Tsunami forecasting with assimilation of tsunami data on dense arrays:

the 2009 Dusky Sound, New Zealand, tsunami

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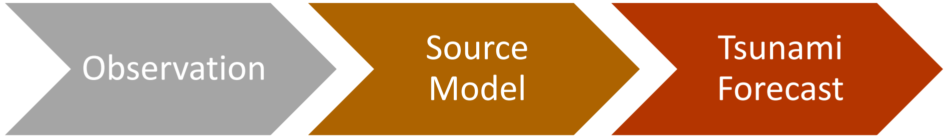
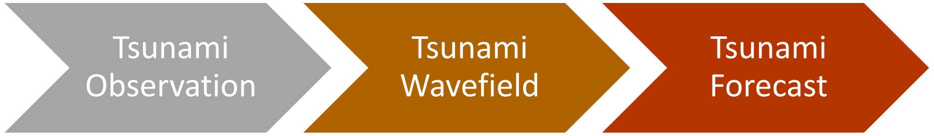
Background (Tsunami Forecasting)

Traditional approach



Data assimilation



	Traditional Approach: Source modeling	Data Assimilation
Source Model	Required • Earthquake model • Sea surface model	Not required
Observation	• Seismic • Tsunami • Crustal movement	Tsunami dense array
Forecasting	• Forward modeling • Pre-computed database	Forward modeling
Coverage	Global	Regional or local

Objective

- **Evaluate different approaches for tsunami forecasting**
  1. Tsunami scenario database (threat level maps) for New Zealand
  2. **Tsunami data assimilation** using MOANA dense array
  3. W Phase source inversion and **tsunami data assimilation**
- Estimate the earthquake source model by a tsunami waveform inversion and simulate the tsunami to get a **reference tsunami threat level map** for the evaluation.

Tsunami data assimilation

Source: Far-field

Tsunami waveforms: Generated from a hypothetical earthquake

Method

Wavefield obtained by solving the linear shallow water equations.

$$X_n^f \equiv F X_{n-1}^a$$

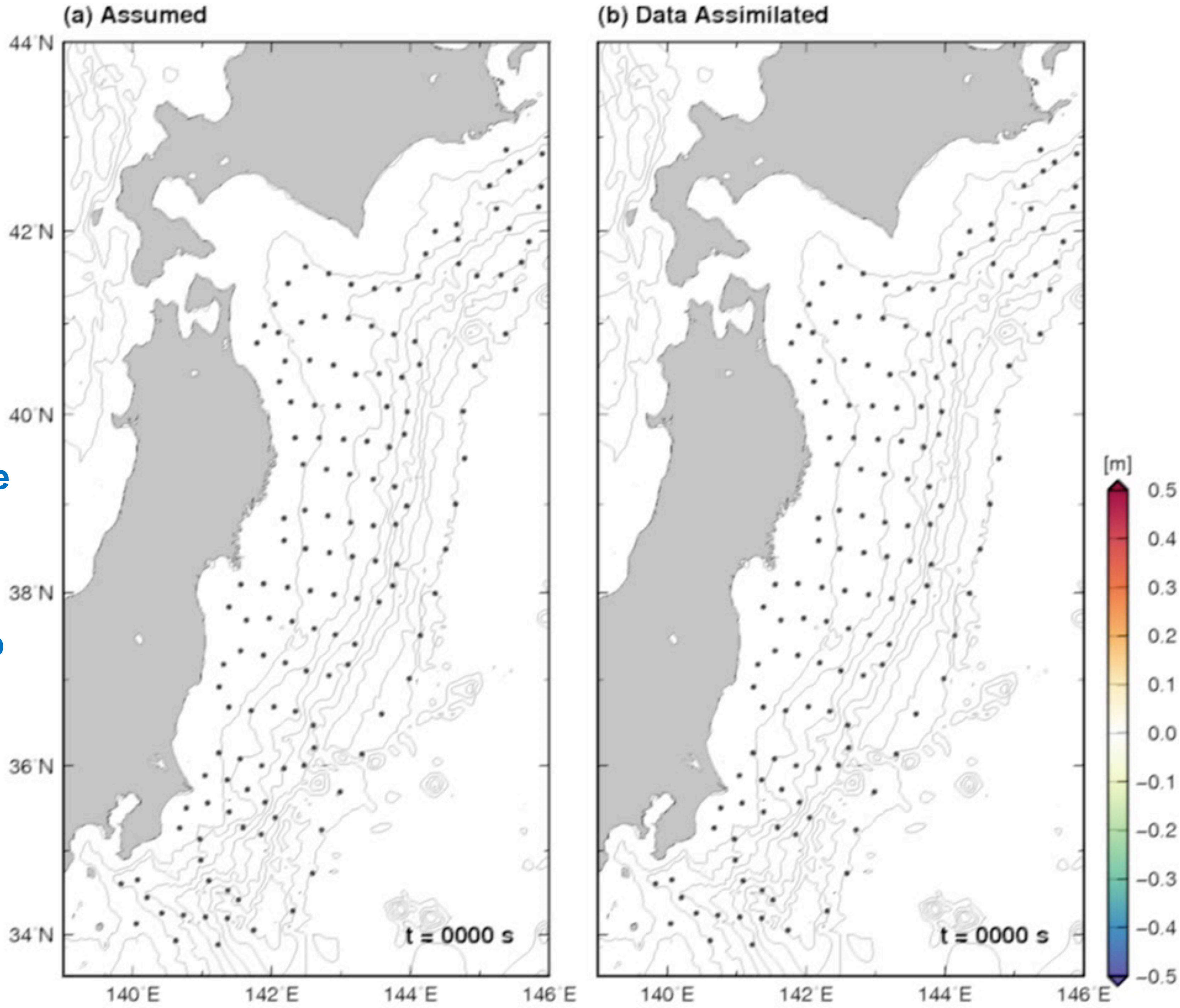
Residual for the current time step

$$y_n - H X_n^f$$

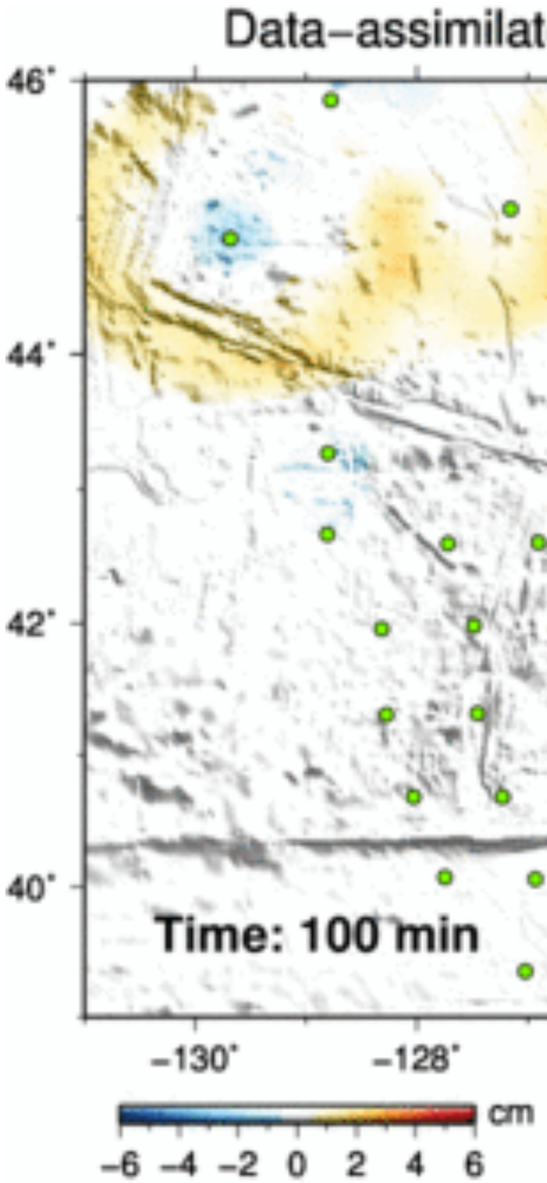
Data-assimilated wavefield

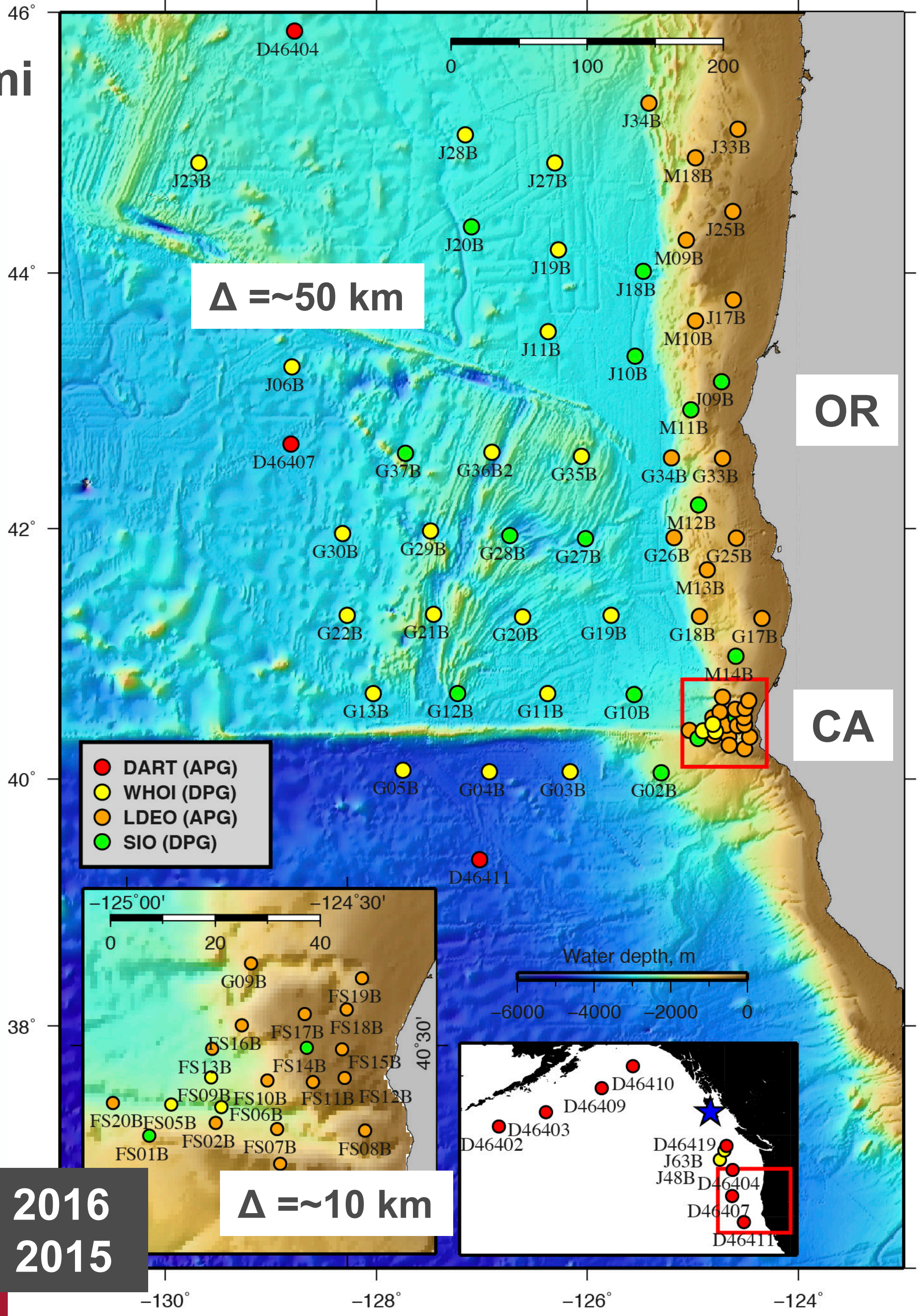
$$X_n^a = X_n^f + W\left[y_n - H X_n^f\right]$$

Maeda et al., GRL, 2015



The 2012 Haida Gwaii Earthquake and tsunami

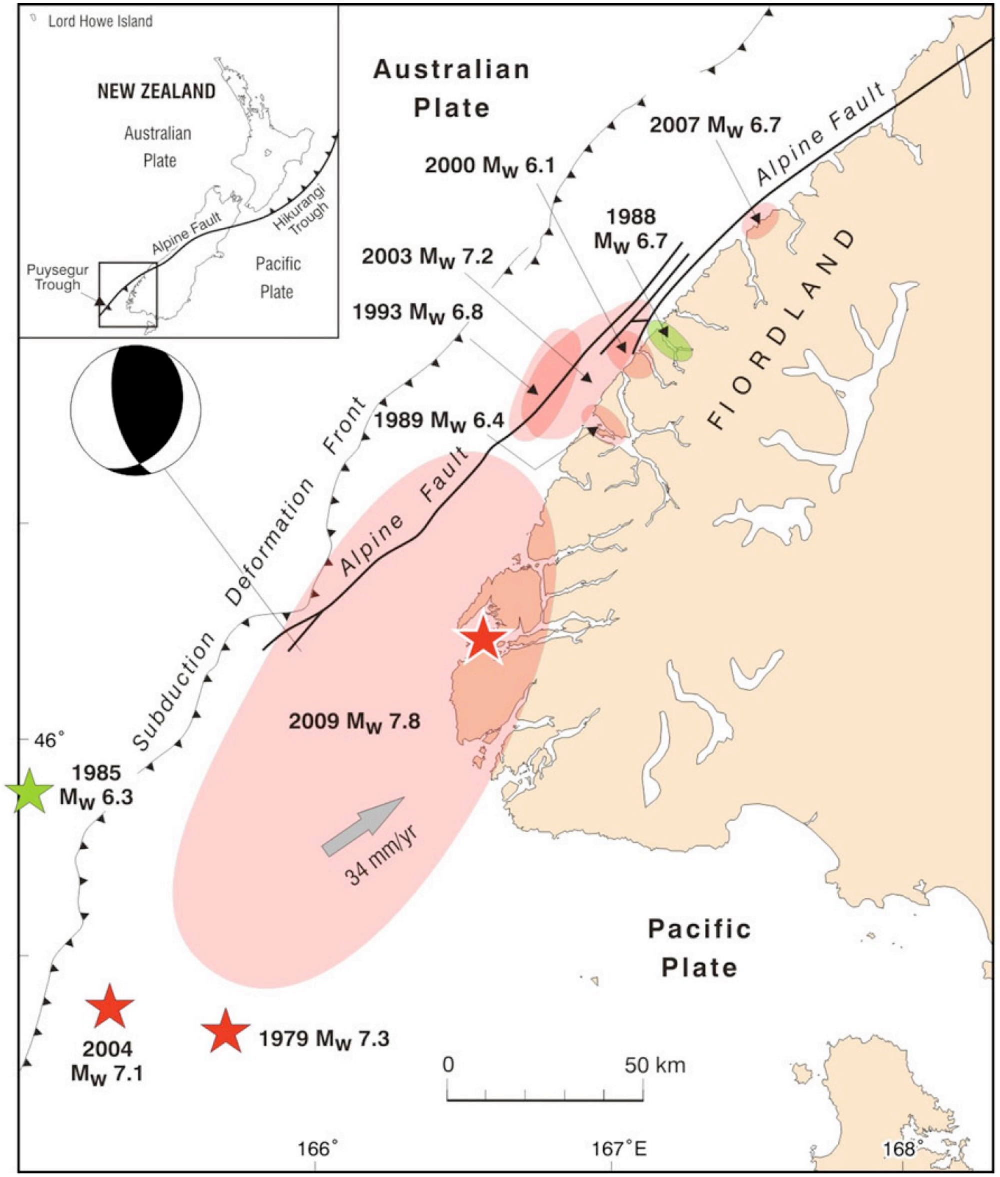




Cascadia Initiative Dense Array

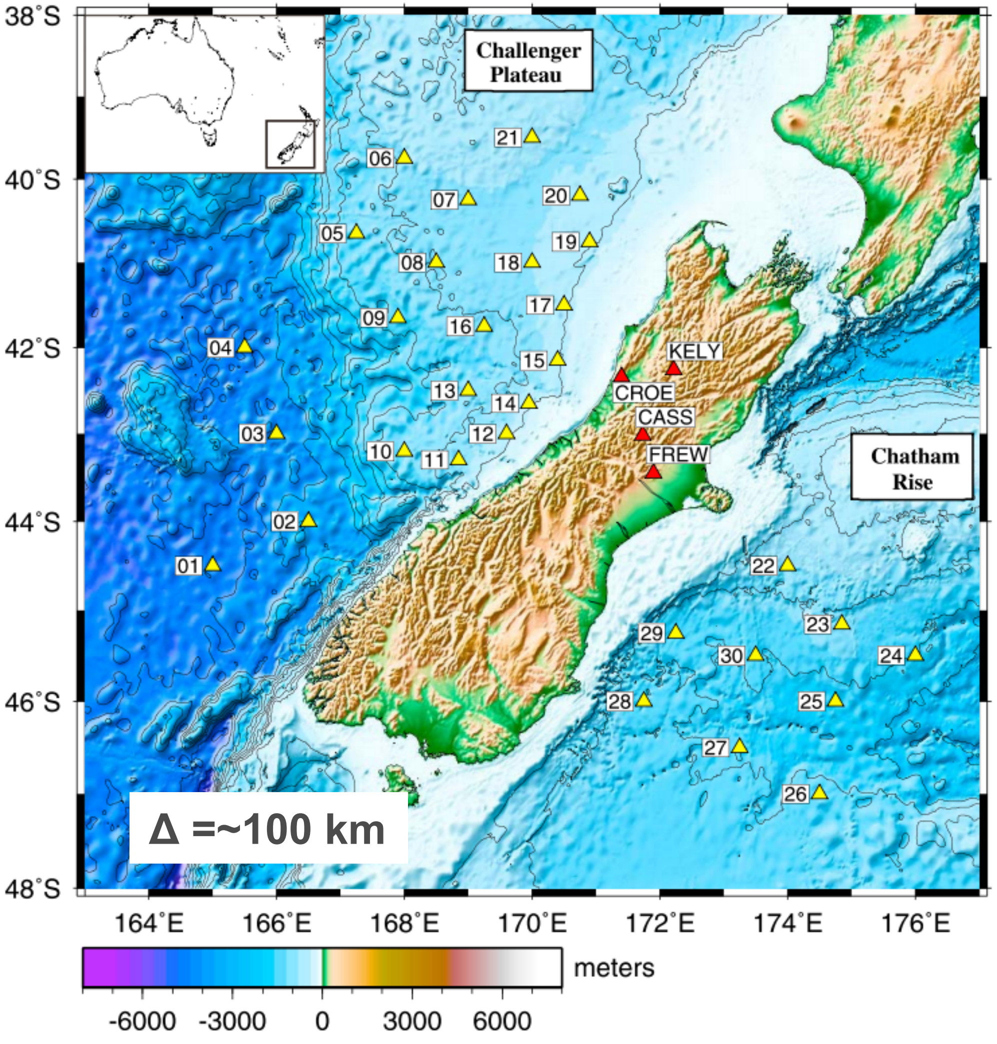
Gusman et al., GRL, 2016
Sheehan et al., SRL, 2015

The 15 July 2009 Dusky Sound Earthquake and tsunami

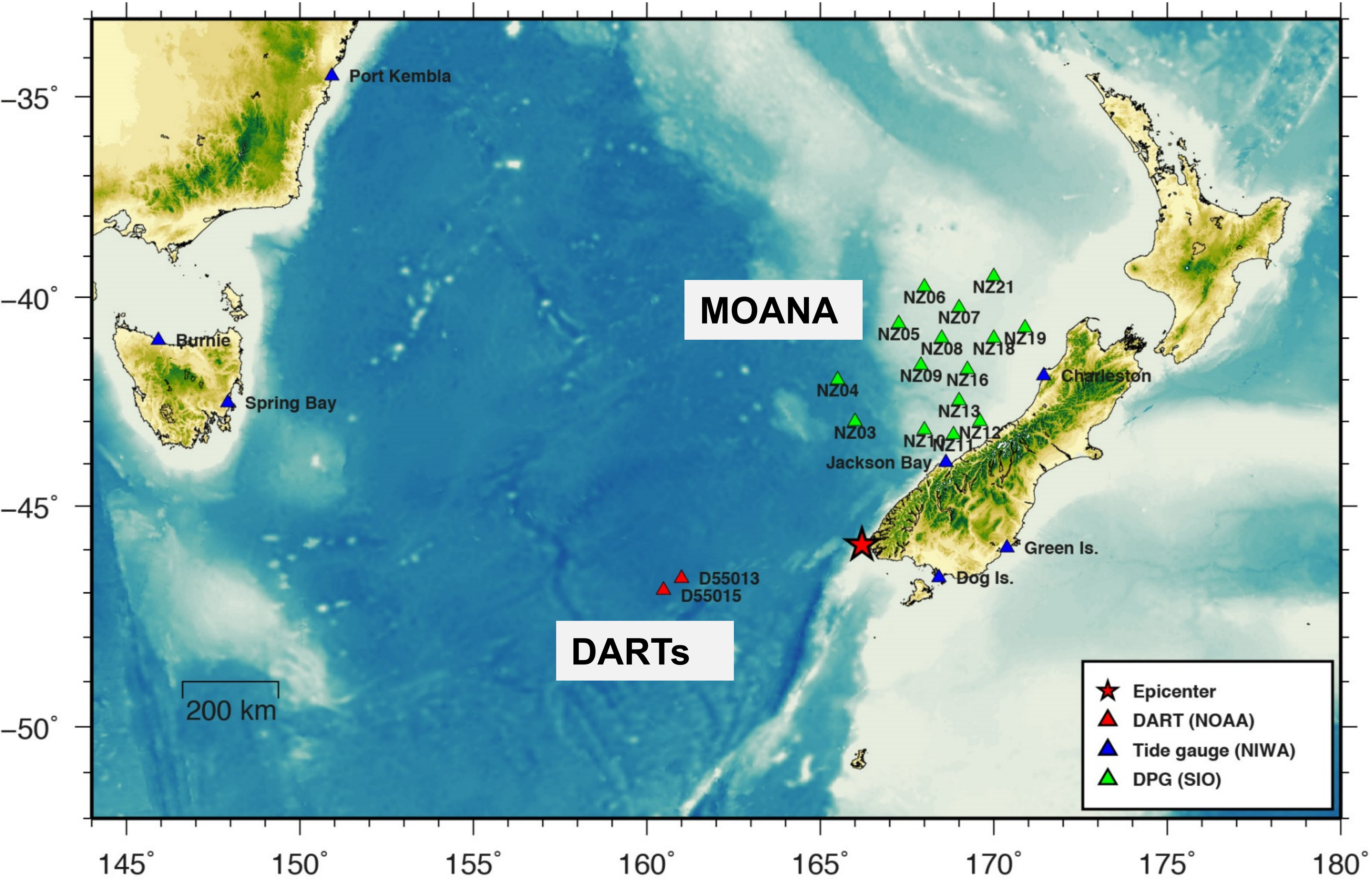


Fry et al. (BNZSEE, 2010)

MOANA (Marine Observations of Anisotropy Near Aotearoa) seismic experiment deployed west and east of South Island, New Zealand (**2009–2010**).

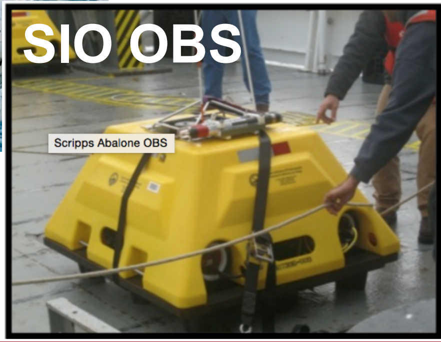


Tsunami Observations

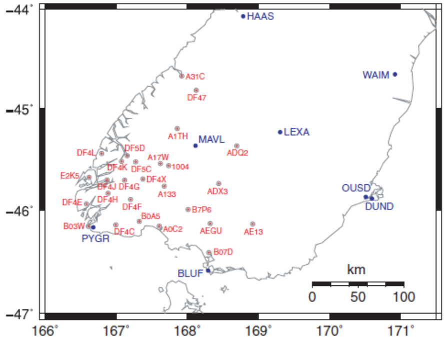


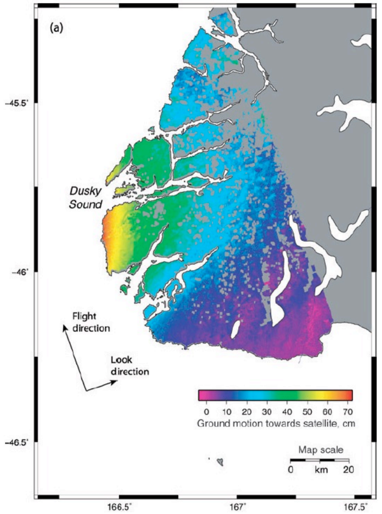
Observation stations

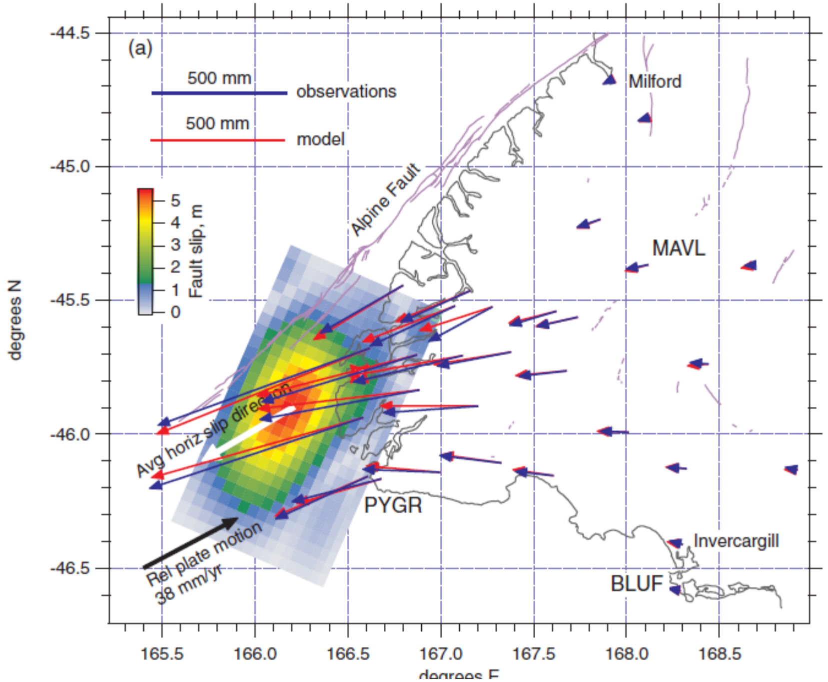
- 7 Tide gauges
- 2 DART buoys (absolute pressure gauges)
- 15 Differential pressure gauges (MOANA OBS network – Scripps Institute of Oceanography)

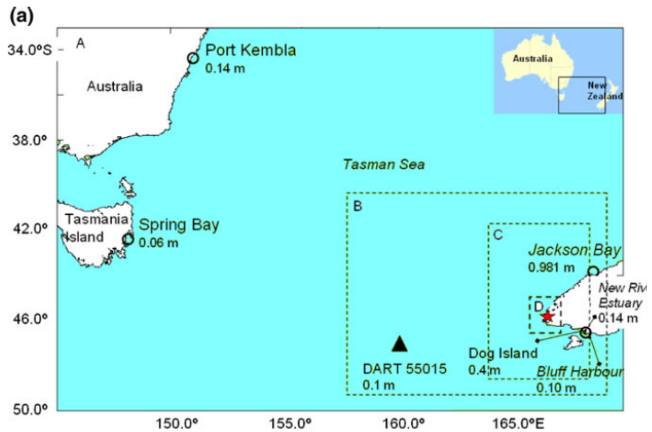


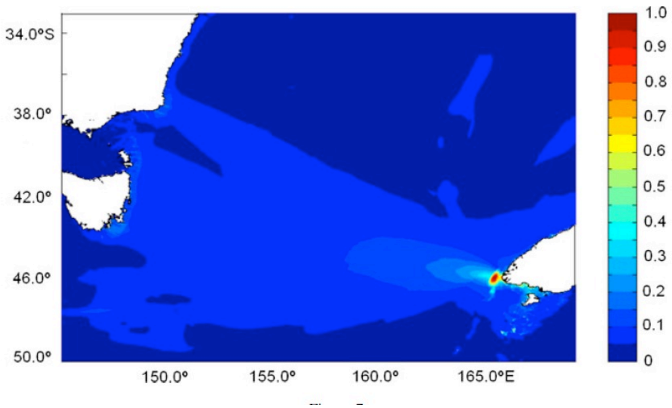
Previous earthquake source model and tsunami simulation

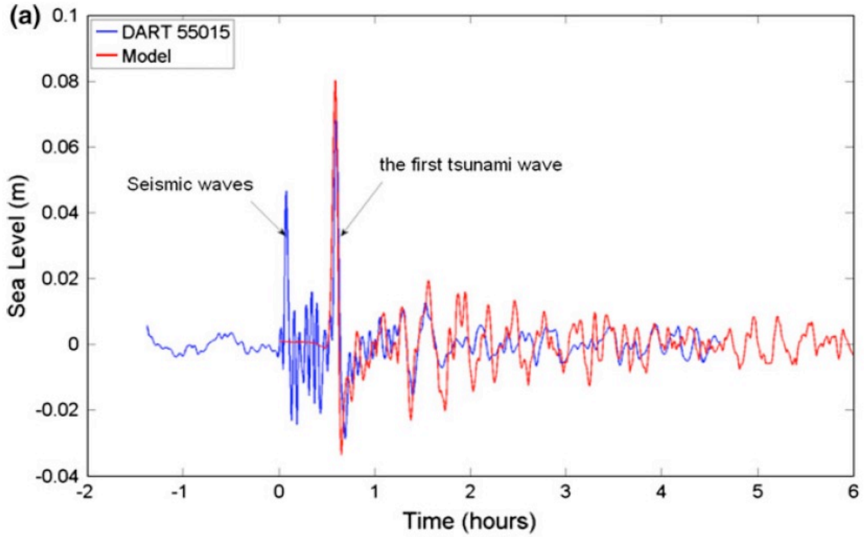


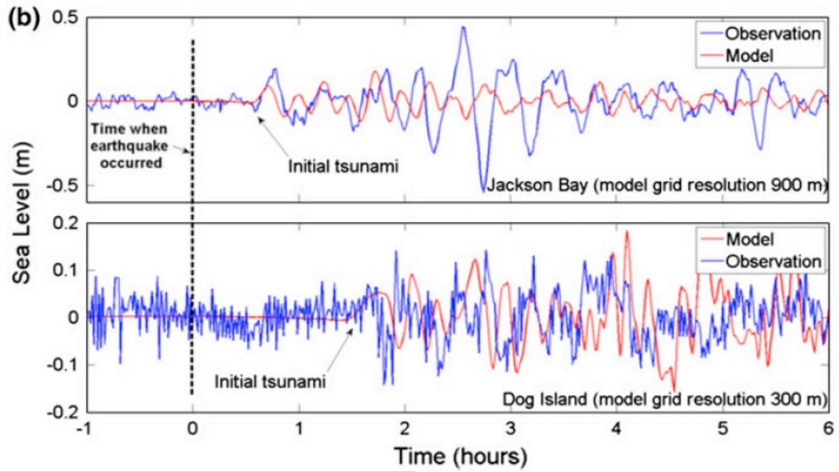










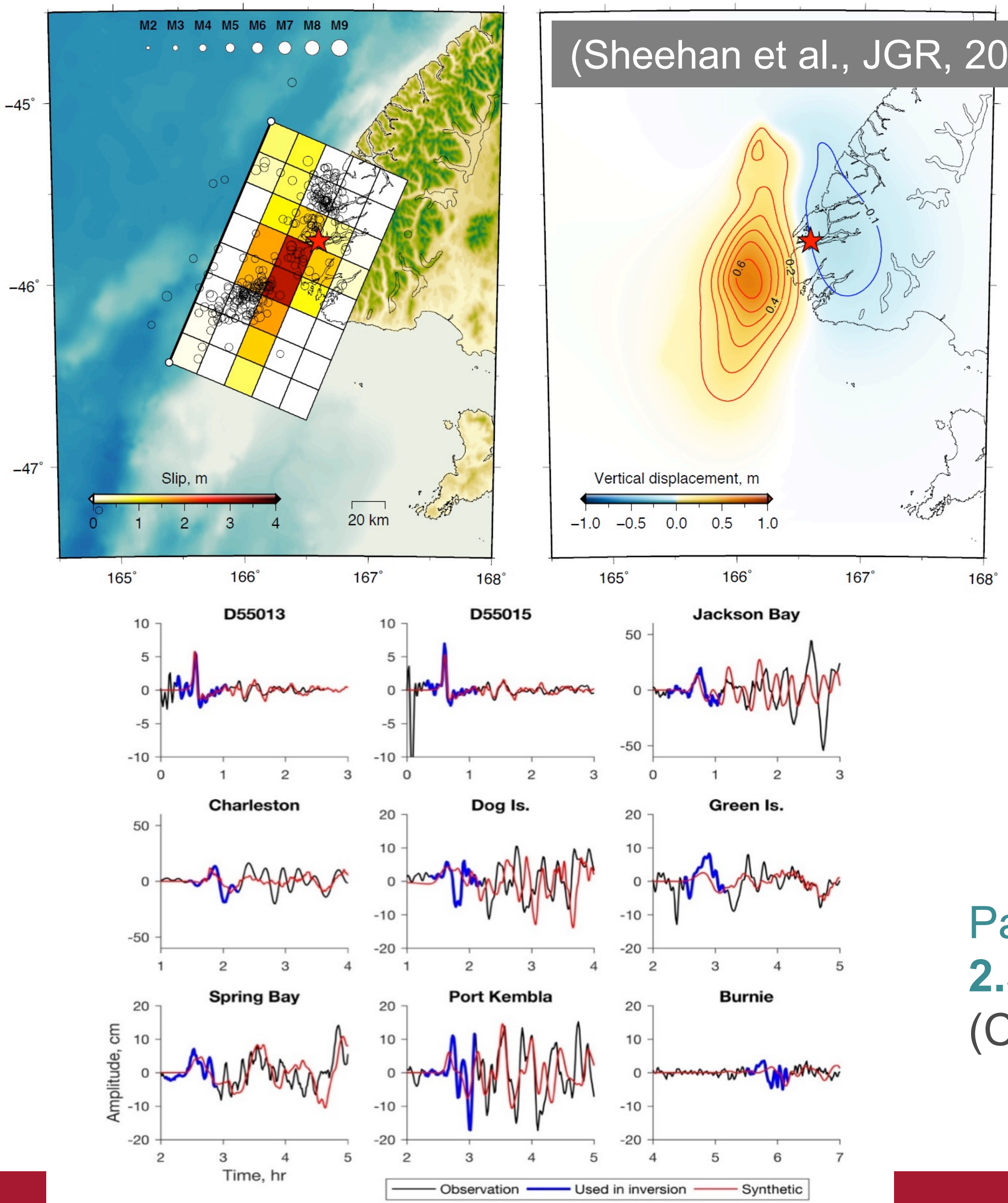


Prasetya et al., PAGEOPH, 2011

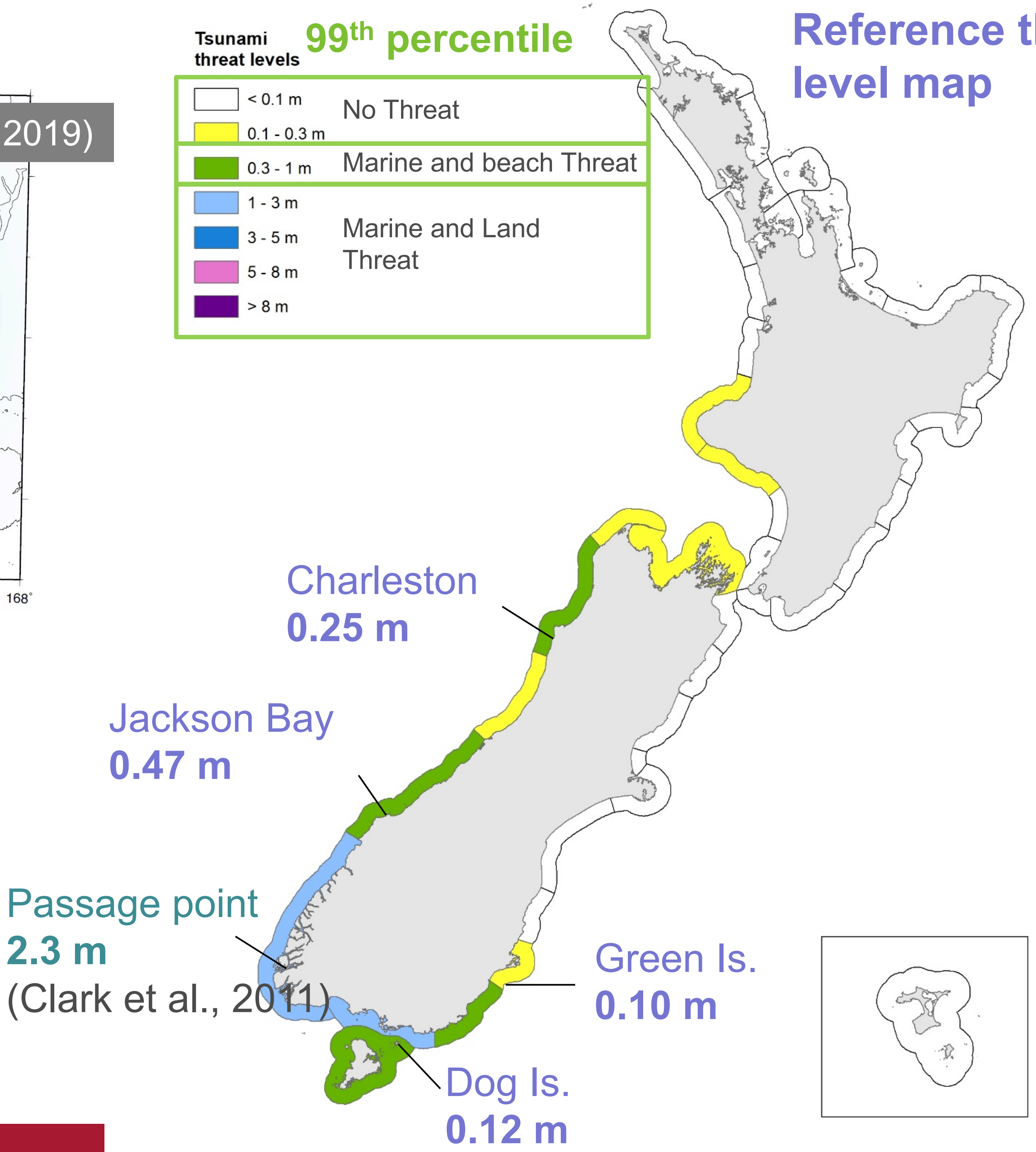
Beavan et al., GJI, 2010

Earthquake source model

(Sheehan et al., JGR, 2019)



Reference threat level map



GeoNet Geological hazard information for New Zealand

EQC

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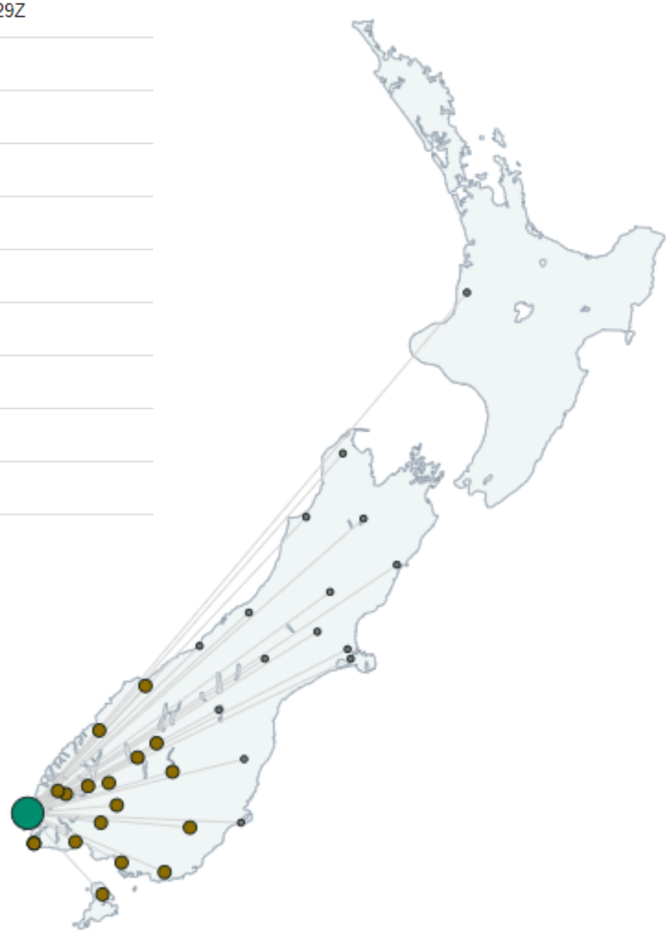
Origin

PublicID	3124785
UTC Time	2009-07-15T09:22:29Z
Latitude	-45.77 (± 0.0 km)
Longitude	166.59 (± 0.0 km)
Depth	12 km (± 0 km)
Depth Type	operator assigned
Earth Model	nz1dr
Used Phase Count	19
Used Station Count	17
Standard Error	0.16 (s)
Azimuthal Gap	230.00 (degrees)
Minimum Distance	0.40 (degrees)

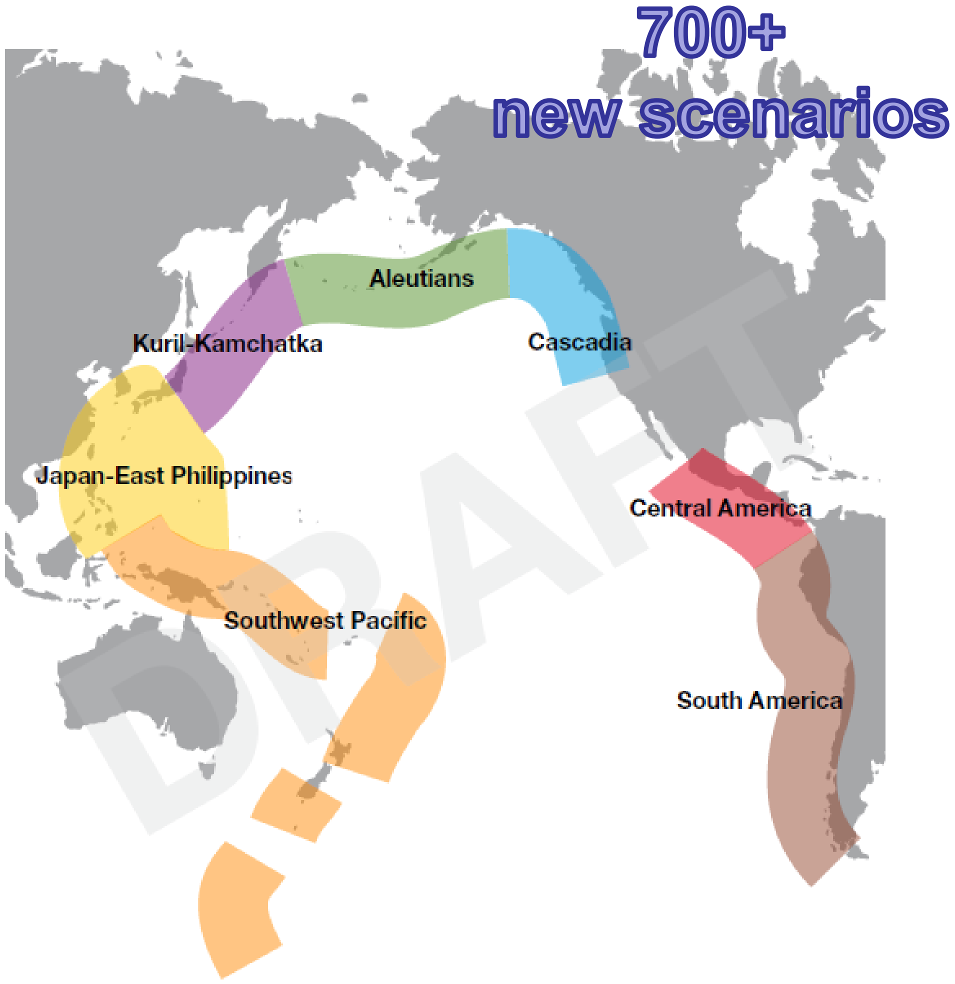
Magnitudes

TYPE	MAGNITUDE
Preferred (Mw)	7.8
Mw	7.8

Latitude	Longitude	Magnitude
-45.77°	166.59°	7.8



TSUNAMI SCENARIO DATABASE



Version 3.00 May 2019

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It is not recommended to use this document after this date.

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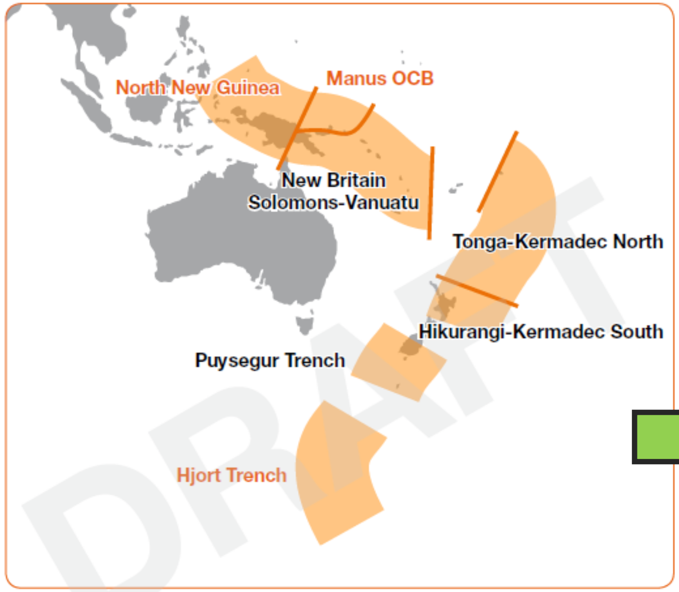
User Guidelines

Tsunami Scenario Database

Latitude	Longitude	Magnitude
-45.77°	166.59°	7.8

Main Index Map >> Southwest Pacific

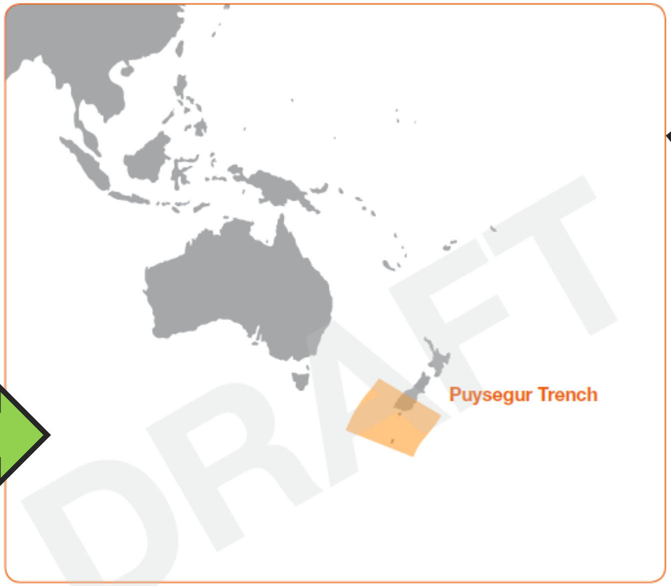
Southwest Pacific



Sub-region (Magnitudes)		Page
North New Guinea (8.7, 8.9, 9.1 and 9.3)	Select	32
Manus OCB (8.7, 8.9, 9.1 and 9.3)	Select	33
New Britain-Solomons-Vanuatu	Select	10
Tonga-Kermadec North	Select	11
Hikurangi-Kermadec South	Select	12
Puysegur Trench	Select	13
Hjort Trench (8.1, 8.3, 8.5, 8.7, 8.9, 9.1 and 9.3)	Select	47

Main Index Map >> Southwest Pacific >> Puysegur Trench

Puysegur Trench

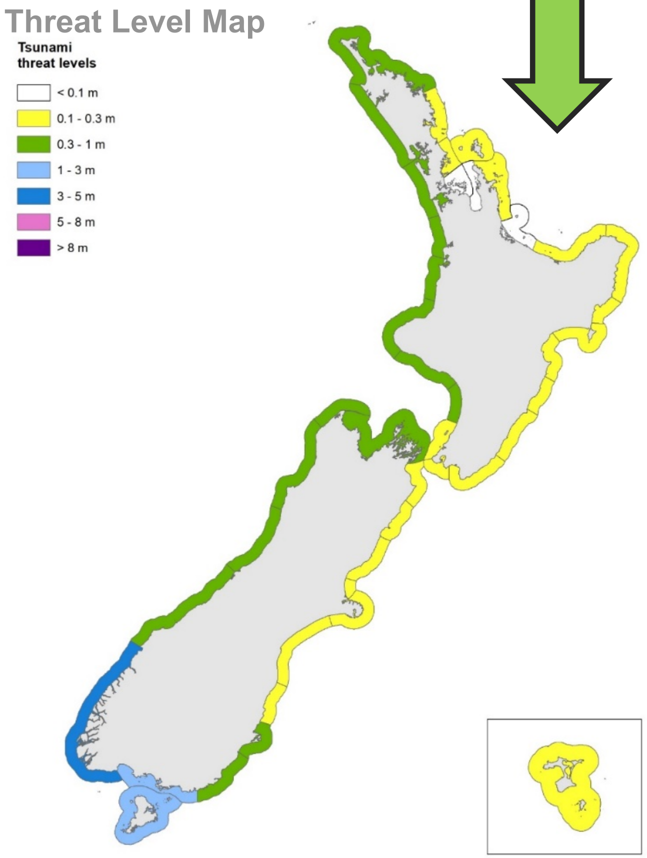


Magnitude		Page
7.5, 7.7 and 7.9	Select	45
8.1, 8.3, 8.5, 8.7, 8.9, 9.1 and 9.3	Select	46

Puysegur Trench

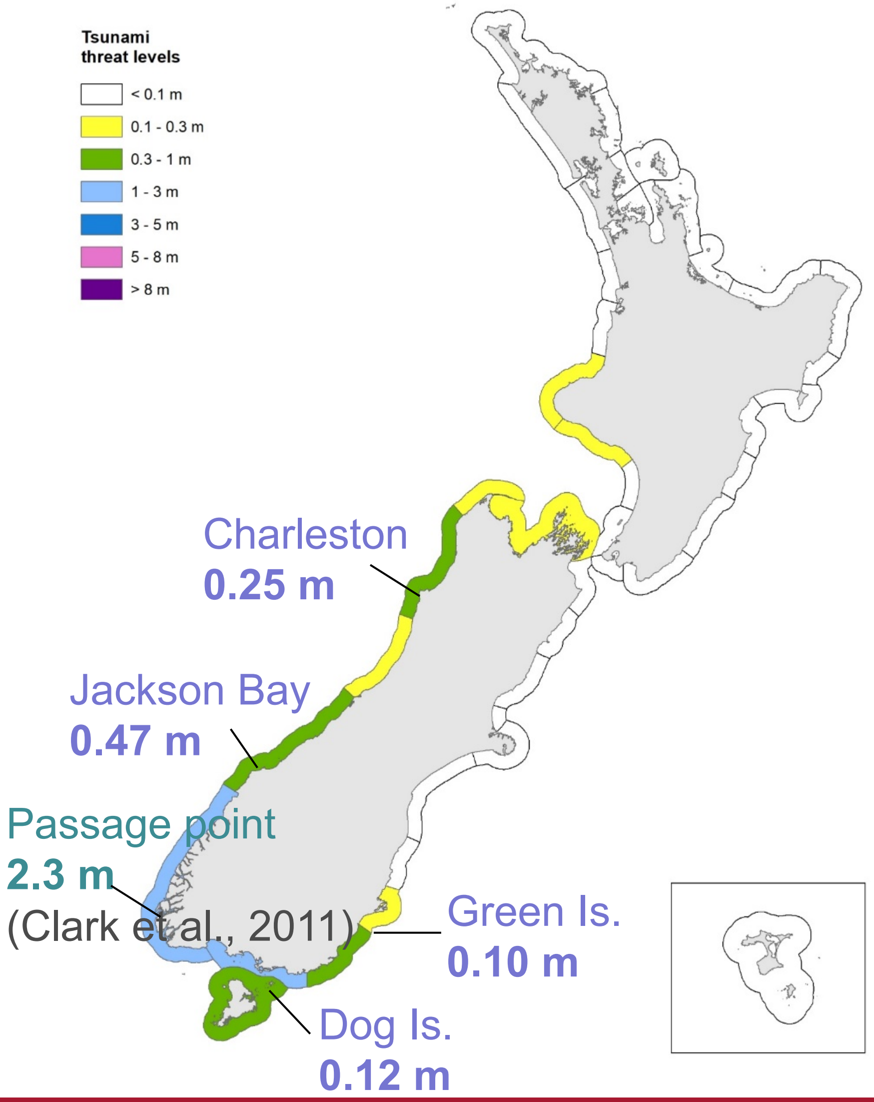
Magnitude	Location		Risk Map	Page
7.5	Long	Lat		
	164.5 E	48.8 S	Map	1284
	165.1 E	47.5 S	Map	1286
	165.7 E	46.2 S	Map	1288
7.7	Long	Lat		
	164.5 E	48.8 S	Map	1290
	165.1 E	47.5 S	Map	1292
	165.7 E	46.2 S	Map	1294
7.9	Long	Lat		
	164.5 E	48.8 S	Map	1296
	165.1 E	47.5 S	Map	1298
	165.7 E	46.2 S	Map	[illegible]

Threat Level Map

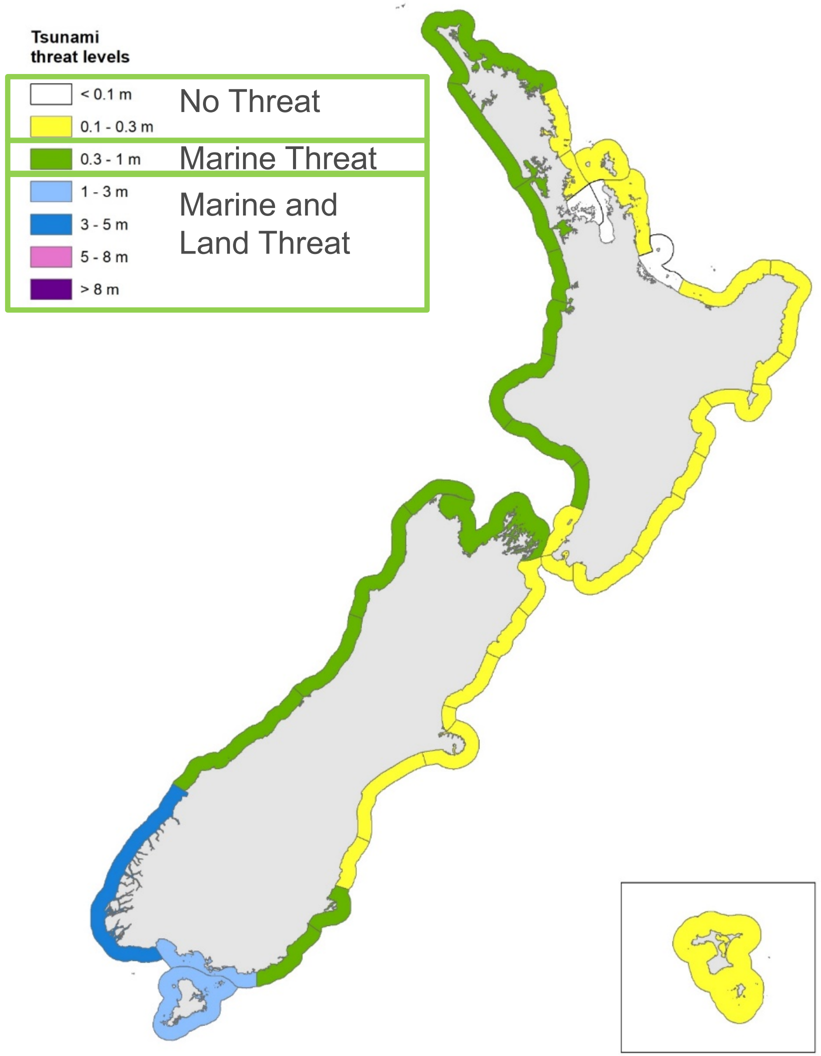


Tsunami Scenario Database

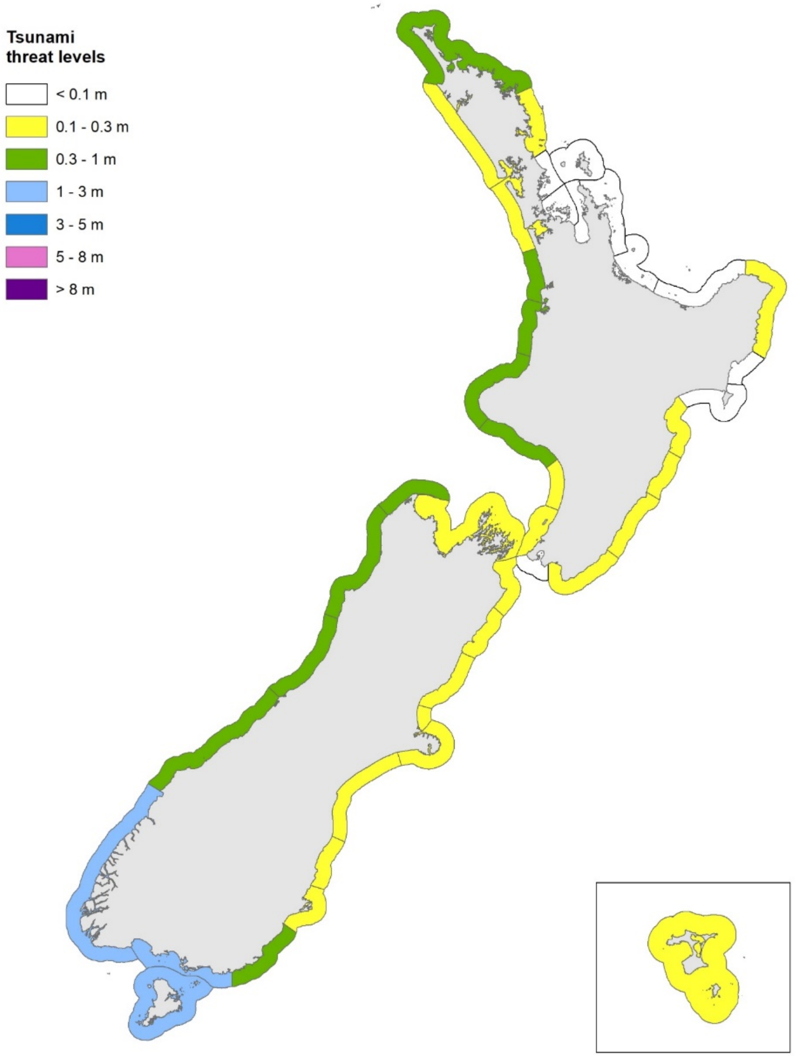
Reference model
Actual earthquake magnitude: 7.8



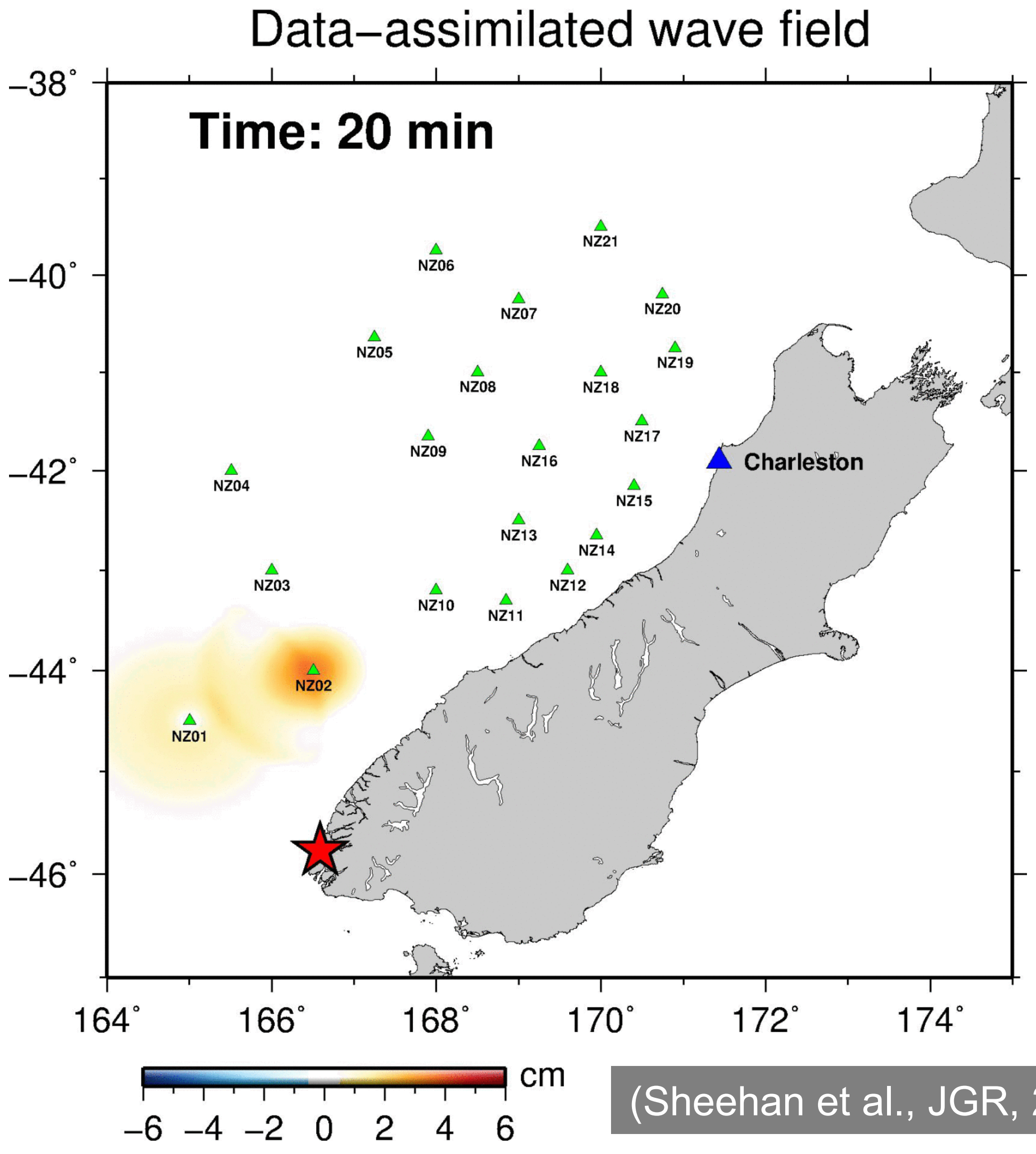
Tsunami threat level database
Scenario magnitude: 7.9

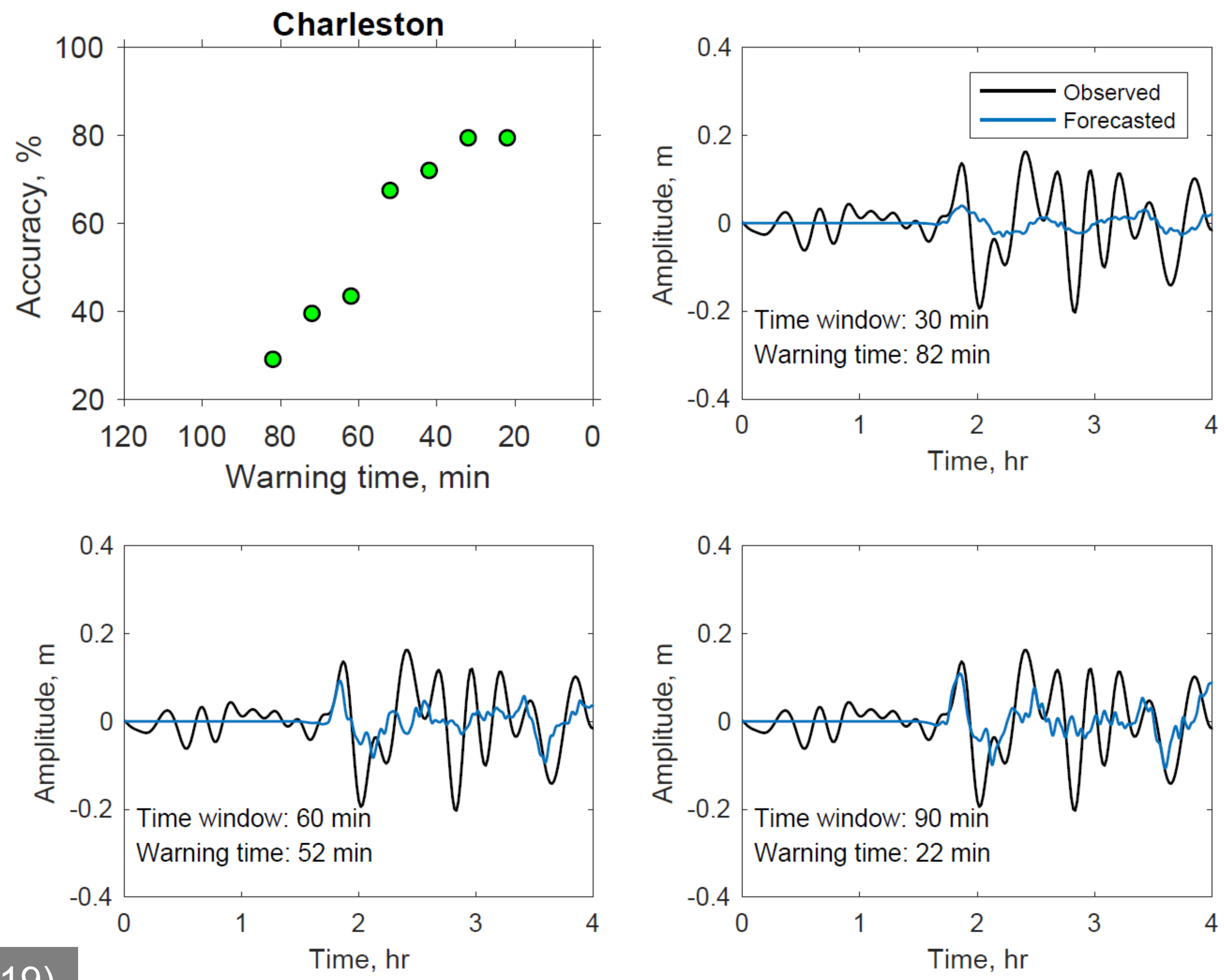


Tsunami threat level database
Scenario magnitude: 7.7



Tsunami Data Assimilation

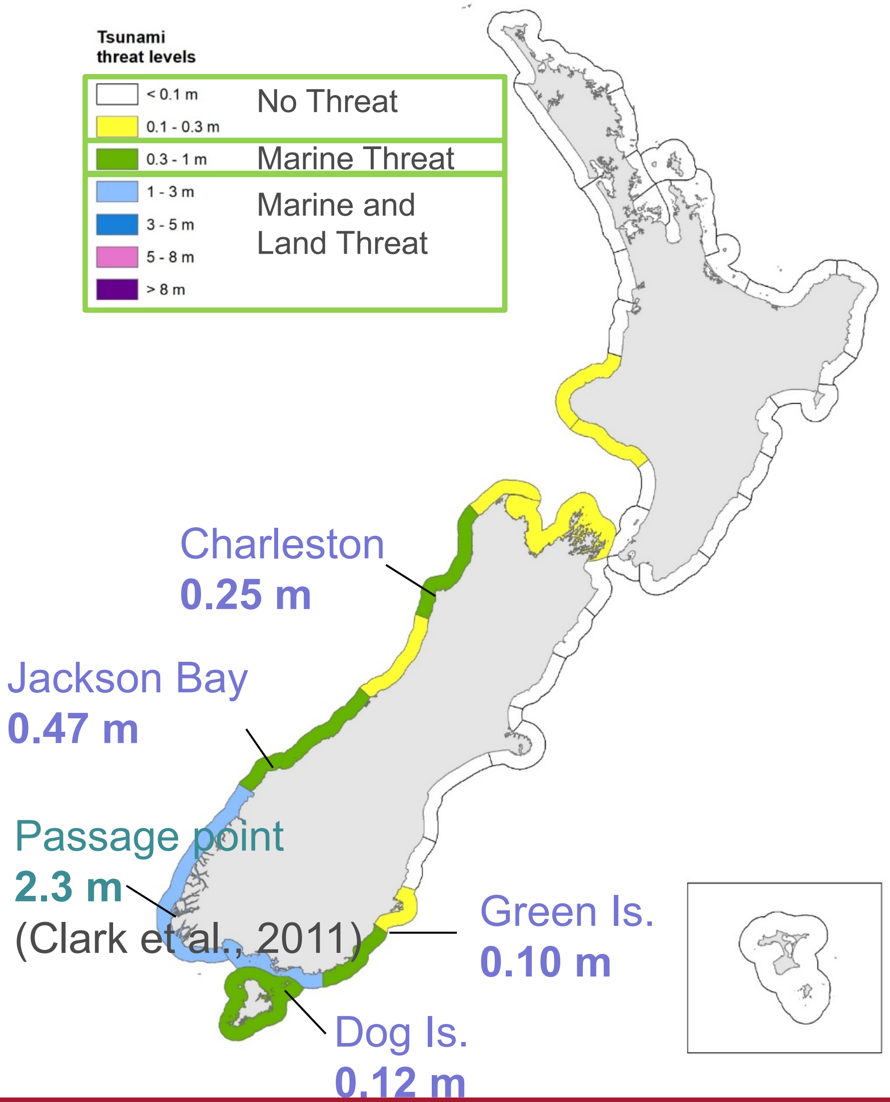




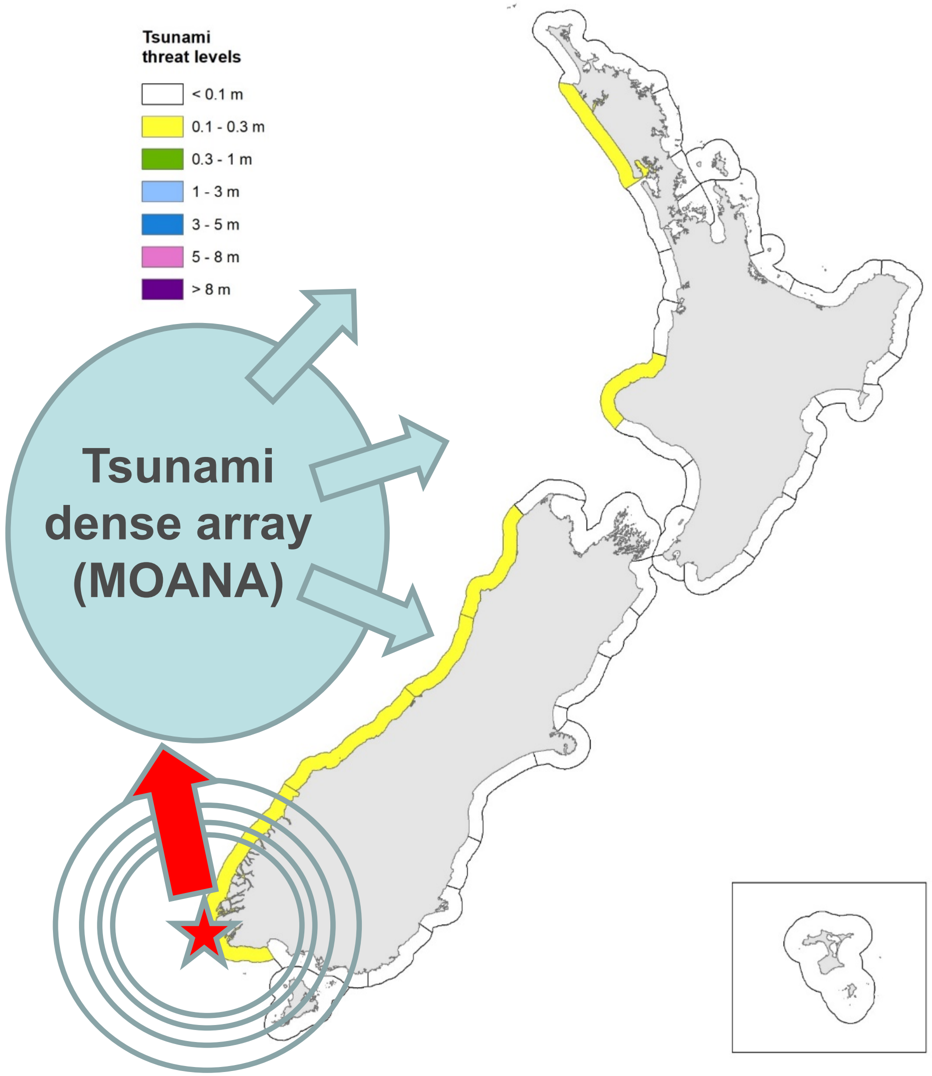
(Sheehan et al., JGR, 2019)

Tsunami Data Assimilation

Reference model
Actual earthquake magnitude: 7.8

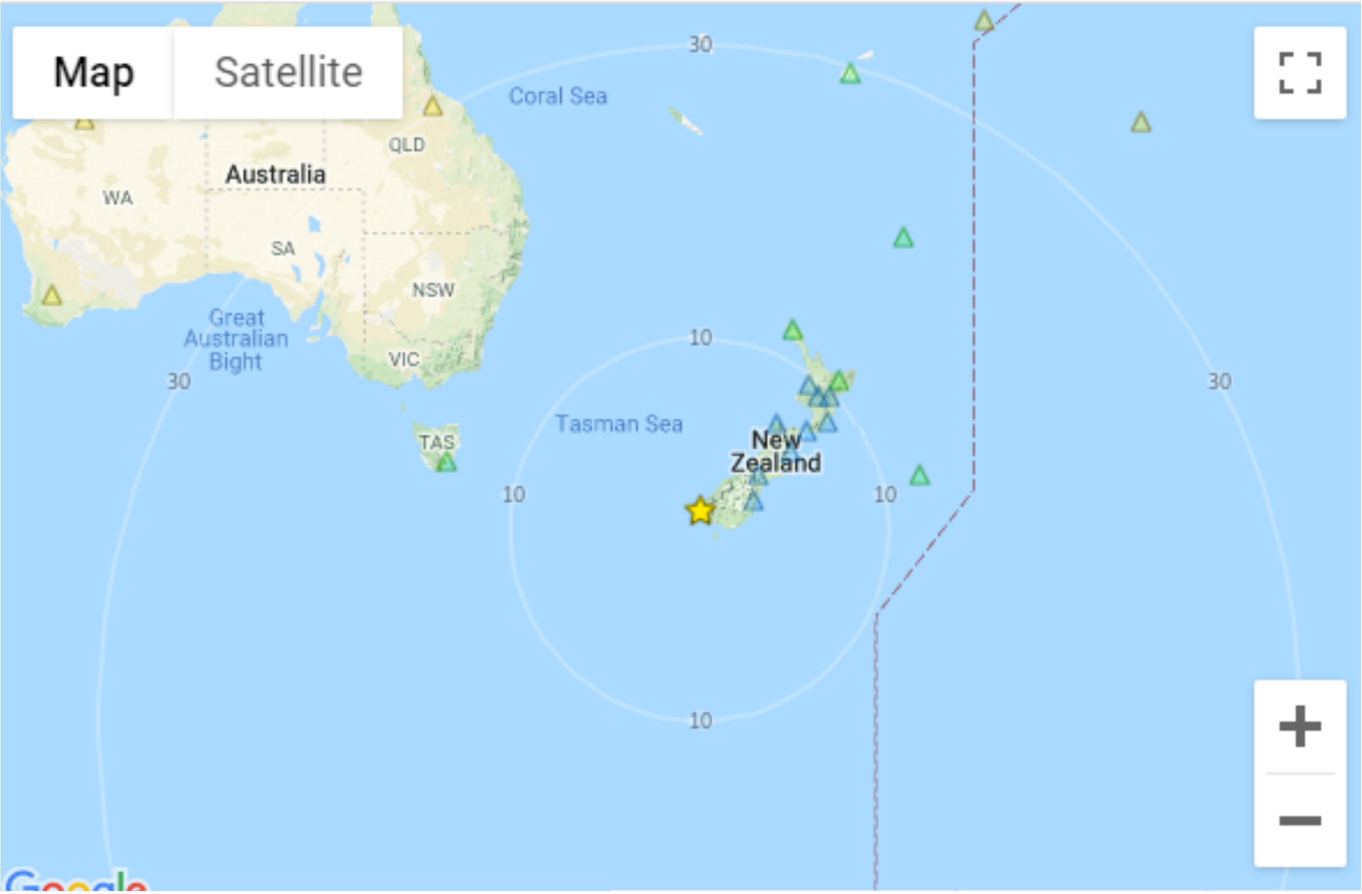


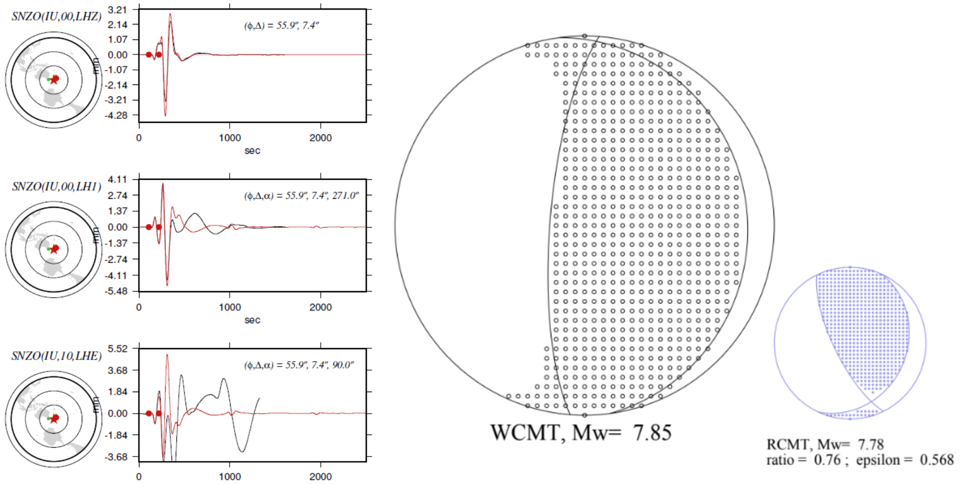
Tsunami data assimilation



W-Phase Source Inversion

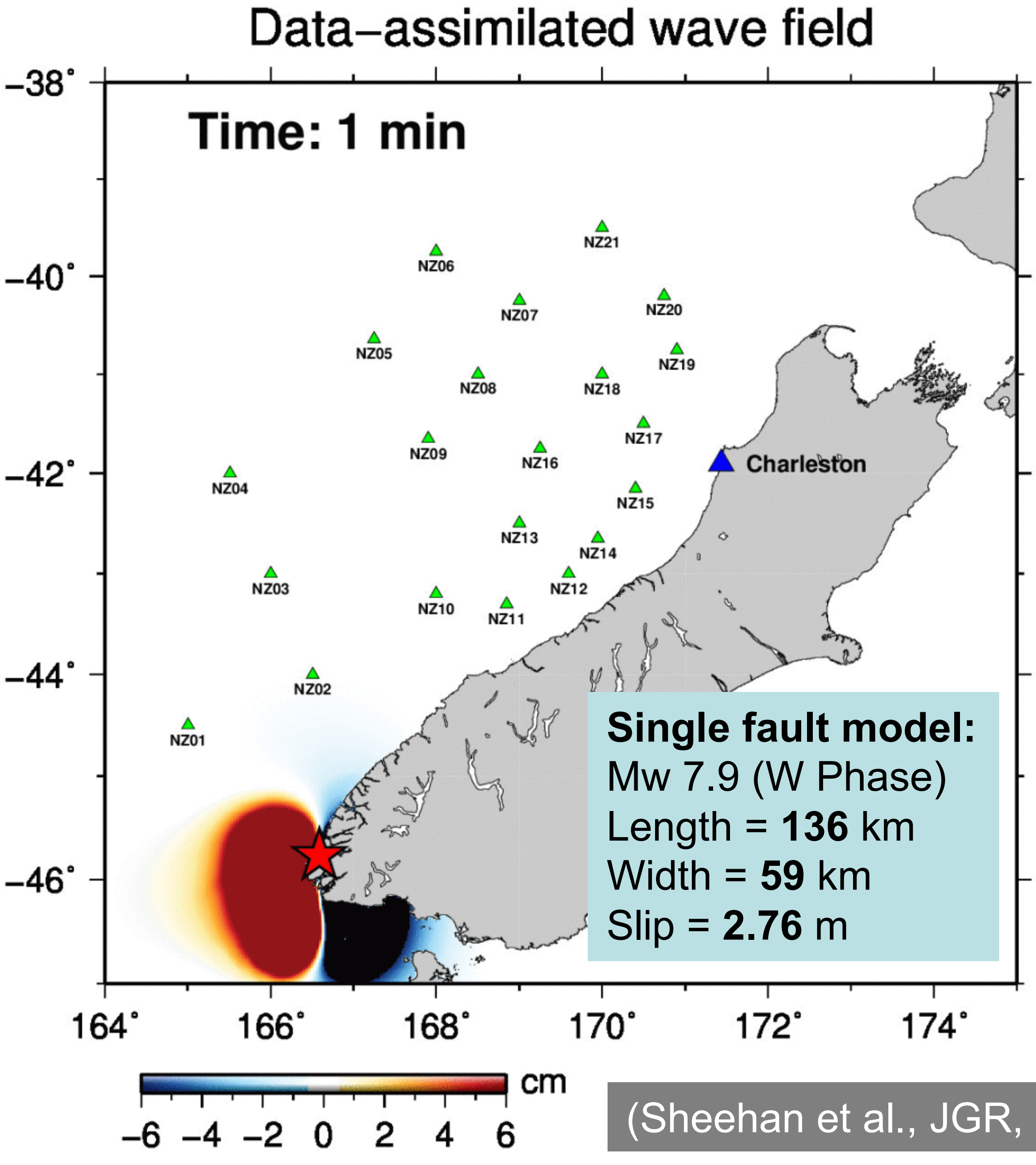
W phase is a long period **phase** arriving before S wave. It can be interpreted as superposition of the fundamental, first, second and third overtones of spheroidal modes or Rayleigh waves and has a group velocity from 4.5 to 9 km s− 1 over a period range of 100–1000 s (Kanamori and Rivera, 2008; Duputel et al., 2012).





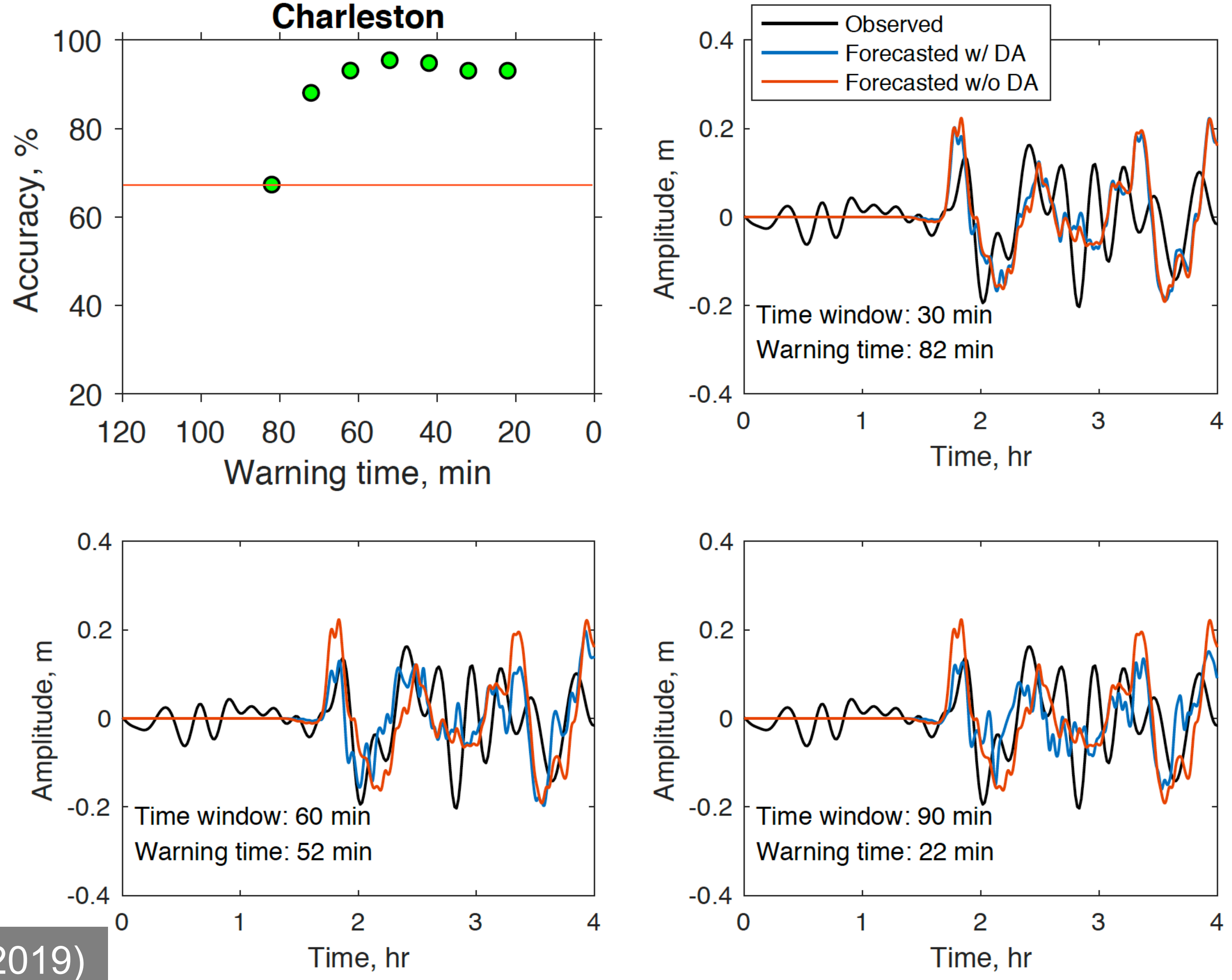
Moment Tensor	7 minutes data (15° epicentral distance)	GCMT solution
Lon	166.404°	166.26°
Lat	-46.150°	-45.85°
Magnitude (Mw)	7.9	7.8
Strike	353°	25°
Dip	15°	26°
Rake	79°	138°
Depth	23.5 km	23.5 km

W Phase Source Inversion + Tsunami Data Assimilation



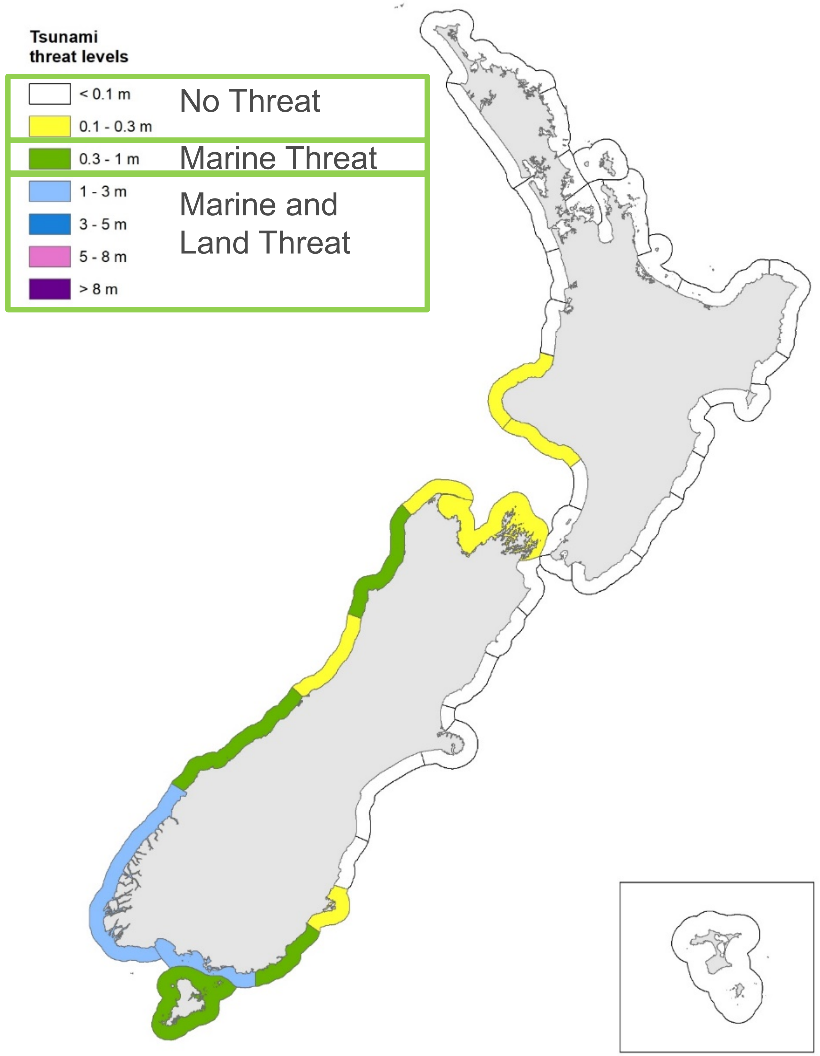
Single fault model:
Mw 7.9 (W Phase)
Length = **136** km
Width = **59** km
Slip = **2.76** m

(Sheehan et al., JGR, 2019)

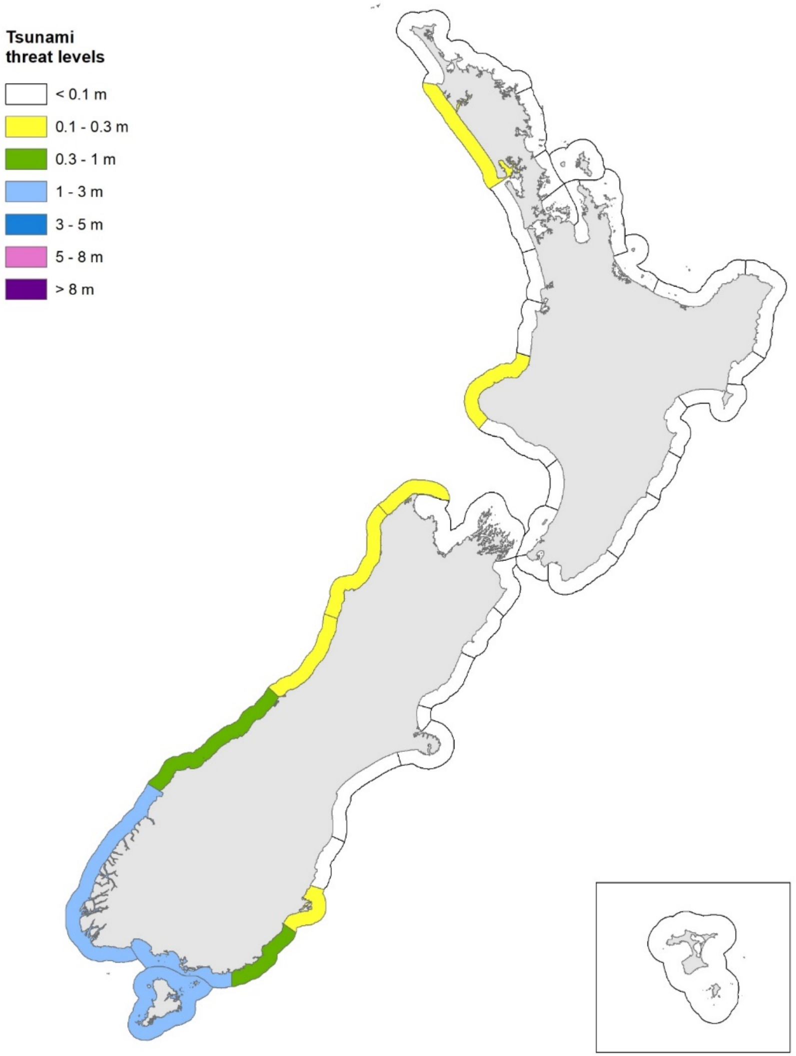


W Phase Source Inversion + Tsunami Data Assimilation

Reference model
Actual earthquake magnitude: 7.8



Fault model (Mw 7.9)
+ tsunami data assimilation



Summary

We have evaluated three tsunami forecasting approaches for the case of the 2009 Dusky Sound earthquake and tsunami:

1. **Tsunami scenario database**: The forecasted tsunami threats are one level higher than the reference in many regions. The scenario magnitude is higher than the actual one and the scenario is a pure thrusting fault.
2. **Tsunami data assimilation**: Gives good forecast of tsunami threat only in regions covered by the tsunami array network. Can forecast tsunamis without any source information.
3. **W phase source inversion and tsunami data assimilation**: Gives the most similar forecast to the reference. The fault model has fault parameters similar to the reference model. The tsunami data assimilation corrects tsunami amplitude.