Final Technical Report

Award G11AP20016

Multiple Event Relocation at the National Earthquake Information Center

Dr. Eric A. Bergman
Global Seismological Services
1900 19th St.
Golden, Colorado 80401
Phone (303) 278-4089
bergman@seismo.com

Term of Award:
2010/12/01 - 2012/08/31

Report Date:
2014/01/23

Abstract

Under this project I carried out the first phase of a process to develop and implement a capability for multiple event relocation in the so-called "Hydra" processing system that is being developed at the National Earthquake Information Center (NEIC) for global earthquake monitoring. In short, the goal is to improve the accuracy of earthquake locations published by NEIC. During this project I applied an existing multiple event relocation code, named "mloc", to suitable sets of earthquakes that became relevant to NEIC operations. In some cases (2011 Lake Van, Turkey; 2012 Chile; 2012 Sumatra; 2012 Ahar, Iran; 2012 Philippines) I carried out rapid response studies that helped clarify important scientific and hazard-response questions related to NEIC products and services within a few hours or days of the occurrence of an important earthquake. Most of the effort under this project, however, was expended in detailed analyses of important earthquake sequences (2010 Maule, Chile; 2011 Mineral, Virginia; 2011 Prague, Oklahoma, and 2011 Trinidad, Colorado) in cooperation with NEIC scientific staff, leading to at least three papers being published in refereed journals. During the course of this project, NEIC leadership determined that such detailed studies of important earthquake sequences, typically based on the recordings of temporary aftershock monitoring networks, should become a standard part of NEIC products and services, and it is now widely accepted that detailed multiple event relocation of the type practiced in this project should be a standard part of such studies. Efforts are continuing to determine the best way to implement such capabilities at the NEIC.

Introduction

In the following sections I review the general advantages of multiple event relocation relative to traditional single-event location as done at NEIC, and then discuss the special characteristics of a multiple event relocation analysis that produces calibrated locations, that is, locations with minimal bias (systematic error). Bias-free earthquake locations are of extreme importance for NEIC products related to disaster response and hazard mitigation. In the simplest example, emergency responders can be sent to an area tens of kilometers distant from the actual epicentral region.

A critical component of calibrated locations is the correct treatment of uncertainties, for which realistic estimates of data uncertainties (e.g., "pick error") are needed. I discuss the method used in *mloc* to estimate uncertainties in the arrival time data from the statistical distribution of the data themselves, so-called "empirical reading errors". Along with other considerations in the analysis, the use of empirical reading errors helps in determining earthquake locations with realistic uncertainties of less than 1 km for some data sets. Such results have been published (or are in press) for several recent important earthquake sequences studied under this project.

Many aspects of NEIC's mission require accurate estimates of earthquake depth as well as epicentral location, and I discuss the procedures being used in *mloc* to constrain focal depths. Significant development of these capabilities took place during this project.

Advantages of Multiple Event Relocation

Currently, earthquake location at the NEIC is done only as a single event procedure, which introduces an unknown bias into each earthquake location that depends on the interaction between the particular distribution of stations available for that event and unmodeled Earth structure relative to the travel time model. When considering clusters of earthquakes within a limited source region (e.g., mainshock-aftershock sequences), these individual location biases add to other uncertainties (e.g., from reading errors) to increase the scatter in relative locations. Multiple event relocation methods improve the resolution of relative locations by considering arrival time differences of the same phase at an observing station from multiple events in the cluster (Douglas, 1967; Dewey, 1972; Jordan and Sverdrup, 1981; Pavlis and Hokanson, 1985; Waldhauser and Ellsworth, 2000), thus removing most of the path-correlated errors in arrival time data sets. It should be emphasized that multiple event location algorithms do not eliminate the problem of systematic location bias (of the cluster as a whole) unless special calibration procedures are employed. This is discussed in detail below. Under this project we continued to explore the applications of a multiple event relocation capability in the context of the real-time processing system for global earthquake monitoring of the National Earthquake Information Center (NEIC), and in the context of detailed studies of important earthquakes sequences that are becoming a standard data product of NEIC.

The advantages of having a capability for multiple event relocation are most obvious when analysts are dealing with a mainshock-aftershock sequence, which forms a natural cluster in space and time. Analysts are able to obtain a clearer image of the source zone and the location within it of the mainshock hypocenter. Moreover they are able to determine if aftershock activity is concentrating in certain subregions of the source zone, which can have important consequences for disaster response. It has proven to be very useful to compare the results of multiple event relocation with the finite-fault models being produced at NEIC for larger earthquakes.

It is also possible to form a cluster for a current singlet earthquake by retrieving from a catalog database older events in the same source region to form a cluster. The ANSS Comprehensive Catalog (COMCAT) makes this a very efficient process. By placing the new event in the context of older seismicity of the region, better insight into its significance is obtained.

Analyzing clusters of earthquakes from the same source region provides multiple observations of seismic phases traveling nearly the same path to any given observing station, making possible statistical analysis that is very helpful in identifying outliers. By flagging such outliers, the analyst can obtain improved single event locations as well as improved relative locations, and derive more reliable estimates of location uncertainty, which can be as important as the epicenter itself.

The advantages of multiple event relocation are even greater in cases where it is possible to calibrate the location of a cluster, so that the locations of all constituent events are known to be substantially free of bias. Calibrated locations permit close comparison of seismological data

with geological and other geophysical data, as well as geographically-defined distributions of populations, infrastructure, and social and political entities that are of direct importance in earthquake hazards reduction programs. Analysis of clusters of earthquakes makes it possible to achieve calibrated locations for the entire cluster when no single event would have adequate data available to achieve a comparable level of location accuracy. It therefore provides a way to extensively leverage a small amount of high-quality seismic data, say from a temporary network that observes a few of the larger aftershocks of a major earthquake, to greatly improve the location accuracy for dozens or hundreds of other events in the region, even though they occurred many years prior. The procedures we applied in this project for calibrating clusters of earthquakes are described in the following section.

Hypocentroidal Decomposition for Calibrated Locations

The location calibration analysis that was used in this project is based on the Hypocentroidal Decomposition (HD) method for multiple event relocation introduced by (Jordan and Sverdrup, 1981). The basic algorithm is completely described in that reference.

Dr. Bergman wrote a general-purpose computer program implementing this algorithm in the late-1980s and used it for several research projects (e.g., Bergman and Solomon, 1990; Wolfe et al., 1993) in which improved relative locations were the primary goal. Beginning in the late 1990s Dr. Bergman began developing the code to support research in the nuclear monitoring community on bias-free or "ground-truth" ("calibrated" is now preferred) earthquake location (Engdahl and Bergman, 2000; 2001; Ritzwoller et al., 2003; Bondar et al., 2004). Working in close collaboration with E.R. Engdahl, the HD code has been thoroughly tested against the Engdahl's single event location algorithms that implement the well-known EHB processing methodology, as well as other multiple event locations codes (Rodi et al., 2002).

The HD code has been heavily developed over the past 10 years for application in studies of earthquake location for which location bias is largely eliminated through specialized calibration procedures (e.g., Walker et al., 2005, 2011; Biggs et al., 2006; Parsons et al., 2006; Tatar et al., 2007; Bondar et al., 2008; Nissen et al., 2010; Roustaei et al., 2010; and Ghods et al., 2012).

The essence of the HD algorithm is the use of orthogonal projection operators to separate the relocation problem into two parts:

- The *cluster vectors*, which describe the relative locations in space and time of each event in the cluster. They are defined in kilometers and seconds, relative to the current position of the *hypocentroid*.
- The *hypocentroid*, which is defined as the centroid of the current locations of the cluster events. It is defined in geographic coordinates and Coordinated Universal Time (UTC).

The cluster vectors are defined only in relation to the hypocentroid. The hypocentroid can be thought of as a virtual event with geographic coordinates and origin time in UTC. The orthogonal projection operators act on the data set of arrival times to produce a data set that

includes only data that actually bears on the relative location of cluster events, i.e., multiple reports of a given seismic phase at the same station for two or more events in the cluster.

The hypocentroid is located very much as an earthquake would be, except that the data are drawn from all the cluster events. Thus it is typical for the hypocentroid to be determined by many thousands of readings. Nevertheless, the hypocentroid is subject to unknown bias because the theoretical travel times (typically ak135, [Kennett et al., 1995]) do not fully account for the three-dimensional velocity structure of the Earth. Geographic locations for the cluster events are found by adding the cluster vectors to the hypocentroid.

The data sets used for the two problems need not be (and usually are not) the same. Because the inverse problem for changes in cluster vectors is based solely on arrival time differences, baseline errors in the theoretical travel times drop out and it is desirable to use all available phases at all distances outside the immediate source region. For the hypocentroid, baseline errors in theoretical travel times are more important and one may wish to limit the data set to a phase set, e.g., teleseismic P arrivals in the range 30-90°, to achieve a more stable result. The choice of data set for determining the hypocentroid has great importance in the "direct" calibration method described below.

Similarly, weighting schemes are different for the two inversions, reflecting the different natures of the two problems. Empirical reading errors for each station-phase pair are used in weighting data for estimating both the hypocentroid and cluster vectors, but the uncertainty of the theoretical travel times, which are estimated empirically for each phase from the residuals of previous runs, is relevant only to the hypocentroid.

Until this point, the HD algorithm is used only to obtain improved relative locations for the cluster events, with a geographic location for the cluster (the hypocentroid) that is biased to an unknown degree by unmodeled Earth structure convolved with the unbalanced distribution of reporting seismic stations. The calibration process attempts to remove this bias.

Calibration of a cluster is done in two ways, which we refer to as "indirect" and "direct" calibration.

Indirect Calibration

If the location and origin time of one or more of the cluster events can be specified with high accuracy from independent information, we can calibrate the entire cluster by shifting it in space and time to optimally match the known location of the calibration event(s). The approach is illustrated in Figure 1.

The most common source of such independent information are temporary seismic network deployments that capture an event with a large number of stations at very short epicentral distances, and which is also large enough to be well recorded at regional and teleseismic distances. Aftershock studies are a frequent source of such data. We normally obtain the

temporary network arrival time data and relocate calibration events ourselves, using a local velocity model when available, to ensure reliable locations. InSAR data has also been used for this purpose, but this requires the use of at least some seismic data at short distance to calibrate origin time. In a few cases, mapped faulting from large events can be used to help constrain the location of calibration events.

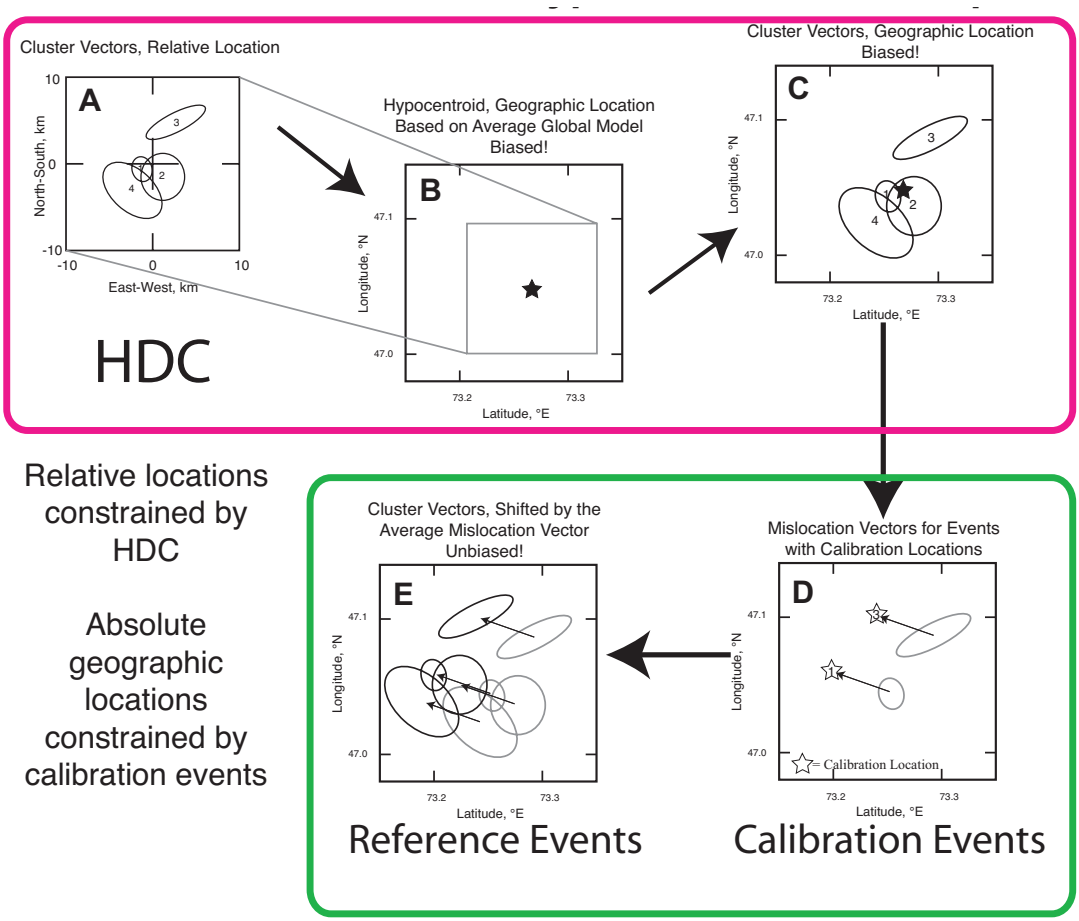

Figure 1. Indirect Calibration

In the direct calibration approach we take into account the uncertainty of the calibration data, and when there is more than one calibration event we also include a contribution to uncertainty to reflect any discrepancy between the relative locations of the calibration events and the cluster vectors of the corresponding events.

Direct Calibration

It is sometimes the case that there are a few permanent seismic stations close to a cluster, but that no single event is well-enough recorded to reach the level of accuracy necessary to serve as a calibration event. On the other hand, the handful of local seismic stations may have recorded many events in the cluster, so that the number of “short distance” readings is rather large, and well-enough distributed to allow the hypocentroid to be located using only these data. We have found that good results can be obtained as long as the epicentral distance is kept about 150-200

km or less. At greater distances we often see rapidly increasing scatter in residuals at different azimuths. The process is illustrated in Figure 2, which can be contrasted with Figure 1.

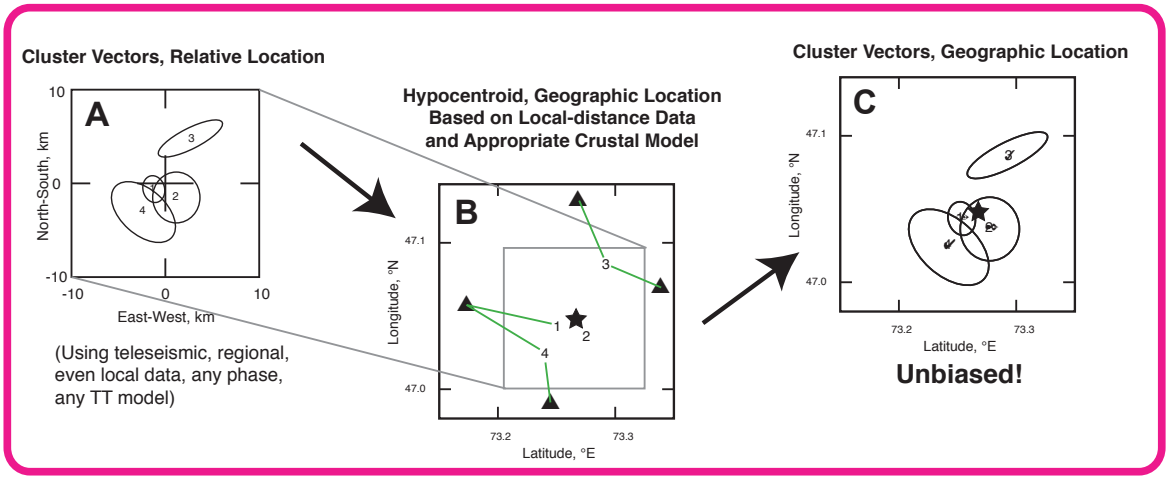

Figure 2. Direct Calibration

In any case where we have the data to locate one or more calibration events for the indirect method, we also have the option to use those same data in the direct calibration method. The decision on which to use is made on a case-by-case basis, because characteristics of the data sets may lead to a better result with one method than the other. Of course, if we are using InSAR data or other remote sensing or geological information to constrain the calibration, we must use the indirect method.

Groomed Readings

Our relocation and calibration methodology departs from standard practice in dealing with outlier arrival time readings by emphasizing consistency between repeated readings (of a given phase from different events in a cluster to the same station) rather than the size of residual against some reference travel time model. A considerable amount of work goes into estimation of what we refer to as "empirical reading errors" from the specific arrival time data set. This estimate is based on a robust estimator of spread (Croux and Rousseeuw, 1992) applied to the travel time residuals for a specific station and phase. The estimator S_n is defined as

$$S_n = c_n \, 1.1926 \underset{i=1,\ldots,n}{lomed} \; \underset{j \neq i}{lomed} \, |x_i - x_j|$$

where "lomed" is the low median and the factor 1.1926 establishes consistency at a normal distribution. The term c_n is a correction term for small sample sizes, which has been tabulated. S_n makes no assumption about the underlying distribution and requires no estimate of central location. A minimum value of 0.15 s for S_n is normally enforced to avoid numerical instability. In addition to their use in weighting the arrival time data for inversion, we also use empirical reading errors to detect outliers in the data, which are flagged. Because outlier readings can cause good readings to have large residuals, the process needs to be done incrementally, starting with the largest residuals, to avoid rejection of good data. We gradually remove the largest outliers,

followed by relocation, until the normalized, de-meaned distribution of each station-phase approaches a Gaussian distribution. It is continued out until the residuals satisfy a 3σ criterion, using the current empirical reading error as the estimate of σ. This "cleaning" process is crucial in providing a self-consistent statistical framework for estimating location uncertainties. The process is illustrated in Figure 3.

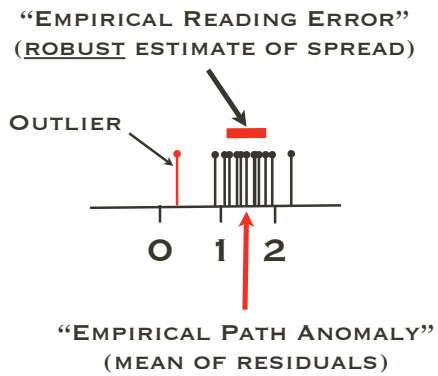

Figure 3. Outlier Removal

The effect of systematic and comprehensive (all phases and stations with 2 or more samples) estimation of empirical reading errors and associated outlier rejection is that the arrival time data set is reduced to one that more closely approaches the assumption of zero-mean, normally-distributed data which underlies the estimation of improved locations and their uncertainties. Gross errors are still possible from, for example, mis-identified phases, mis-associated readings, incorrect station locations, and temporary equipment or operational problems at stations.

Depth Determination

The HD code can treat focal depth as a free parameter, but in most cases it is necessary to fix the depths (it is no different for other methods of multiple event relocation). The reason is that typical arrival time data sets do not contain the information needed to resolve depth for all events in a cluster. Some events in the cluster may have depth phase reports but it is rare to have a set in which the same depth phase is observed for all events from the same station. There are also severe problems with correct phase identification of depth phases. Similarly, there might be a station very close to the epicenter of one event in the cluster, but unless the cluster is quite small that station will not be close enough to other events (even if it reported them all) to provide adequate depth resolution. We usually take the course of developing constraints on the focal depth of as many events in a cluster as possible, and then specifying an appropriate default depth for the remaining events. Each inversion is done with depths fixed, but there are many rounds of adjustment in depths and locations before the process is judged to have converged.

In this project we have gained substantial experience with methods of specifying depth constraints in the detailed analysis of aftershocks of the 2010 Maule, Chile earthquake, with Drs. Harley Benz and Gavin Hayes. We have performed careful analyses for several hundred events that have depth constraints from one or more of the following types of analysis:

- Arrival times at stations very near to the epicenter (usually <1.5 focal depths). These usually provide the strongest constraint on focal depth, with uncertainties of ~3 km.
- Teleseismic relative depth phases (pP-P and sP-P). Raw depth phase arrival times cannot be used in calibrated relocation studies where there are usually baseline offsets for the teleseismic phases in the 1-D global travel time model. These data are the most problematic, because uncertainties about the correct phase identification make the error's probability density function strongly bi-model (or worse).
- Centroid depths from regional moment tensor analysis (RMT). These are usually very reliable but the resolution is quite variable, ranging from about 5-20 km, depending on the source depth, source time function complexity and distribution of waveforms relative to the focal mechanism.

The comparison of depth estimates from these sources shows that all them are capable of providing useful depth constraint, but there are many complications that need to be taken into consideration. Procedures and protocols for this purpose have been implemented in the HD code under this project.

Exploring the Utility of Multiple Event Relocation at NEIC

Although continued development of the HD code to better meet the requirements of NEIC has been an important focus, the main thrust of this project has been the application of HD analysis to selected sequences of earthquakes that NEIC research personnel identified as being of exceptional importance, and also in applying HD in a rapid response mode to support the activities of the real-time monitoring system and its personnel. These activities have served to demonstrate to many NEIC personnel and management the utility of having a well-integrated capability for multiple event relocation as part of the real-time monitoring system and as a tool for more detailed research efforts. In the follow sections we discuss one example of each type.

Maule, Chile: Detailed study of a Major Earthquake Sequence

The February 27, 2010 Mw 8.8 Maule, Chile earthquake was followed by a massive aftershock sequence and an almost equally massive exercise in deployment by many institutions of temporary seismic stations to record them. Dr. Bergman worked closely with Drs. Benz and Hayes at NEIC in a detailed study of the rupture history of this earthquake sequence, combining finite fault modeling of the mainshock, single-event locations of most recorded aftershocks, regional moment tensors, and calibrated relocations of the mainshock and ~1100 of the larger aftershocks through July 2011, taking advantage of the many cases in which large earthquakes were recorded by temporary stations at very short epicentral range. A major effort for the relocation exercise was to merge the PDE data set with that of the temporary networks. Because of the dimensions of the rupture zone and number of events, the calibrated relocation study has been divided into studies of 15 subclusters that have been calibrated separately using the direct calibration method discussed above (Fig. 5).

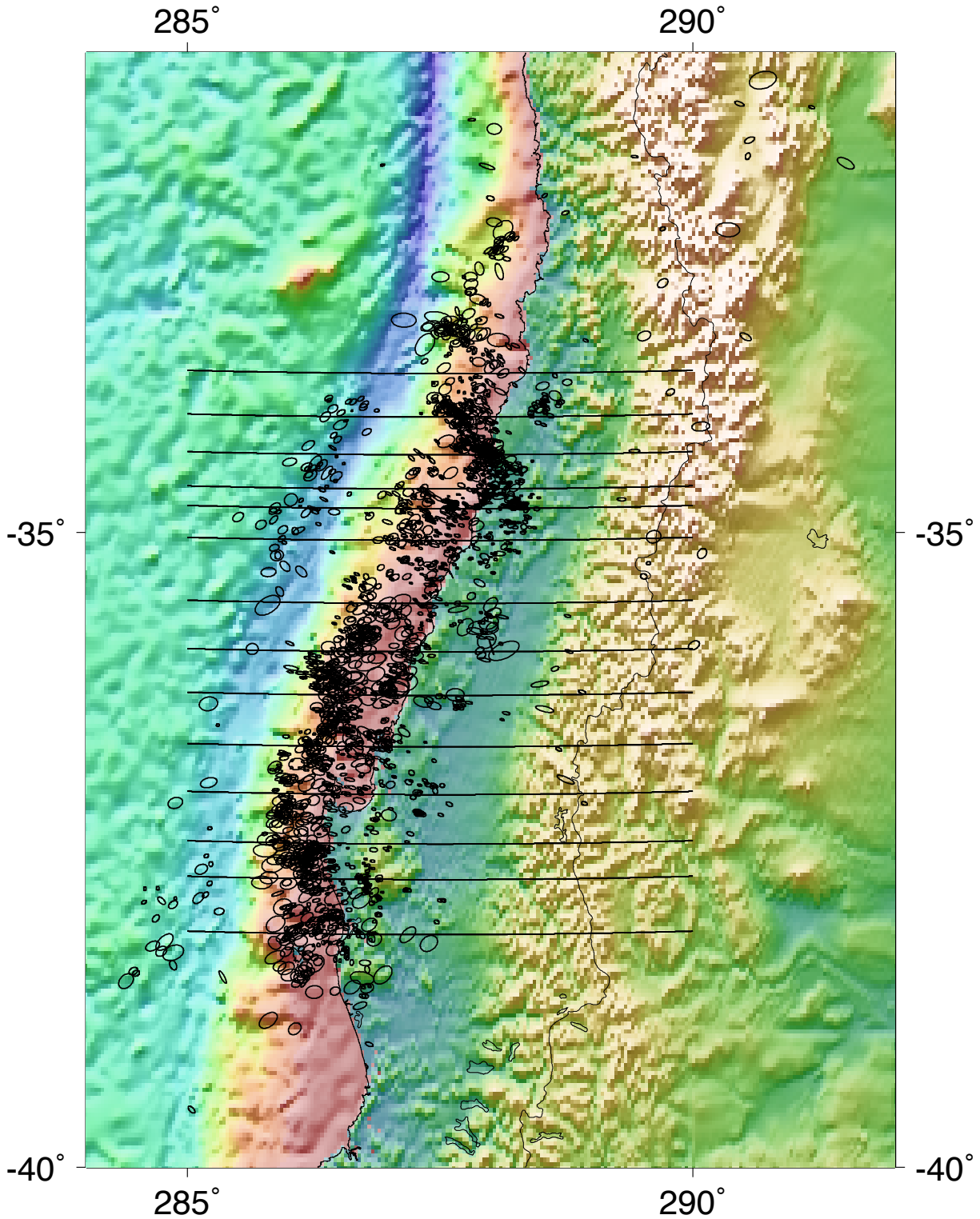

Figure 5. Subclusters of the 2010 Maule, Chile sequence that were analyzed for calibrated locations.

All subclusters are calibrated to a level of 1-2 km at 90% confidence level, meaning that this is the level of uncertainty in the location of the cluster as a whole. When the uncertainties in relative location of the individual events are added, approximate 2/3 of the events have location accuracies of better than 5 km, and virtually all events have location accuracy better than 10 km. Figure 6 shows the relocation results for a subset of the sequence which contains the mainshock. Although examples of location bias (i.e., change from starting locations) in all directions can be seen, the overall trend of the calibrated relocation is to move the cluster several tens of km to the WSW, relative to the single event locations from either the PDE, using the standard NEIC data stream, or by Harley Benz, using the temporary network data. The pattern of epicenters is also considerably tightened by relocation, emphasizing the tendency for the aftershocks to surround the regions of greatest slip in the finite fault model.

The pattern of focal depths is shown in Figure 7, a cross section along the blue line shown in Fig. 6.

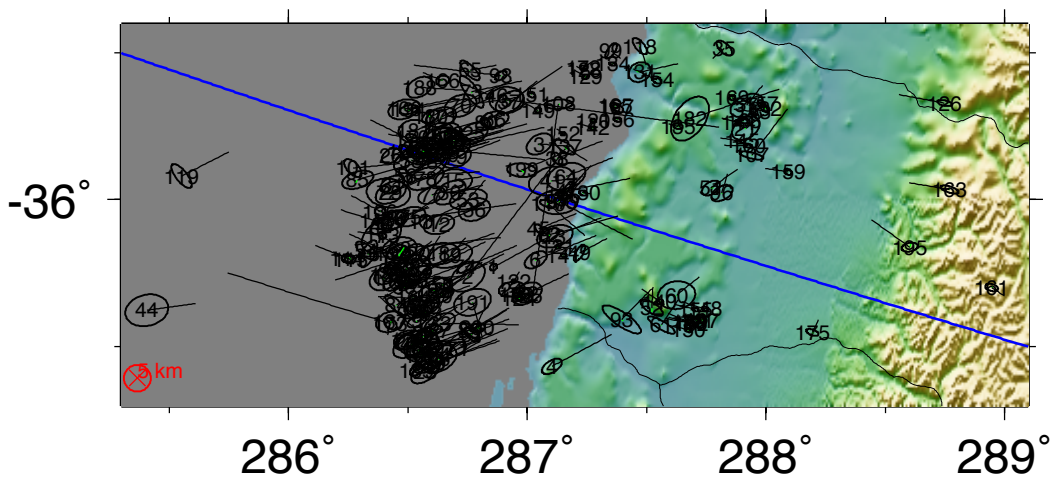

Figure 6. Calibrated relocations for a subset of events of the Maule sequence (see Fig. 5). The mainshock epicenter (#1) is isolated from any aftershock epicenters, in a region that presumably ruptured almost complete in the initial rupture. Red circle of radius 5 km provides scale for confidence ellipses. For each event the black vector traces the change in location from the original single event location (either PDE or temporary network solution) to the calibrated location.

Our study of the Maule sequence demonstrates the value of combining calibrated earthquake locations with other seismological data sets to gain a fuller and more detailed image of the rupture history of major earthquakes. HD analysis makes it possible to place the mainshock and early large aftershocks on the same reference grid as smaller aftershocks that are well-located by temporary stations that are rushed to the scene afterwards. As such it contributes significantly to a variety of research efforts in the EHP that seek to reduce the hazards of such events by better

understanding the details of their occurrence. As we accumulate a background data set of calibrated locations in all major seismic zones it will become much easier to determine a rapid initial location for a new event that is much less subject to location bias, by reference to the nearby calibrated events and their arrival time data sets.

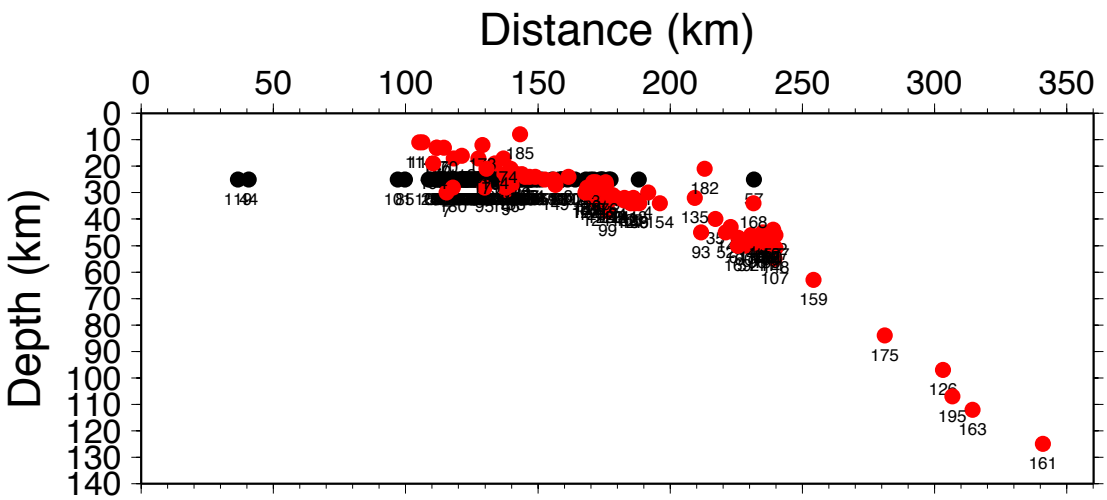

Figure 7. Depth profile along the line shown in blue in Figure 6. Symbols in red are events whose depth was constrained using one of the types of data discussed above. Symbols in black are events set at the cluster default depth of 24 km.

Lake Van, Turkey: Rapid Response to a Damaging Earthquake

Beginning a few hours after the October 23, 2011 (Mw 7.1) earthquake near Lake Van, Turkey, we began collecting and analyzing arrival time to data to determine calibrated locations for a cluster of earthquakes based on the mainshock. Within about 1 day we received readings from Iranian stations for some of the events, through the cooperation of one of our colleagues in Iran. Several days into the study, Dr. Gavin Hayes alerted us to the fact that arrival time data were being published on the website of the Turkish Seismological Service (DEPREM), and we collected local distance readings for the mainshock and all available aftershocks in our cluster. These readings were very helpful in calibrating the cluster as a whole and also helped to constrain the relative locations of some aftershocks, including focal depth.

The cluster of 59 earthquakes includes all significant earthquakes in the epicentral region since 1964, the mainshock and 22 of the largest aftershocks during the first 14 hours. The results of the calibrated relocation study are shown in Figure 8. The calibrated location of the mainshock epicenter is ~14 km northwest of the location published on the NEIC website. Based on similar comparisons between global network locations and calibrated locations in this region, this level of location bias is typical. Location errors of this magnitude can have significant negative consequences for disaster response efforts.

Initial results of this study, including calibrated location for the mainshock, were sent by e-mail to NEIC personnel on Oct 24, one day after the event. The calibrated location of the mainshock

was then used for an update on the NEIC website of the finite rupture model for this event. A detailed report on the calibrated relocation study was submitted to NEIC personnel on October 31, 2011. The study was updated in March 2012 to include a much larger set of aftershocks that provides more detail about the rupture pattern and its association with landforms and known geological features in the source region.

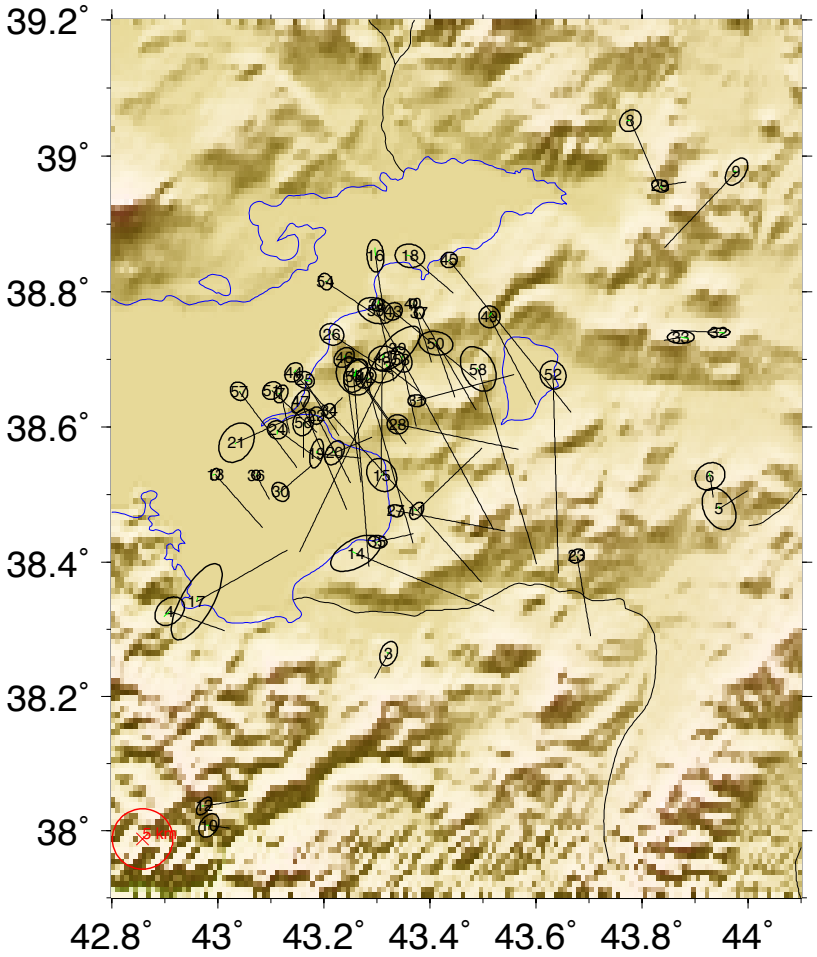

Figure 8. Map of relocated epicenters in the Van cluster. Confidence ellipses are 90% level for relative locations. Confidence ellipses for absolute (calibrated) location are larger by 0.2 (for largest ellipses) to 1.2 km (smallest ellipses). Red circle in lower left corner has a radius of 5 km, for scale. Black vectors show the change in location from the location given in the input data file. For the October 23, 2011 mainshock and aftershocks, that location is the NEIC location. For earlier events it is from a reviewed EHB location.

Other Earthquake Sequences Studied

In addition to a major study for the Maule, Chile sequence that was discussed above, I carried out extensive relocation analyses of three other earthquakes sequences, related to the M_w 5.3 Trinidad, Colorado (600+ earthquakes) and M_w 5.8 Mineral, Virginia (454 earthquakes) events, which both occurred on August 23, 2011, and the M_w 5.6 Prague, Oklahoma event on November 6, 2011 (1240 earthquakes).

In all three cases, dense local networks of seismometers were deployed, although usually by several different institutions. Combining these datasets and conducting calibrated multiple event relocation analyses we obtained unprecedented resolution of the faulting episodes. Among the most important aspects of our analysis is the ability to constrain the locations of the mainshocks and early large aftershocks, which occurred before the networks were in place, by linking them to the later well-recorded aftershocks. All these studies have been published or are in the process of being published.

In the context of rapid-response studies, similar to the Lake Van, Turkey study discussed above, I preformed analyses of earthquakes sequences in 2012:

- Ahar, Iran (Aug. 11, 2012)
- Jimalalud, Philippines (Feb. 6, 2012)
- Chile (Jan. 23, 2012)
- Sumatra (April 11, 2012)

In all cases the results of these studies were communicated rapidly (usually within 24 hrs) to NEIC personnel, who expressed gratitude at having independent verification of the locations of the events.

Papers Resulting from this Project

A paper on the 2011-2012 Trinidad, Colorado earthquake sequence is in preparation, with authorship including Bergman and several NEIC scientific personnel.

Hayes, G. P., Bergman, E. A., Johnson, K., Benz, H. M., & Brown, L. (2013). Seismotectonic framework of the 2010 February 27 M_W 8.8 Maule, Chile earthquake sequence. *Geophysical Journal International*. doi:10.1093/gji/ggt238

McNamara, D. E., Benz, H. M., Herrmann, R. B., Bergman, E. A., Earle, P. S., Meltzer, A., et al. (2013). The Mw 5.8 Mineral, Virginia, Earthquake of August 2011 and Aftershock Sequence: Constraints on Earthquake Source Parameters and Fault Geometry. *Bulletin of the Seismological Society of America*. doi:10.1785/0120130058

McNamara, D. E., Benz, H. M., Herrmann, R. B., Bergman, E. A., Baldwin, R., & Earle, P. S. (in review 2014). The November 2011 Oklahoma earthquake and aftershock sequence: Constraints on source parameters, fault geometry and aftershock characteristics. *Bulletin of the Seismological Society of America*, 1–35.

References

Bergman, E.A. and S.C. Solomon, 1990. Earthquake swarms on the Mid-Atlantic Ridge - Products of magmatism or extensional tectonics? *J. Geophys. Res.*, **95**, 4943.

Biggs, J., E.A. Bergman, B. Emmerson, G. Funning, J. Jackson, B. Parsons, and T. Wright, 2006. Fault Identification for Buried Strike-Slip Earthquakes using InSAR: The 1994 and 2004 Al Hoceima, Morocco Earthquakes. *Geophy. J. Int.*, **166**, 1347-1362.

Bondar et al., 2004. Collection of a reference event set for regional and teleseismic location calibration. *Bull. Seism. Soc. Am.*, **94** (4), 1528-1545.

Bondár, I., E.A. Bergman, E.R. Engdahl, B. Kohl, Y-L Kung, and K. McLaughlin, 2008. A hybrid multiple event location technique to obtain ground truth event locations. *Geophy. J. Int.*, **175** (1), 185-201.

Croux, C., and P. J. Rousseeuw, 1992. Time efficient algorithms for two highly robust estimators of scale, Computational Statistics, V1, Dodge and Whittaker, ed., Physica-Verlag, Heidleberg, pp. 411-428.

Dewey, J.W., 1972. Seismicity and tectonics of western Venezuela, *Bull. Seismol. Soc. Amer.*, **62**, 1711-1751.

Douglas, A., 1967. Joint Epicentre Determination, *Nature*, **215**, 47-48.

Engdahl, E.R. and E.A. Bergman, 2000. Identification and validation of Reference Events within the area being regionally monitored by IMS stations in Asia and North Africa, *22nd Seismic Research Symposium*, New Orleans, USA. http://www.cmr.gov/srs/srs2000/papers/02-13.pdf

Engdahl, E.R. and E.A. Bergman, 2001. Validation and generation of reference events by cluster analysis, *23rd Seismic Research Review*, Jackson Hole, USA. http://www.cmr.gov/srs/srs2001/Screen/02-09.pdf

Engdahl, E.R., R. van der Hilst, and R.P. Buland, 1998. Global teleseismic earthquake relocation with improved travel times and procedures for depth determination. *Bull. Seism. Soc. Am.*, **88** (3), 722-743

Ghods, A., Rezapour, M., Bergman, E.A., Mortezanejad, G., and Talebian, M., 2012, Relocation of the 2006 Mw 6.1 Silakhour, Iran, Earthquake Sequence: Details of Fault Segmentation on the Main Recent Fault: Bulletin of the Seismological Society of America, v. 102, no. 1, p. 398–416, doi: 10.1785/0120110009.

Jordan, T.H. and K.A. Sverdrup, 1981. Teleseismic location techniques and their application to earthquake clusters in the South-central Pacific, *Bull. Seism. Soc. Am.*, **71**, 1105-1130.

Kennett, B.L.N., E.R. Engdahl, and R. Buland, 1995. Constraints on seismic velocities in the Earth from travel times, *Geophys. J. Int.,* **122**, 108-124.

Nissen, E., Yamini-Fard, F., Tatar, M., Gholamzadeh, A., Bergman, E.A., Elliott, J.R., Jackson, J.A., and Parsons, B.E., 2010, The vertical separation of mainshock rupture and microseismicity at Qeshm island in the Zagros fold-and-thrust belt, Iran: Earth and Planetary Science Letters, v. 296, no. 3-4, p. 181–194, doi: 10.1016/j.epsl.2010.04.049.

Parsons, B., T. Wright, P. Rowe, J. Andrews, J. Jackson, R. Walker, M. Khatib, M. Talebian, E.A. Bergman and E.R. Engdahl, 2006. The 1994 Sefidabeh (eastern Iran) earthquakes revisited: new evidence from satellite radar interferometry and carbonate dating about the growth of an active fold above a blind thrust fault, *Geophys. J. Int.*, **164**, 202–217.

Pavlis, G. L. and N.B. Hokanson, 1985. Separated earthquake location, *J. Geophys. Res.*, **90**

(B14), 12,777-12,789.
Ritzwoller, M.H., N.M. Shapiro, A.L. Levshin, E.A. Bergman, and E.R. Engdahl, 2003. Ability of a global three-dimensional model to locate regional events, *J. Geophys. Res.,* **108** (B7), 2353, ESE 9-1 - ESE 9-24.
Rodi, W., E.R. Engdahl, E.A. Bergman, F. Waldhauser, G. Pavlis, H. Israelsson, J. Dewey, and M. Toksöz, 2002. A new grid-search multiple event location algorithm and a comparison of methods, *24th Seismic Research Review,* Pointe Vedra Beach, USA. http://www.cmr.gov/srs/srs2002/screen/02-19.pdf
Roustaei, M., Nissen, E., Abbassi, M.R., Ghorashi, M., Gholamzadeh, A., Tatar, M., Yamini-Fard, F., Bergman, E.A., Jackson, J.A., and Parsons, B.E., 2009, Vertical separation of surface folding, earthquake faulting, and aftershocks in the Zagros Simply Folded Belt (Iran): Geophysical Journal International, v. 142, p. 1–24.
Tatar, M., J. Jackson, D. Hatzfeld and E.A. Bergman, 2007. The 28 May 2004 Baladeh earthquake (Mw 6.2) in the Alborz, Iran: implications for the geology of the South Caspian Basin margin and for the seismic hazard of Tehran, , *Geophys J. Int.*, **170**, 249-261.
Waldhauser, F., and W.L. Ellsworth, 2000. A double-difference earthquake location algorithm: Method and application to the Northern Hayward fault, California, *Bull. Seism. Soc. Am.*, **90**, 1353-1368.
Walker, R.T., E.A. Bergman, J. Jackson, M. Ghorashi, and M. Talebian, 2005. The 2002 June 22 Changureh (Avaj) earthquake in Qazvin province, northwest Iran: epicentral relocation, source parameters, surface deformation and geomorphology, *Geophys. J. Int.*, **160**, 707-720.
Walker, R.T., Bergman, E.A., Szeliga, W., and Fielding, E.J., 2011, Insights into the 1968-1997 Dasht-e-Bayaz and Zirkuh earthquake sequences, eastern Iran, from calibrated relocations, InSAR and high-resolution satellite imagery: Geophysical Journal International,, p. no–no, doi: 10.1111/j.1365-246X.2011.05213.x.
Wolfe, C.J., E.A. Bergman and S.C. Solomon, 1993. Oceanic transform earthquakes with unusual mechanisms or locations - Relation to fault geometry and state of stress in the adjacent lithosphere. *J. Geophys. Res.*, **98**, 16187