Effect of seismometer clock synchronization error on hypocenter solution
T. O'Reilly
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When considering effects of clock drift on hypocenter computation, we must distinguish between the autonomous real-time computation performed at sea when the event occurs, from post-recovery analysis. For post-recovery analysis, the seismic data-logger clock offsets from GPS can be directly measured, and a linear drift assumed. However it is very difficult to directly compare data-logger clocks to GPS time while the system is deployed; hence network clock synchronization techniques such as NTP or IEEE-1588 must be employed instead.

Project PI Dave Clague states that the system must be capable of discriminating between seismic events underneath Axial caldera from more distal events – *autonomously, in real time*. Given the caldera dimensions of roughly 3 km by 6 km, this requirement implies spatial hypocenter resolution of 1000 meters or so. This capability obviously depends on accurate synchronization between station clocks, but how accurate is "accurate"? The answer to this question could have significant impact on project cost. E.g. NTP can achieve 10s of milliseconds accuracy, possibly with existing MOOS hardware. More accurate schemes such as IEEE-1588 would definitely require additional network hardware.

To answer this problem I've run some Monte Carlo-style tests (with lots of assistance from David Oppenheimer and Fred Klein of USGS) using the following procedure:

1. Assuming event hypocenter and station geometry, determine "actual" p-wave arrival times at the stations
2. Introduce random "jitter" in p-wave arrival times, corresponding to clock synchronization errors
3. Compute "apparent" hypocenter from jittered arrival times

Steps 2 and 3 were run repeatedly for given hypocenter location and station geometry. The resulting apparent hypocenters were then plotted on maps, giving a visual indication of the hypocenter "dispersion" resulting from clock jitter.

The USGS hyp2000 application (http://geopubs.wr.usgs.gov/open-file/of02-171/) was used to compute hypocenters for simulated seismic events in the Axial area. The crustal model of West et al (http://www.nature.com/nature/journal/v413/n6858/full/413833a0.html) was adapted for input to hyp2000 by David Oppenheimer. Note that s-wave arrival times were not considered in these tests.

Test results are plotted on a bathymetric map of Axial in the following figures. Computed hypocenters are plotted as small colored circles. The circles are color-coded according to hypocenter depth. The "actual" hypocenter is represented by a diamond labeled 'A'. The seismic stations are represented as gold stars.

Figures 1-4 show computed hypocenter dispersion for an event near the center of the seismometer array, at a depth of 2 kilometers below the caldera surface, at station clock jitter limits of 10, 50, 100, and 250 milliseconds. Each figure represents 1000 hypocenters computed after introducing random jitter within the specified limit. You can see that dispersion is less than 500 meters or so at 10 milliseconds jitter. Dispersion is on order of 1000 meters at 50 milliseconds jitter, at 2000-3000 meters at 100 milliseconds jitter. At 250 milliseconds jitter, dispersion is several kilometers, and depth is quite large for many of the solutions.

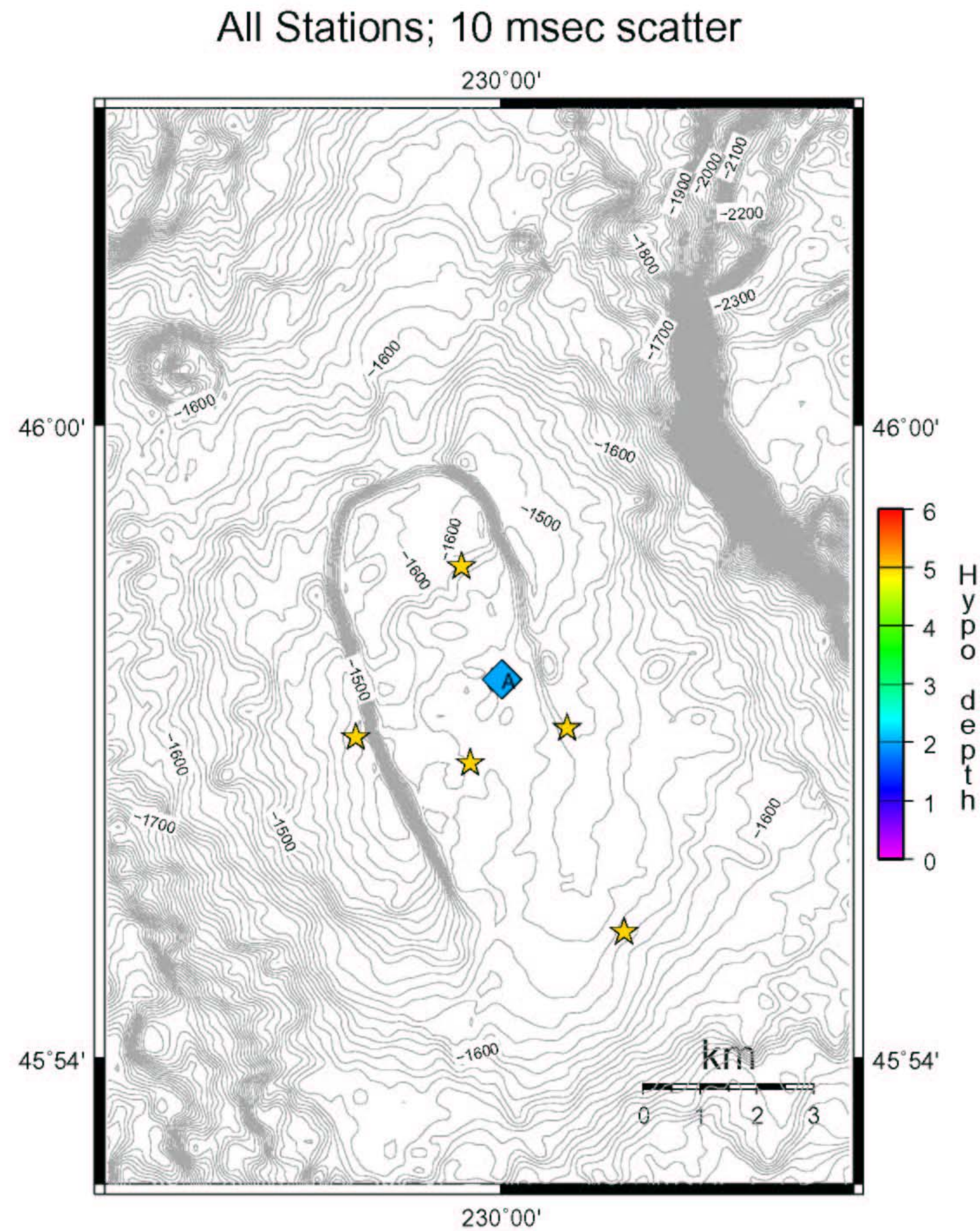
All Stations; 10 msec scatter
230°00'
46°00'
45°54'
-1500
-1600
-1700
-1800
-1900
-2000
-2100
-2200
-2300
A
km
0
1
2
3
Hypo depth
0
1
2
3
4
5
6

Figure 1

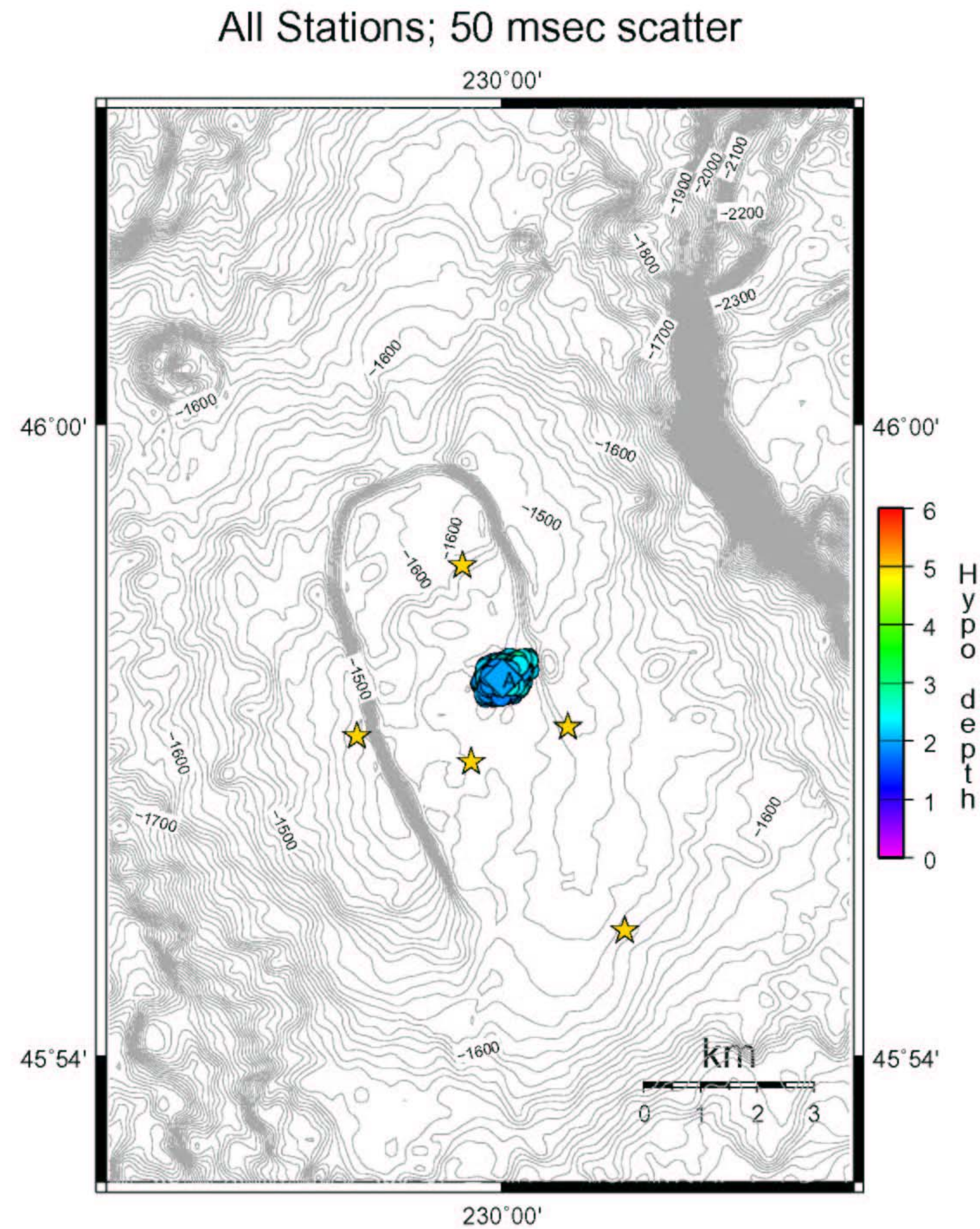
All Stations; 50 msec scatter
230°00'
46°00'
45°54'
-1900
-2000
-2100
-2200
-1800
-2300
-1700
-1600
-1500
-1700
km
0 1 2 3
6
5
4
3
2
1
0
Hypo depth

Figure 2

All Stations; 100 msec scatter

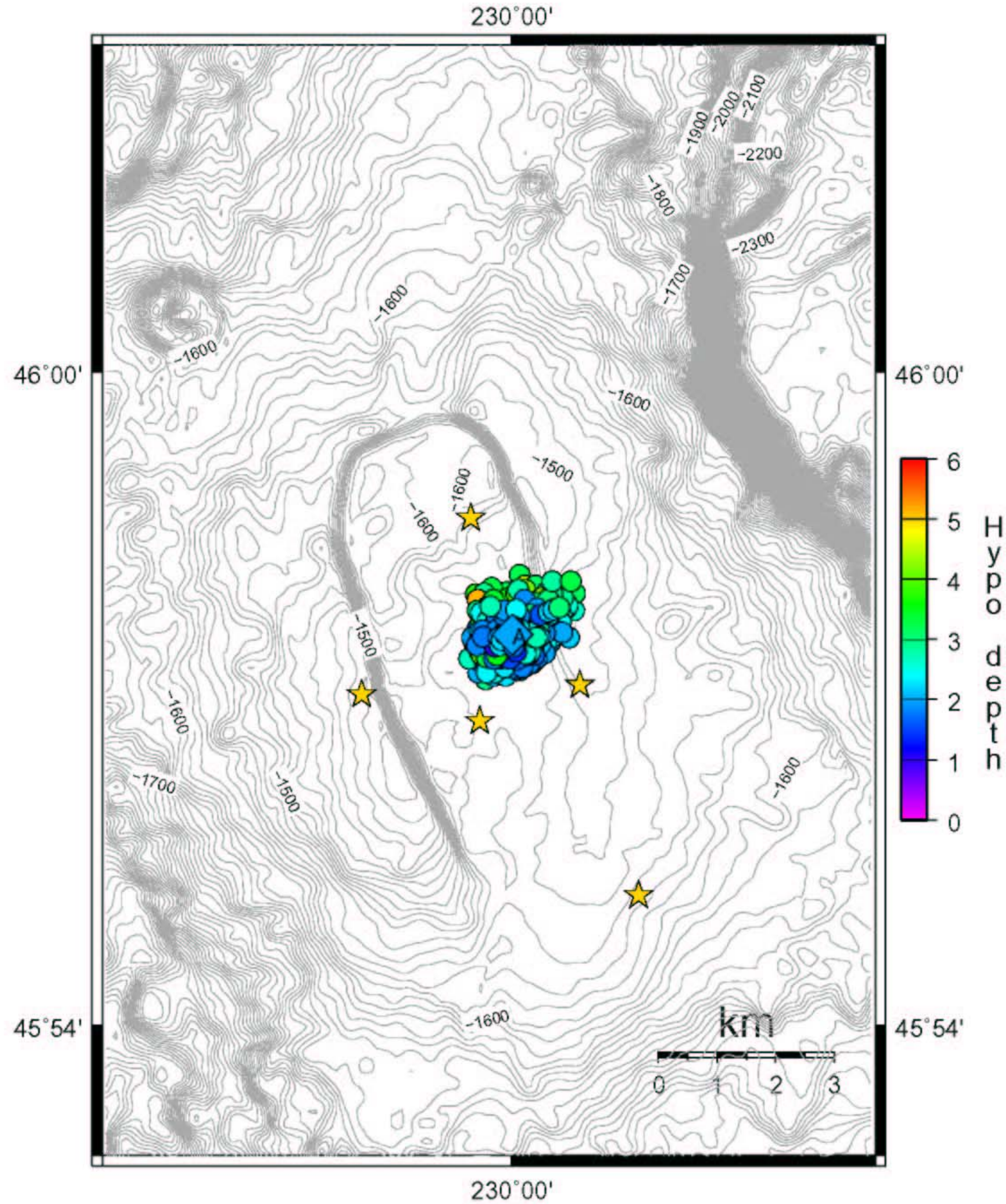

Figure 3

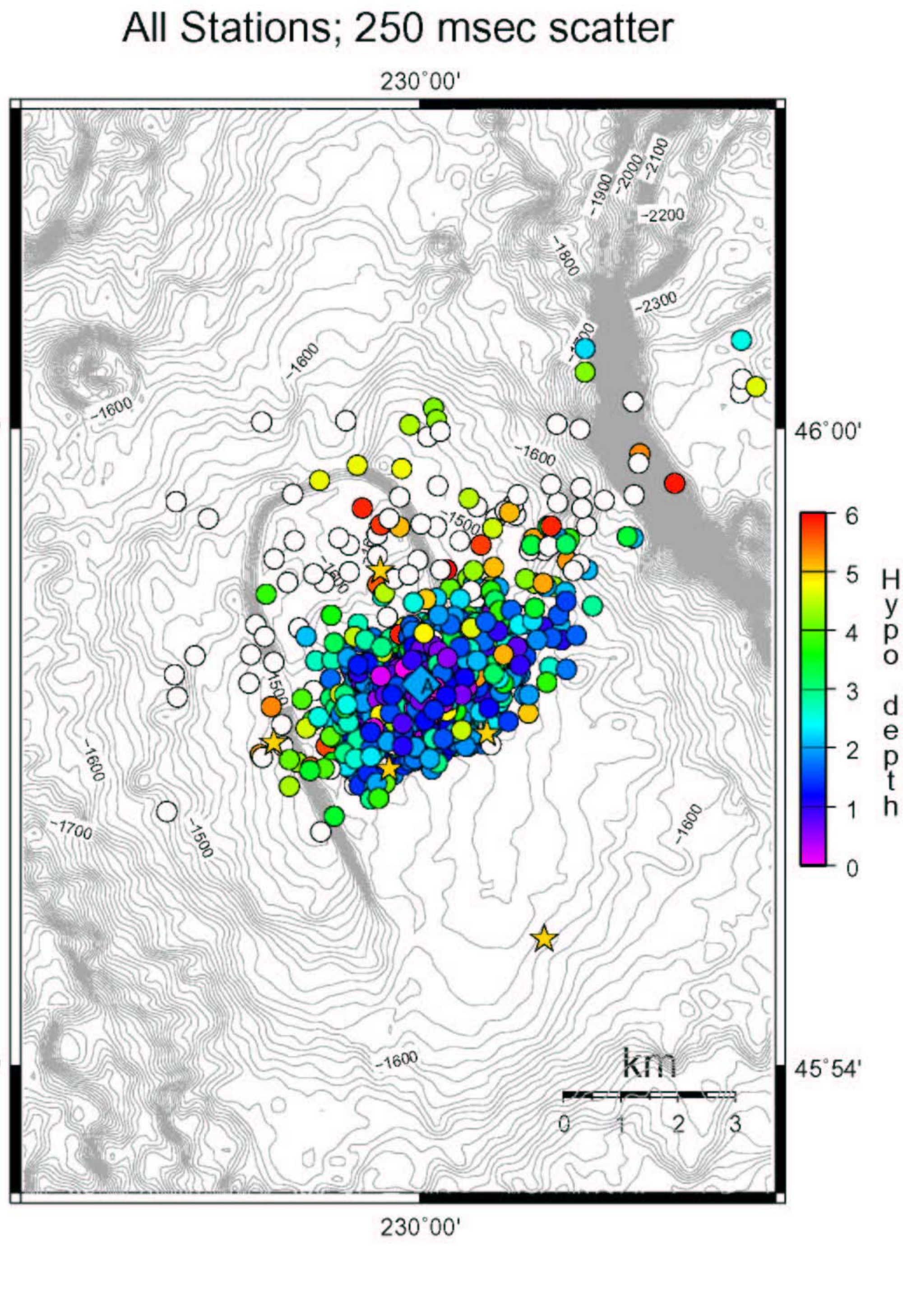
All Stations; 250 msec scatter
230°00'
46°00'
45°54'
-1600
-1500
-1700
-1800
-1900
-2000
-2100
-2200
-2300
km
0 1 2 3
Hypo depth
0
1
2
3
4
5
6

Figure 4

Figures 5 through 7 show results for an event located external to the seismic array, at a depth of 2 kilometers below the caldera surface. The dispersions are signficantly greater than those computed for the central seismic event at the same clock jitter limits (Figures 1-4). Note also the elongated east-west locus of computed hypocenters; I do not understand what causes this, but maybe it is the crustal model – David Oppenheimer, do you have an opinion on this?

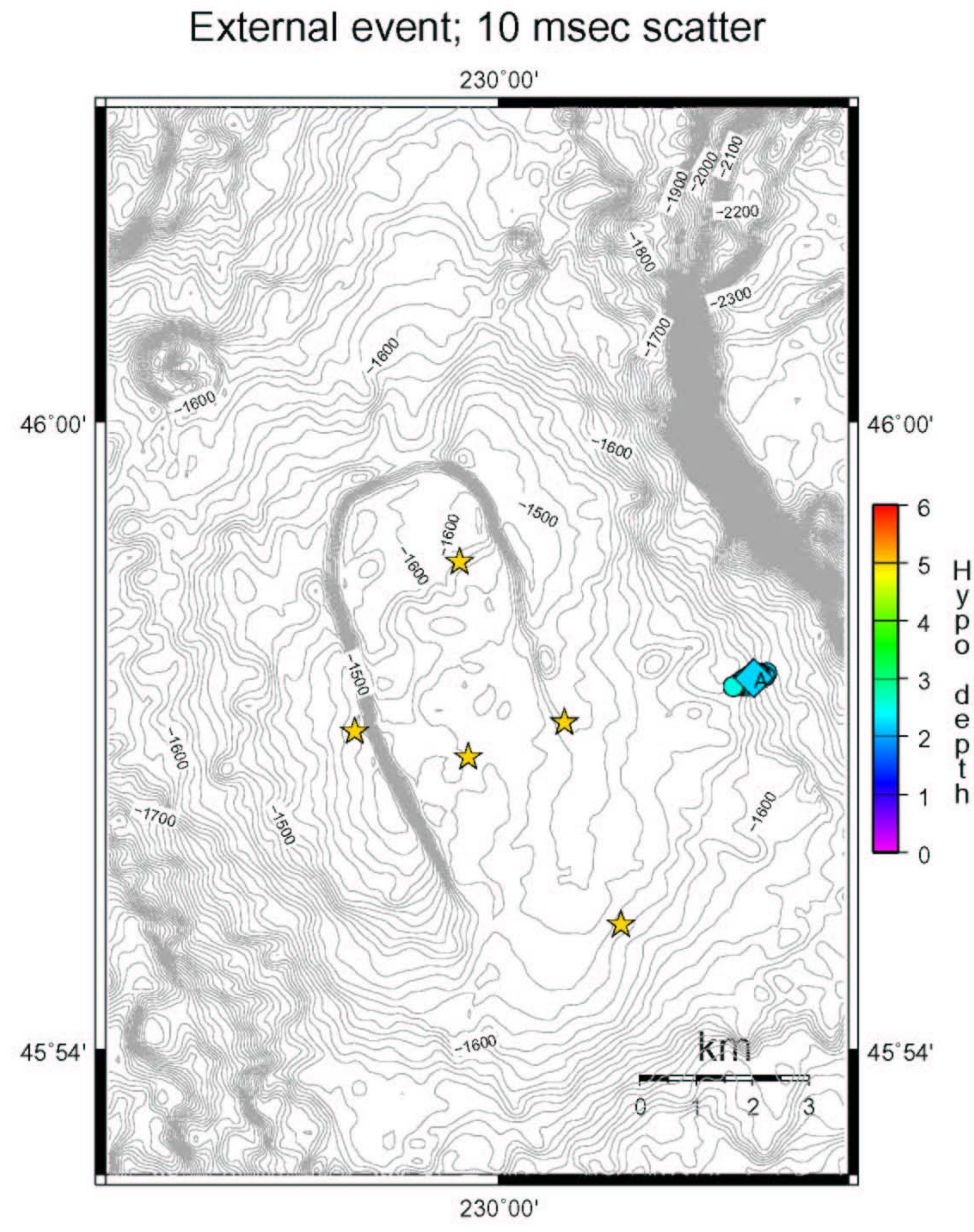
External event; 10 msec scatter
230°00'
46°00'
45°54'
-1600
-1500
-1700
-1800
-1900
-2000
-2100
-2200
-2300
A
km
0
1
2
3
6
5
4
3
2
1
0
Hypo depth

Figure 5

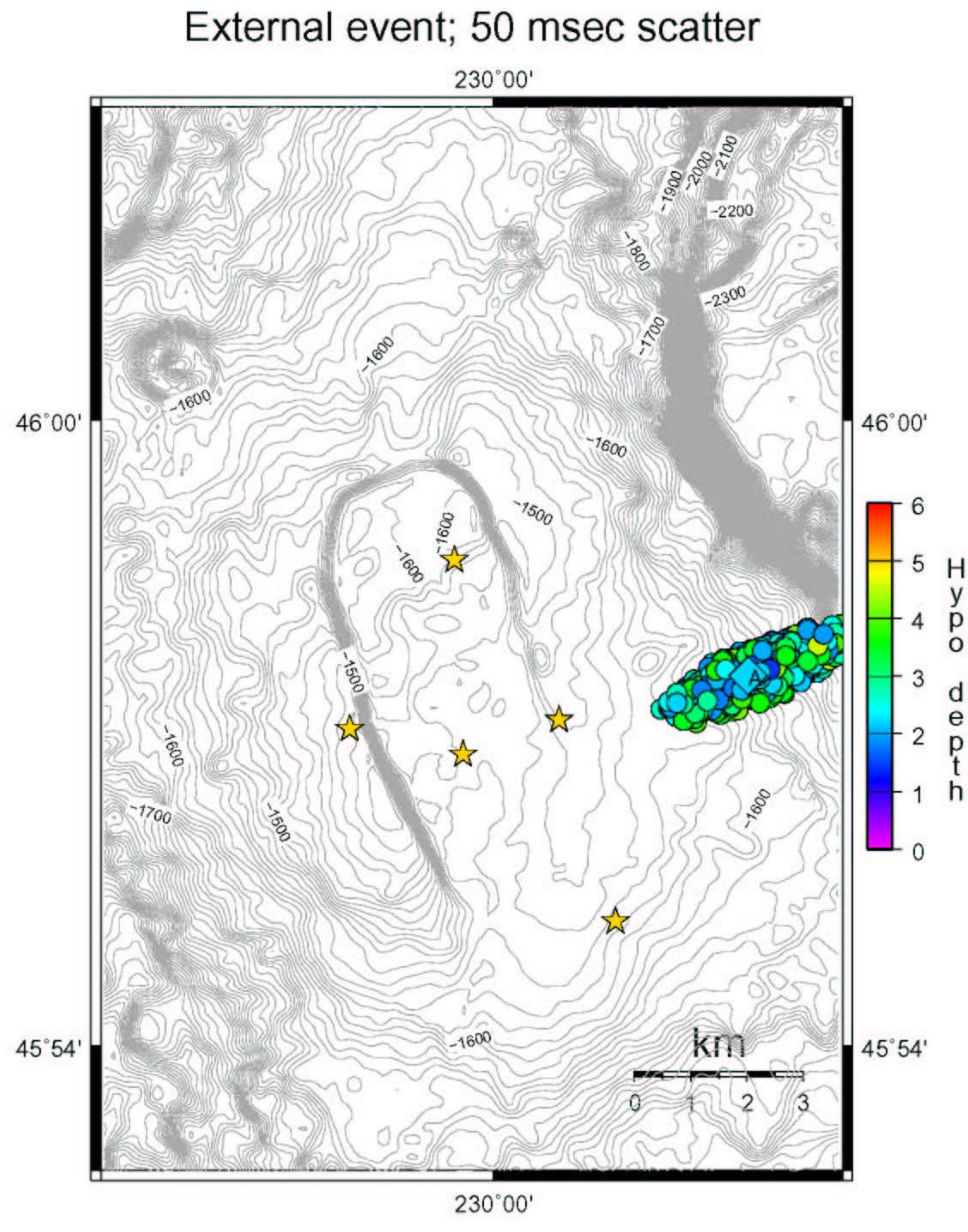
External event; 50 msec scatter
230°00'
46°00'
45°54'
km
0
1
2
3
Hypo depth
0
1
2
3
4
5
6
-1500
-1600
-1700
-1800
-1900
-2000
-2100
-2200
-2300

Figure 6

External event; 100 msec scatter

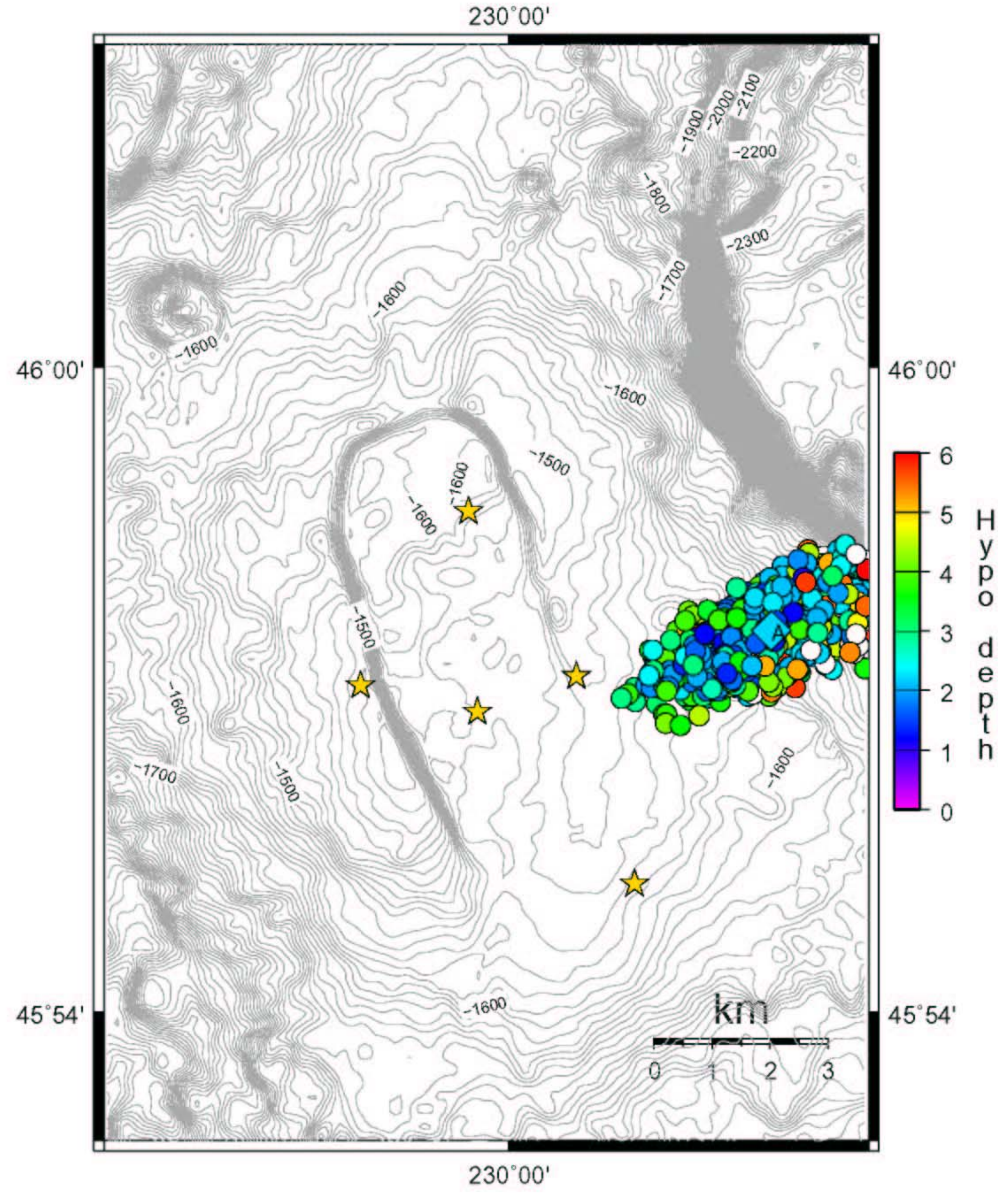

Figure 7

Finally, Figures 8 through 10 show the effect of “losing” a seismic station, in this case the North station. As in figures 1-4, the seismic event occurred near the center of the caldera at a depth of 2 kilometers. For all clock jitters considered, we see that some hypocenter locations are several kilometers in error. Note also the bi-modal distribution of hypocenter solutions. I don’t understand why these occur; does anyone have any ideas?

Here are some preliminary conclusions I’ve drawn from these tests:

1. Limiting clock jitter to less than 10 milliseconds results in significant improvement in hypocenter resolution relative to jitter of 50 or 100 millseconds
2. Clock jitter of 250 milliseconds results in unacceptably large errors in hypocenter location
3. Loss of just one of our five stations results in serious degradation of hypocenter solution.

Based on my tests so far, I think these conclusions remain in effect when the station geometries are “slightly” adjusted.

Note also that timing jitter is not the only source of error in hypocenter location. Crustal velocity model in particular can be difficult to estimate. The hyp2000 software allows the user to estimate input errors; perhaps the next step would be to determine if the 500 meter accuracy implied by our results at 10 milliseconds jitter is realistic, based on these other uncertainties.

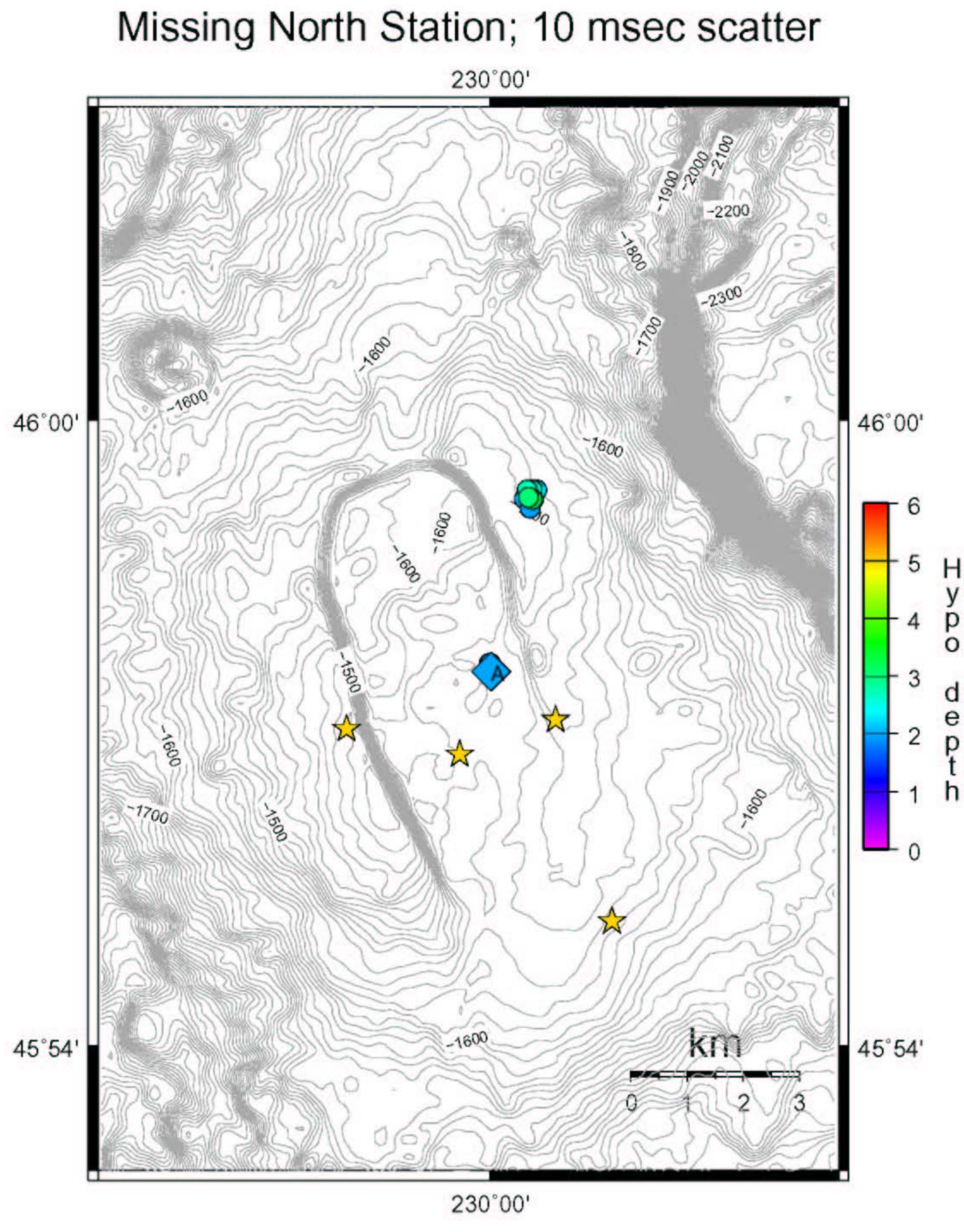
Missing North Station; 10 msec scatter
230°00'
46°00'
45°54'
-1900
-2000
-2100
-2200
-1800
-2300
-1700
-1600
-1500
-1700
A
km
0
1
2
3
Hypo depth
0
1
2
3
4
5
6

Figure 8

Missing North Station; 50 msec scatter

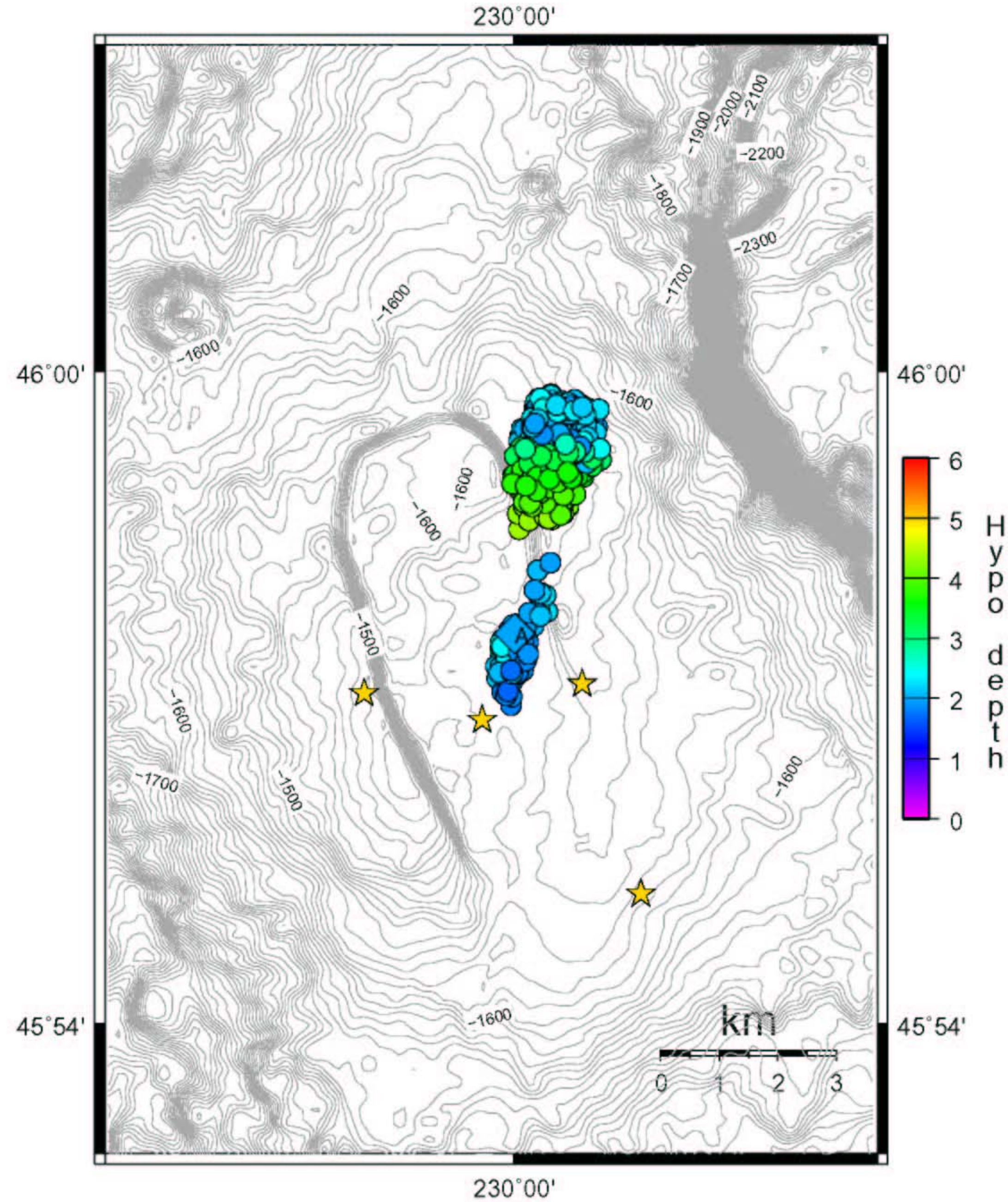

Figure 9

Missing North Station; 100 msec scatter

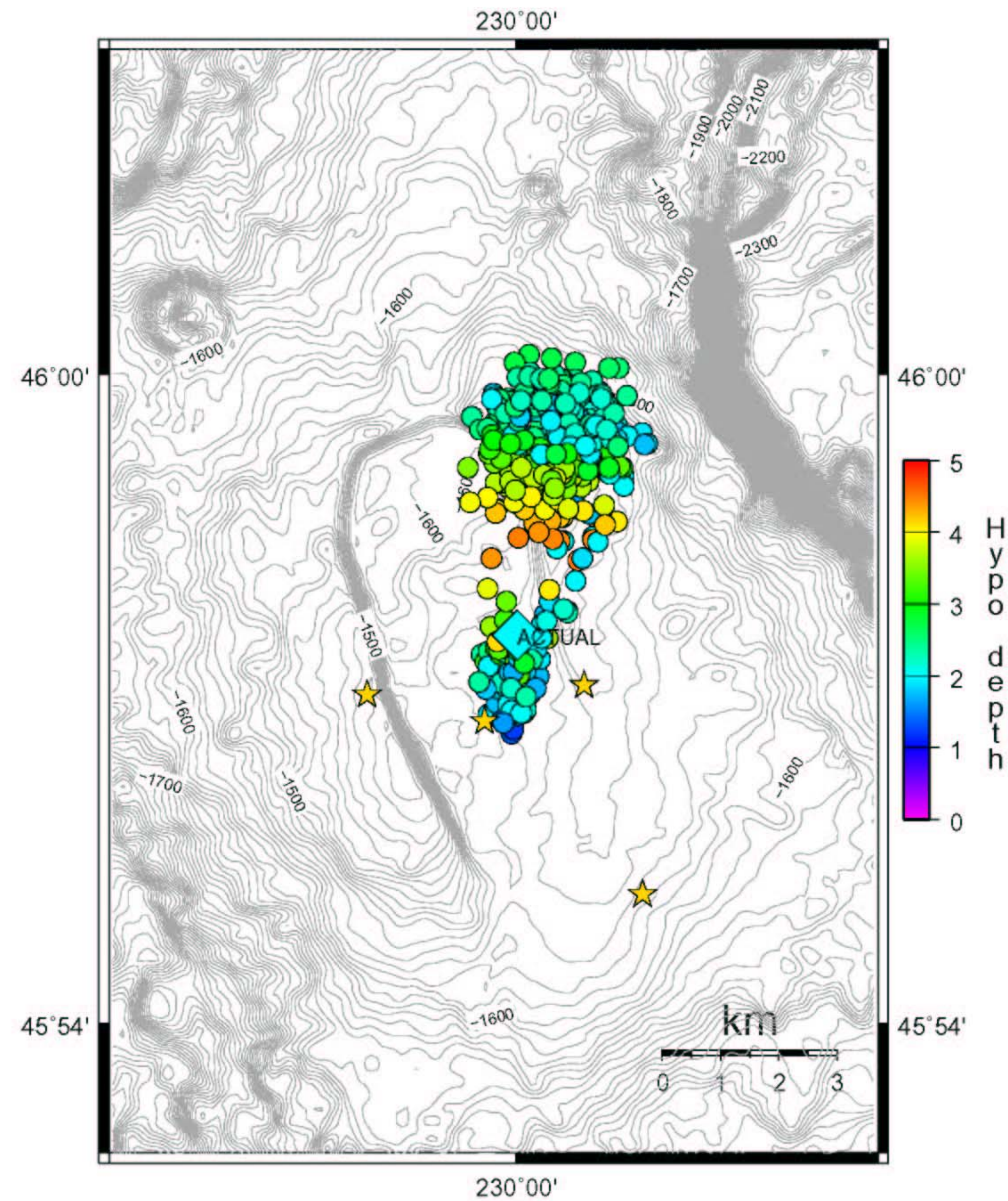

Figure 10