Tsunami Edge Waves in Relation to the 2010 Chile Earthquake

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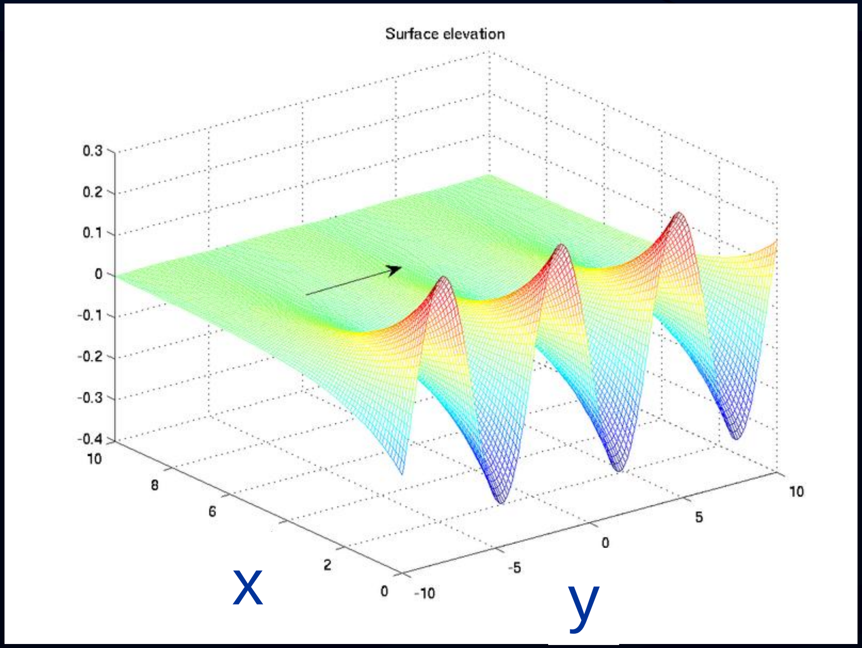
Outline

- What are Edge Waves?
  - Characteristics
  - Theory
  - Special Analytic Cases
- Observations of Edge Waves
  - Propagation
  - Relation to Maximum Amplitude
- 2010 Chile Tsunami
  - Indirect/Anecdotal Observations
  - Dependence on Slip Distribution
- Conclusions

What are Edge Waves?

- Characteristics
  - Trapped by refraction
  - Propagate parallel to shore
  - Exponential decay in amplitude from shore
  - Distinct modes
  - Slower phase/group speeds than non-trapped waves (dependent on bathy slope)
  - Airy phase possible
  - Scatter during propagation
  - *e*-folding distance > 400 km



Tsunami Propagation

- Linearized Shallow-Water Wave Equations (aka Linear Long-Wave Equations)
  - Continuity Equation

$$\frac{\partial(\zeta + h)}{\partial t} + \nabla \bullet \left[(h + \zeta)\mathbf{u}\right] = 0$$

  - Momentum Equation

$$\frac{\partial \mathbf{u}}{\partial t} = -g \nabla \zeta$$

ζ: wave amplitude
u: depth-averaged horizontal velocity field
h: water depth

Phase speed: $\sqrt{gh}$

Nearshore Propagation

- Constant Beach Slope (*s*)

$$h(x) = x \tan \alpha = sx$$

- Substitution

$$\frac{\partial^2 \zeta}{\partial t^2} - \nabla \bullet gh \nabla \zeta = 0$$

$$\zeta(\mathbf{x}, t) = \eta(x) e^{i(k_y y - \omega t)}$$

$$x\eta'' + \eta' + \left(\frac{\omega^2}{sg} - k_y^2 x \right) \eta = 0$$

Transformation

$$\xi = 2k_y x \quad \text{and} \quad \eta = e^{-\xi/2} f(\xi)$$

Kummer's Eqn.

$$\xi f'' + (1 - \xi) f' + \frac{1}{2} \left(\frac{\omega^2}{k_y sg} - 1 \right) f = 0$$

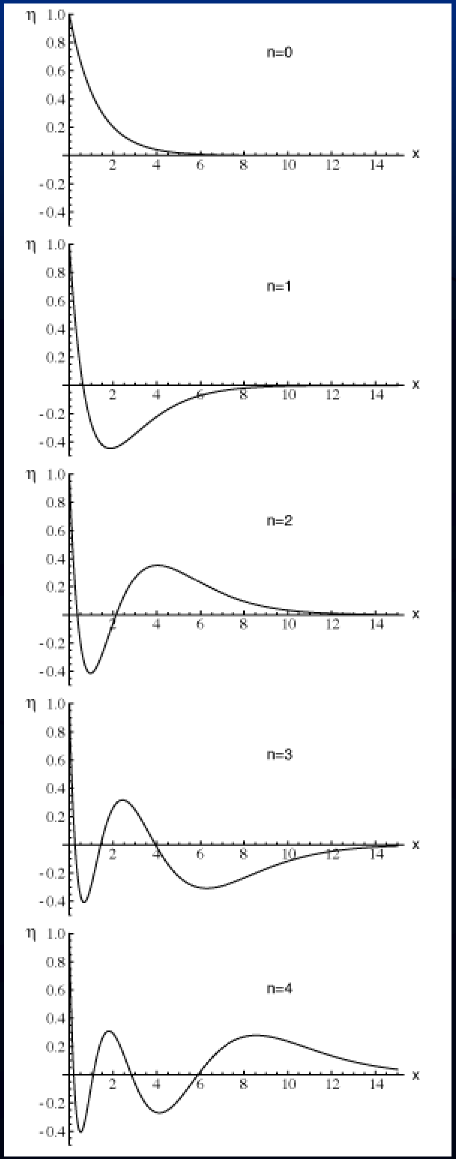
Nearshore Propagation (cont.)

- Dispersion Relation

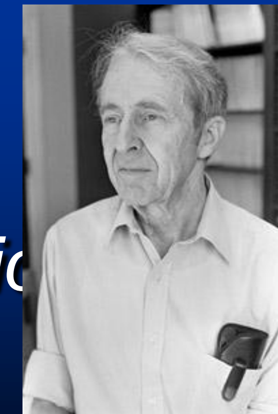
$$\omega^2 = gk_y(2n+1)\tan\alpha$$

- Cross-Shore Profile (Laguerre Polynomials)

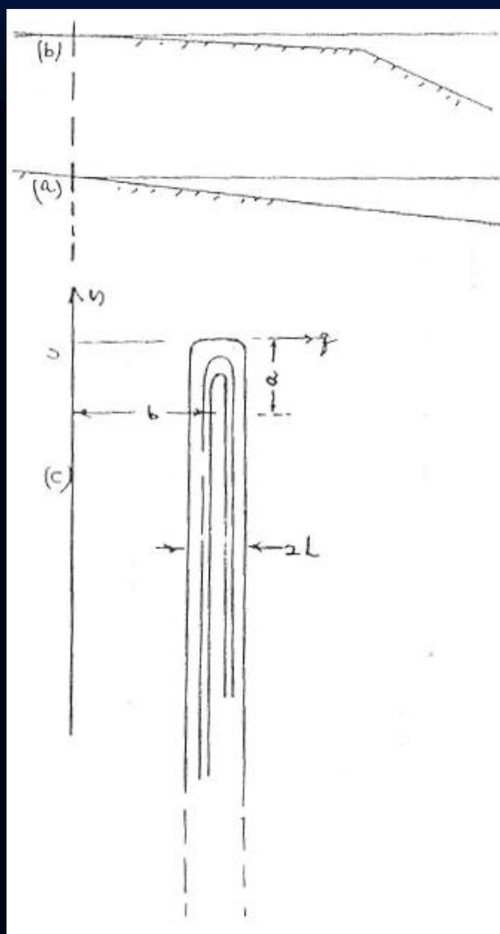
$$\eta(x) = e^{-k_y x} L_n(2k_y x)$$



Edge Wave Runup



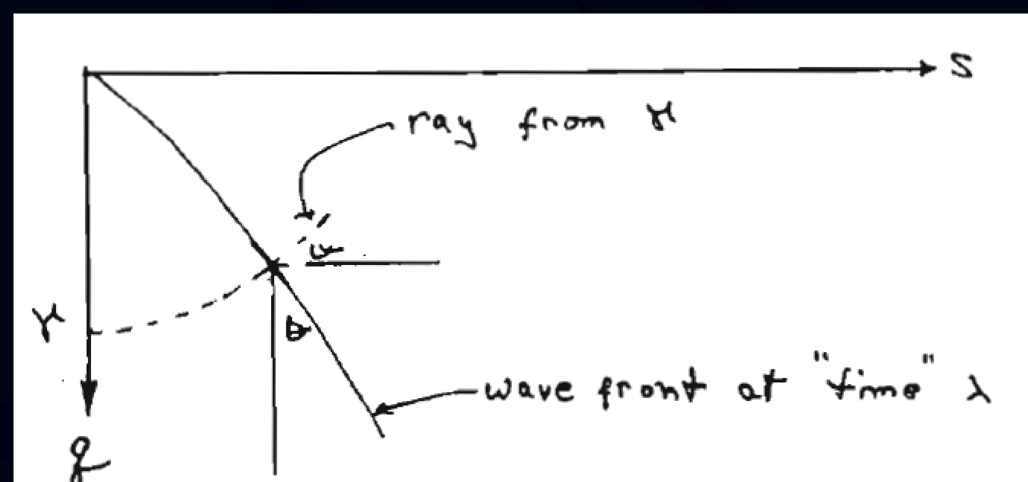
- Carrier (1995): *"On-Shelf Tsunami Generation and Coastal Propagation"*



$s \le -2a$ Broadside Runup

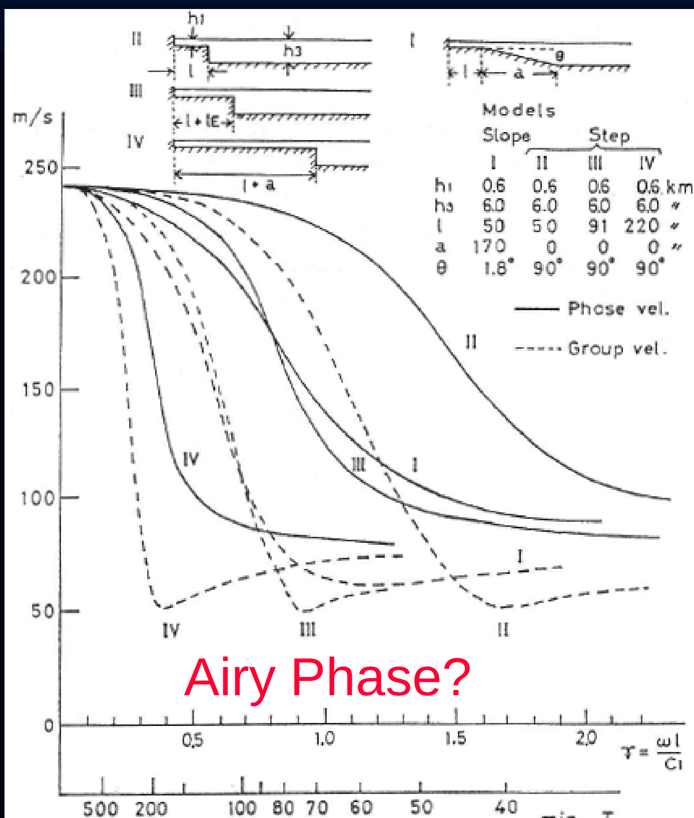
$s > 2a$ Edge Wave Runup

$$\zeta_{\max}(q=0) \approx \sum_{n=1}^{3} \zeta_n^{+}(q=0)$$



Other Special Cases

- Stepped Bathymetry



Stokes mode (*n*=0)
Ishii & Abe (1980)

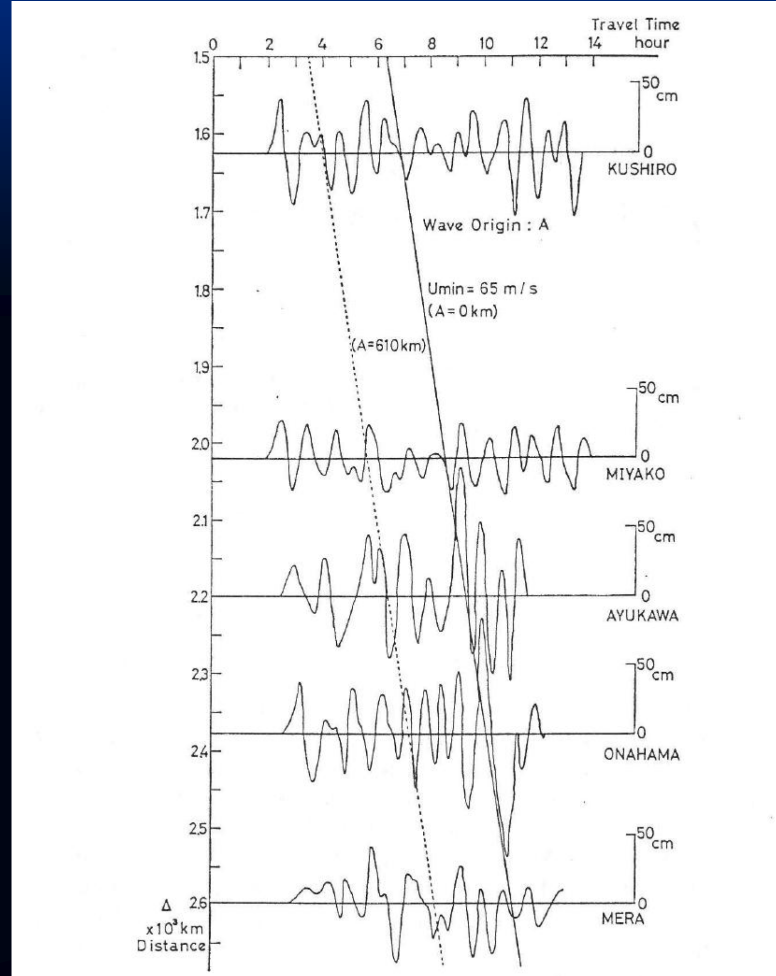
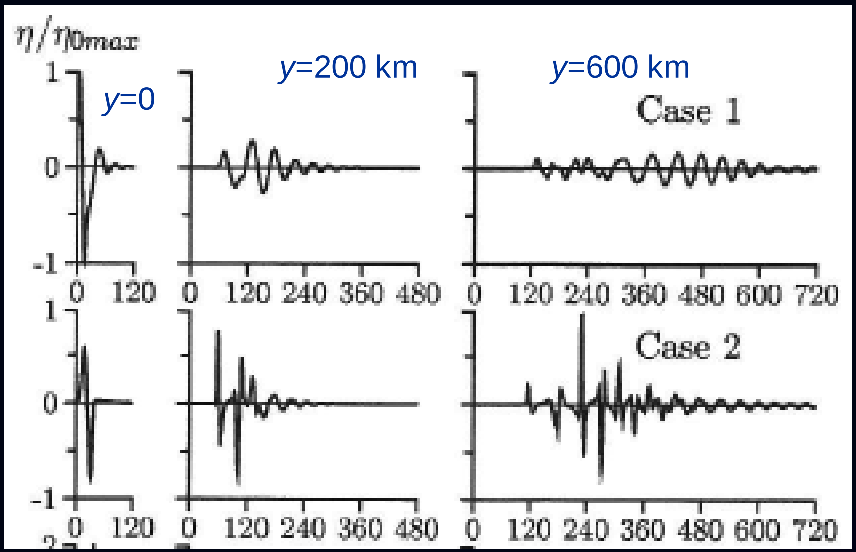


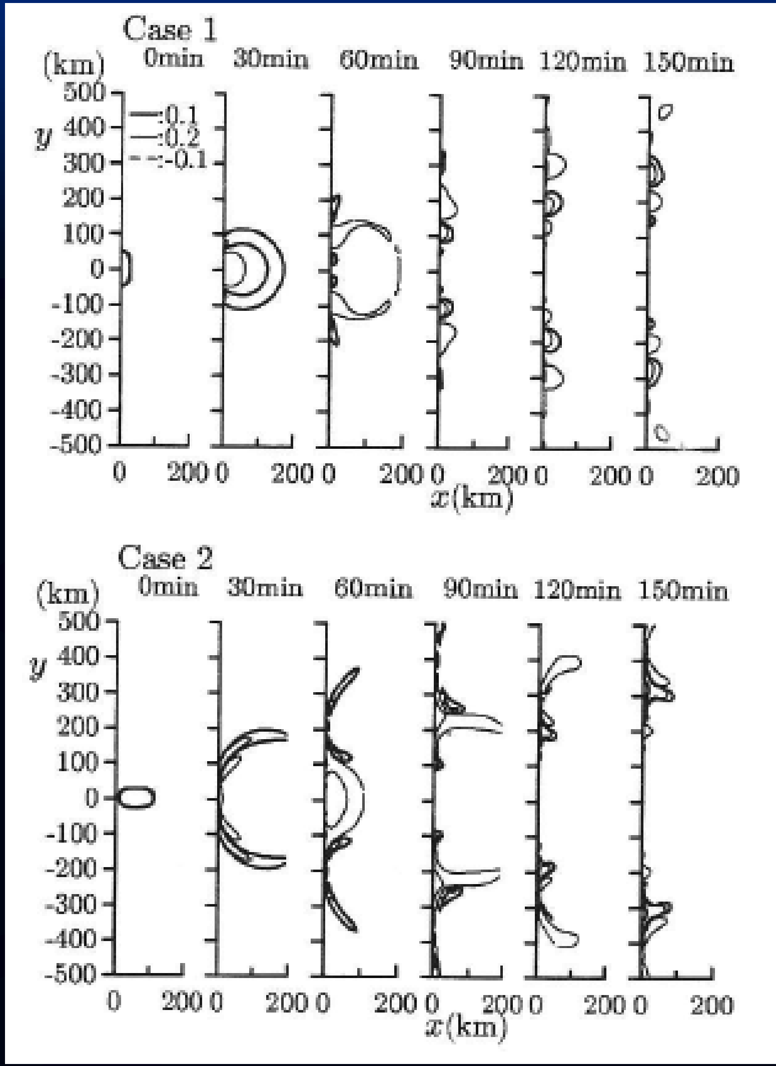
Fig. 7. Time histories observed for the Kamchatka tsunami of 1952, after excluding the ocean tide and the component having a period shorter than 30 min. From top to bottom the records at observation points are arranged according as the distances from the origin along the curved shelfs. The abscissa is the lapse time measured from the origin time of the mainshock. Both the solid and broken lines show the travel time curve of 65 m/sec in which the former is assumed to be the epicenter and the latter is assumed to be a fault marginal one with the epicentral distance of 610 km.

Other Special Cases

- Constant Slope: 2D
  - Clues to generation by tsunamis



t (min)



Fujima et al. (2000)

Observations of Edge Waves

- Near-Field Oblique: Maximum amplitude is associated with late arrivals, resulting from the excitation, scattering, and resonance of edge waves
  - 1983 Nihonkai-Chubu M_w=7.7 earthquake

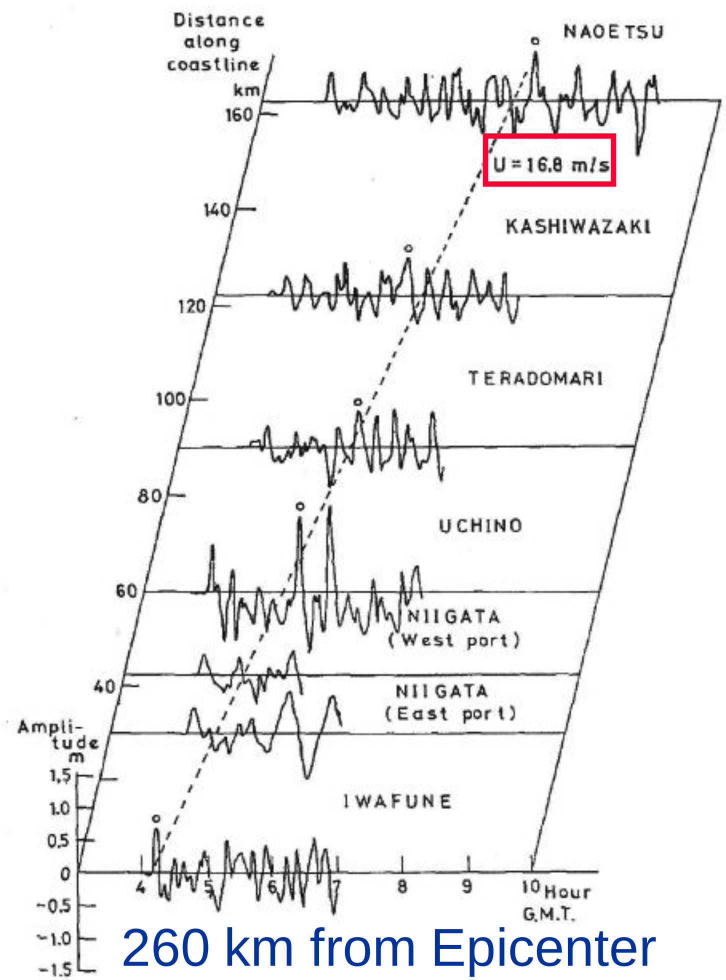


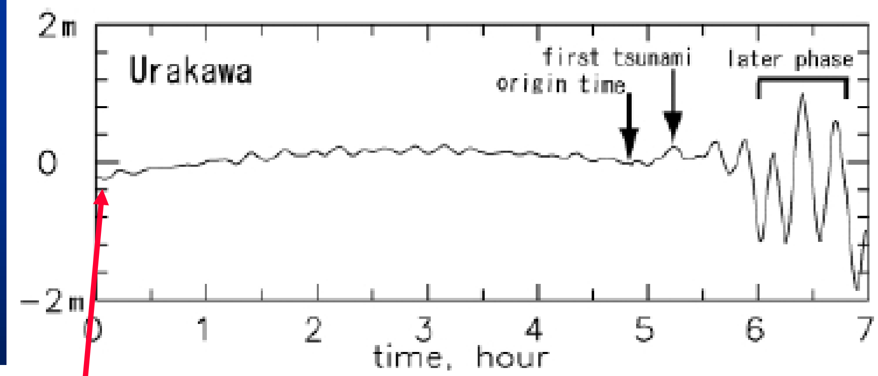
Fig. 10. Tsunami wave forms observed along the coast of Niigata Prefecture arranged in order of distance. Distance is taken from Iwafune to the south along the smoothed coast line. Tides were excluded from these time histories. Broken line represents the minimum group velocity of 16.8 m sec^{-1} expected from the edge wave model by Ishii and Abe (1980) and open circles indicate the arrival times of the maximum amplitude wave or a larger one.

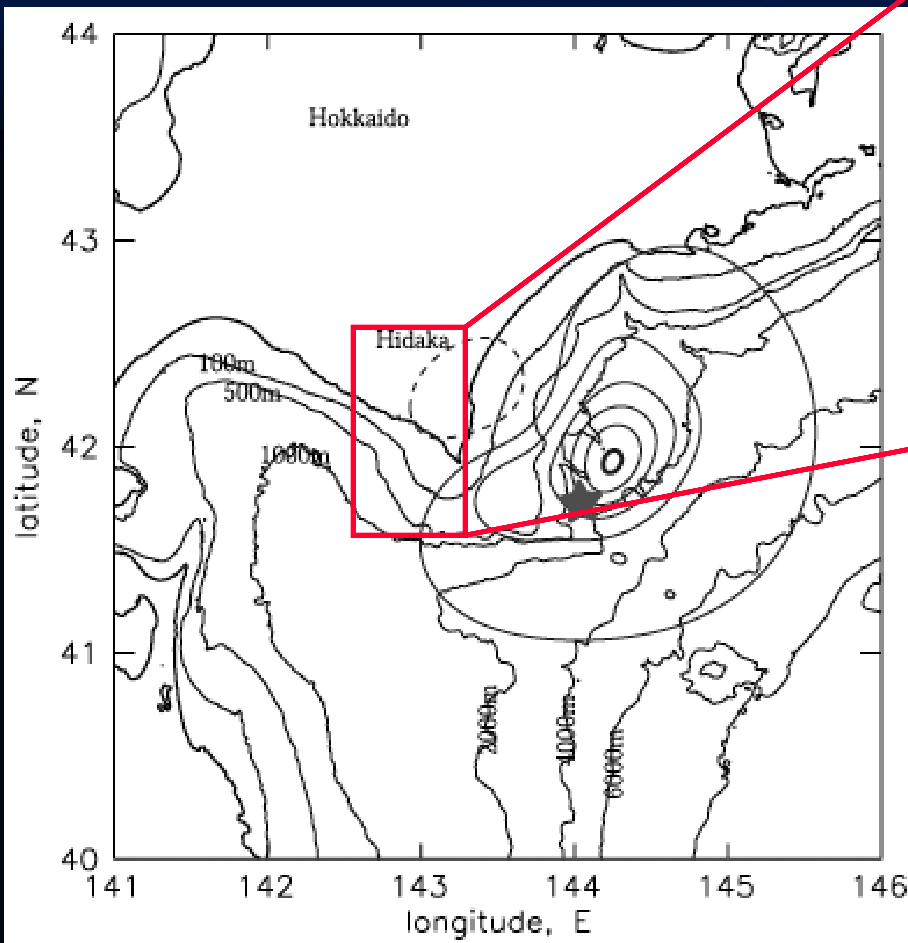
Abe & Ishii (1987)

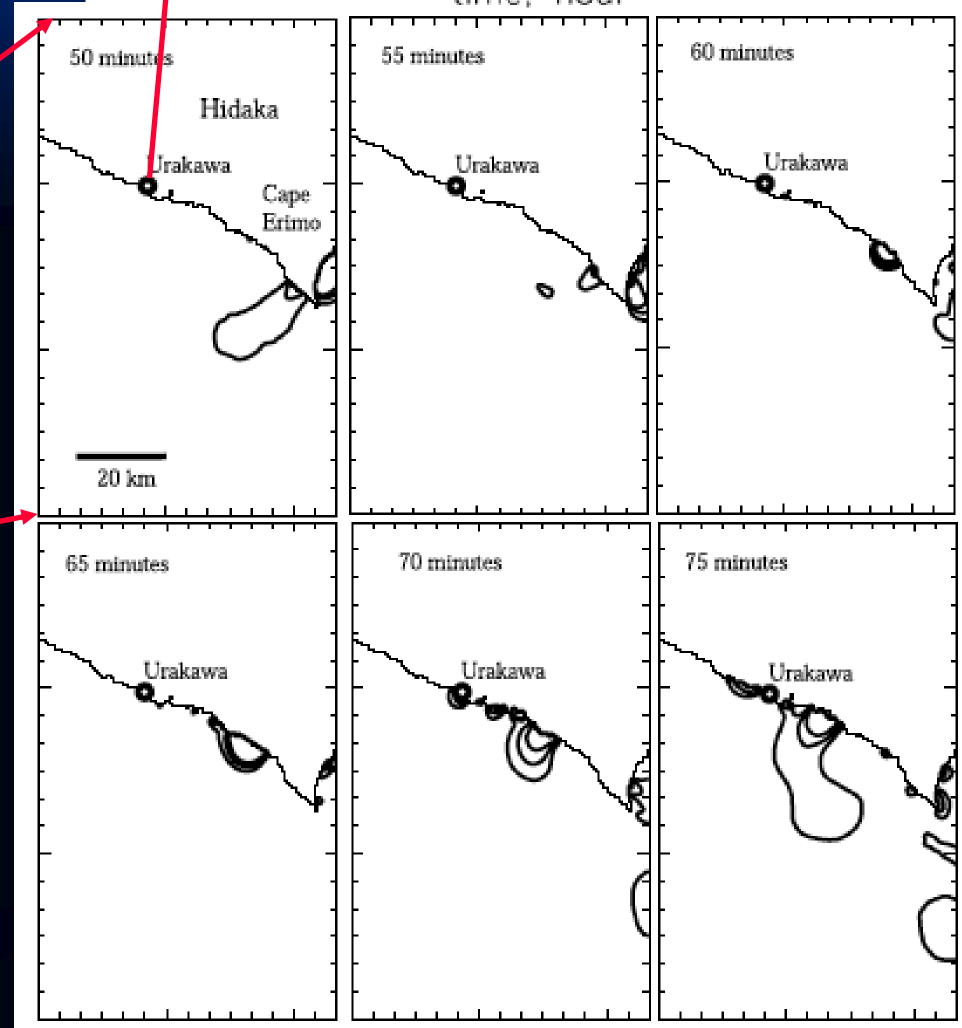
Near-Field Oblique

- Tokachi-Oki M_w=8.0 2003 EQ

Tanioka et al. (2004)

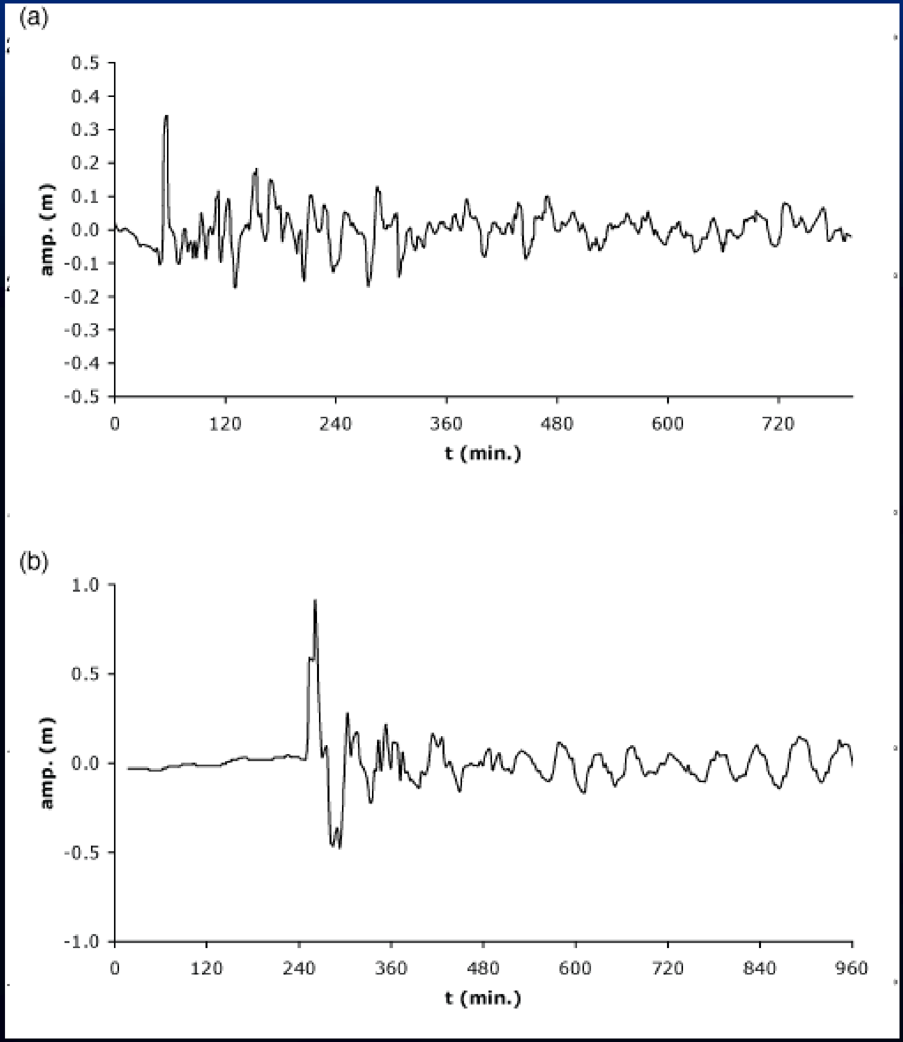






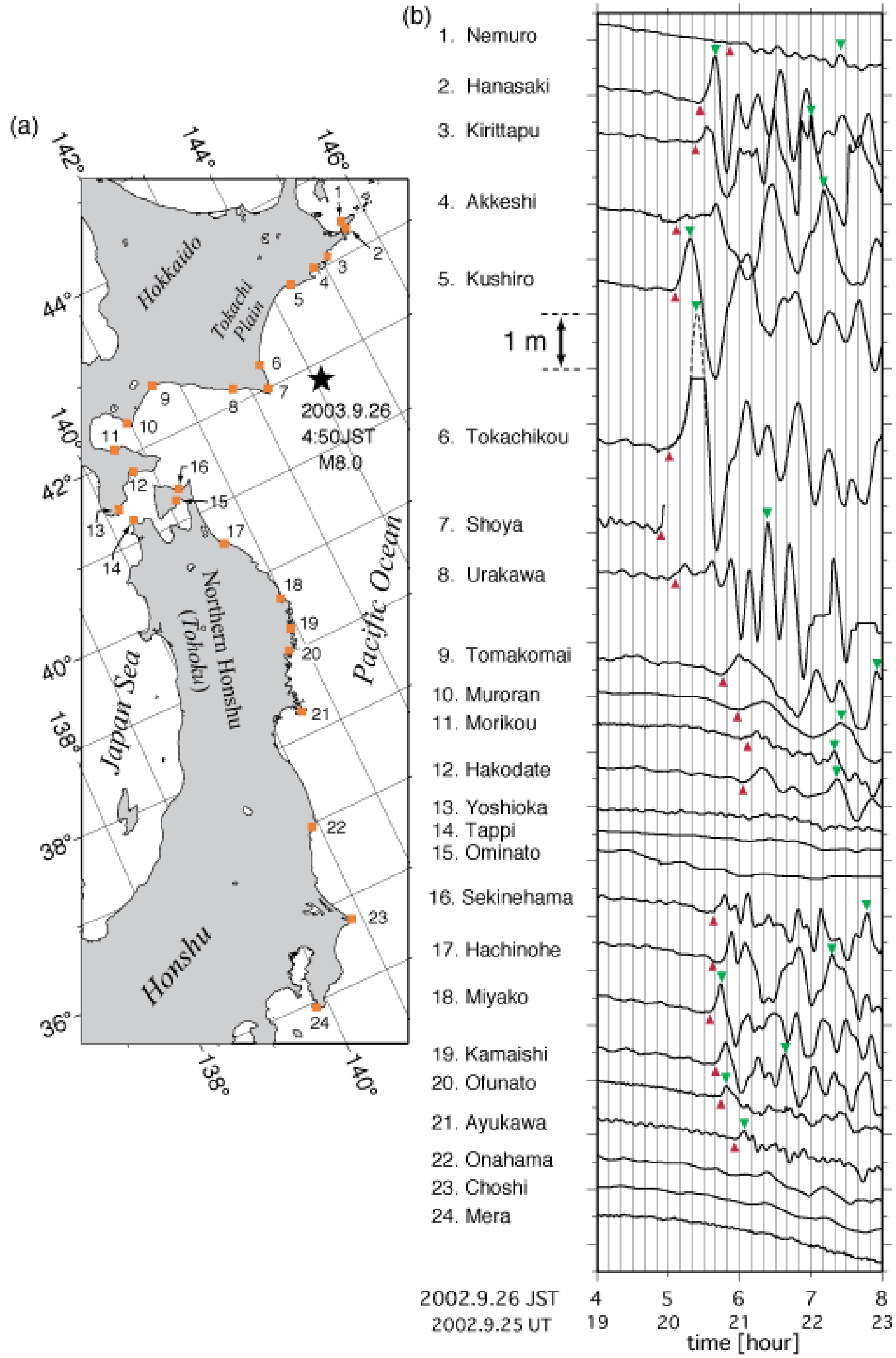
Observations of Edge Waves

- Tsunami Regimes & Hypotheses (Geist, 2009)
- Broadside
  - Max. amp. associated with first (non-trapped) arrival
- Oblique
  - Max. amp. associated with edge waves (late arrivals)



After Carrier (1995)

Observations of Edge Waves

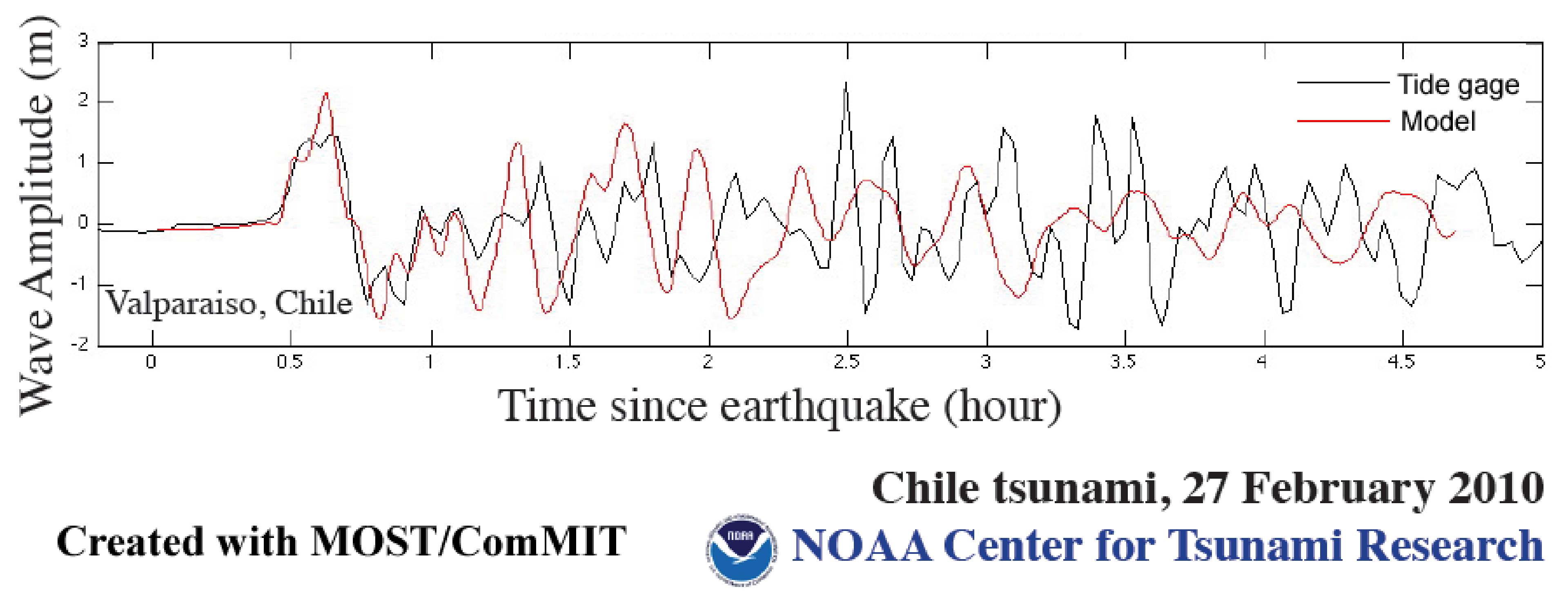


Oblique Broadside Oblique

Modified from Hirata et al. (2004)

2010 Chile Tsunami

- Indicators of Edge Waves?



2010 Chile Tsunami

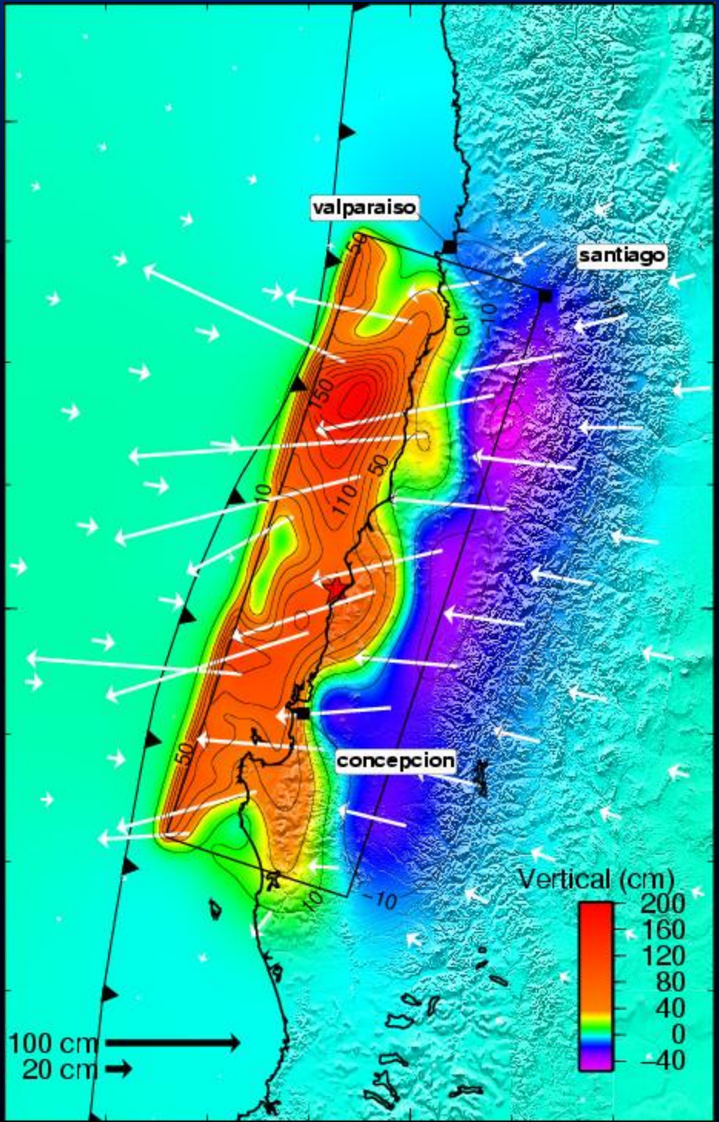
- Indicators of Edge Waves?

Figure 3. Sequential flow directions (red arrows) at La Trinchera indicate multiple strong onshore flows from waves approaching from different directions. View toward the east

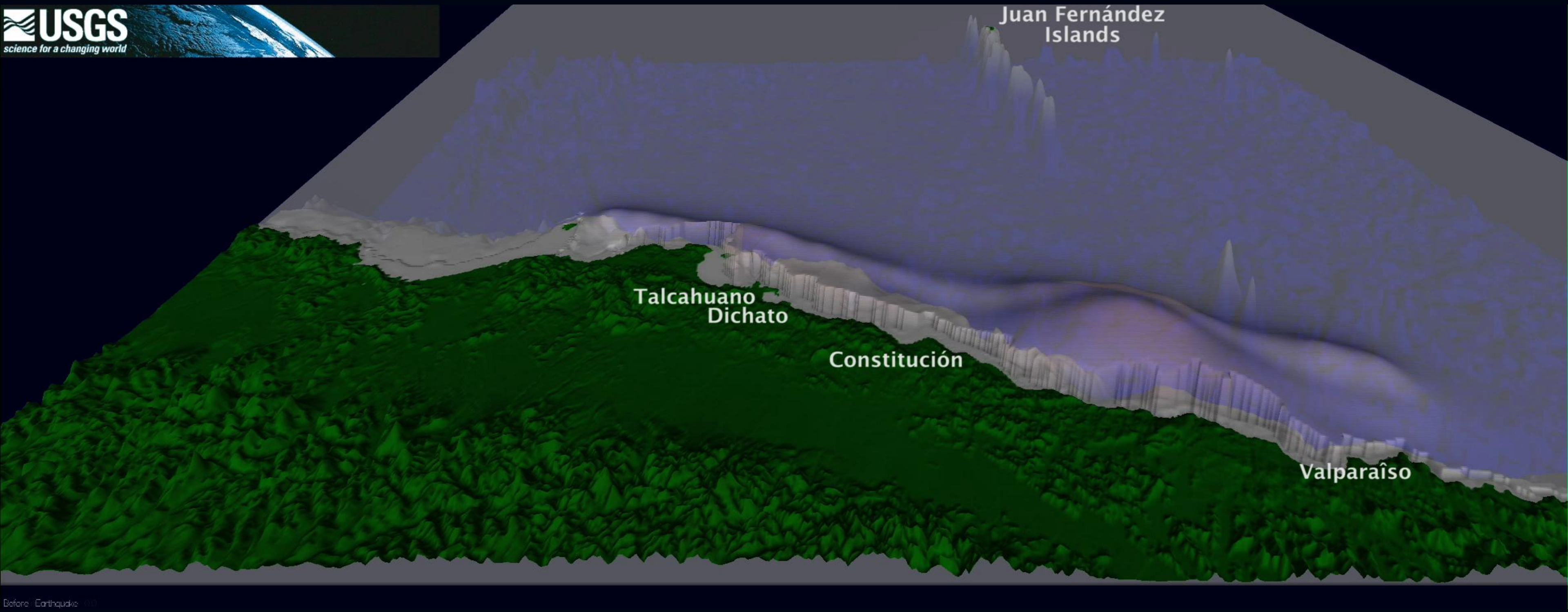
Figure 6. Field evidence at Constitucion indicates flow during multiple waves approaching from different directions. View is toward the northeast.

Morton et al. (2010): USGS Open-File Report 2010-1116

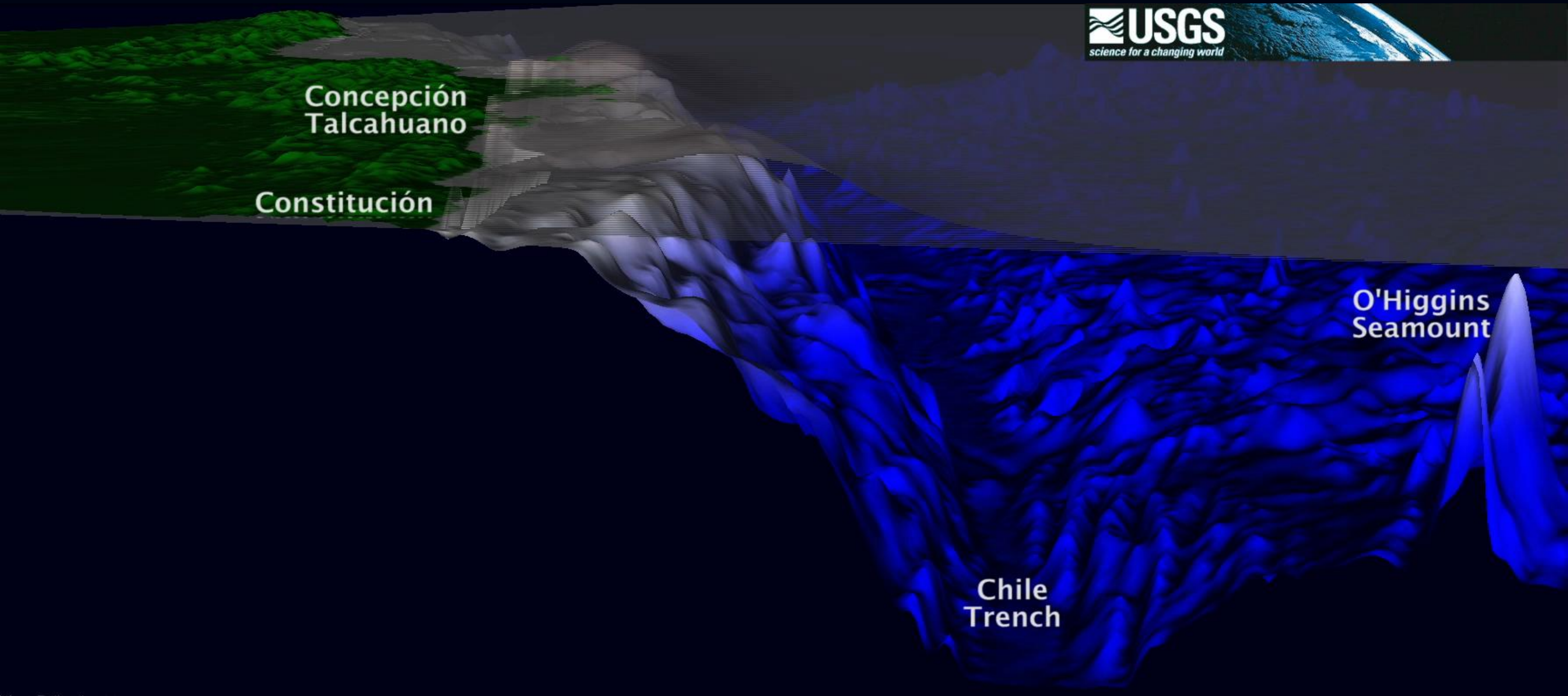
2010 Chile Earthquake: Coseismic Displacement



Anthony Sladen, Cal Tech


USGS
science for a changing world
Juan Fernández
Islands
Talcahuano
Dichato
Constitución
Valparaîso
Before Earthquake

Pelluhue


USGS
science for a changing world
Concepción
Talcahuano
Constitución
O'Higgins
Seamount
Chile
Trench

Conclusions (1 of 3)

- Persistent edge waves develop for “on-shelf” tsunamigenic earthquakes, like the 2010 Chile event
  - Interesting physics
  - Numerically difficult to model
  - Complex runup

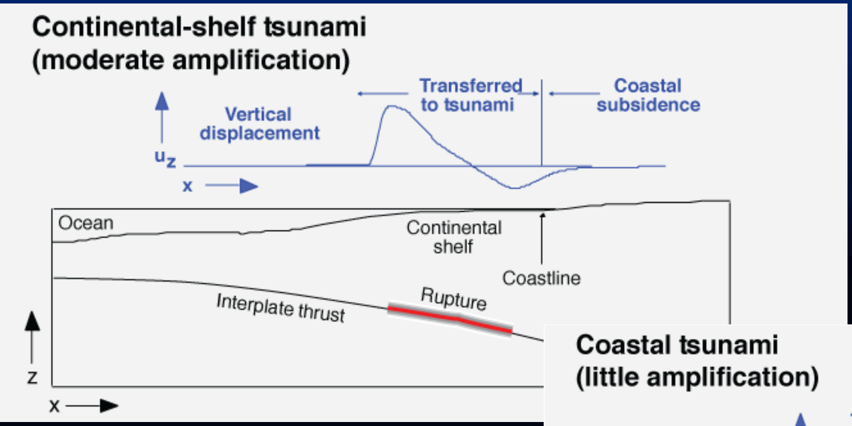
Conclusions (2 of 3)

- Max. tsunami amplitude oblique to regions of high slip are associated with late edge wave arrivals
  - Scattering from coastline irregularities
  - First arrival dominant broadside from high slip

Conclusions (3 of 3)

- Multiple high slip regions can result in multiple sources of edge waves and constructive interference
  - Dependent on slip distribution
  - Effect of near shore subsidence unknown
  - Other way edge waves can be generated

Chile 2010: Effect of Earthquake Depth



Chile 2010