3rd QUEST Workshop
Monday, 21st May

Uncertainty in CMT-style source inversion: A problem for full-waveform inversion?

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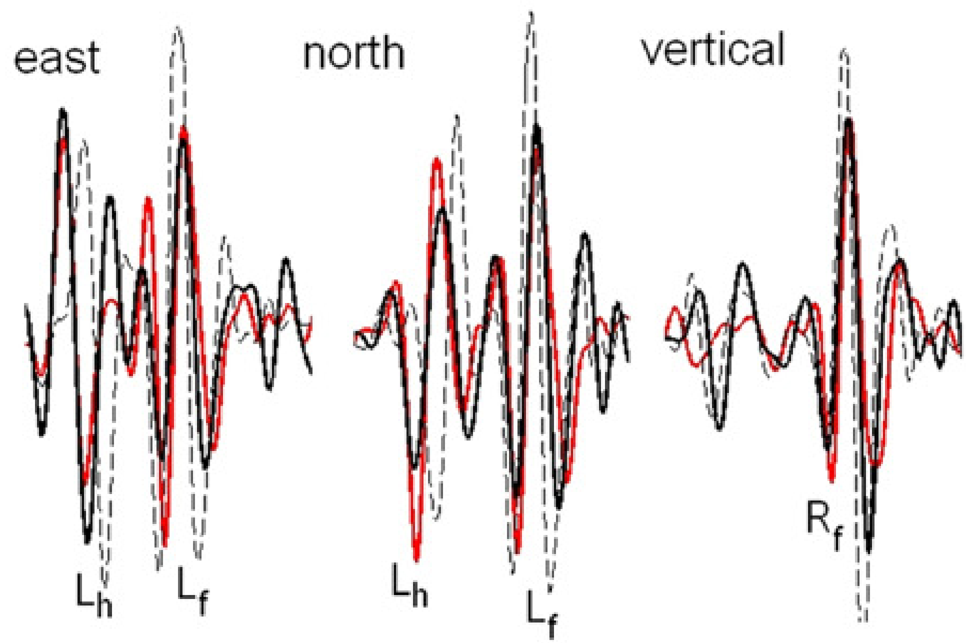
Full-waveform inversion: try to make synthetic waveforms match data as closely as possible

→ Improve earth model

But what about source parameters? Often, these simply come from catalogues… are they accurate enough?

Can inaccuracies in source parameters alter synthetic seismograms enough to introduce model biases?



From Fichtner et al., 2010.

We will focus on the CMT algorithm:

- Well-known and widespread;
- Introduced by Dziewonski, Chou & Woodhouse (1981);
- Developed into method for routine determination by Dziewonski & Woodhouse (1983);
- Forms the basis of numerous catalogues, including the Global CMT Catalogue (GCMT).

But:

- Are CMT-derived source parameters accurate?
- What are the typical uncertainties on a CMT source determination?

Dziewonski, Chou & Woodhouse (1981), JGR, 86, pp.2825-2852.
Dziewonski & Woodhouse (1983), JGR, 88, pp.3247-3271.

Overview

Determine (up to) ten parameters:

- Six independent components of the seismic moment tensor;
- Centroid location (depth, lat, lon);
- Centroid time;

Represent these by the ten-component vector **f.**

Source is determined by matching seismic waveforms, **d**, to synthetic (forward-modelled) seismograms, **s**.

'Matching': Minimise least-squares misfit, $m^2 = \frac{(\mathbf{d}-\mathbf{s_i})^\mathbf{T}(\mathbf{d}-\mathbf{s_i})}{\mathbf{d^Td}}$

Leads to iterative algorithm of the form:

$$\mathbf{f_{i+1}} = \mathbf{f_i} + \left(\mathbf{A^TA}\right)^{-1}\mathbf{A^T}\left(\mathbf{d}-\mathbf{s_i}\right) \quad \text{where } A_{ij} = \frac{\partial s_i}{\partial f_j}$$

So, CMT source parameters are only as good as the synthetic seismograms used! (Earth model, wave propagation framework…)

What does `accuracy' mean in the context of source determination?

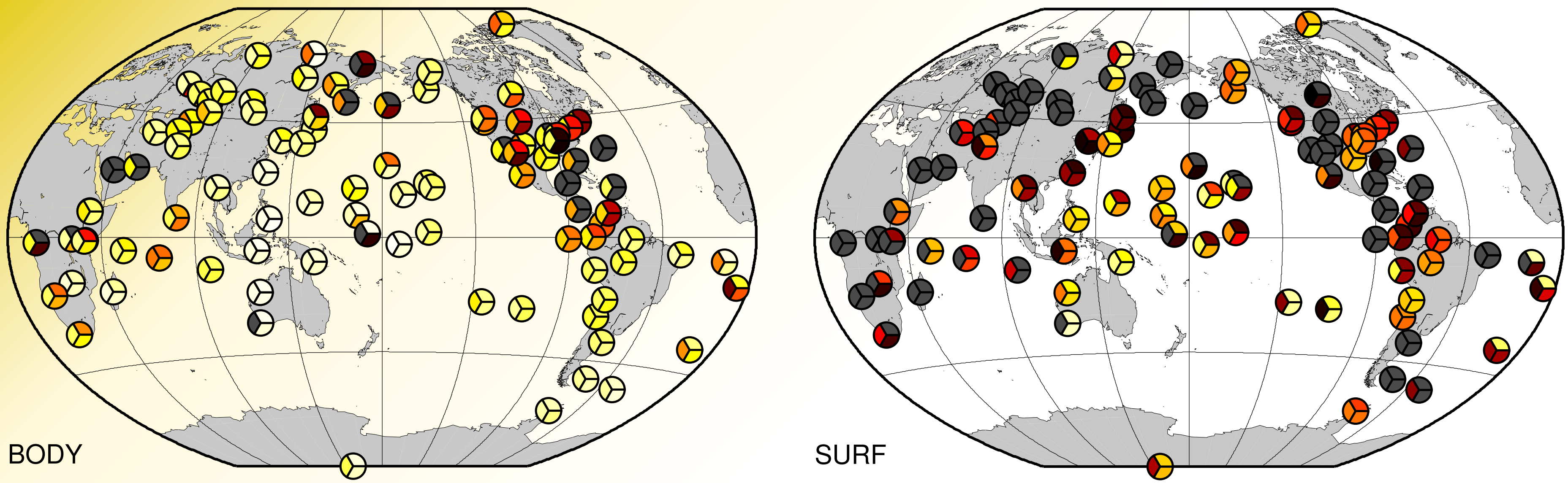
1 'Numerical' accuracy – how well do the final synthetic seismograms match the data?

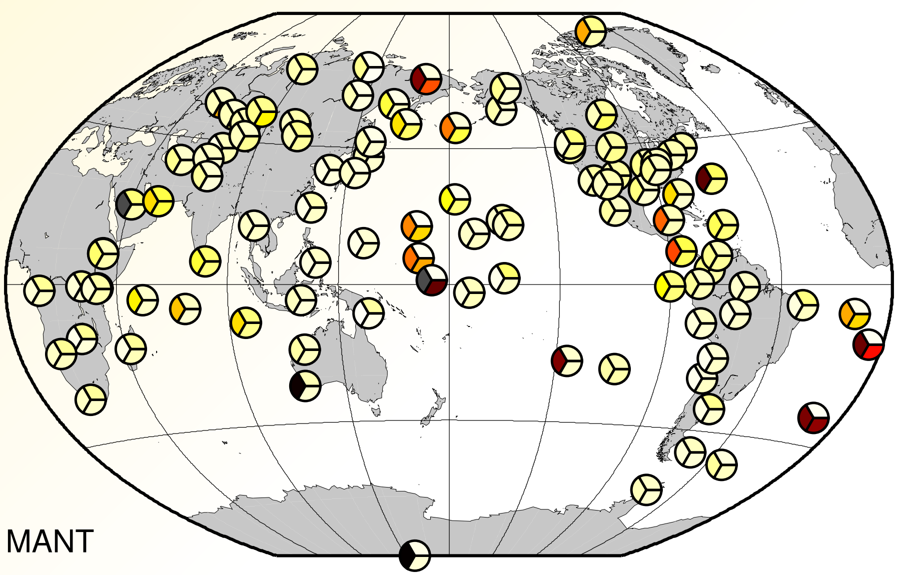
2 'Geological' accuracy – do the source parameters match what one might observe 'on the ground'?

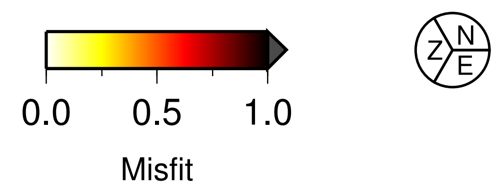
Catalogue 'standard errors' attempt to estimate (1). But:

- Ignores potential for significant systematic errors arising from deficiencies in Earth model and forward modeling theory;
- Rarely have information about exact dataset and forward-modeling approach used during determination → users are likely to make different choices.

Catalogue determinations rarely use most accurate forward methods or most up-to-date models: computational costs; long-term consistency.







Misfit between SPECFEM in S40RTS and normal mode summation in M84C

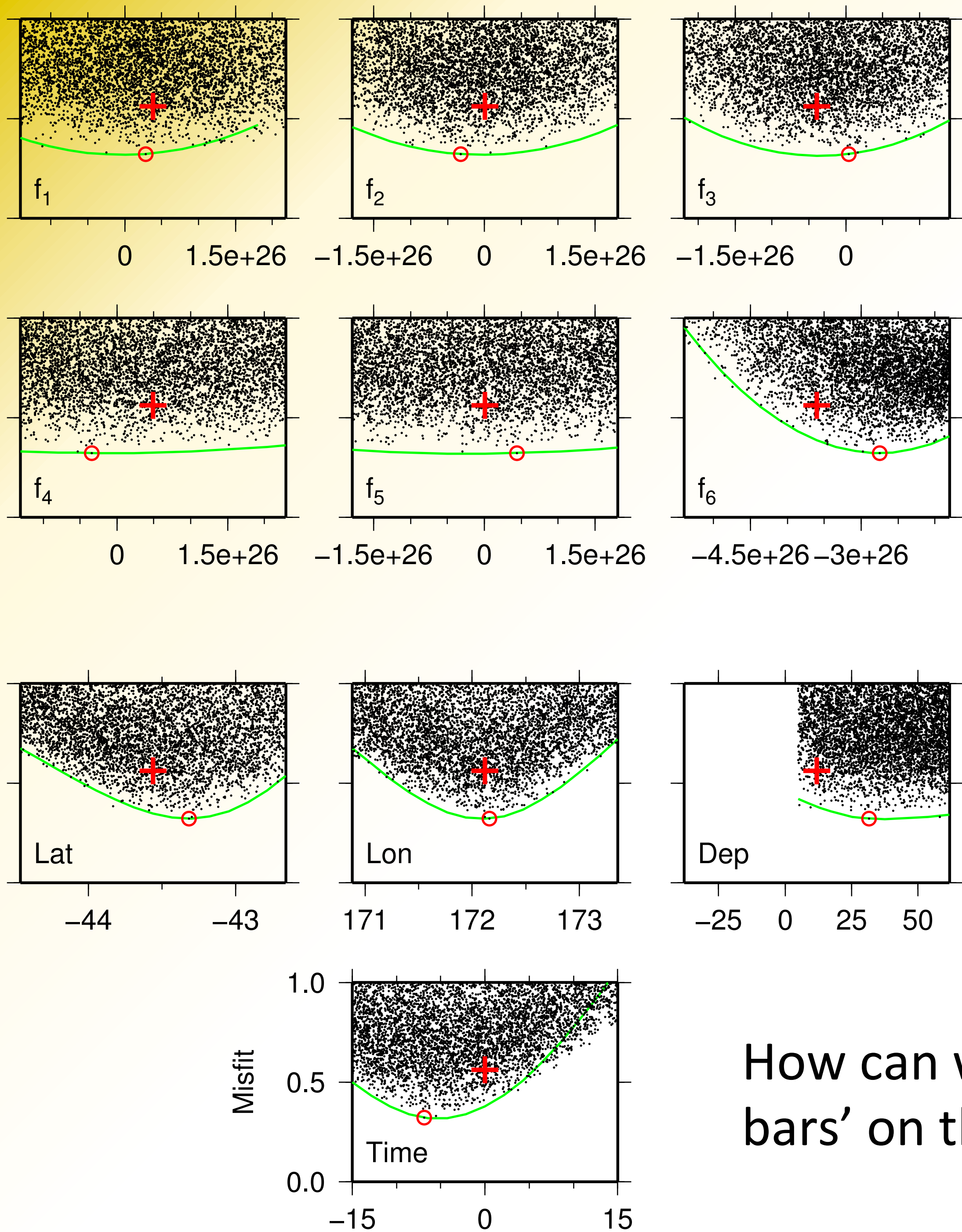
Waveform differences can be quite large – and depend on frequency band used!

Can we *quantify* how this might affect CMT inversion?

Experiment:

1. Generate high-quality synthetic data using known source parameters: SPECFEM & S40RTS;
2. Generate 10,000 sets of source parameters `close' to the known source;
3. Compute approximate synthetic seismograms for these 10,000 sources: Normal mode summation & M84C;
4. Observe relationship between waveform misfit and source parameters.

- CMT algorithm would return minimum-misfit solution – how does this compare to 'true' solution?
- Curvature of misfit surface determines how well-constrained individual parameters are.



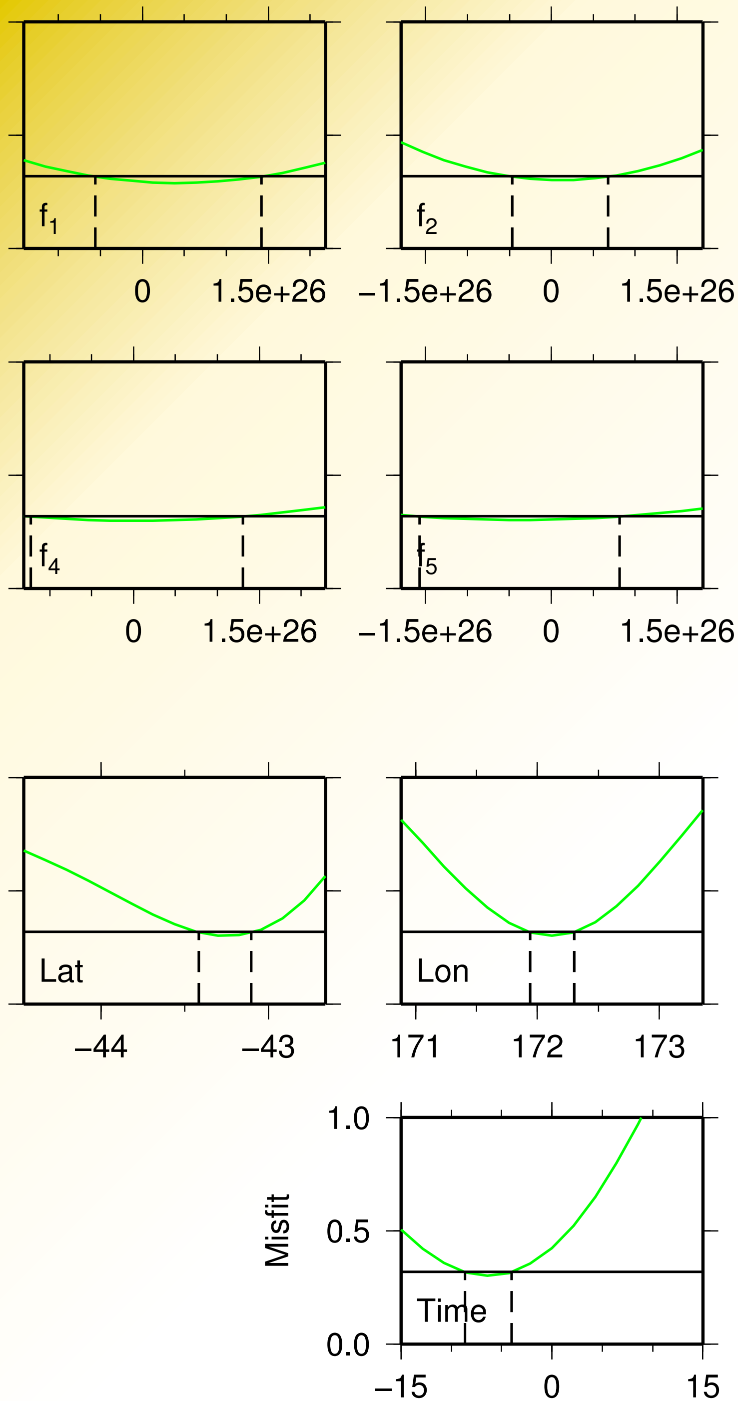
Misfit vs. source parameters

Circle: sample with minimum misfit

Cross: misfit generated by 'true' source

Minima may be far from 'true' values; some parameters poorly constrained.

How can we estimate realistic 'error bars' on the location of the minima?

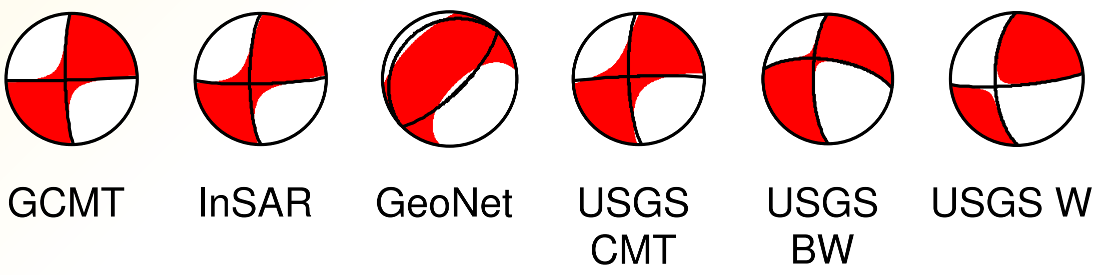


Our approach: define 'misfit threshold' and report ranges of 'low misfit' solutions.

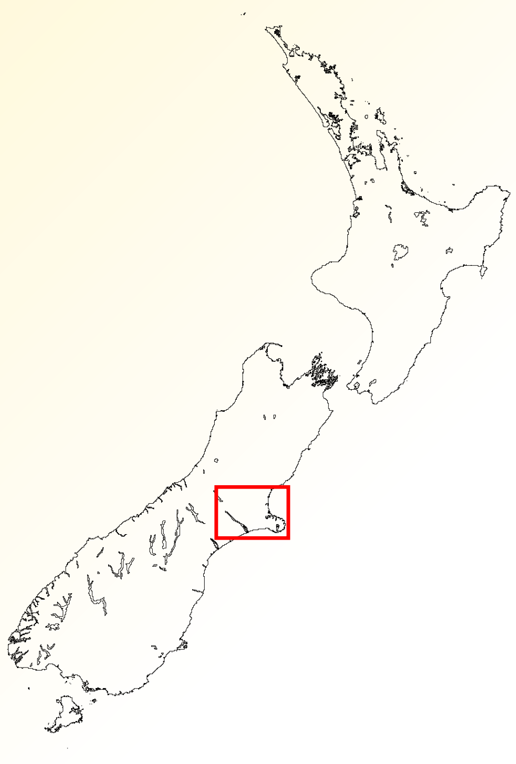
Represents pragmatic approach to uncertainty estimation – formal treatment impossible due to lack of information on model and wave propagation uncertainties.

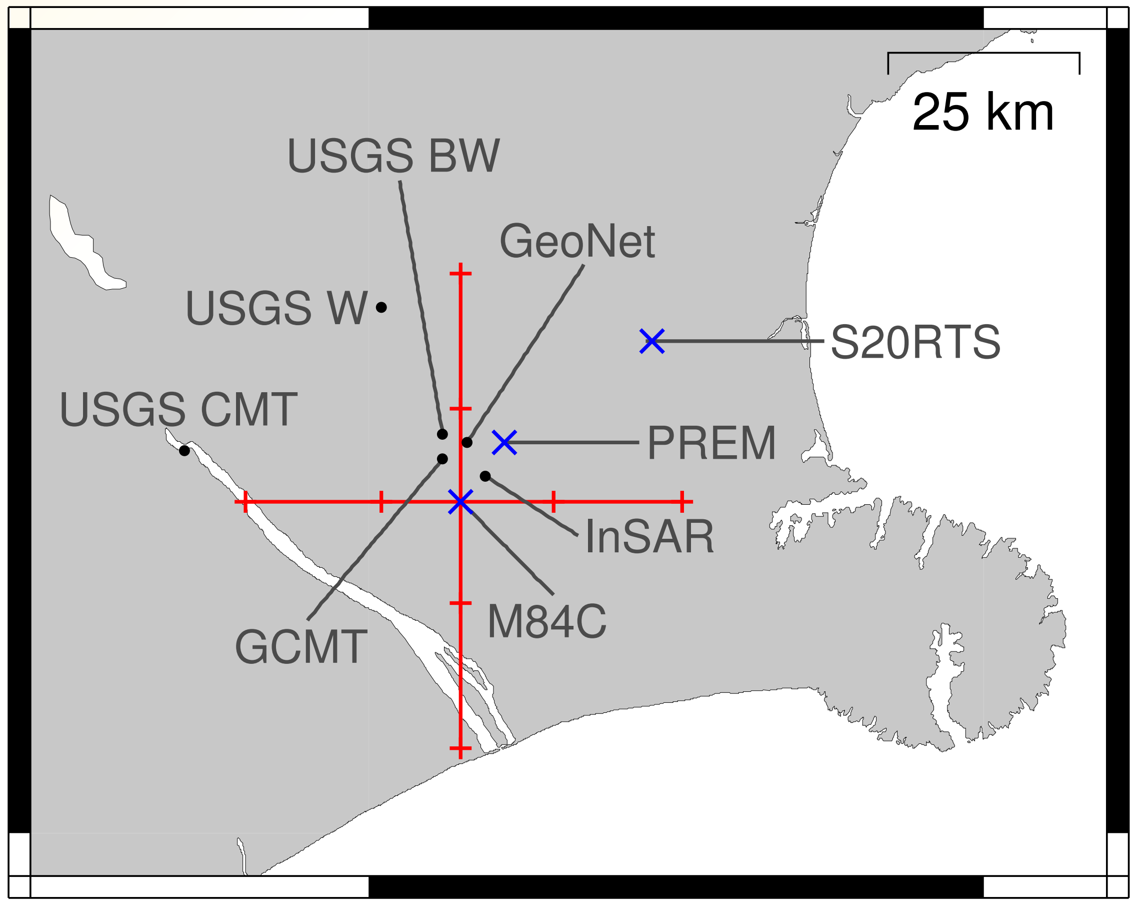
Example 1: Darfield earthquake
New Zealand, 3rd September 2010

Shallow (5-10km)

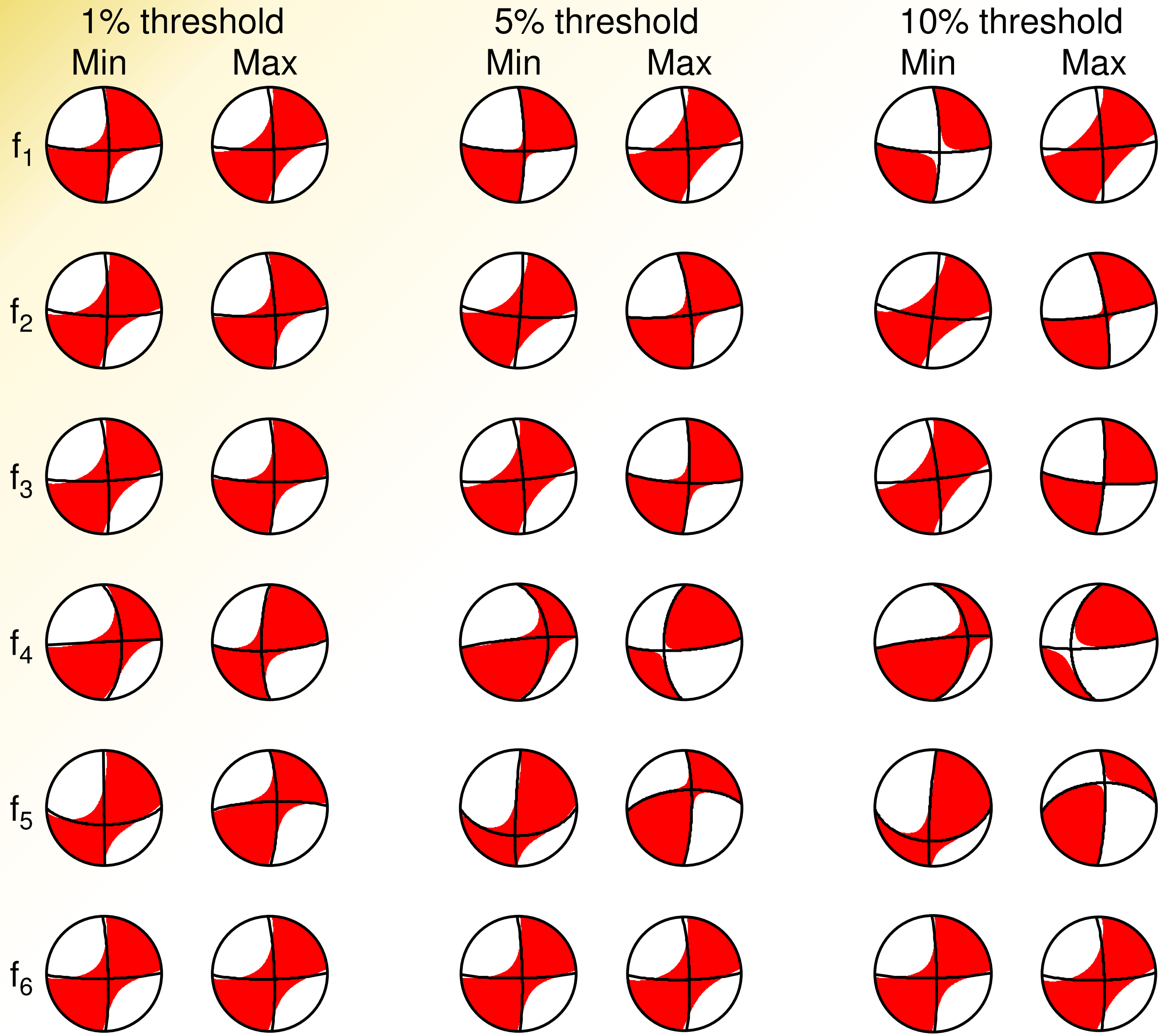


Invert real data using three different earth models, and normal mode summation



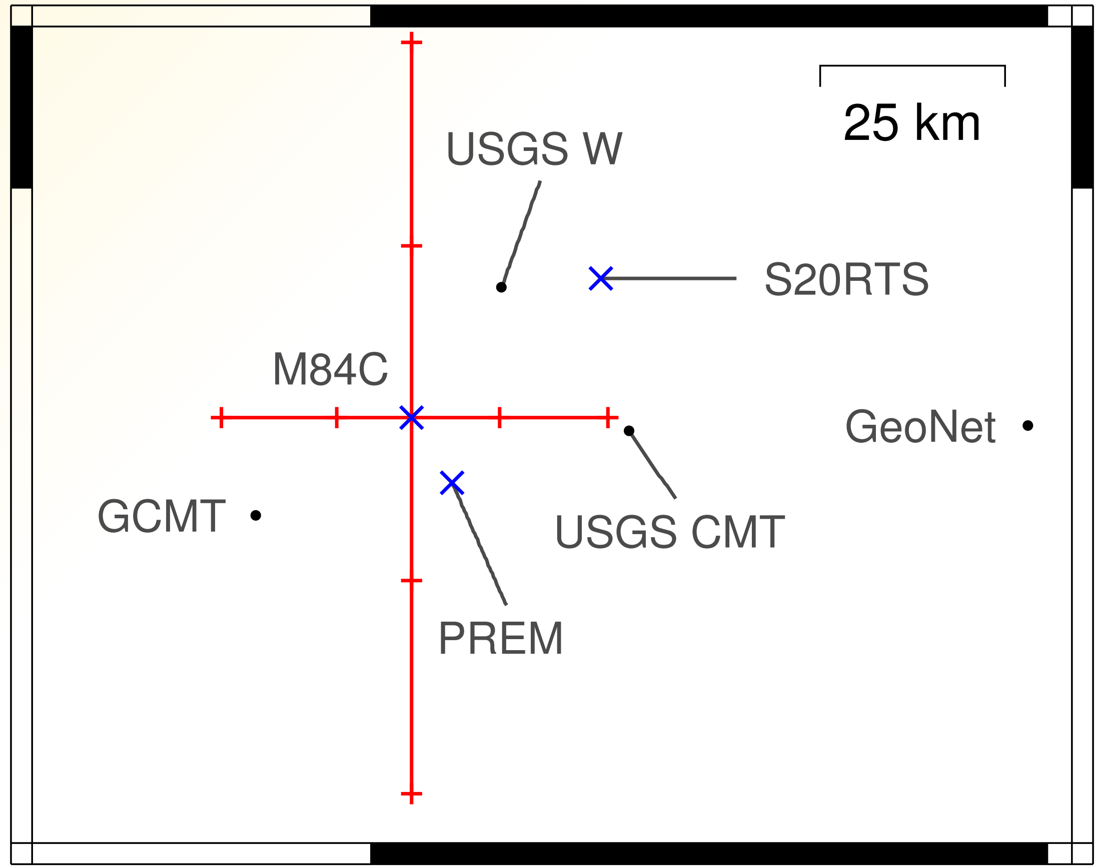


Misfit threshold: minimum fit + n%

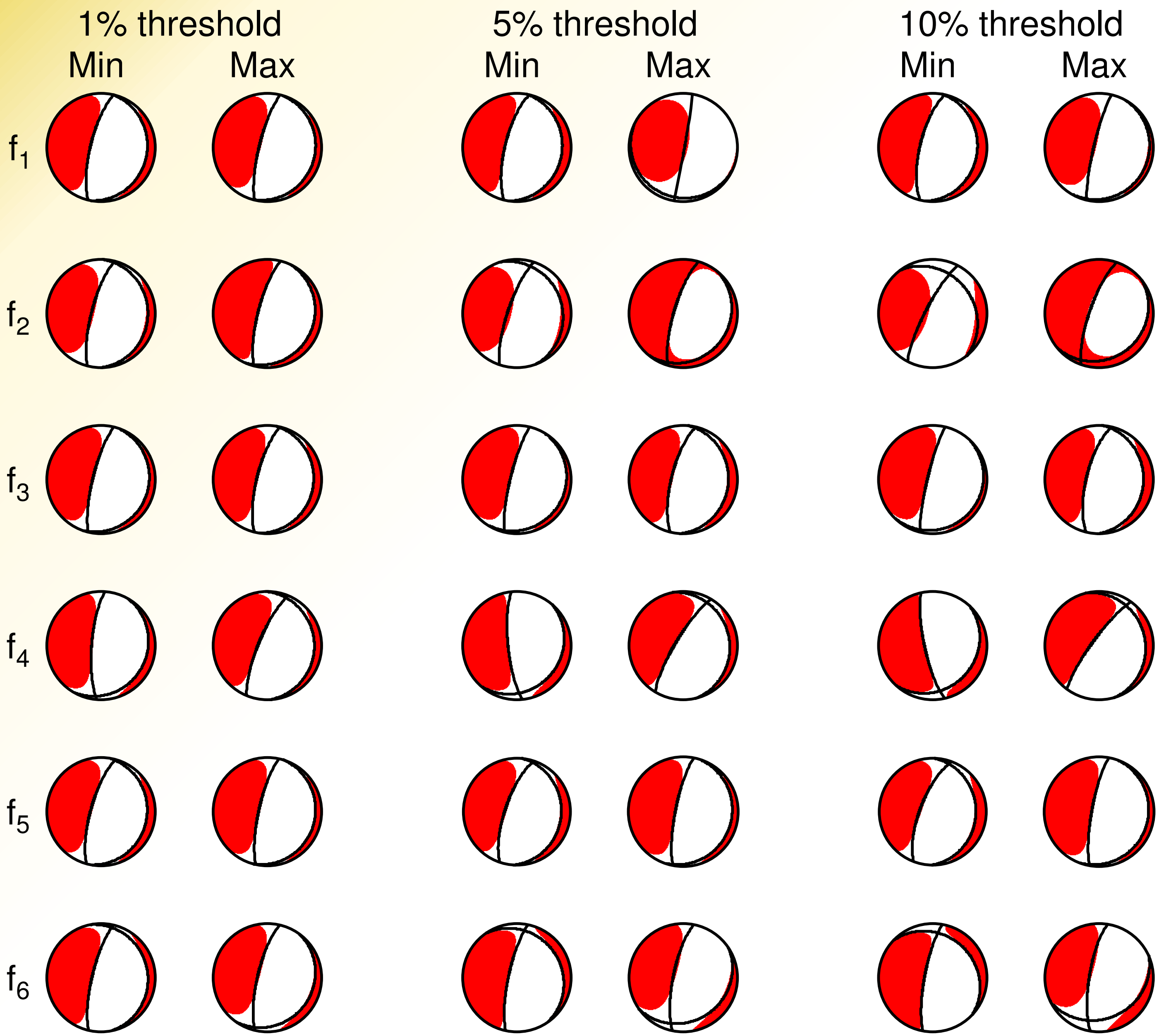


Some potentially-significant differences e.g. double couple vs. non-double couple…

Example 2: Kermadec Islands earthquake
18th April 2011
Deep (100km)



Observed patterns are generally similar to those from Darfield event

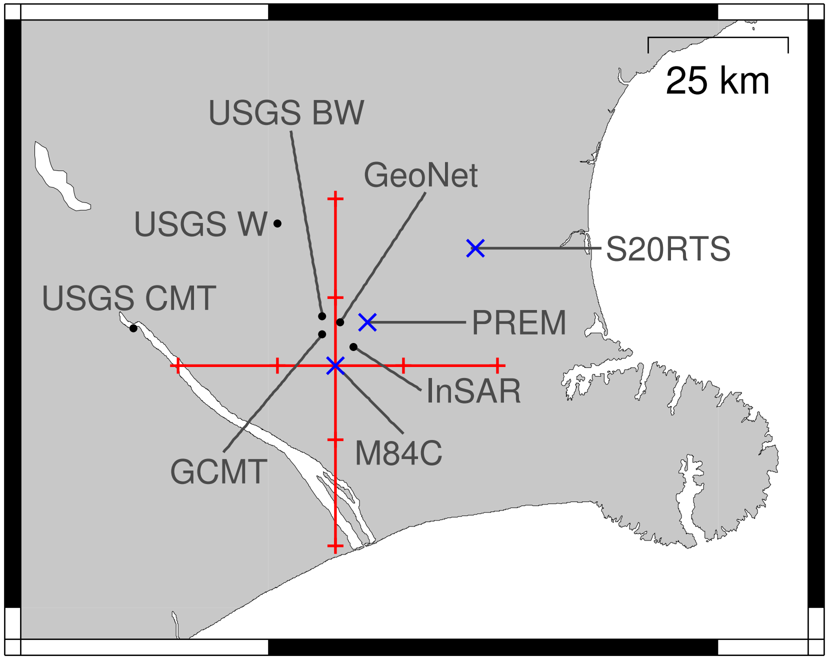


On balance, threshold in 5-10% range seems appropriate

Does it matter?

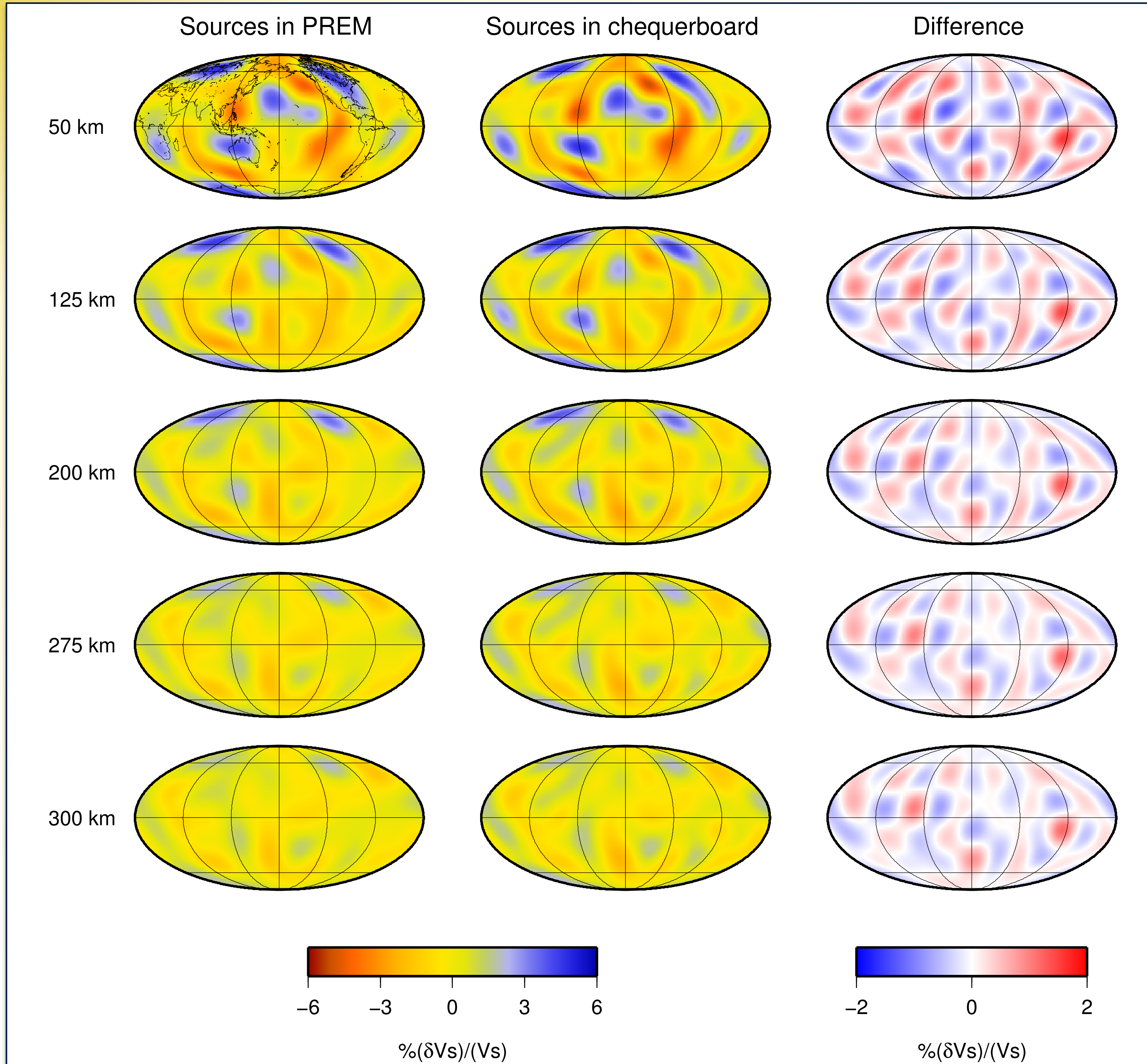
- Depends on application! But potentially, yes – particularly if one tries to use source parameters determined in one model to compute synthetics in a different model!

- For example, global tomography: Valentine & Woodhouse (2010) showed that it is possible for source determination model to become 'imprinted' in final results – due to systematic errors in source determination being ignored.



- Similar results now being reported for travel-time tomography by Myers *et al*.

Valentine & Woodhouse (2010), GJI, 180, pp.847-857.


Sources in PREM
Sources in chequerboard
Difference
50 km
125 km
200 km
275 km
300 km
–6
–3
0
3
6
%(δVs)/(Vs)
–2
0
2
%(δVs)/(Vs)

What can we do to improve accuracy?

1. Try to make catalogue parameters *geologically* accurate
   - Incorporate information from new datasets, e.g. local seismic networks, InSAR, GPS…
   - However, each dataset comes with its own questions…

2. Calculate and report full uncertainties on earth models, including effects of source parameter errors
   - Currently theoretically and computationally challenging

3. Ensure self-consistency during tomographic inversion
   - Perform source determinations as integral part of tomographic inversion
   - Valentine & Woodhouse (2010) suggests a unified approach to source and structure inversion
   - Alternating between source and structure inversion is effective (but slow!)

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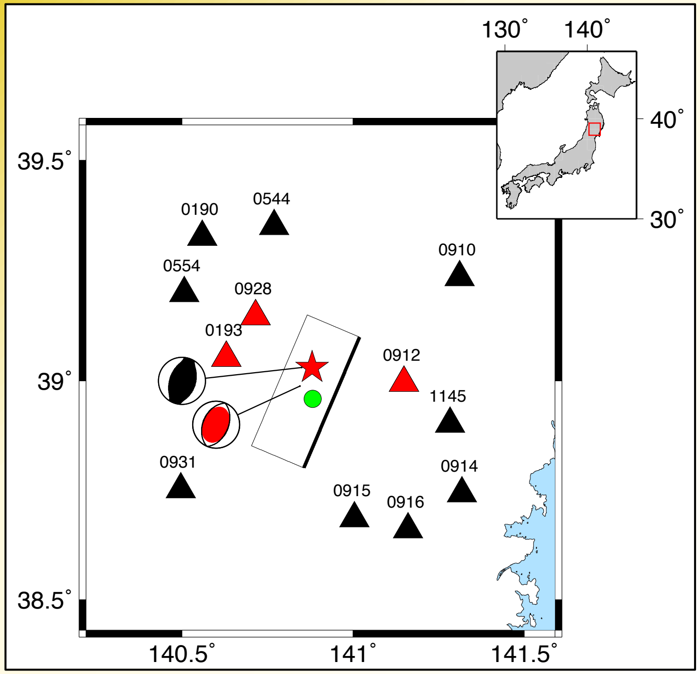
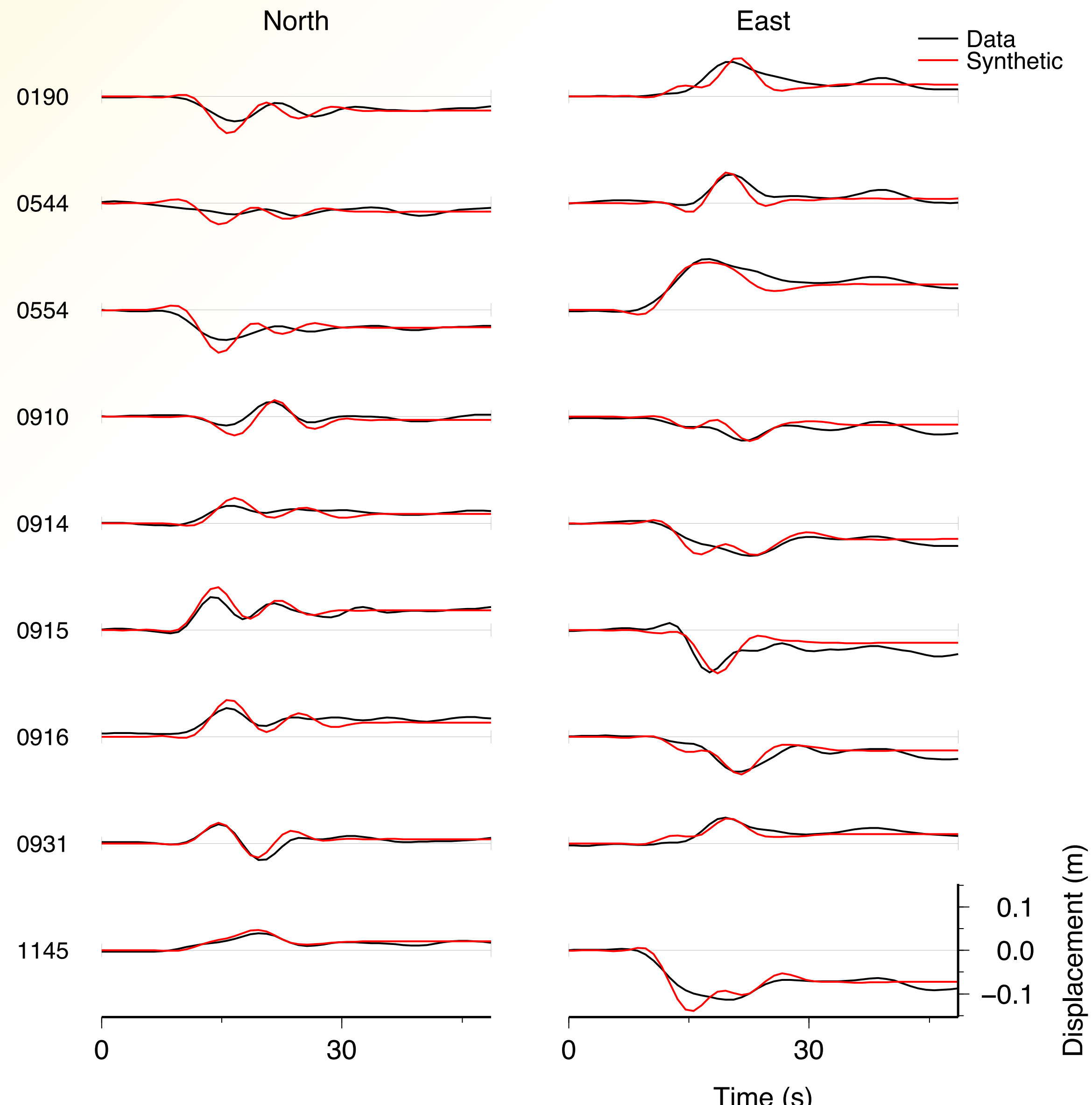
CMT inversion using continuous GPS waveforms





Open question: how do we combine different datasets and methods?

O'Toole, Valentine & Woodhouse, in review.

Summary

- The CMT algorithm gives the best-fitting source parameters for some given dataset, earth model and forward-modeling strategy – solution is only as good as these choices! *Unfortunately, catalogues currently do not provide much information about these choices.*

- Different, apparently reasonable choices may lead to quite significant waveform differences – potentially a problem if subsequent analysis involves waveform-matching (e.g. full-waveform inversion).

- For complete self-consistency, users of source parameters may need to consider performing their own source determinations.

Source parameters for global seismology: How accurate are CMT-style source inversions?

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Key references:

- Valentine, A.P. & Trampert, J., *in review*. Assessing the uncertainties on seismic source parameters: Towards realistic error estimates for centroid-moment-tensor determinations.
- Valentine, A.P. & Woodhouse, J.H., 2010. Reducing errors in seismic tomography: Combined inversion for sources and structure. *Geophysical Journal International*, 180, 847-856.
- O'Toole, T.B., Valentine, A.P. & Woodhouse, J.H., *in review*. Centroid-moment tensor inversion using high-rate GPS waveforms.

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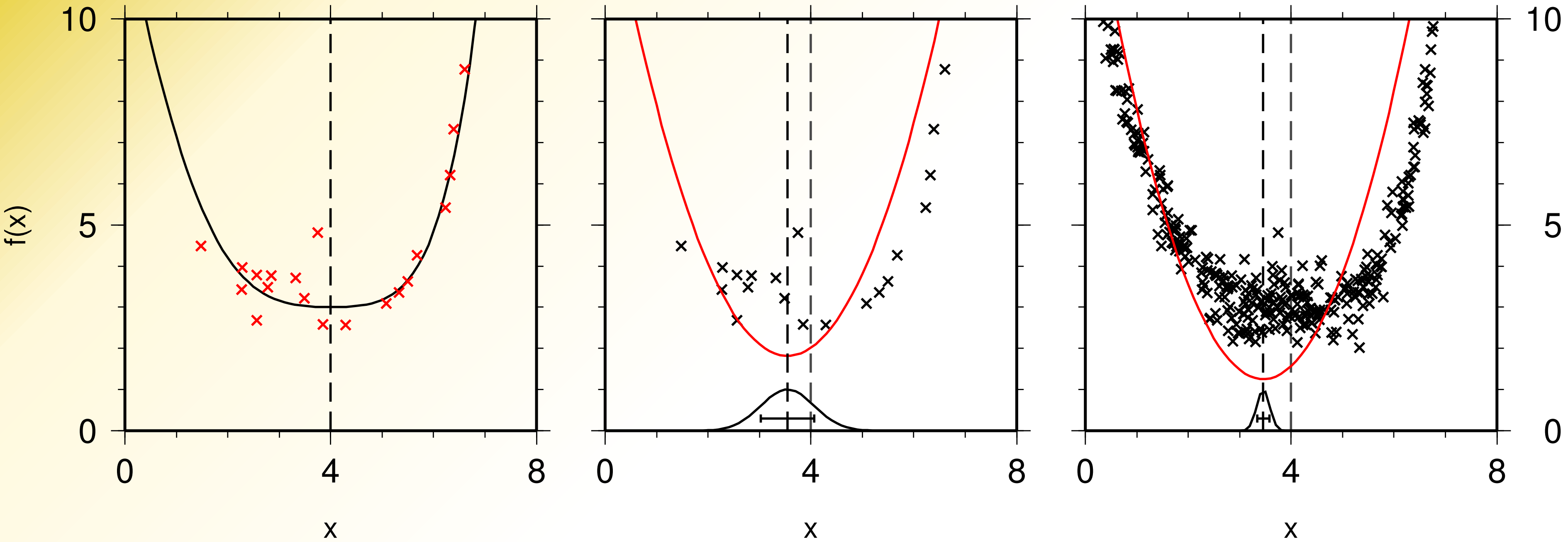
- John Ristau, GeoNet, New Zealand

QUEST Quantitative Estimation of Earth's Seismic Sources and Structure

MARIE CURIE ACTIONS

Additional material

The flaw of standard errors…



- Have noisy samples of some function;
- Try to fit an oversimplified (quadratic) model to data, and estimate location of minimum;
- With few data points, model appears to describe data tolerably, and error bars sensible;
- With more data, it becomes obvious that model does not suit data, and error analysis proves over-confident.