USGS Award Number: G12AP20136
Project Duration: 12 months

Final Technical Report

Integrating USArray and Cooperative New Madrid Seismic Network Data to Establish Central US Catalog Location and Magnitude Sensitivities

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Submitted on July 1, 2013

ABSTRACT

The Earthscope USArray Transportable Array (TA) temporarily expands earthquake identification and location ability within the central United States when combined with the Cooperative New Madrid Seismic Network (CNMSN). I developed an automated process that combines the Array Network Facility (ANF) earthquake catalog and phase onset times for local earthquakes recorded on the TA with like CNMSN data, which focuses on the New Madrid seismic zone. The integrated data were used to relocate seismicity following procedures closely allied to the original CNMSN location procedure using HYPOELLIPSE and the soon-to-be implemented new CNMSN location procedure using Hypoinverse. This allows me to 1) understand if differences in seismicity pattern between the Central Missouri Valley catalog (1974-1994) and the CNMSN catalog (1995-present) are a function of station distribution, 2) provide more accurate estimates of earthquake locations outside of the Mississippi embayment, and 3) assess how changes in CNMSN processing effect catalog location and magnitude estimates in the central US.

All original goals of the project were met. The addition of the TA data affected the catalog locations across the study area. The current CNMSN network geometry, and the care taken by analysts to remove anthropogenic events, appears sufficient to detect most small magnitude earthquakes. The ANF catalog, and likely the CMV catalog, contain many anthropogenic events outside of the Mississippi embayment. The addition of select TA stations would not necessarily increase earthquake detections rates. The inclusion of phases at stations outside of the embayment had a significant effect on hypocentral location throughout the study area. Events inside the embayment shifted to the north and west by 0.25-0.50 km when TA data was added. Depths changed by almost 2 km with standard deviations of 2-5 km depending on subregion. Finally, as CNMSN operators adopt the AQMS there will be changes in location technique and magnitude calculation. Changes in hypocentral location with Hypoinverse were smaller than catalog changes due to the incorporation of TA data across all subregions. Ultimately, changes in event-station geometry affect the catalog more than choice of location algorithm. Depth remains a particularly sensitive and difficult parameter to constrain.

Introduction

This proposal provided funding to design and implement a procedure to integrate USArray Transportable Array (TA) recordings of central US earthquakes with the Cooperative New Madrid Seismic Network (CNMSN), which is charged with providing earthquake hypocenters and magnitude estimates for the central US in cooperation with the US Geological Survey. Waveforms and phases recorded at all broadband seismic stations reporting to the IRIS Data Management Center were also included in the data integration. The integrated data are being used to relocate seismicity within and outside of the Mississippi embayment and to calculate local coda magnitudes. Goals include: 1) understand how differences in seismicity patterns between the Central Missouri Valley catalog (1974-1994) and the CNMSN catalog (1995-present) are a function of station distribution, 2) provide more accurate estimates of earthquake locations outside of the Mississippi embayment, 3) identify important azimuths and distances that would optimize location and magnitude accuracy if more stations could be added to the CNMSN and 4) document how changes in CNMSN processing that will be implemented during 2011 affect catalog location and magnitude estimates in the central US.

The TA temporarily expands earthquake identification and location ability within the central United States. The Array Network Facility (ANF) already provides seismic phases and earthquake locations for events detectable on the TA. The CNMSN had no plans to integrate TA data into network operations, including earthquake location, during the passage of the TA, but has over time ended up adding select TA data to network locations if the analyst felt it improved the earthquake location (M. Withers, personal communication). The current CNMSN station configuration provides excellent coverage of the New Madrid seismic zone but has fewer stations located outside of the Mississippi embayment (Fig. 1). The TA provides valuable information for earthquakes located at the edges of the current CNMSN and outside of the embayment. Prior to the current network, the Central Missouri Valley network reported locations in the central US using a more diffuse regional station spacing, and, in fact, that catalog reported many more earthquakes outside of the embayment and along the northern stretches of the New Madrid seismic zone. Understanding the true rate of seismicity outside of the embayment and even along the northern edge of the New Madrid seismic zone is a primary science goal of this project. Analysis on the impact of adding regional stations at a range of azimuths and distances to the CNMSN provides useful information for future planning if the resources for additional permanent stations became available.

Documenting the distribution and magnitude of seismicity associated with the NMSZ and outside of the Mississippi embayment is directly applicable to reducing loss and assessing seismic hazard in the central US. This project provides a more complete picture of the distribution of small magnitude seismicity regionally and documents primary causes of changes in catalog location and magnitude estimates that will aid future researchers using these catalogs.

Project Plan

This final technical report focuses on the methodical approaches developed to fulfill the stated project goals, provides final data coverage statistics, and outlines relocation results of New Madrid seismicity using TA data in addition to CNMSN data. The one-year work plan follows:

1. **Design a process to gather TA and IU waveforms of local earthquakes**: When local earthquakes are reported by CERI, travel times will be predicted to TA and IU stations and relevant waveforms extracted from the IRIS DMC.
2. **Gather CNMSN broadband waveforms for earthquakes reported in the ANF catalog**: The ANF is the operating manager for USArray and is charged with archiving and quality control related to the TA. The facility also maintains a catalog of local earthquakes recorded by the TA

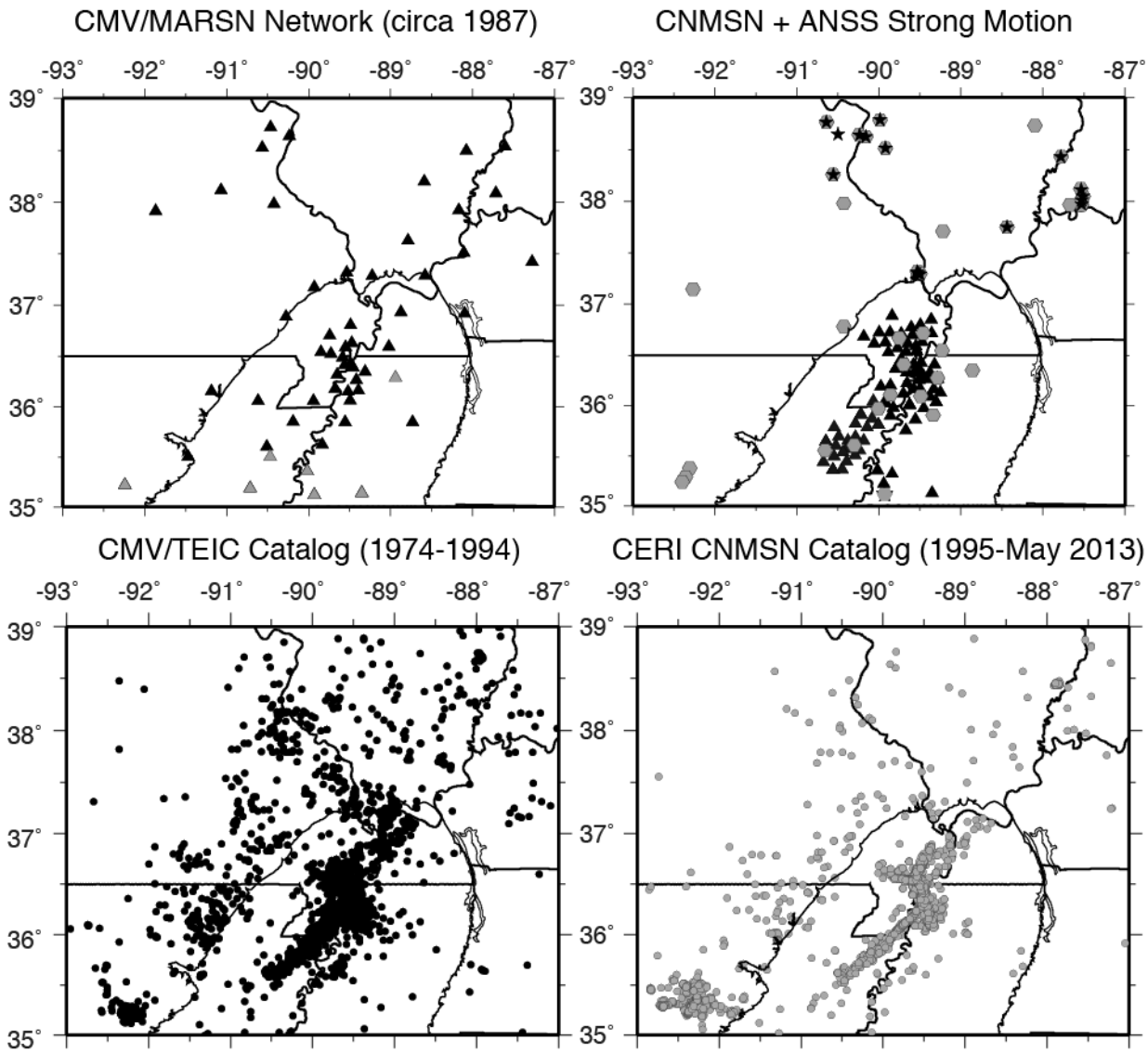

Figure 2: (top) The CMV and MARSN networks circa 1987 and current CNMSN network. Triangles: Short-period stations; Hexagons: Broadband stations; Stars: Strong motion stations. (bottom) CERI catalog earthquake locations (circles). The Mississippi embayment is shown for context. On the left are shown locations from 1974-1994, when the catalog was primarily known as the Central Mississippi Valley, but also known as the Tennessee Earthquake and Information Center (TEIC, now CERI) catalog. On the right are catalog locations from 1995 through May 2013 from the CERI CNMSN catalog.

and reports seismic phases to the IRIS DMC. If ANF reports an event not in the CNMSN catalog, we will extract available CNMSN waveforms for the relevant time period.

3. **Design a process to gather TA and IU waveforms of local earthquakes**: When local earthquakes are reported by CERI, travel times will be predicted to TA and IU stations and relevant waveforms extracted from the IRIS DMC.
4. **Gather CNMSN broadband waveforms for earthquakes reported in the ANF catalog**: The ANF is the operating manager for USArray and is charged with archiving and quality control related to the TA. The facility also maintains a catalog of local earthquakes recorded by the TA

and reports seismic phases to the IRIS DMC. If ANF reports an event not in the CNMSN catalog, we will extract available CNMSN waveforms for the relevant time period.

5. **Waveform Integration and Phase Picking**: An Antelope database (BRTT.com) will be used to integrate event waveforms and ANF and CNMSN reported phases. Body wave (P and S) onsets will be identified using Antelope software when ANF or CNMSN phases aren't available.
6. **Earthquake Location and Magnitudes**: HYPOELLIPSE will be used to locate earthquakes using all standard parameters employed by the CNMSN.
7. **Analysis**: Spatial and temporal comparisons to previous catalogs; location sensitivity to station distribution.

All steps are completed with some minor modifications detailed below. The time period covered in the study is July 2011 – March 2013. Figure 2 shows station distribution in the study area and the ANF and CNMSN catalogs for the study time period. The ANF reported 715 events and CNMSN 640 events over the study period, but event distribution varies considerably.

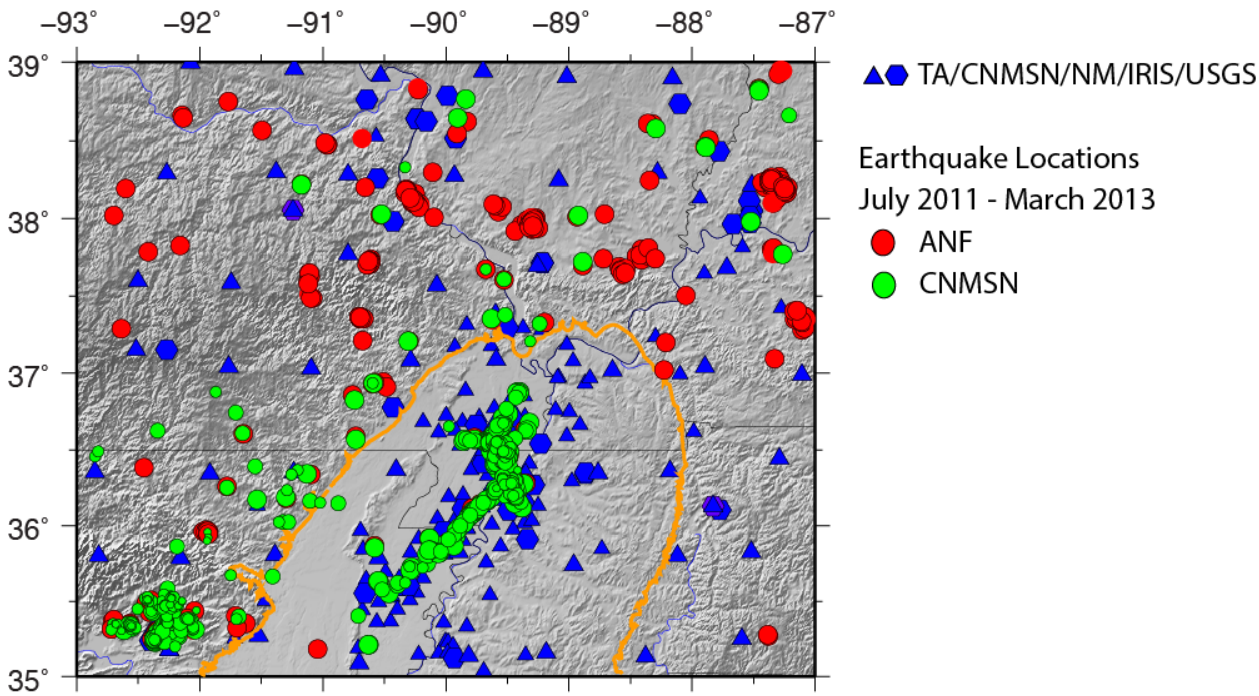

Figure 2: Event waveforms and phases from the TA network and other regional stations have been integrated with like data from the CNMSN in the study area. All recording stations operating from July 2012 through March 2013 are shown (blue). Earthquakes reported by CERI as part of CNMSN operations (green) and by the ANF as part of TA operations (red) over the same time period serve as the event database. Orange: Mississippi embayment.

Designing an integrated database [Work Plan Activities 1-4]

The Antelope database package is available through IRIS for research purposes and has become an academic standard for maintaining metadata and waveforms associated with temporary PASSCAL passive seismic experiments. It is also be used by the ANF for TA analysis. I developed a procedure to associate CNMSN reported local earthquakes with detections and arrivals reported for TA stations by the ANF using the Antelope package. I maintain all data in CSS3.0 formatted ASCII tables for flexibility and

to facilitate data exchange with other scientists. The phase and waveform data integration is controlled by a set of shell and perl scripts that in turn call a variety of Antelope, Earthworm, and IRIS webservice scripts. All programs are run as nightly cron jobs, and data integration is entirely automated. The system is set up so that undergraduate students with minimal training can verify and/or pick phase onsets from earthquakes recorded the previous day using the Antelope *dbloc2* program.

Step 1) Access to ANF data-The ANF picks phases at TA stations and provides hypocenters calculated using those onsets as the TA marches across the US. When an event is reported by the NEIC or other regional networks, that hypocenter is also added to the ANF origin tables. ANF associated phase onsets are checked by analysts in quasi-real time during weekdays and the following week for weekend data. The pre-final event review is done about one to two weeks afterwards and final review occurs a few months in arrears. I have made arrangements with the ANF to access detections and analyst reviewed picks via an Antelope database (Frank Vernon, personnel communication). Every night, the most current ANF Antelope tables are remotely synced. Events and associated phases located in the study area (Fig. 1) are added to the integrated database.

Step 2) Integrating CNMSN waveforms of ANF earthquakes-Continuous waveforms for CNMSN broadband data are now archived at the IRIS DMC. At the beginning of this project, however, both continuous broadband and short-period data were only available on waveservers for approximately one week to allow for data analysis. When a new event is added by the ANF, scripts access the CERI waveforms using Earthworm tools and extract the time period that would contain the event recordings. These waveforms are then added to the integrated database.

Step 3) Access to CNMSN hypocenter and phase data-CERI analysts picks phases at CNMSN and other regional broadband stations for earthquakes recorded on at least four CNMSN stations. Hypocenter, phase and waveform data are archived at CERI, with the final archive directory created within seven days of the event, and the hypocenter catalog is updated nightly. When a new event is added to the CNMSN hypocenter catalog, the event is added to the integrated database. When the final archived phase onsets and CNMSN waveforms are archived, they too are added to the integrated database.

Step 4) Integrating non-CNMSN waveforms of CNMSN earthquakes- IRIS has developed webservices that allow a user to access waveforms from the DMC directly from a web browser or unix command line. When a new CNMSN earthquake occurs, scripts use these tools to cut and download event waveforms from all regional broadband stations located in the study area and reported to the IRIS DMC. This includes stations associated with the TA, Global Seismic Network, the New Madrid network (SLU/CERI), and ANSS networks. The waveforms are then added to the integrated database.

Step 5) Associating phases and earthquakes across networks-After all phase and waveform data have been added, a set of scripts carefully associates origins, phases and waveforms so that when any individual earthquake is accessed, the appropriate waveforms and phases appear on screen.

The integrated database extends from 1 July 2011 through March 2013 (Fig. 3). However, consistent extraction of CNMSN waveforms of ANF recording events north of the New Madrid seismic zone did not begin until late January 2012, when all scripts went live. The near real-time aspect of the project was successful through June 2012 but was not reestablished once the project was moved to Southern Methodist University (SMU) due to technical difficulties. It also became apparent that collecting and analyzing waveforms in in near-real time was not necessary to meet the science goals.

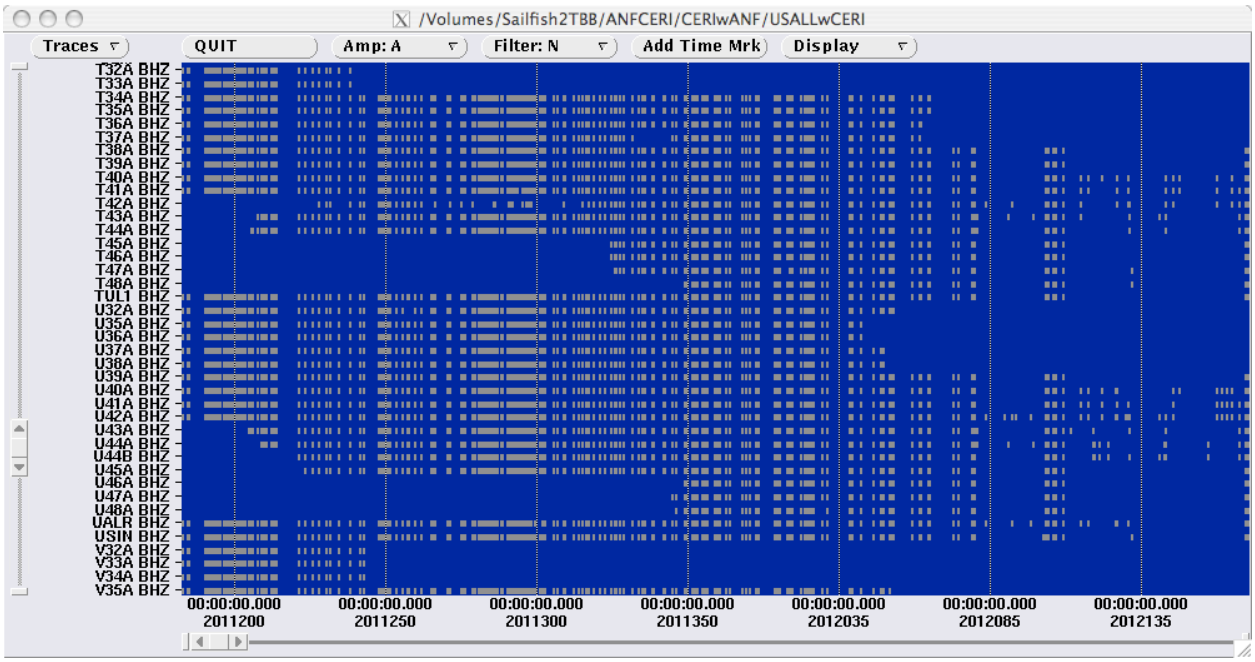

Figure 3: Screen shot showing waveform data (gray). The integrated database contains event waveforms starting in July 2011 and extending through June 2013. This figure shows data in the integrated database for a subset of TA and regional broadband data. Not all stations record every earthquake.

Phase onset verification/identification by undergraduate analysts [Work Plan Activity 5]

The integrated database contains a) CNMSN recordings of ANF catalog events and b) TA and regional broadband recordings of CNMSN catalog earthquakes. Both cases result in waveforms that have not been reviewed by an analyst. During 2012 [January-May], two Univ. of Memphis undergraduate students [Eric Gamble and Hieu Doan] were trained to identify and pick P and S first arrivals on local and regional waveforms using the Antelope *dbloc2* program. The students were tasked with reviewing the integrated database, focusing on adding phase onsets on TA and regional stations for CNMSN catalog hypocenters. Earthquakes occurring in the NMSZ and north from July 2011 through May 2012 were reviewed, taking advantage of the near-real time integrated database. The ongoing event sequence in Arkansas was not included in the additional phase identification.

However, as will be discussed below, having the students add additional phases yielded relocations that did not differ significantly from relocations derived by simply combining the CNMSN and ANF phase picks for events in both catalogs. This is in part because the ANF and CNMSN analysts picked many more phases using each other networks than originally planned when the proposal was written. I therefore discontinued the near-real time phase identification aspect of the project and returned unspent salary money associated with hiring additional undergraduate analysts once the project moved to SMU.

Earthquake Relocation & Analysis [Work Plan Activities 6 & 7]

CERI locates earthquakes using HYPOELLIPSE (*Lahr*, 1999), the CNMSN and ANSS stations, and a set of four one-dimensional velocity models for the study region. While the TA moved through the region, TA data was incorporated into the catalog location if the CERI analyst felt the location was improved. Which velocity model is used depends on the location of the earthquake (Fig. 4). For earthquakes within

the northern Mississippi embayment, a model developed for the New Madrid seismic zone is used (Fig. 4 PANDA; *Chiu et al.* [1992]). For earthquakes in Arkansas, a velocity model developed for the Enola earthquake swarm, which occurred in northeast AR, is used (Fig. 4 Enola, AR). For events outside of the embayment and in the southern embayment, a more standard crustal structure is used, with the presence of shallow sediments being the only difference between the two (Fig. 4 Uplands & Embayment). In HYPOELLIPSE, station elevations are accounted for in the location and station corrections are not used for network locations. Hypocenters are found using Geiger's method to minimize the root-mean-square (RMS) of the travel-time residuals. Confidence ellipses at the 68% level are also determined. The CNMSN reports 640 earthquakes in the study region from 1 July, 2011 through 31 March, 2013 (Fig. 2, Table 1). Most catalog earthquakes occur in Arkansas and along the NMSZ. Approximately 42% of the events are quality 'A', with standard horizontal errors (seh) and standard vertical errors (sez) ≤ 1.34 km. Another 38% are quality 'B', with seh and sez ≤ 2.67 km.

Like many local networks incorporated in the ANSS, CERI is moving to the recently standardized ANSS Quake Monitoring System (AQMS). The AQMS is based on the California Integrated Seismic Network software package and requires replacing HYPOELLIPSE with Hypoinverse (*Klein*, 2002) for catalog earthquake locations. As part of this study, I relocate 629 CERI catalog events from July 2011-March 2013 in Hypoinverse using the parameters set up for the CNMSN by Mitch Withers at CERI (Table 1). This provides a good subcatalog to identify and document changes in location induced by switching to the new processing software. This final task provides valuable information of CERI catalog users, in addition to the network operators.

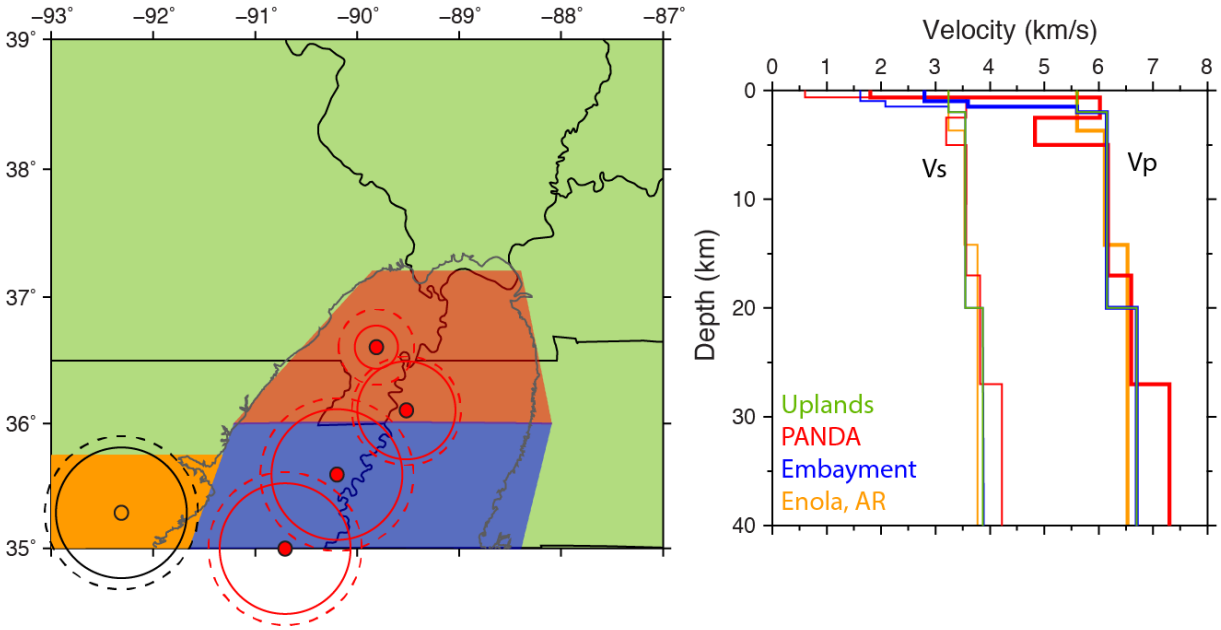

Figure 4: (left) Study area color coded by the velocity model used for event relocation. CERI HYPOELLIPSE event archive files contain a comment line indicating which velocity model is used during location. This information was used to extract the velocity polygons shown here and to name subregions used throughout the study. The circles represent the node (filled), inner circle boundary (solid), and transition boundary (dotted) used to assign velocity in Hypoinverse. In Hypoinverse the default model is the Uplands model. Note that the embayment model does not extend into the study area with the new AQMS processing. Green: Uplands; Red: PANDA; Blue; Embayment; Orange: Enola. (right) Velocity models used by HYPOELLIPSE and Hypoinverse by the CNMSN.

Table 1: Initial Catalog Information, 1 June 2011 - 31 March 2013

Catalog	Subregion	Number of Events	Catalog	Subregion	Number of Events
CERI	All	640	ANF	All	715
	Uplands	57		Uplands	607
	PANDA	332		PANDA	24
	Embayment	39		Embayment	4
	Enola	212		Enola	80

The ANF detects and reports local and regional events as the TA moves across the US. The ANF uses all available TA station data and all ANSS stations streaming real-time data to the IRIS DMC. Note that this means both CERI and ANF pick phases on regional broadband stations (network codes NM, IU, AG) but that ANF does not pick phases on CNMSN short-period and some of the CNMSN broadband stations. Phase onsets are detected and associated into events using processing software standard to the Antelope software package. Locations are calculated using *locsat2* and the 1D IASP91 earth model. Events are reviewed by ANF analysts, and additional phases are added if needed. Over the time period of this study, the ANF reports 715 events (Fig. 2, Table 1).

Unlike CERI, the ANF does not remove blasts, shots, or all anthropogenic activity. This fundamental difference between the ANF and CERI catalogs is best seen by simply separating the catalogs into day (UTC hours 1100-2300; Local hour 6 AM – 6 PM) and night (UTC hours 2300-1100; Local hour 6 PM – 6 AM) (Fig. 5). Areas of clustered seismicity in Illinois, Indiana and Kentucky evident in the ANF catalog are quarries. Daytime events located along the Mississippi and Missouri rivers are also suspect anthropogenic events. Regions active during the day and night, such as the NMSZ, are producing earthquakes. When suspect quarries are removed, the ANF catalog contains ~200 events.

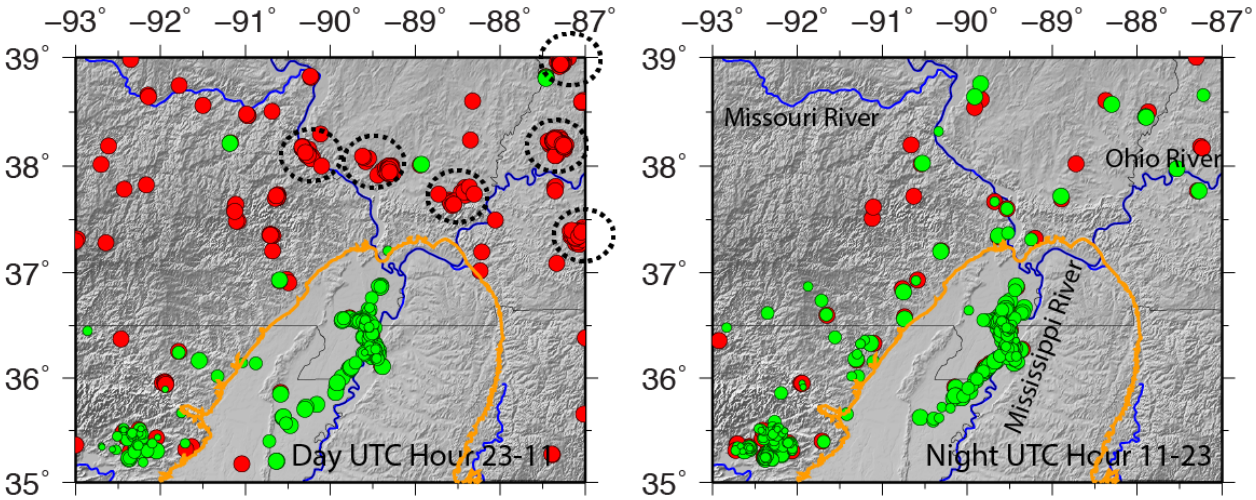

Figure 5: Events reported by the ANF (red) and earthquakes reported by CERI (green) separated into day (left) and night (right). Events interpreted as blasts associated with quarries are marked by black dashed circles. Rivers are shown in blue and the Mississippi embayment in orange.

Hypocenter Comparison Studies

For comparison studies, the CERI and ANF event catalogs are each divided into four subregions. Subregion assignment is based the initial catalog location and the spatial association with the velocity models shown in Figure 4 (Table 1). The velocity models remain associated with the earthquakes during all relocations in HYPOINVERSE. There are six phase catalogs used to make catalog comparisons:

1) the original CERI analyst-derived phases used to produce the CERI catalog (CERI)

2) the original ANF analyst-derived phases used to produce the ANF catalog (ANF)

3) the original CERI analyst phases minus all TA data. This phase set reflects what the CERI network location would have been if the TA had not been passing through the region. (CERI w/o TA)

4) the CERI and ANF phase catalogs combined for all events in common. Since both networks analyst pick phases on NM, IU and AG stations, duplicate phase identifications are removed. The CERI network analyst's pick is preferred over the ANF analyst's pick in such cases. (CERI+ANF)

5) the CERI and UM/SMU phase catalogs combined for all events in common. A subset of CERI catalog events had additional phases identified on TA stations from the integrated ANF and CNMSN waveform database. This phase identification effort was more comprehensive than the CERI analyst approach to adding TA data. Analysts at U. of Memphis and SMU focused on adding all phases to events occurring in the NMSZ (PANDA and Embayment) and north of the NSMZ (uplands). Events in Arkansas (Enola) were left out of this analysis. (CERI+UM/SMU)

6) the ANF and UM/SMU phase catalogs combined for all events in common. Most events in the ANF catalog occurred outside of the embayment, where the CNMSN network consists of broadband stations reported as network NM. The UM/SMU phase catalog contains phases identified on the broadband and short-period stations in the embayment. (ANF+UM/SMU)

Each of these phase catalogs was used to produce event locations in HYPOELLIPSE. The relocations were then compared to the original CERI and/or ANF catalog data. The comparisons are shown in a tables organized by phase catalog (Table 2) and by subregion (Table 3). Because the CERI and ANF catalogs contain very different data distributions, and the phase catalogs cover different time ranges, the number of events in common available for comparison differs greatly across phase catalogs and subregions.

Variability between the original CERI catalog and the original ANF catalog (CERI-ANF, Tables 2 & 3) can be attributed to a combination of factors. The station and phase distribution differs, the velocity models differ, and the location algorithms differ. There are 114 events in common between the catalogs over the 20-month study period, and 65 of those events are in Arkansas. The largest difference between the catalog locations is in depth, especially inside the embayment (PANDA, Embay) and Arkansas (Enola), where the CNMSN velocity models differ most from IASP91. To look at the effect of velocity model and location algorithm, I relocated the original ANF phase catalog in HYPOELLIPSE using the CNMSN parameters provided by Mitch Withers (CERI-ANFhypoe, Tables 2 & 3). Mean epicentral differences for Uplands and PANDA events are small and within 1.34 km seh and sez associated with high quality ('A') events in HYPOELLIPSE. Epicentral differences are higher for Arkansas earthquakes. Depth remains more variable with mean depth ≥1.34 km, and standard deviations range from 1.4-5.8 km. However, all depth differences are significantly reduced when the CNMSN location procedures are used (Tables 2 &3; Figure 6).

Table 2: Hypocentral Changes Organized by Phase Catalogs

Catalog	Subregion	Number of Events	Δ Latitude* (km)	Δ Longitude* (km)	Δ Depth* (km)
CERI – ANF	Total	114	-1.04±1.20	0.37±1.40	-3.55±5.54
	Uplands	23	-0.51±1.90	-0.74±1.91	0.03±8.41
	PANDA	23	-0.91±0.83	0.24±1.17	-5.10±3.36
	Embayment	3	-1.00±0.50	1.05±1.07	-4.60±0.54
	Enola	65	-1.27±0.92	0.79±0.99	-4.23±4.36
CERI-ANFhypoe	Total	114	-1.22±1.36	0.36±1.52	1.29±4.32
	Uplands	23	-0.37±1.58	-0.20±1.00	-2.31±5.78
	PANDA	23	-0.91±1.45	-0.57±2.01	-0.58±3.52
	Embayment	3	-1.52±1.15	0.51±1.37	-4.47±1.44
	Enola	65	-1.61±1.07	0.86±1.22	1.85±3.65
CERI – (CERI w/o TA)	Total	249	-0.24±1.27	0.12±1.50	0.33±2.84
	Uplands	48	-0.35±1.94	-0.25±2.00	-0.16±3.45
	PANDA	30	0.23±0.75	0.20±0.76	1.56±2.00
	Embayment	25	0.50±1.17	0.05±1.42	0.46±2.65
	Enola	150	-0.42±1.01	0.24±1.41	0.22±2.73
CERI – (CERI + ANF)	Total	108	-0.35±1.04	-0.23±1.20	0.60±3.05
	Uplands	18	-0.27±1.86	-0.32±2.05	-0.15±4.57
	PANDA	22	-0.03±0.41	-0.14±0.95	-0.80±2.10
	Embayment	3	-0.26±0.29	0.12±0.54	-2.04±1.37
	Enola	60	-0.52±0.83	-0.25±0.91	1.46±2.46
CERI – (CERI + UM/SMU)**	Total	218	-0.51±0.46	-0.49±0.48	-1.76±1.34
	Uplands	21	-0.49±0.29	-0.44±0.23	-2.40±1.23
	PANDA	171	-0.49±0.48	-0.49±0.49	-1.75±1.34
	Embayment	17	-0.50±0.42	-0.54±0.64	-1.54±1.02
	Enola	9	-0.81±0.47	-0.56±0.34	-0.94±0.86
ANF – (ANF + UM/SMU)***	Total	12	-0.79±0.57	-0.45±0.20	-2.75±1.87
	Uplands	8	-0.94±0.62	-0.45±0.23	-2.42±1.94
	PANDA	3	-0.41±0.34	-0.46±0.15	-2.55±0.27
	Enola	1	-0.72	-0.5	-5.98

*Mean ± StandardDeviation

**Data Range 1 July 2011 - 31 July 2012

***Date Range 1 Jan 2012 - 30 June 2012

Table 3: Hypocentral Changes Organized by Subregions

Subregion	Catalog	Number of Events	Δ Latitude* (km)	Δ Longitude* (km)	Δ Depth* (km)
Uplands	CERI – ANF	23	-0.51±1.90	-0.74±1.91	0.03±8.41
	CERI – ANFhypoe	23	-0.37±1.58	-0.20±1.00	-2.31±5.78
	CERI – (CERI w/o TA)	48	-0.35±1.94	-0.25±2.00	-0.16±3.45
	CERI – (CERI + ANF)	18	-0.27±1.86	-0.32±2.05	-0.15±4.57
	CERI – (CERI + UM/SMU)**	21	-0.49±0.29	-0.44±0.23	-2.40±1.23
	ANF – (ANF + UM/SMU)***	8	-0.94±0.62	-0.45±0.23	-2.42±1.94
PANDA	CERI – ANF	23	-0.91±0.83	0.24±1.17	-5.10±3.36
	CERI – ANFhypoe	23	-0.91±1.45	-0.57±2.01	-0.58±3.52
	CERI – (CERI w/o TA)	30	0.23±0.75	0.20±0.76	1.56±2.00
	CERI – (CERI + ANF)	22	-0.03±0.41	-0.14±0.95	-0.80±2.10
	CERI – (CERI + UM/SMU)**	171	-0.49±0.48	-0.49±0.49	-1.75±1.34
	ANF – (ANF + UM/SMU)***	3	-0.41±0.34	-0.46±0.15	-2.55±0.27
Embayment	CERI – ANF	3	-1.00±0.50	1.05±1.07	-4.60±0.54
	CERI – ANFhypoe	3	-1.52±1.15	0.51±1.37	-4.47±1.44
	CERI – (CERI w/o TA)	25	0.50±1.17	0.05±1.42	0.46±2.65
	CERI – (CERI + ANF)	3	-0.26±0.29	0.12±0.54	-2.04±1.37
	CERI – (CERI + UM/SMU)**	17	-0.50±0.42	-0.54±0.64	-1.54±1.02
Enola	CERI – ANF	65	-1.27±0.92	0.79±0.99	-4.23±4.36
	CERI – ANFhypoe	65	-1.61±1.07	0.86±1.22	1.85±3.65
	CERI – (CERI w/o TA)	150	-0.42±1.01	0.24±1.41	0.22±2.73
	CERI – (CERI + ANF)	60	-0.52±0.83	-0.25±0.91	1.46±2.46
	CERI – (CERI + UM/SMU)**	9	-0.81±0.47	-0.56±0.34	-0.94±0.86
	ANF – (ANF + UM/SMU)***	1	-0.72	-0.5	-5.98
Total	CERI – ANF	114	-1.04±1.20	0.37±1.40	-3.55±5.54
	CERI – ANFhypoe	114	-1.22±1.36	0.36±1.52	1.29±4.32
	CERI – (CERI w/o TA)	249	-0.24±1.27	0.12±1.50	0.33±2.84
	CERI – (CERI + ANF)	108	-0.35±1.04	-0.23±1.20	0.60±3.05
	CERI – (CERI + UM/SMU)**	218	-0.51±0.46	-0.49±0.48	-1.76±1.34
	ANF – (ANF + UM/SMU)***	12	-0.79±0.57	-0.45±0.20	-2.75±1.87

*Mean ± StandardDeviation
**Data Range 1 July 2011 - 31 July 2012
***Date Range 1 Jan 2012 - 30 June 2012

TA data was incorporated into the CERI catalog when the analyst reviewing the earthquake could reduce location uncertainty. Over the 20-month period, approximately 38% of the catalog had one or more phases included from a TA station. Over half of these events were in Arkansas (Table 2, CERI – CERI w/o TA). To see how adding TA data affects the CERI catalog, I remove all phases recorded at TA stations and relocate the associated events. Mean epicentral changes are small (<0.5 km) with standard deviations less than 2.0 km. Mean depth changes are also small, with the exception of events in the central NMSZ (PANDA). For all regions, the standard deviations for the mean depth are ≥2.0 km, however, suggesting that depth is not very well constrained. In the PANDA subregion, the mean depth difference is 1.56 km with a standard deviation of 2.0 km; the range of depth differences is -1.77 to 6.41 km. A positive mean depth indicates that the earthquake depths shallow in the second dataset. This can be seen in the example earthquakes shown in Figure 6 by comparing the CERI catalog locations (red) with the CERI w/o TA locations (orange). Without the additional TA data, the example event epicenters are pulled southeast, toward the CNMSN stations.

The remaining three sets of comparisons are conducted to mimic catalogs that incorporate all or most CNMSN and ANF reporting stations. The first method was to simply combine the ANF and CERI phase catalogs, removing all duplicates. Duplicate phases were most likely to occur at NM network stations and in the TA stations nearest the NMSZ and earthquake producing regions in Arkansas. For the 25 events in the NMSZ (PANDA) and to the north (Uplands), mean epicentral locations changes were small (<0.5 km), with standard deviations <1.0 km. Again, depth changes are higher with a mean change of <1 km and standard deviation ~2-4 km. For the example earthquakes (Fig. 6), combining CERI and ANF phases (blue) places the relocated hypocenters much closer CERI catalog locations (red) to either of the ANF phases only derived locations (green, dark green). Interestingly, the CERI+ANF relocations lie closer to the CERI phases w/o TA relocations (orange) than to the CERI catalog (red). Combining the ANF and CERI phase catalogs makes a bigger difference in Arkansas. The events show a mean epicentral change of ~0.5 km northward, ~0.3 km westward, and shallowing in depth of ~1.5 km when all TA data is included.

In order to guarantee a comprehensive set of phases identified on TA stations, analysts at Univ. of Memphis and Southern Methodist University (UM/SMU) picked P and S phase onsets on all TA stations for all NMSZ earthquakes and Uplands earthquakes recorded from 1 July 2011 - 31 July 2012. Analysts were told to ignore Arkansas earthquakes, though a few were analyzed by mistake. These 9 events are included in Tables 2 & 3 for completeness but not discussed further. Unlike the CERI + ANF data, there appears to be slightly higher mean change in epicenter for the CERI + UM/SMU dataset. For PANDA, Embayment and Uplands subregions, there is an ~0.5 km shift north and ~0.5 km shift west. The standard deviations, however, are small (<1 km). There are many more earthquakes included in the CERI – (CERI + UM/SMU) comparison, particularly in central portion of the NSMZ. I attribute the northwest shift to the fact that most added TA recordings of central NMSZ earthquakes were at stations in southern and central Missouri. As a reminder, only 30 central NSMZ earthquakes in the CERI catalog did not have any TA data added (Tables 2 and 3). The addition of TA stations also appears to lead to systematically deeper hypocenters. This is consistent with the shallowing in depth noted when TA data was removed from the CERI phase catalog. The example earthquakes (Fig. 6) show some, but not all, of these trends. Relocations using the UM/SMU phases result in much shallower earthquakes depths compared to the CERI catalog. The depth difference for event 2 is outside of the mean and standard deviation for the PANDA subregion. The first event is moved north-northwest but the second event is moved west-southwest relative to the initial catalog locations.

We also started to analyze ANF catalog events by manually identifying phase onsets on CNMSN stations. However, we quickly discovered that we were simply repicking phases already in the CERI catalog or spending too much time hand-picking blasts. The ANF + UM/SMU relocations are included for completeness of the final technical report but are not interpreted.

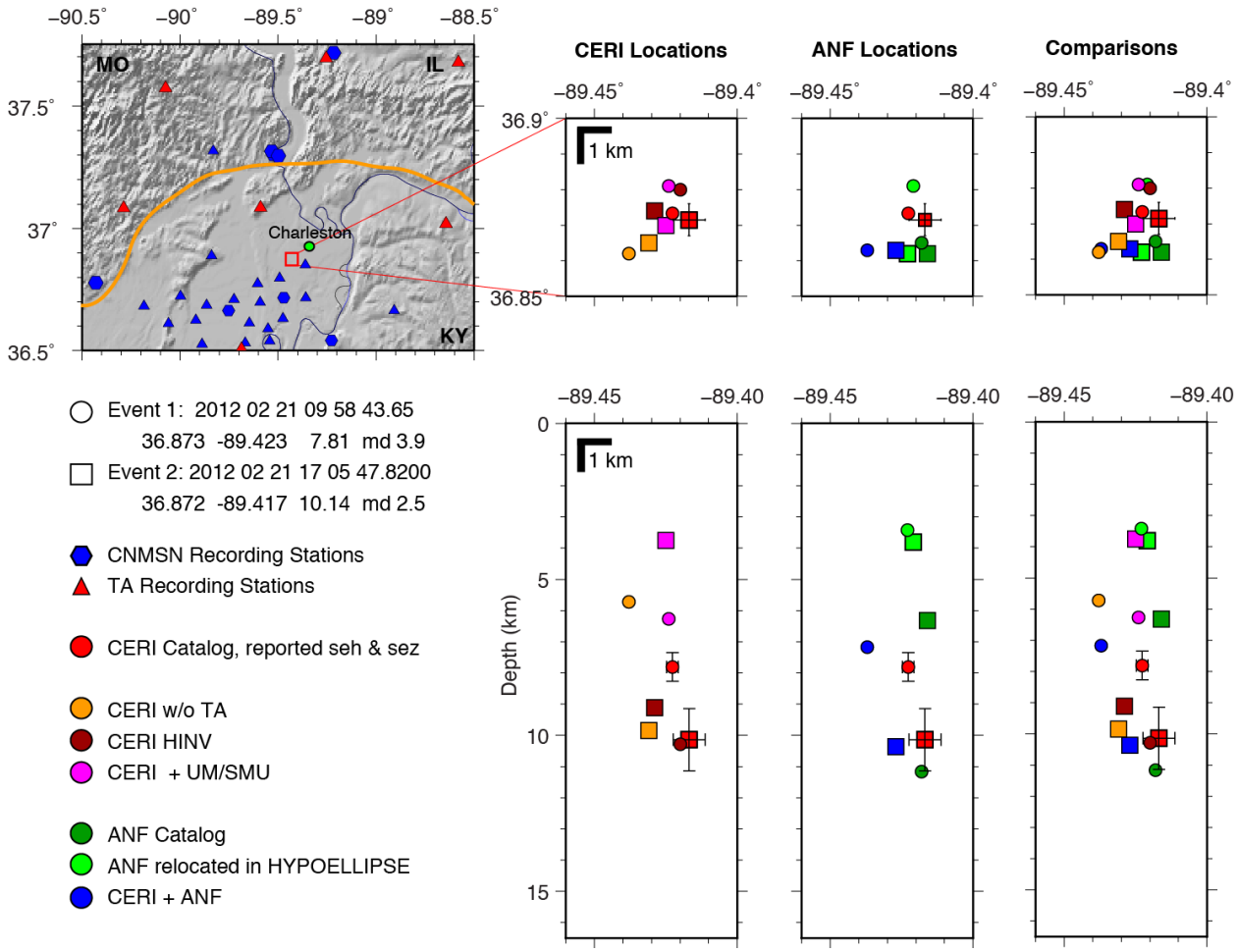

Figure 6: Comparison of two hypocenters using all phase catalogs and locations procedures discussed in the text. The example earthquakes are an m_d 3.9 mainshock (circle) and m_d 2.5 aftershock (squre) that occurred in Feb. 2012 just southwest of Charleston, MO. (left top) The events occur in the PANDA subregion, within the Mississippi embayment (orange line), and are spatially associated with the southwest-northeast trending northern arm of the NMSZ (see Fig. 1 & 2). The events occur in the red box. All CNMSN and TA stations recording one or both earthquakes are shown. (right, column 1) Mapview and depth sections of CERI catalog locations (red), relocations in HYPOELLIPSE with all TA stations removed (CERI w/o TA, orange), relocation using Hypoinverse (dark red), and relocations in HYPOELLIPSE with manually analyzed TA data (CERI + UM/SMU). (right, column 2) Mapview and depth sections of CERI catalog locations (red), ANF catalog locations (dark green), relocations in HYPOELLIPSE of the ANF phase data (light green), and relocations in HYPOELLIPSE combining the CERI and ANF phase catalogs (blue). (right, column 3) All relocations. Absolute location varies considerably more than the formal standard horizontal and vertical errors (seh & sez) computed by HYPOELLIPSE. The inclusion of various phase catalogs leads a ~6-7 km depth range and variations over ~3 km range in epicenter.

HYPOELLIPSE versus Hypoinverse

The final comparison involved relocating the CERI catalog using Hypoinverse rather than HYPOELLIPSE (Table 4). This location algorithm change will soon be implemented in the CERI catalog with the change to AQMS processing. For the 629 events, mean epicentral and depth changes are

very small (<0.2 km) with associated standard deviations of <2.0 km. The PANDA subregion has means near zero with ranges of <0.25-0.75 km, suggesting that there will be no systematic changes in the bulk of the NMSZ. North of the NMSZ (Uplands), mean depth change is -1.14 km±2.85 km, suggesting that relocation in Hypoinverse will in general lead to deep event locations outside of the embayment, not including Arkansas.

This is likely due to the different way Hypoinverse and HYPOELLIPSE specify velocity model for each earthquake. Hypoinverse defines cylindrical regions for each velocity model centered on user-defined nodes (Fig. 4) (Klein, 2002). An inner cylinder and outer transition cylinder are specified. If an earthquake occurs in the inner cylinder, that model is used exclusively. If an event occurs in the outer circle or overlapping circles, a user-defined weighting scheme is used to calculate travel time. Quoting Klein (2002), "[sic] if the travel time for model #1 is 1.10 sec, model #2 is 1.20 sec, and the weight of model #1 is 20% (and model #2 is 80%), the travel time used is 1.12 sec." CERI will use the same 1D velocity models used previously but the areal coverage of the velocity models will change under AQMS processing (see Fig. 4). As used during testing, the Embayment model is no longer used and the PANDA model extends through the entire NMSZ. The Uplands model is taken as the default velocity model and will be used for more events inside the Mississippi embayment borders.

Relocations of the example earthquakes, located in the PANDA subregion in HYPOELLIPSE but in the Uplands subregion in Hypoinverse, show more variability than the mean and standard deviation of the PANDA subregion data in general. The larger earthquake shifts to the northeast and 2 km deeper. The smaller earthquake shifts to the northwest and shallows by ~1 km. These values are more consistent with the mean location changes calculated for Uplands subregion earthquakes because the Uplands model was used for relocation in Hypoinverse.

Absolute earthquake location is a function of location algorithm, velocity model, event-station geometry, and pick quality. This study explores the first three parameters but does not focus on pick quality. The example earthquakes (Fig. 6) exhibit absolute locations that vary more than the formal standard horizontal and vertical errors (seh & sez) computed by HYPOELLIPSE. The inclusion of various phases, or changing the event-station geometry, leads a ~6-7 km depth change range and variations over an ~3 km range in epicentral parameters. Switching to Hypoinverse has less effect on hypocenteral location for the example earthquakes.

The inclusion of the TA data has had a greater effect on the CERI catalog than the switch to Hypoinverse will have in the future (compare Table 3 and Table 4). First, within the NMSZ (PANDA subregion), the inclusion of additional stations outside of the embayment had a mean effect on epicenter on the order of 0.25-0.50 km in latitude and/or longitude with standard deviations of 0.5-1 km. These values are still

Table 4: Hypocentral Changes Due to Location Algorithm

Catalog	Subregion	Number of Events	Δ Origin Time (s)	Δ Latitude (km)	Δ Longitude (km)	Δ Depth (km)
CERI HYPOE - HINV	All	629	0.022±0.193	-0.16±0.53	0.0±0.85	-0.02±1.70
	Uplands	55		-0.22±1.19	0.20±1.26	-1.14±2.85
	PANDA	328		-0.08±0.22	0.02±0.24	-0.08±0.71
	Embayment	37		-0.01±0.78	-0.26±1.59	-0.08±2.09
	Enola	209		-0.30±0.50	-0.03±1.10	0.39±2.11

within the boundaries used to define 'A' quality absolute locations in HYPOELLIPSE. For depth, however, the mean change is ~1.7 km. Adding stations to the north and outside of the embayment leads to systematically deeper earthquake depths using HYPOELLIPSE. In Arkansas (Enola subregion), adding TA data has a stronger effect on latitude than on longitude and depth remains the most dependent parameter on station geometry, based on the larger means and standard deviations associated with adding the ANF phases or removing the TA. Finally, north and east of the embayment (Uplands subregion), mean epicentral changes are on the order of 0.25-0.50 km, similar to the PANDA region, but the variability as indicated by the standard deviations are on the order of 2 km. Depth variability is also higher in the Uplands subregion.

The move to AQMS software will also affect magnitude estimates in the CERI catalog. A comparison between the current duration magnitude reported in the CERI catalog, and the duration magnitude solutions calculated with Hypoinverse have a mean change of -0.057 with standard deviation of 0.192. Magnitude changes range of ±0.73.

Detection Rates in Missouri, Illinois and Kentucky

The TEIC/CMV catalog from 1974-1994 contained many more events in Missouri, Illinois and Kentucky than the CERI catalog for a similar time length (Fig. 1). A rate comparison between the two catalogs is impossible since network geometry changes over the years, which would directly affect detection rates. The passage of the TA mimics and expands on the earlier station coverage and can provide some insight into the question, does the current CNMSN network miss earthquakes in Missouri, Illinois and Kentucky that the previous network did not?

If we directly compare the number of Uplands subregion events in the ANF and CERI catalogs over the study time period, there are 10.65 times more events in the ANF catalog. This number includes blasts, however, and is hence meaningless. If only nighttime events are used (Fig. 5) the number of events in the ANF catalog (40) is close to the number of events in the CERI catalog (35), yielding a rate 1.1. Similarly, if blasts are removed from the ANF catalog but daytime and nighttime events are considered, the rate is closer to 1.2. However, based on comparison of origin times, only about 40% of the CERI earthquakes are in the ANF catalog for the Uplands region. While the number of events appears the same, the CERI catalog contains more earthquakes on the western edge of the embayment than the ANF catalog. The ANF catalog, in turn, contains more events in central MO, IL, IN, KY and TN; many of those disappear in a nighttime catalog.

A look at the nighttime ANF map (Fig. 5) suggests that the current CNMSN network may miss a few earthquakes in central MO but is otherwise complete. The ANF catalog Uplands distribution bears a striking resemblance to the TEIC/CMV catalog in the same region. It is likely that a percentage of events in the TEIC/CMV catalog are anthropogenic and not true earthquakes.

Which TA stations were particularly important to detecting and locating Uplands events?

To test which stations are particularly important to constrain earthquake location in the Uplands subregion, I conduct a jackknife test using the ANF phase catalog. The 35 stations with the most associated phases are systematically removed from the event location in HYPOELLIPSE. One station is removed at a time. I then calculate the mean change and associated standard deviation in latitude, longitude and depth for events affected by removing the station (Fig. 7). In this way, I identify the most significant stations in controlling location. In order to control for blasts, only nighttime earthquakes are used. Results indicate TA stations S44A in IL, T41A and T42A in MO, and U42A in AR had the greatest effect on hypocenter

location for nighttime events. A similar analysis for the entire catalog only highlights stations nearest blasting areas. The long-deployed IU Global Seismic Network stations CCM and WCI also are identified in both the overall catalog and nighttime catalog as significant contributors to location stability. When they are removed, event locations become highly variable, as evidenced by the large mean change and standard deviations exhibit in Figure 7.

For all stations starred in Figure 7, however, most of the variance comes from a 3-5 events with few associated phases and HYPOELLIPSE quality D. When these earthquakes are removed, the epicentral and depth mean changes for all stations drop to near zero and standard deviations remain below 1 km. This suggests that the most conservative conclusion is that no TA station proves any more or less important than another.

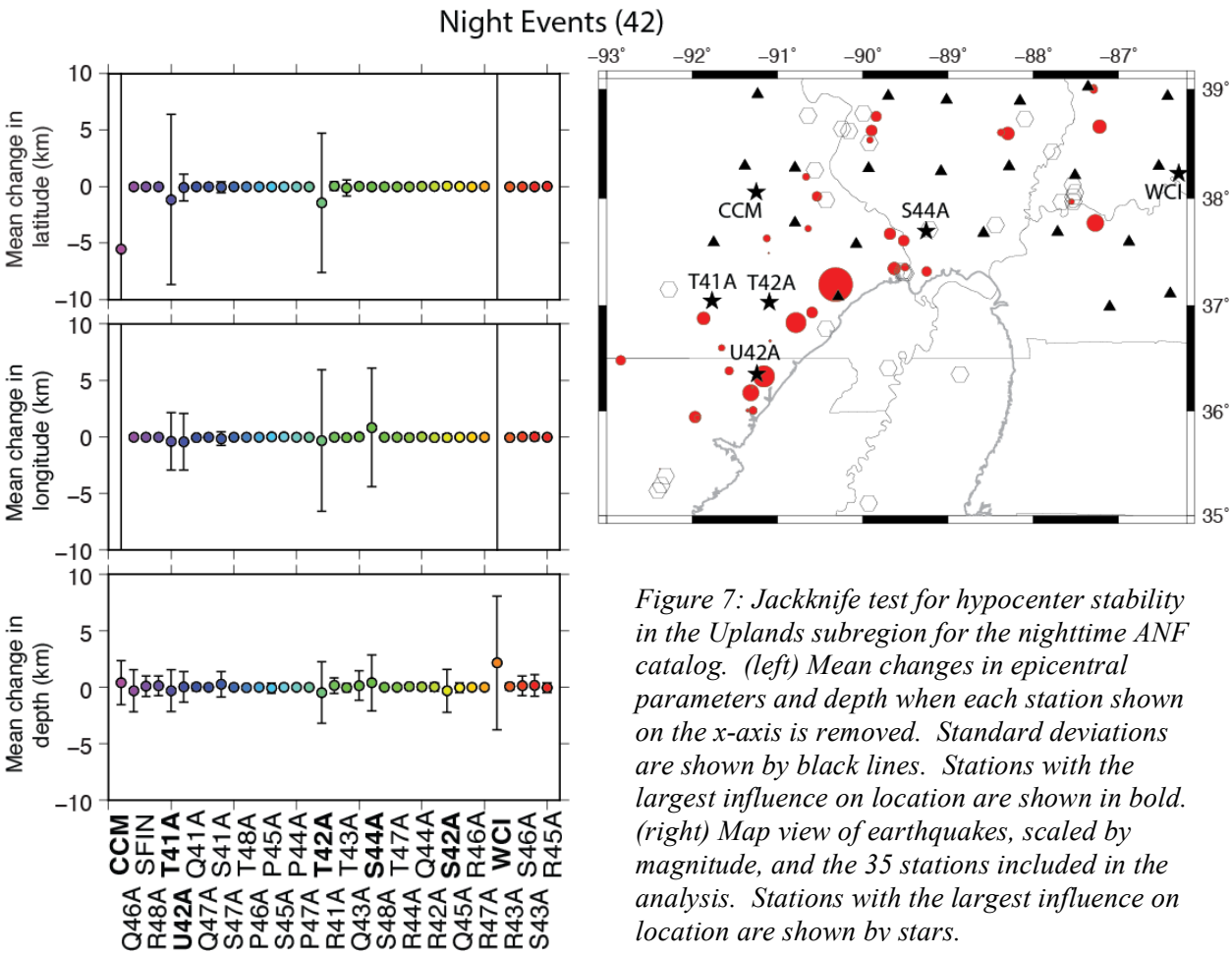

Figure 7: Jackknife test for hypocenter stability in the Uplands subregion for the nighttime ANF catalog. (left) Mean changes in epicentral parameters and depth when each station shown on the x-axis is removed. Standard deviations are shown by black lines. Stations with the largest influence on location are shown in bold. (right) Map view of earthquakes, scaled by magnitude, and the 35 stations included in the analysis. Stations with the largest influence on location are shown by stars.

CONCLUSIONS

All original goals of the project were met. A number of the scripts written to meet project goals of combining ANF and CMNSN waveform data in near real-time have been adapted for USGS and National Science Foundation projects. ANF, IU and CNMSN data was originally combined so that phase onsets could be picked on all TA data and used in relocation studies. However, initial analysis of the combined datasets revealed that some TA data was being incorporated into CERI catalog and the ANF was

identifying and picking many of the earthquakes in the CERI catalog. Relatively few phases were being added from the TA or the CNMSN for events outside of the Mississippi embayment. I determined this was not an efficient use of time or money, and chose to analyze the data though summer 2012 rather than through 2013.

The addition of the TA data affected the catalog locations across the study area. The current CNMSN network geometry, and the care taken by analysts to remove anthropogenic events, appears sufficient to detect small magnitude earthquakes. The addition of select TA stations would not necessarily increase earthquake detections rates outside of the Mississippi embayment. A few additional stations in south/southcentral MO would potentially be helpful; this statement is based on how well recorded NMSZ events were recorded on S44A, T41A and T42A during the combined analysis of TA, IU and CNMSN waveforms. The inclusion of phases at stations outside of the embayment had a significant effect on hypocentral location throughout the study area. Events inside the embayment shifted to the north and west by 0.25-0.50 km when TA data was added. Depths changed by almost 2 km with standard deviations of 2-5 km depending on subregion.

Finally, as CNMSN operators adopt the AQMS there will be changes in location technique and magnitude calculation. The affect of these changes on catalog location and magnitude were tracked for the nearly 2-year duration of this study. Epicentral changes associated with the change from HYPOELLIPSE to Hypoinverse were small (<0.25 km), especially inside the embayment. The largest changes in depth were noted for Uplands subregion earthquakes. The example earthquakes (Fig. 6) highlight the change in velocity model distribution with the transition to AQMS (Fig. 4). The example events were located in HYPOELLIPSE using the PANDA velocity model, but under the new software these events will be located within the Uplands velocity model. The Embayment model will no longer be used in the study area.

Changes in hypocentral location with Hypoinverse were smaller than catalog changes due to the incorporation of TA data across all subregions. Ultimately, changes in event-station geometry affect the catalog more than choice of location algorithm. The 68% confidence intervals reported by HYPOELLIPSE appear to underestimate the variability in absolute earthquake location. The standard deviations around the mean changes reported here were frequently on the order of kms rather than meters. Depth remains a particularly sensitive and difficult parameter to constrain. None of these statements are unique to the CNMSN, however, and are inherent to the location of small magnitude earthquakes.

Caveat: All conclusions in this technical report are based on HYPOELLIPSE and Hypoinverse parameters provided in 2011-2013 by the Cooperative New Madrid Seismic Network at CERI. Any changes to Hypoinverse parameterization during AQMS adoption by network operators could potentially change these conclusions.

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