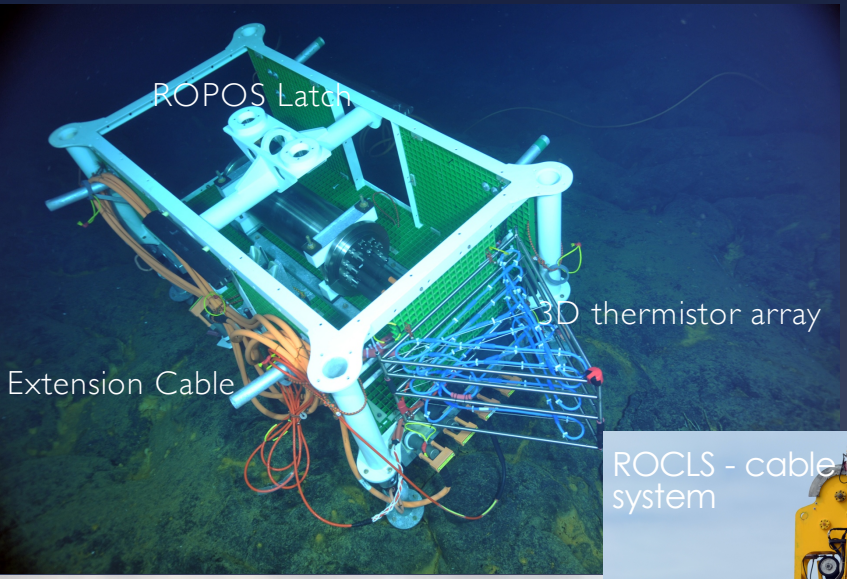
Primary Infrastructure: L-3 Mari Pro Inc. and UW



7 PRIMARY NODES - Large Substations

- Each Primary Node -10 GbE, 8 kW
- 2 Backbone Expansion Ports (10kV)
- 5 Science Ports (1 GbE, 375 V)
  - ROV Wet mate Connectors
- 2 High Bandwidth Science Ports (10GbE, 375V)
  - ROV Wet mate Connectors
- Pulse per Second Timing
- Science Interface Assembly removable by ROV

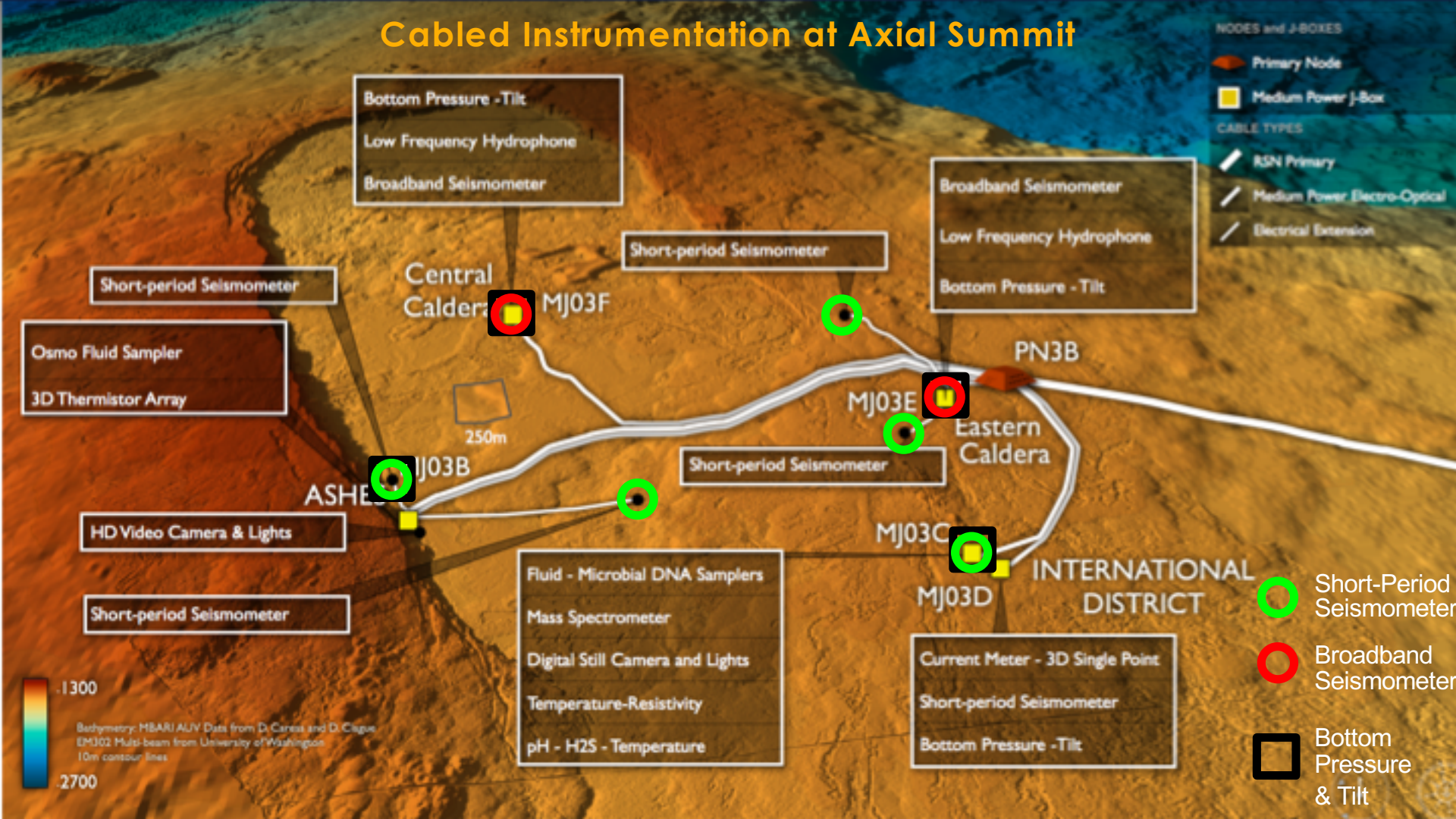
Secondary Infrastructure – UW-APL



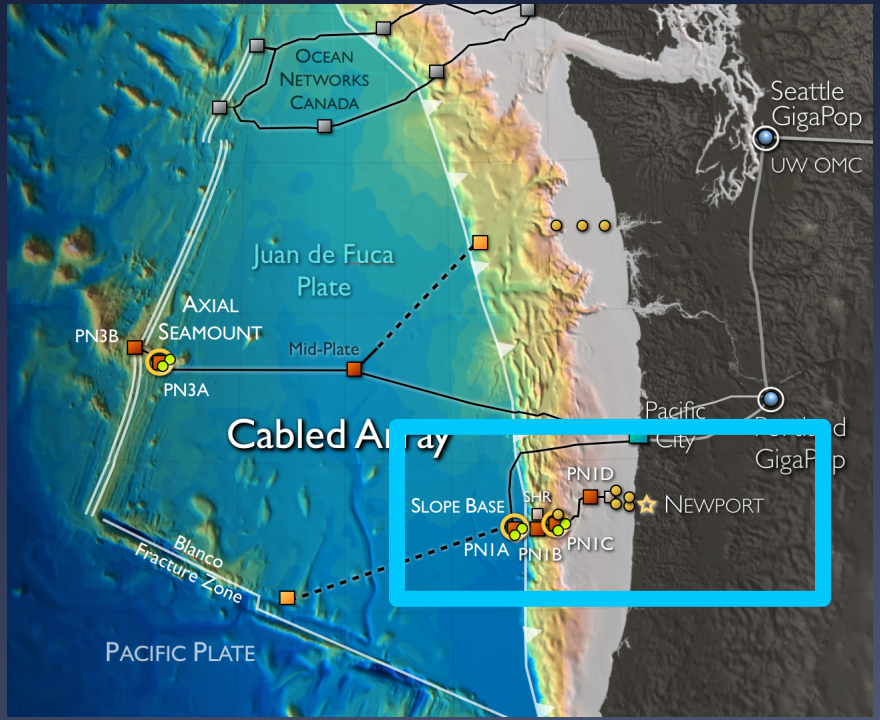
18 Secondary Junction Boxes

- Provide 8 configurable science ports with 1 Gbs bandwidth, up to 200W of power per port (±12/24/48 VDC), and one expansion port 10Amp, 375VDC), 10/100BASE-T, RS232 or RS485 data links

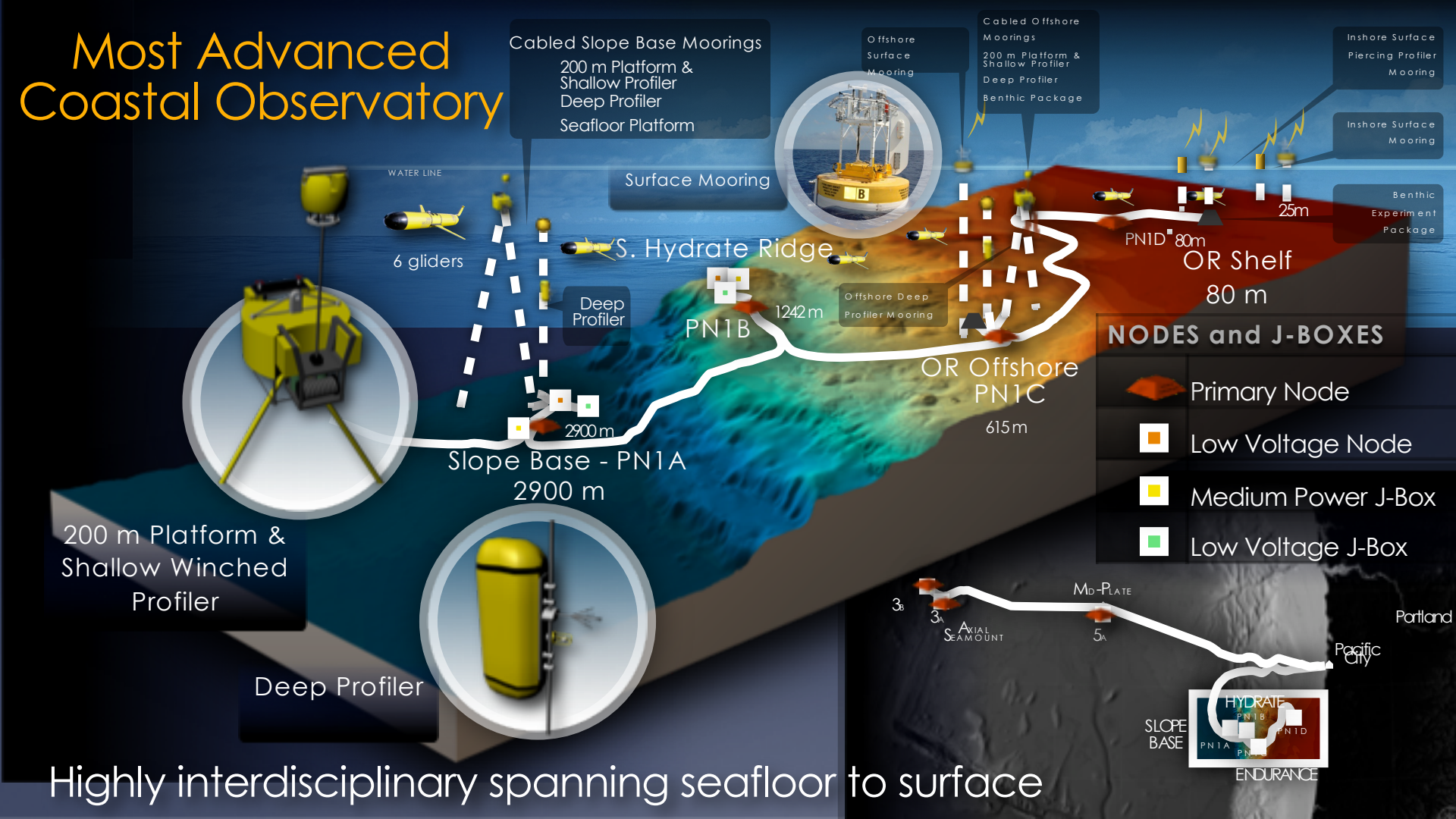
- Extend power and bandwidth to instruments and platforms
- Setup specifically for each platform/site; can easily be daisy chained for expansion
- 5-7 swapped out each

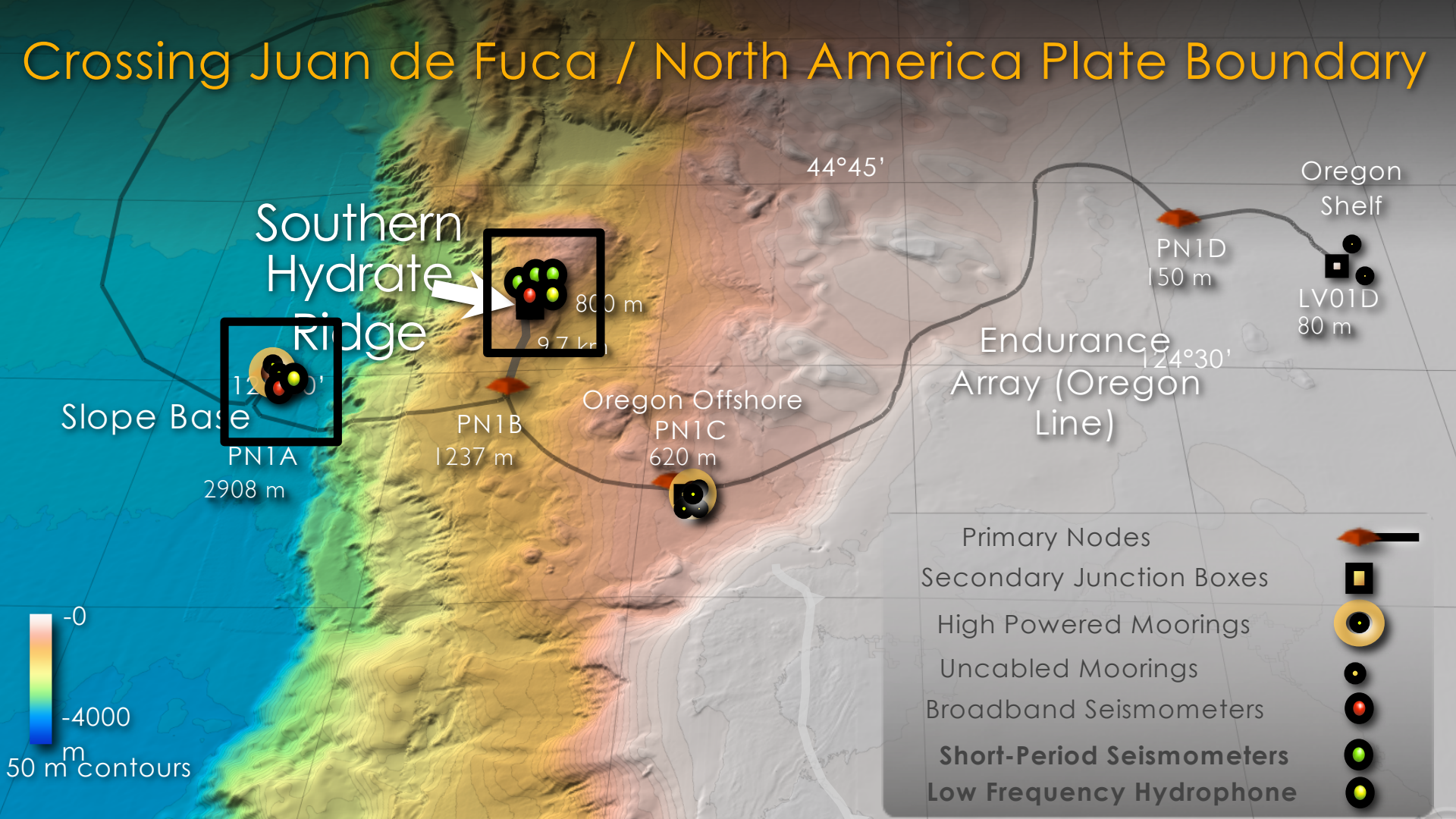

Cabled Instrumentation at Axial Summit
NODES and J-BOXES
Primary Node
Medium Power J-Box
CABLE TYPES
RSN Primary
Medium Power Electro-Optical
Electrical Extension
Bottom Pressure -Tilt
Low Frequency Hydrophone
Broadband Seismometer
Short-period Seismometer
Central Caldera
MJ03F
Short-period Seismometer
Broadband Seismometer
Low Frequency Hydrophone
Bottom Pressure - Tilt
PN3B
Osmo Fluid Sampler
3D Thermistor Array
MJ03E
Eastern Caldera
250m
MJ03B
ASHE
Short-period Seismometer
HD Video Camera & Lights
MJ03C
Fluid - Microbial DNA Samplers
Mass Spectrometer
Digital Still Camera and Lights
Temperature-Resistivity
pH - H2S - Temperature
INTERNATIONAL DISTRICT
MJ03D
Short-period Seismometer
Current Meter - 3D Single Point
Short-period Seismometer
Bottom Pressure -Tilt
-1300
-2700
Bathymetry: MBARI AUV Data from D. Caress and D. Clague
EM302 Multi-beam from University of Washington
10m contour lines
Short-Period Seismometer
Broadband Seismometer
Bottom Pressure & Tilt

Cabled Array and Endurance Coastal Array



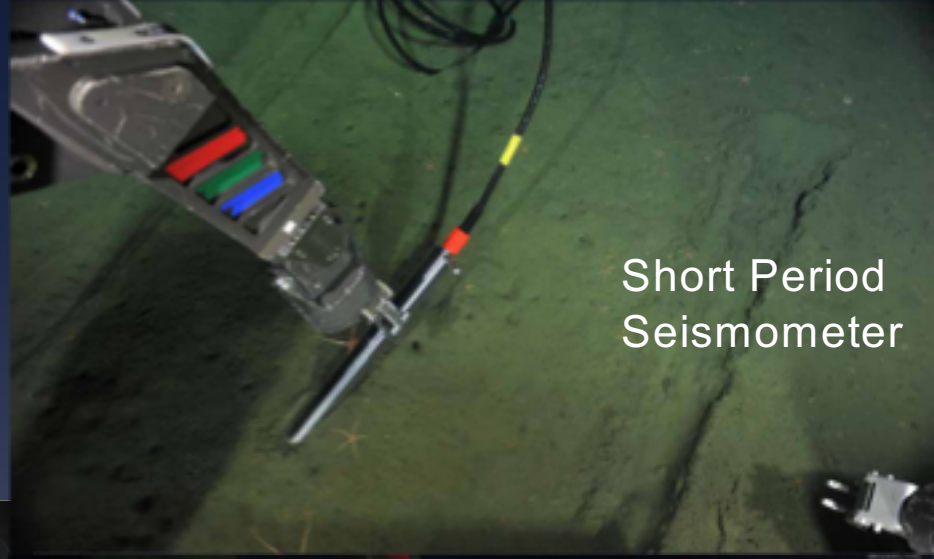
- Hypoxia events and ocean acidification
- Global biogeochemistry and carbon cycling
- Climate variability and ecosystems
- Coastal ocean dynamics and ecosystems
- Ocean circulation, mixing and ecosystems
- Methane seeps and novel microbial communities
- Offshore seismic activity in the Cascadia Subduction Zone


Most Advanced Coastal Observatory
Cabled Slope Base Moorings
200 m Platform & Shallow Profiler
Deep Profiler
Seafloor Platform
Offshore Surface Mooring
Cabled Offshore Moorings
200 m Platform & Shallow Profiler
Deep Profiler
Benthic Package
Inshore Surface Piercing Profiler Mooring
Inshore Surface Mooring
Benthic Experiment Package
WATER LINE
6 gliders
Surface Mooring
S. Hydrate Ridge
Deep Profiler
PN1B
1242 m
Offshore Deep Profiler Mooring
25m
PN1D
80m
OR Shelf
80 m
OR Offshore
PN1C
615 m
2900 m
Slope Base - PN1A
2900 m
NODES and J-BOXES
Primary Node
Low Voltage Node
Medium Power J-Box
Low Voltage J-Box
200 m Platform & Shallow Winched Profiler
Deep Profiler
3B
3A
Axial Seamount
Md-Plate
5A
Portland
Pacific City
SLOPE BASE
HYDRATE
PN1B
PN1D
PN1A
ENDURANCE
Highly interdisciplinary spanning seafloor to surface


Crossing Juan de Fuca / North America Plate Boundary
Southern Hydrate Ridge
800 m
9.7 km
Slope Base
PN1A
2908 m
PN1B
1237 m
Oregon Offshore
PN1C
620 m
44°45'
PN1D
150 m
Oregon Shelf
LV01D
80 m
Endurance Array (Oregon Line)
124°30'
-0
-4000 m
50 m contours
Primary Nodes
Secondary Junction Boxes
High Powered Moorings
Uncabled Moorings
Broadband Seismometers
Short-Period Seismometers
Low Frequency Hydrophone

Cabled Array Seismometer on the Cascadia Margin

- Guralp Broadband (CMG1T/5T triaxial) at Slope Base and Hydrate Ridge
- 3 Guralp Short-period seismometers (6TF) at Hydrate Ridge



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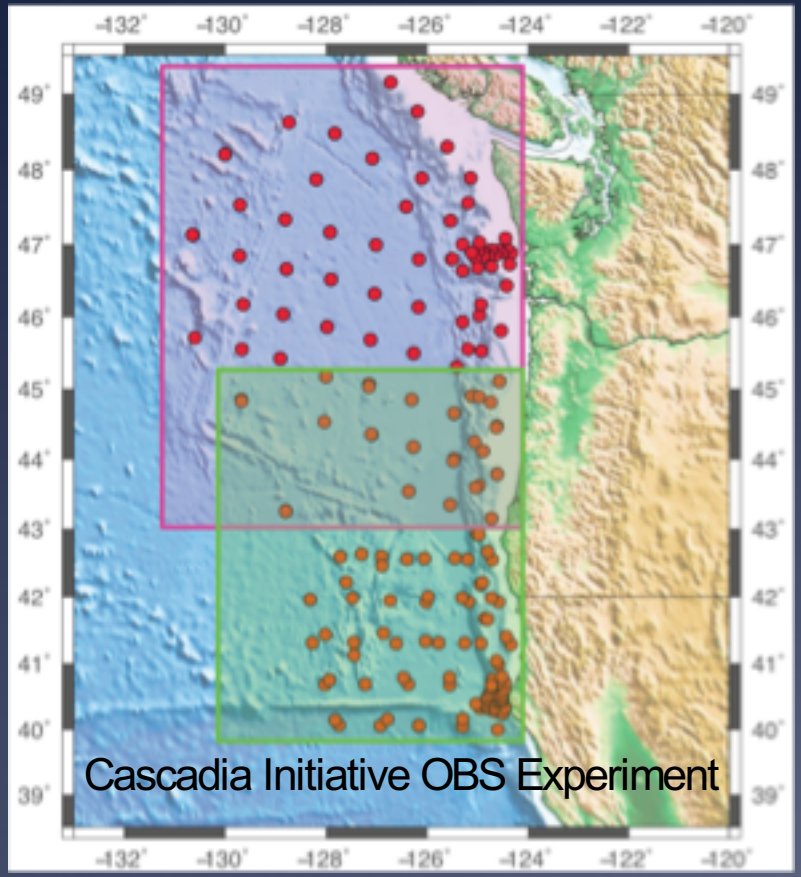
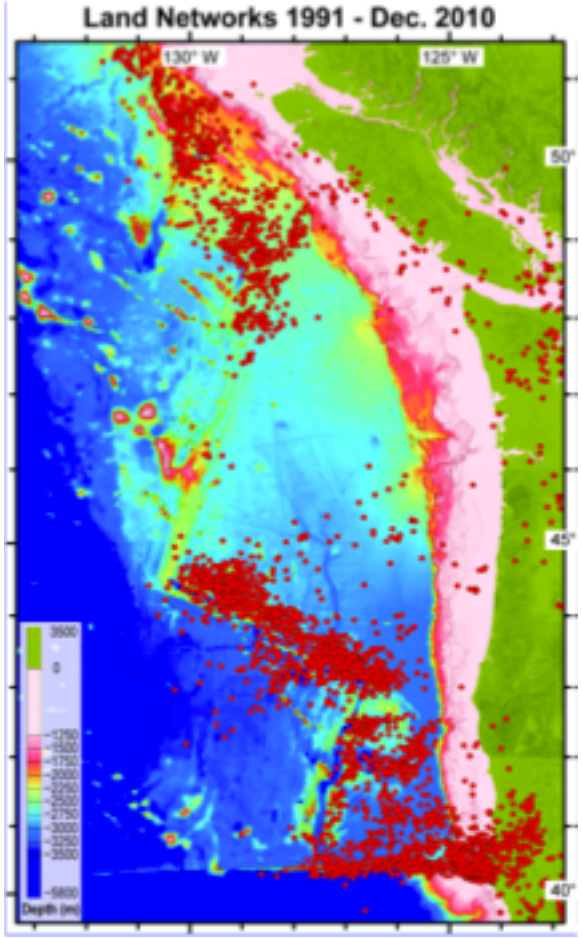
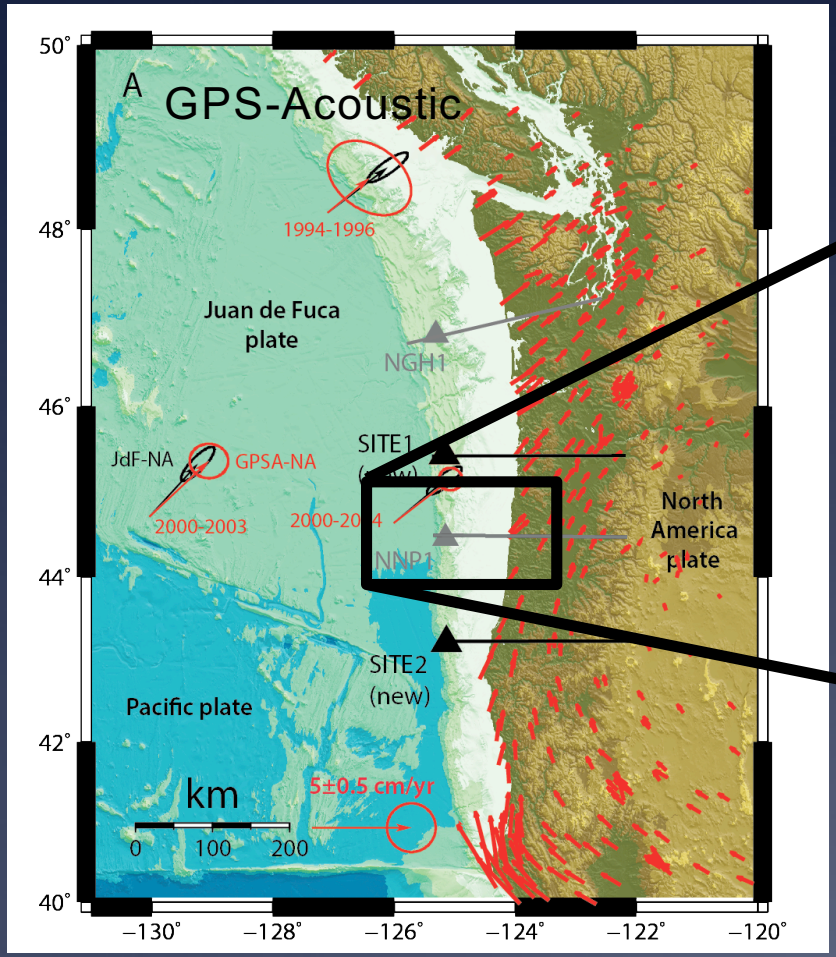
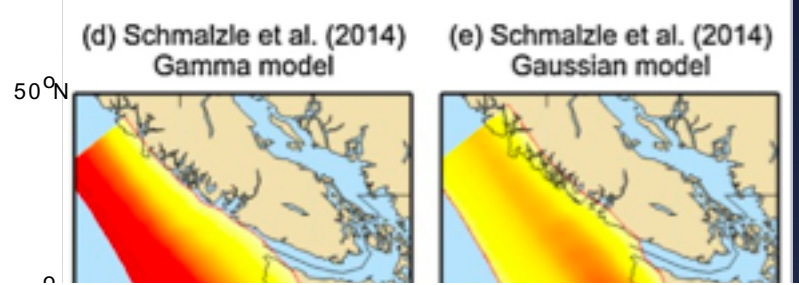
Offshore Seismicity

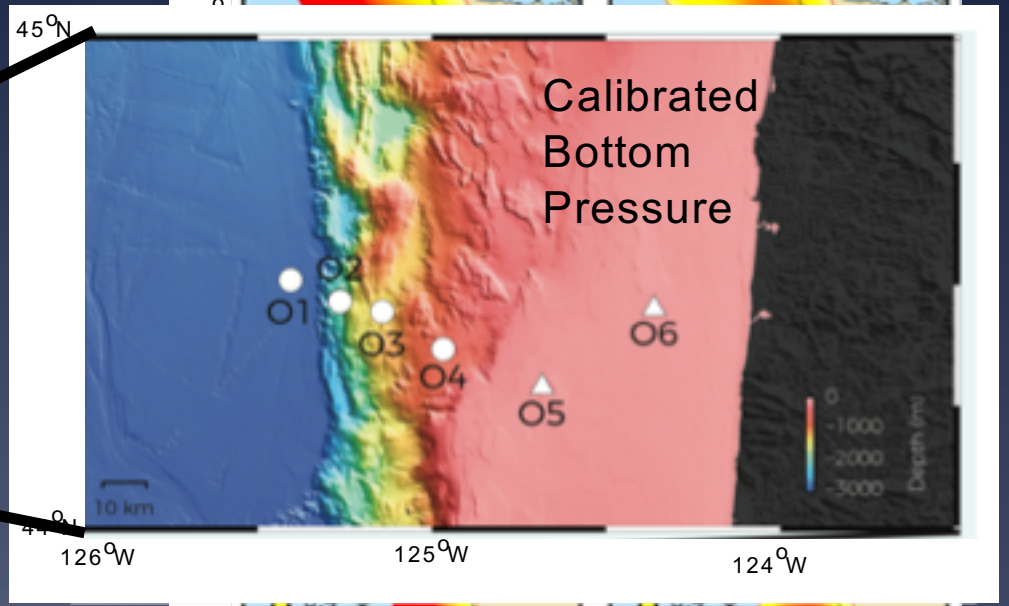


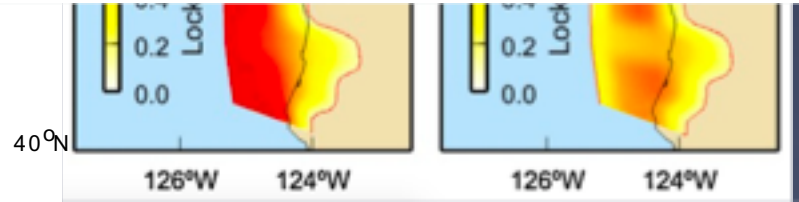


Geodesy


A
GPS-Acoustic
1994-1996
Juan de Fuca plate
NGH1
JdF-NA
GPSA-NA
2000-2003
2000-2004
SITE1
NNP1
North America plate
SITE2 (new)
Pacific plate
5±0.5 cm/yr
km
0
100
200
50°
48°
46°
44°
42°
40°
−130°
−128°
−126°
−124°
−122°
−120°

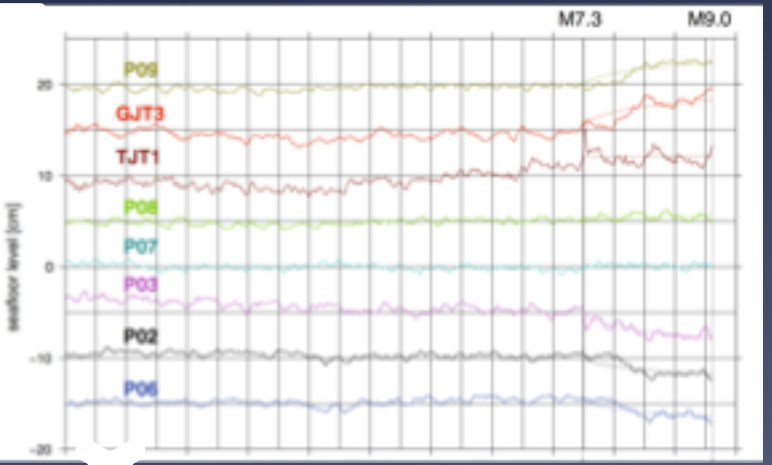

(d) Schmalzle et al. (2014)
Gamma model
(e) Schmalzle et al. (2014)
Gaussian model
50°N

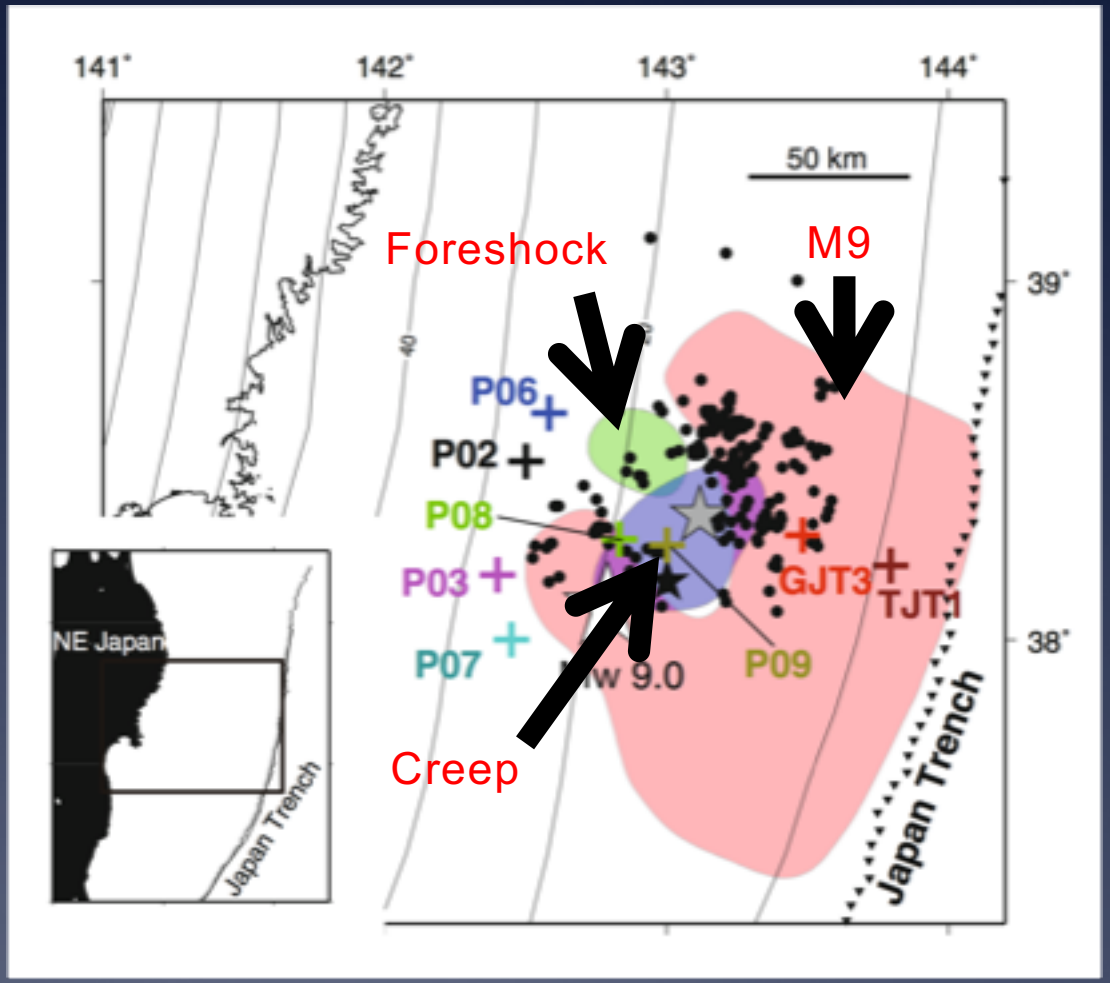

45°N
Calibrated
Bottom
Pressure
O1
O2
O3
O4
O5
O6
10 km
126°W
125°W
124°W


40°N
0.2
0.0
126°W
124°W
126°W
124°W

Tokoku Precursory Activity

Seafloor Pressure



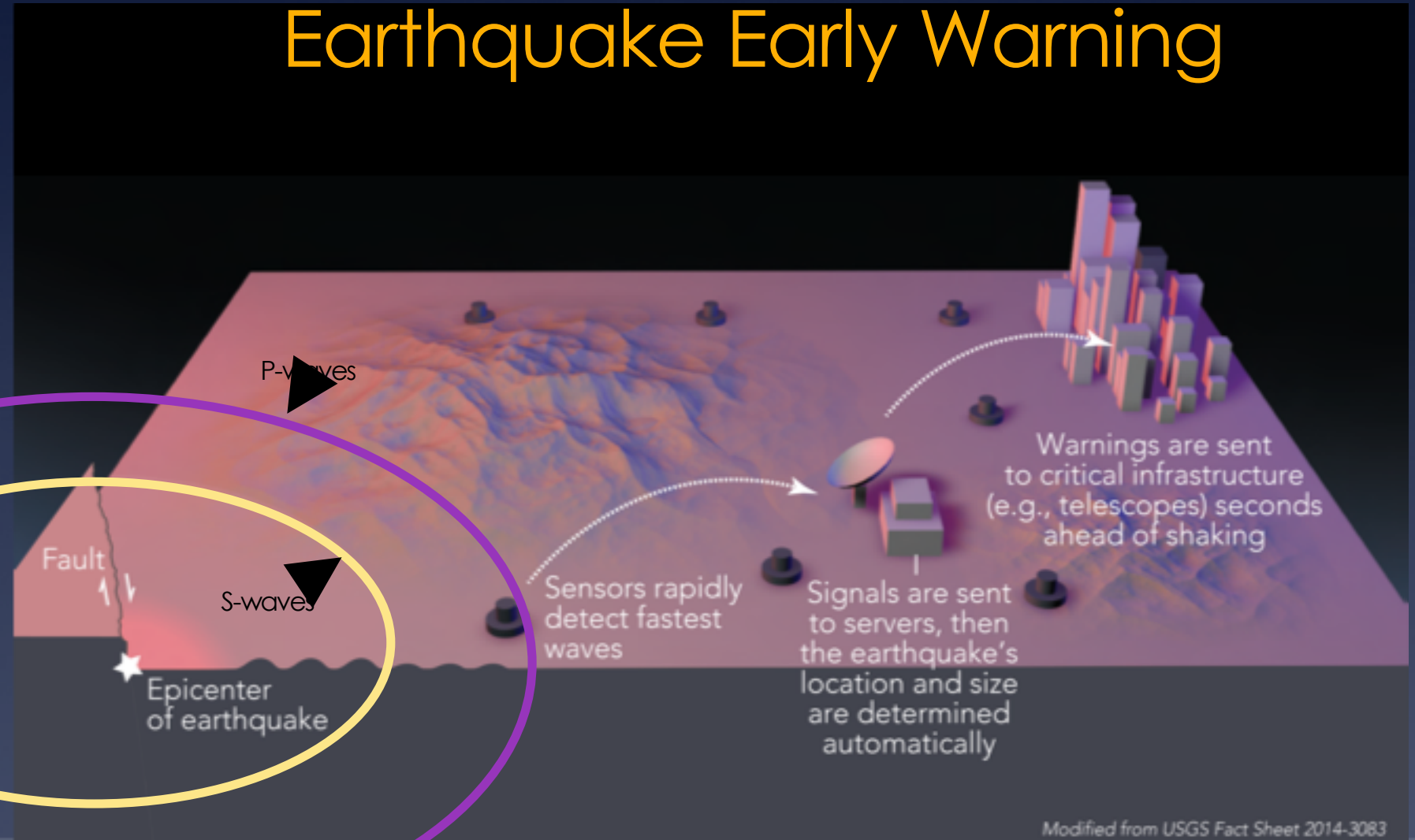


Hino et al., 2014

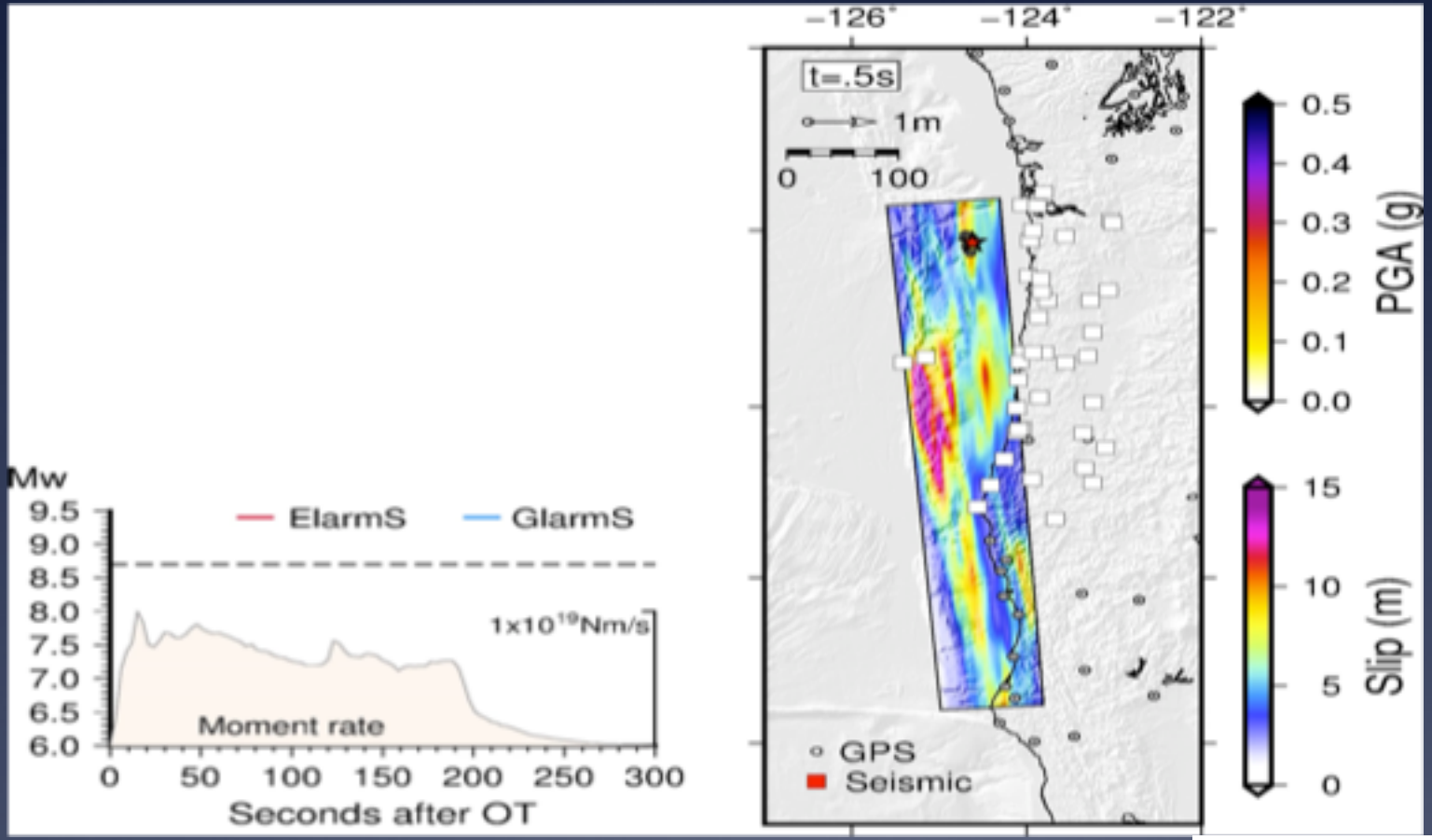
Offshore Infrastructure for Hazards Science

- Assessing the dimensions and segmentation of the locked-zone
  - Tsunamigenic potential
  - Shaking pattern on land
- Transient processes
  - Slow-slip
  - Microseismic cycles
  - Tremor
  - Slow-slip
- Baseline observations
  - Changes in the subduction environment
  - Earthquake precursors

Earthquake Early Warning



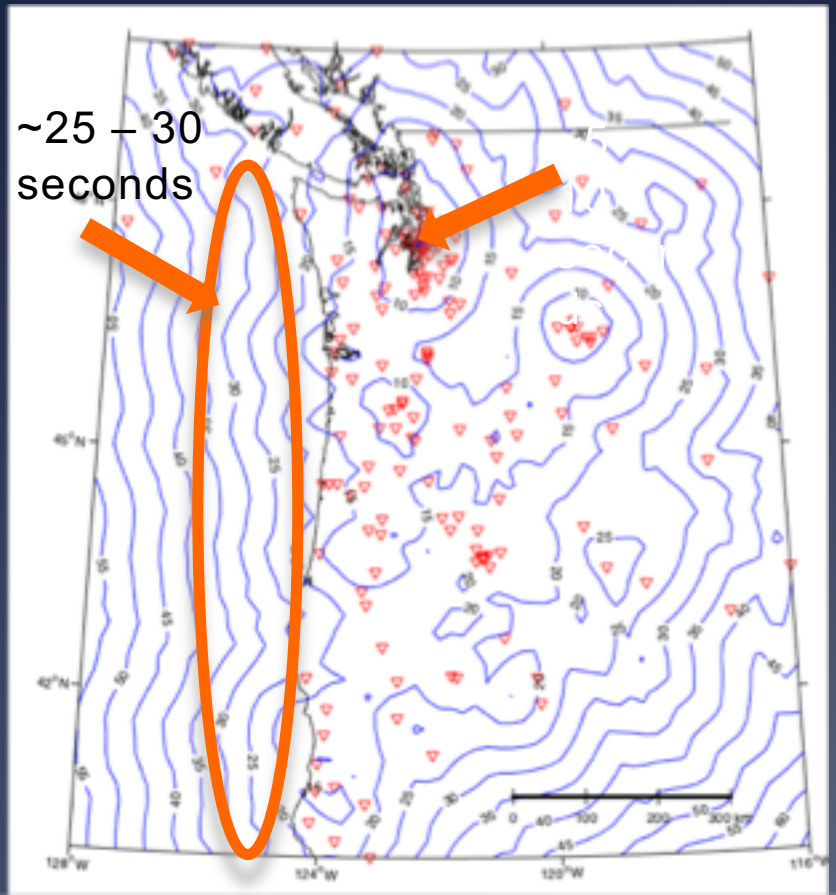
Tracking the Growth of Big Earthquakes with GPS



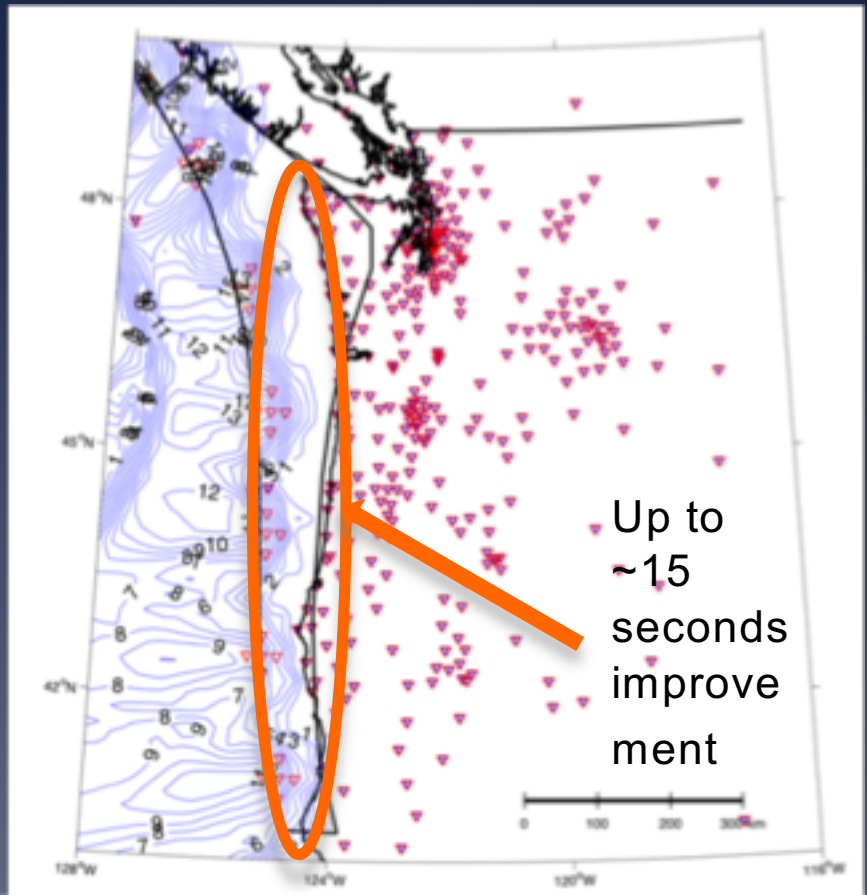
Ruhl et al. [2017 - GRL]

Current Cascadian EEW: ShakeAlert

Current Network Detection Times



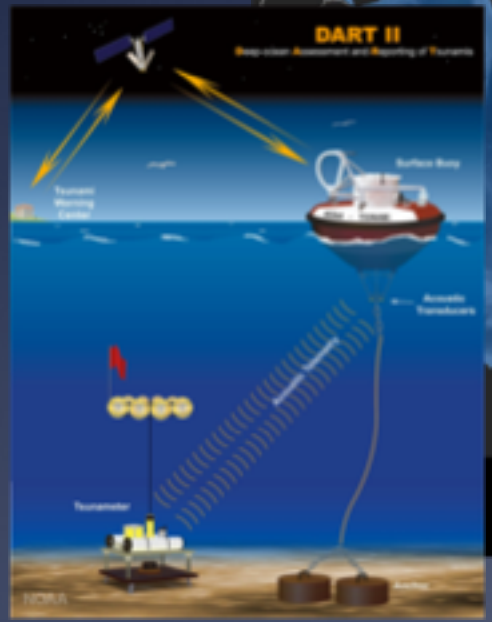
Improvements in Network Detection Times

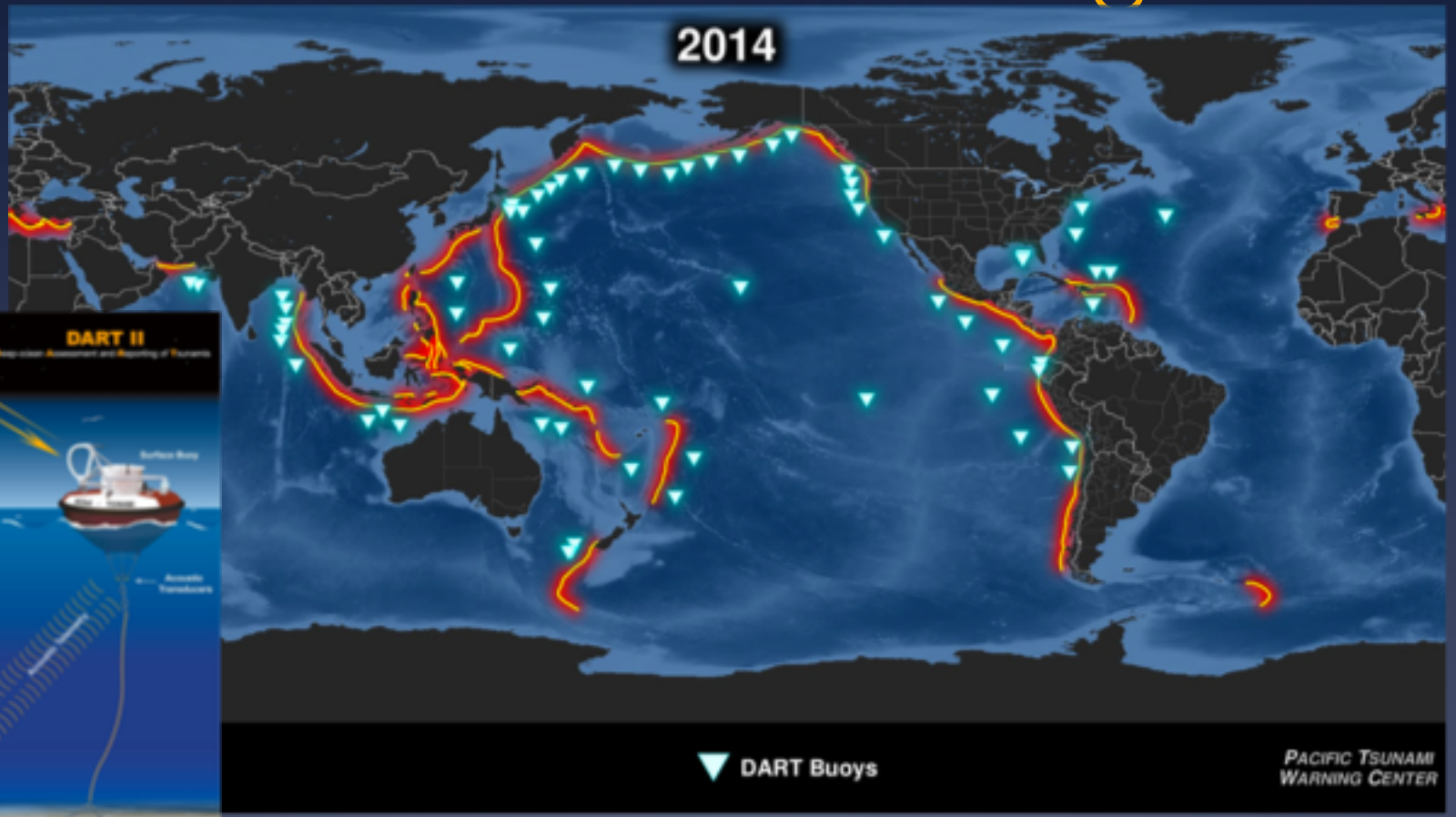


Offshore Infrastructure for Earthquake Early Warning

- Adds up to 15 s to early warning
- Enables a warning for coastal communities near the epicenter
- Increases reliability of warnings – EEW is most reliable for earthquakes that occur within the seismic & geodetic network

NOAA Tsunami Warning

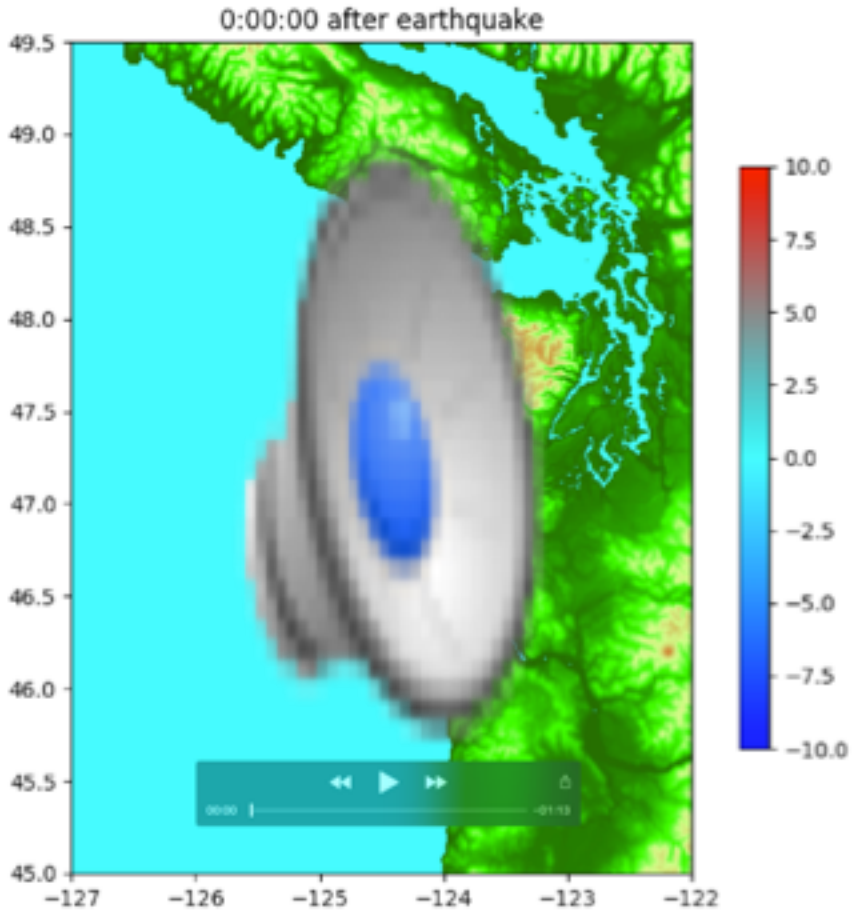




Designed to detect and provide a warning for far field tsunamis

Cascadia Tsunami Simulation

Nearest NOAA Tsunami Buoys



Offshore Infrastructure for Monitoring Incoming Tsunami

- Shaking is warning for Coastal Communities but they may not feel a "tsunami earthquake"
- For Puget Sound there is time for a warning
- Tsunamis generated by submarine landslides
- When has danger past (hours on coast, days in Puget Sound)
- Accurate real time modeling for regional damage estimates and disaster response

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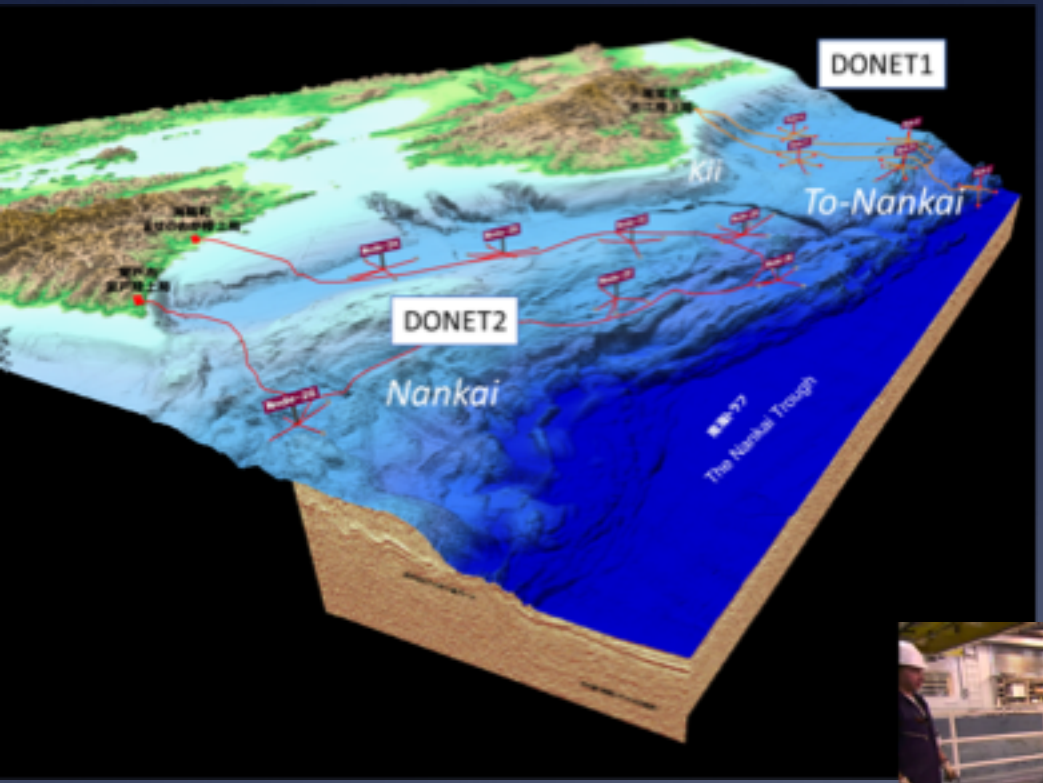
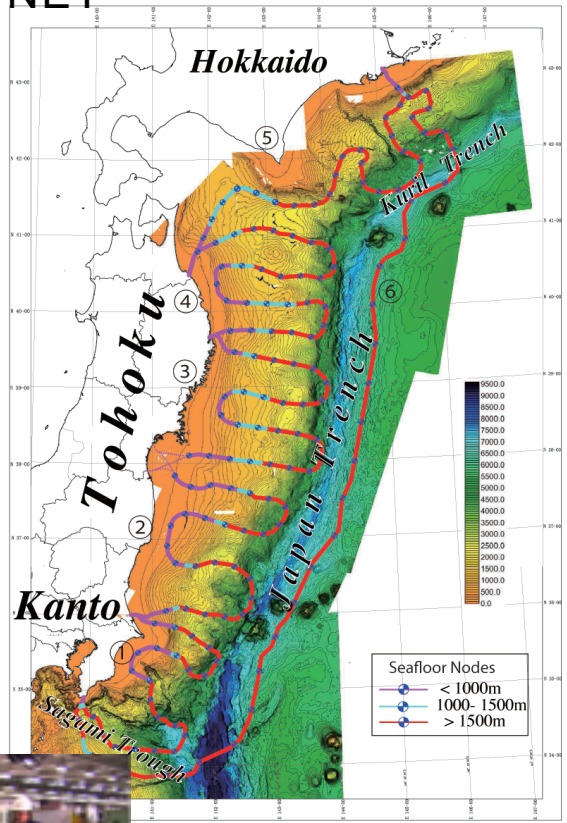
Japanese Systems



S-NET



Early Warning Only – Specifications 1

- System Design Life
  - 25 years standard in telecommunications industry – will require replacement/service life extension
- Spatial Coverage
  - Full subduction zone – Do not know where earthquakes nucleate
- Supported Instrumentation
  - Accelerometer/Seismometer
  - Pressure Sensor
- Instrument Density
  - Modeling
    - Earthquakes
    - Tsunamis

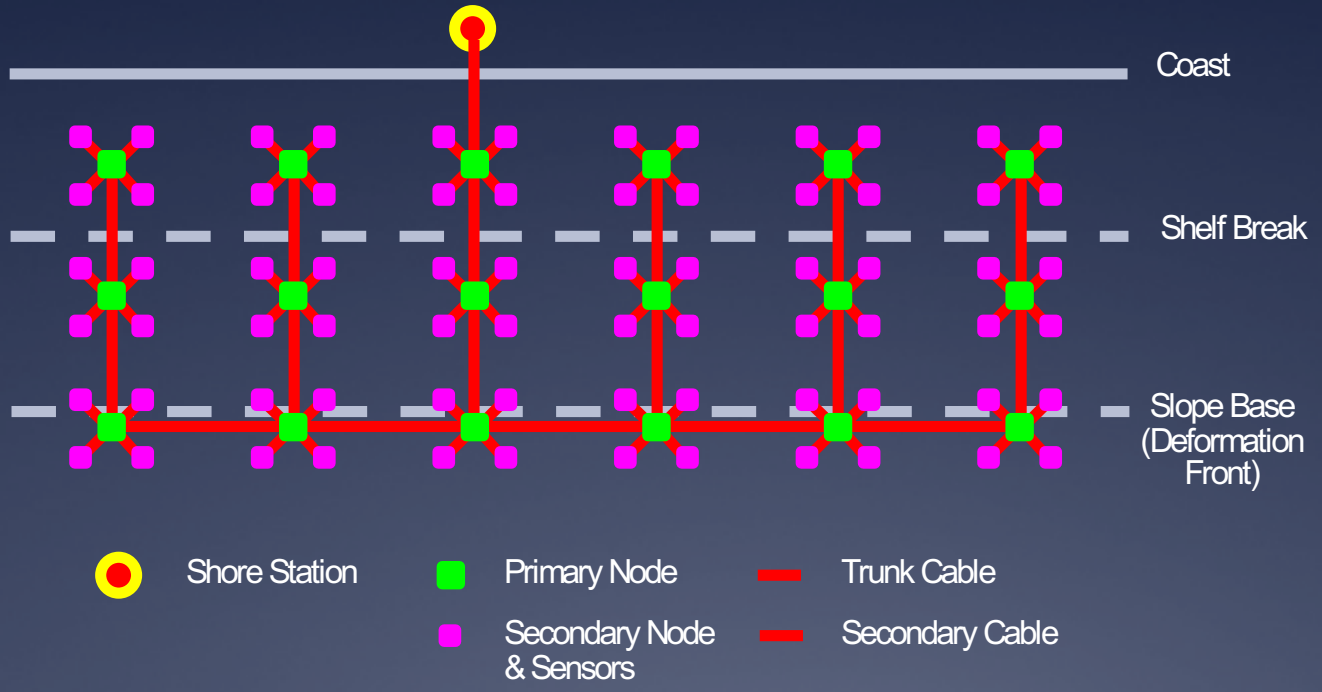
Early Warning Only – Specifications 2

- Latency
  - 2 s (station to alert center) for EEW on land
- Reliability/Availability/Survivability
  - Must be reliable
  - Scheduled maintenance should aim not to take down whole system
  - At least part of the system must work after a great earthquake
    - Tsunami monitoring
    - Aftershocks
- Maintainability
  - Outages must be fixable quickly
  - Minimize maintenance

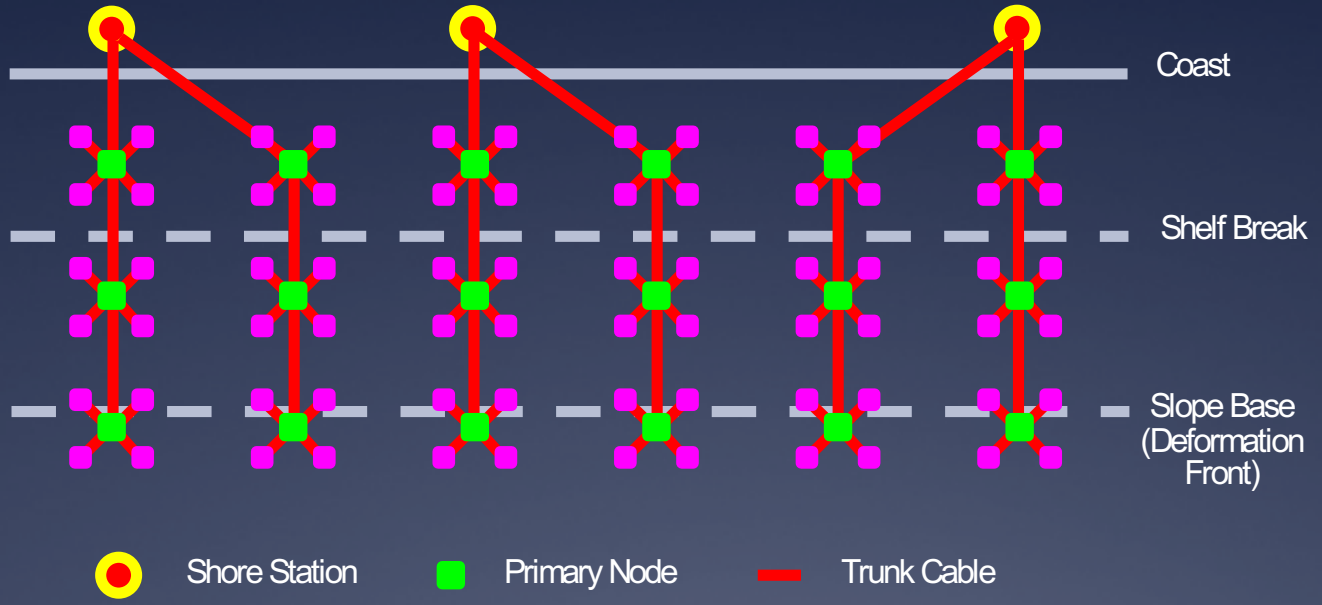
Science - Specifications

- Broad Instrumentation Support
  - Geodesy
  - Oceanographic applications
- Sensor Distribution/Density
  - Not as uniform as early warning
  - Areas of particular interest
- Expandability/Upgradeability
  - Sensor development
  - Adapt to scientific discoveries

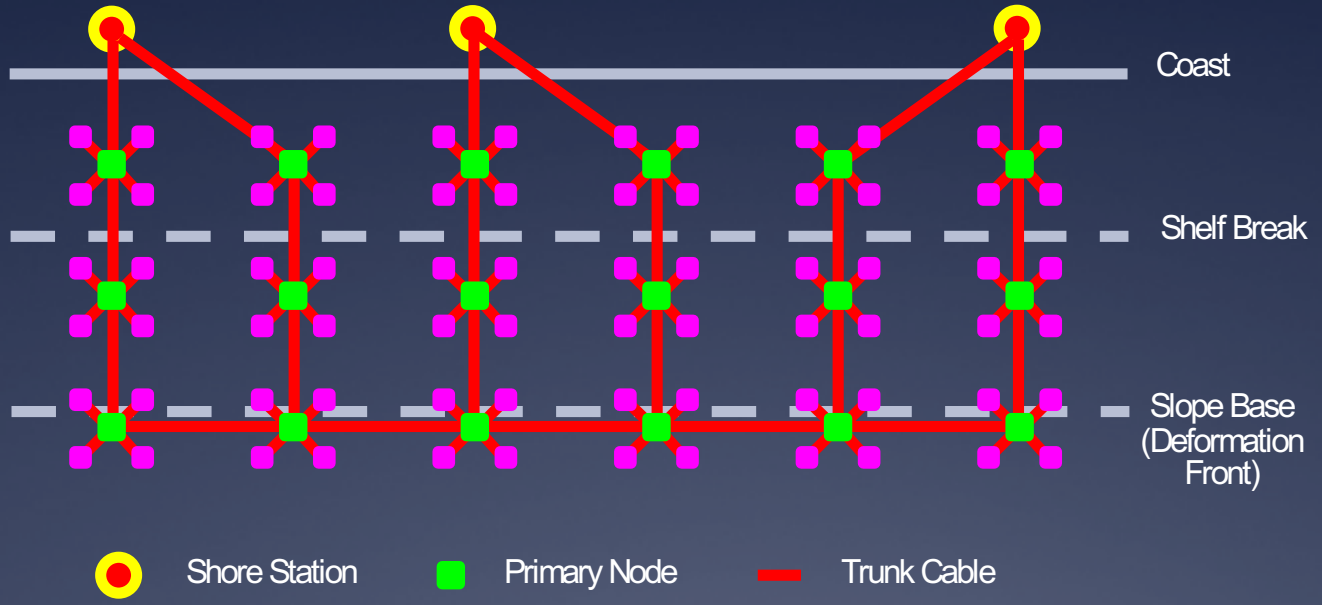
Design Options - Single Shore Station



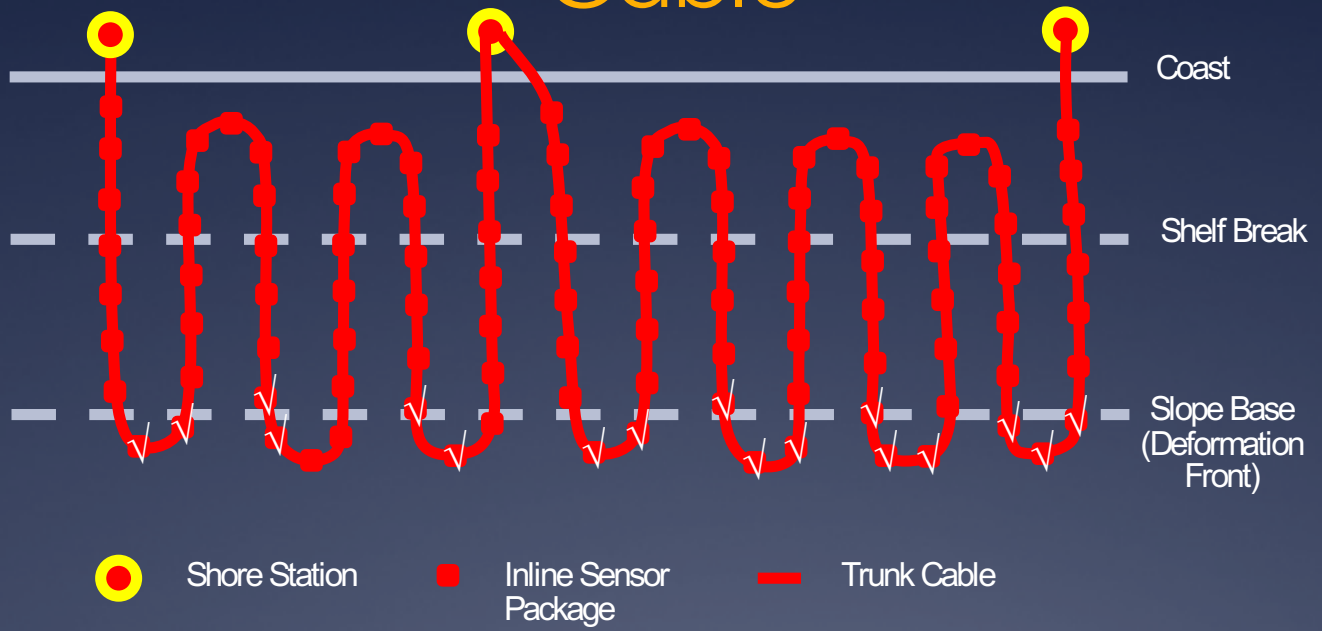
Multiple Shore Stations



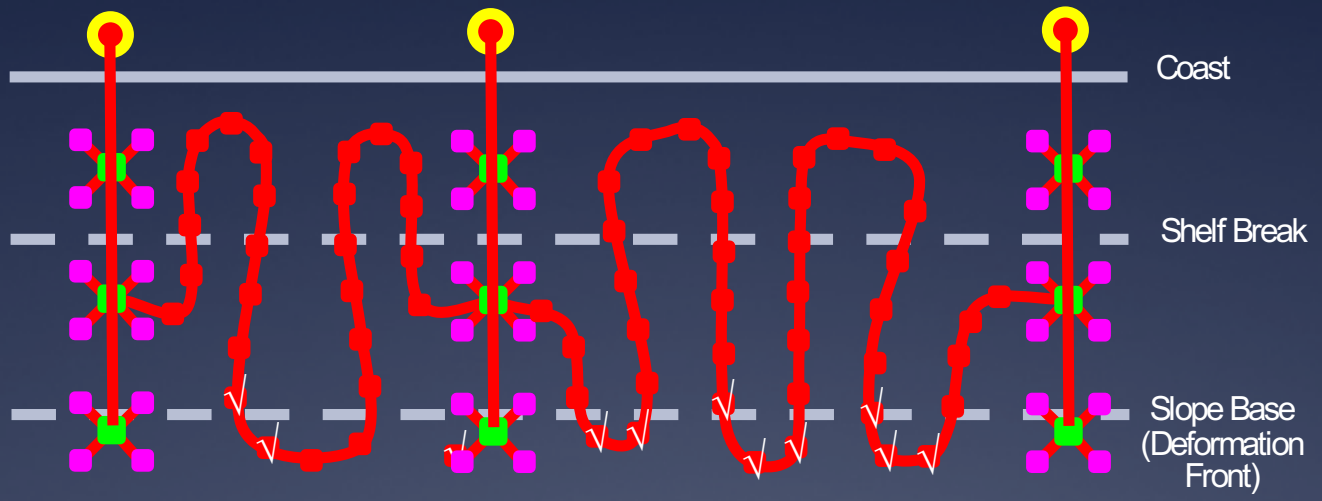
Multiple Shore Stations - Interconnected



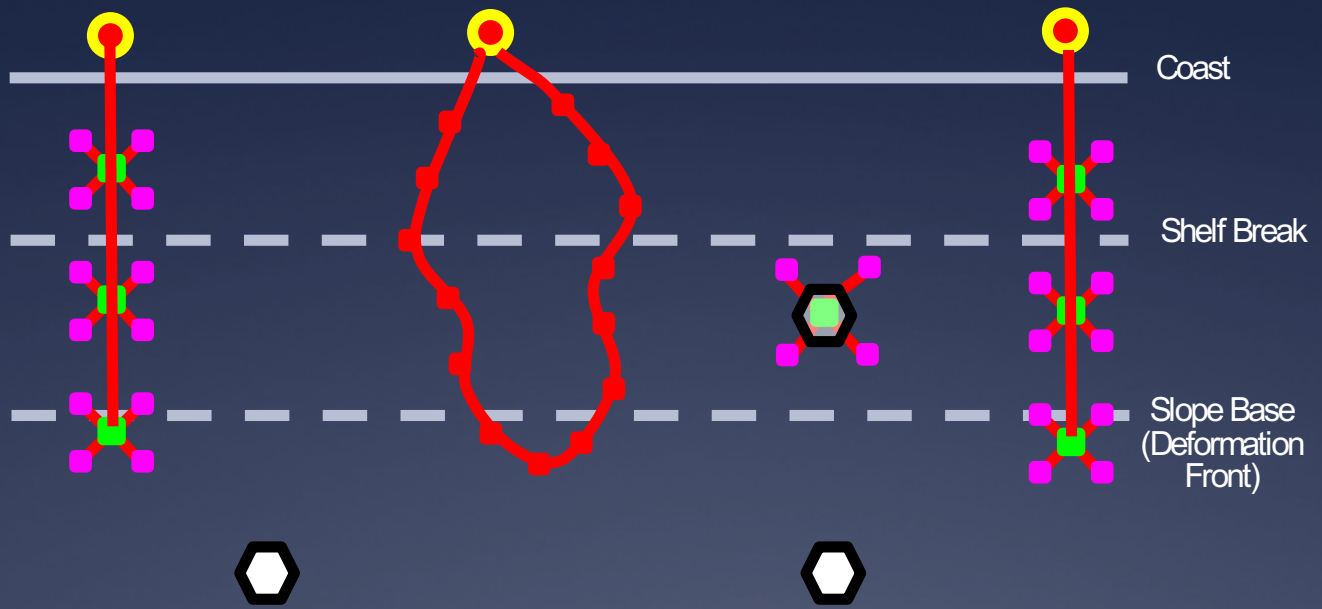
Sensors Integrated into Trunk Cable



Hybrid System



Hybrid Cabled & Uncabled System



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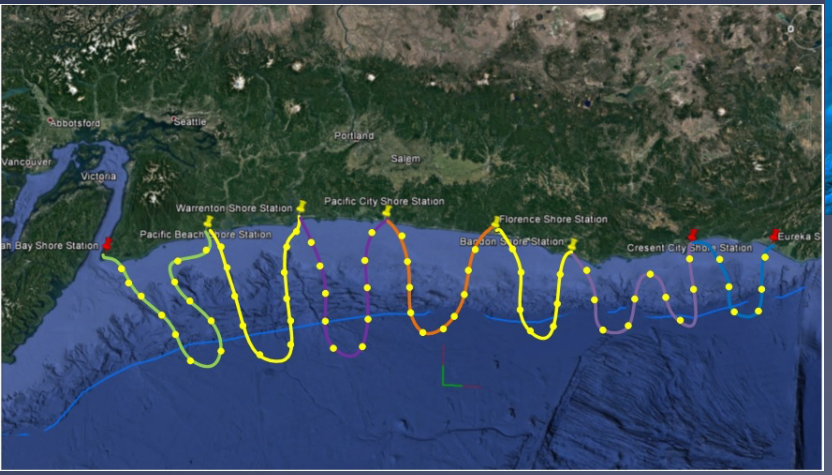
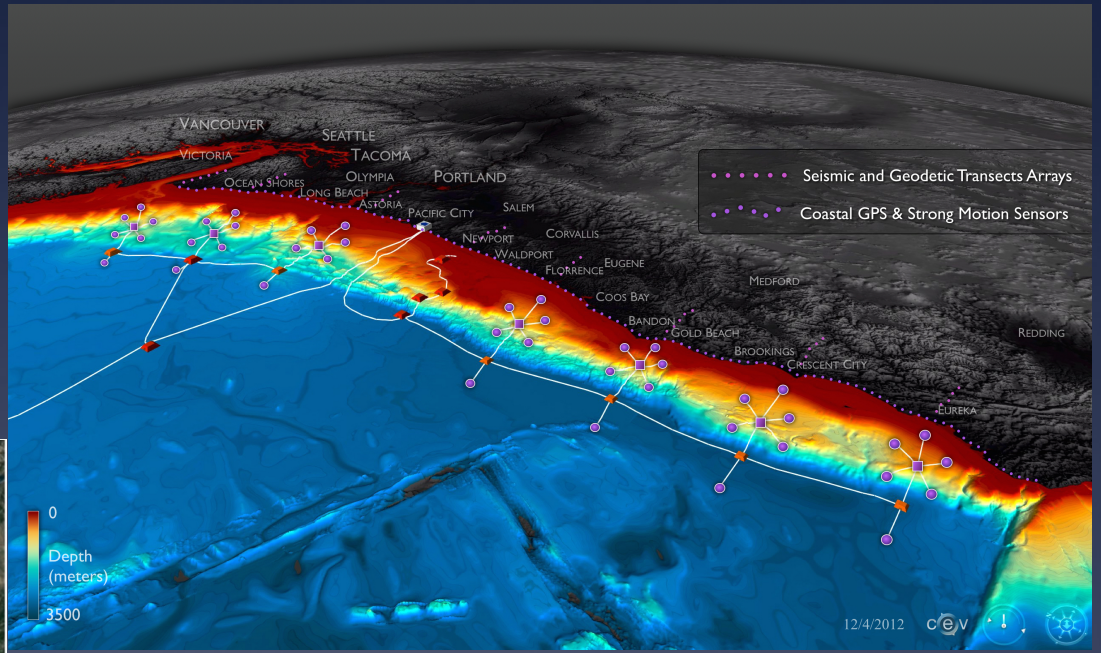
A Full System

The UW is conducting a feasibility study

- Rationale
- Requirements
- Engineering Approaches
- Costs
- A Path to a System

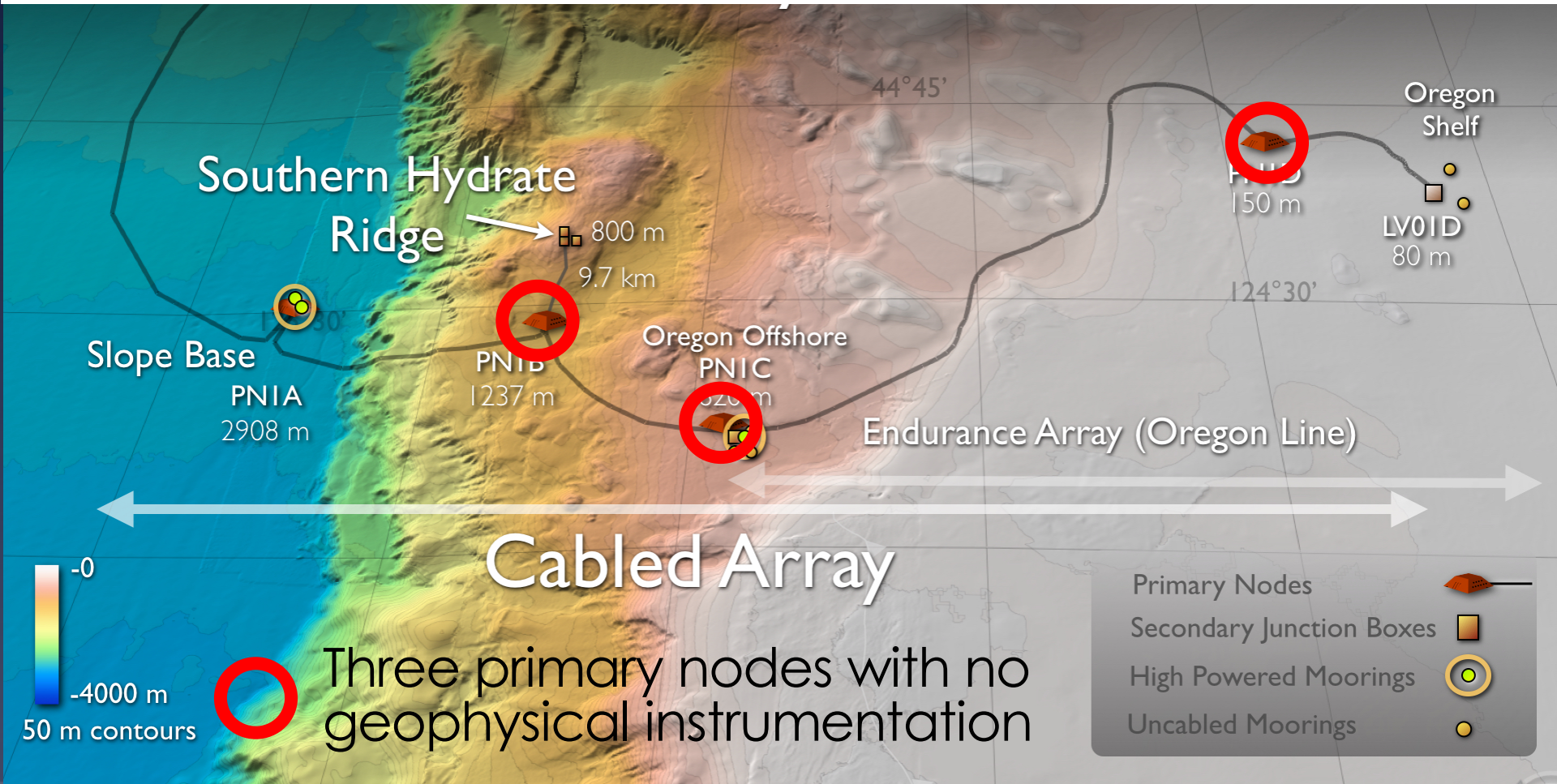
So what do we do in the short term?





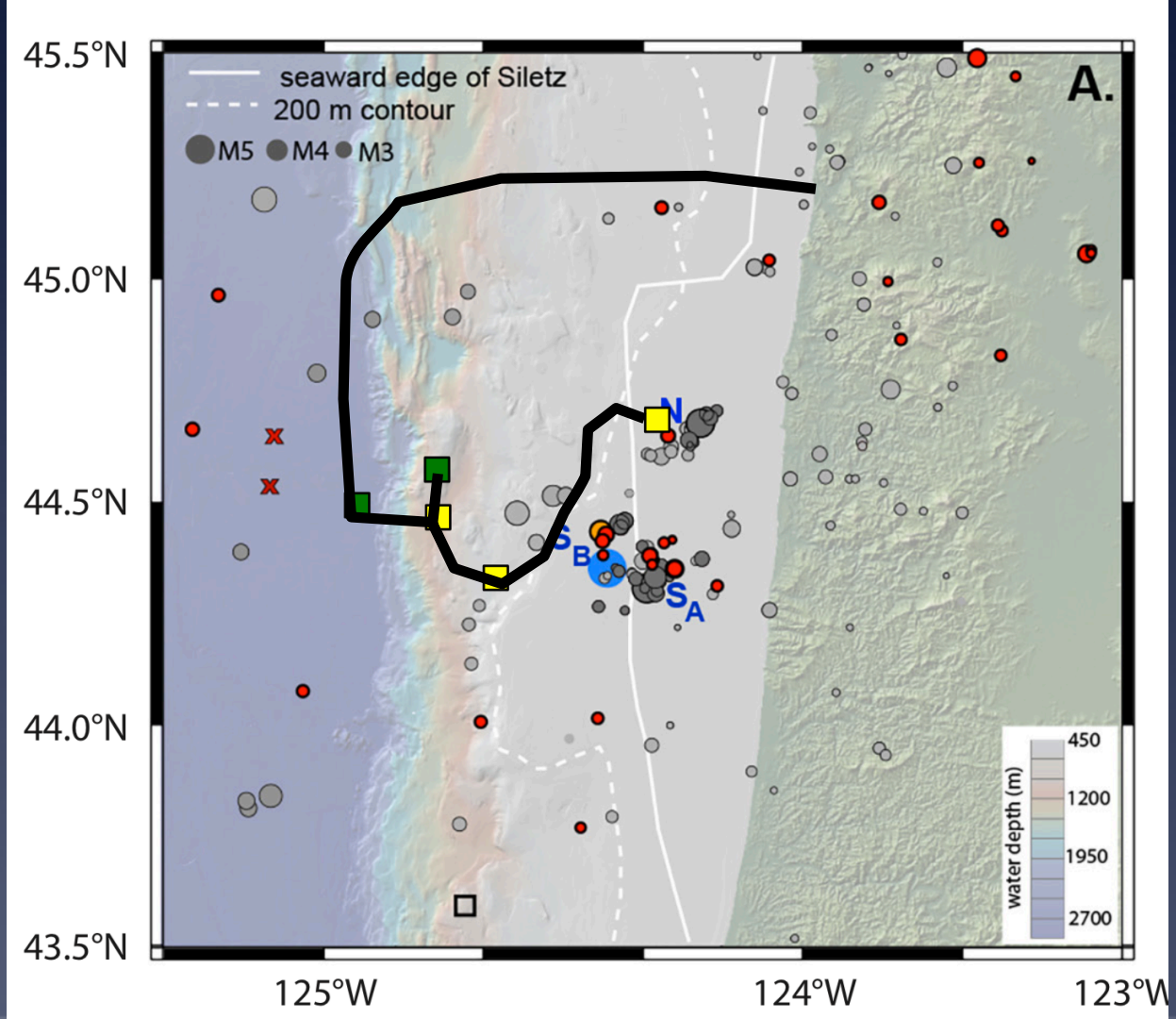
GORDON AND BETTY MOORE FOUNDATION

Expand Geophysical Capabilities of Cabled Array



Seismology

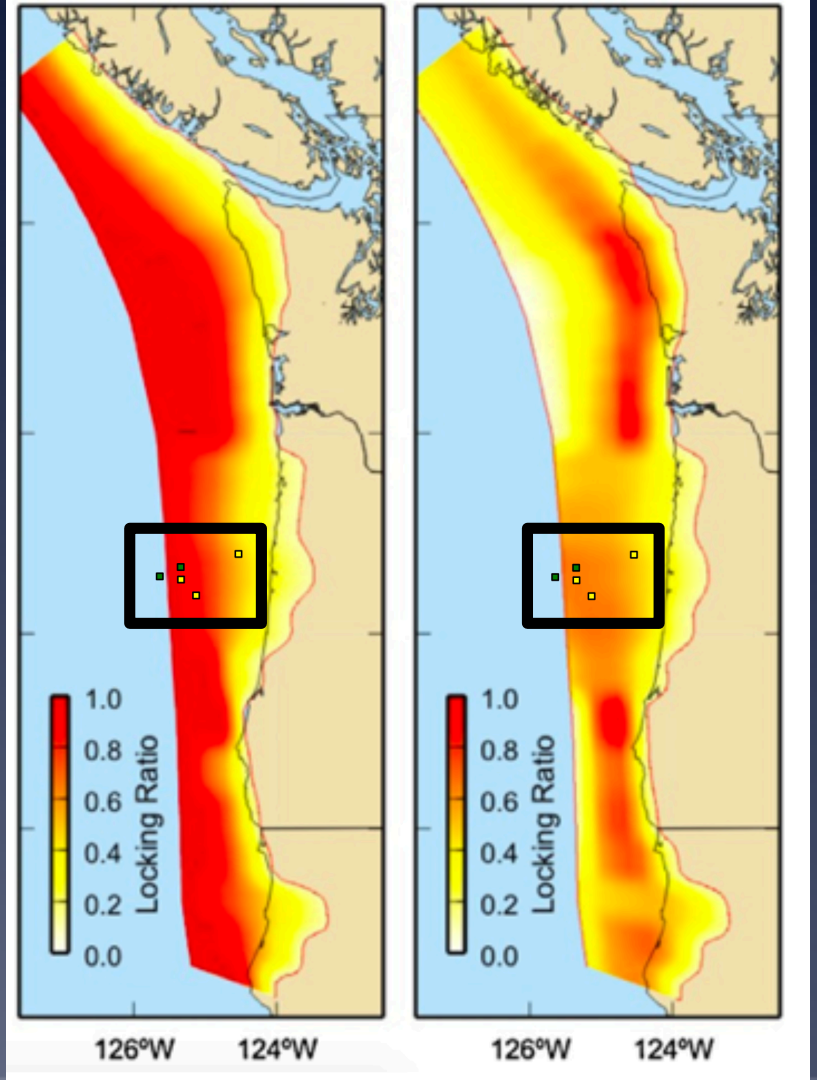
Eastern node PN1D lies above northern cluster of Central Oregon Offshore Earthquakes



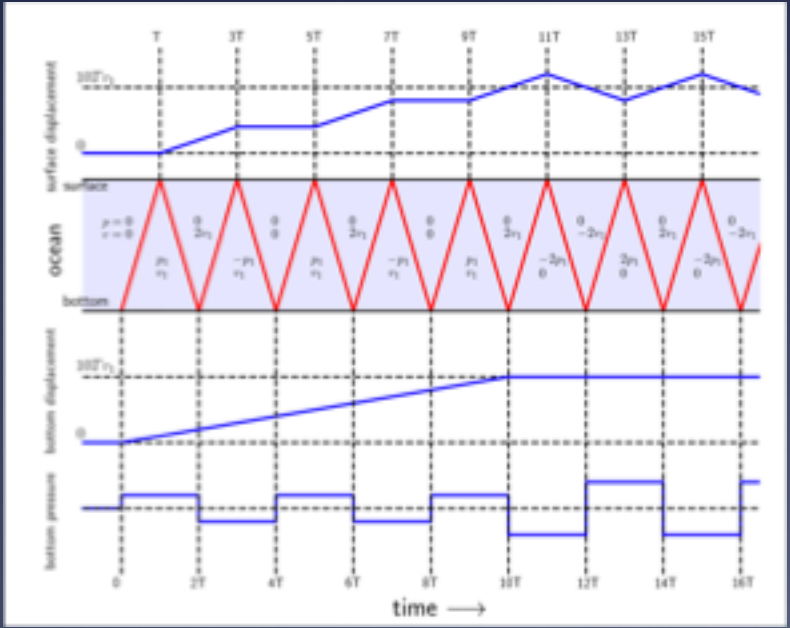
Tréhu et al. (2017)

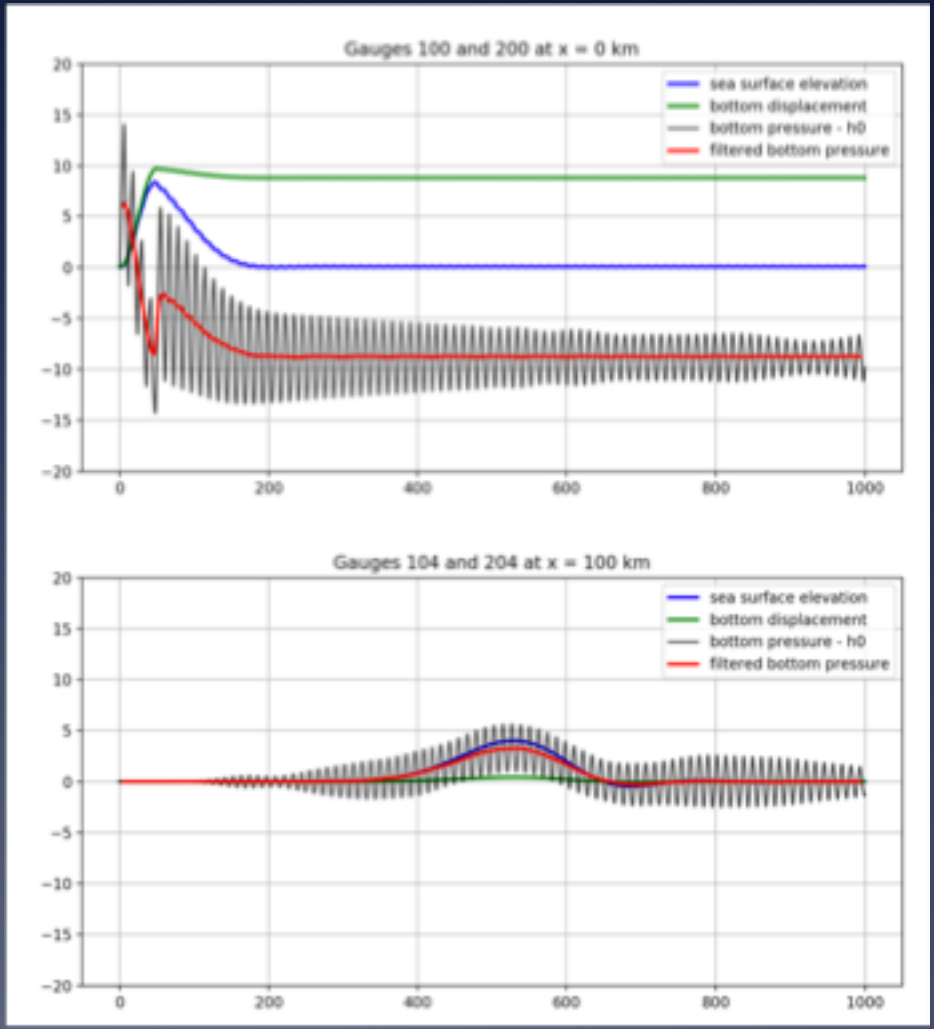
Geodesy

Lies central within the portion of the subduction zone which appears to be only partially coupled



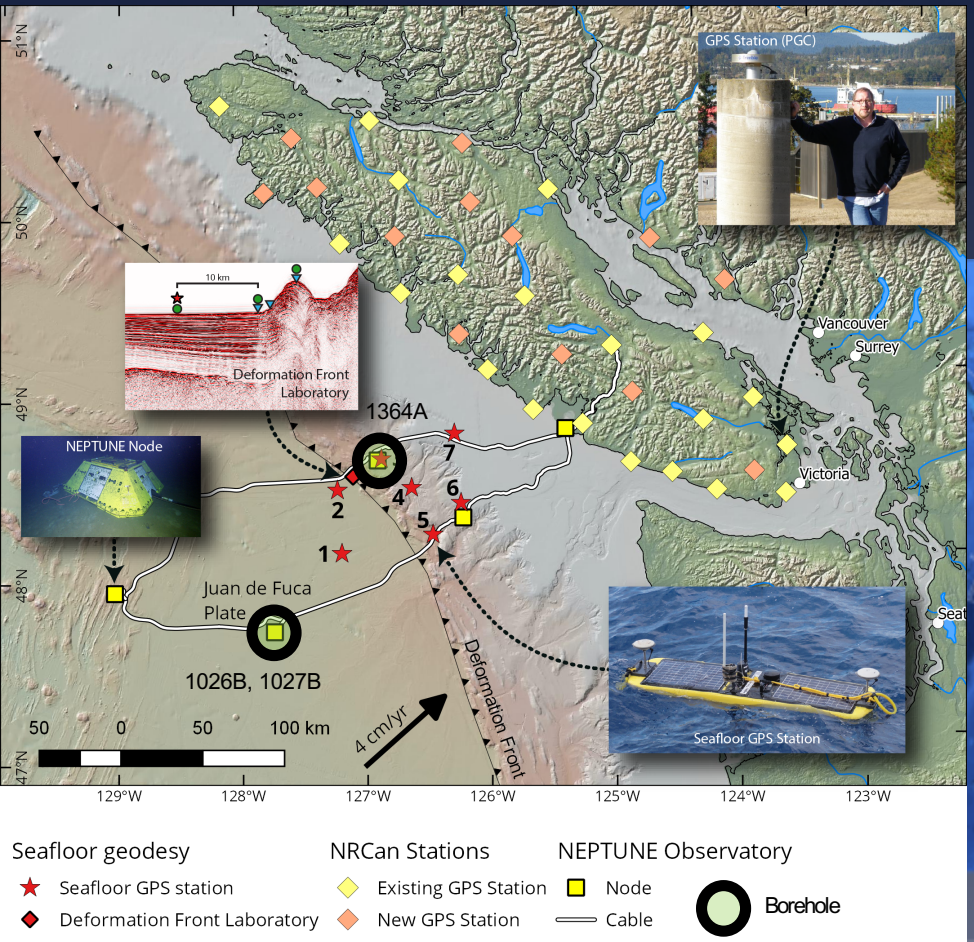
Are Observations of the sea surface required in the tsunami source zone?





Ocean Networks Canada

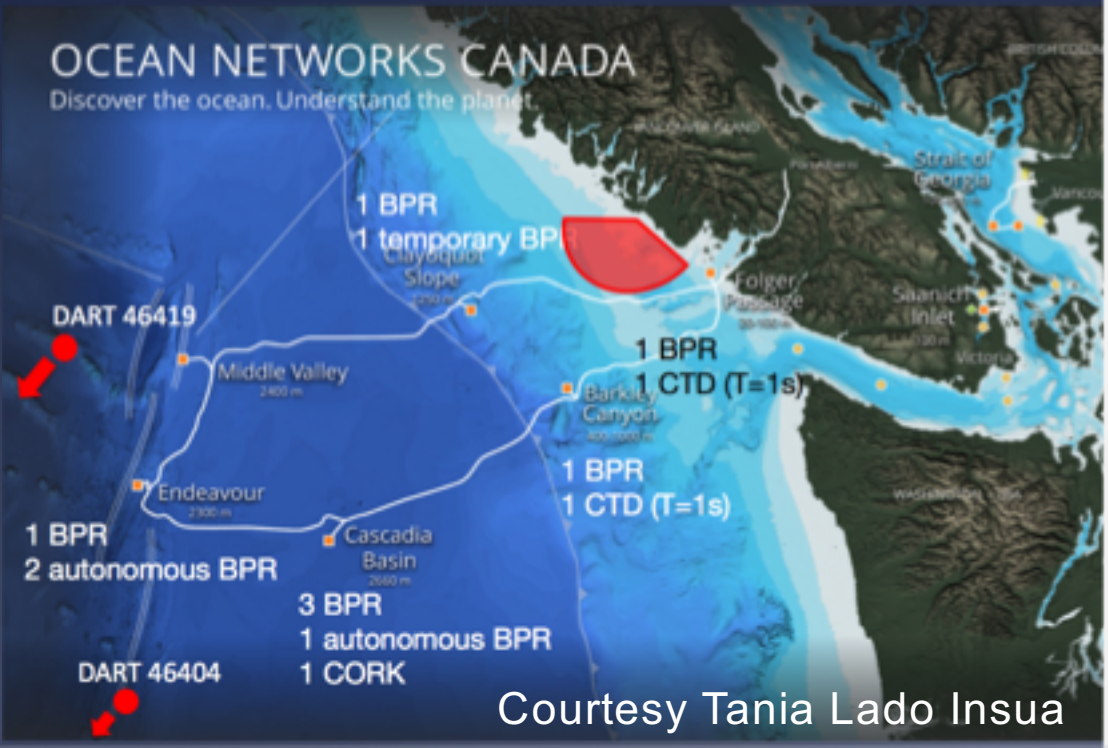
- Borehole Geodesy
- Dense GPS-Acoustic
- Offshore Infrastructure for EEW



Courtesy Martin Heeseman

ONC- Tsunami

Integrating bottom pressure, coastal radar and tsunami modeling.



Courtesy Tania Lado Insua

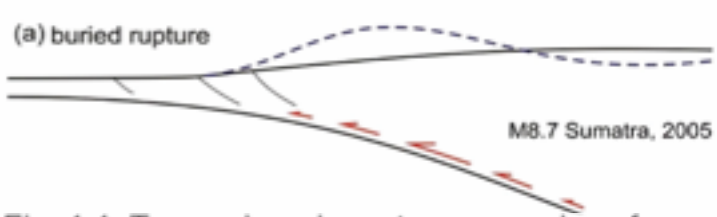
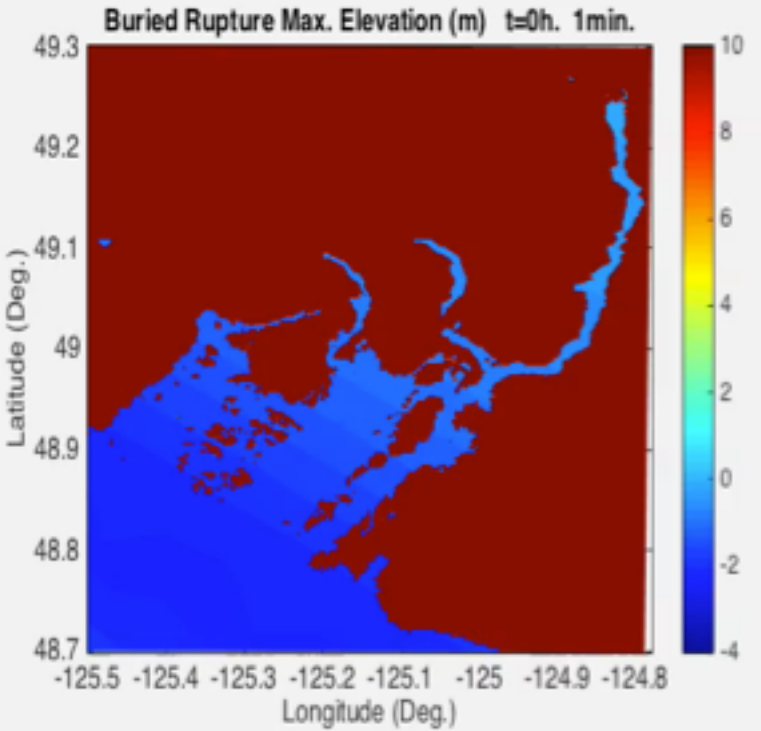
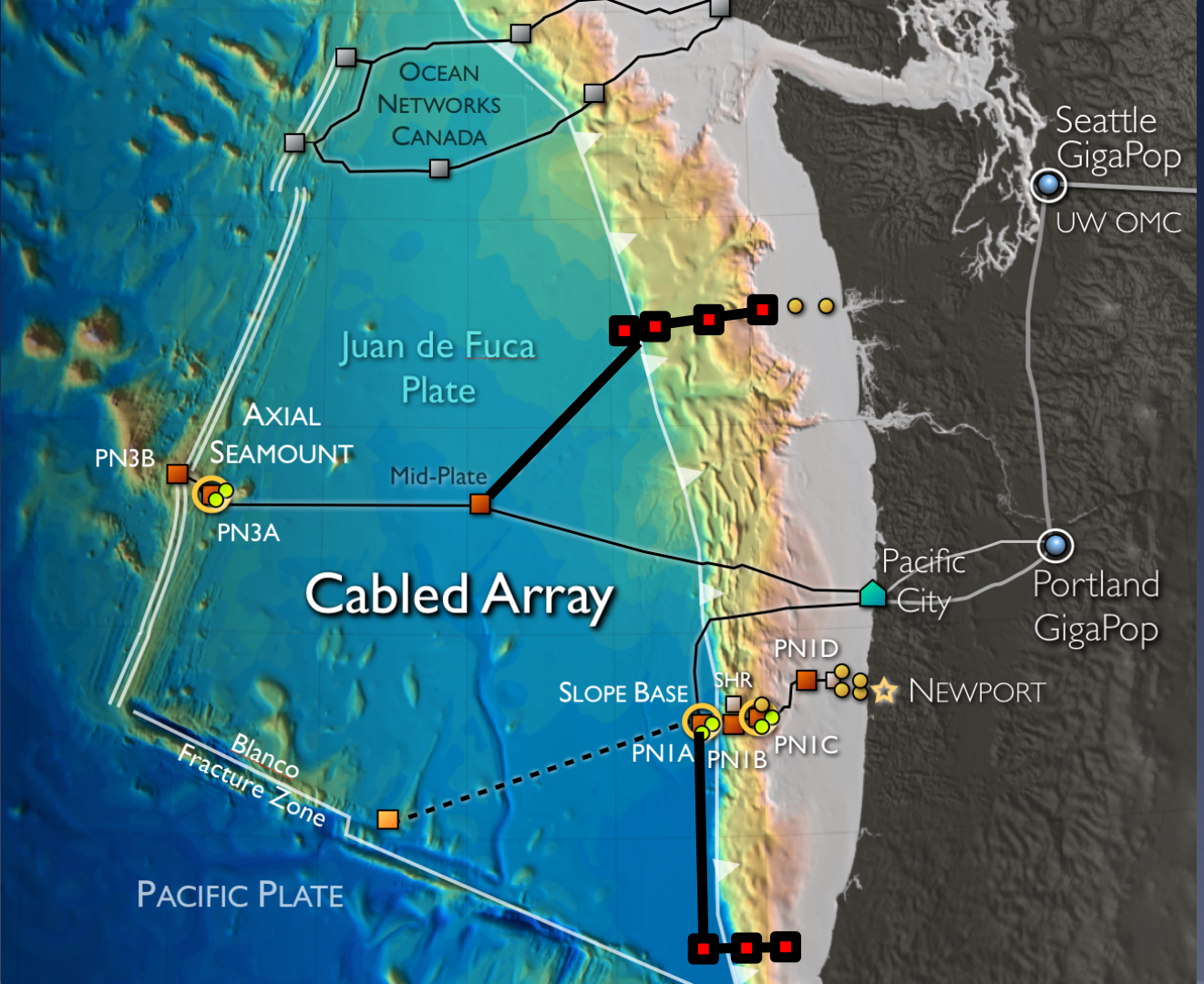


Fig. 1.1. Tsunami-genic rupture scenarios of subduction earthquakes [*Wang and Tréhu*, 2016].





Expanding The Cabled Array

With a relatively modest investment could initiate efforts off central Oregon

- Sustained Observations for science
- Instrument Development
- Offshore EWW
- Tsunami Early Warning Research
- Engagement

Midscale Infrastructure Investment

- Grays Harbor, WA
- Southern Cascadia