British Seismology Meeting, Reading, 2017

Accurate seismic event location: A question of context

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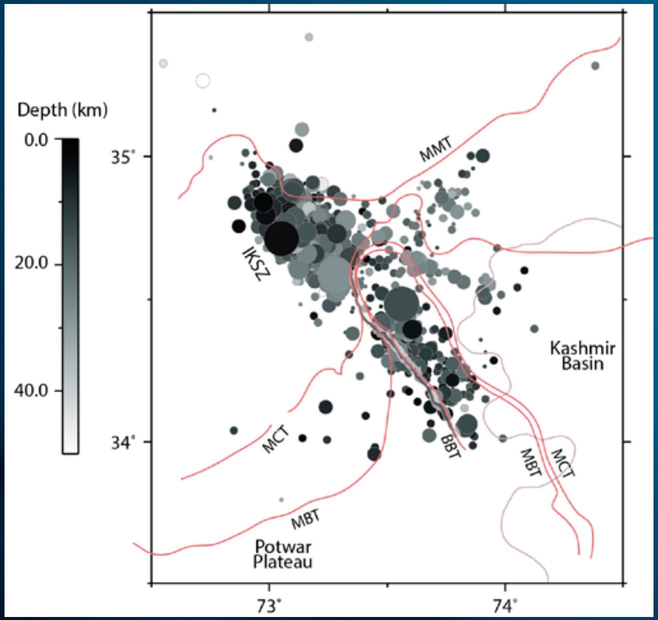
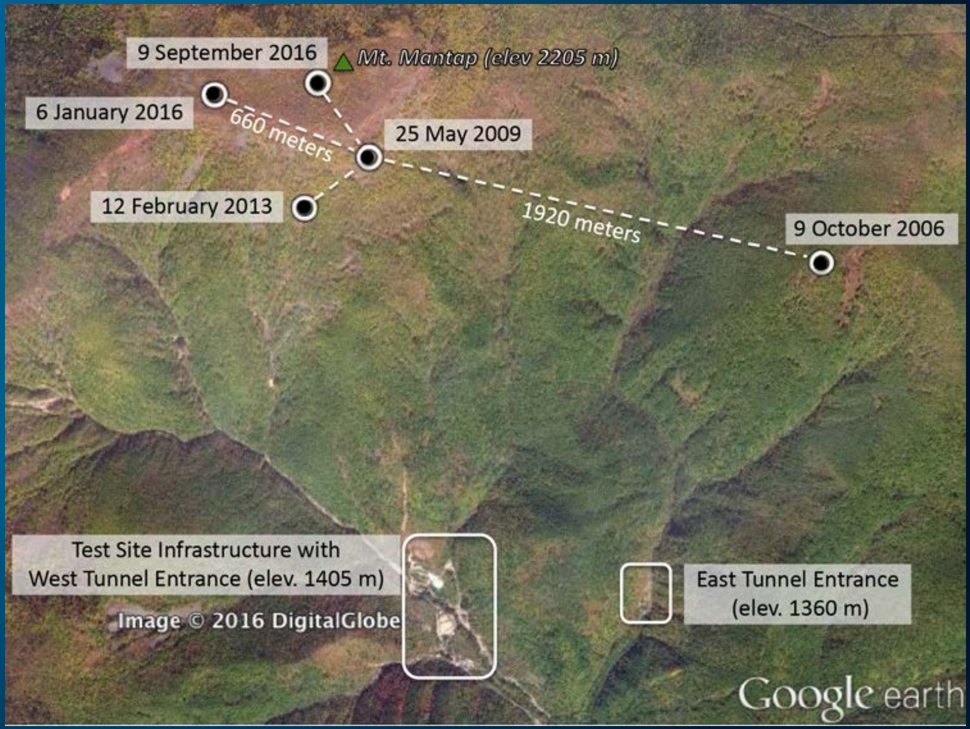




Accurate seismic event location: A question of context

«Joint Epicenter Determination»
by Alan Douglas

50 years anniversary in July 2017!

In some sense forms the basis for most of the subsequent improvements to seismic event location algorithms.

Considering multiple seismic events together we can mitigate the effects of deficiencies in our velocity model.

NATURE, VOL. 215, JULY 1, 1967

Joint Epicentre Determination

THIS communication describes a method of determining station travel time corrections and the positions and origin times of more than one earthquake simultaneously. Application of the method to earthquakes from the same region should reveal any regional bias in travel times. Some preliminary results are presented.

Suppose the rough epicentre, depth and origin time of a seismic event are known, the equation of condition for calculating the corrections to these approximate values is[1]

$$\delta H + \delta h \frac{\partial T}{\partial h} + x \cos \alpha_j \frac{\partial T}{\partial \Delta_j} - y \sin \alpha_j \frac{\partial T}{\partial \Delta_j} = \delta T_j \quad (1)$$

where $\delta T_j = A_j - H - T_j$; H is the approximate origin time of the event; h is the approximate depth of the event; Δ_j is the distance from the approximate epicentre to station j; α_j is the azimuth from the approximate epicentre to station j; A_j is the time of arrival (of the P waves) at station j; T_j is the travel time (of the P waves) from the approximate epicentre to station j; $\partial T/\partial \Delta_j$ is the partial derivative of the travel time T $(= f(\Delta_j,h))$ with respect to distance at the point Δ_j,h; $\partial T/\partial h$ is the partial derivative of the travel time T with respect to depth at Δ_j,h; T, $\partial T/\partial \Delta_j$, and $\partial T/\partial h$ are obtained from travel time tables.

Accurate seismic event location: A question of context

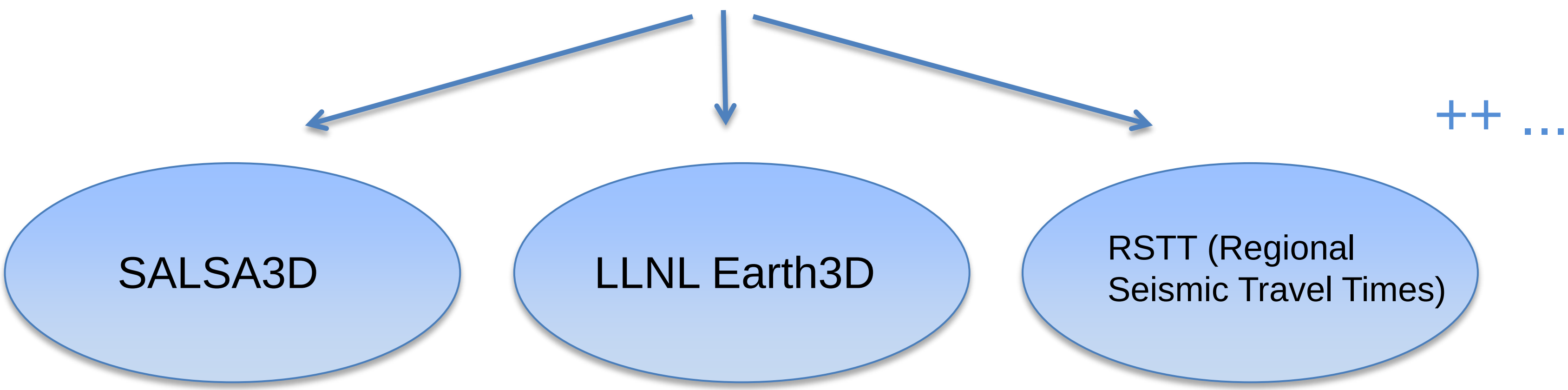
Our characterization of seismic traveltimes in the Earth is improving constantly ...

Jeffreys and Bullen travel-time tables ...

PREM (Dziewonski and Anderson, 1981)

IASP91 (Kennett and Engdahl, 1991)

ak135 (Kennett, Engdahl and Buland, 1995)
Still the standard 1-d velocity model after 20+ years!
Now the challenge is characterizing 3D structure ...



Accurate seismic event location: A question of context

We also need to adapt our methods of locating seismic events ...

Source-station correction terms
(both explicit and implicit)

Pattern recognition – «stamp collecting»!
(often applied to vast swarms/microseismicity)

(Used in combination with other location procedures ...)

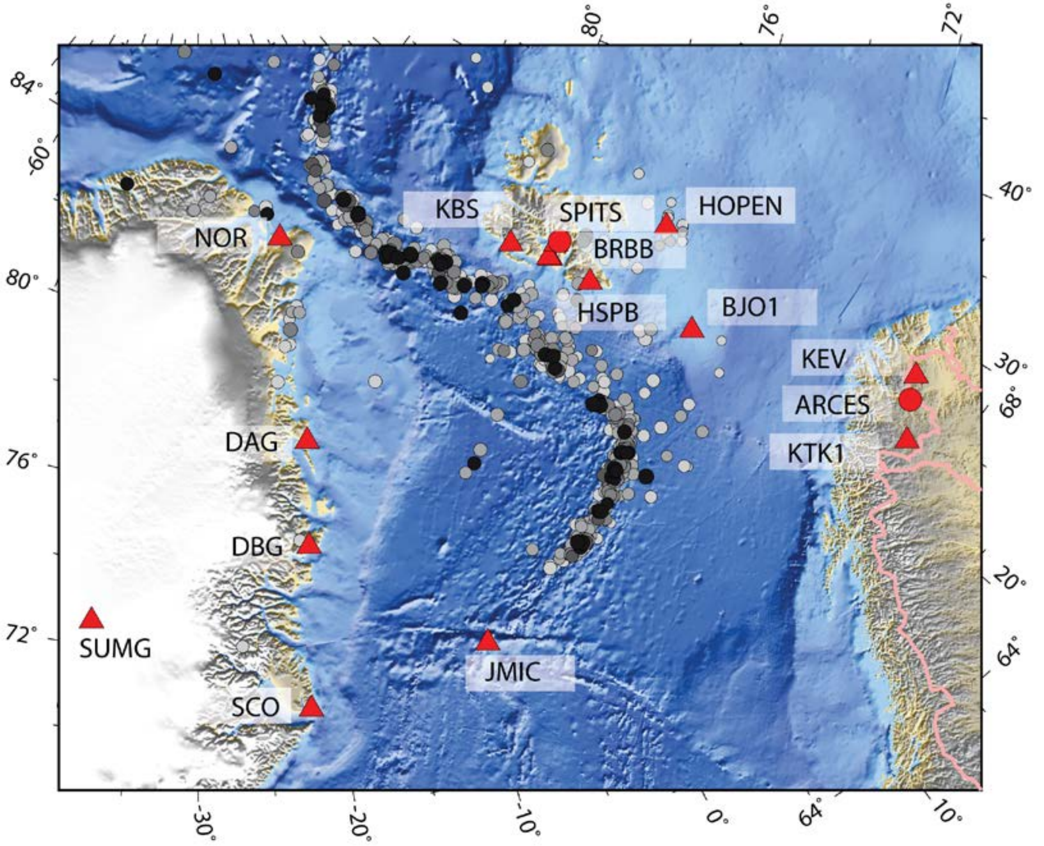
Probabilistic
(Calculates joint probability distributions)

Grid search / migration
(Precalculated traveltime tables for 3D volumes)

Differential
(e.g. Double Differences)

Accurate seismic event location: A question of context

Location of remote seismicity can be problematic ...

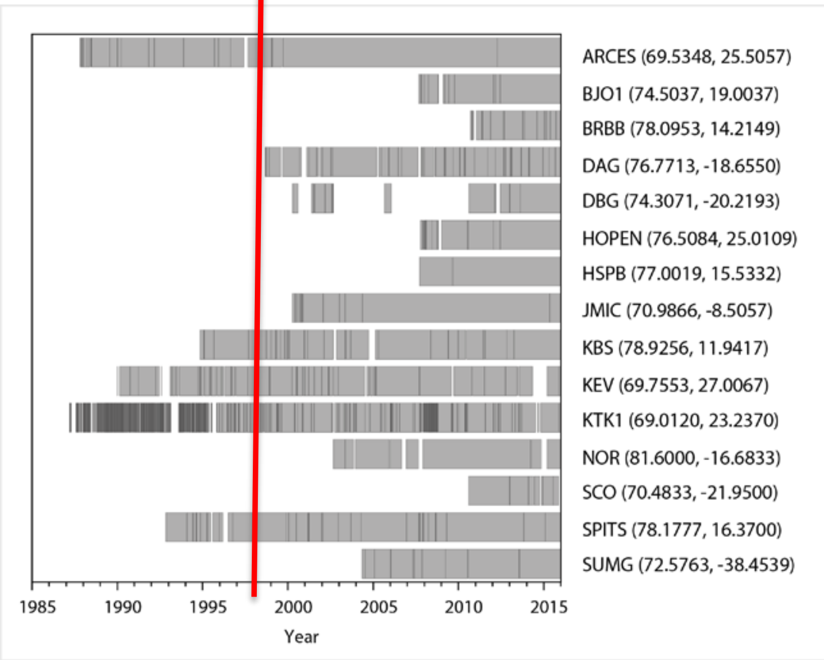


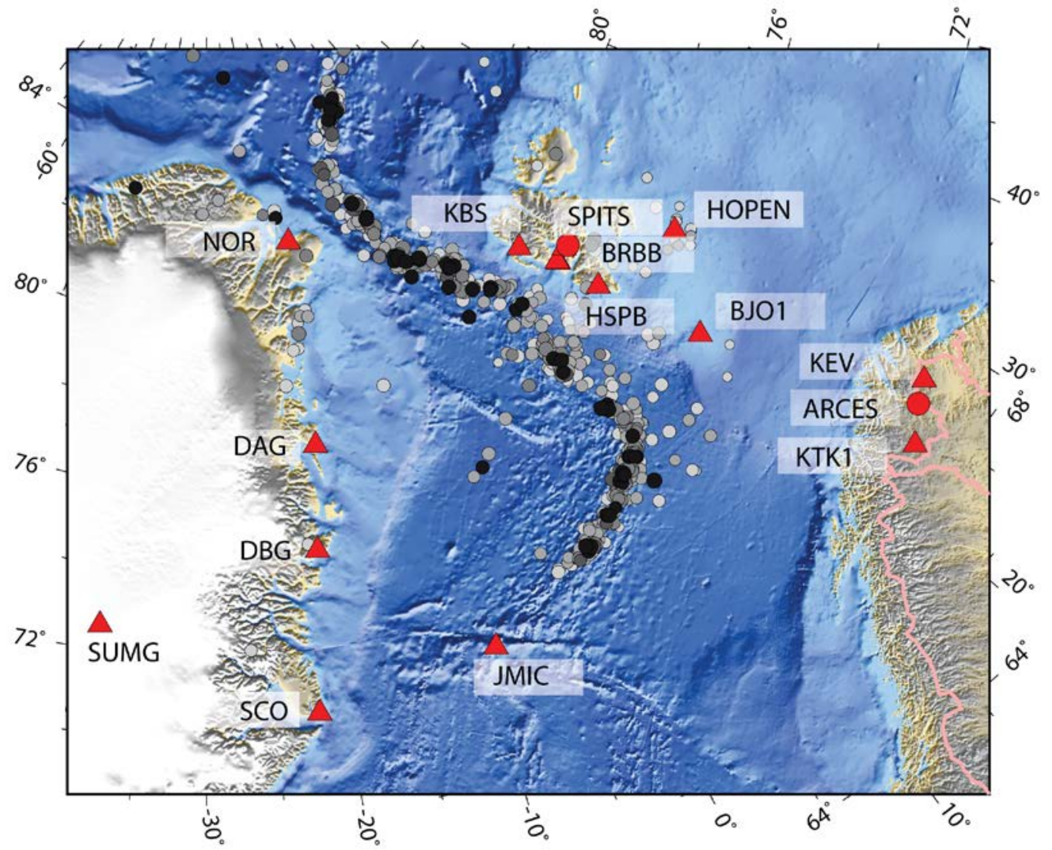
(Engen et al., 2003)

Accurate seismic event location: A question of context

Location of remote seismicity can be problematic ...

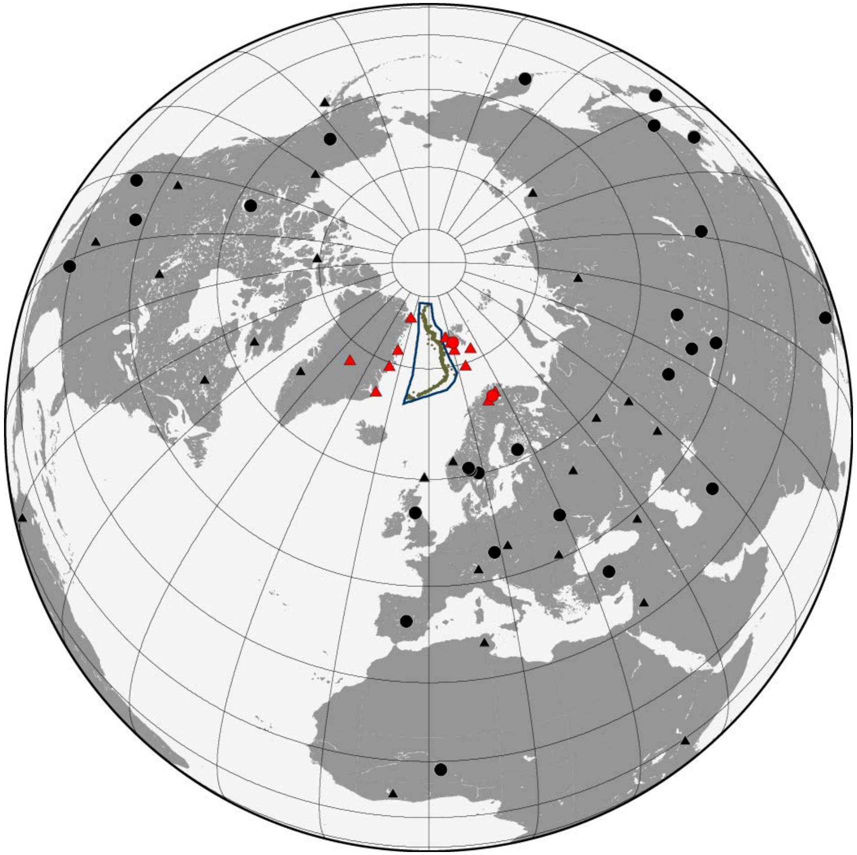
Study of Engen et al. (2003)





(Engen et al., 2003)

Location of remote seismicity can be problematic ...



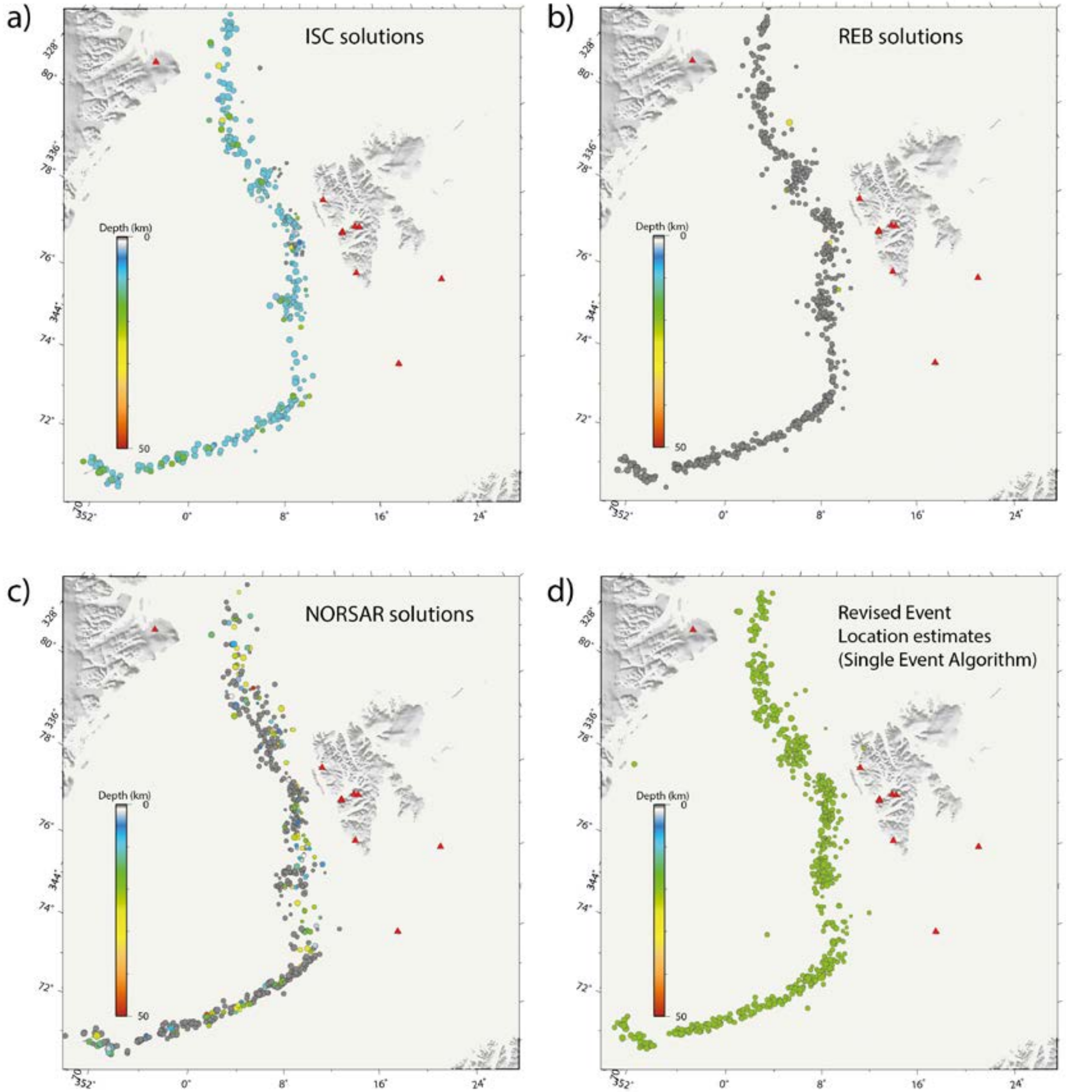
Many events in our region of interest also well-located teleseismically ....

Accurate seismic event location: A question of context

A huge effort has been made to relocate events on the Arctic mid-Atlantic ridge since ~1998.

This includes many new readings e.g. from Greenland stations that have never been used before.

Is there a real improvement?



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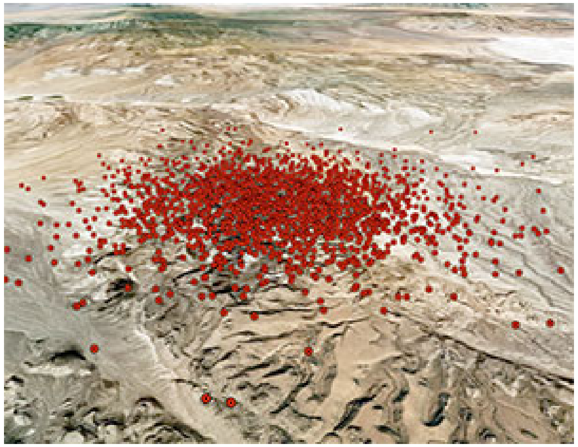
Bayesian Hierarchical Seismic Event Locator (Bayesloc)

Download open-source version (BayeslocRelease2011.tar.gz is ~45 Mbytes)

What does Bayesloc do?

Given a set of seismic arrivals for one or more events, Bayesloc estimates the joint probability of event locations, corrections to travel time predictions, precision of arrival time measurements, and phase labels for the arrival times. Bayesloc also accepts probabilistic prior constraints on any of the input parameters, which can significantly tighten the distribution of all parameters.



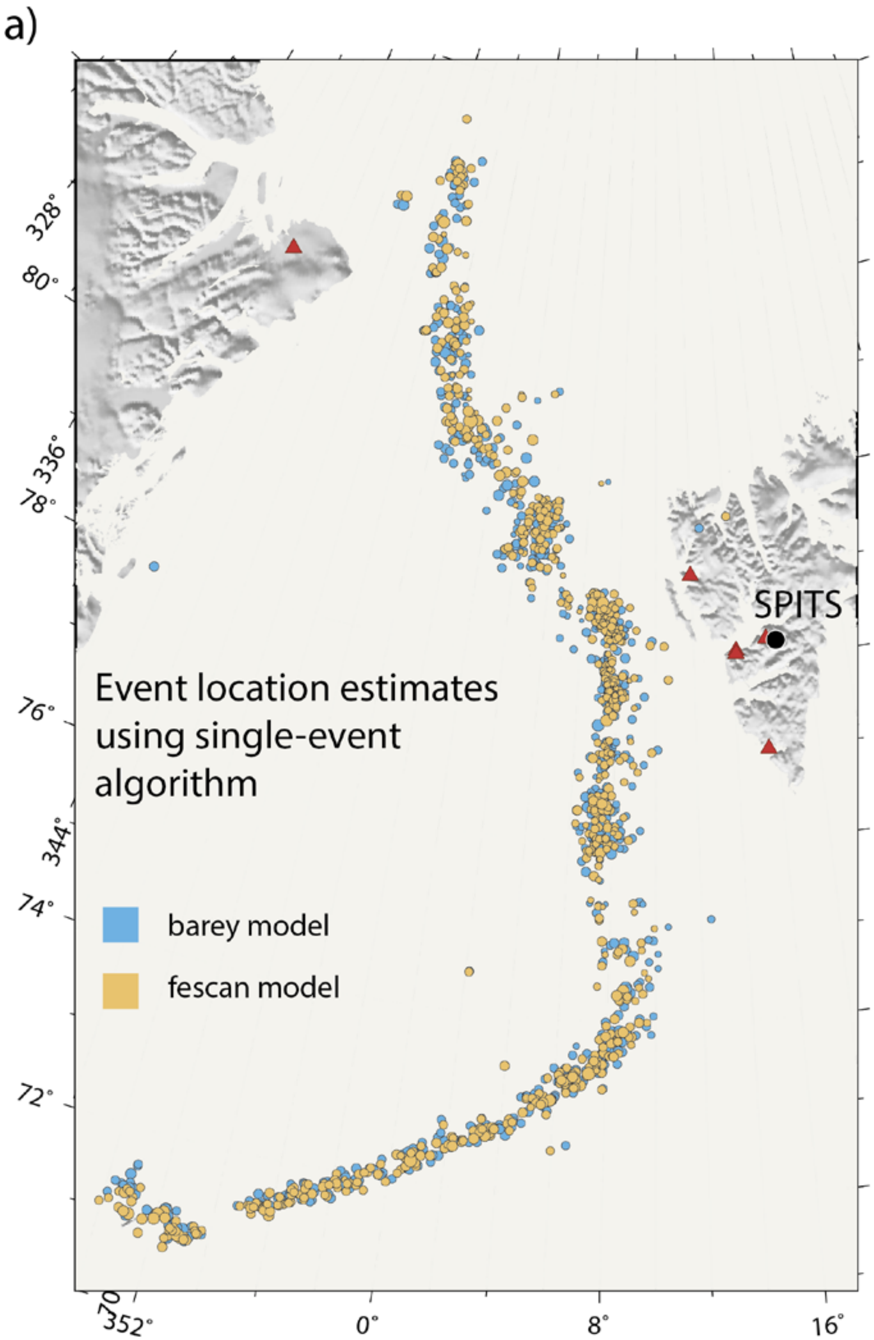
MCMC sampling

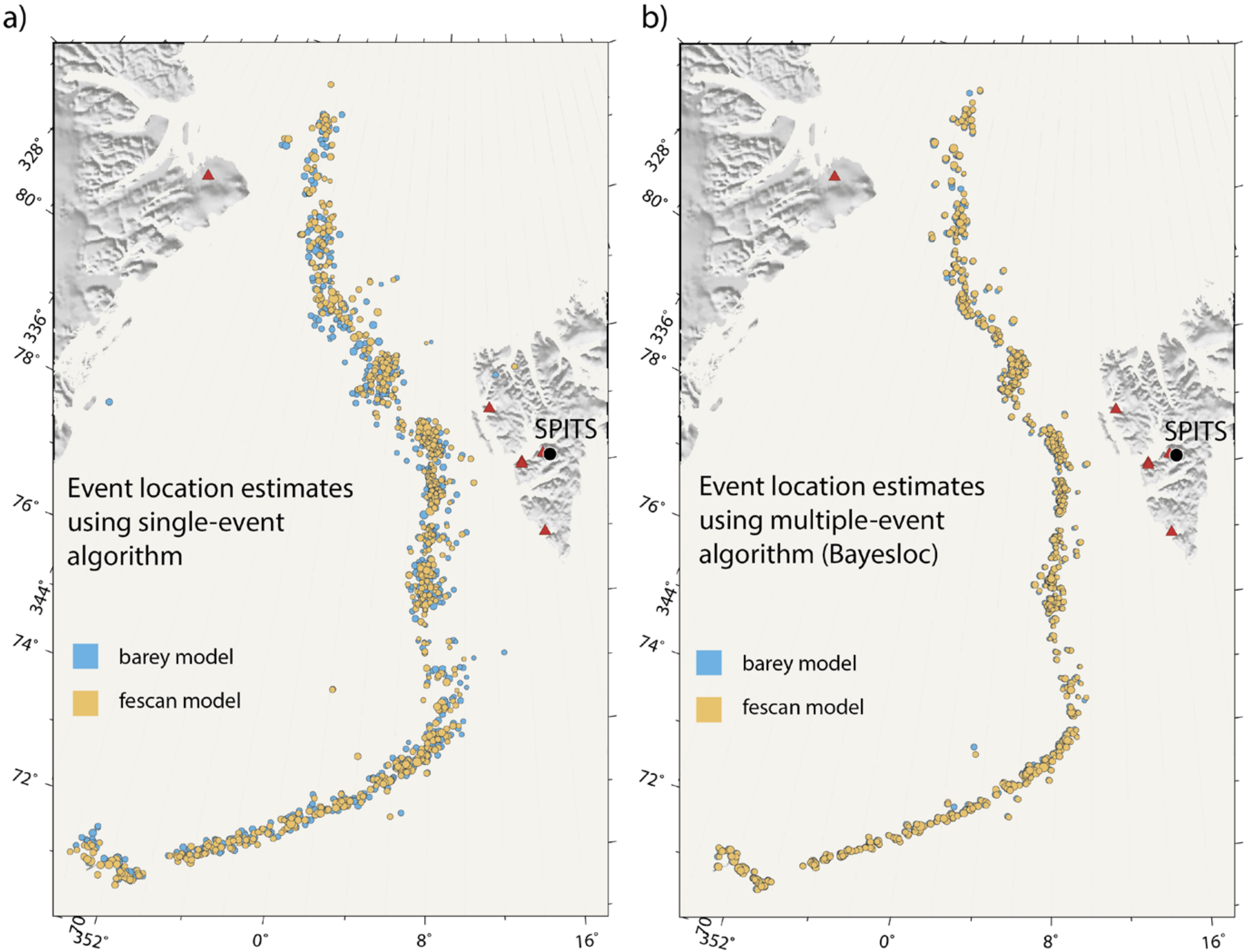
Documentation

The Bayesloc download includes a users guide, including a "Quick Start" that describes rudimentary usage. Input and output file formats are specified.

Code

Bayesloc is a C++ code. Bayesloc utilizes a number of open source libraries, all of which are included in the Bayesloc download. Bayesloc is known to work on Unix-based systems: Linux, OS-X, Solaris. Uses are free to port Bayesloc to other systems.


a)
328°
80°
336°
78°
76°
344°
74°
72°
70
352°
0°
8°
16°
SPITS
Event location estimates
using single-event
algorithm
barey model
fescan model


a)
b)
Event location estimates using single-event algorithm
Event location estimates using multiple-event algorithm (Bayesloc)
barey model
fescan model
barey model
fescan model
SPITS
SPITS
328°
336°
344°
80°
78°
76°
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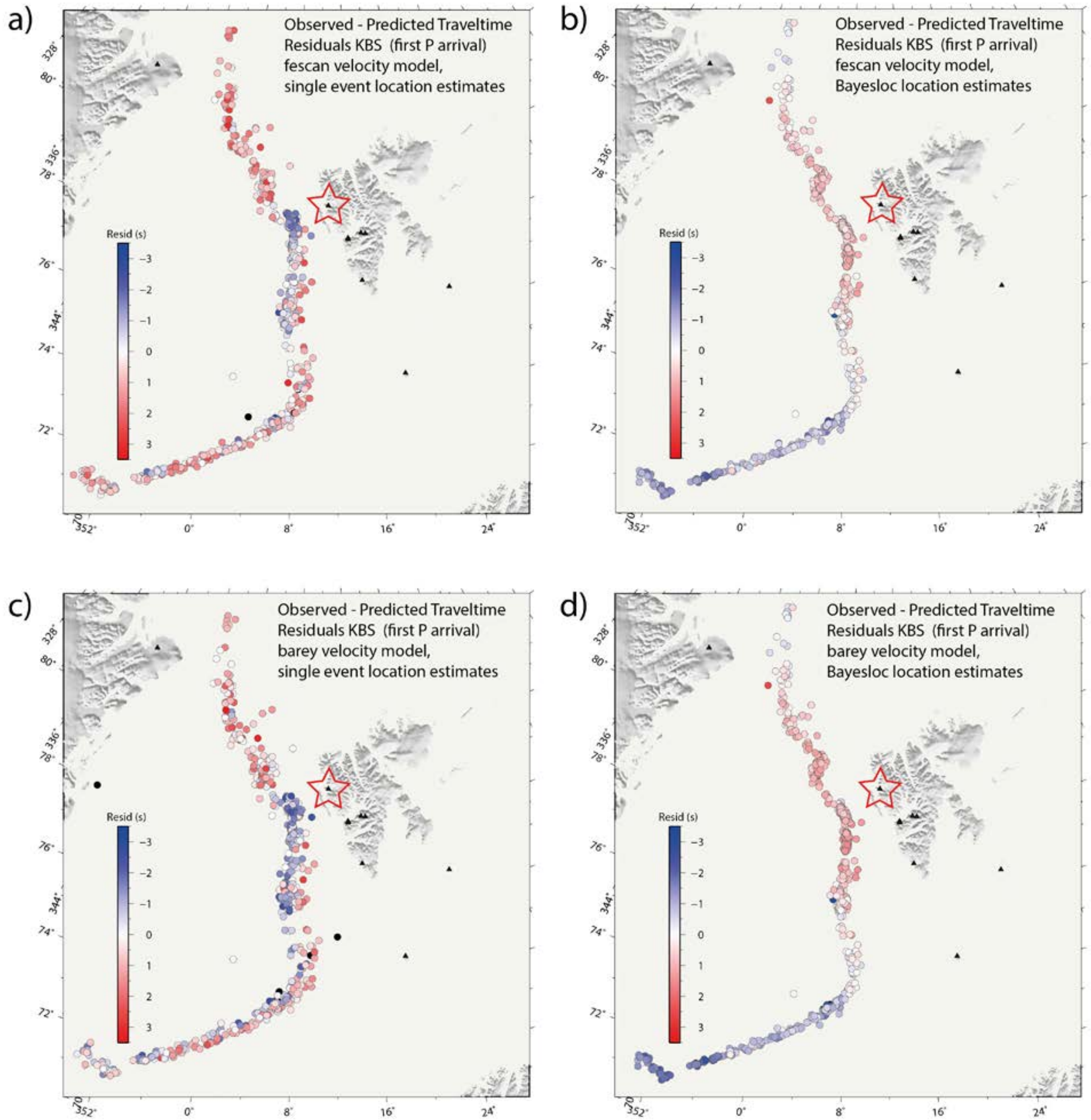
352°
0°
8°
16°

Why do we have this improved robustness of the hypocenter locations from Bayesloc?



Bayesloc estimates the joint probability distribution of ...

...

corrections to travel time predictions

...

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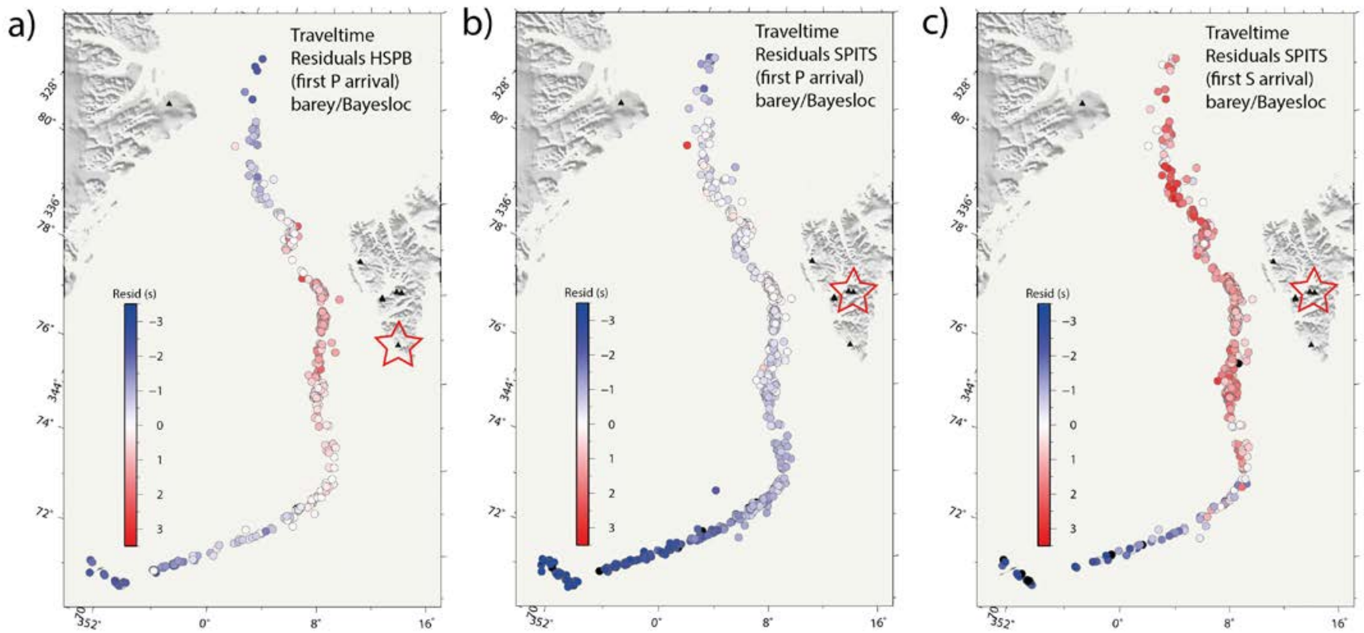


Bayesloc estimates the joint probability distribution of ...

...

corrections to travel time predictions

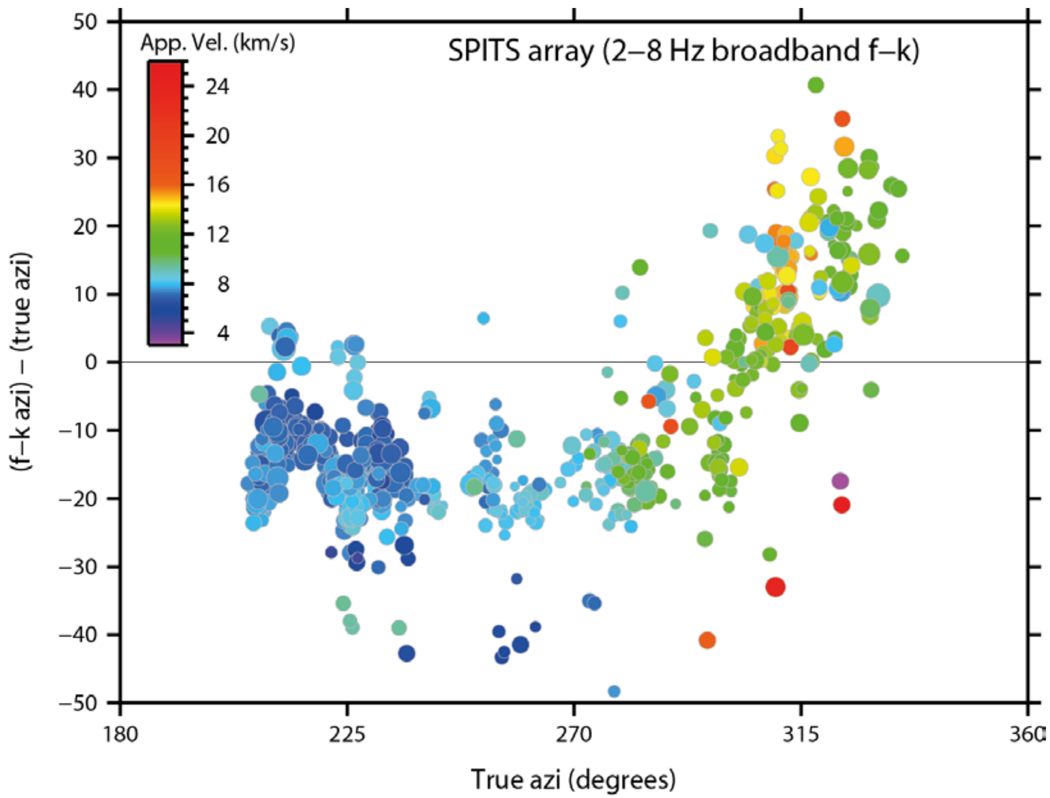
...

It’s not only seismic traveltimes we need to calibrate ...

The most sensitive station to events on this part of the ridge is the SPITS array on Svalbard.

Being an array, we can measure the backazimuth (direction) of an incoming wavefront.

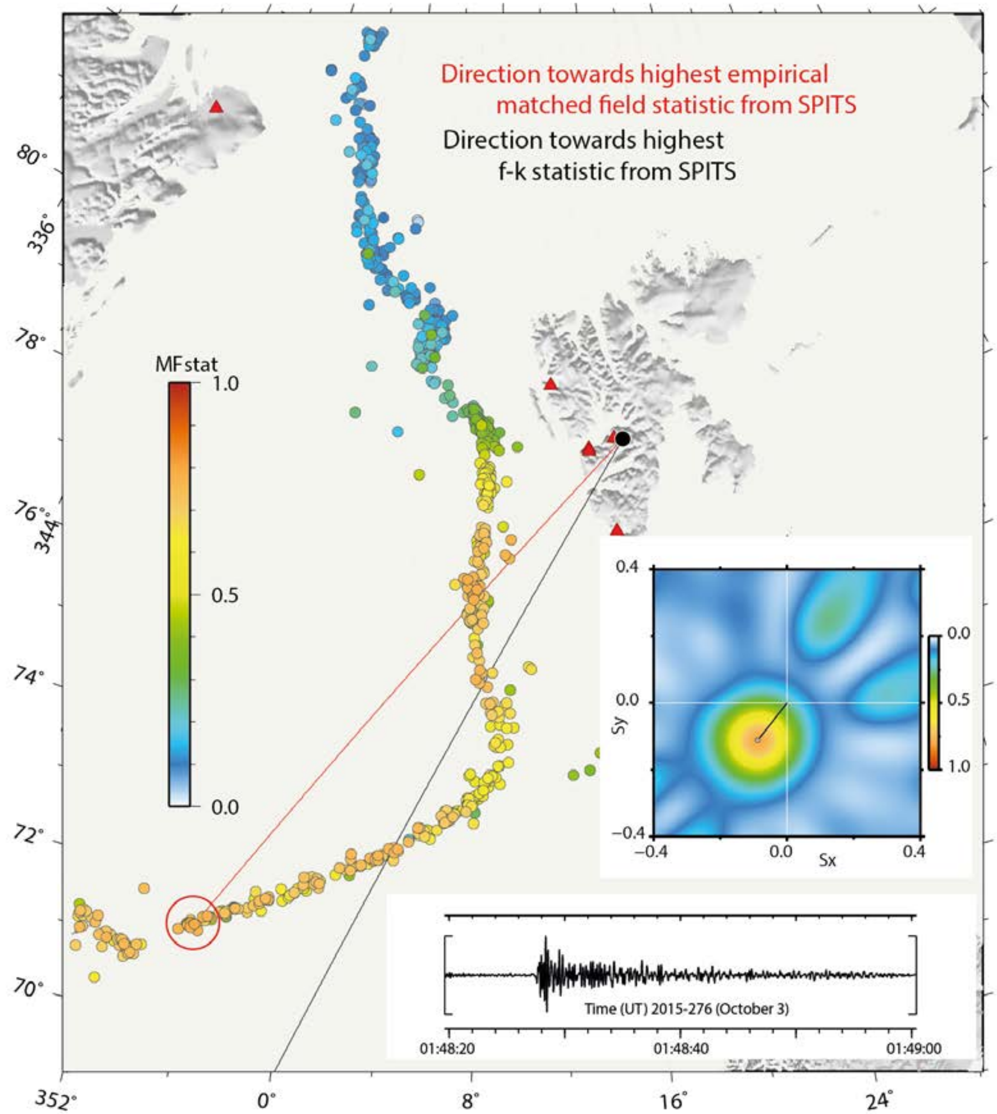
With the relocations we can estimate the deviations from the true backazimuth.



The most sensitive station to events on this part of the ridge is the SPITS array on Svalbard.

Being an array, we can measure the backazimuth (direction) of an incoming wavefront.

With the relocations we can estimate the true backazimuth from empirical observations of earlier events (Empirical Matched Field Processing)



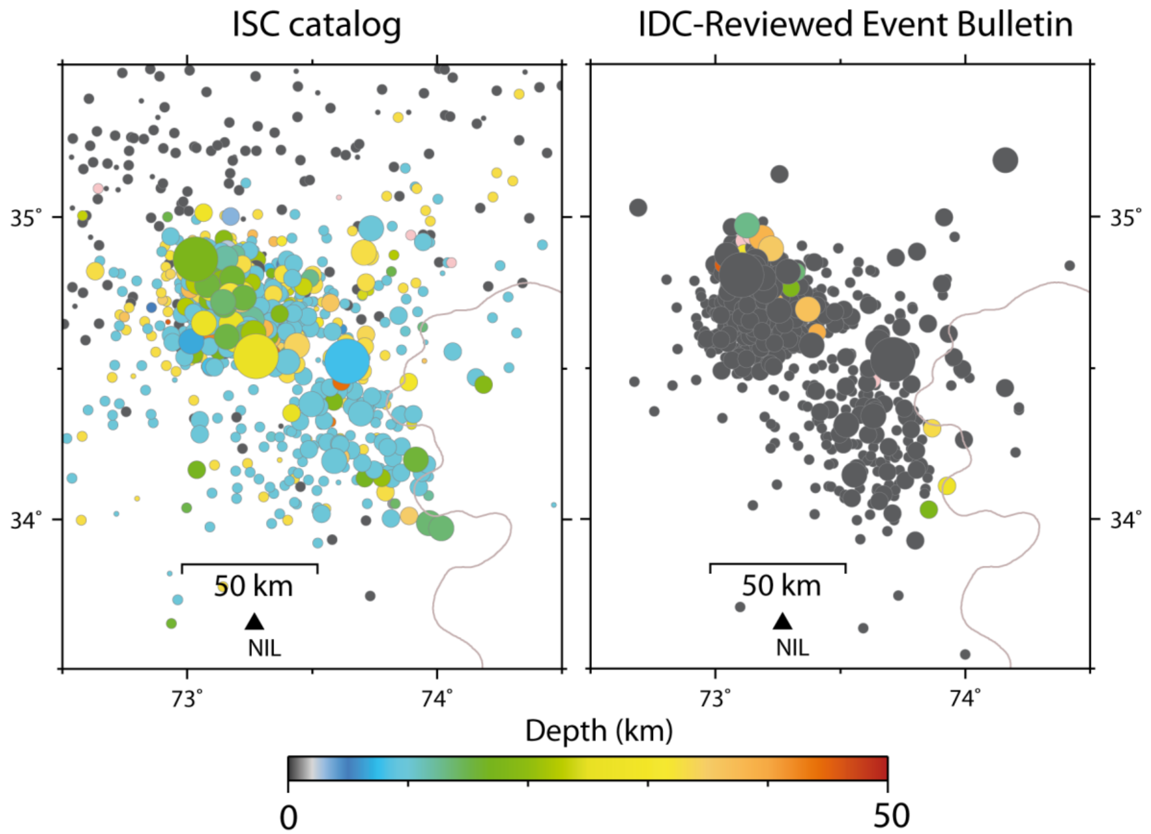
The October 8, 2005, Kashmir earthquake and aftershocks

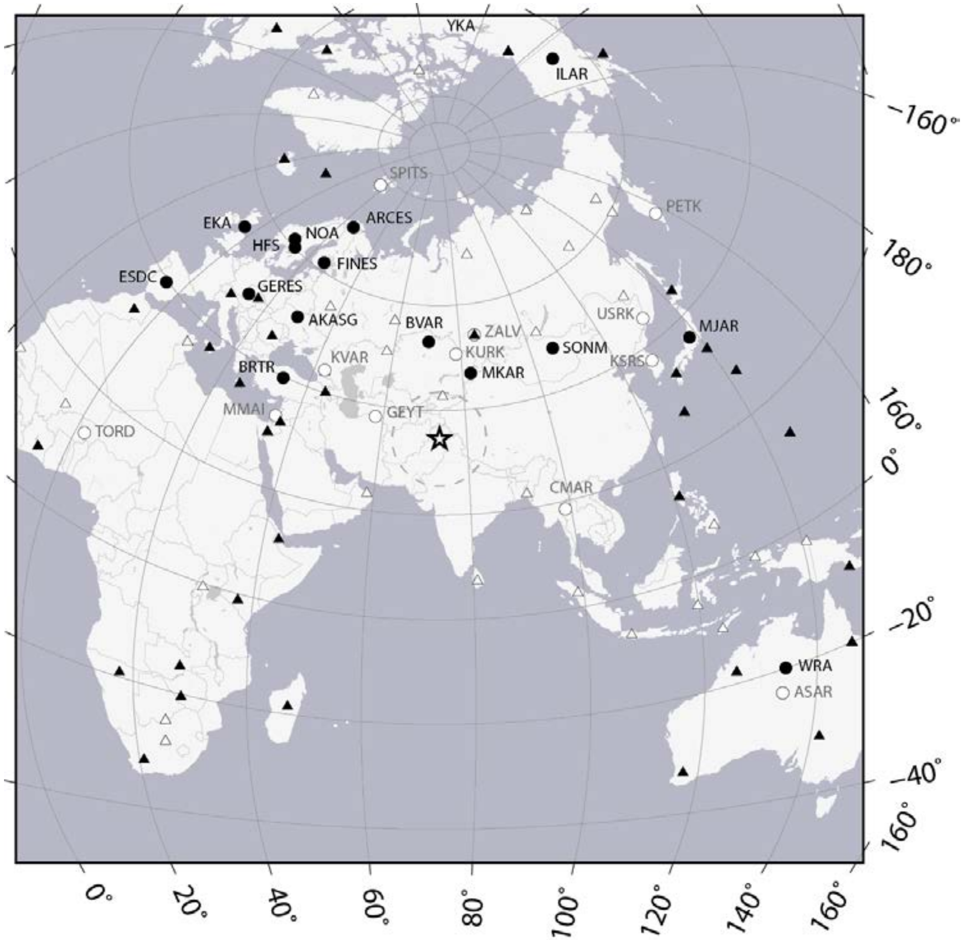
Another situation of challenging earthquake location is the aftershock sequence from the M = 7.6 October 8, 2005, Kashmir earthquake.

Very few (open) stations at regional distances.

Poor azimuthal distribution both regionally and teleseismically.

Very high traveltime residuals for the regional stations!





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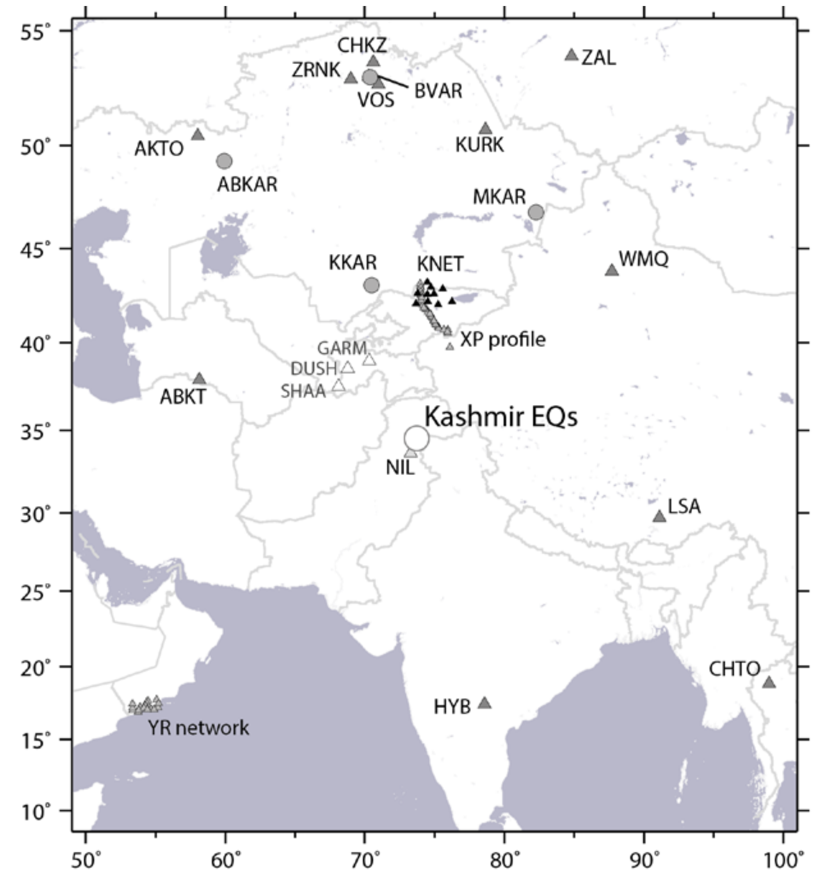

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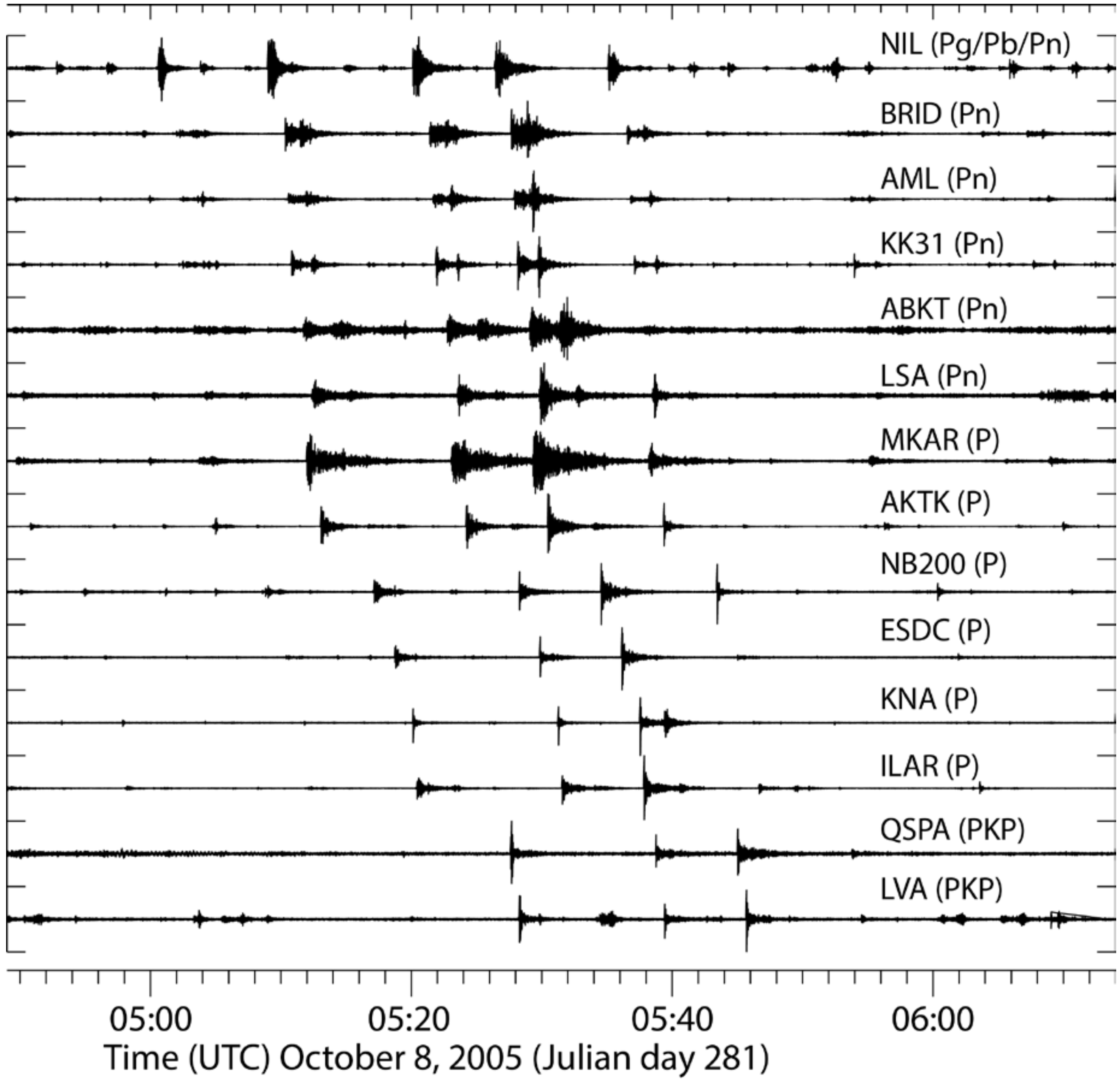
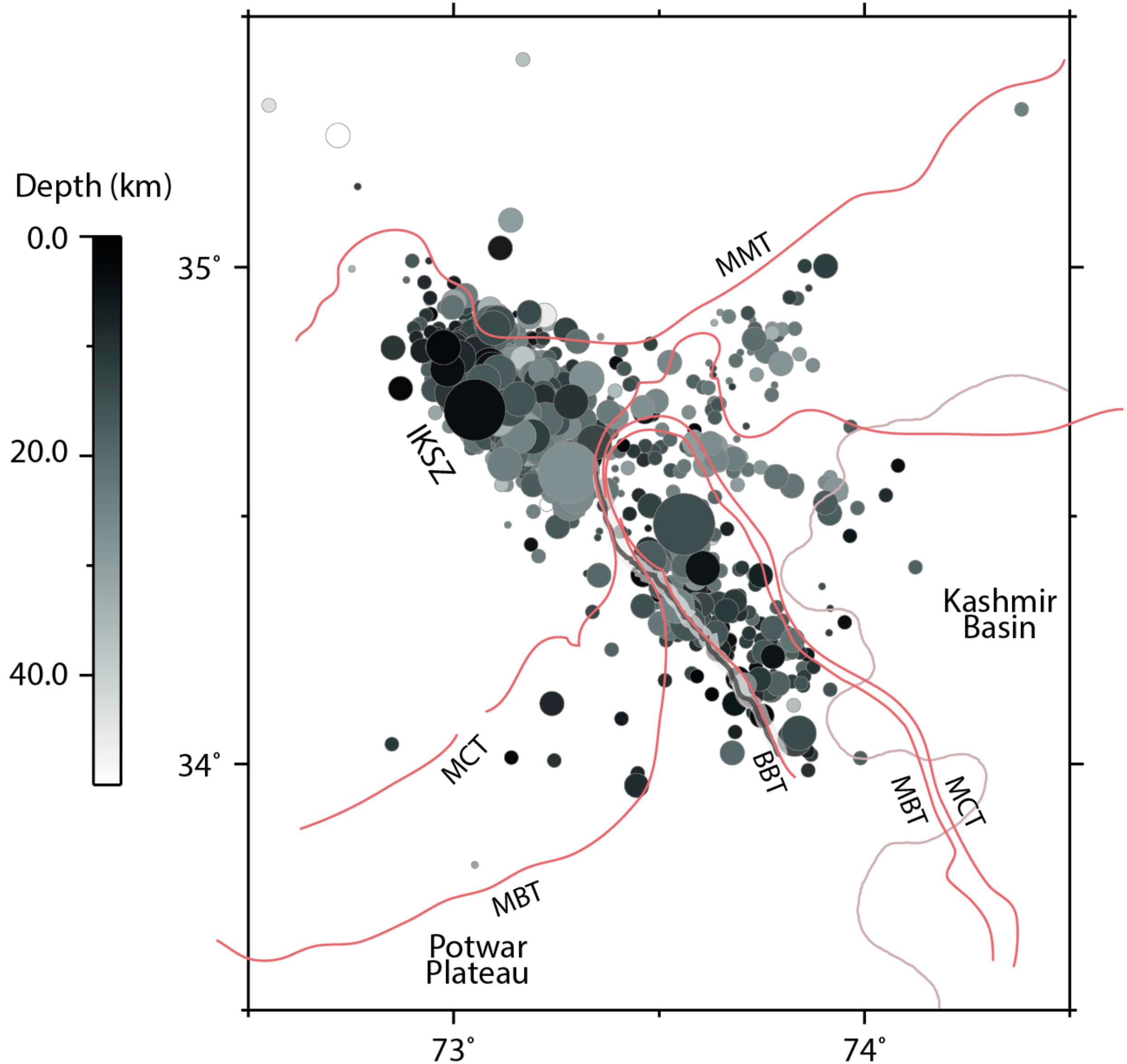


The October 8, 2005, Kashmir earthquake and aftershocks

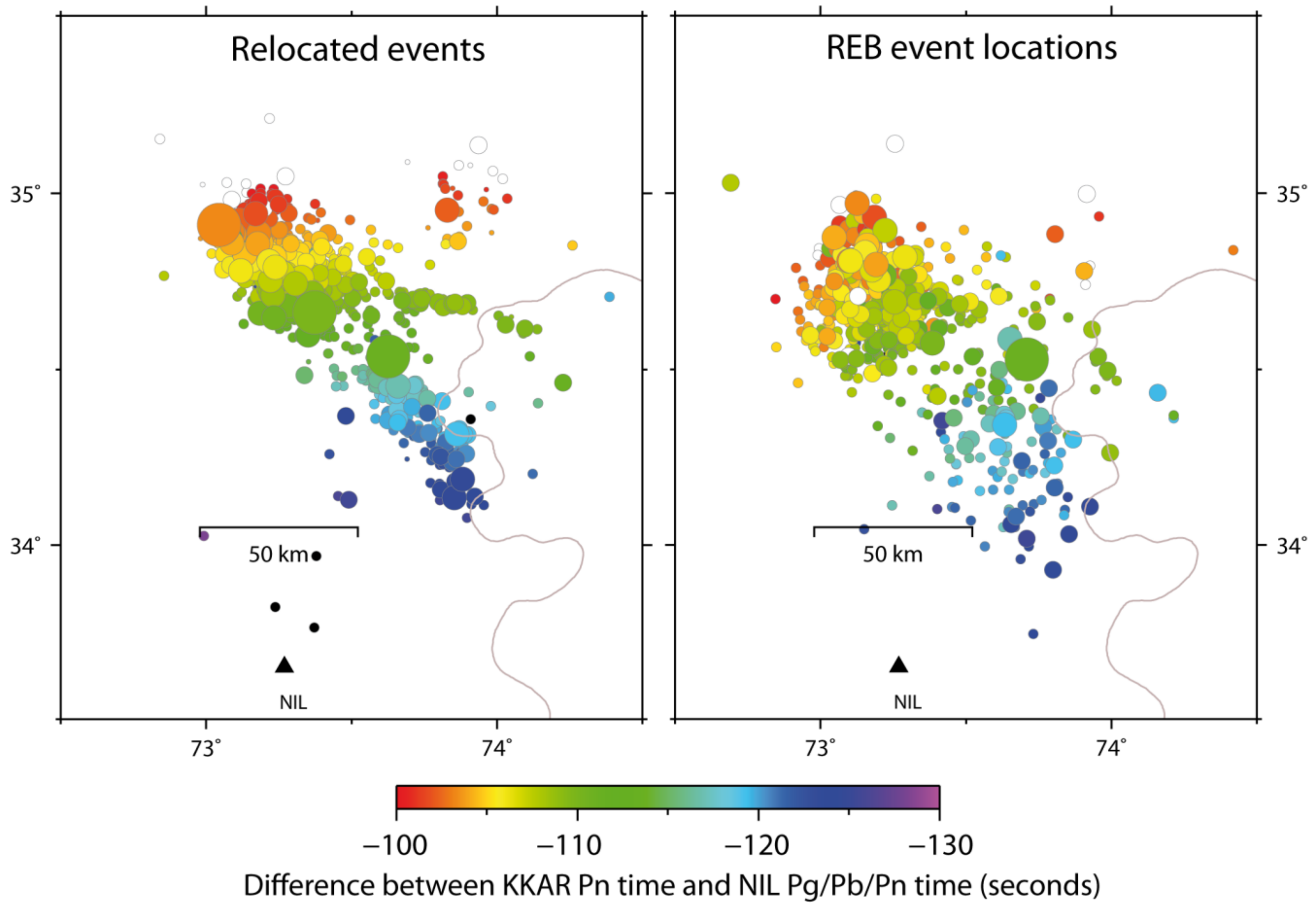
Bayesloc resolves distinct clusters of aftershocks which we can relate to tectonic features.



The October 8, 2005, Kashmir earthquake and aftershocks

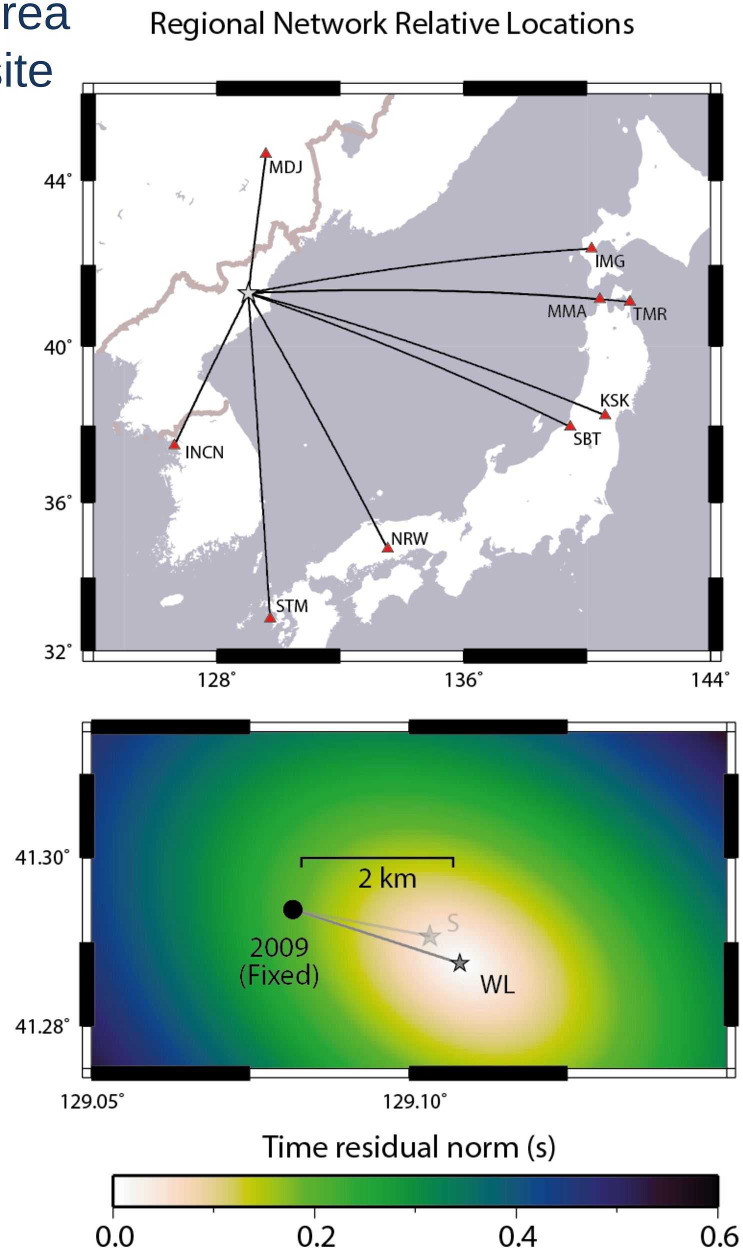
Again – we need to evaluate our relocations.

Examine traveltime residuals and traveltime differences for different station pairs.



The North Korea nuclear test-site

High accuracy relative event locations can provide much information about the likely yield and state of the testing infrastructure.



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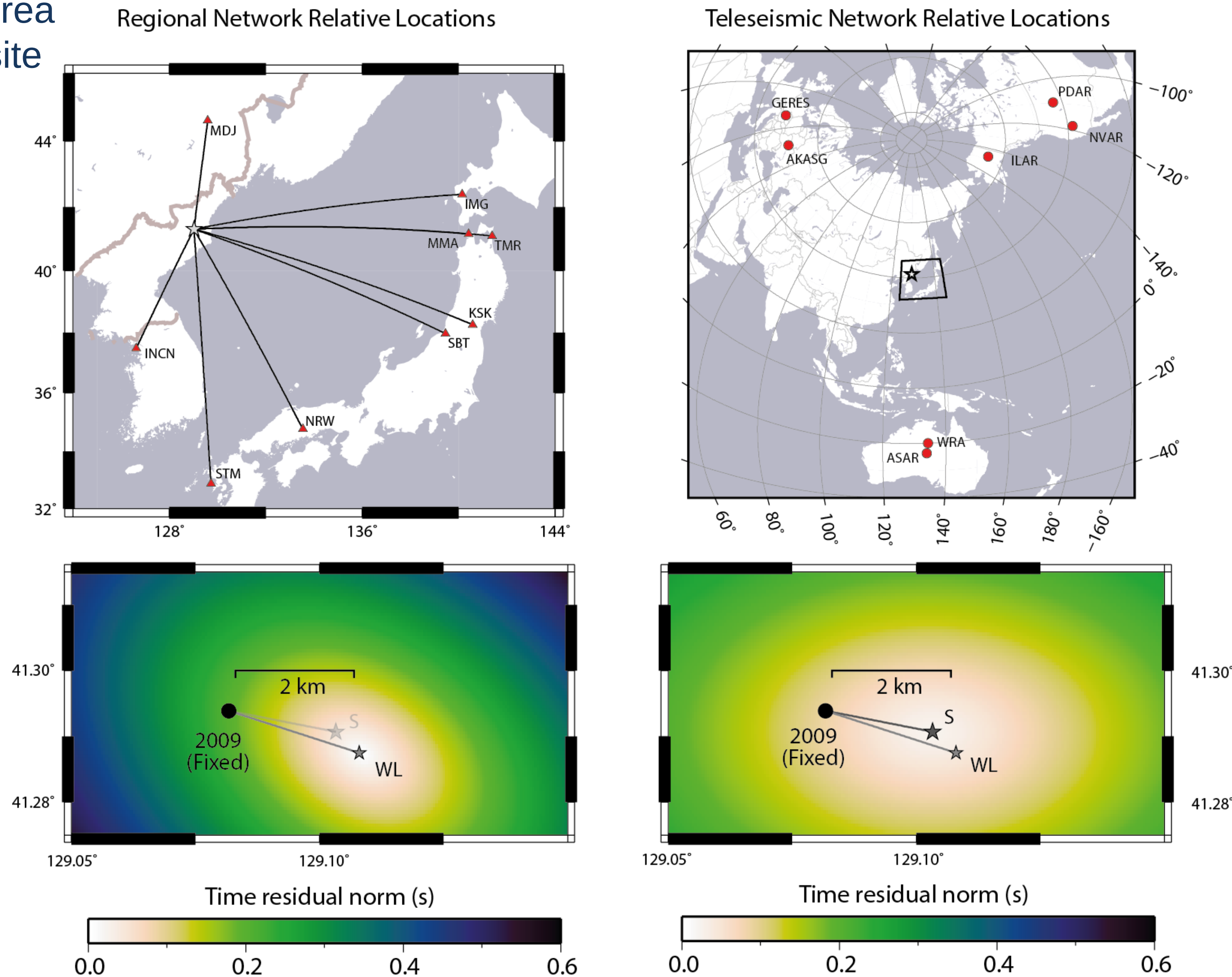

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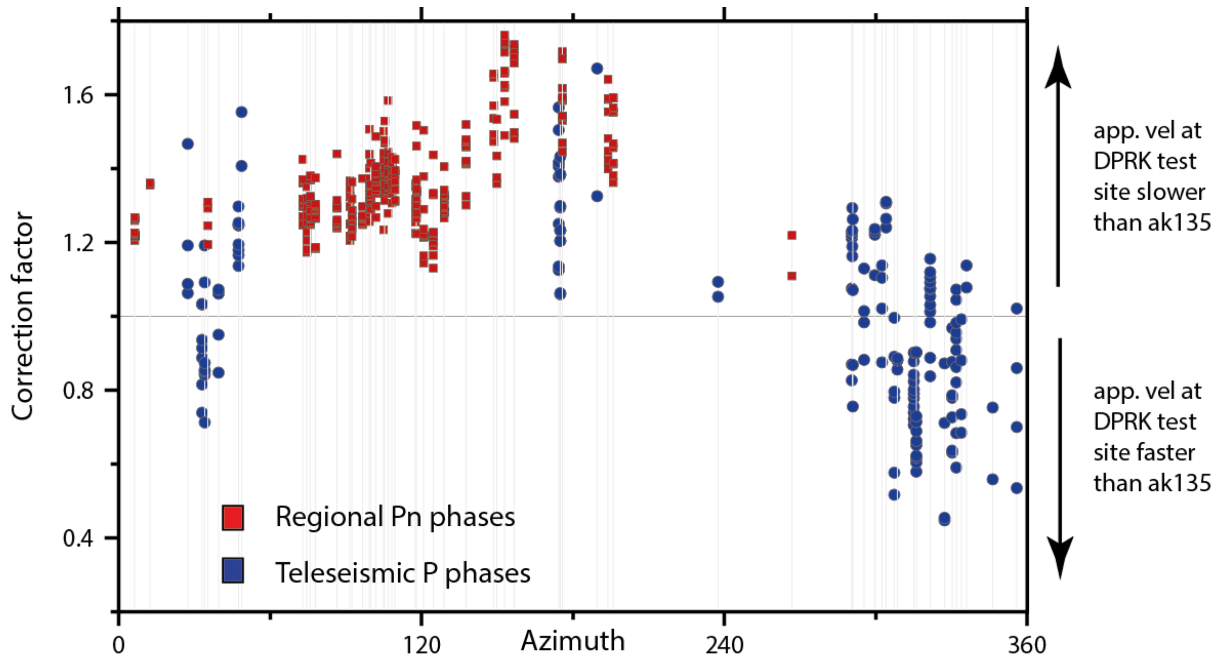
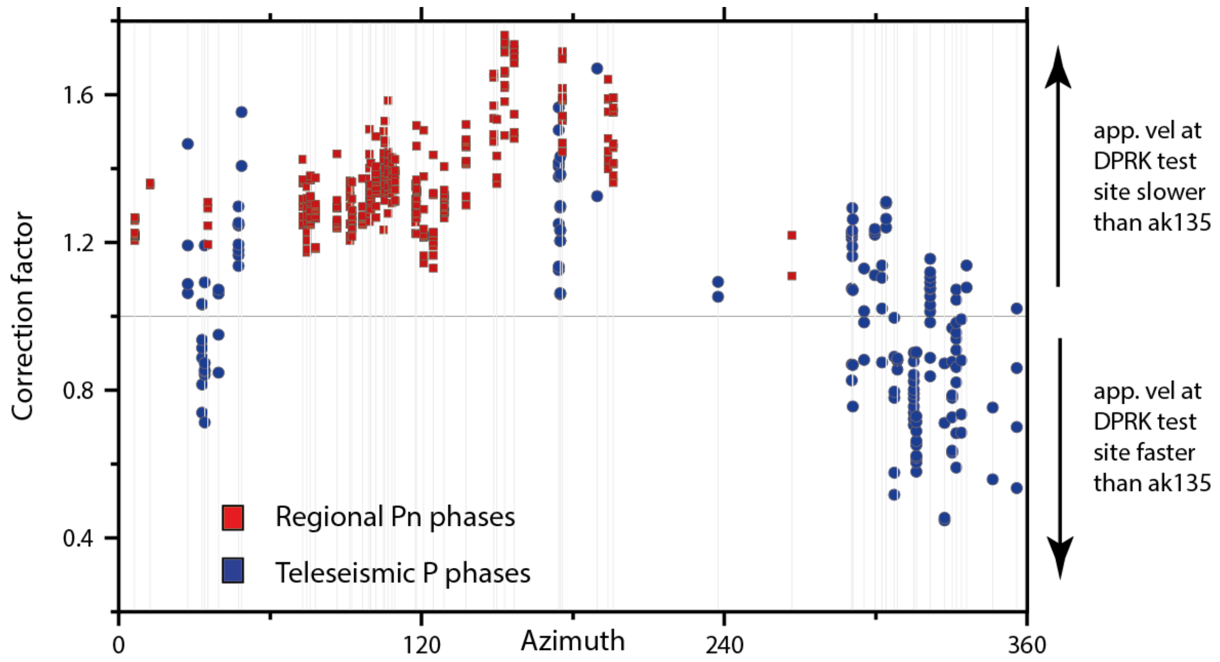

Correction factor
1.6
1.2
0.8
0.4
0
120
Azimuth
240
360
Regional Pn phases
Teleseismic P phases
app. vel at DPRK test site slower than ak135
app. vel at DPRK test site faster than ak135


1.6
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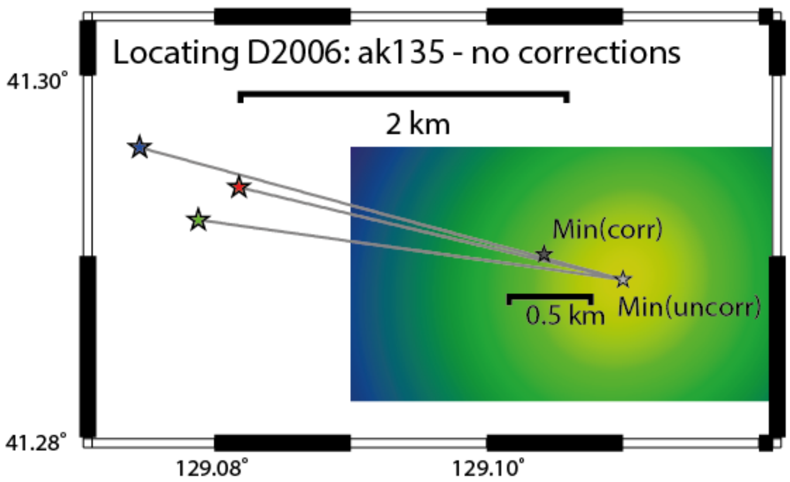
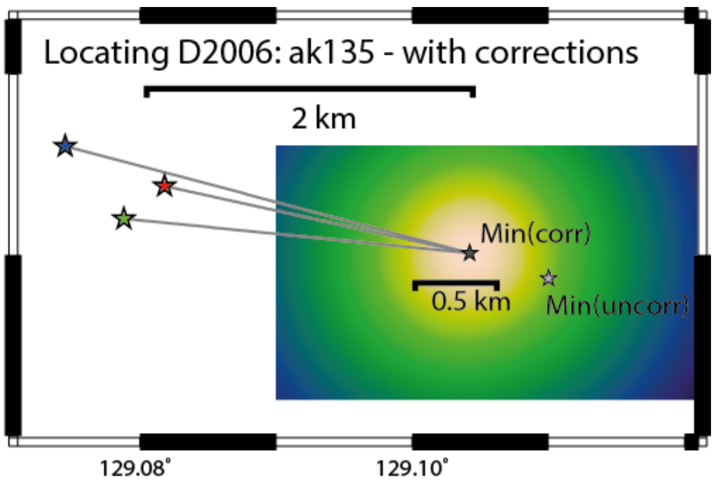
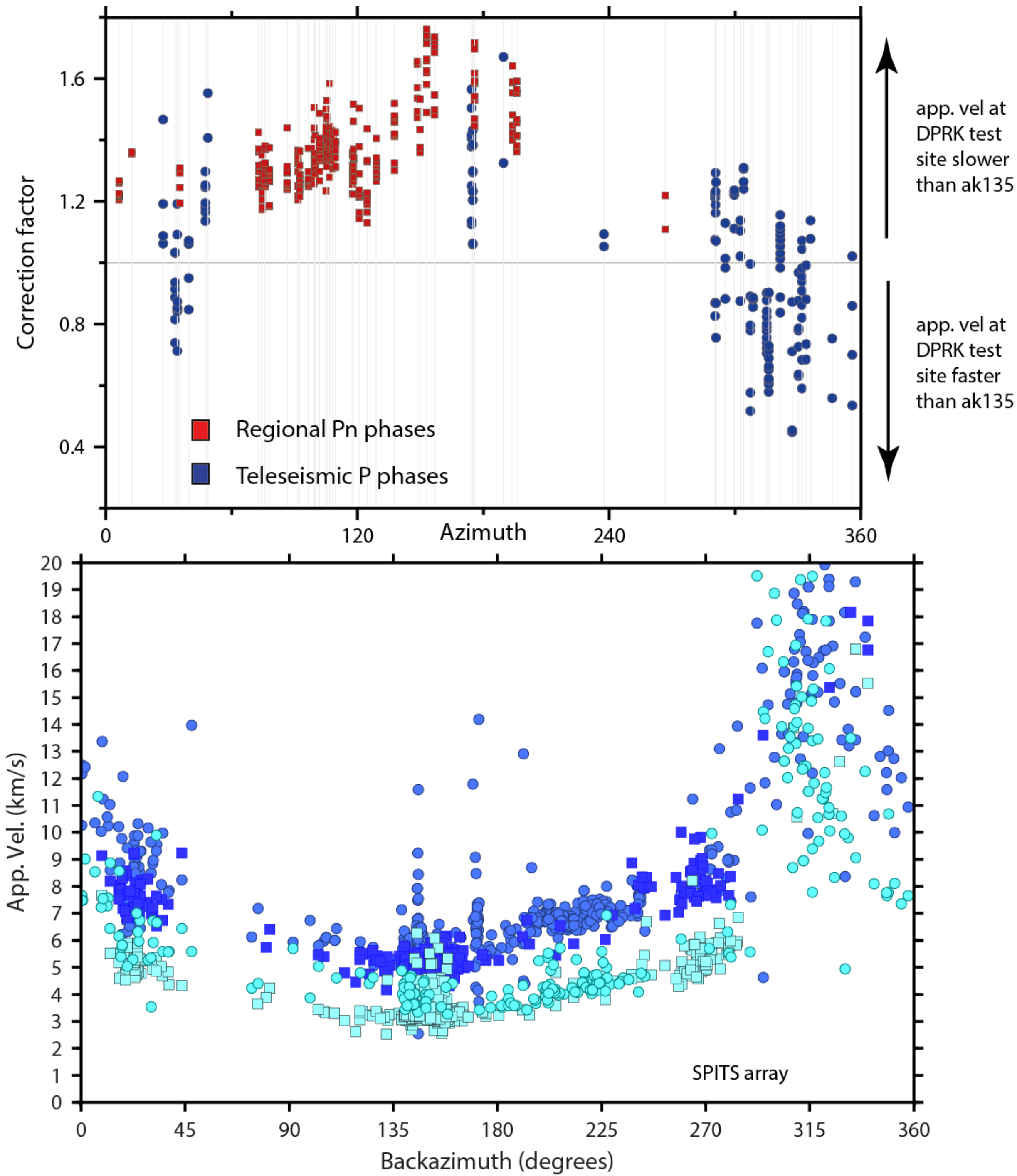

Locating D2006: ak135 - no corrections
2 km
Min(corr)
0.5 km
Min(uncorr)
41.30°
41.28°
129.08°
129.10°


Locating D2006: ak135 - with corrections
2 km
Min(corr)
0.5 km
Min(uncorr)
129.08°
129.10°


Correction factor
1.6
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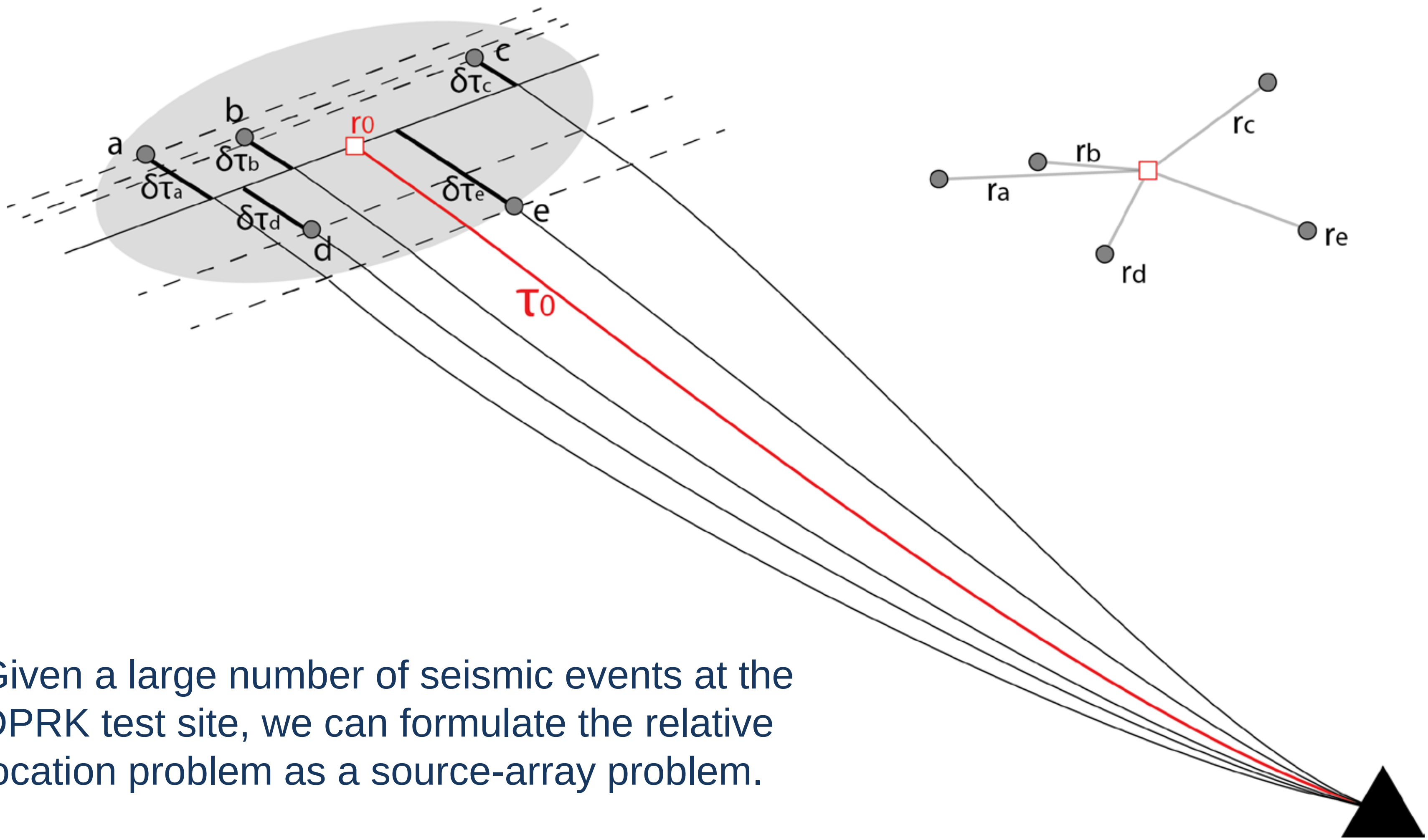
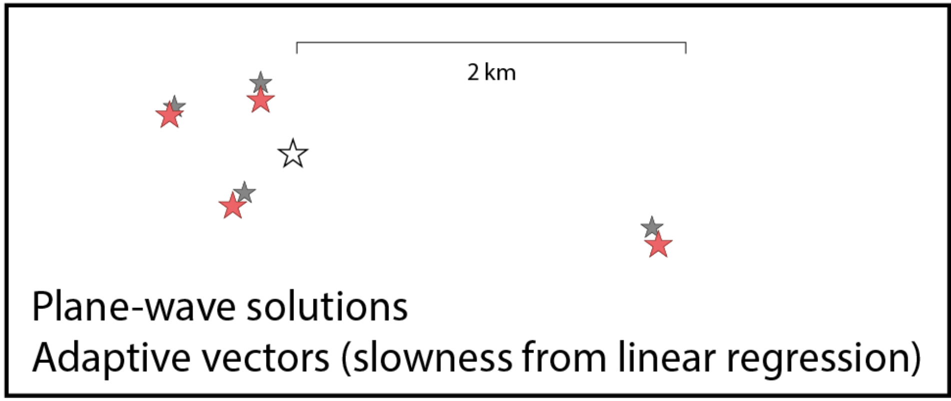
Regional Pn phases
Teleseismic P phases
app. vel at DPRK test site slower than ak135
app. vel at DPRK test site faster than ak135
0
120
Azimuth
240
360
App. Vel. (km/s)
SPITS array
0
45
90
135
180
225
270
315
360
Backazimuth (degrees)

Accurate seismic event location: A question of context



Given a large number of seismic events at the DPRK test site, we can formulate the relative location problem as a source-array problem.

Accurate seismic event location: A question of context



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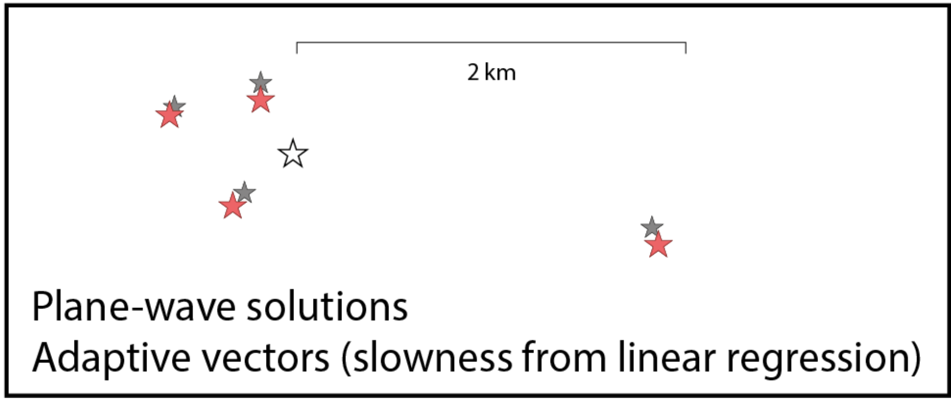

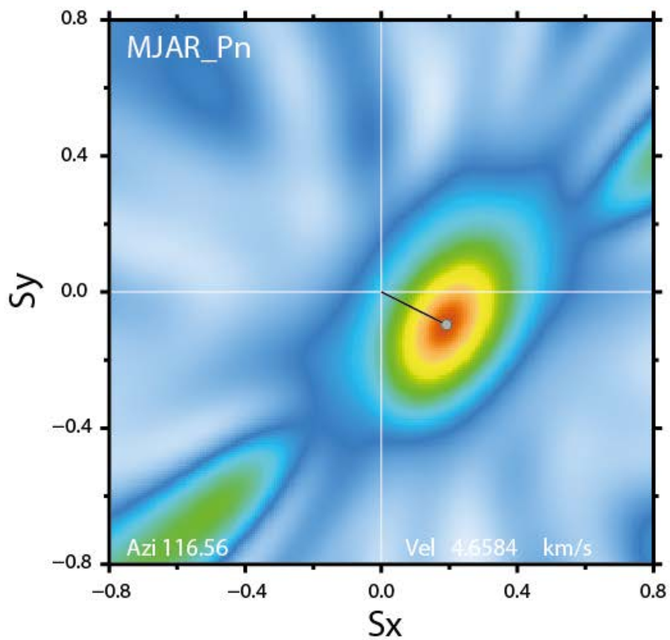

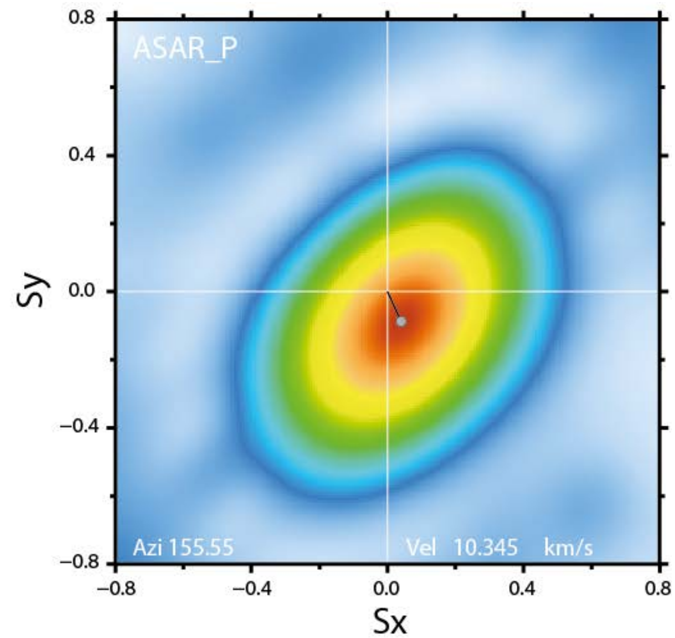

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SUMMARY

- Our knowledge of Earth Structure is always improving – but it is not perfect!
  (It never will be either ... not at every spatial scale ...)

- For regions with significant seismicity, our knowledge of the velocity model does not need to be perfect for significantly improved seismic event locations.

- Probability-based multiple event location algorithms can make good estimates of the uncertainty and bias of traveltimes along individual paths ... even when estimates of the full velocity structure are difficult/impossible.

- Apply double-difference type calculations with caution!

  Are there multiple datasets which can be applied to the problem?
  Are there different methods which can make independent estimates?