The NEPTUNE Canada measurements of approaching tsunamis off the British Columbia coast: an opportunity for regional modelling and forecasting

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- 1. NEPTUNE Canada
- 2. Tsunami measurements
- 3. Samoa 2009 tsunami: first experience of the regional modeling and prediction based on the NEPTUNE bottom pressure records.
- 4. Bonin 2010 tsunami: measurement on the edge
- 5. High frequency analysis: seismic waves
- 6. Chilean 2010 tsunami: measurements and modeling
- 7. Tohoku 2011 tsunami: impact on British Columbia and Washington State Coasts.
- 8. Discussion.

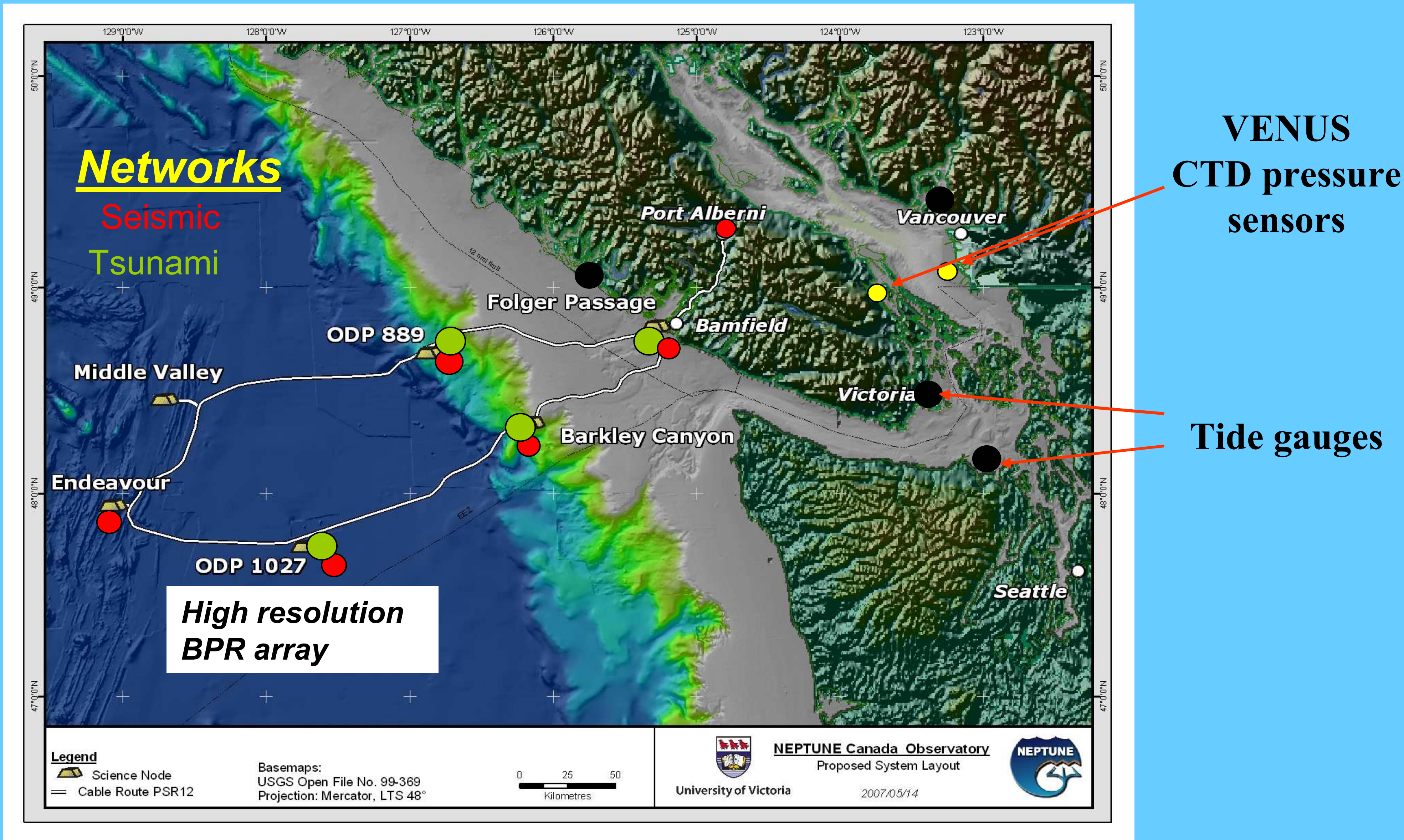
NEPTUNE Canada:

- North
- East
- Pacific
- Time-series
- Undersea
- Networked
- Experiments

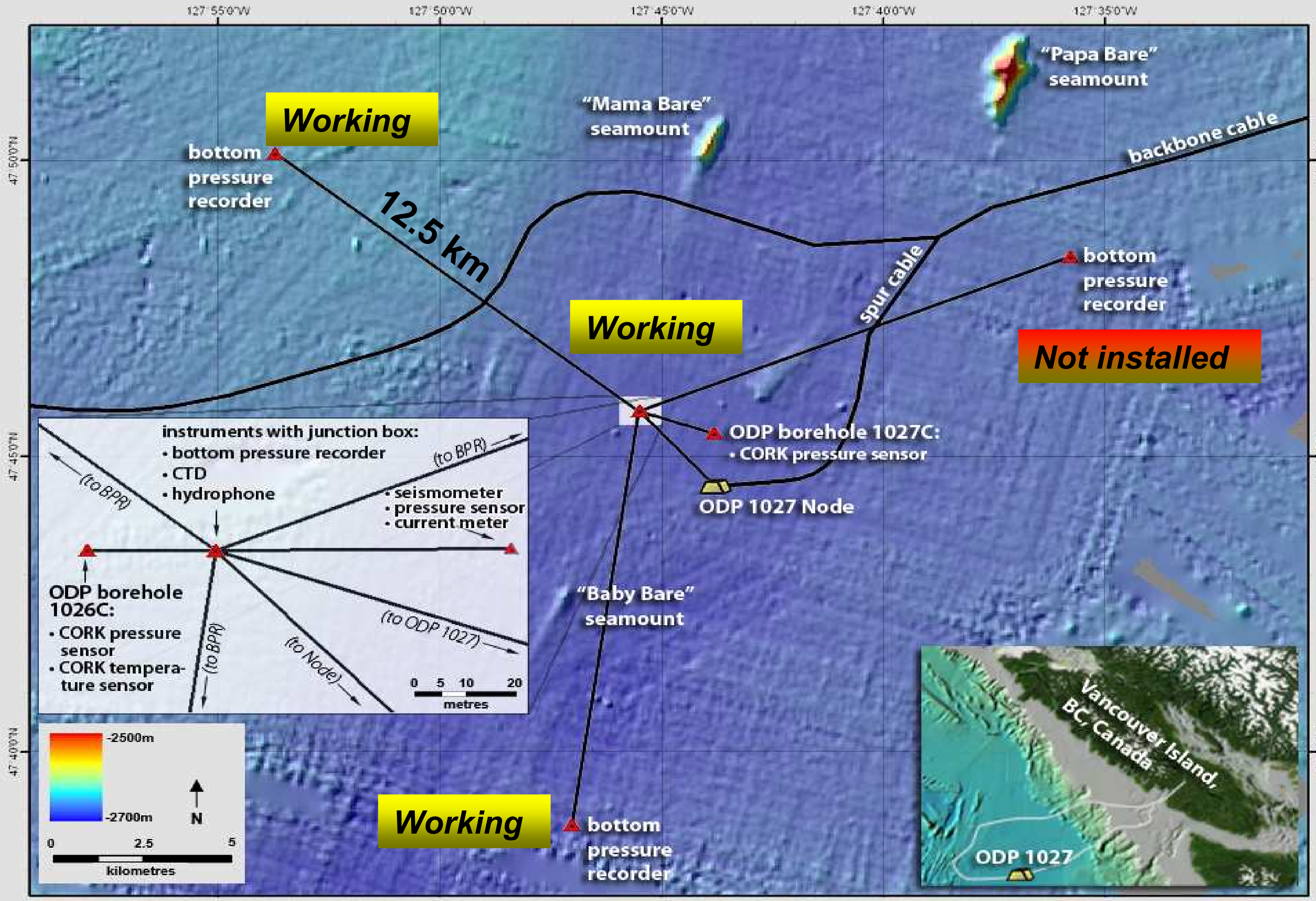
- University of Victoria
- University of Toronto
- IOS (DFO)
- ….
- ….

www.neptunecanada.ca

NEPTUNE-Canada Tsunami Array of Bottom Pressure Recorders (BPRs)



The Tsunami High Resolution Array: September 2009



Proposed system layout for ODP 1027, October, 2008

Basemap: U of Bremen S)111/1492006; Overlays: NEPTUNE Canada

NEPTUNE recorded tsunamis: 2009-2011

Location	*Date*	*Magni-tude*	*BPR Sites*					
			1027-S	*CORK*	*1027-NW*	*889*	*BC*	*FP*
Samoa	*29 Sept 2009*	*8.1*	√	√	√	√	√	√
Vanuatu	*7 October 2009*	*7.8*	√	√	√	√	√	√
Chile	*27 Feb 2010*	*8.9*	√	√	-	√	√	-
Bonin Islands	*21 Dec 2010*	*7.4*	-	√	-	√	√	√
Honshu (Japan)	*9 March 2011*	*7.2*	-	√	-	√	√	√
Tohoku (Japan)	*11 March 2011*	*9.0*	-	√	-	√	√	√

√ **Crest first** √ Trough first

NEPTUNE TSUNAMIMETER

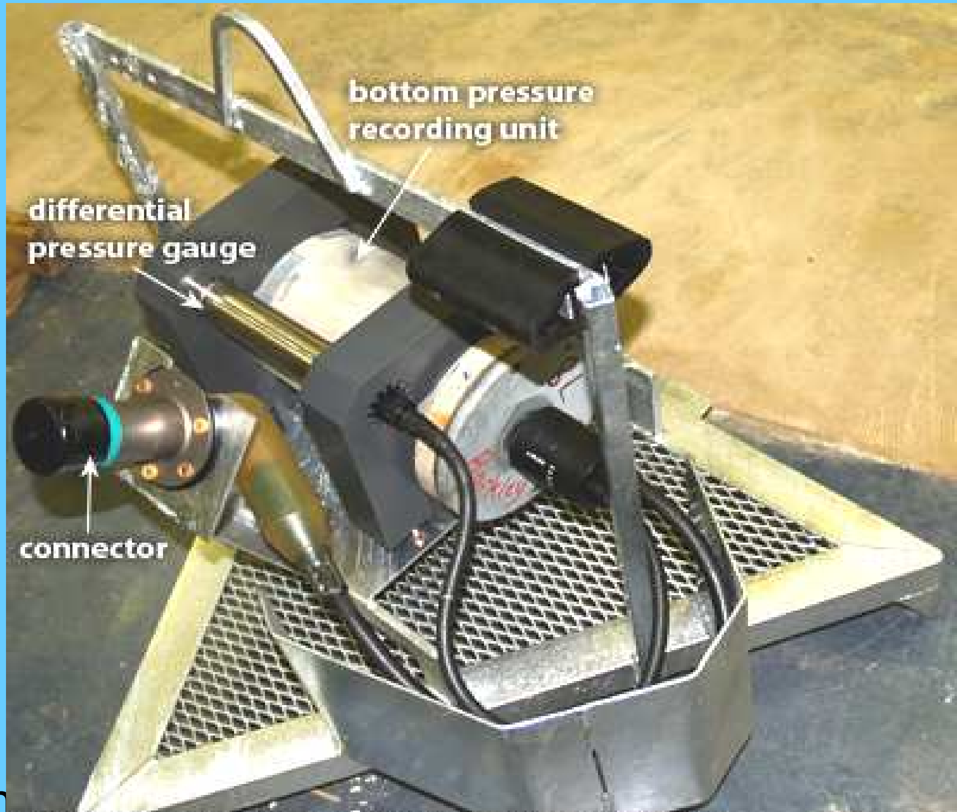
3 BPR array in 2600m surrounding the BPR at ODP Borehole 1026; the NE leg not deployed.

ODP 889: 1260m

Barkley Upper Slope: 400m

Folger Deep: 100m

Failed: Folger 27-Nov; NW 21-Feb



Barkley Canyon Bottom Pressure Recorder (BPR) with differential pressure gauge and platform

BPR (Bottom Pressure Recorders)

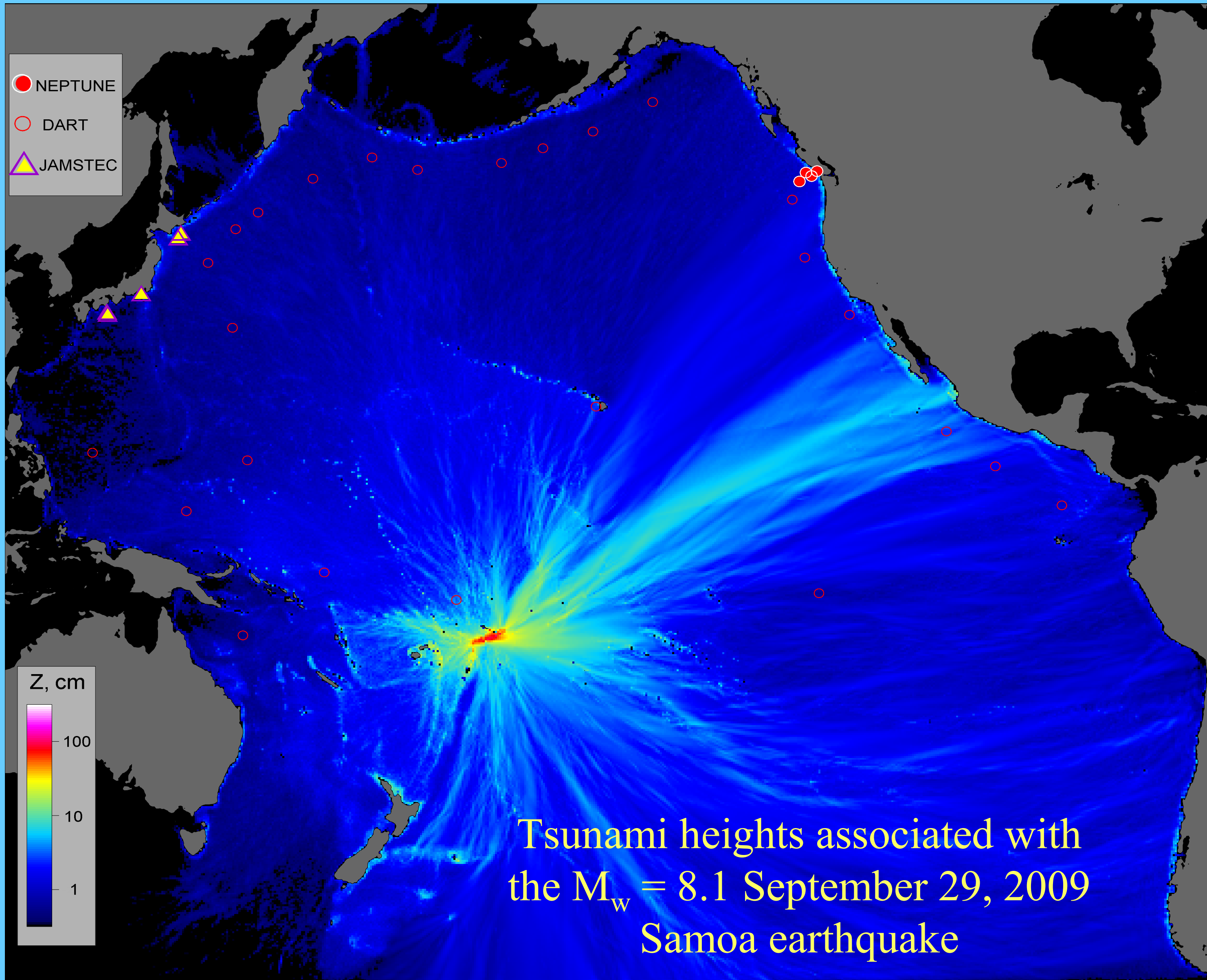
PGC in collaboration with Bennest Enterprises developed a novel way to process data from Paroscientific Digiquartz pressure sensors substan enhancing pressure resolution.

This, along with the Cabled observatory enabled high temporal resolution gives us an unprecedented look at both seismic and oceanic waves in real-time

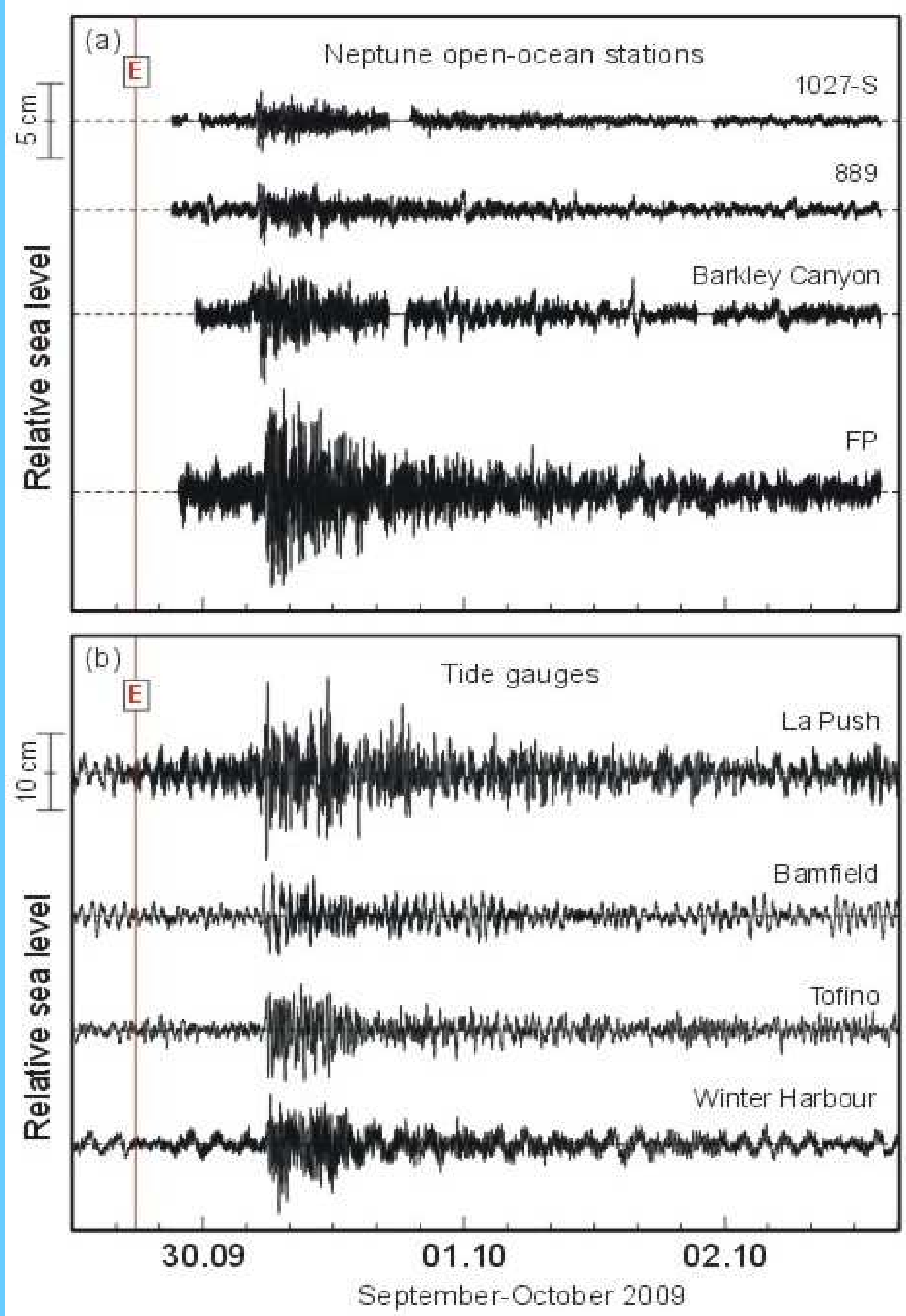
1 sec sampling, 0.4Pascal (~0.04mm ocean depth), 5microK.

DART: 15min -> 15s acoustic modem-> satellite

On September 29, 2009 tsunami waves were generated by the major (Mw = 8.1) earthquake at 17:48:10 UTC 2009 near the Samoa Islands

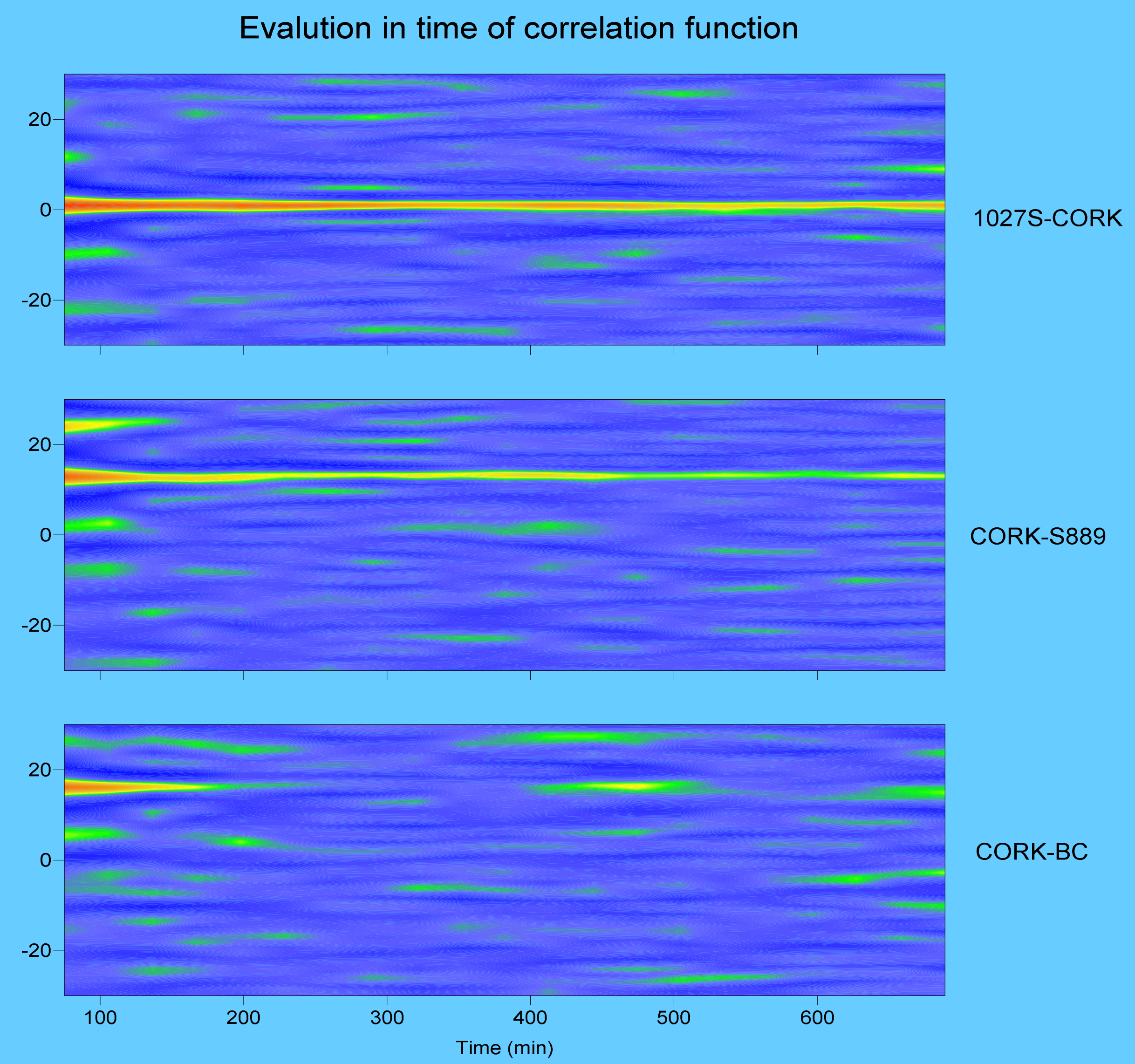


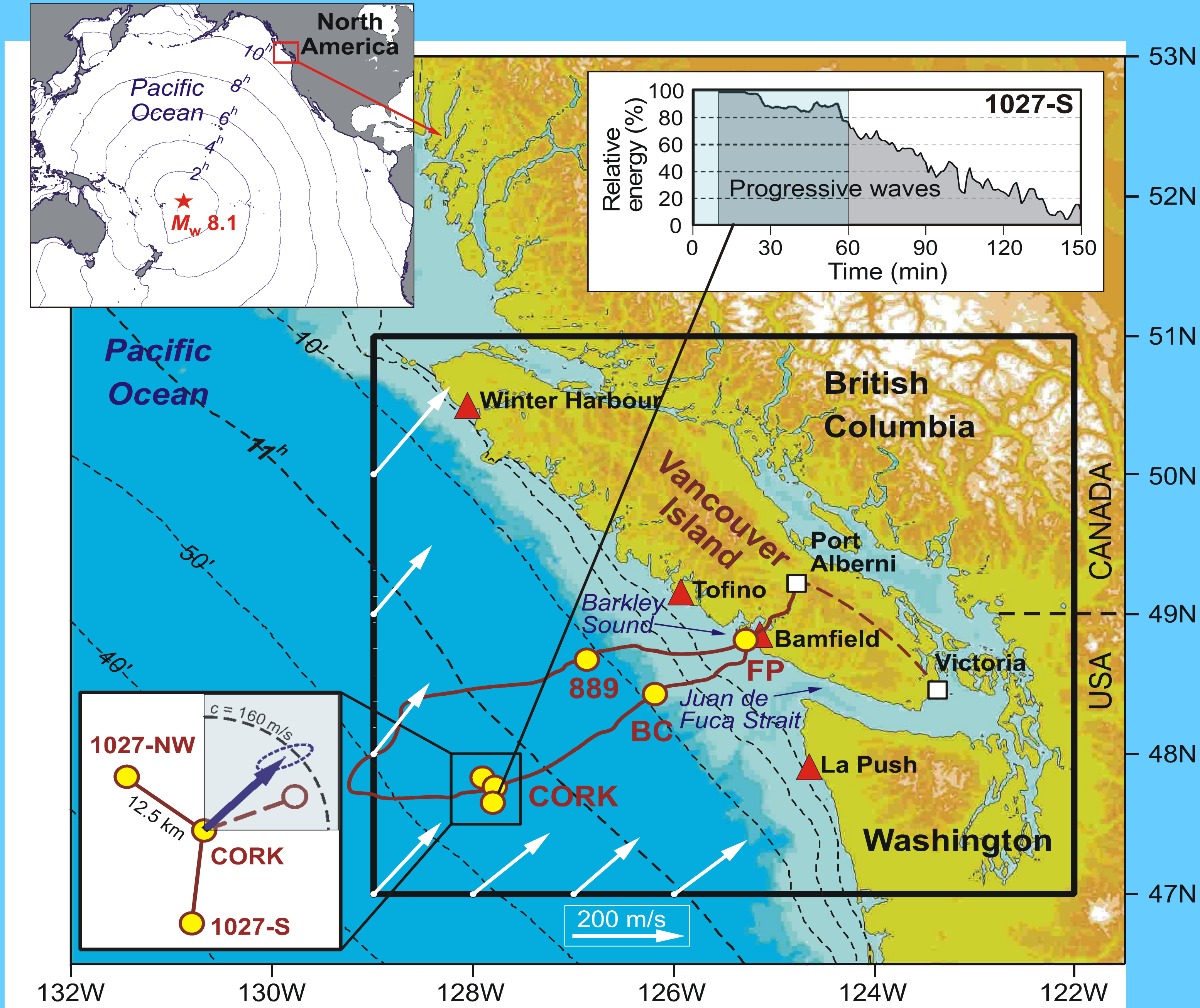
- As part of the NEPTUNE-Canada cabled seafloor observatory, an array of six high-precision bottom pressure recorders was installed in the late summer of 2009 at depths from 100 to 2600 m seaward of the southwest coast of Vancouver Island in the northeast Pacific. On September 30, 2009, the array recorded waves of 2.5 to 6 cm amplitude associated with the transoceanic tsunami



Data processing

- Surprisingly, waves continue arrive to the shore at least in 10 hours. Correlation between outer (CORK) station and slope (889 BPR) station shows only waves which are going to the shore and absolutely no reflected waves





North America
Pacific Ocean
10h
8h
6h
4h
2h
M_w 8.1
1027-S
Relative energy (%)
Progressive waves
Time (min)
0
30
60
90
120
150
100
80
60
40
20
0
Pacific Ocean
10′
11h
50′
40′
Winter Harbour
British Columbia
Vancouver Island
Port Alberni
Tofino
Barkley Sound
Bamfield
FP
Victoria
889
BC
Juan de Fuca Strait
La Push
CORK
Washington
CANADA
USA
1027-NW
c = 160 m/s
12.5 km
CORK
1027-S
200 m/s
53N
52N
51N
50N
49N
48N
47N
132W
130W
128W
126W
124W
122W

Basic of the regional tsunami modeling

- Waves in the region are forced by incoming plane wave through the open boundary
- Reflected waves at outer station are small so the incoming waves have the same parameters as recorded on the outer station
- To force the model we need the direction of the waves and time series at outer station

Boundary conditions

$$\zeta = \zeta_{in} + \zeta_{out}$$

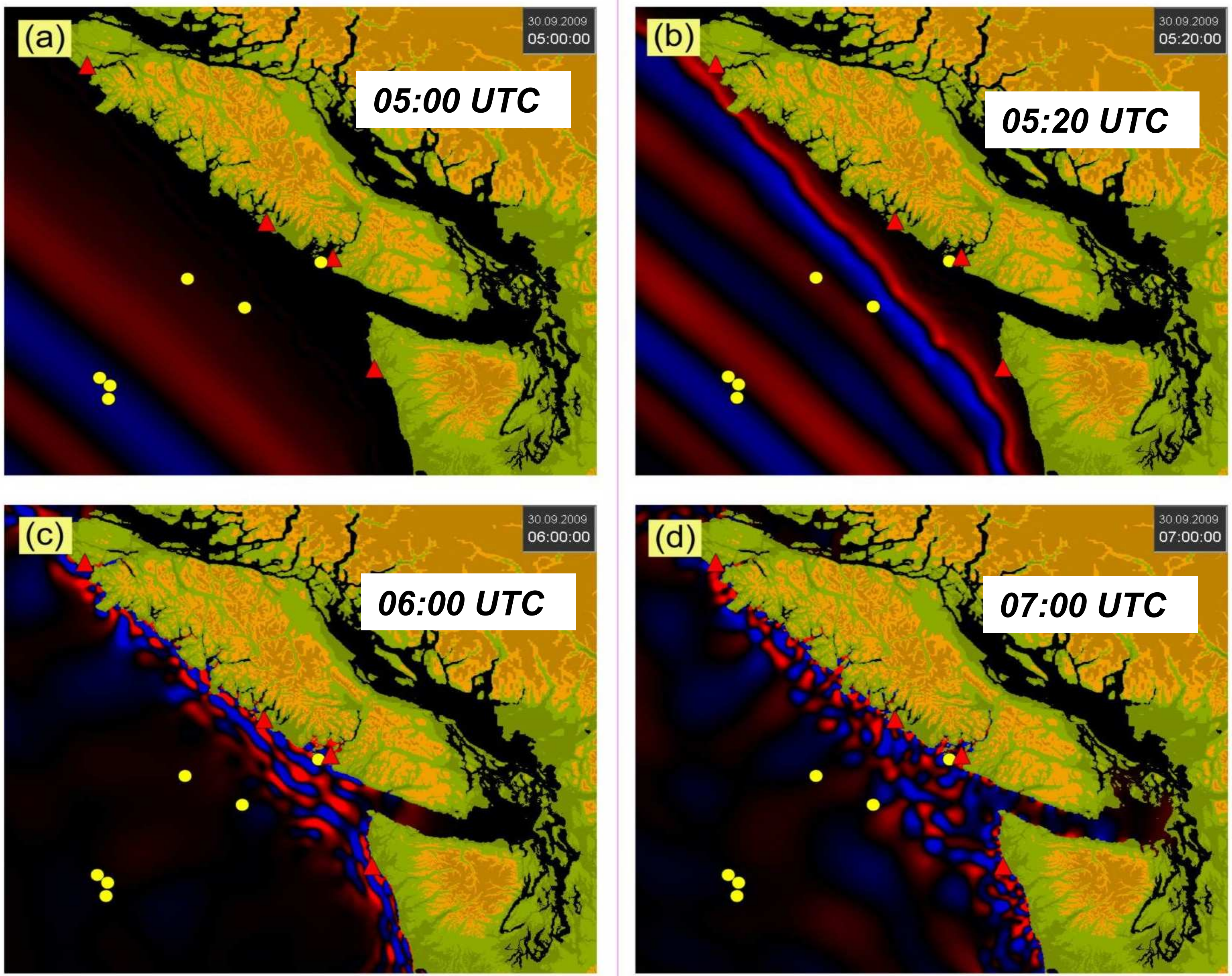
ζ_{in} is a prescribed function equal to the record at most remote station

$$\zeta_{in} = f(t - \mathbf{d} \cdot \mathbf{r})$$

d is “slowness” vector,

$$|\mathbf{d}| = c^{-1} = (gh)^{-1/2}$$

$$\frac{\partial \zeta_{out}}{\partial n} = \frac{1}{c} \frac{\partial \zeta_{out}}{\partial t}$$



IOS regional tsunami model and recording sites

30 September 2009

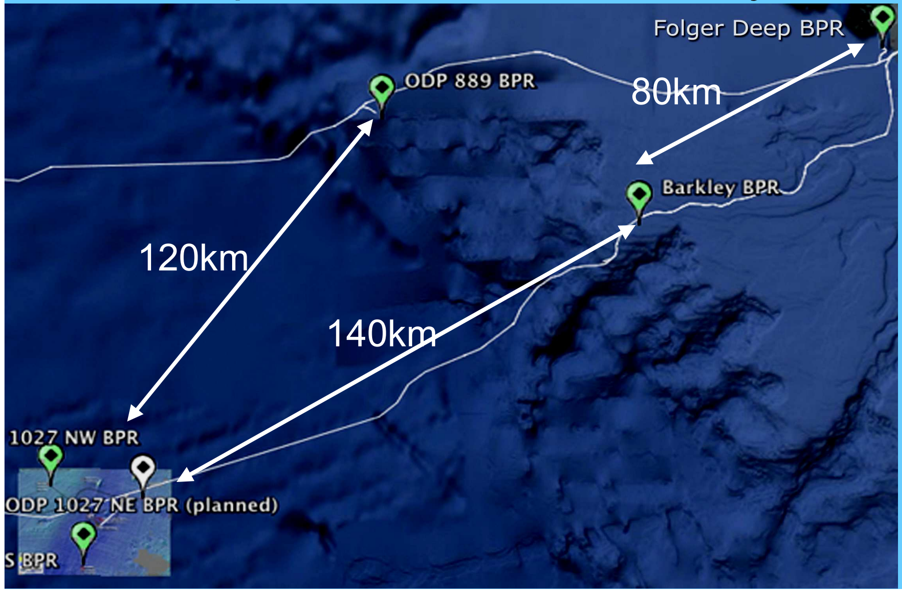
30.09.2009
04:10:00

Regional Tsunami Numerical Model

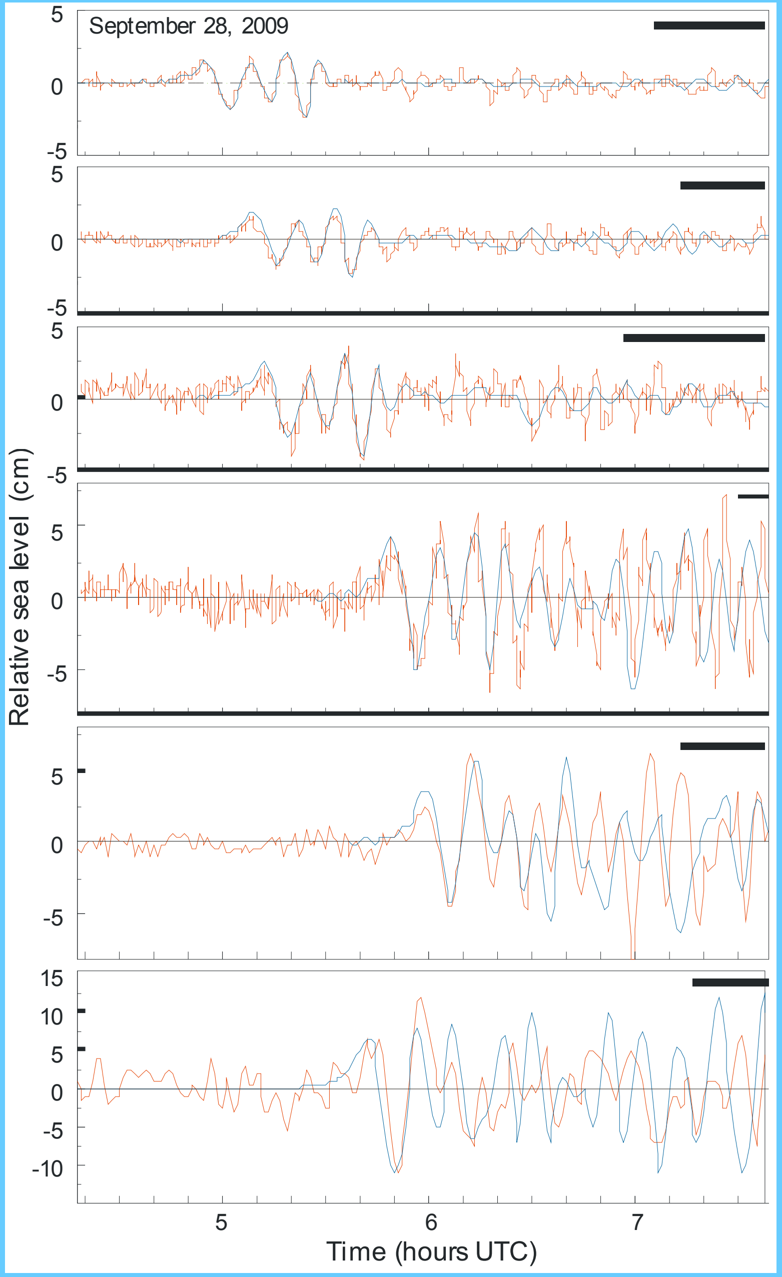
•Driven by the BPR tsunami data; model initialized using the first observed tsunami waves transposed to the boundaries

•Comparison shows near perfect agreement between data and simulated records. Some differences on the onshore tide gage sites reflect quality of the bathymetry

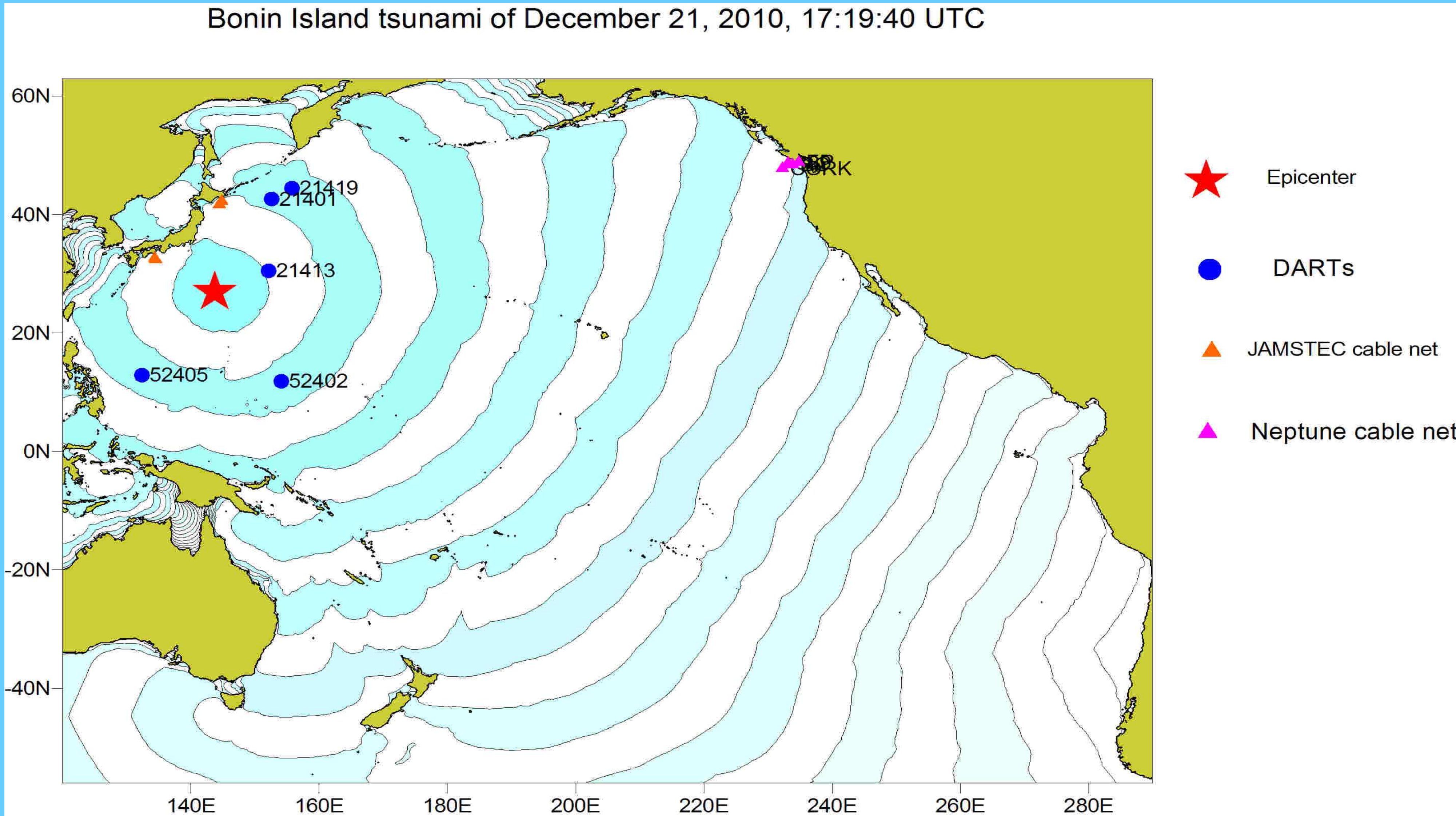
Neptune-Canada BPR array



Comparison between observations and model



Bonin Island 2010 tsunami

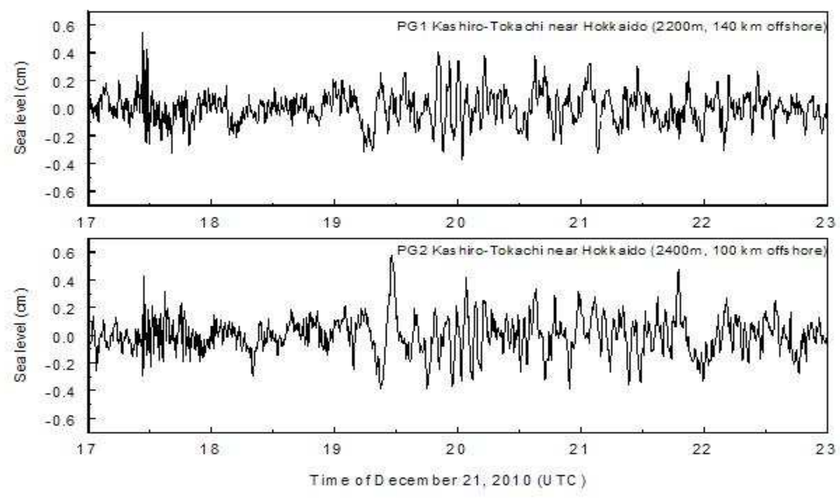


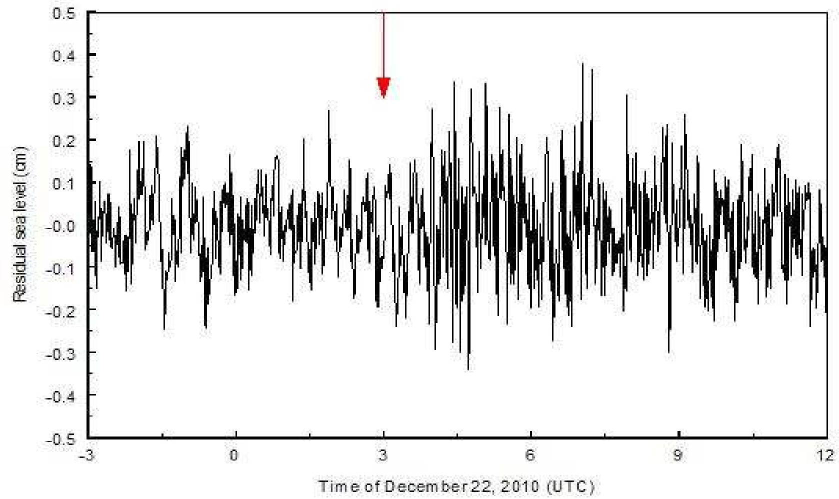
Amplitude of waves was about 1 cm at nearest DART 21413 station.

At Hokkaido cable BPR amplitude was about 0.6 cm

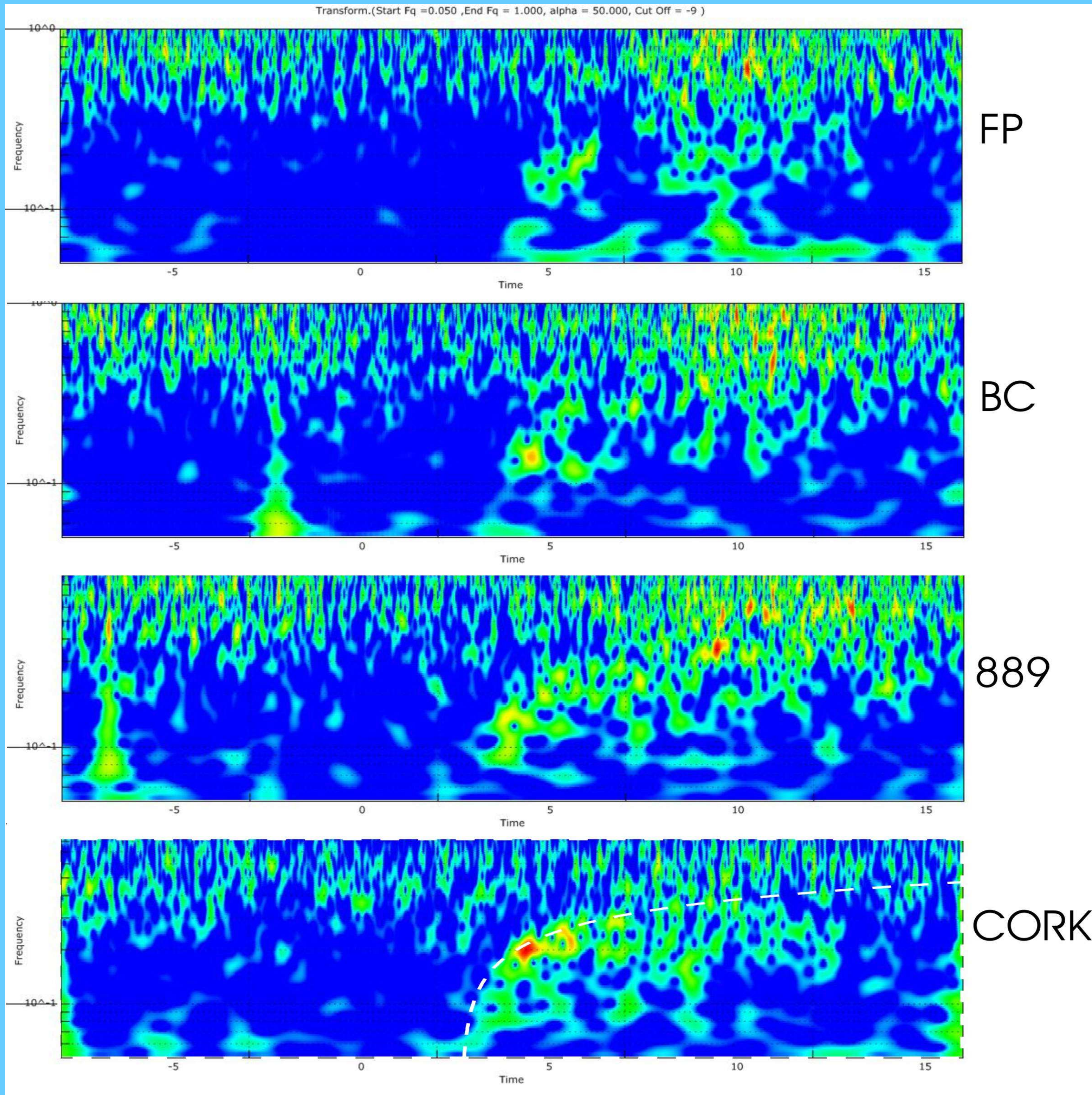
Is the CORK record shows tsunami?

CORK location is ~6 thousand km away…

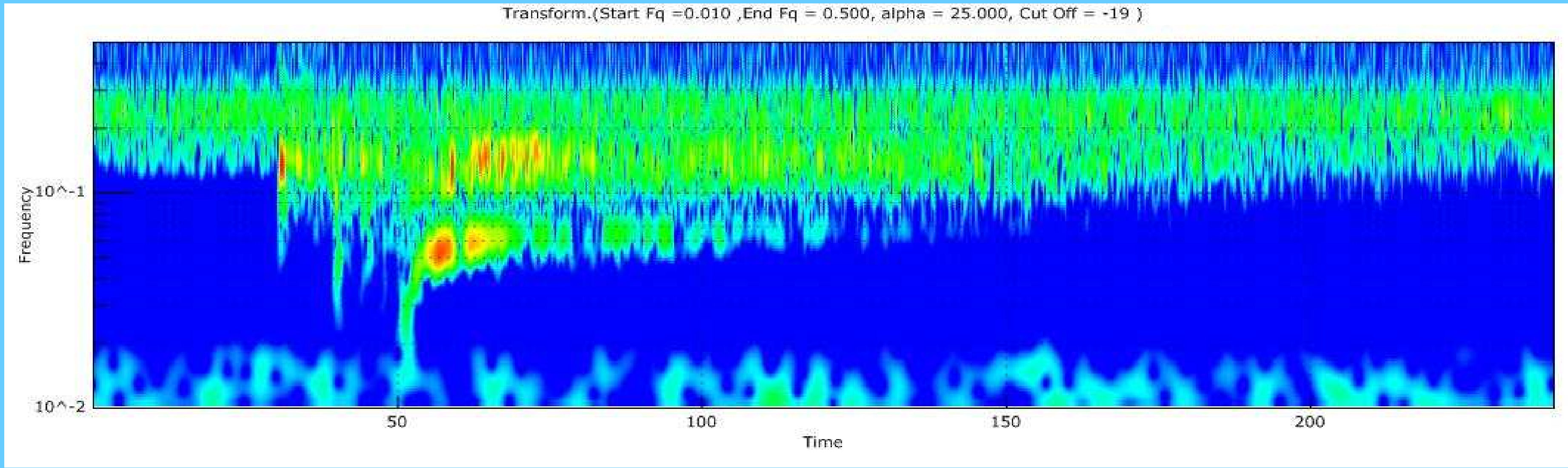




- F-t (wavelet) diagram confirms it is a tsunami record!
- Low picture shows theoretical arriving time for the dispersive waves



High frequency measurements



- If we go to the higher frequencies, we also can see arriving waves. It is not sea waves but seismic waves (Rayleigh and P-waves)

- Here is a simplify theory how bottom pressure will react to the vertical bottom movement.
- Let the sea bottom oscillated with amplitude *b* and angular frequency *w*:

$$z(t) = b\sin(\omega t + \varphi)$$

- The acceleration of the sea bottom is

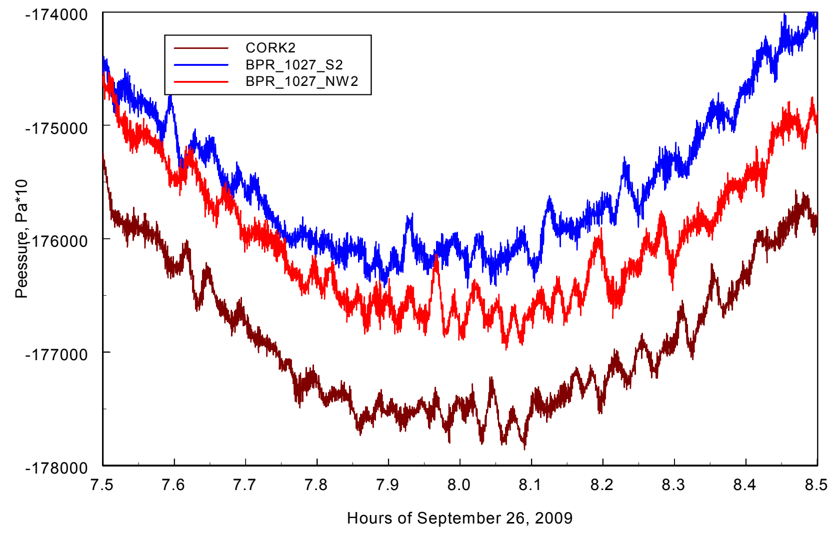
$$a(t) = \frac{d^2 z}{dt^2} = -b\omega^2 \sin(\omega t + \varphi)$$

- Bottom pressure at steady sea bottom is

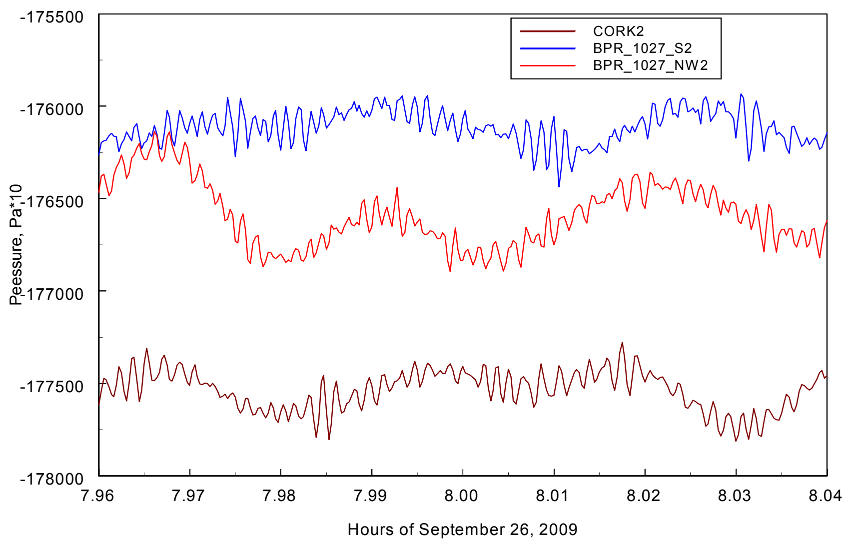
$$p = \rho(g + a(t))h = p_0 - \rho h\omega^2 b\sin(\omega t + \varphi)$$

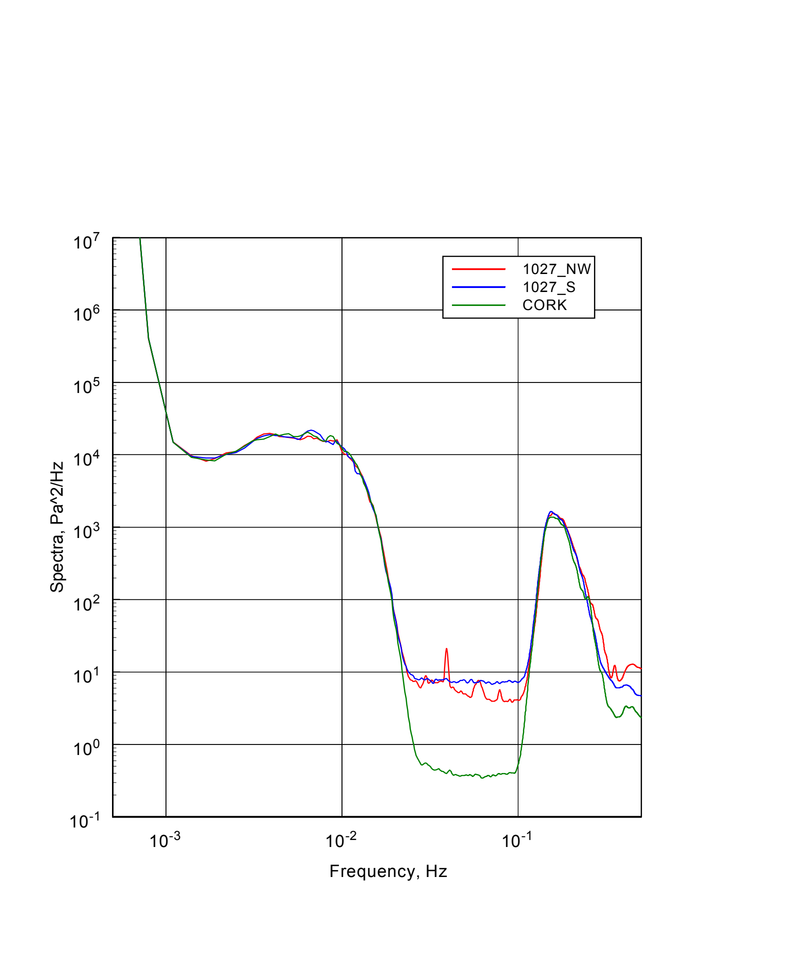
- If the water column moves as a whole body (the wave period is bigger than the double travelling time of the acoustic wave from the bottom to the sea surface). The entire water column in this case will move simultaneously with bottom, and the bottom pressure becomes:
- Thus, the amplitude of the bottom pressure oscillation is proportional to the water depth and square of the frequency.
- The typical wave speed of the Rayleigh wave is 3km/s, so, at period 7 sec Rayleigh wave will have a length about 20 km, accordingly, the depth in the formulas means some average (on the wavelength scale) depth. At steep slope as at sites ODP 889 and Barkley Canyon, we need some value of “effective” depth instead of the specific depth at the side. Taken into account such remarks, the spectral ration for the “DPR / ODP 889” ~6.7 (amplitude ratio 2.6) and “DPR / Canyon” is 9.7 (amplitude ration 3.1). So, “effective depth” for the station 889 will be 1040 m and for the Canyon station 870 m.

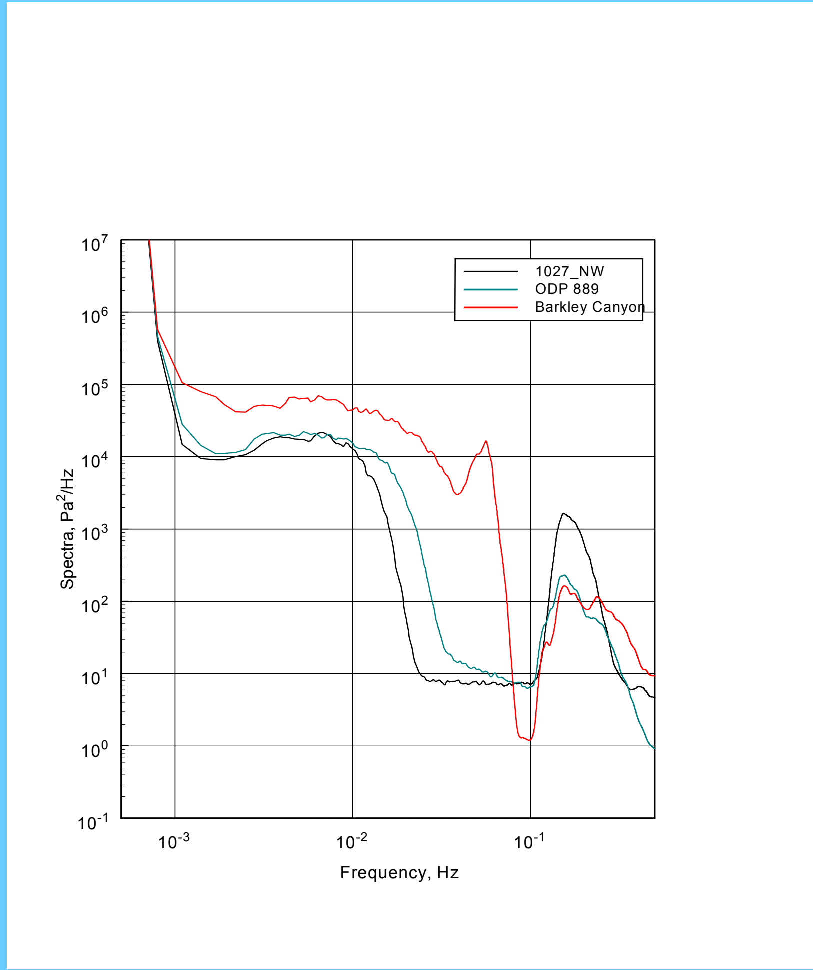
Records on the September , 26 at low tide. The vertical scale is 4 cm only



Part of high- frequency records. The vertical scale is 25 mm, so the typical 7-sec wave height is about 1 mm







- Waves at frequencies 0.001-0.015 Hz are infragravity waves, higher than 0.1Hz are microseimic activity

"Wave climate" – micriseismic activity is different in the Pacific, Atlantic and Arctic

- Webb, S. C. Broad seismology and noise under the ocean, *Rev. of Geophysics* 36, 105-142. 1998.

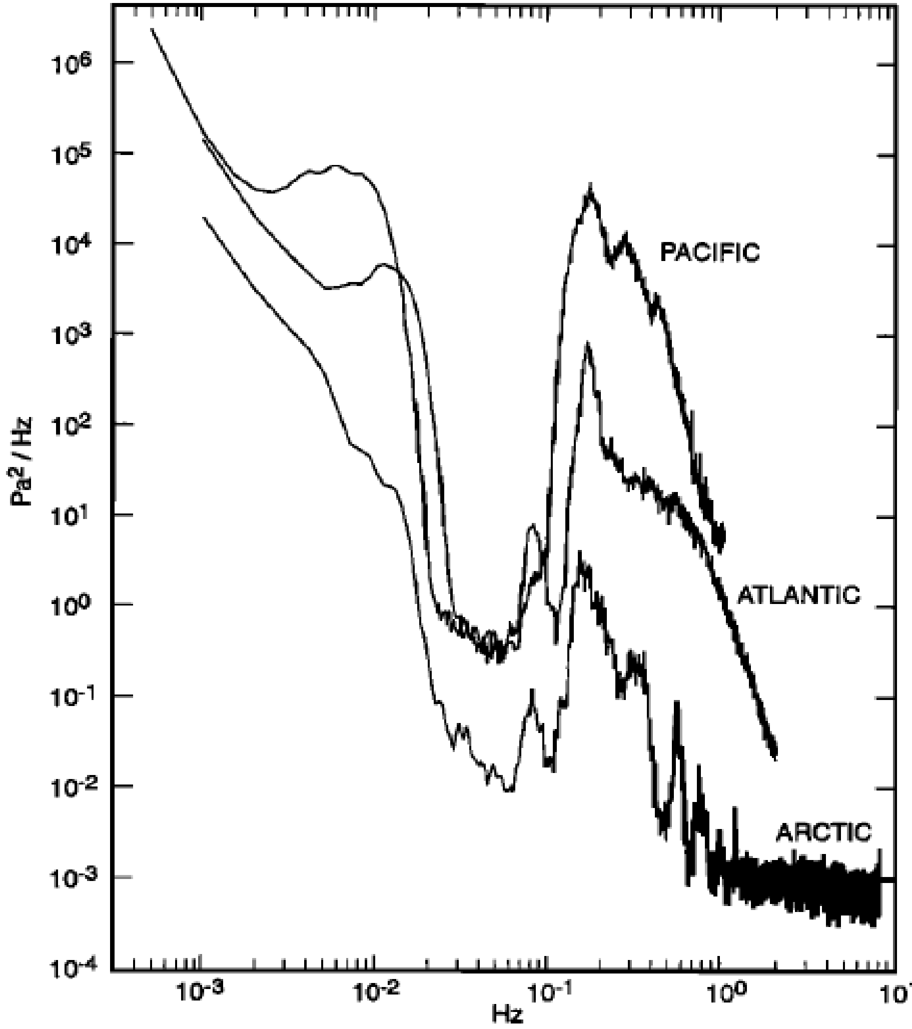
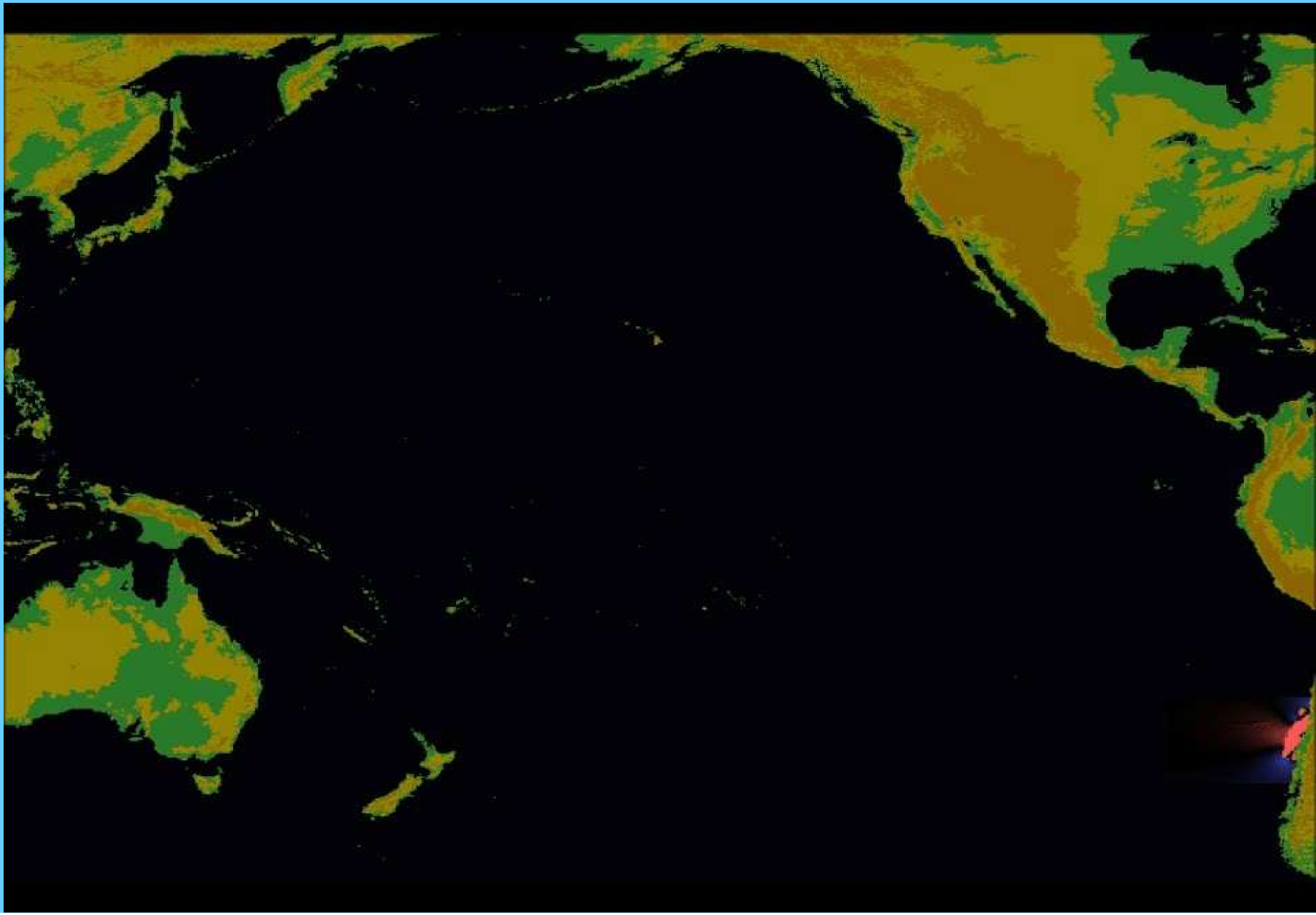
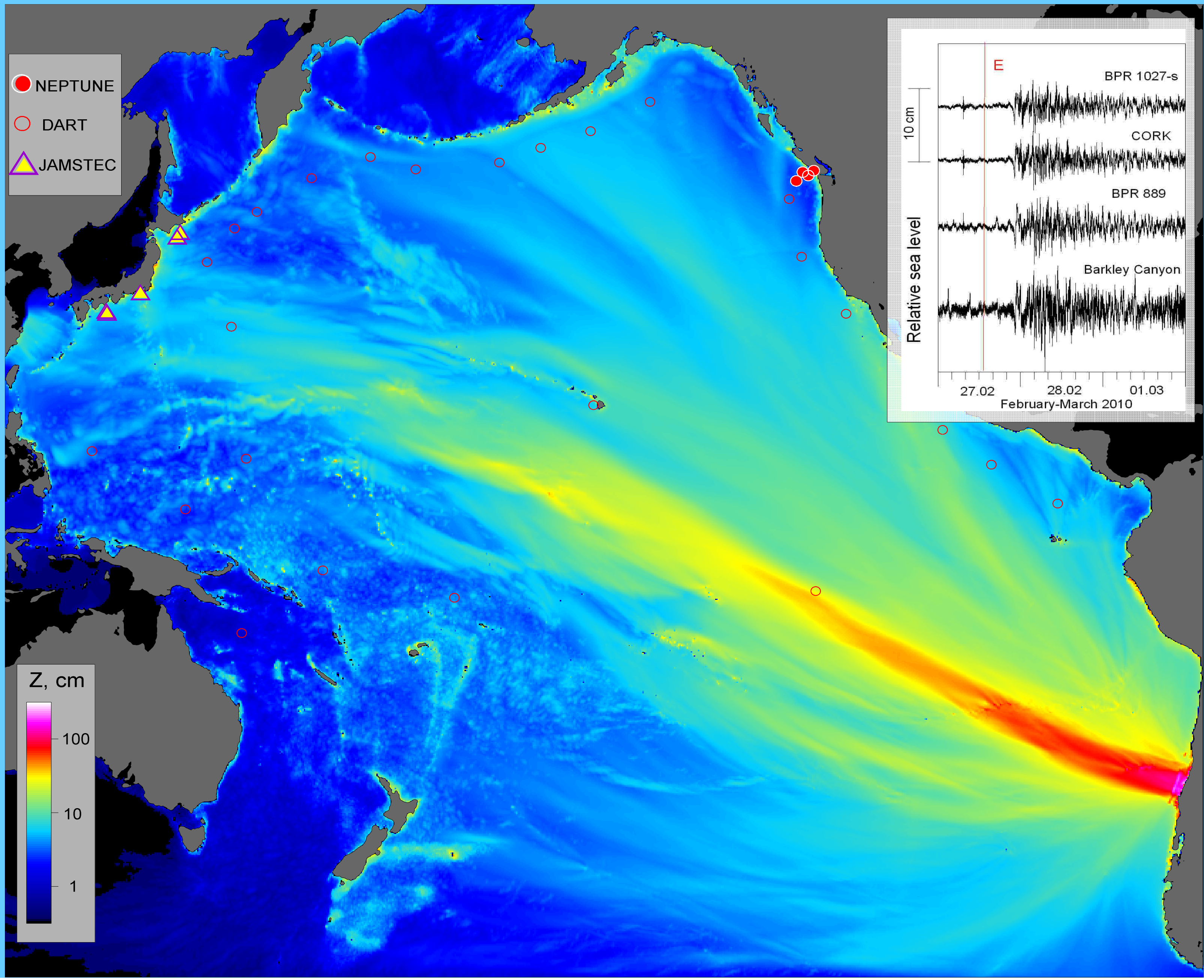


Figure 2. Pressure spectra from the seafloor from three oceans. Infragravity waves drive long-period pressure fluctuations below 0.03 Hz. The Arctic and Atlantic are quieter because of a quieter ocean wave climate.

Chilean 2010 tsunami

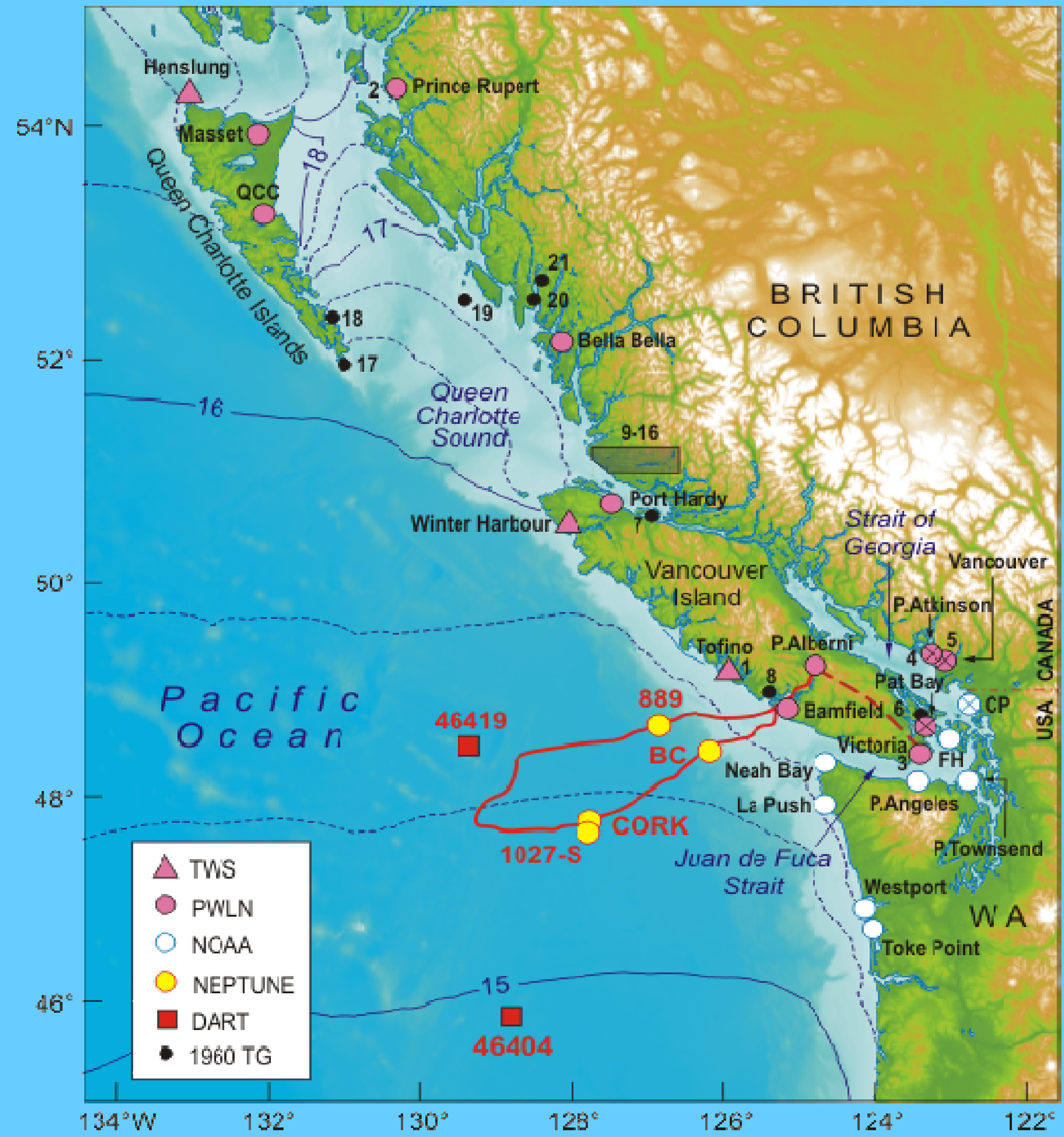


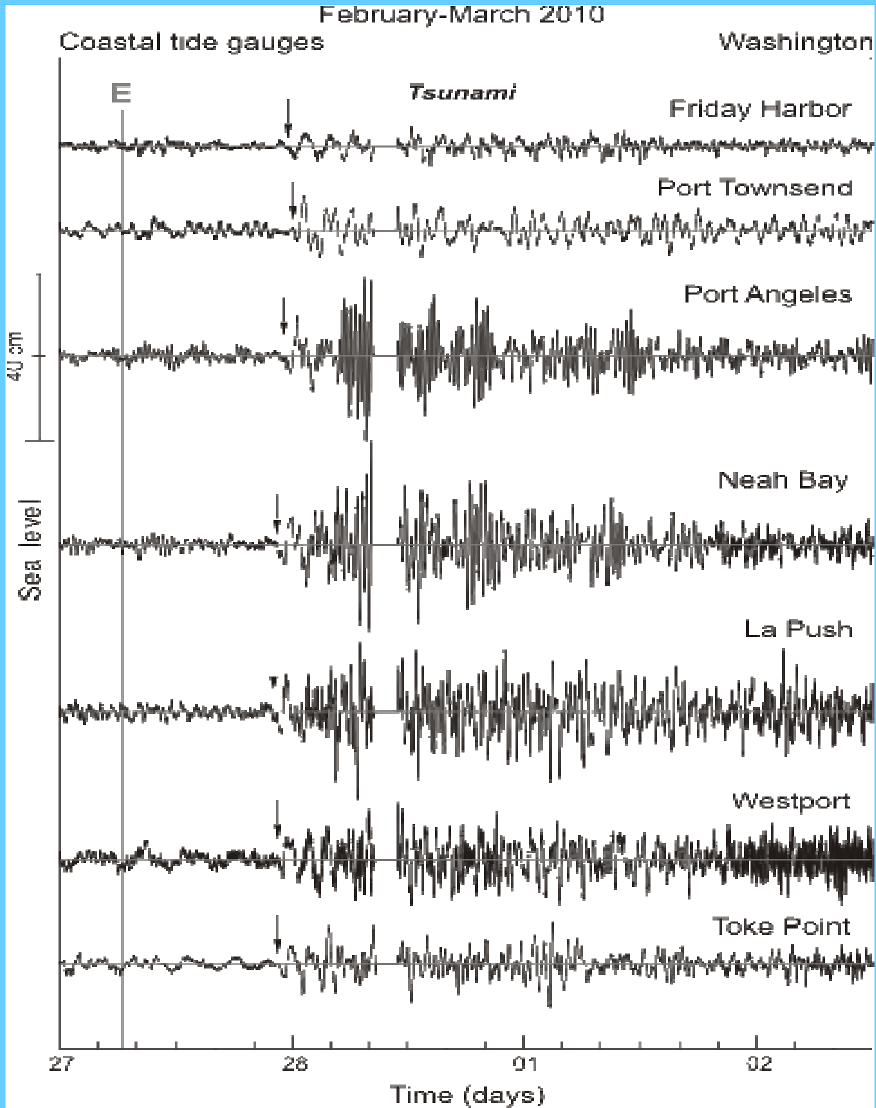
Chilean 2010 tsunami

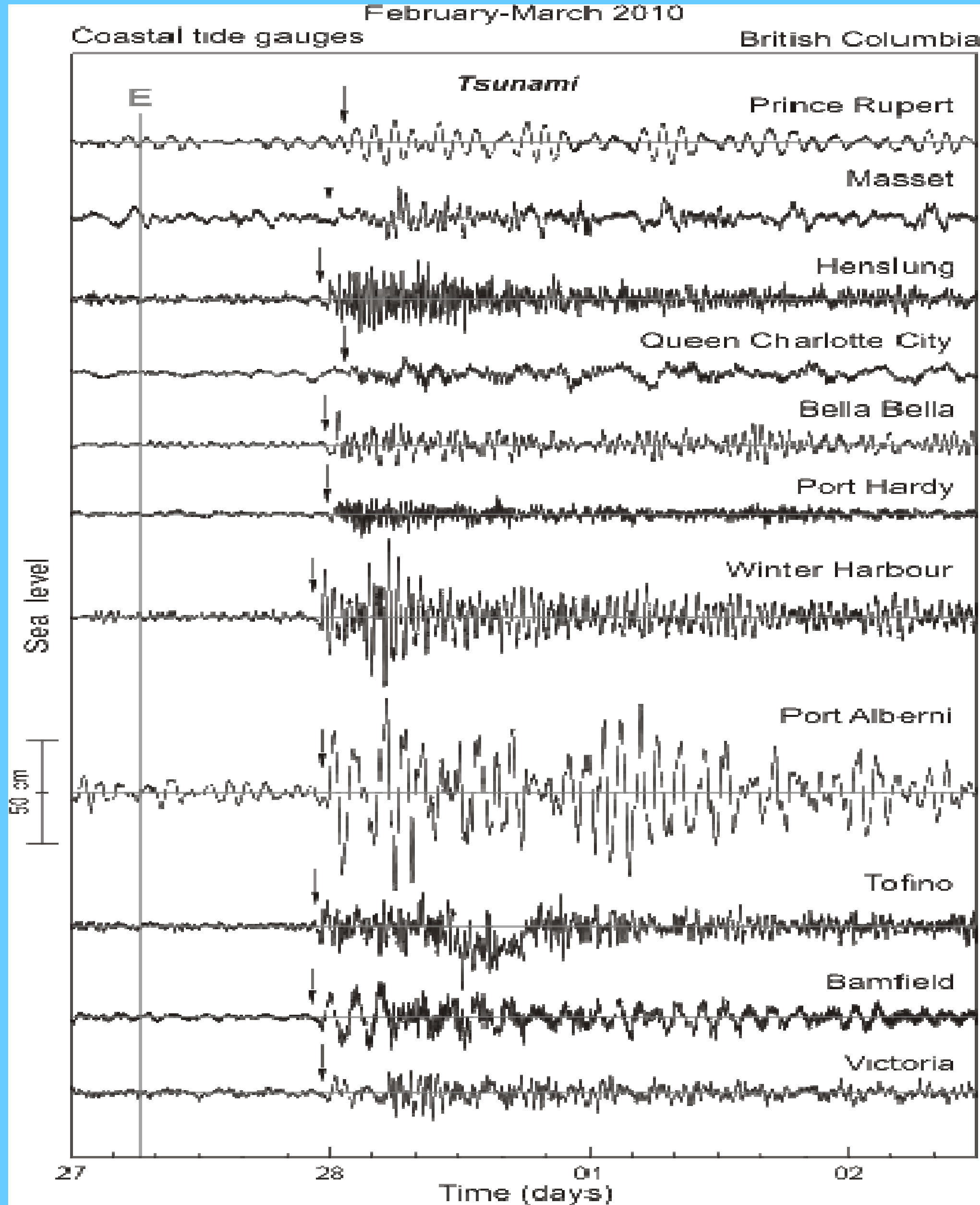


We used DARD 46404 and DART 46419 records as well as coastal TG to analyse Cilean tsunami at the British Columbia and Washington State coast

DART 46419 lost transmission but was recovered in May 2010.



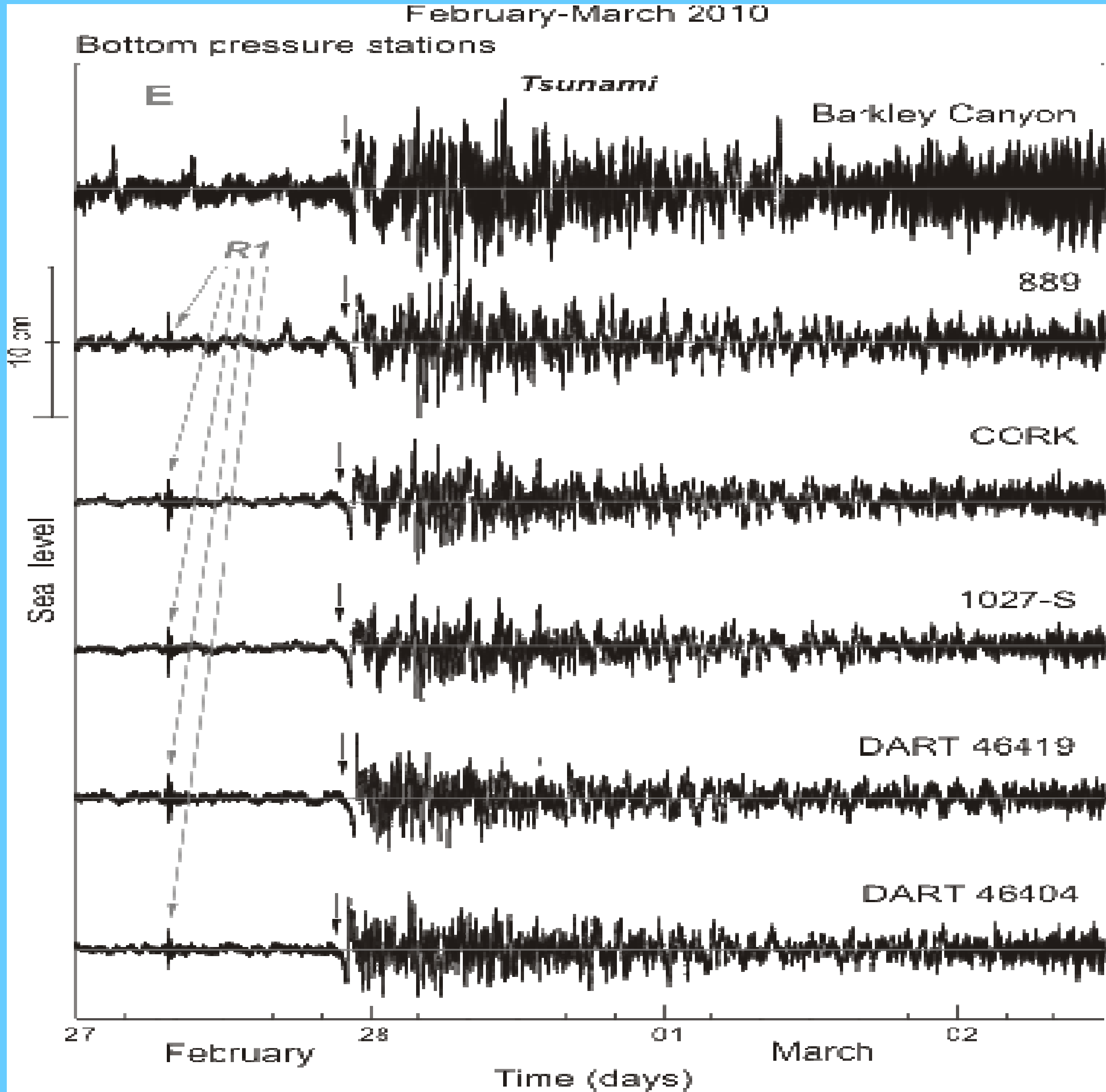




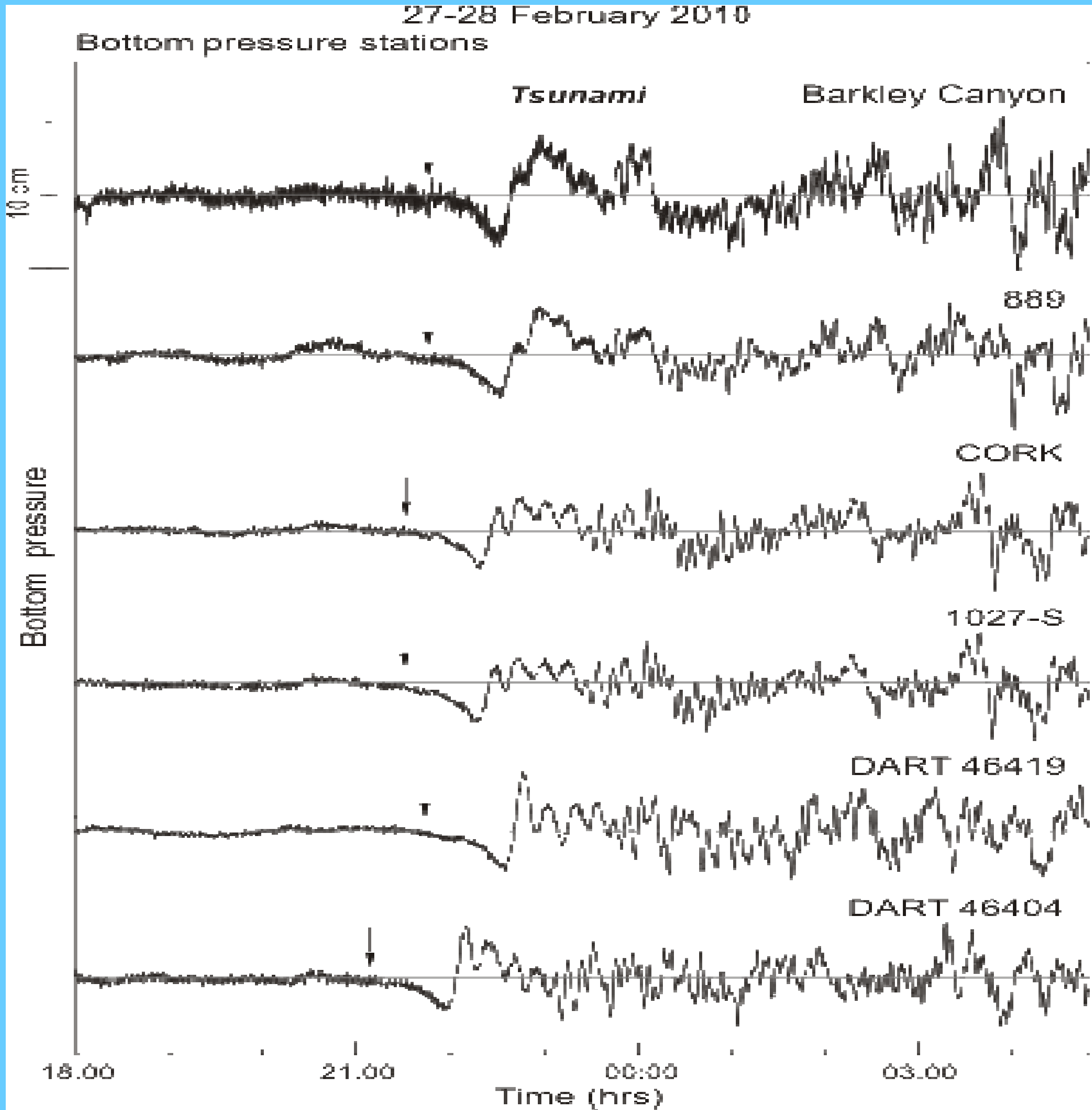
Tide gage records

All 4 NEPTUNE stations and DARTs show clear tsunami records. Increase in high frequency energy on March, 2 related to the local storm.

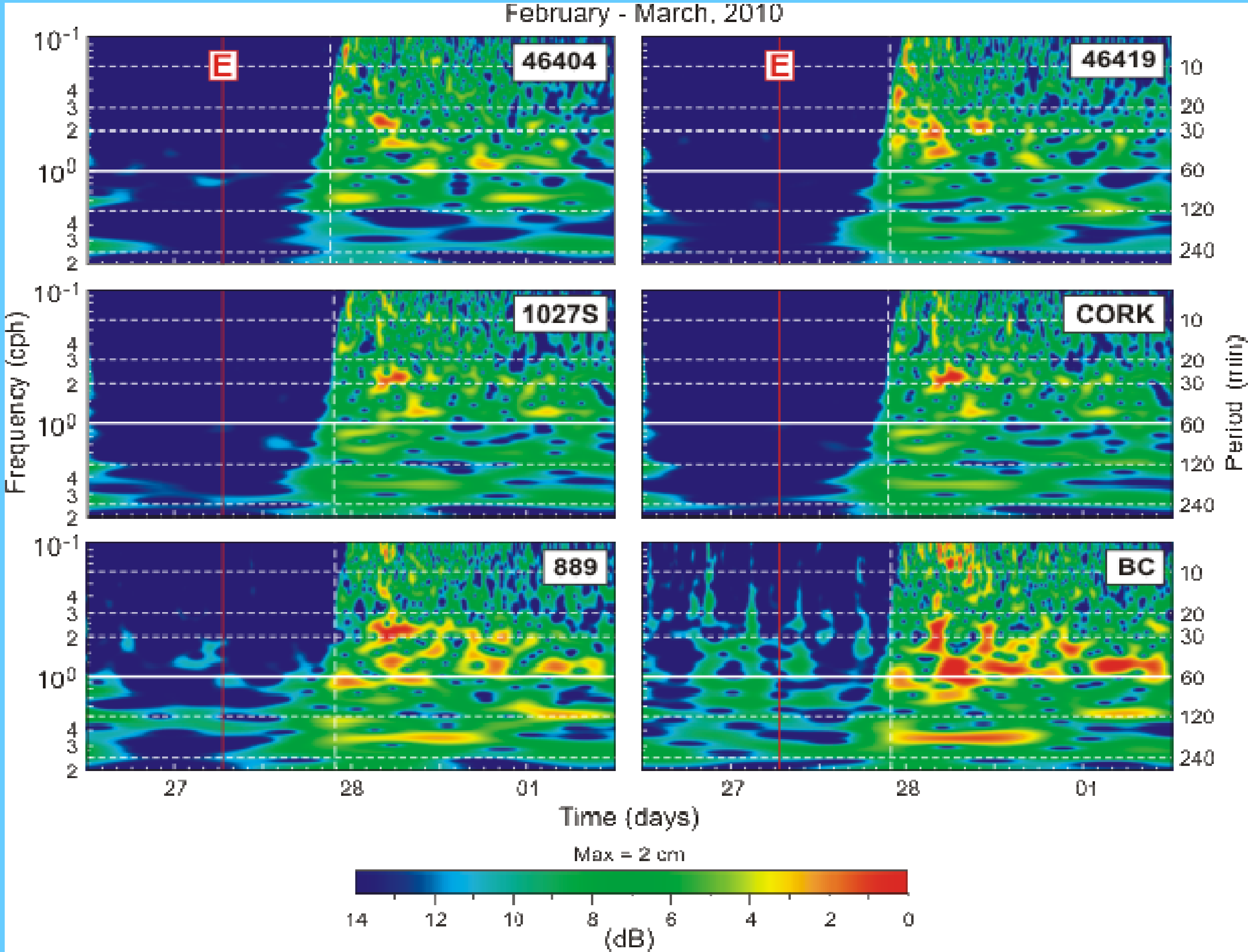
We also can see a seismic signal on deep stations

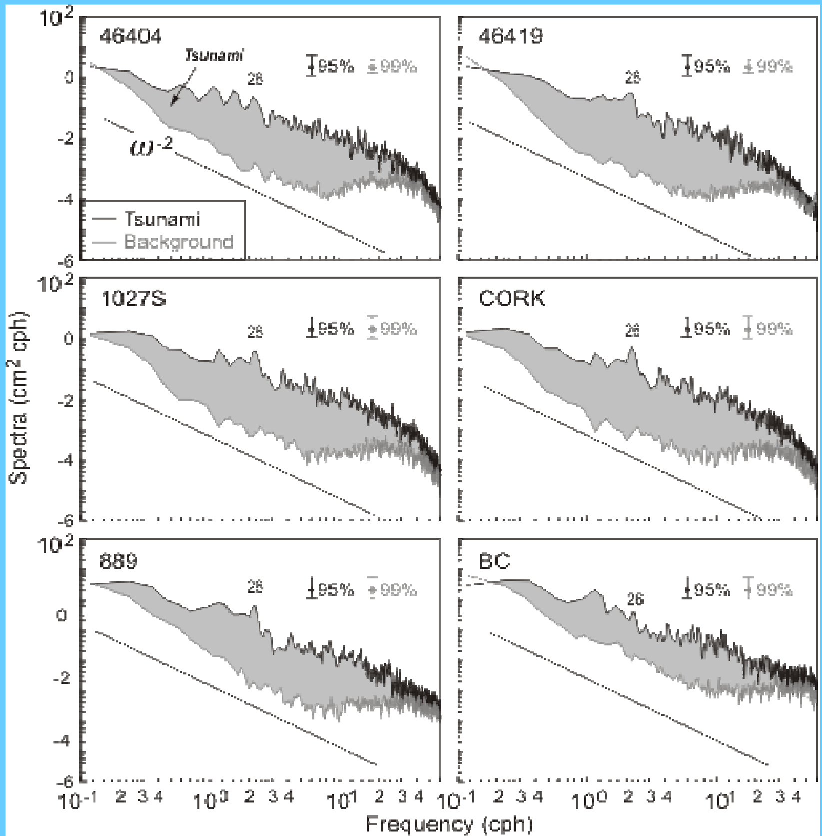


- Arrival time estimation is sometimes a problem. Result depends on the record resolution and threshold.
- Often tsunami start is a smooth change in sea level.

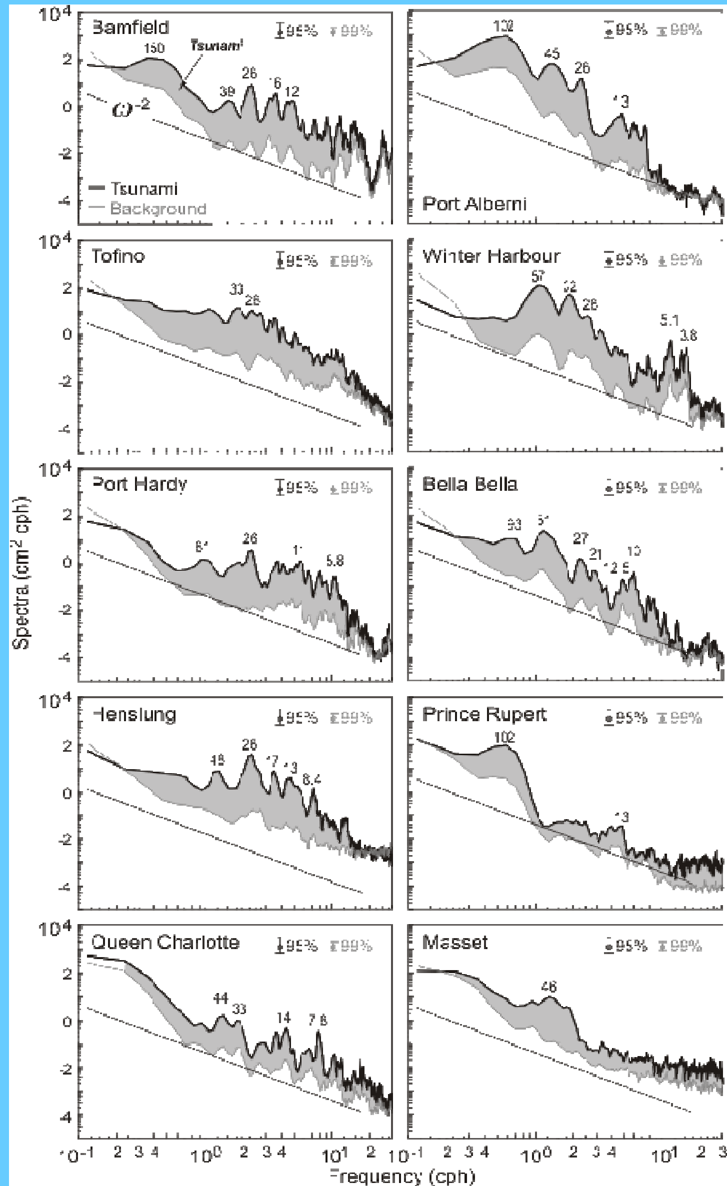


- F-t diagrams show that Chilean tsunami has a broad spectra

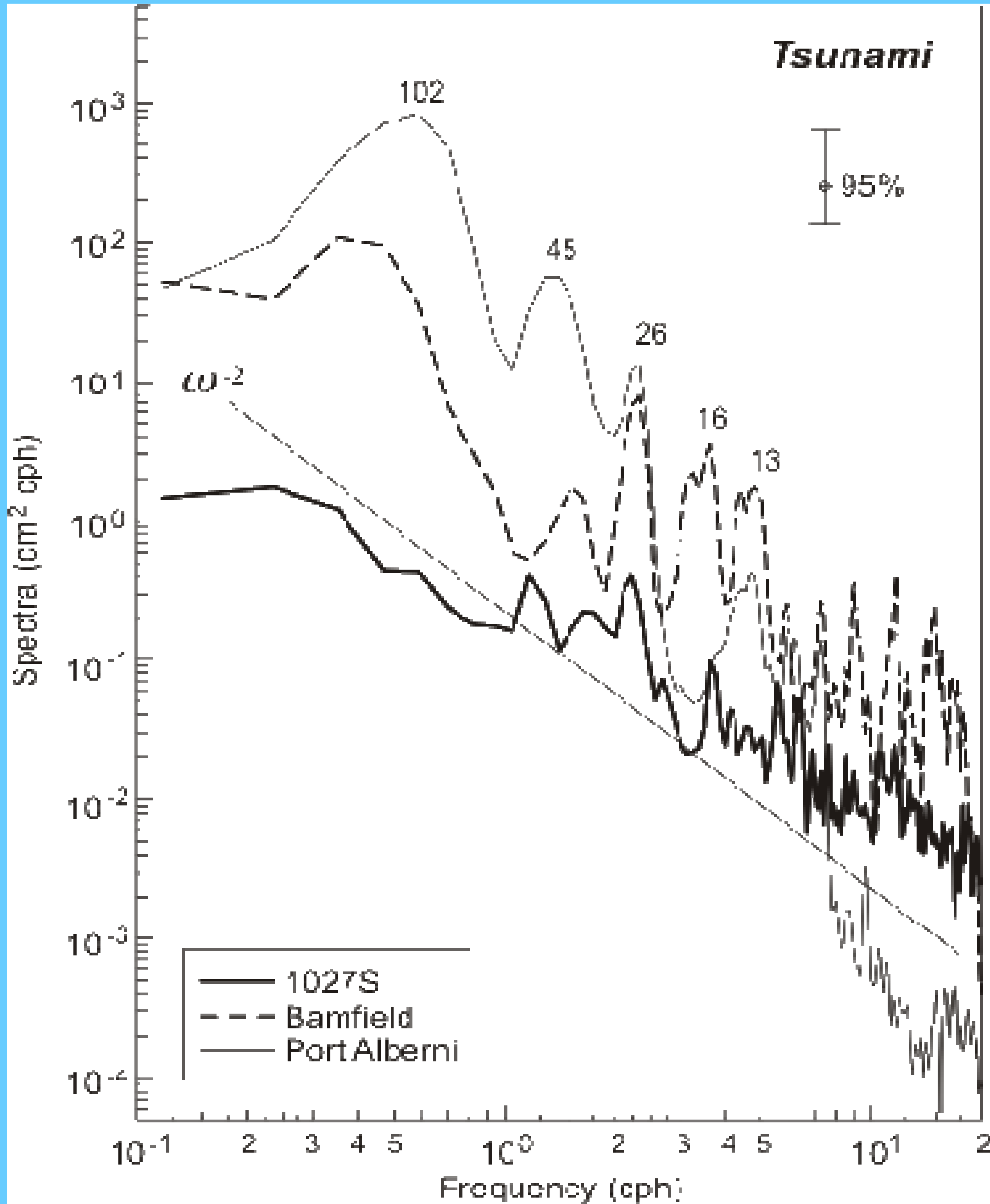


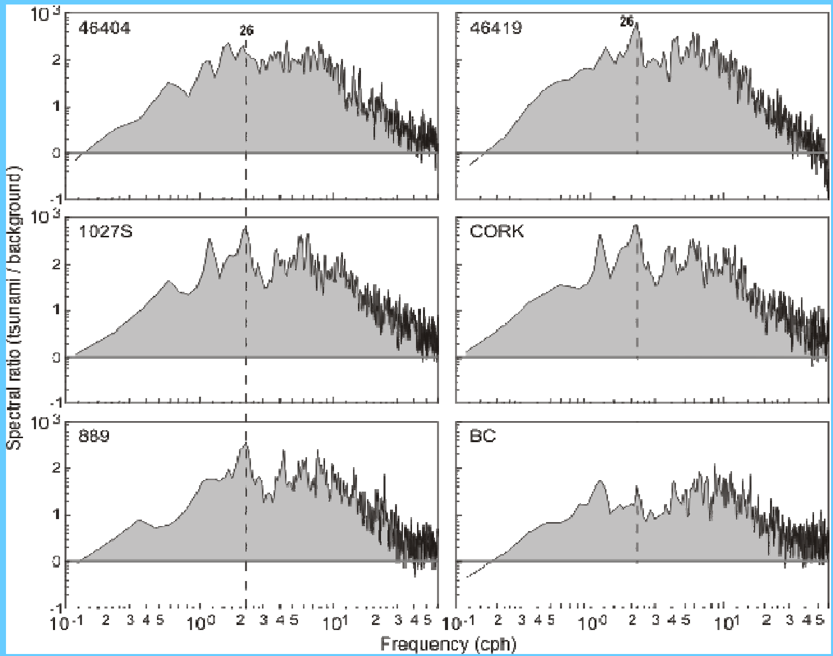


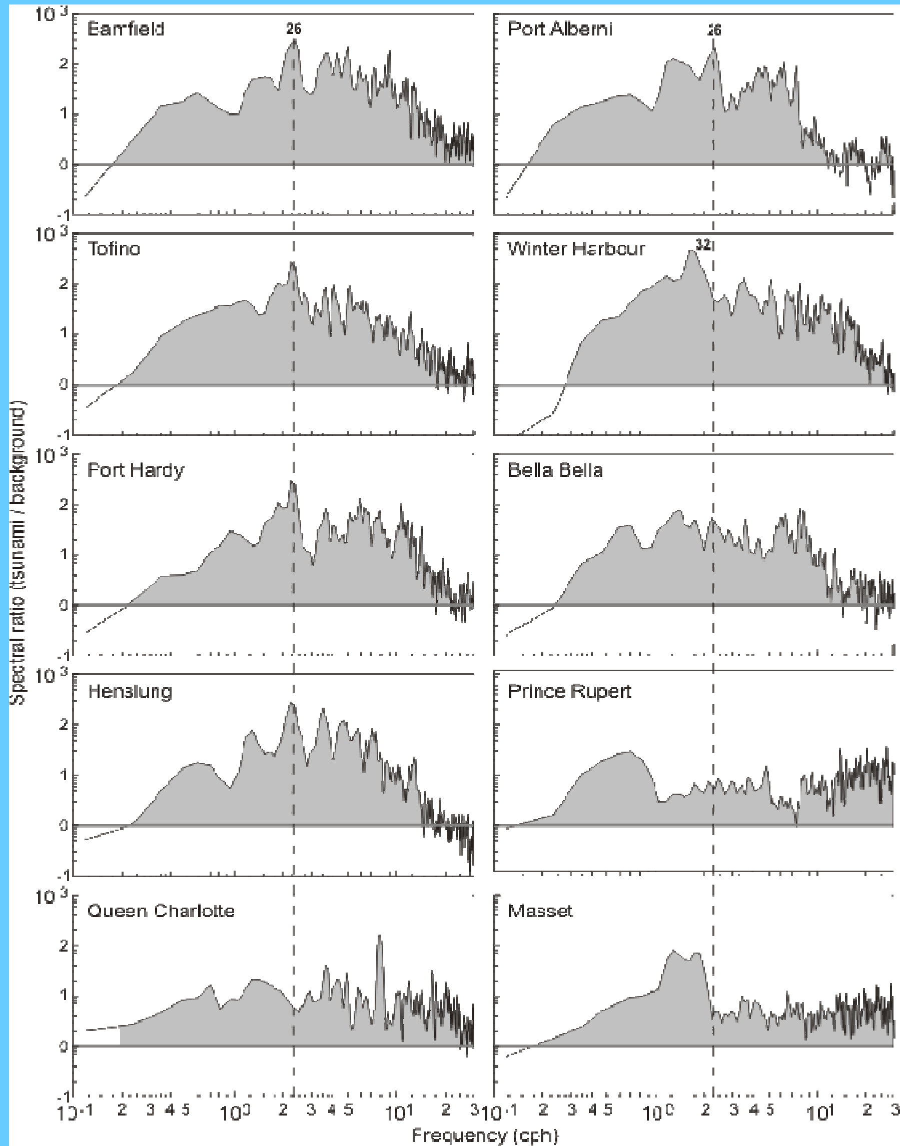
- Here are comparison tsunami spectra with background spectra at both deep water stations and some tide gages. Deep water spectra are smooth, background spectra show a broad maximum related to the infragravity waves



- Transformation tsunami spectra on the shelf and in Alberni Inlet.
- Inlet filters high frequency tsunami waves
- Eigen frequency of the fundamental mode of the Inlet is about 100 min

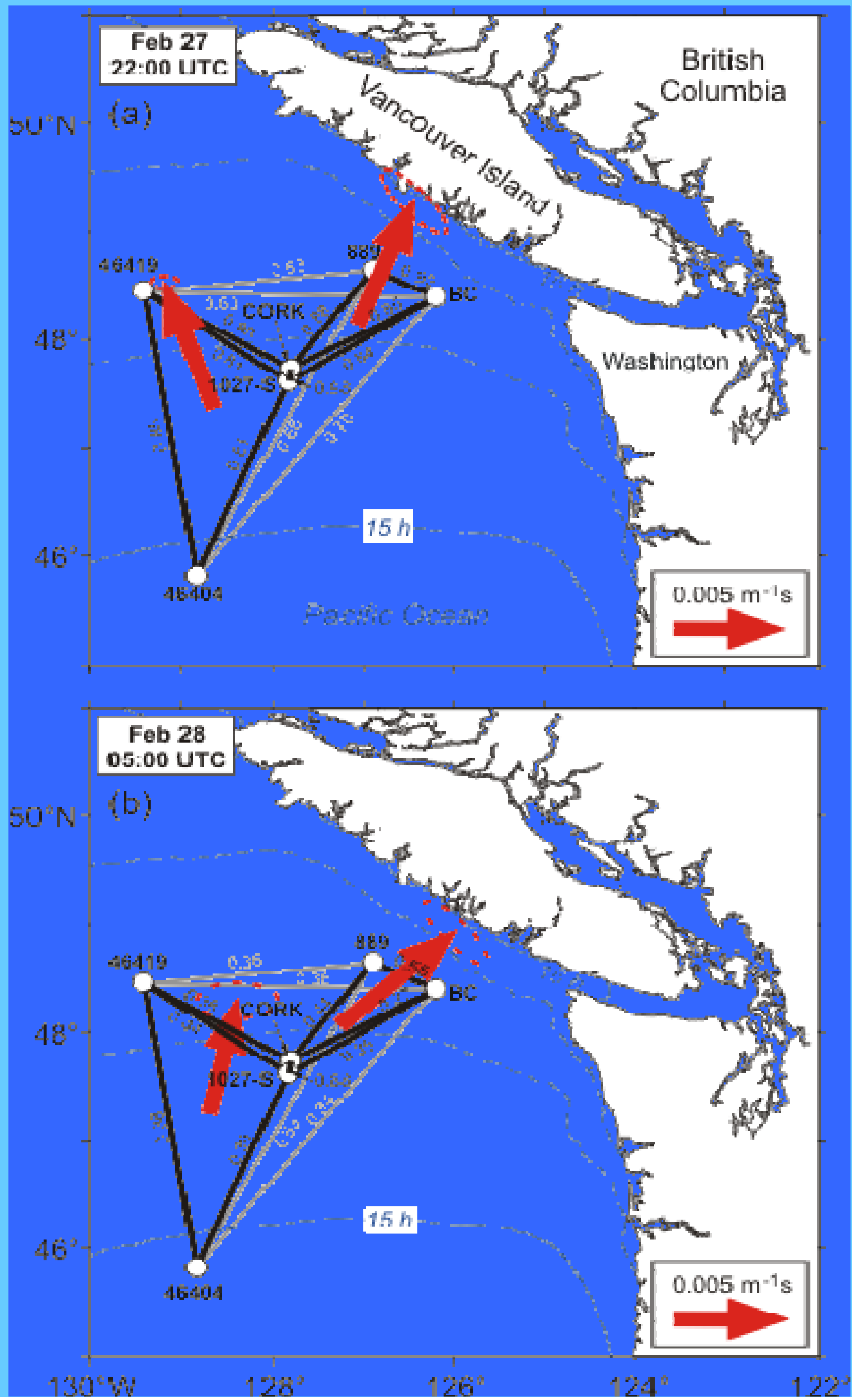






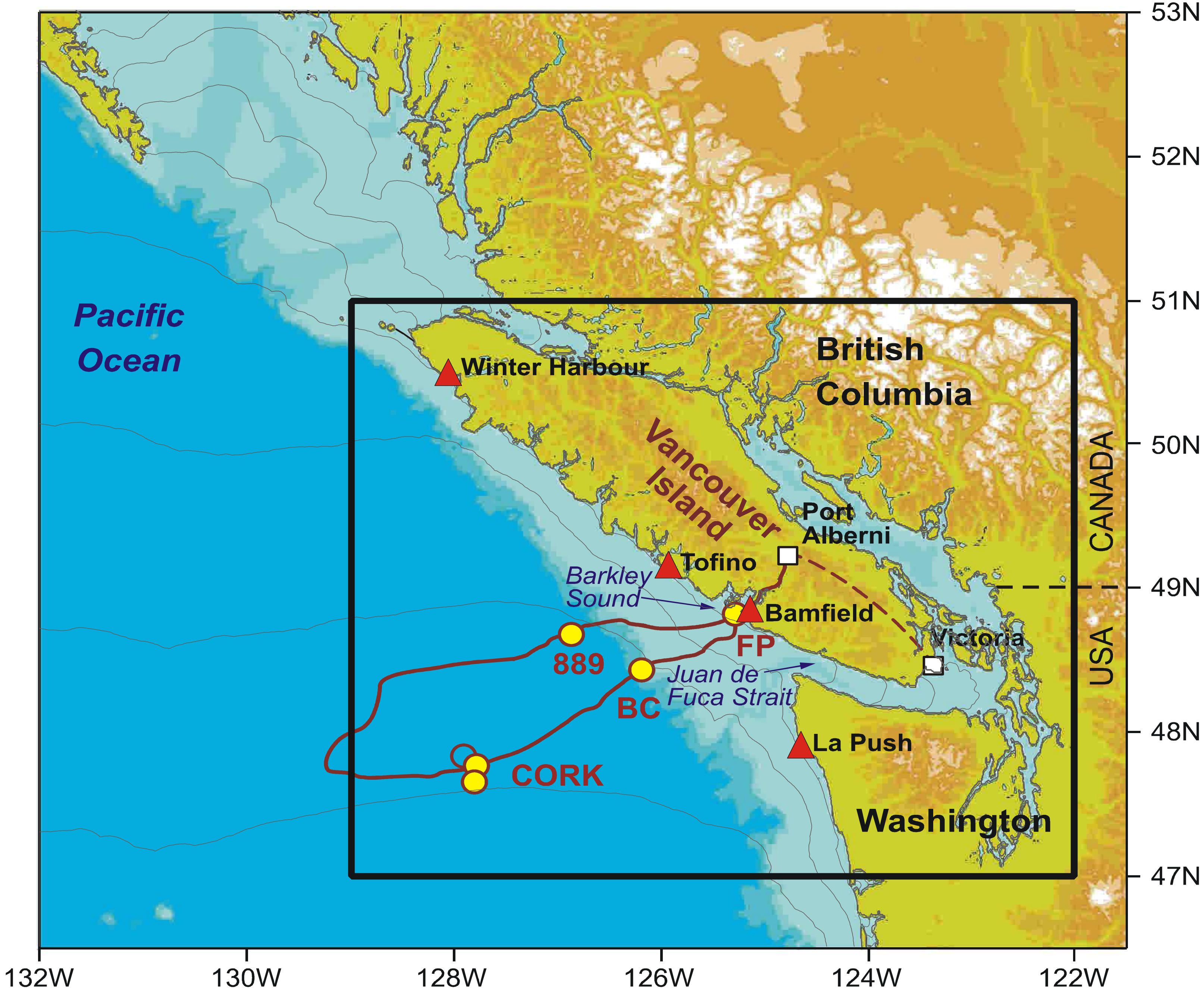
- Spectra are different but spectral ratios tsunami-background are almost the same.

- We estimated direction of the waves in two set of the stations using cross-correlation. Wave undergo refraction because of depth change.
- The directions of the initial wave train and later wave train are differ by 20°



- Return to the Regional Model

NEPTUNE-Canada measurements of the 2010 Chilean tsunami

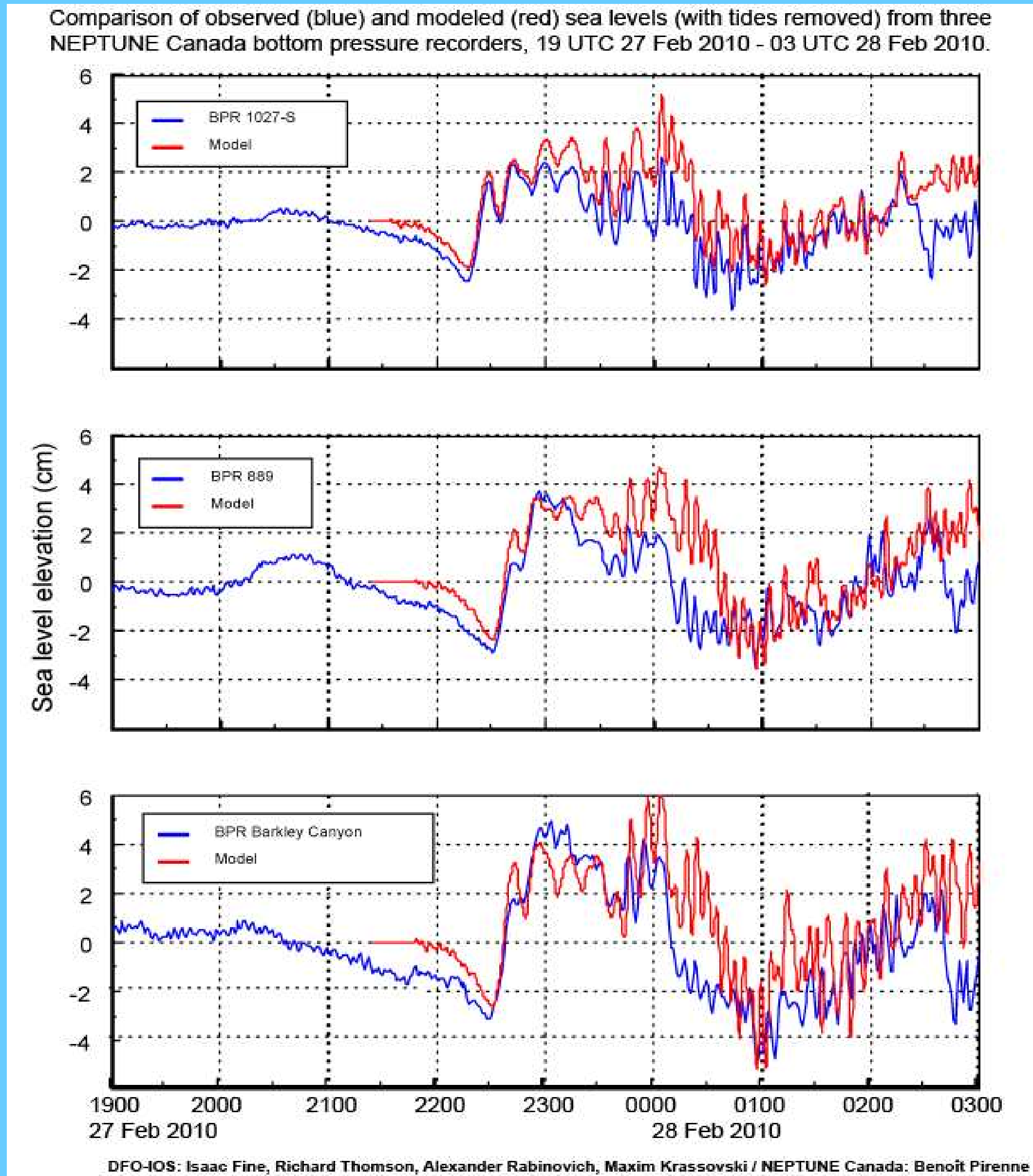



27.02 IOS
21:24:00

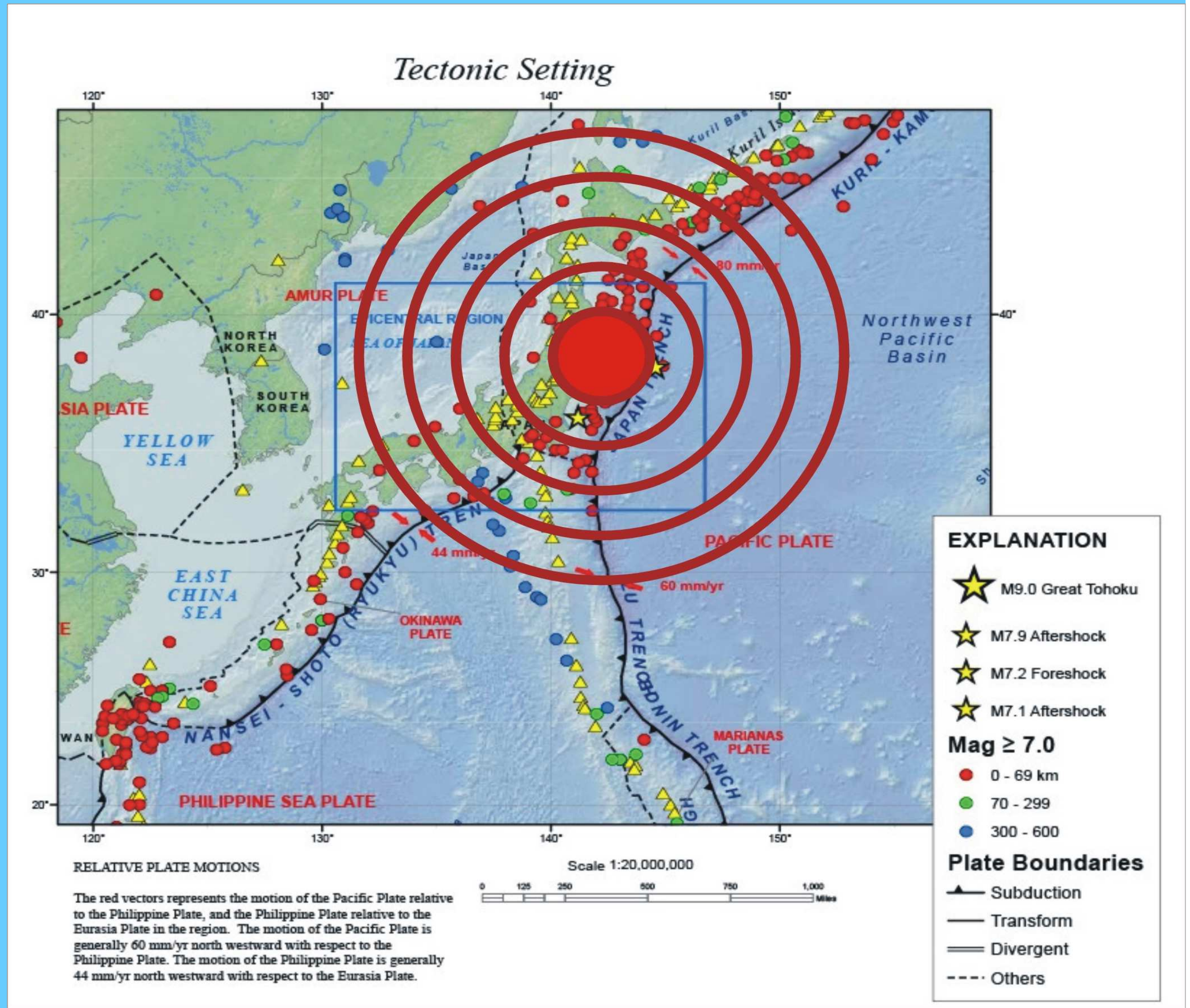
IOS Regional Tsunami Model

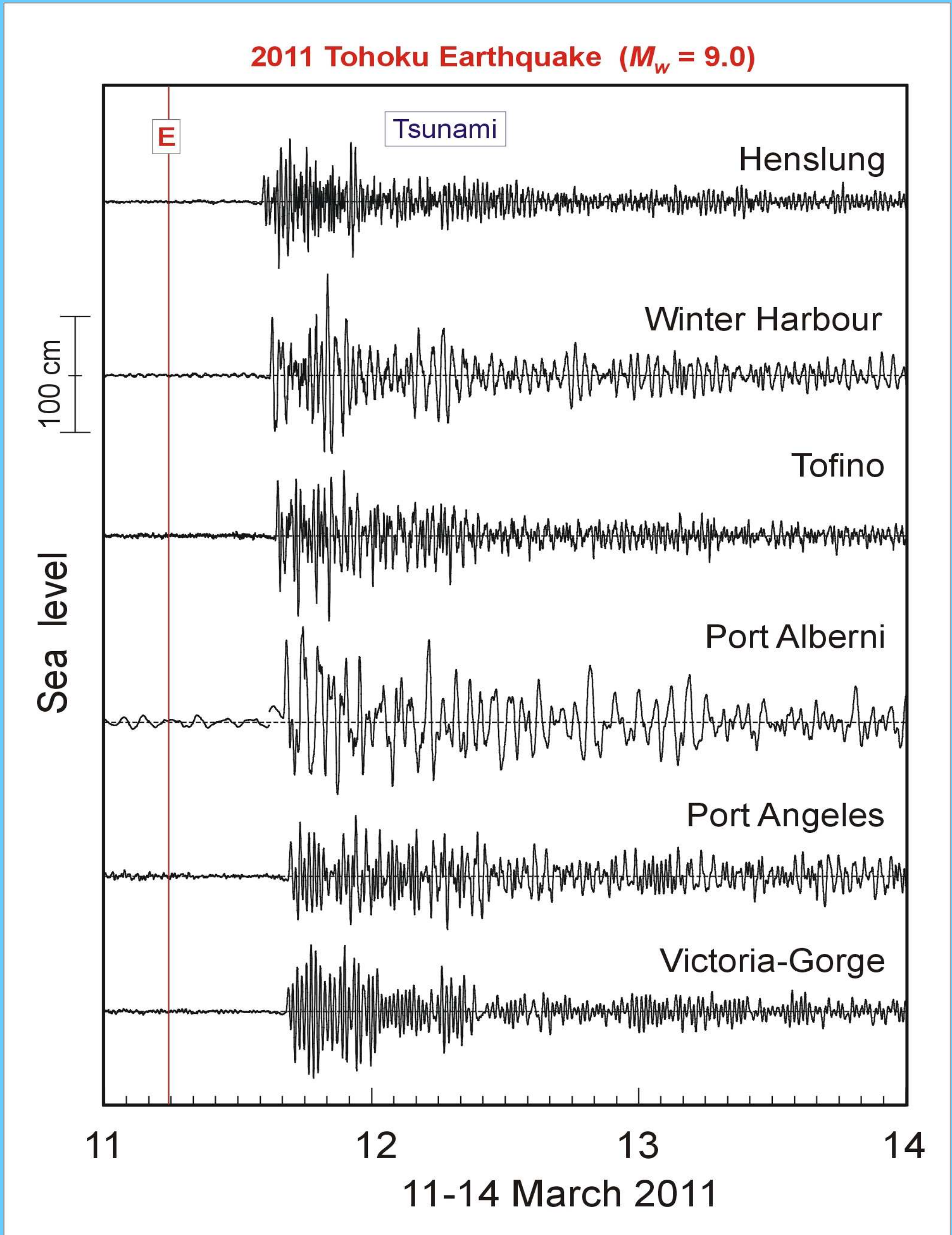
• Both the complexity of the wave and the loss of BPRs in the array limited our ability to extrapolate the observed pressure at 1026B to a wave at the model boundaries

• The modelled tsunami has spatially variable skill such that one pressure record at neighbouring pairs can be well represented whereas the other not; likely a result of inaccurate bathymetry.

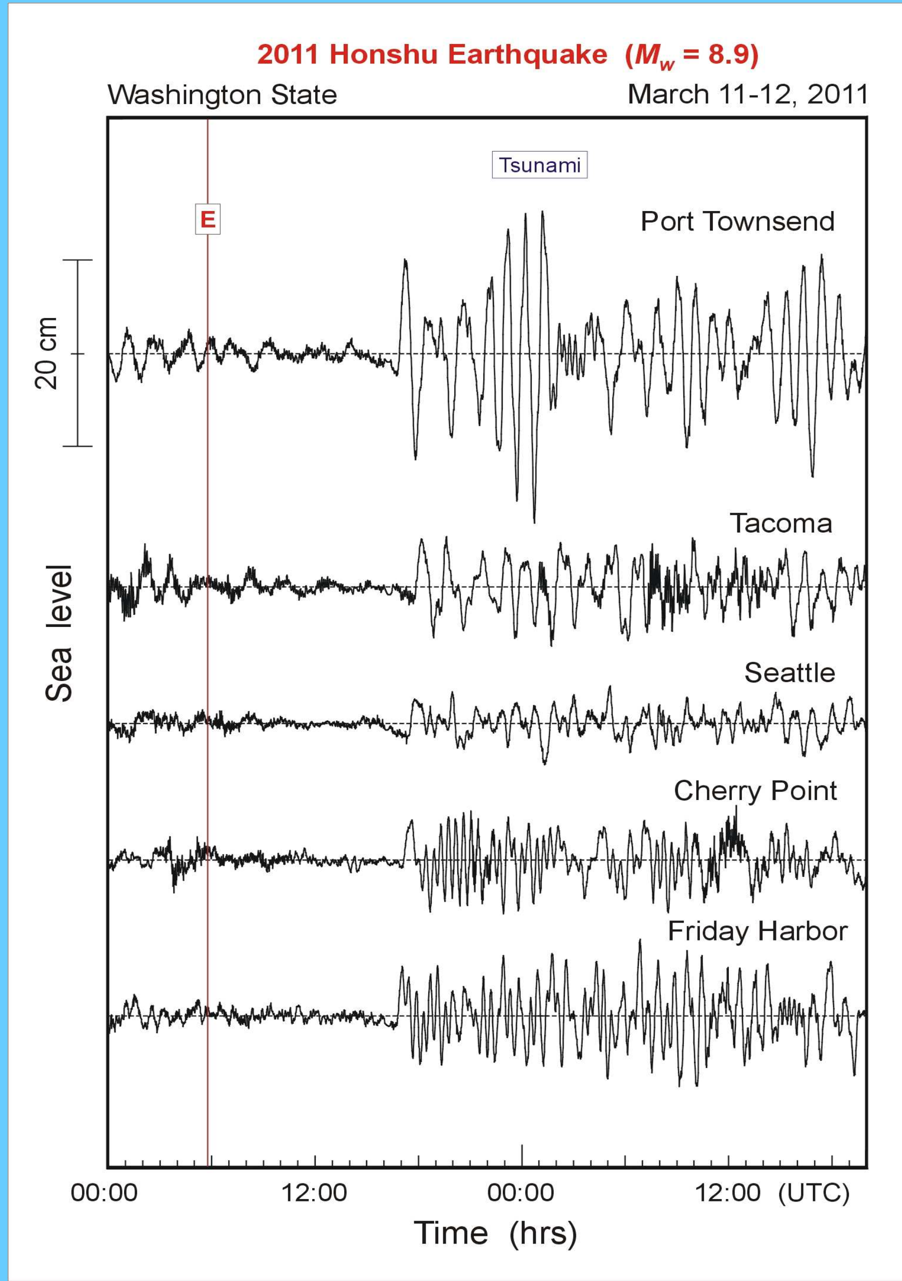


Tohoku 2011 tsunami



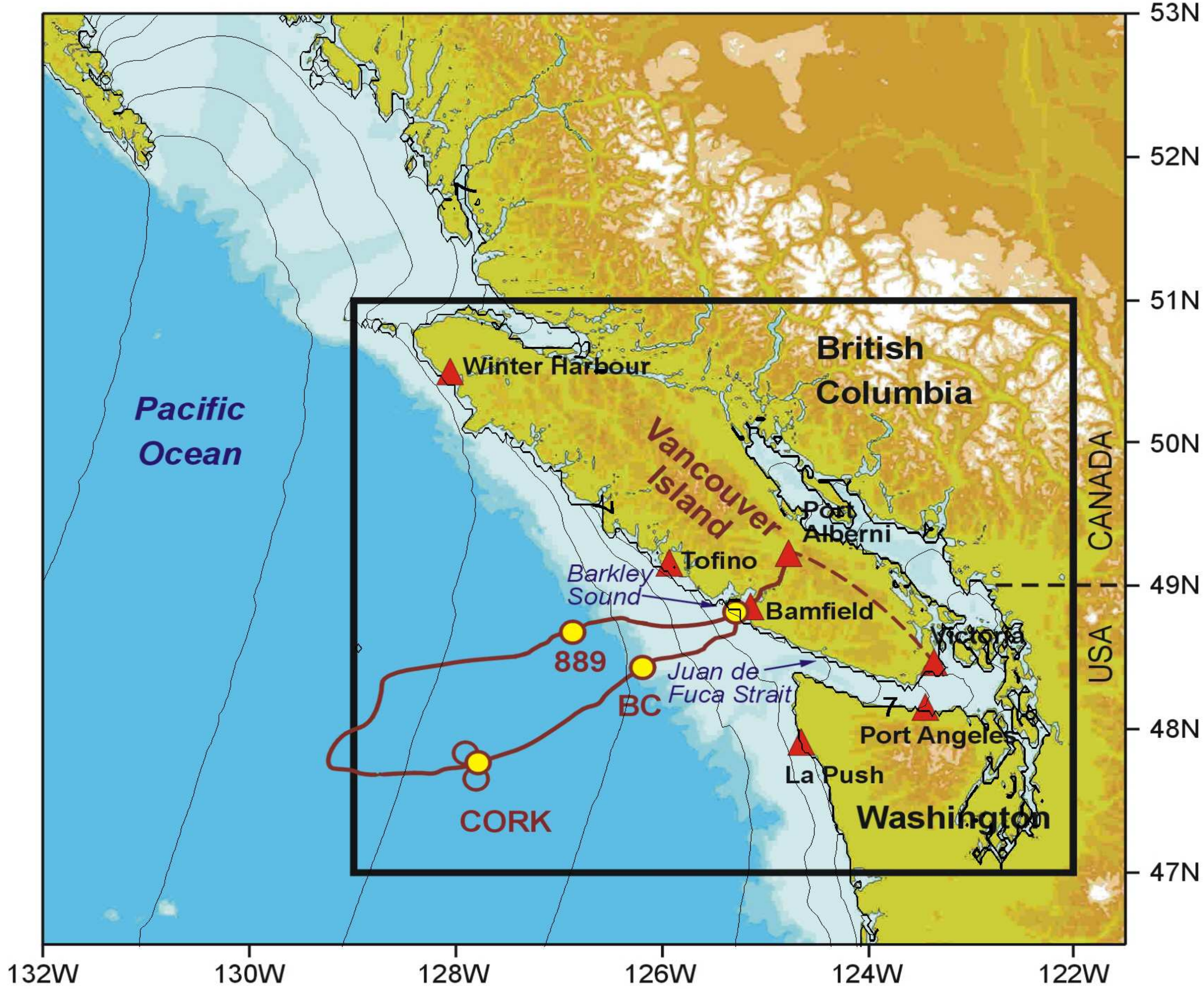


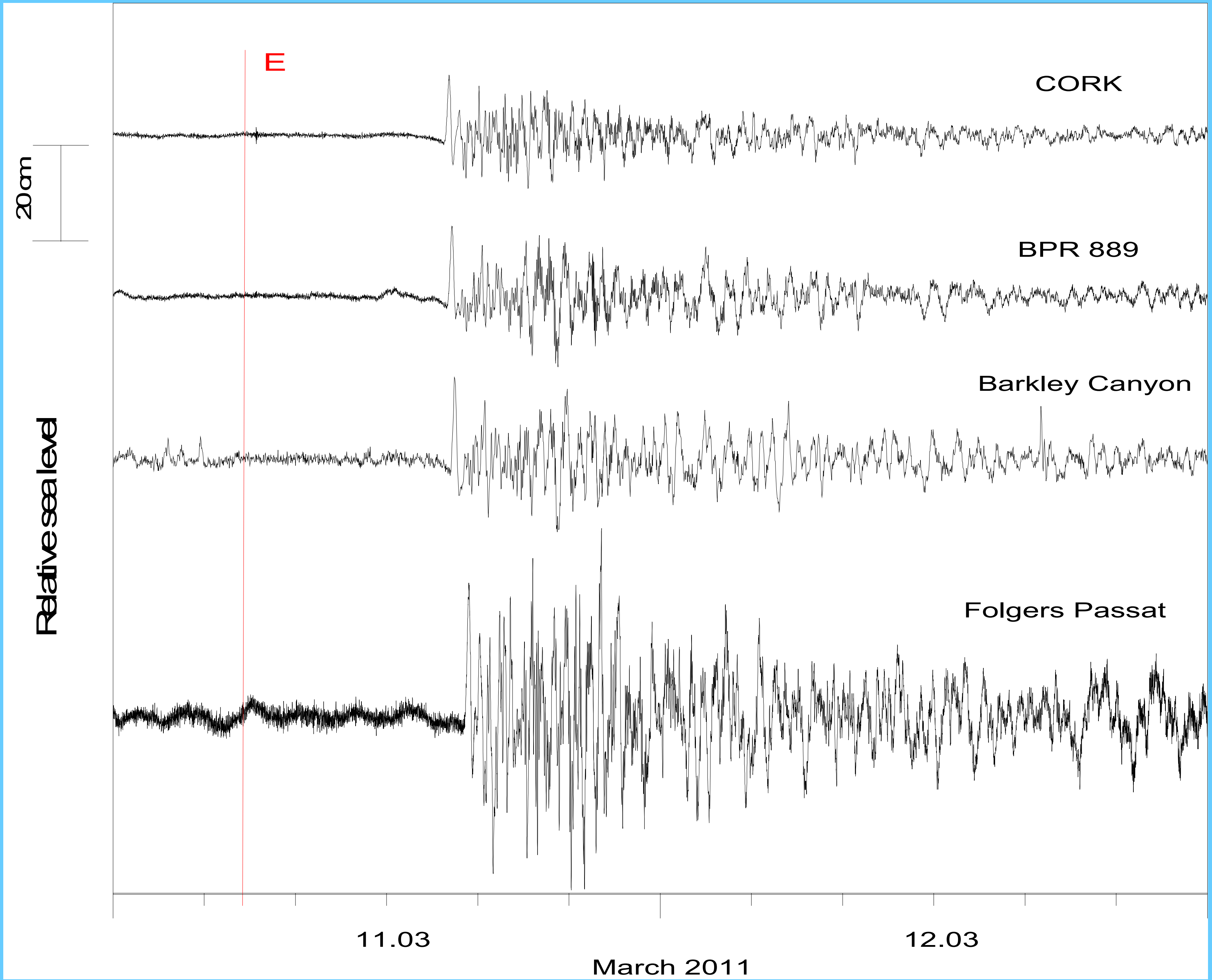
2011 Tohoku Earthquake (M_w = 9.0)
E
Tsunami
Henslung
Winter Harbour
Tofino
Port Alberni
Port Angeles
Victoria-Gorge
100 cm
Sea level
11
12
13
14
11-14 March 2011



2011 Honshu Earthquake (M_w = 8.9)
Washington State
March 11-12, 2011
Tsunami
E
Port Townsend
Tacoma
Seattle
Cherry Point
Friday Harbor
20 cm
Sea level
00:00
12:00
00:00
12:00 (UTC)
Time (hrs)

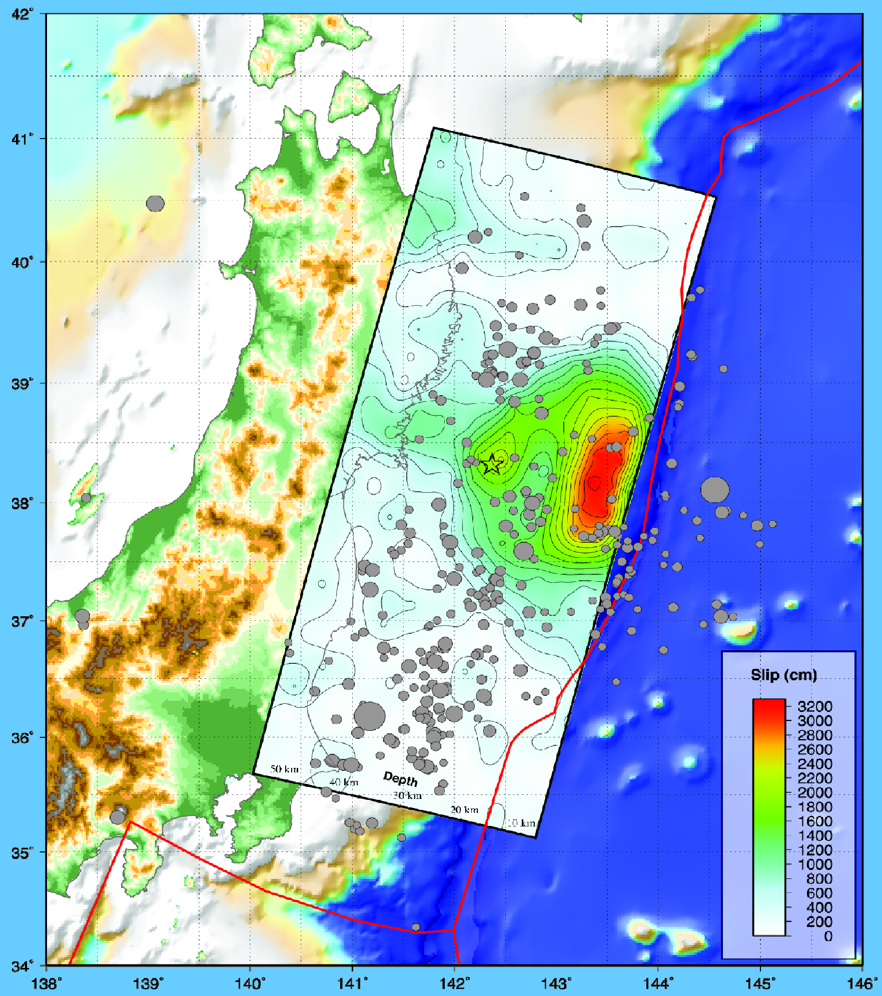
NEPTUNE-Canada measurements of the 2011 Tohoku tsunami





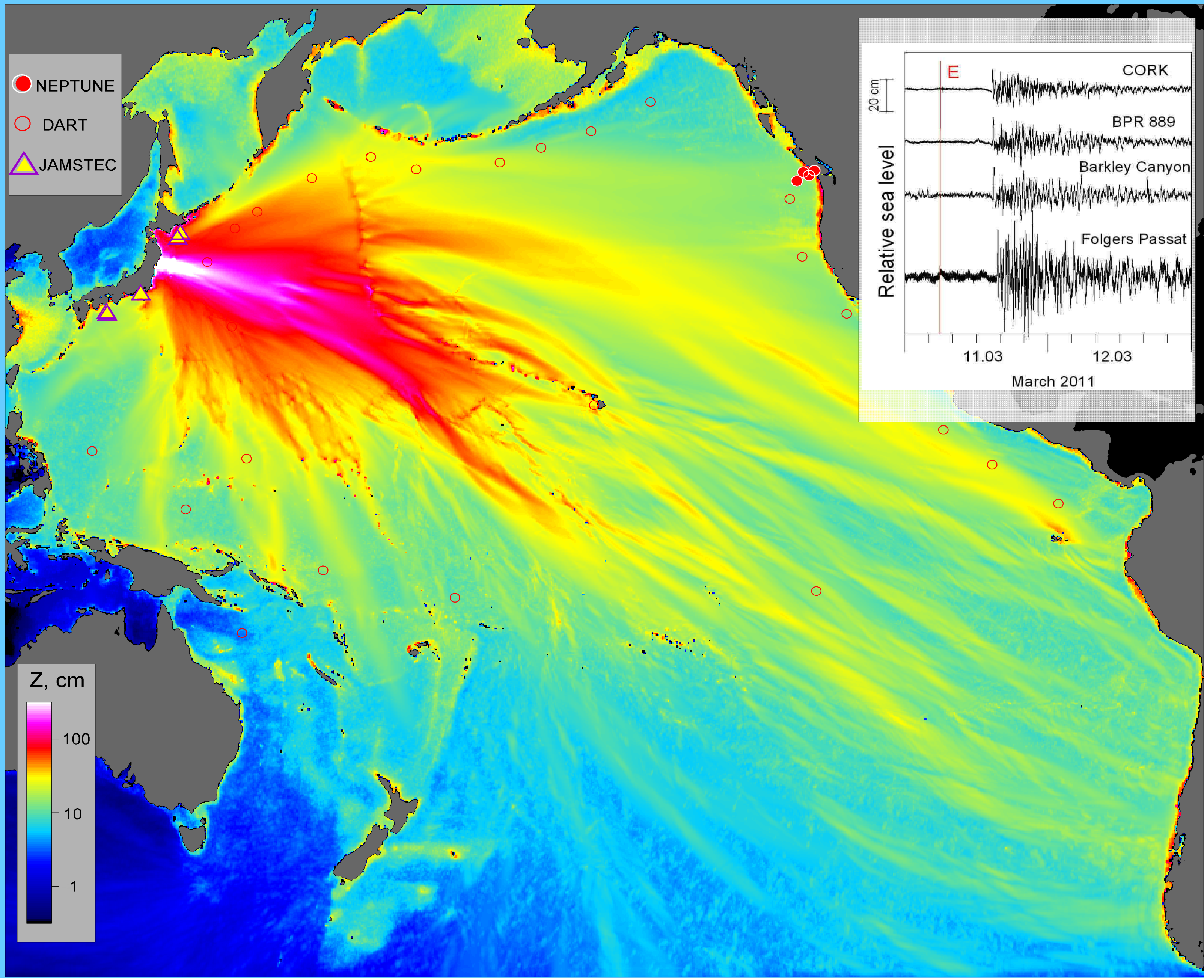
E
CORK
BPR 889
Barkley Canyon
Folgers Passat
20 cm
Relative sea level
11.03
12.03
March 2011

"We used GSN broadband waveforms downloaded from the NEIC waveform server. We analyzed 39 teleseismic broadband P waveforms, 22 broadband SH waveforms, and 55 long period surface waves selected based upon data quality and azimuthal distribution. Waveforms are first converted to displacement by removing the instrument response and then used to constrain the slip history based on a finite fault inverse algorithm (Ji et al., 2002). We use the USGS hypocenter (Lon.=142.37 deg.; Lat.=38.32 deg.). The fault planes are defined using the updated W-Phase moment tensor solution of the NEIC, adjusted to match local slab geometry "

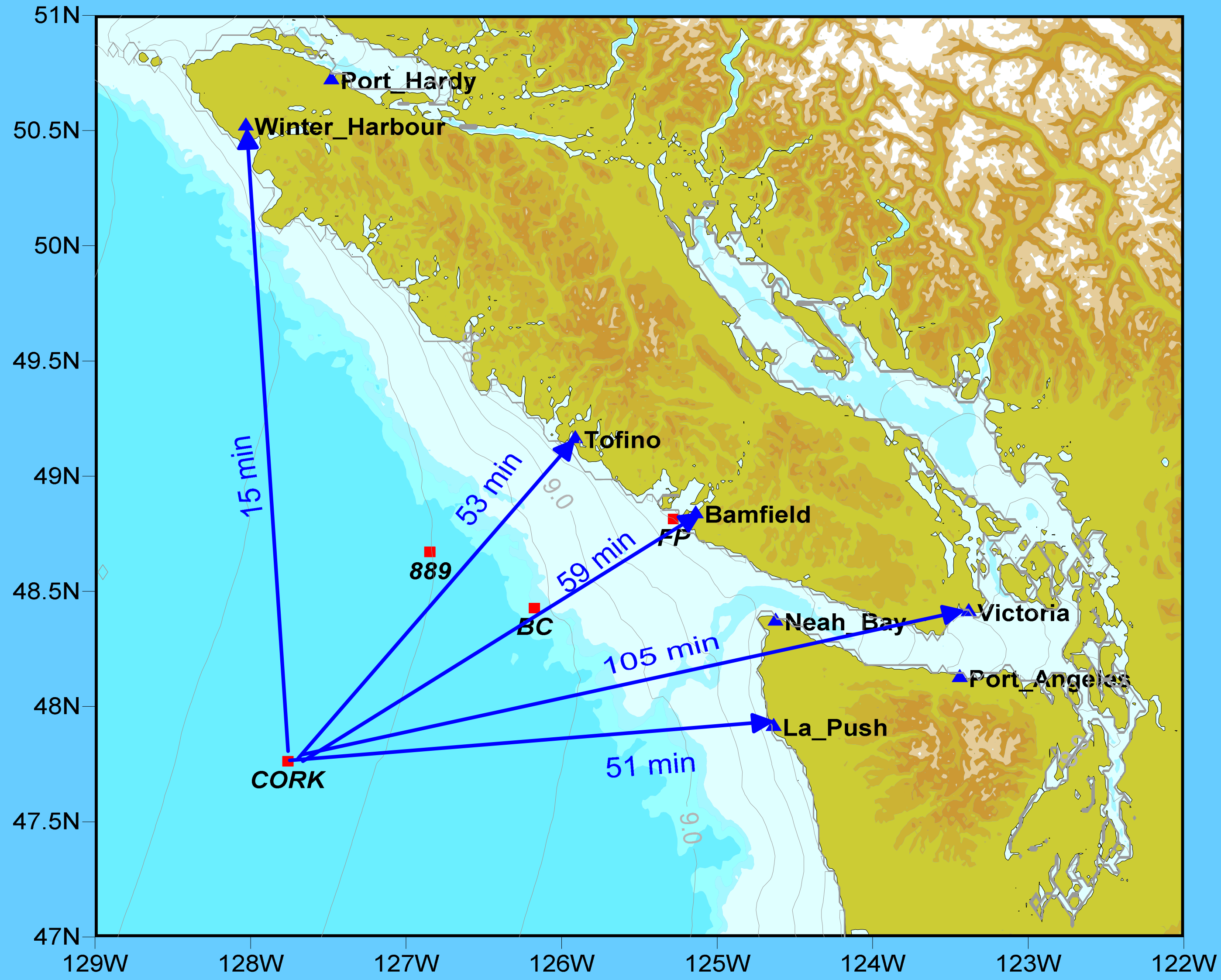


http://earthquake.usgs.gov/earthquakes/eqinthenews/2011/usc0001xgp/finite_fault.php

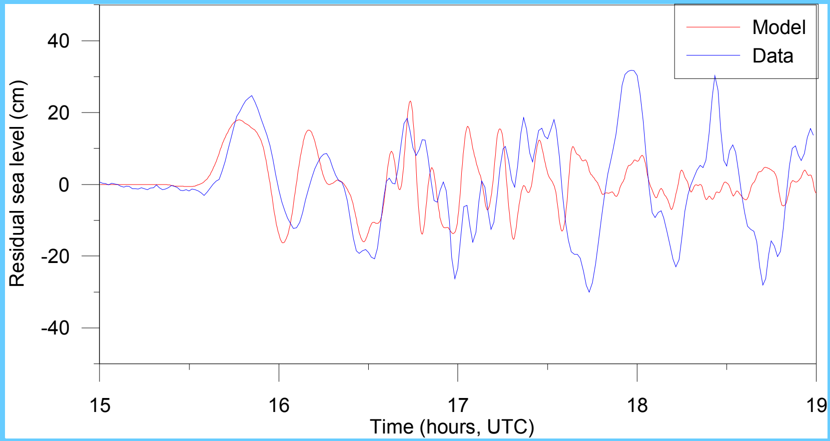
Tohoku 2011 tsunami

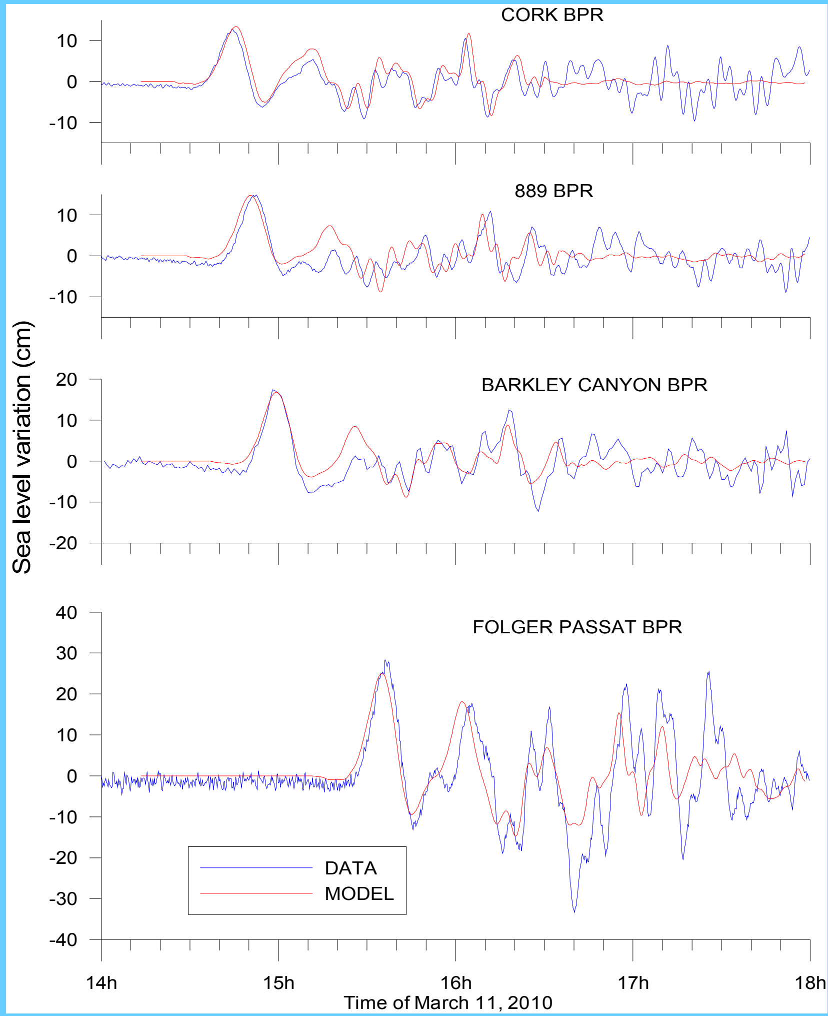


- On March 11, 2011, waves came from northwest. At Winter Harbour tsunami came just in 15 min after arriving at CORK. However, it is still 53 min advantage time lag to Tofino.




11.03
IOS
14:22:00





Comparison model and observation is really good for off-shore stations. Again, we are still working on the coastal station. Some of records are OK (see Neah Bay site above) . All others comparisons can be described from `good` to `fair` except Victoria and Port Angeles.

Samoan Earthquake	Chilean Earthquake	Tohoku Earthquake
200 km south of the Samoan Islands	Offshore Maule, Chile	East from Honshu, Japan
Tuesday, September 29, 2009, 17:48:11 UTC	Saturday, February 27, 2010, 06:34:14 UTC	Friday, March 11, 2011, 05:46:23 UTC
M_w=8.0 (indicating 1/16th of the energy released in the Chilean earthquake)	M_w=8.8 (7th strongest earthquake since 1900)	M_w=9.0 (4th strongest earthquake since 1900, highest tsunami in Pacific since 1964)
Tsunami travelled 8300km to arrive at the Neptune array 11 hours later, averaging 755 km/h	Tsunami travelled 10,650km to arrive at the Neptune array 16 hours later, averaging 666 km/h	Tsunami travelled 6,930km to arrive at the Neptune array 8.6 hours later, averaging 806 km/h
Well defined narrow band (9-13min) wavetrain with trough to crest height ~5cm	Broad band wave energy (5-150min) max trough to crest wave height ~6cm	Most of energy in mid range (20-60 min), Trough to crest wave height ~20 cm

Discussion

- of the Great tsunami on the BC coast?
- Next step in the modeling.
- We need better bathymetry!


FIN