A framework of ground truth event locations across Iran from a two tiered multi-event relocation approach

T1.2-P2

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2 Event Calibration

• **mloc** is a multiple event relocation technique [*Bergman and Solomon,* 1990, GJR; *Walker et al.,* 2011, JGI], based on *Jordan and Sverdrup* [1981, SSA]'s hypocentroidal decomposition method.

• Like many other multi-event location methods, **mloc** estimates improved relative locations of clustered events by minimizing path-correlated errors in travel-times.

• Unlike other methods, **mloc** has been specialized to determine *calibrated locations* - latitude, longitude, *depth* and *origin time* - when appropriate data sets are available.

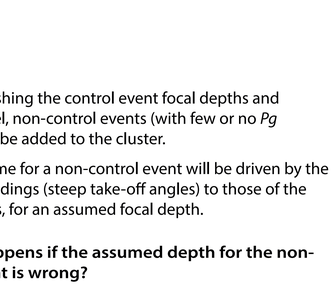
• **mloc** separates the inversion problem into two steps, each using different datasets:

(1) Relocation of the cluster vectors, in which all available data are used, giving *relative locations*.

(2) Relocation of the hypocentroid, in which direct arrival phases *Pg* and *Sg* (at distances <1°) are preferred, giving *absolute locations*, and hence reduces the bias coming from the unknown earth structure.

• The location uncertainty is fully quantified and calibrated and is estimated from the actual data.

• **mloc** 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 (Fig. 3).



[*Bergman,* 2014, NEIC] Fig. 3

1 Introduction

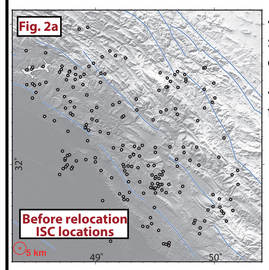
• Uncertainties in standardized earthquake locations, which run into tens-of kilometers in many regions of the world, are a serious limitation to seismotectonic studies and nuclear treaty monitoring.

• We have developed a new two-tiered multiple-event relocation approach that seeks to improve upon these catalog locations, and have applied it to Iran (Fig. 1a), a country with abundant seismicity (> 40,000 ISC Bulletin events since 1960), a recent surge in station coverage, but with known shortcomings in location accuracy.

• Our purpose is to generate a comprehensive catalog of calibrated, relocated earthquake hypocenters for the entire Iran region, by:

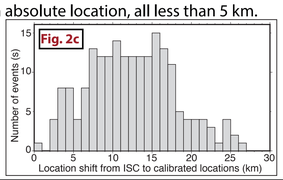
(1) developing *calibrated* earthquake clusters using near source data, aftershock deployments, and InSAR studies using **mloc** (**panels 1 - 5**). These clusters will not only include calibrated epicenters, but also hypocenters whose depth and origin time are well-constrained with rigorously-assessed errors.

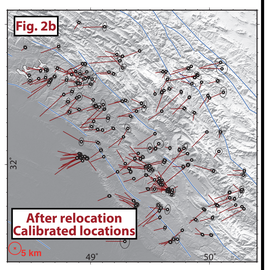
(2) incorporating this backbone of trusted hypocenters into **Bayesloc**, there by extending the analysis to the whole of Iran and the full back-catalogue of instrumental seismicity (**panel 6**).



• From Fig. 2a to Fig. 2b: After the relocation, scattered seismicity in the Shushtar cluster collapses into discrete clusters and trends.

• Confidence ellipses show with 90% confidence bound for each absolute location, all less than 5 km.





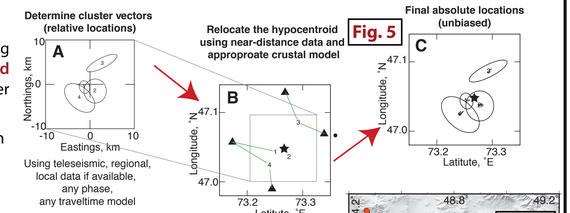
4 Direct Calibration

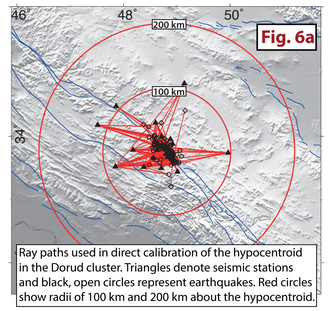
• In *direct calibration* mode, **mloc** uses direct crustal phases (*Pg* and *Sg*) recorded at shorter epicentral distances (<1°) and well-enough distributed to allow the hypocentroid to be located using only these data (Fig. 5).

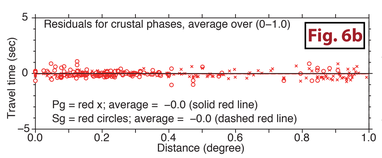
• By keeping ray path lengths short, the accumulated traveltime error from unknown velocity structure and the possible location error are minimized.

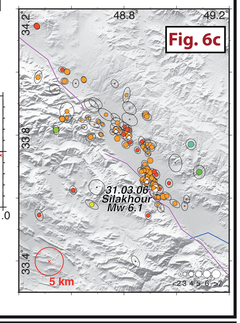
• The Dorud cluster (Fig. 6) was calibrated by using data up to 100 km for the hypocentroid (Fig. 6a and 6b). All the avalable data were used for the cluster vector calculation.

• Calibration level for the entire cluster is 1.5 km, with 104 events having 1 - 3 km of location error (Fig. 6c).









3 Depth and origin-time calibration

Depth trades off with origin time:

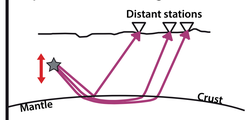
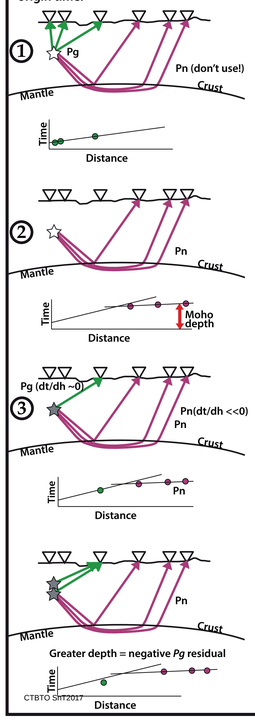


Fig. 4

A new routine to calibrate depth and origin time:



• Earthquake depths can be difficult to determine if only regional stations (at distances of >10s of kilometers) are available. Since the takeoff angles of the rays are very similar, changes in the earthquake depth may be compensated by a shift in the origin time.

• For this reason, depth is usually kept fixed in most multiple event relocation techniques.

• For locally-recorded events, direct phase arrivals (*Pg* and *Sg*) provide strong constraints on the focal depth.

• We start by selecting "control events" which have good *Pg* and *Sg* readings, good azimuthal coverage, and depth control from close-in stations.

• These control events are relocated separately in order to first constrain the focal depths and second to refine the local crustal velocity model.

• Next we incorporate *Pn* and *Sn* arrival times for the same control events, thereby determining the crustal thickness and upper mantle velocity.

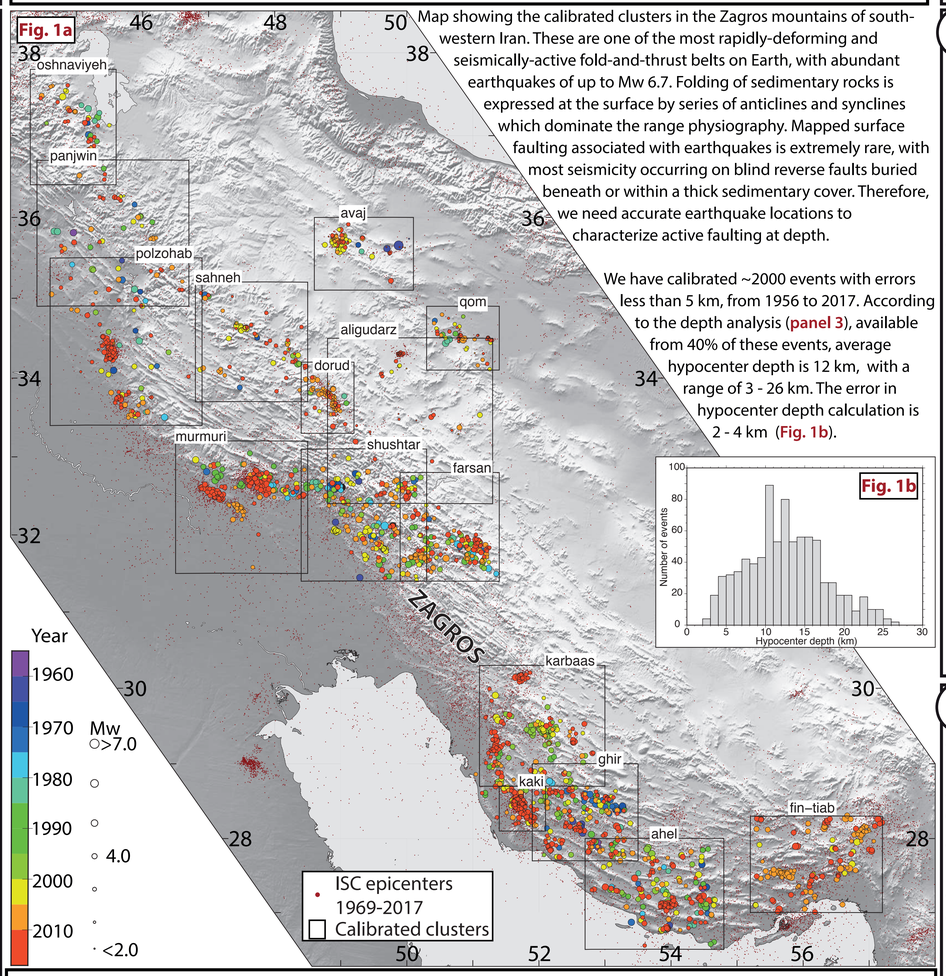
• After establishing the control event focal depths and velocity model, non-control events (with few or no *Pg* readings) can be added to the cluster.

• The origin time for a non-control event will be driven by the fit of its *Pn* readings (steep take-off angles) to those of the control events, for an assumed focal depth.

So, what happens if the assumed depth for the non-control event is wrong?

• If the assumed depth is greater than the true depth, its origin time must be later to fit the *Pn* arrivals with shorter ray-paths, leading to a negative *Pg* residual.

• *Pg* arrivals at regional distances have no dependence on depth (ray-path lengths stay the same) but are affected by changes in origin time.



Map showing the calibrated clusters in the Zagros mountains of south-western Iran. These are one of the most rapidly-deforming and seismically-active fold-and-thrust belts on Earth, with abundant earthquakes of up to Mw 6.7. Folding of sedimentary rocks is expressed at the surface by series of anticlines and synclines which dominate the range physiography. Mapped surface faulting associated with earthquakes is extremely rare, with most seismicity occurring on blind reverse faults buried beneath or within a thick sedimentary cover. Therefore, we need accurate earthquake locations to characterize active faulting at depth.

We have calibrated ~2000 events with errors less than 5 km, from 1956 to 2017. According to the depth analysis (**panel 3**), available from 40% of these events, average hypocenter depth is 12 km, with a range of 3 - 26 km. The error in hypocenter depth calculation is 2 - 4 km (Fig. 1b).

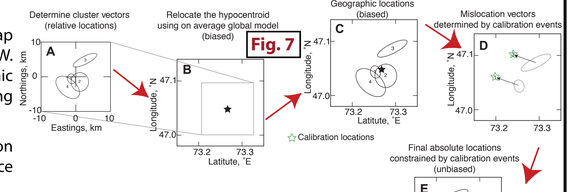
5 Indirect Calibration

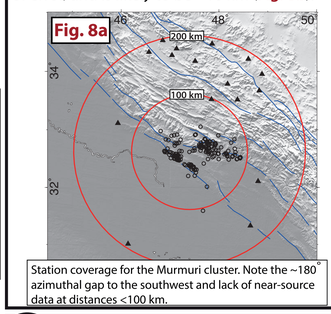
• In regions where near-source data are rare we can obtain calibrated locations using an *indirect calibration* (Fig. 7). This can be achieved if the location of one or more of the cluster events is known accurately from independent information, i.e. **(1)** previously published epicenters from local aftershock deployments, **(2)** recent magnitude 5-6 earthquakes that have been imaged with InSAR, **(3)** field mapping, **(4)** ground truth events, and **(5)** man-made explosions .

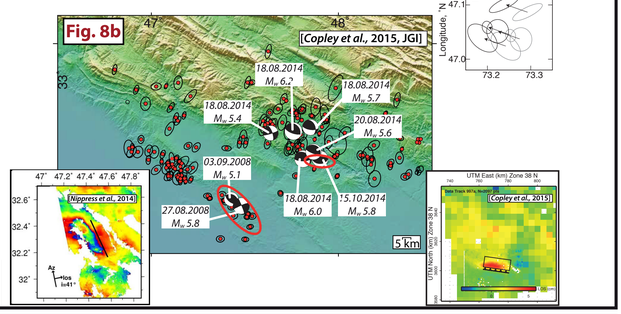
• Locations are determined by shifting the entire cluster in space and time to match to the known location of the ground truth event(s).

• The Murmuri cluster (Fig. 8a) had an azimuthal gap in near-source arrival time data of ~180° to the SW. We first located the cluster vectors with teleseismic arrivals. Then, we calibrated the entire cluster using InSAR-derived fault planes.

• Uncertainties in the positions of the hypocenter on each of the model fault planes is an additional source of error, and is likely to be ~10 km (Fig. 8b).







6 From clusters to regional catalogs

• Our calibrated relocation analyses are restricted to areas with dimensions of ~100 km and are ill-suited for clusters with large numbers (>200) of events.

• We are currently incorporating **Bayesloc** in order to expand the relocation across a much larger region with large numbers of earthquakes, whilst retaining a rigorous assessment of location error.

• **Bayesloc** is a multiple-event relocation algorithm [*Myers et al.,* 2007, JGI], that accepts probabilistic, a priori constraints on all of the model parameters, enabling it to integrate both trusted data sets, such as clusters calibrated with mloc, and poor quality data sets.

• It uses a Markov Chain Monte Carlo method for solving large scale, non-linear stochastic inverse problems, which reduces the assumptions from linearized relocation techniques and also allows us to relocate all of the instrumentally-recorded earthquakes in Iran.

• **Bayesloc** was already applied to >5,000 events in Middle East [*Myers et al.,* 2011, JGR] yielding mislocations of ~5 km with respect to the available GT1 epicenters, but in this instance no local or regional calibration was used.

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