# Earthquake Catalog: Quality Control (QC)

- I created a custom (deep-learning) enhanced earthquake catalog automatically. How good is it?
  - No ground truth available
- Before using or interpreting your enhanced catalog, do this first:
  - Compare with a **reference catalog**
  - Data visualization (make plots!) to check for quality

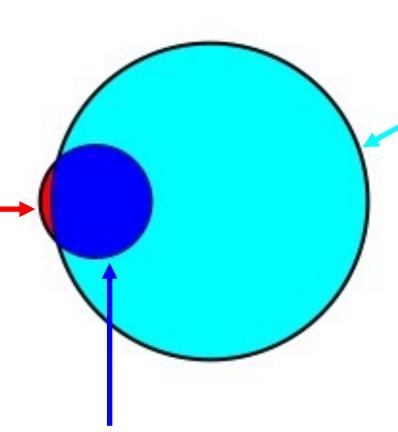
# What is a **reference catalog**?

- Authoritative, high-quality earthquake catalog for a region
  - Good baseline for comparison: manually reviewed, meets performance standards
  - United States: Comprehensive Catalog (ComCat), complete to M2.5-3.0, <u>https://earthquake.usgs.gov/earthquakes/search/</u>, <u>https://earthquake.usgs.gov/data/comcat/</u>
  - **International**: ComCat is complete to M4.5 globally. For more complete catalogs, refer to the country/region's authoritative monitoring website.
    - Turkey: <u>https://deprem.afad.gov.tr/event-catalog</u>
    - New Zealand: <u>https://quakesearch.geonet.org.nz/</u>
    - Italy: <u>https://terremoti.ingv.it/bsi</u>

Event comparison: reference catalog vs. enhanced catalog (Need locations) (small circle) (big circle)

MISSED events (only in reference catalog)

- Manually detected and/or picked by analysts
- Check why they were missed (esp. larger events?)



### MATCH events (common to both catalogs)

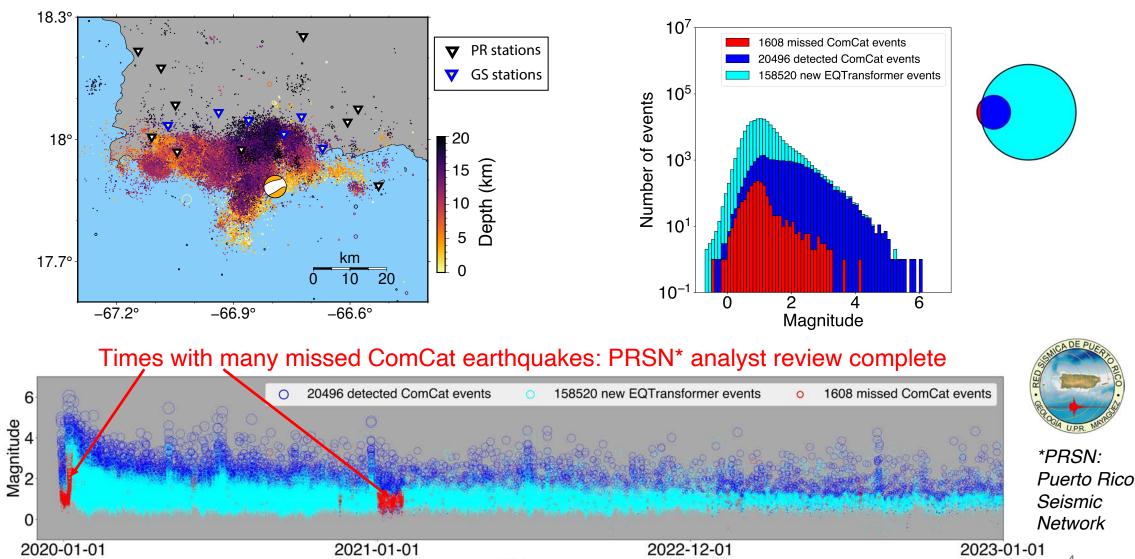
- Origin times match within X~5 seconds
- Hypocenters match within Y~25 km

**NEW** events (only in enhanced catalog)

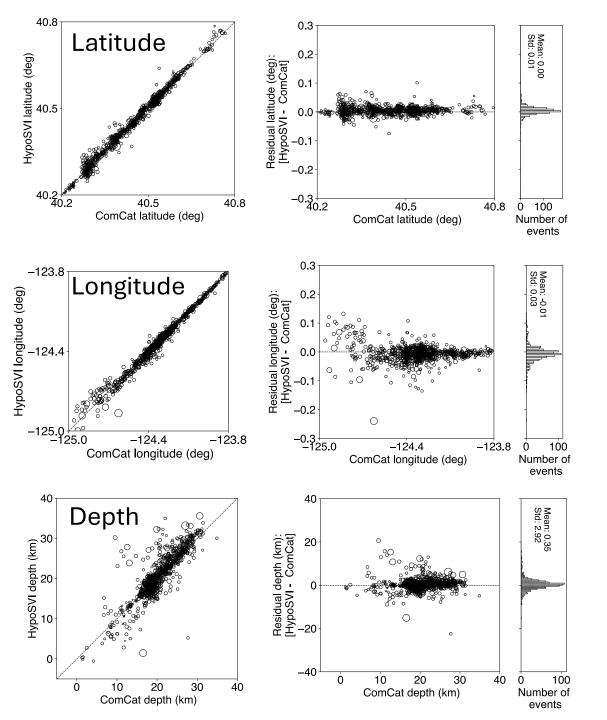
- Newly detected small local earthquakes?
- False detections from noise? <sup>(2)</sup>
- Other signals (quarry blasts, sonic booms, explosions)? 🧐
- Regional or teleseismic earthquakes? 🧐

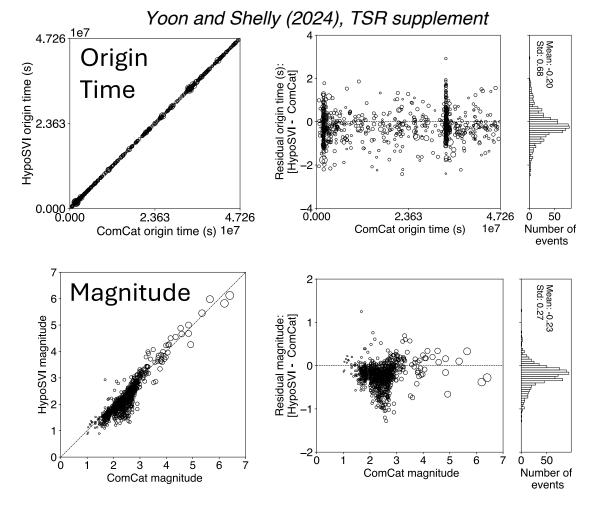
### Event comparison example: SW Puerto Rico sequence

Yoon et al. (2023), BSSA



Date





## MATCH events: location, magnitude comparison

Horizontal axis: ComCat (reference catalog) Vertical axis: Enhanced catalog 5

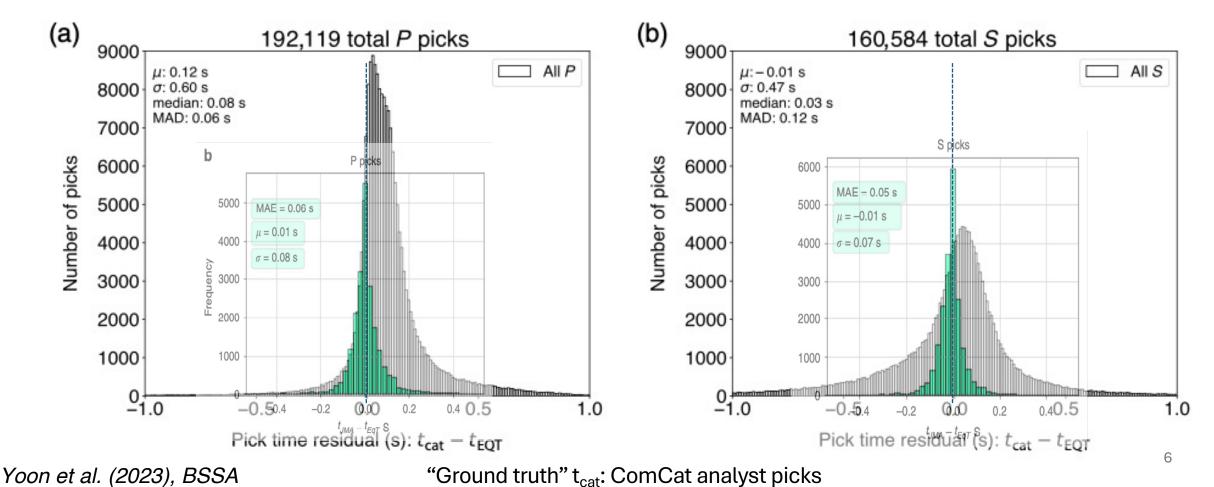
## MATCH events: Pick time comparison for each station

→ residual histograms

EQTransformer on Puerto Rico seismic data: less accurate pick times than

Mousavi et al. (2020) on STEAD test dataset

... but good enough for automatic catalog workflow



# EQT **pick quality** (number of picks, pick accuracy) **degrades** with increasing event-station distance

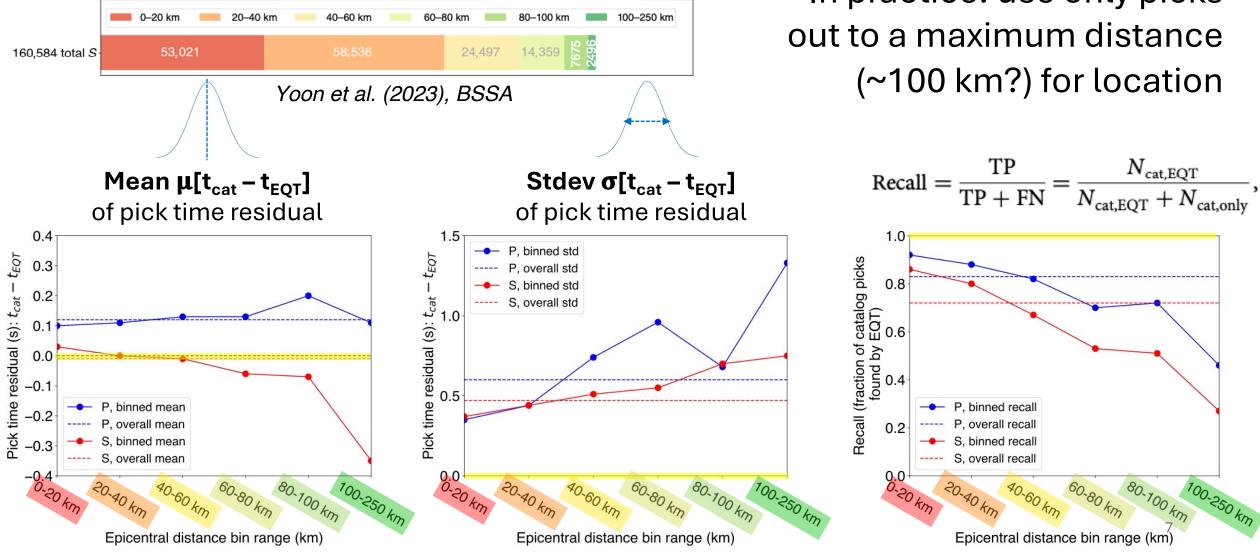
20,472

30,571

192.119 total P

57,741

In practice: use only picks out to a maximum distance (~100 km?) for location



# Reference Catalog Tip: Select boundaries carefully

**Example: Mendocino Triple Junction, CA** 

M 1 M 2

### **Region big enough:** includes most

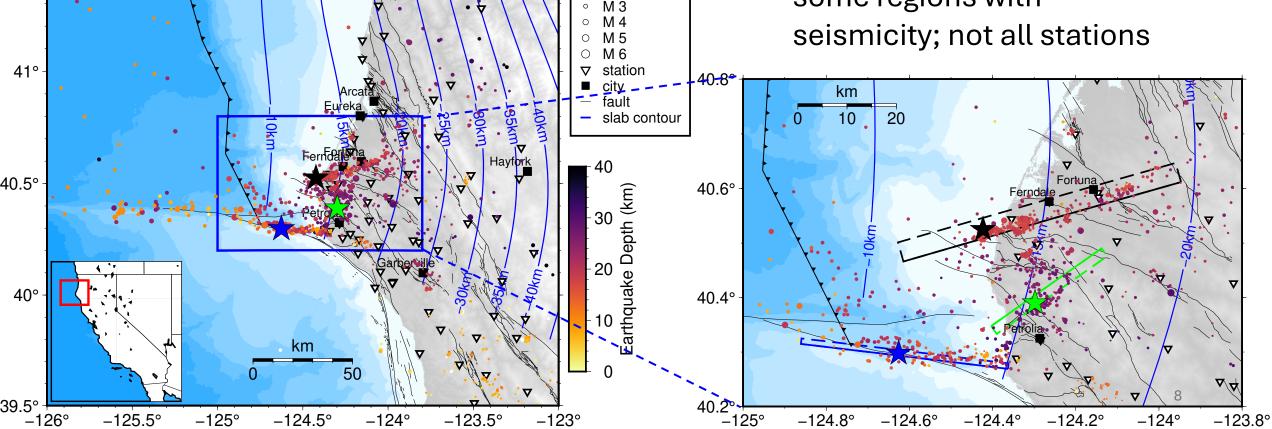
seismicity and all stations used

41.5°

Yoon and Shelly (2024), TSR

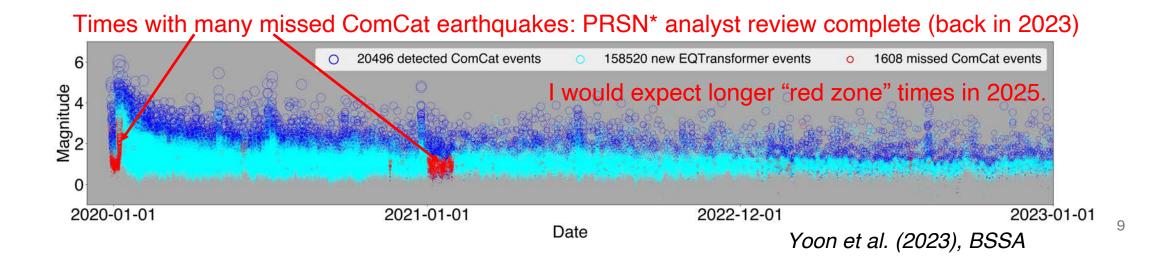
### **Region too small**: missing

some regions with



# Reference Catalog Tip: It changes over time

- Reference catalog changes over time due to analyst review
  - New or deleted events; updated location/magnitude for existing events
  - Expect frequent changes to catalog: hours to days after large earthquake
  - Complete analyst review for active aftershock sequence: months to years
    - July 2019 M7.1 Ridgecrest CA sequence
      - 2019-07-07: 45% complete, 2019-07-08 to 2019-07-31: <10% complete each day
      - Catalog processing status (updated daily):
        <u>https://service.scedc.caltech.edu/ftp/catalogs/catalog\_status/</u>



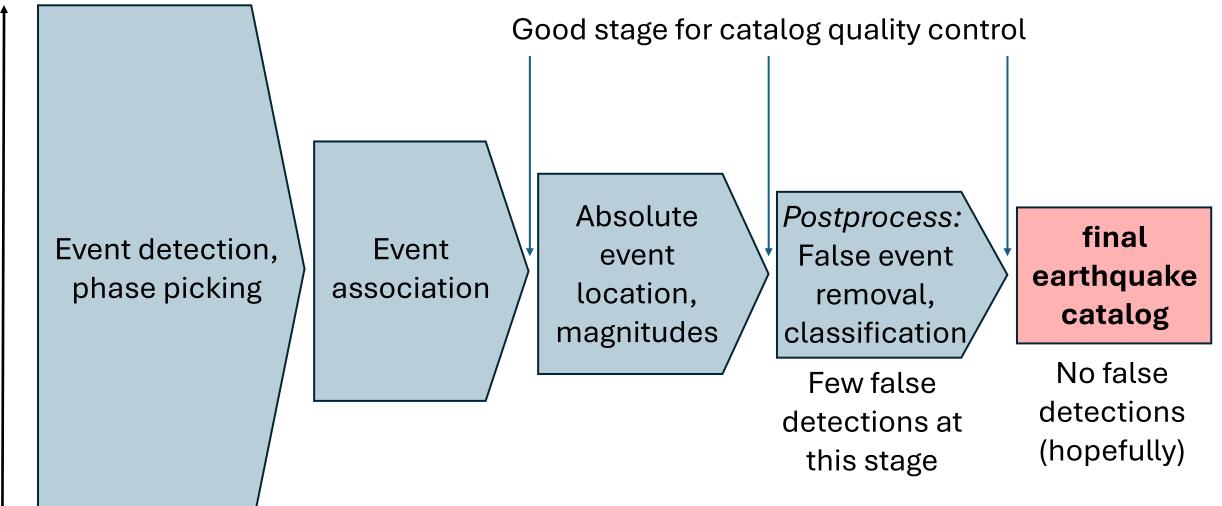
# Reference Catalog Tip: It changes over time

- Save the reference catalog file itself, with filename including the date you downloaded it.
  - When reference catalog changes in the future, you still have the original version, so you can easily reproduce your results.

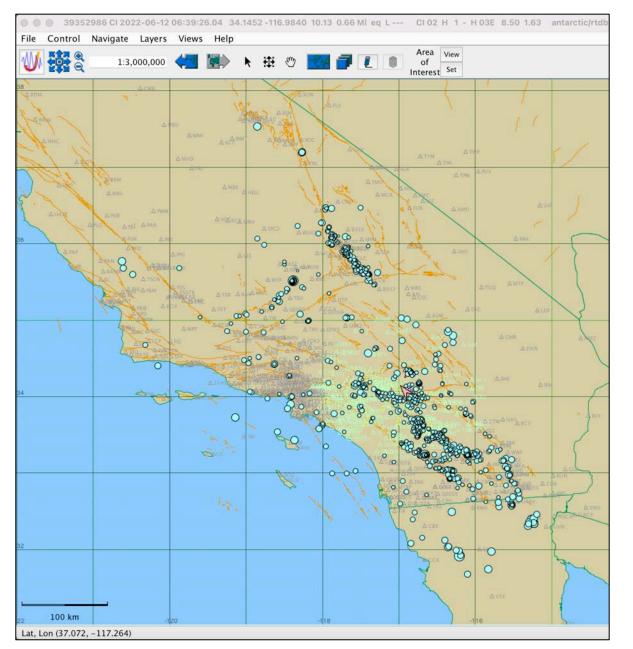
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  - Compare with a reference catalog
  - Data visualization (make plots!) to check for quality

# Catalog QC: Most false detections drop out at each step of automatic workflow, but not all.



## Earthquake Catalog QC: Think like an analyst



HHZ SEED 7.25 Km 142* (bias,max-b	(as,min-bias)=(-150.0, 1241.76	,-8/2.22)	Cursor time 96:39:19.83 counts 668 1.8	1651E-4 cms
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10 H	IFE DI SE	× 20220612 06:39:32.357 🚯 🖨 🗶	<b>Ξ</b> ● <b>?</b> I <b>Ⅲ</b> 32.96 0 <b>↓  ↓ ↓</b> ■	
	06:39		06:40	
Q FHO HHZ HHZ SEED 7.3km	06:39		06:40	
. Q ENQ HIN HIN T- SEED 7.3km	06:39		06.40	
.C. EHO HHE HHE SEED 7.3km	06:39		106.40	
CI EHO HNZ HNZ SEED Z.3km	06:39		06:40	
CI FHO HNN HNN SEED 7.3km	06:39		106.40 i i i i i i i i i i i i i i i i i i i	
Q EHQ HNE HNE SEED 7.3km	06:39		06.40	
CH EHO BHZ BHZ - SEED 7,3km	06:39		06.40	
CI EHO BHN BHN SEED 7.3km	06:39		06-40	
CI EHO BHE BHE - SEED 7, 3km	06:39		06:40	
NP.5075 HNZ HNZ SEED 8.68m	06:39		06:40	
NP.5076 HNZ HNZ SEED 9.2km	06:39		06.40	
NP 5300 HNZ HNZ DO SEED 11.2km	06:39			
CI SVD HHZ HHZ SEED 11.4km	06:39	and the second state of th	06:40	

# AQMS Jiggle manual review and picking interface at SCSN

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ID	ONHO	DATETIME	LAT	LON	MZ	Z	MAG MTY	AUTH	ETYPE	GT SR	ESRC	GAP	DIST	1945	ERR_H	ERR_Z	ERR_T CE	S USED	0 51	PR	V	LODAT	E	OAUTH	COMMEN
		2022-06-12 05:24:00.600						CI I	earthquake						0.45				0.00A						
3935294		2022-06-12 05:58:39.320						CI	earthquake						0.27				0.00 A						
3935295		2022-06-12 06:23:19.720						CI	earthquake						0.46				A 66.6				6:27:41		
3935296		2022-06-12 06:25:06.770						CI	earthquake						0.43		1		0.08A				6:29:45		
3935297		2022-06-12 06:34:02.930						CI	earthquake				15.00			1.04			0.00 A				6:38:36		
3935298		2022-06-12 06:39:26.040						CI	earthquake						0.48				0.00 A				6:43:51		
		2022-06-12 07:05:19.140						ID	earthquake				15.00			1.84			0.00 A				7:09:50		
		2022-06-12 08:24:17.870						CI	earthquake				33.00		0.78				A 66.0				8:29:01		
		2022-06-12 09:08:01.440						D	earthquake				15.00		0.52								9:13:17		
3935302		2022-06-12 09:20:24.030 2022-06-12 09:40:30.300						a	earthquake				15.00			1.88			A 60.0				9:24:47		
		2022-06-12 09:40:30.300 2022-06-12 09:55:38.990							earthquake						0.48				A 60.0				9:45:31 0:00:07		
3935385		2022-06-12 09:55:38.990 2022-06-12 10:01:05.960						D D	earthquake				15.00			1.39			0.00 A				0:00:07		
		2022-06-12 10:01:05.960 2022-06-12 10:06:48.530						a	earthquake				12.00			1.12			0.00 A				0:05:52		
		2022-06-12 10:06:48.530						a	earthquake				19.80			1.12			0.00 A				0:11:02		
		2022-06-12 10:55:12.760						CI	earthquake						0.30				0.00 A				1:01:02		
		2022-06-12 10:50:44.010						CI	earthquake						0.20				0.00 A				1:32:12		
		2022-06-12 11:27:30.030						a	earthquake				26.00			1.38			0.00 A				2:12:22		
		2022-06-12 12:08:40.150						CT	earthquake						0.30				0.00 A				2:13:52		
		2022-06-12 12:11:28,640						a	earthquake				3.00			0.68			0.00 A				2:15:27		
		2022-06-12 12:11:55,480						CI	earthquake				3.00		1.14				0.00 A				2:15:57		
		2022-06-12 13:02:27,538						CI	earthquake						8.29				8.08 A				3:07:03		
		2022-06-12 13:11:57,250						CI	earthquake				18.88			1.15			0.08A				3:16:23		
		2822-06-12 13:25:23,440						CI	earthquake				18,00			7.01			0.00 A				3:30:27		
		2022-06-12 13:48:27.600						CI	earthquake						0.45								3:52:52		
		2022-06-12 14:51:48.760						CI I	earthquake	L RT	6 RT6		45.00			2.31		10 15	0.00 A				4:57:22		
		2022-06-12 15:45:17,990						CI	earthquake	L RT	S RT6		5,00			0.71		18 39	0.00 A				5:49:58		
3935326	6	2022-06-12 16:12:07.290	33,962	-117.214	13.22	12.69	0.77 Ml	CI	earthquake	L RT	5 RT6	206.0	11.00	0.12	0.86	1.24		4 14	0.00 A	24.3	0 2022-	-06-12 1	6:16:07	CI	
3935327	4	2822-86-12 16:19:52.368	33,714	-116,748	17.72	16.35	1.11 ML	CI	earthquake	L RT	RT6	107.0	3,80	0.14	0.56	0.97		3 21	0.00A	26.0	0 2022-	-06-12 1	6:24:28	CI	
3935329		2022-06-12 16:24:07.380	34,038	-117.255	15.55	14.88	1.23 Ml	CI	earthquake	L RT	S RTG	127.0	12.00	0.20	0.62	0.87	5	16 24	0.00 A	26.6	0 2022-	-05-12 1	6:29:13	CI	
3935329	8	2022-06-12 16:28:33.640	35.028	-116.957	5.09	4.13	2.16 Ml	CI	earthquake	L RT	AT6	58.0	17.00	0.17	0.16	0.67	16	3 44	0.00 A	31.2	0 2022-	-06-12 1	6:33:53	CI	
3935331	4	2022-06-12 16:33:47.730	35.664	-117.520	14.68	13.95	1.34 Ml	CI	earthquake	L RT	5 RT6	159.0	18.00	0.17	0.45	1.10	1	8 21	A 66.6	27.1	0 2022-	06-12 1	6:38:33	CI	
3935332	2	2022-06-12 16:38:26.690	34.269	-118.440	18.79	10.37	1.32 Ml	CI	earthquake	L RT	5 RT6		4.00		0.59	0.96		19	0.00A	27.0	0 2022-	-06-12 1	6:43:13	CI	
3935333		2022-06-12 16:38:36.670	34.026	-117.261	16.68	16.05	1.25 Ml	CI	earthquake	L RT	5 RT6		11.00		0.69	0.91	1	2 21	0.00 A				6:43:16		
		2022-06-12 16:40:51.700						CI	earthquake	L RT	5 RT6		4.00		0.63	0.93	1	19 17	0.00 A	25.6	0 2022-	-06-12 1	6:45:25	CI	
		2022-06-12 17:08:06.050						CI	earthquake	L RT	S RT6		11.00		0.49		3		0.00A	25.4	0 2022-	-06-12 1	7:12:19	111	2
		2022-06-12 17:58:53.990						CI	earthquake						0.47										0
		2022-06-12 18:28:57.960						CI	earthquake				27.00			1.95			0.00A				8:33:34		
		2022-06-12 19:36:38.600						CI	earthquake				9.00			1.12			A 60.6				9:41:14		
3935344	2	2022-06-12 20:46:20.360	36.092	-117.698	1.33	-0.07	2.00 Ml	CI	earthquake	L RT	5 RTG	153.0	14.00	0.14	0.41	0.36	1	7 19	0.00A	30.5	0 2022-	-06-12 2	0:51:34	CI	

# Earthquake Catalog QC Tips: Check Parameters

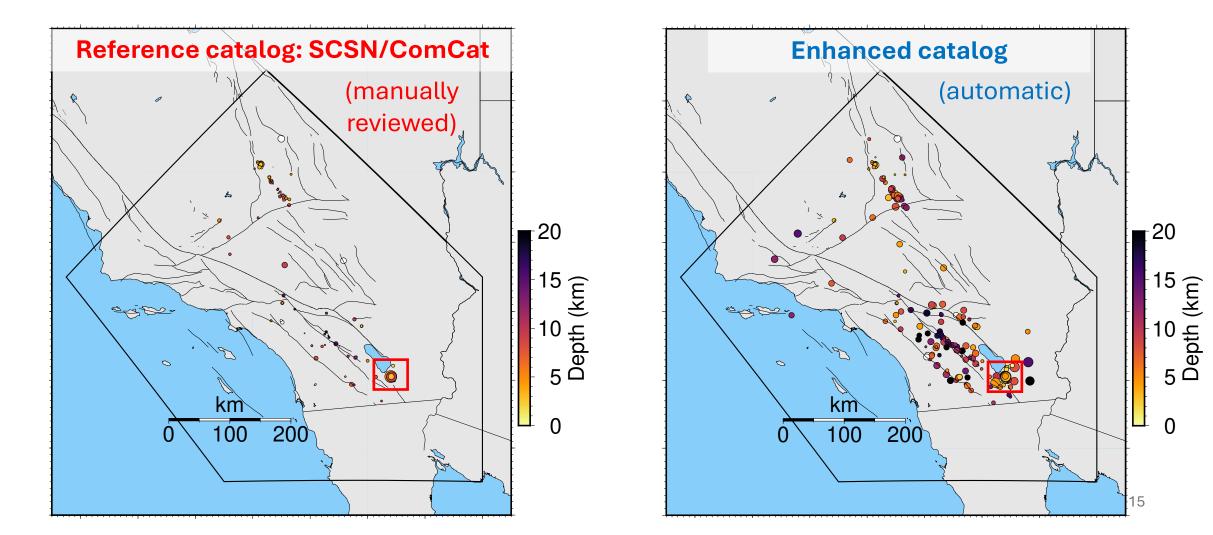
- Compare enhanced catalog with reference catalog on plots
  - Plot reference & enhanced catalogs side-by-side
  - Separate plots for MATCH, NEW, MISSED category events
- Visualize enhanced catalog  $\rightarrow$  are results reasonable for earthquakes?
  - Locations (epicenters) in map view
    - Are events near known seismogenic areas, past seismicity, faults? Known quarries?
  - Depth cross-sections
    - Are events at expected seismogenic depths (0-30 km, unless in subduction zone)?
  - Magnitude-frequency distribution
    - Do event magnitudes follow Gutenberg-Richter distribution (lots of small events)?
  - Magnitude vs. time, Seismicity rate (number of events vs. time)
    - If aftershock sequence, does number of events decrease as 1/time after mainshock (Omori decay)?

### Catalog QC, locations in map view: SCSN



2020-09-30 00:00:00 UTC to 2020-10-01 00:00:00 UTC (24 hours)

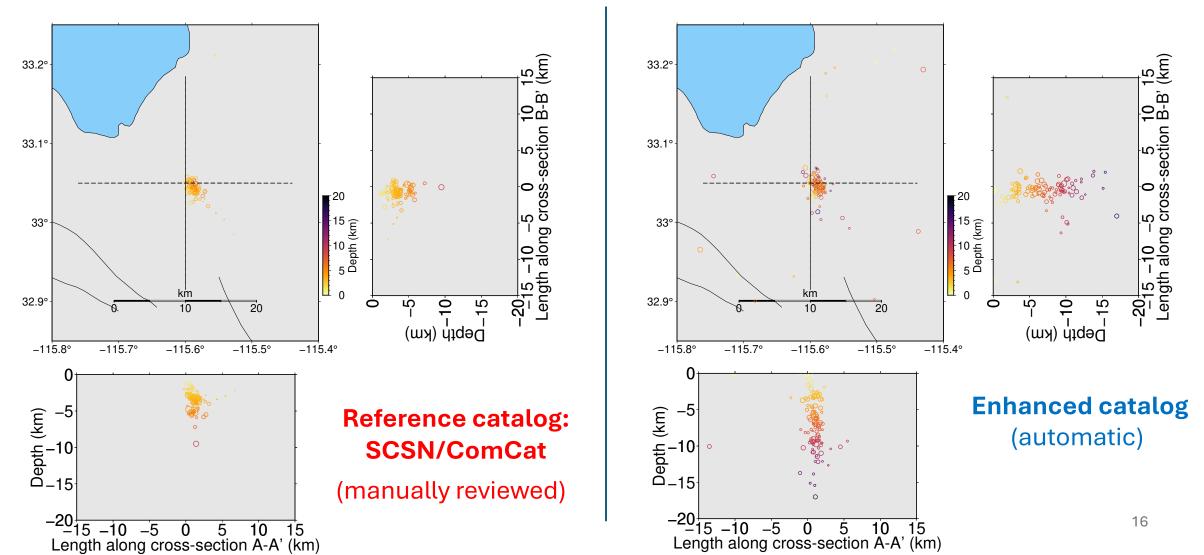
#### Enhanced catalog: events are on known faults with active seismicity



# Catalog QC, zoomed locations in map view & depth cross-section: SCSN

2020-09-30 00:00:00 UTC to 2020-10-01 00:00:00 UTC (24 hours)

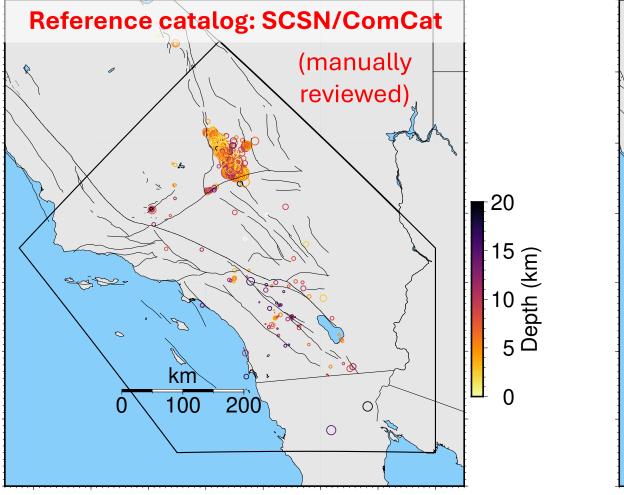
Enhanced catalog: Similar epicenters. Larger range of depths, but still reasonable

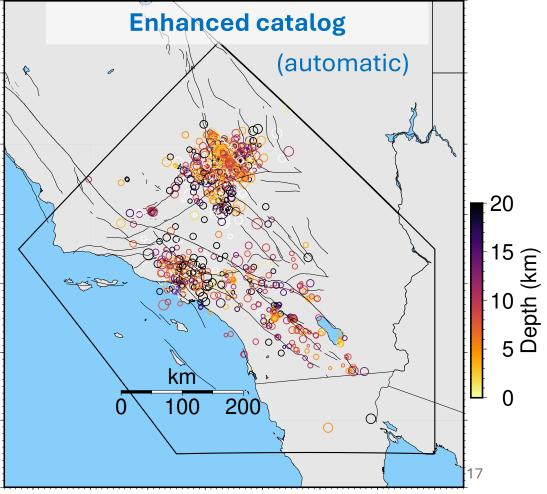


### Catalog QC, locations in map view: SCSN

2019-07-04 00:00:00 UTC to 2019-07-07 01:14:00 UTC (73 hours)

#### Ridgecrest first 3 days ( $M_w$ 6.4 & 7.1, aftershocks), enhanced catalog: association errors $\rightarrow$ false detections with bad locations/magnitudes





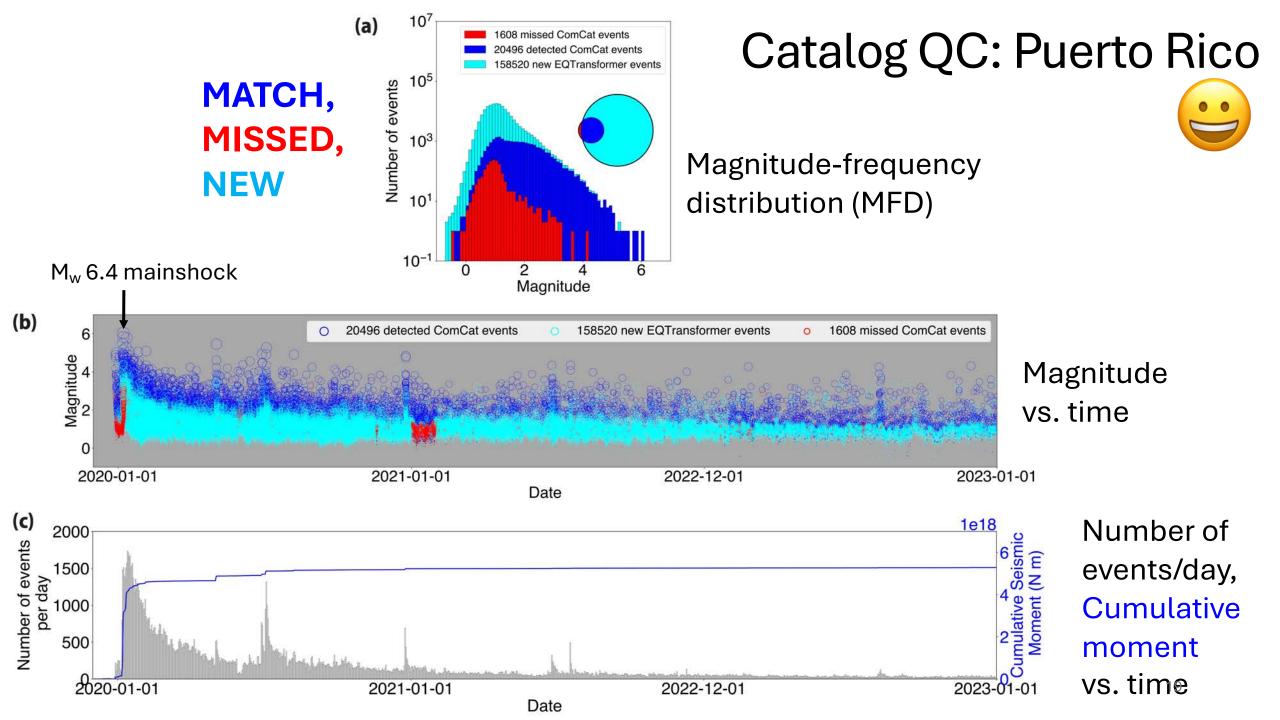
# Earthquake Catalog QC Tips: Check Parameters

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### • Visualize enhanced catalog $\rightarrow$ are results reasonable for earthquakes?

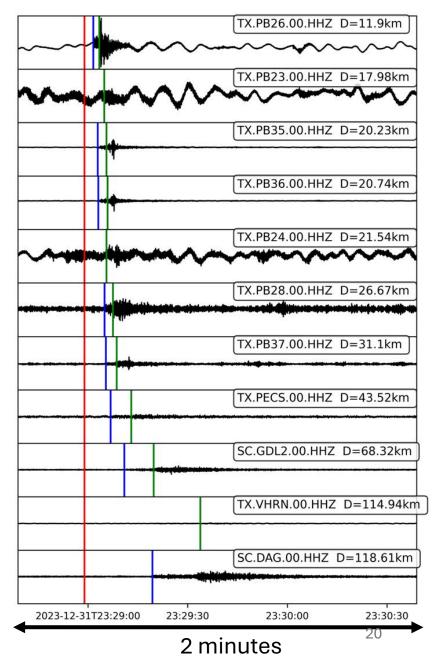
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  - If aftershock sequence, does number of events decrease as 1/time after mainshock (Omori decay)?



# Earthquake Catalog QC Tips: Check Waveforms

- When in doubt, **plot event waveforms** 
  - Overlay picks on event waveforms, ordered by event-station distance, especially for "NEW" events not in reference catalog
    - Earthquake or noise?
    - **Distance** from event to **nearest station**?
    - Frequency content & time duration local, regional, or teleseismic earthquake? Quarry blast?
    - **Moveout** (from P, S pick times) & **attenuation** (from amplitudes) with distance?
      - Do actual picks match predicted arrival times (from ray-tracing through velocity model)?

PyOcto Event #340 : 5/5/10 No Match to TexNet, Match to GaMMA, NSD<75.0 Red: Event, Blue: P Pick, Green: S Pick



### Check "NEW" events in enhanced catalog, not in reference catalog Sorted by magnitude (Southwest Puerto Rico)

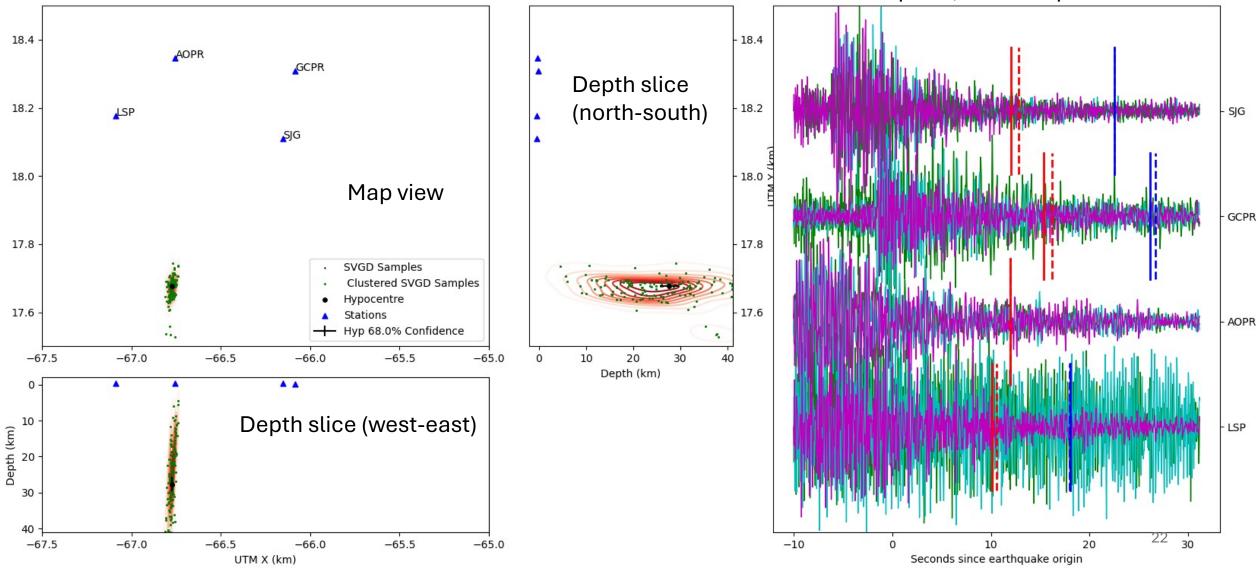
Origin time (UTC)	OT (seconds)	Latitude	Longitude	Depth	Magnitude	EventID
2020-01-07T08:35:15.030000	30915.030000	17.871833	-66.721667	6.420000	4.320000	1000335
2020-01-07T11:21:01.620000	40861.620000	18.034167	-66.800000	13.78000	0 4.360000	1000569
2020-01-07T08:29:18.320000	30558.320000	18.139667	-66.810000	7.660000	4.440000	1000328
2020-01-07T08:29:36.930000	30576.930000	17.963500	-66.752333	29.16000	0 4.480000	1000330
2020-01-07T08:51:09.400000	31869.400000	17.676333	-66.773667	27.61000	0 4.760000	1000356

#### Catalog QC: False detection in coda of larger earthquake (also, too deep?)

2020-01-07T08:51:09.400000 31869.400000 17.676333 -66.773667 **27.610000 4.760000** 10003

Earthquake 2020-01-07 08:51:09.396302640 +/- 0.50s Hyp=[-66.77,17.68,27.61] - Hyp Uncertainty (km) +/- [0.35,0.84,1.97]

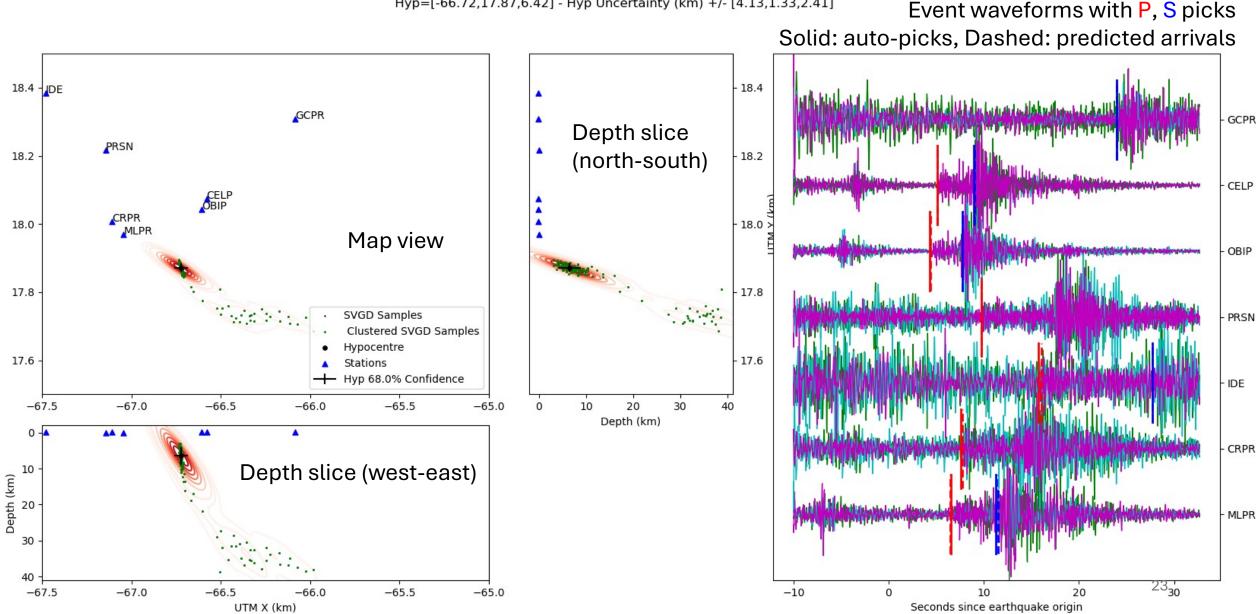
004.76000010003560s<br/>0.84,1.97]Event waveforms with P, S picks<br/>Solid: auto-picks, Dashed: predicted arrivals



#### Catalog QC: Real (newly detected) earthquake (reasonable depth)

2020-01-07T08:35:15.030000 30915.030000 17.871833 -66.721667 **6.420000 4.320000** 1000335

Earthquake 2020-01-07 08:35:15.029341138 +/- 0.05s Hyp=[-66.72,17.87,6.42] - Hyp Uncertainty (km) +/- [4.13,1.33,2.41]





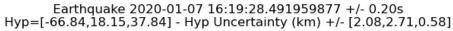
### Check "NEW" events in enhanced catalog, not in reference catalog Sorted by depth (Southwest Puerto Rico)

Origin time (UTC)	OT (seconds)	Latitude	Longitude	Depth	Magnitude	EventID
2020-01-07T16:19:28.490000	58768.490000	18.146667	-66.835500	37.84000	0 2.980000	1001012
2020-01-07T20:43:26.700000	74606.700000	17.933500	-66.923333	38.81000	0 1.570000	1001342
2020-01-07T15:58:52.370000	57532.370000	18.353667	-67.028000	39.16000	0 1.310000	1000980
2020-01-07T20:27:22.970000	73642.970000	17.931000	-66.846500	39.80000	0 1.560000	1001320
2020-01-07T22:21:53.870000	80513.870000	18.466000	-66.986833	40.58000	0 2.170000	1001466

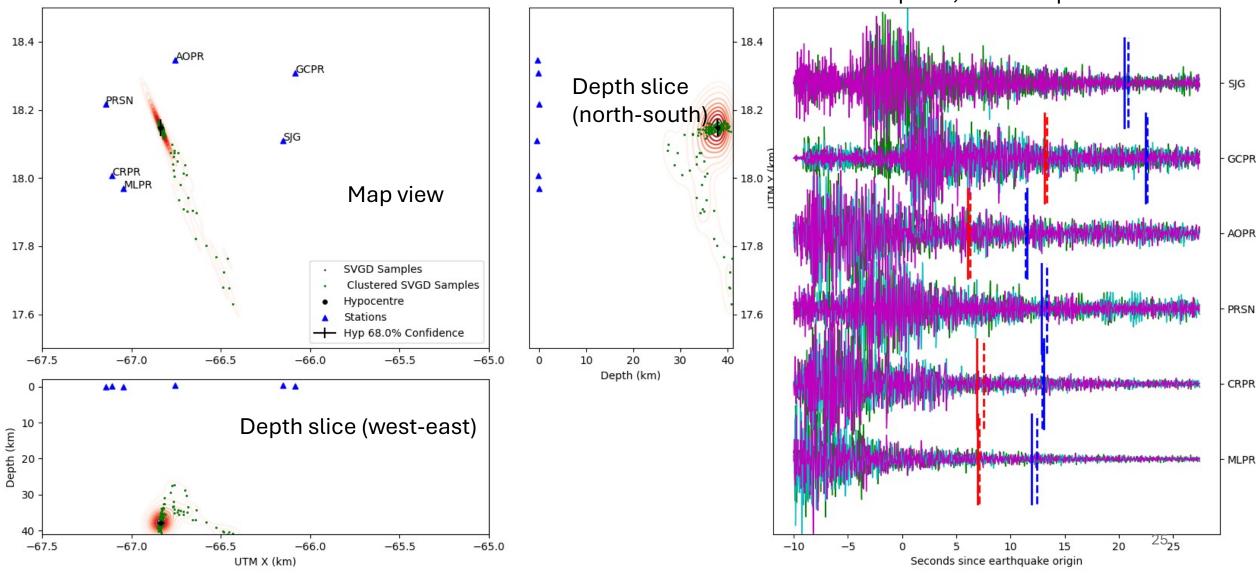
Unrealistic depths for the region? (SW Puerto Rico)

#### Catalog QC: False detection in coda of larger earthquake (also, too deep?)

2020-01-07T16:19:28.490000 58768.490000 18.146667 -66.835500 **37.840000 2.980000** 1001012



Event waveforms with P, S picks Solid: auto-picks, Dashed: predicted arrivals



# **Post-processing:** automatic removal of false detections in coda of larger earthquakes

- Visual detection of event waveforms with unrealistic depths (30-40 km): false detections in coda of larger earthquakes
  - EQTransformer (Mousavi et al., 2020) with low thresholds for event detection and P, S picks
- Devised an empirical algorithm to remove these specific false detections (Yoon et al., 2023, BSSA)
  - Apply only to NEW events not in reference catalog, not to MATCH events. Must meet ALL 4 criteria below for removal.
  - 1) current event was within 45 seconds of the previous event in time;
  - 2) current event had 14 or fewer phases;
  - 3) previous event had at least 5 more phases than the current event;
  - 4) current & previous events within 1 local magnitude unit of each other

PyOcto Event #90 : No Match to ComCat or GaMMA Red: Event, Blue: P Pick, Green: S Pick

- Catalog QC: West Texas
- After event association

- (Left) new local earthquake 🐸
- (Right) false detection 🐸
  - o large distance (307 km) to nearest station; IM network?

2-minute waveforms Vertical lines: Origin time, P, S

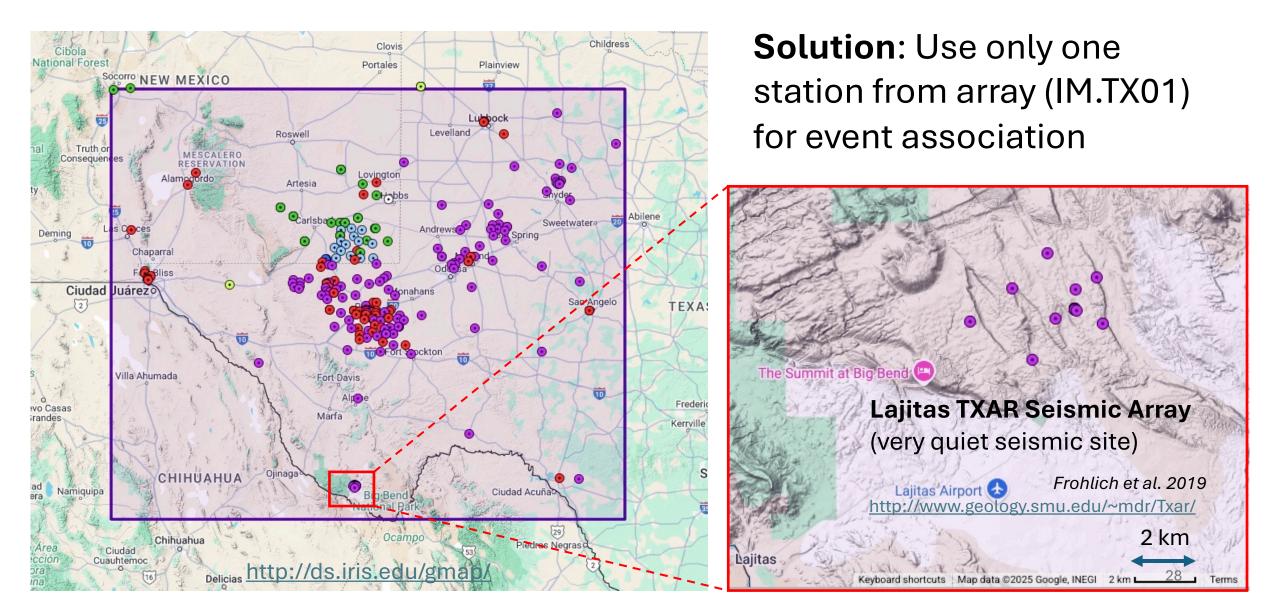
27

	TX.PB05.00.HHZ D=307.73k
	TX.PB23.00.HHZ D=377.52k
$\sim$	
	TX.PB26.00.HHZ D=381.65k
	IM.TX09SHZ D=400.91km
and and an	~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
	IM.TX02SHZ D=401.56km
~~~~~	
	IM.TX04SHZ D=401.71km
~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~	multilles an man with the sources
	IM.TX08SHZ D=401.83km
~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~	
	IM.TX31BHZ D=402.08km
A MARANA CONTRACTOR	
	[IM.TX01SHZ D=402.1km]
	IM.TX03SHZ D=402.79km
	IM.TX07SHZ D=403.44km
	IM.TX06SHZ D=404.16km
	A CONTRACTOR OF A CONTRACTOR O
1706	IM.TX10SHZ D=405.21km
B-12-31T10:25:00 10:25:30	10:26:00 10:26:

PyOcto Event #82 : No Match to ComCat or GaMMA Red: Event, Blue: P Pick, Green: S Pick

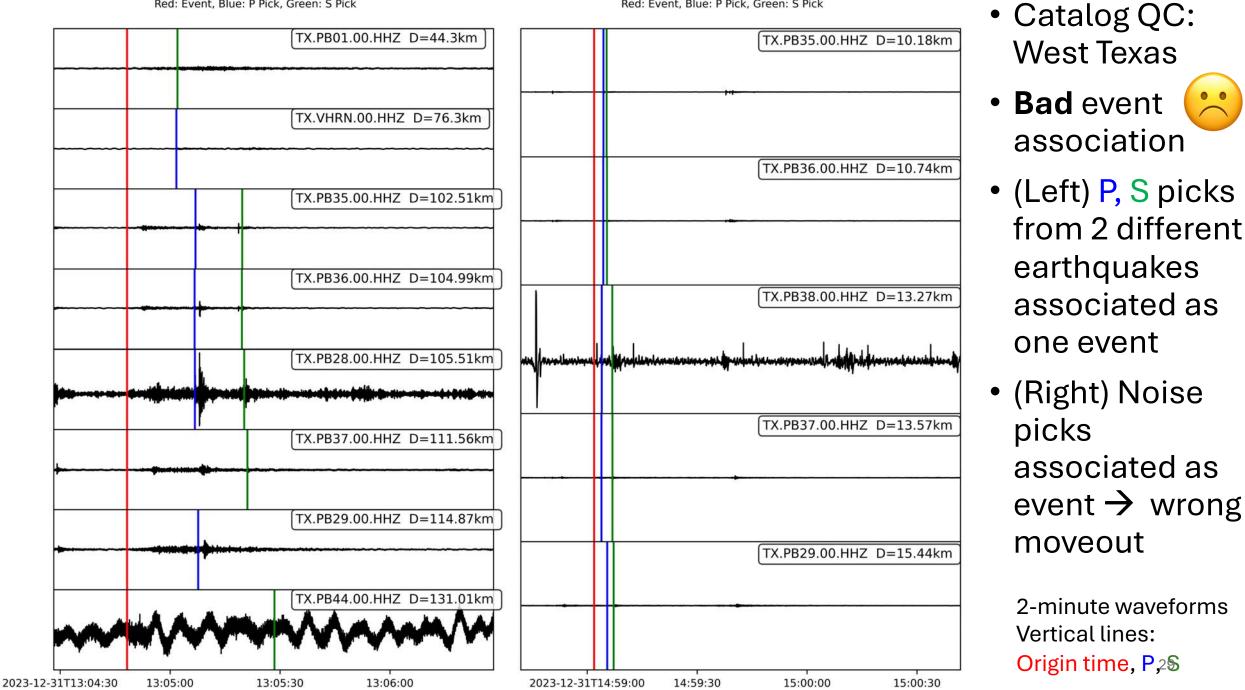
N			
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**Problem:** Incorrect association/location due to **uneven station distribution** (array far from rest of network & seismic sources)

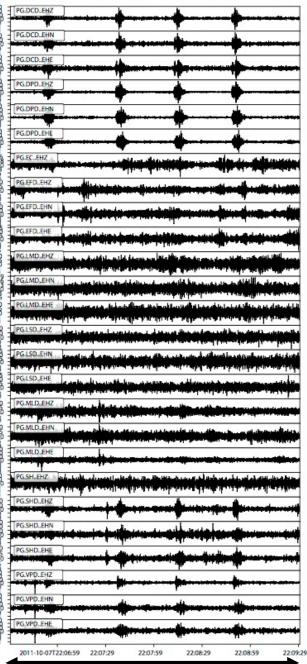


PyOcto Event #218 : 5/5/10 No Match to TexNet, Match to GaMMA, NSD<75.0 Red: Event, Blue: P Pick, Green: S Pick

PyOcto Event #250 : 5/5/10 No Match to TexNet, Match to GaMMA, NSD<75.0 Red: Event, Blue: P Pick, Green: S Pick



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- Catalog QC: Central CA
- Filtered 3-12 Hz
- Non-earthquake signals: active-source survey



Yoon et al. (2019), BSSA

3 minutes

#### Deep teleseismic earthquakes (depth 600+ km) recorded in Central CA



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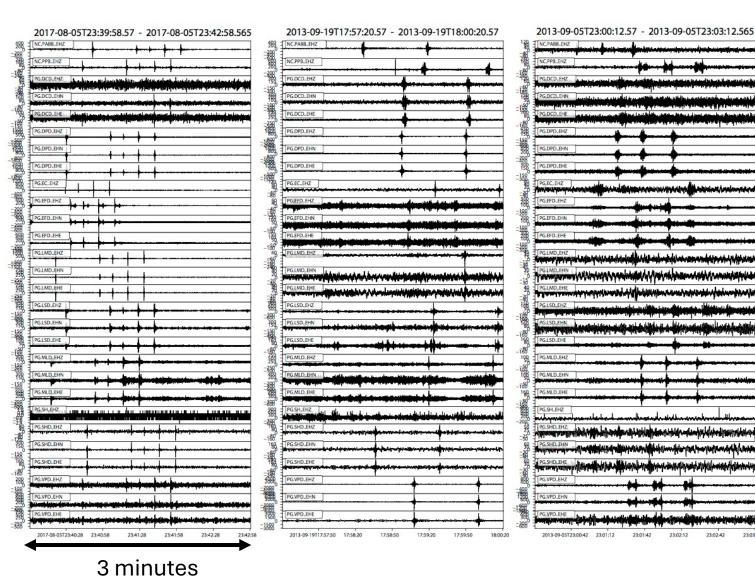
Very little moveout (waves hit all stations at same time)

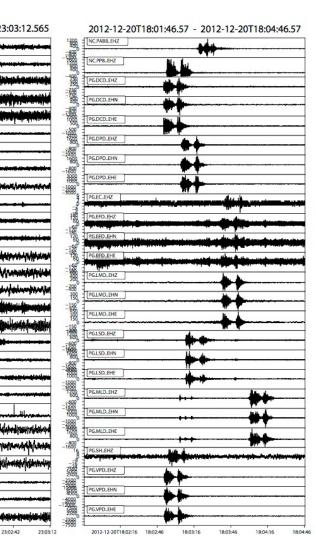
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Yoon et al. (2019), BSSA



#### Infrasound signals recorded in Central CA



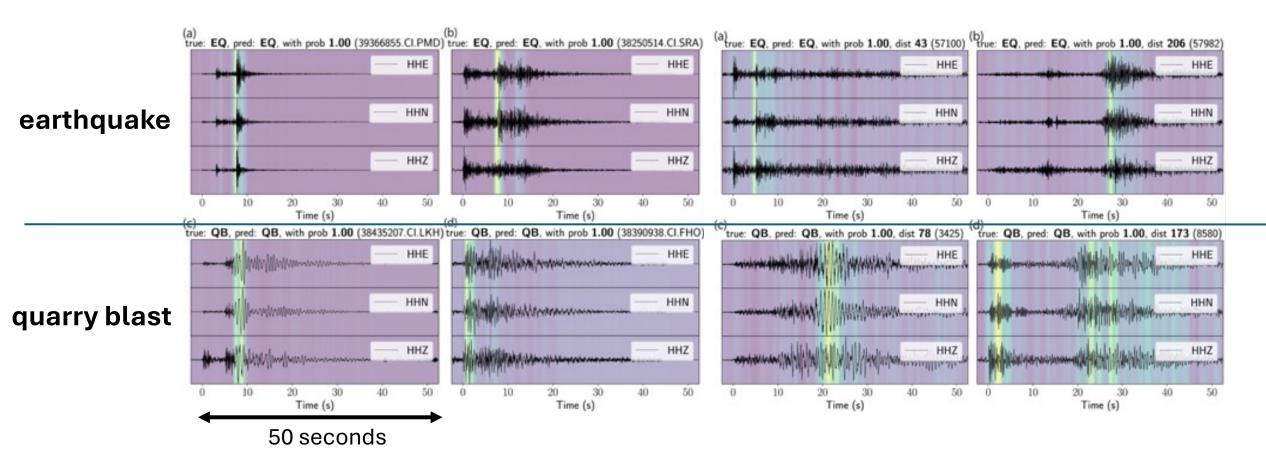


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Slower moveout from sound waves

Yoon et al. (2019), BSSA

# **Quarry blasts**: often in enhanced catalogs, but not 'interesting' to many seismologists Check ComCat for blast events



Check waveform plots: lower frequency content?

Events located near known quarry?

Events occur only in local daytime?

Figures: Zhu et al. (2024), GJI

Automated post-processing strategies to remove false detections & unwanted signals from catalog

[Machine-learning] classifiers: discriminate different seismic signals

- Teleseismic earthquakes, quarry blasts, cultural noise sources, infrasound, ...
- Assemble training data set, create classifier model

Empirical algorithms: remove specific false detections after visual inspection

- e.g. false detections in coda of larger earthquakes
- may be specific to network geometry & source distribution

Simple thresholding & filtering to discard non-earthquake signals

• easy & effective, but be aware of tradeoffs

## Simple thresholding & filtering to discard non-earthquake signals

- easy & effective, but be aware of tradeoffs

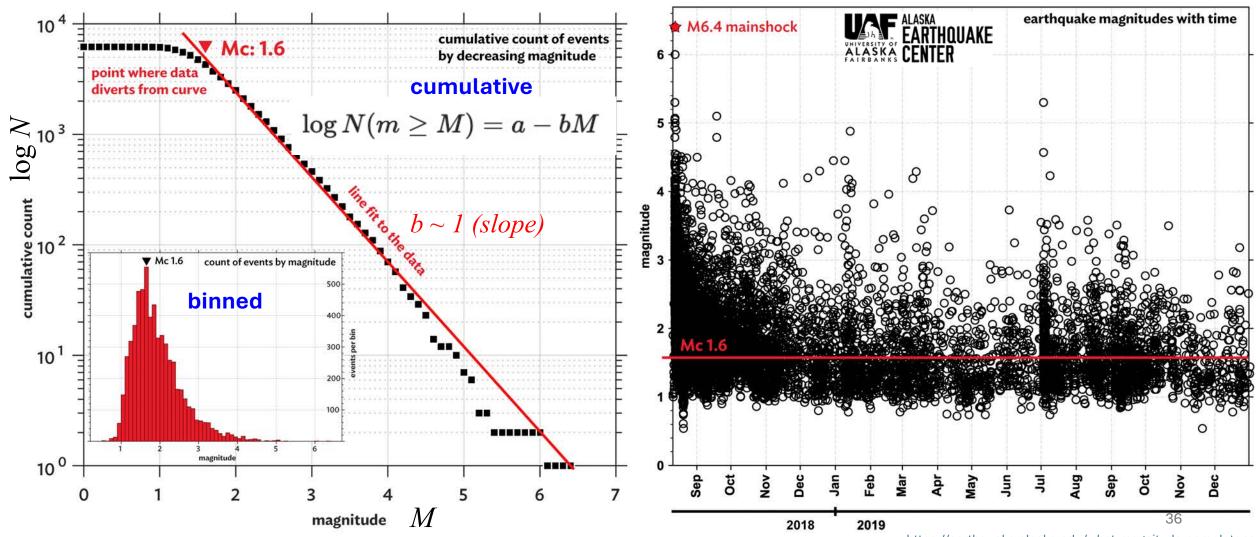
- Restrict locations to a certain region and/or depth range
- Set minimum threshold on:
  - Number of (P, S) picks
  - $\odot$  Number of stations per event
  - $\odot$  Output probabilities for P, S picks
- Set maximum bound on:
  - $\odot$  Distance to nearest station
  - **O** Distance to farthest contributing station with picks
  - o Azimuthal gap
  - $\circ$  RMS residual
  - Travel time residual for P, S pick at given station

### Magnitude of Completeness (Mc)

#### Magnitude-frequency distribution (MFD) (Gutenberg-Richter)

Mc: lowest magnitude above which the earthquake catalog is "complete"

#### Lower Mc is better (more complete)



https://earthquake.alaska.edu/what-magnitude-completeness

## Many different methods to get catalog Mc

Maximum Curvature (MAXC): max value of 1<sup>st</sup> derivative of MFD (typically, max of binned MFD)
 \* most reliable for small sample sizes (~50-100 events)

\* works best with local datasets with fewer heterogeneities

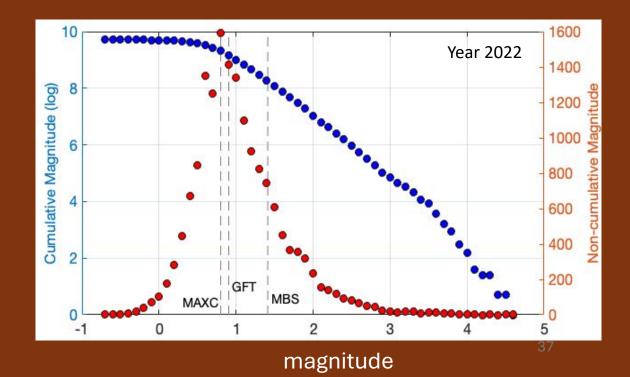
- Goodness-of-fit Test (GFT): lowest magnitude cut-off where Gutenberg-Richter relation holds

Mc by b-value Stability (MBS): first magnitude increment where |b<sub>avg</sub> - b| < uncertainty of b</li>
 \* tends to produce the highest (i.e., most conservative) Mc

\* More info and original R codes from CORSSA: <u>https://corssa.org/</u> <u>https://doi.org/10.5078/corssa-39071657</u>

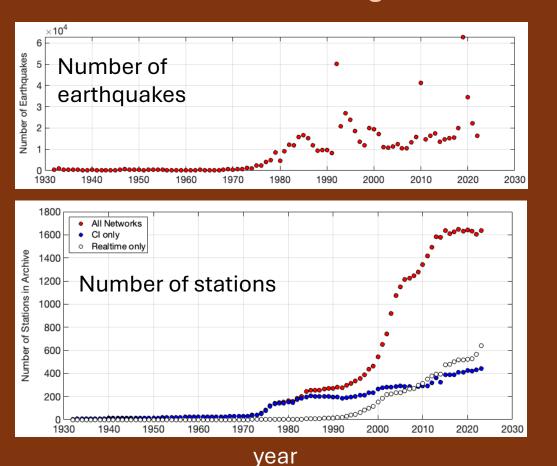
\* Matlab codes available on Github: https://github.com/gtepp/research\_codes

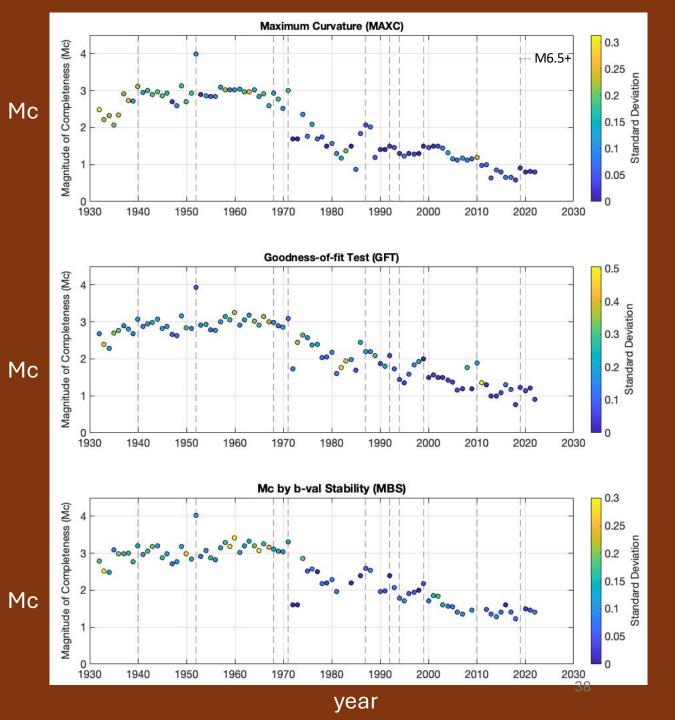
\* Other methods to get Mc: ZMAP (Wiemer, 2001) b+ positive (van der Elst, 2021)



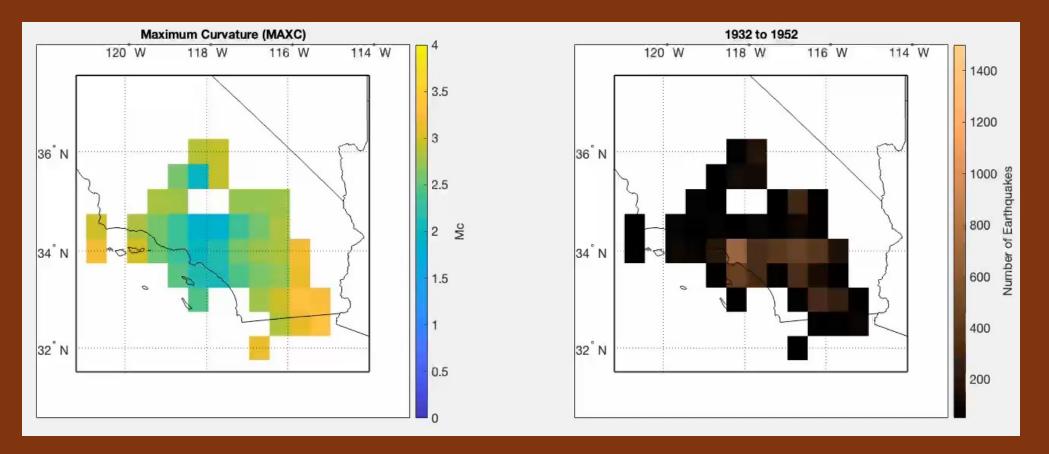
# Temporal Mc changes

Past 90 years: SCSN Mc has decreased from ~3 to ~1 Full SCSN Catalog



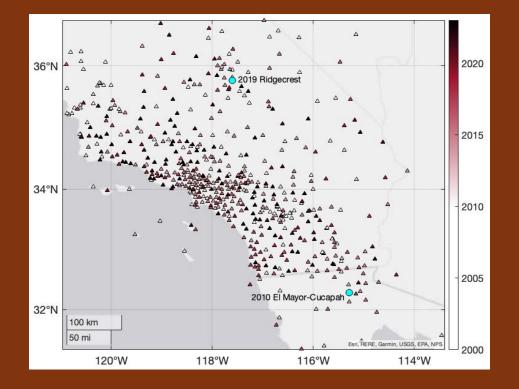


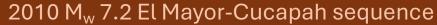
# Spatial Mc Changes

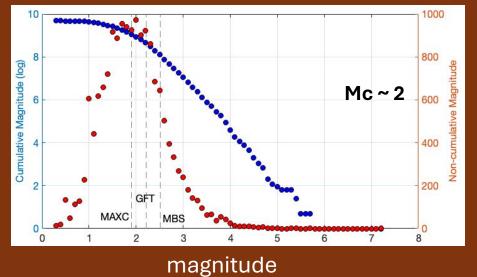


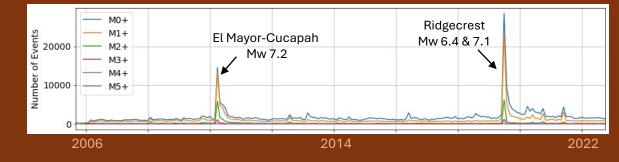
- Bins: 0.5° (~50 km) squares
- 1932-1972: 20 years
- 1973-2022: 10 years
- Maximum curvature method
- Minimum 30 EQs/bin

Past 90 years: SCSN Mc has decreased from ~3 to ~1, but not uniformly throughout the region





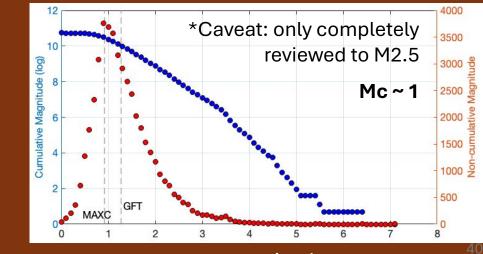




Expect higher Mc earlier in aftershock sequence

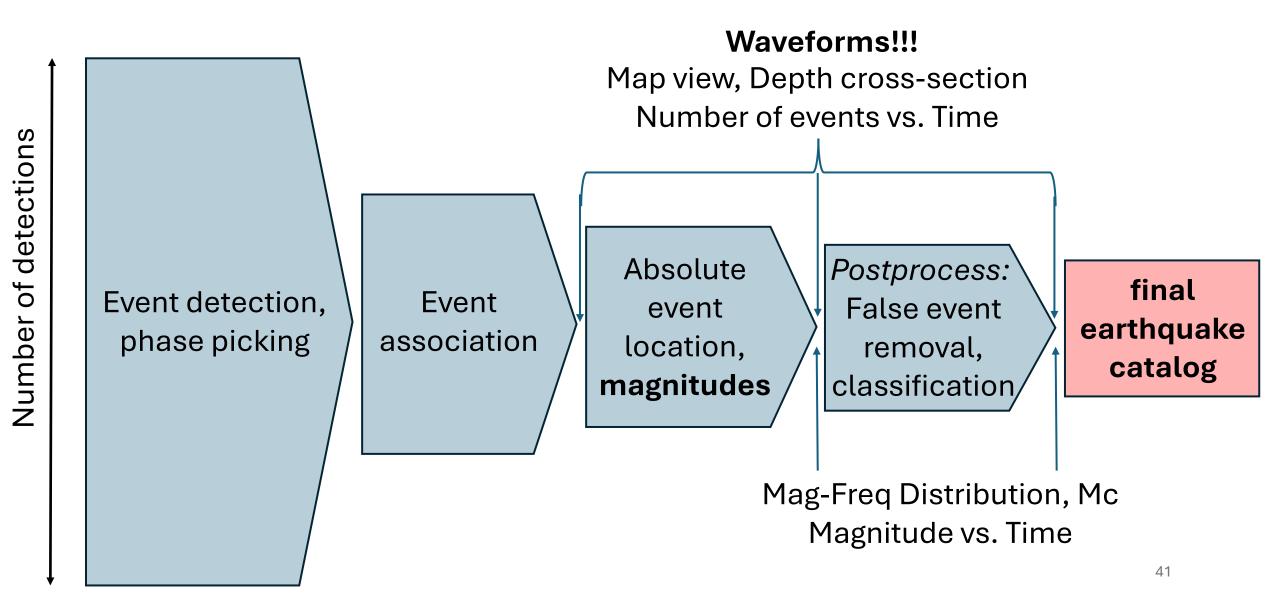
Ridgecrest Mc is ~1 mag. unit lower than El Mayor-Cucapah Mc





magnitude

## Catalog QC: Summary of things to check in plots Compare against a reference catalog!



# Extra slides

# Earthquake Catalog QC General Tips

- Make plots think like an analyst use visual tools. Waveforms!
- Use seismology domain expertise
  - If enhanced catalog events don't look like real earthquakes, figure out why.
- Rule out all sources of noise (background or cultural). Be sure it's not an artifact.
- Check it's not a regional/teleseismic earthquake.
- Check it's not a quarry blast, sonic boom, infrasound, active-source explosion, or other unwanted seismic signal.
- Only then have you discovered new earthquakes.

# Reference Catalog: How to download?

- For bulk downloads of catalog events from ComCat
  - ComCat search API: <u>https://earthquake.usgs.gov/fdsnws/event/1/</u>
    - (I create the URL string, then call wget with a bash script)
  - Python libcomcat: <a href="https://code.usgs.gov/ghsc/esi/libcomcat-python">https://code.usgs.gov/ghsc/esi/libcomcat-python</a>
  - ObsPy get\_events() with USGS Client (I save QuakeML files with picks): <u>https://docs.obspy.org/packages/obspy.clients.fdsn.html</u>
- For ANSS networks, all finalized local events are sent to ComCat. Can also download reference catalog from regional seismic network, which may contain extra events.
  - SCSN: Quarry blasts, teleseismic/regional events.
    - <u>https://scedc.caltech.edu/</u>
  - NCSN: Extra events not all events are submitted to ComCat; catalogs available in other formats.
    - <u>https://www.ncedc.org/ncedc/catalog-search.html</u>

# Alternative (non-authoritative) reference catalogs

- Regional seismic network websites (for ANSS networks) also have alternative (non-authoritative) earthquake catalogs and data sets for download, to use as reference catalogs
  - SCSN: template-matching, relocated, deep-learning, focal-mechanism, <u>https://scedc.caltech.edu/eq-catalogs/altcatalogs.html</u>, <u>https://scedc.caltech.edu/data/deeplearning.html</u>
  - NCSN: real-time double-difference. https://www.ncedc.org/ncedc/catalog-search.html

# MATCH events: location, magnitude comparison

- Compare enhanced vs. reference catalog
  - Location (latitude, longitude, depth, origin-time)
  - Magnitude
  - Distribution of residuals (ideally zero) are they low enough for you?
- It's difficult to exactly reproduce locations & magnitudes from ComCat (or other reference catalog)
  - Differences in monitoring software, velocity model, manual pick times/weights, filtering before amplitudes, ...
  - Just check that these values are close enough for your needs.

# Reference Catalog Tip: Select boundaries carefully

- Carefully select the bounding box or circular radius for downloading your reference catalog, before comparing it to enhanced catalog. It should include:
  - Entire seismogenic region of interest to you
    - Check past seismicity locations on web map: <a href="http://ds.iris.edu/ieb/">http://ds.iris.edu/ieb/</a> or <a href="https://earthquake.usgs.gov/earthquakes/map/">https://earthquake.usgs.gov/earthquakes/map/</a>
  - All seismic stations you plan to use for catalog generation
    - Check station locations and availability on web map: <u>http://ds.iris.edu/gmap/</u> or <u>https://www.fdsn.org/networks/</u>
- NEW events in your enhanced catalog might be from reference catalog events outside your selected bounding region
  - Check waveforms: could be a regional distance earthquake if higher duration and amplitude

## Catalog QC, locations in map view: TexNet



Many scattered event locations – possible false detections?

## Enhanced catalog: 2023-12-31 (1 day) GaMMA associator (3 P, 3 S, 6 total picks)

#### $\nabla$ $\nabla \nabla$ 33° -15 $\nabla$ $\nabla$ 5 Earthquake Depth (km) 32° 31° 3 $\nabla$ v 💑 km km 30° <sup>·</sup> 200 200 400 400 0 0 0 $\nabla$ $\nabla$ 48 29° · \_\_\_\_\_0° +\_\_\_\_ \_\_100'07° -103° –107° -106° -105° -104° -102° -101° -106° -104° -103° -102° -101° -105° -100°

## Reference catalog: TexNet (2015-2024: 9 years)

## Catalog QC, locations in map view: TexNet

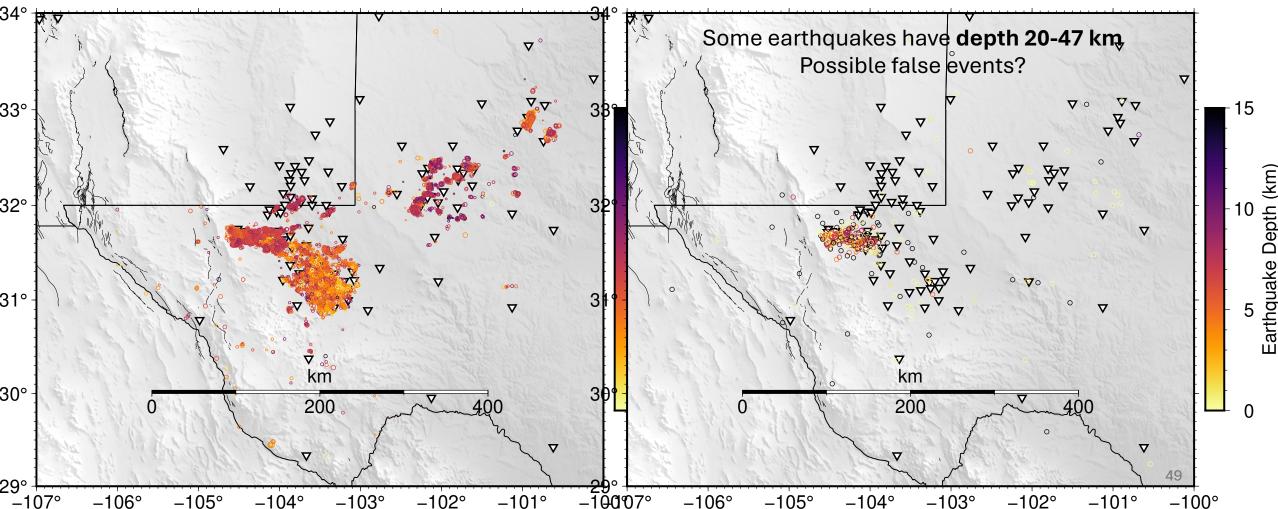
**Reference catalog:** 

TexNet (2015-2024: 9 years)



Removed false detections (fewer scattered events) with stricter association criteria

## Enhanced catalog: 2023-12-31 (1 day) GaMMA associator (4 P, 4 S, 8 total picks)



## Catalog QC: 2020 M2.8 earthquake, southwest Puerto Rico



Earthquake 2020-01-07 05:59:47.516874763 +/- 0.16s Hyp=[-66.85,17.90,6.72] - Hyp Uncertainty (km) +/- [1.99,2.48,2.14] Event waveforms with P, S picks Solid: auto-picks, Dashed: predicted arrivals AGPROBPR EMPR HUMP 18.4 - DE 18.4 AOPR ROPR ECPR SJG GCPR Depth slice GCPR PRSN 18.2 18.2 (north-south) LSP HUMP OBIP SJG OBIP CELP CRPR 18.0 18.0 MLPR GBPR ECPR Map view EMPR AOPR 17.8 17.8 SVGD Samples QBPR **Clustered SVGD Samples** GBPR Hypocentre 17.6 17.6 Stations AGPR Hyp 68.0% Confidence -67.0 -65.5 20 -67.5-66.5-65.010 30 LSP -66.00 40 Depth (km) 0 -ROPR PRSN Depth slice (west-east) 10 Depth (km) 0500 IDE CRPR 30 MLPR 40 3050 -67.5-66.5 -65.5 -1020 -67.0-66.0-65.00 10 UTM X (km) Seconds since earthquake origin

### Catalog QC: False detection in coda of larger earthquake (also, too deep?) 2020-01-07T08:29:36.930000 30576.930000 17.963500 -66.752333 **29.160000 4.480000** 1000330

-67.5

-67.0

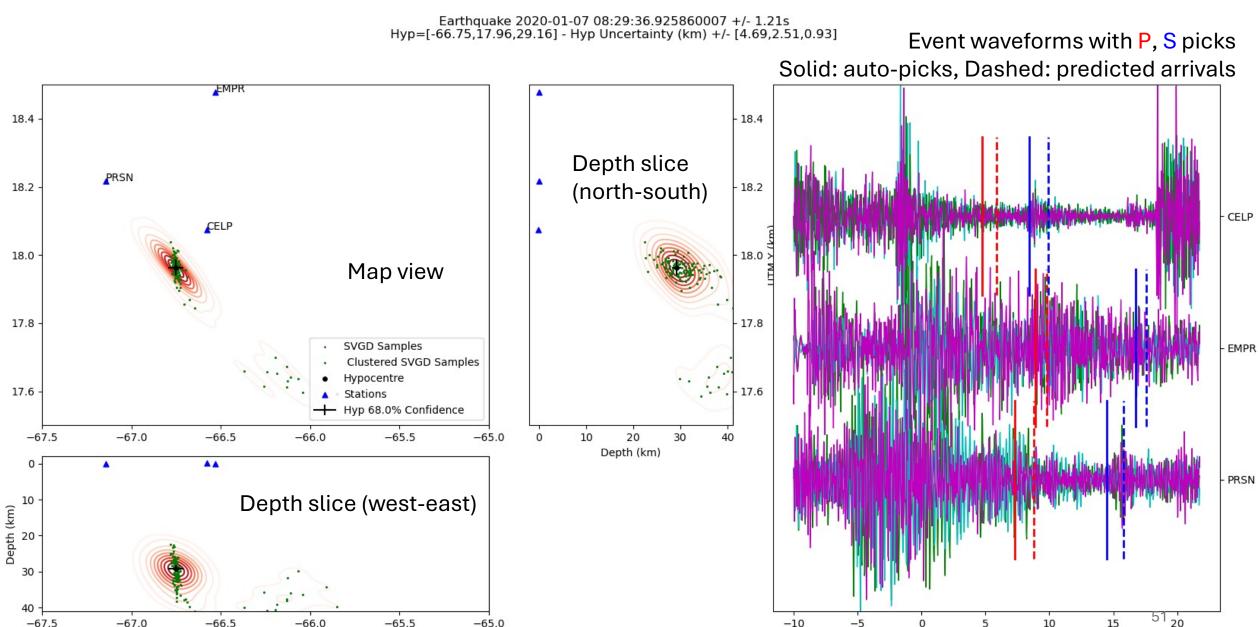
-66.5

UTM X (km)

-66.0

-65.5

-65.0



-10

-5

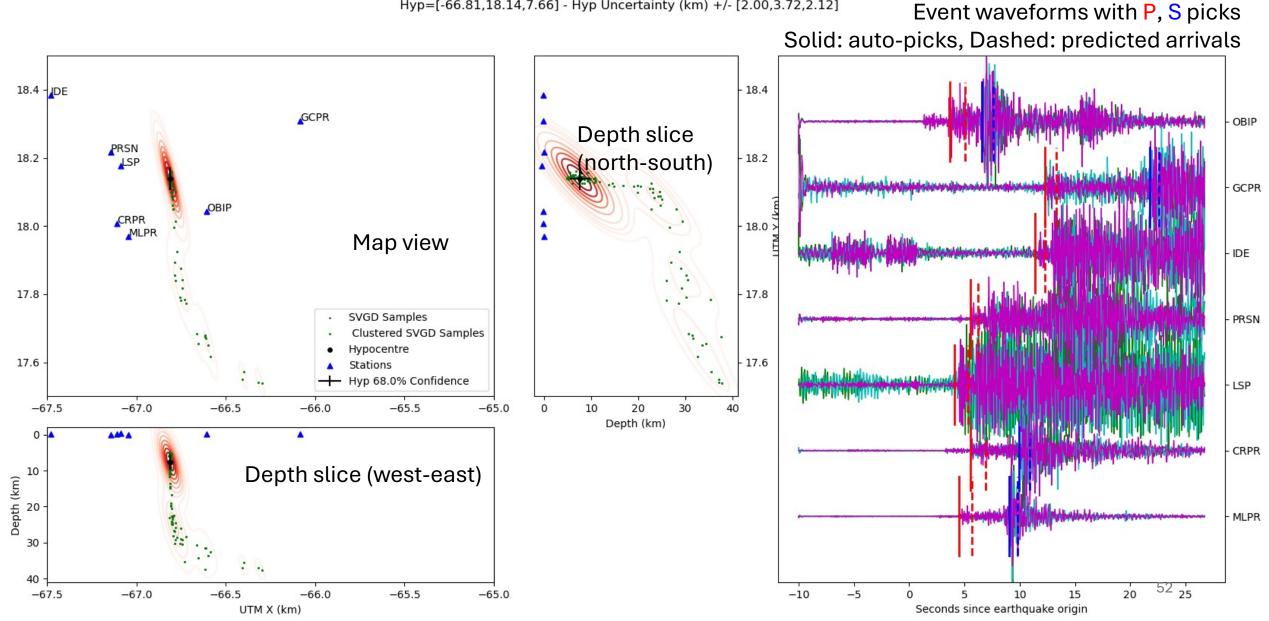
15

10

Seconds since earthquake origin

### Catalog QC: Real (newly detected) earthquake 2020-01-07T08:29:18.320000 30558.320000 18.139667 -66.810000 7.660000 4.440000 1000328

Earthquake 2020-01-07 08:29:18.318609738 +/- 1.01s Hyp=[-66.81,18.14,7.66] - Hyp Uncertainty (km) +/- [2.00,3.72,2.12]



### Catalog QC: False detection in coda of larger earthquake (also, too deep?) 2020-01-07T22:21:53.870000 80513.870000 18.466000 -66.986833 40.580000 2.170000 1001466

-67.5

-67.0

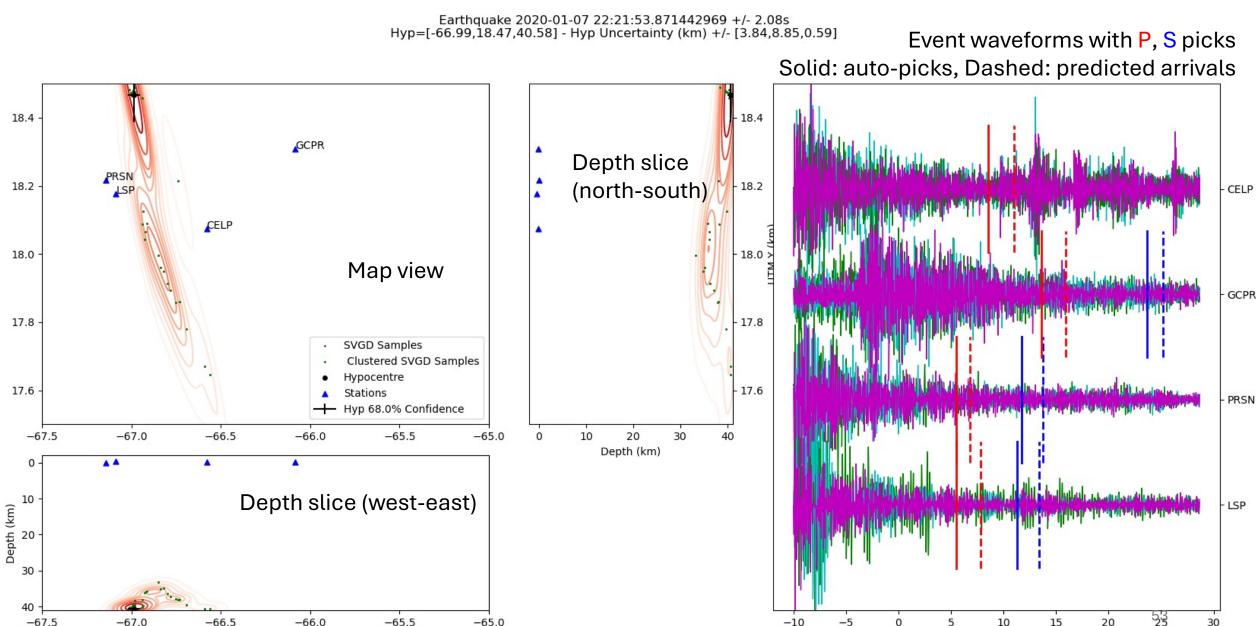
-66.5

UTM X (km)

-66.0

-65.5

-65.0



-10

-5

20 15 Seconds since earthquake origin

30

10

### Catalog QC: False detection in coda of larger earthquake (also, too deep?) 2020-01-07T20:27:22.970000 73642.970000 17.931000 -66.846500 **39.800000 1.560000** 1001320

-67.0

-67.5

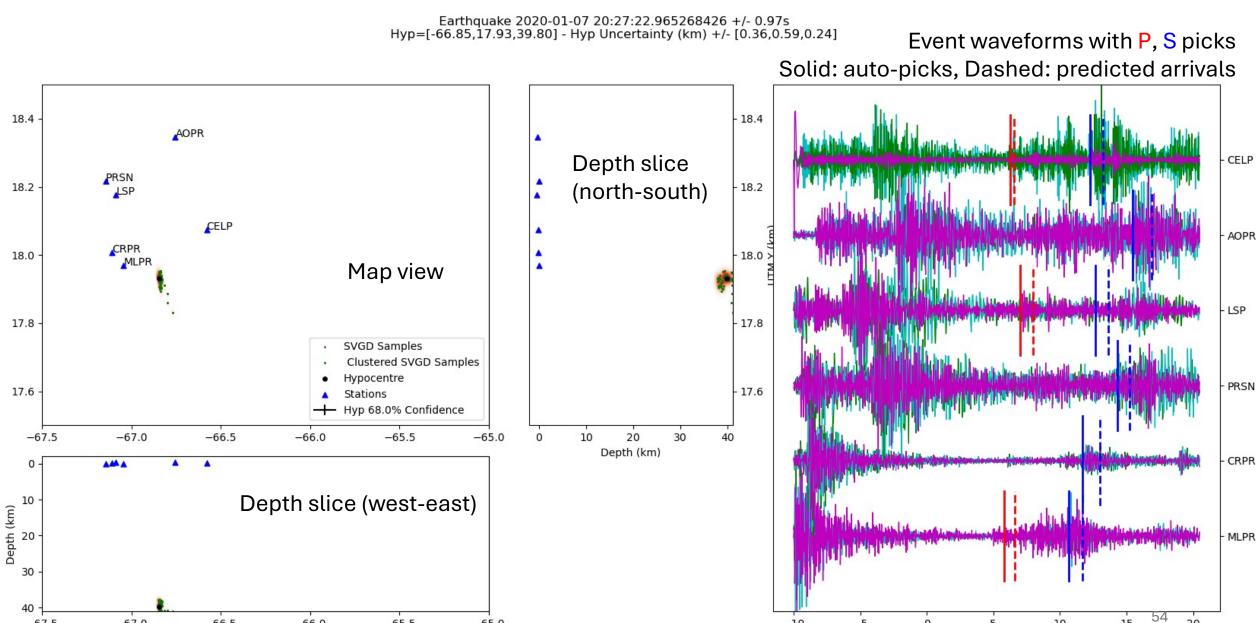
-66.5

UTM X (km)

-66.0

-65.5

-65.0



-10

-5

0

10

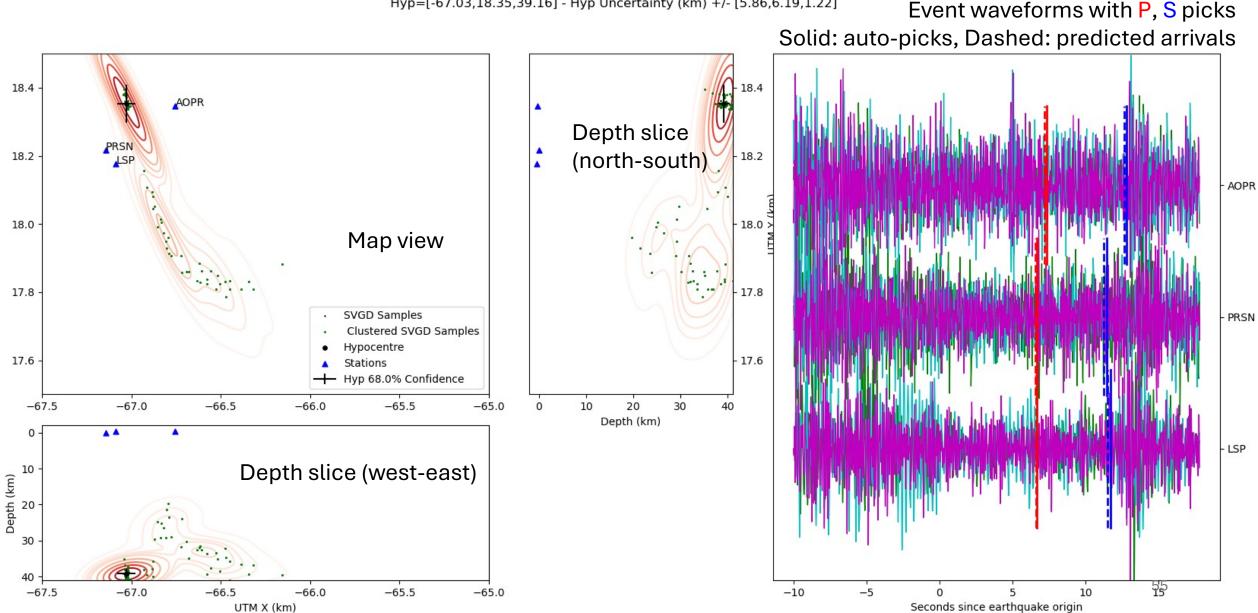
Seconds since earthquake origin

15

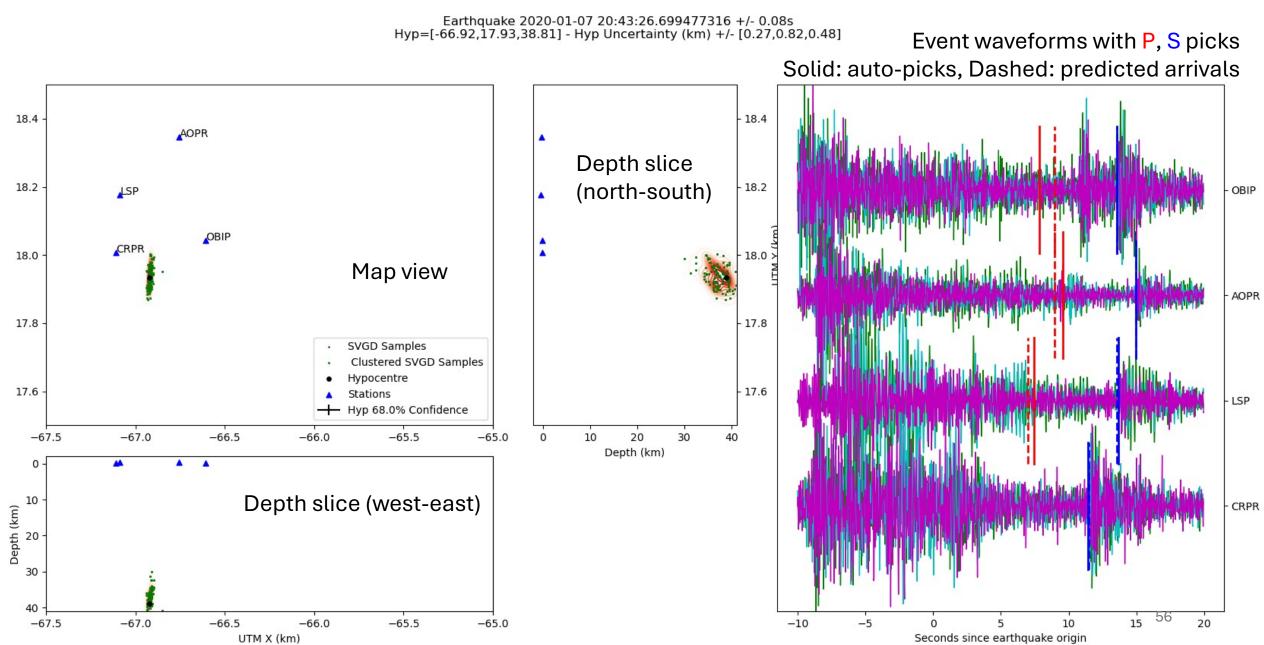
20

### Catalog QC: False detection in noise (also, too deep?) 2020-01-07T15:58:52.370000 57532.370000 18.353667 -67.028000 **39.160000 1.310000** 1000980

Earthquake 2020-01-07 15:58:52.367385814 +/- 0.17s Hyp=[-67.03,18.35,39.16] - Hyp Uncertainty (km) +/- [5.86,6.19,1.22]



# Catalog QC: False detection in coda of larger earthquake (also, too deep?) 2020-01-07T20:43:26.700000 74606.700000 17.933500 -66.923333 **38.810000 1.570000** 1001342



PyOcto Event #83 : 6/6/12 No Match to IRIS or GaMMA Red: Event, Blue: P Pick, Green: S Pick

- Catalog QC: West Texas
- Bad event associations – dominated by array
- Notice large distance to nearest station

2-minute waveforms

Vertical lines: Origin time, P, S

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				(IM.TX10SHZ D=	72.35km
m With	-MM			MMMMMM	MMMM
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ä			1	IM.TX03SHZ D=	74.42km
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		2		IM.TX08SHZ D=	74.51km
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				[IM.TX04SHZ D=	75.04km
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			Ι.	[IM.TX09SHZ D=	75.6km
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				TX.PECS.00.HHZ	D=243.0
		مبمب	~~~~~		****
2023-12-3	31T06:5	3:00	06:58:30	06:59:00	06:59

PyOcto Event #79 : 6/6/12 No Match to IRIS or GaMMA Red: Event, Blue: P Pick, Green: S Pick

	TX.PECS.00.HHZ D=190.76k
	TX.MB02.00.HHZ D=321.99
	IM.TX08SHZ D=407.85km
	IM.TX07SHZ D=408.67km
	IM.TX09SHZ D=409.04km
www.www.www.www.www.www.www.www.www.www.www.www.www.www.www.www.www.www.www.www.www.www.www.www.www.www.www.ww	
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	IM.TX03SHZ D=410.01km
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www.www.	IM.TX02SHZ D=410.58km
	[IM.TX06SHZ D=411.15km
www.www.www.www.www.www.www.www.www.ww	
23-12-31T06:30:00 06:30:3	30 06:31:00 06:31:30

PyOcto Event #213 : 5/5/10 No Match to TexNet, Match to GaMMA, NSD<75.0 Red: Event, Blue: P Pick, Green: S Pick

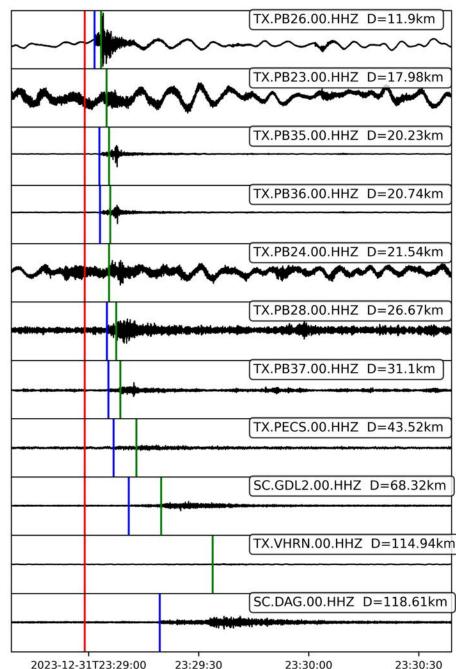
- Catalog QC: West Texas
- **Good** event association examples
- P, S picks on earthquake signals with expected moveout

2-minute waveforms

Vertical lines: Origin time, P, S

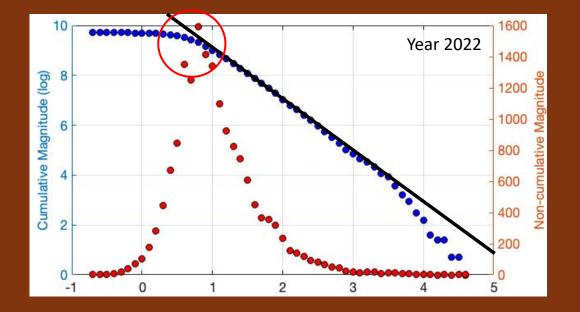
1215/20				
(m			TX.PB25.00.HHZ	D=12.77km
$\sim$				
3km			TX.PB26.00.HHZ	D=13.09km
				D 16 10km
~			TX.PB20.00.HHZ	D=16.18km
3km			TX.PB24.00.HHZ	D = 16.55 km
			17.1 024.00.1112	B=10.55km
1km			TX.PB23.00.HHZ	D=19.28km
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			TX.PB34.00.HHZ	D=20.87km
1km		17112-96-14128 9-2-1 9 tour altrain		
$\sim$			TX.PB31.00.HHZ	D=26.39km
/km				
			TX.PB35.00.HHZ	D=37.96km
			TX.PB36.00.HHZ	D 20 C21/m
(m			ТХ.РВ30.00.ПН2	D=38.02Km
			TX.PB28.00.HHZ	D = 44.26  km
2km				
			NX.WTX35HHZ	D=44.34km
2km			TX.PB37.00.HHZ	D=48.86km
94km			TX.PB29.00.HHZ	D=49.61km
			SC.GDL2.00.HHZ	D=80.97km
1km		-		122 72/102
			SC.DAG.00.HHZ D	0=152.72KM
0:30	2023-12-31T12:49:00	12:49:30	12:50:00	12:50:30

PyOcto Event #340 : 5/5/10 No Match to TexNet, Match to GaMMA, NSD<75.0 Red: Event, Blue: P Pick, Green: S Pick



## Magnitude of Completeness

- lowest magnitude at which the catalog is "complete" (based on Gutenberg-Richter relation)
- examine frequency-magnitude distribution obtained by binning earthquake magnitudes
- one approach for evaluating the quality of a catalog



### Can consider:

- temporal changes of Mc
- spatial variations of Mc across region

\* More info and original R codes from CORSSA: <u>doi:10.5078/corssa-0018080</u>

\* Matlab codes available on Github: https://github.com/gtepp/research\_codes

59

### Calculated with different methods, including

- Maximum Curvature: max value of 1<sup>st</sup> derivative of FMD (typically, max bin of non-cum FMD)
  - \* most reliable for small sample sizes (<~50-100 events)
  - \* works best with local datasets with fewer heterogeneities

- Goodness-of-fit Test: lowest magnitude cut-off where Gutenberg-Richter relation holds

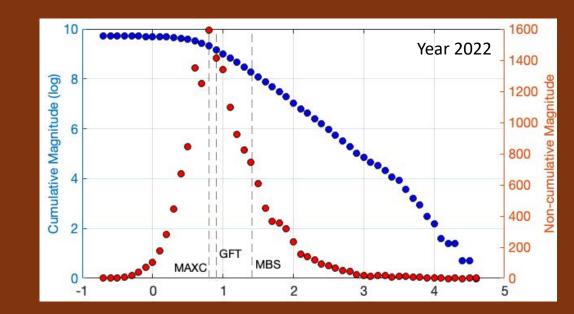
Mc by b-value Stability: first magnitude increment where |b<sub>avg</sub> - b| < uncertainty of b</li>
 \* tends to produce the highest (i.e., most conservative) Mc

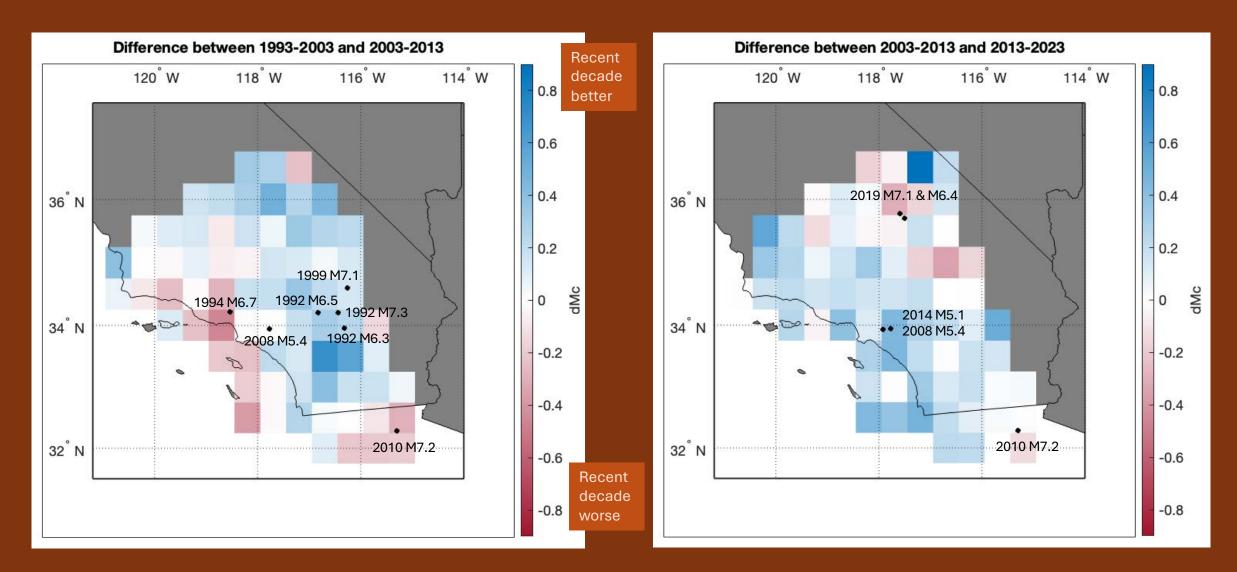
### Bootstrapping

- gives sense of variation from sampling
- 200 sets with resampling
  - mean and st. dev.

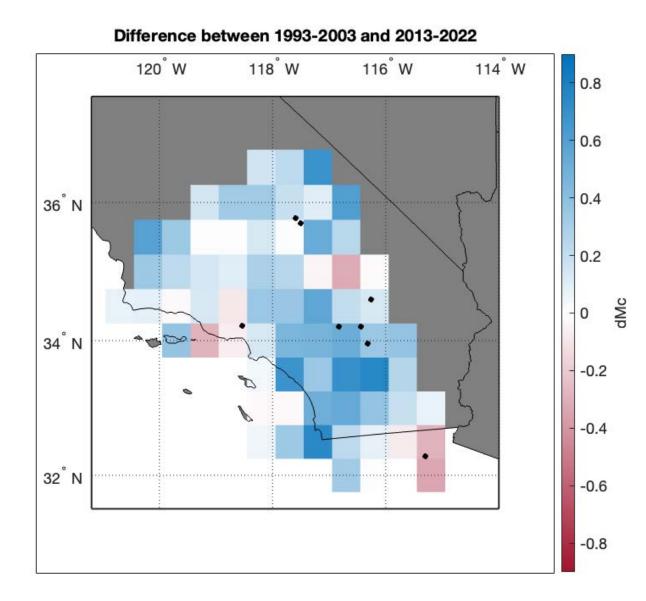
original: 1, 1, 1, 2, 2, 3

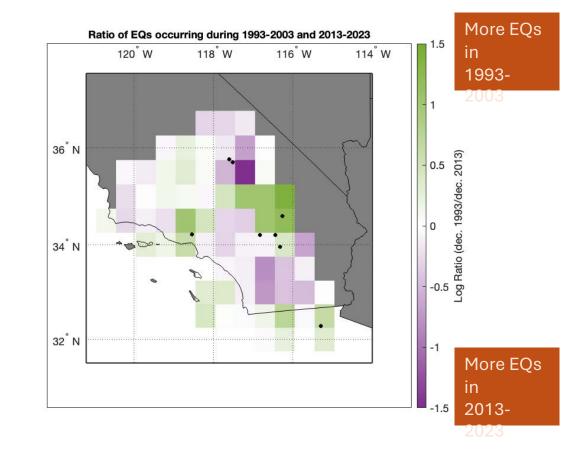
sample A: 1, 2, 2, 2, 3, 3 sample B: 1, 1, 1, 1, 2, 2 sample C: 1, 1, 2, 2, 3





Better: 1994 Northridge Worse: 2010 El Mayor, 2019 Ridgecrest\*, 1992 Landers-Big Bear & Joshua Tree, 1999 Hector Mine \*incomplete





-> small improvement (~0.2-0.7 m.u.) in most areas over past 30 years

-> regions with worse Mc typically have fewer earthquakes