Table S12 for "Volcanic earthquake catalog enhancement using integrated detection, matched-filtering, and relocation tools"
(last updated June 5, 2023)

A) Parameter recommendations for REDPy (See REDPy documentation and config.py comments for additional details)				
Parameter Name	**What it controls**	**Default Value**	**Recommended Value**	**Remarks**
-	number of input stations	-	3 to 5, or more	Using more stations provides better detection sensitivity and more accurate event cluster determinations, but comes at the expense of a larger computational cost.
samprate	sampling rate used for all stations	-	comply with station with lowest sampling rate	traces from stations with different sampling rates will be re-sampled.
fmin	lower band of bandpass filter (Hz)	1	dependent on network	We recommend that user finds the ideal bandpass range by maximizing SNR on a subset of events from the analyst-derived catalog.
fmax	upper band of bandpass filter (Hz)	10		
nstaC	minimum number of stations a trigger must show up on	2	at least half of nsta (e.g. if nsta=3, nstaC=2)	We recommend using more stations if signal to noise is poor.
lwin	long time window for STA/LTA (s)	7	dependent on network and signal-to-noise ratio (SNR)	A balance should be struck between how relaxed/conservative the STA/LTA parameters are and the minimum CC coefficient used to determine repeaters. The goal is to capture small, repetitive events, and at the same time, minimize the amount of noise that gets through. For single station applications of REDPy, we recommend using conservative STA/LTA parameters (higher trigon and trigoff, longer lwin), as the tool will not be checking for coincident triggers recorded on other stations.
swin	short time window for STA/LTA (s)	0.8		
trigon	cutoff ratio for triggering STA/LTA	3		
trigoff	cutoff ratio for ending STA/LTA trigger	2		
winlen	cross-correlation window length in samples	1024	2^n is preferred	-
cmin	minimum cc coefficient to be considered a repeater	0.7	0.7 or higher	Using a higher cc coefficient would allow for a more accurate determination of REDPy repeaters, and less generic REDPy clusters. If porting over REDPy cluster cores as EQcorrscan templates, we recommend a high cc coefficient (~0.85) so that core events are less generalized and more templates are obtained.
ncor	number of stations correlation must be exceeded on	4	at least half of nsta	Usually the same value as nstaC
minorph	minimum amount of time to keep the smaller orphans alive (days)	7	7 or less	The time for which orphans are kept should well exceed the typical inter-event time of the observed repeating events. However, keeping orphans for an overly long time might result in greater computational cost, as the library of orphans that are correlated on new triggers would be larger.
maxorph	maximum amount of time to keep the largest orphans (trigon +7) alive (days)	30	30 or less	
filomin	lower bound of on low frequency window (Hz)	1	dependent on catalog	By calculating the spectra of known high-frequency and low-frequency events from the analyst derived catalog, the user can determine frequency bands that would create a bimodal distribution that separates majority of the two types of events.
filomax	upper bound of on low frequency window (Hz)	2.5		
fiupmin	lower bound of on low frequency window (Hz)	5		
fiupmax	upper bound of on upper frequency window (Hz)	10		

B) Parameter recommendations for convert_redpy() (wrapper function to process REDPy output into ObsPy)				
Parameter Name	**What it controls**	**Default Value**	**Recommended Value**	**Remarks**
max_dt	max time difference to consider a REDPy repeater the same event as an analyst-derived event (s)	4	4 or less	Most REDPy detections that are coincident with an analyst-derived event should show a time difference of 2 s or less. Unless observed inter-event times are very short (e.g. swarms where events are a few seconds apart), keeping a slightly relaxed max_dt is acceptable.
tolerance	factor above median trace amplitude for boxcar removal	4 x 10^4	depends on data	We found numerous boxcar-like pulses in the data downloaded from IRIS for Alaska stations. As such, we use a simple code to remove data that demonstrate anomalously large amplitudes over successive time samples.
add_redpy_pick_to_associated	add the REDPy STA/LTA trigger time as a low confidence P-phase pick for detections that are associated with an analyst-derived event (assuming the pick doesn't already exist)	True	True	Having more picks on associated REDPy events will maximize the success rates during template creation, which imposes a minimum station requirement.
add_campaign_pick_to_associated	use STA/LTA to make low confidence P-phase picks on campaign stations for detections that occur during the period of the campaign	True	True	This will better anchor the located template events during the relocation phase.

C) Parameter recommendations for create_tribe() (wrapper function to process REDPy output and analyst-derived catalog into EQcorrscan templates)				
Parameter Name	**What it controls**	**Default Value**	**Recommended Value**	**Remarks**
resampling_frequency	frequency used to resample traces prior to final merge (Hz)	50	comply with station with lowest sampling rate	This is necessary to avoid stream merging errors.
lowcut	filter lowcut (Hz)	1	dependent on network	Discussed above in table (A), see fmin and fmax.
highcut	filter highcut (Hz)	10		
prepick	pre-pick time (s)	1	1 or less	Keep the value low, perhaps just enough to capture pick uncertainty.
length	template length (s)	8	Depends on the duration of observed earthquake signals.	Note that the length of the template is calculated from the pre-pick time. For example, if pre-pick is 1s and length is 8s, the template would span 1s before the pick time and 7s after it. We recommend that the length of templates incorporate signal coda.
min_snr	minimum signal-to-noise (SNR)	5	1 to 5 (depends on network)	Increasing the minimum SNR would ensure high quality templates. However, certain low amplitude template events might get discarded, as channels that fail that minimum SNR check might get removed, leaving the template with less channel traces than needed (see min_stations).
process_len	length to process data in (s)	86400	86400	Process day-long chunks of data at a time.
tolerance	factor above median trace amplitude for boxcar removal	4 x 10^4	depends on data	Discussed above in table (B)
channel_convention	only accept P picks made on vertical channels and S picks made on horizontal channels	True	True	EQcorrscan follows a convention where templates are generated with P-phases on the vertical channel and S-phases on the horizontal channels.
use_all_analyst_events	attempt to convert all analyst-derived events to templates. (i.e. REDPy groupings are ignored)	False	False	We use REDPy to group similar looking events together, so that a representative template can be used for the matched-filter scan. Having all analyst-derived events as templates will introduce redundancy and increase computation cost.

D) Parameter recommendations for scan_data() (wrapper function to conduct matched-filter scan using EQcorrscan)				
Parameter Name	**What it controls**	**Default Value**	**Recommended Value**	**Remarks**
min_stations	minimum number of unique stations (where picks are made) required to keep a template for matched-filtering	3	preferably 4 or more	As the subsequent relocation step involves a colocation assumption between templates and their respective detections, having a high cross-correlation value on multiple stations is needed to ensure its validity.
min_picks	minimum number of picks required to keep a template for matched-filtering	0	-	Less restrictive condition compared to min_stations.
resampling_frequency	frequency used to resample traces prior to final merge (Hz)	50	comply with template sampling rate	Template and continuous waveform data must match in sampling rate
threshold_type	threshold type (MAD/absolute/av_chan_corr)	av_chan_corr	av_chan_corr	As discussed in the main body of the paper, we find the ideal MAD threshold varies greatly for the Alaska volcano seismic networks we tested the threshold on. MAD is less robust when a small number of stations is used. Absolute channel correlation is also not feasible as our templates vary in the number of channel traces they contain. As such, we recommend average channel correlation, which is intuitive and easily verifiable.
threshold	threshold value	0.6	9 to 15 for MAD 0.6 or above for absolute/av_chan_corr	Start with a lower threshold value in the initial scan. Lower scoring detections can be filtered out afterwards using the rethreshold function without having to repeat the scanning process.
trig_int	trigger interval for EQcorrscan detections (s)	8	greater than or equal to template length (see length in create_tribe)	Ensures that codas of a signal are not redetected as a separate detection.
decluster	whether or not to remove coincident detections from different templates (trig_int applies to individual templates, so different templates can in fact trigger on the same event)	True	True	Declustering is important as different templates can trigger on the same event.
decluster_metric	metric used to choose the preferred template during declustering. (avg_cor/cor_sum/thresh_exc)	avg_cor	cor_sum	Here we suggest the use of absolute correlation sum (cor_sum) as we want to choose a template with more picks over one with less picks, even though the template with less picks might score better in average correlation value (avg_cor). Doing so will help ensure that more matched-filter detections are relocatable.
max_zeros	maximum number of zeros allowed in each day-long merged trace	100	100	EQcorrscan returns errors if the input trace contains too many zeros, which it deems as bad data. This check is put in place to discard such data before it is fed to EQcorrscan.
npts_threshold	maximum number of missing data samples per data chunks before chunks are discarded	100	100	This check is put in place to discard overly-short data chunks that produces stream merging errors.
tolerance	factor above median trace amplitude for boxcar removal	4 x 10^4	depends on data	Discussed above in table (B)
parallel_process	use parallel processing	True	True	Running the matched-filter scan in parallel is faster.

E) Parameter recommendations for calculate_catalog_FI() (optional function to calculate FI of detections on user-defined station(s))				
Parameter Name	**What it controls**	**Default Value**	**Recommended Value**	**Remarks**
reference_station	station(s) to obtain waveform from	-	high SNR stations	FI is computed from the stack of frequency spectrums from the reference stations.
reference_channel	channel(s) to obtain waveform from	-	vertical components	-
min_match	minimum number of reference station-channels	-	2 or 3	Not every event has picks on all reference stations. A minimum number of matches must be established so that FI values are not skewed due to the stack being calculated on a unreasonably small number of stations.
resampling_frequency	frequency to resample traces prior to final merge (Hz)	50	comply with station with lowest sampling rate	Discussed above in table (C)
prepick	pre-pick time (s)	-	same as parent template	Capture pick uncertainty
length	length of signal to calculate spectra for (s)	-	same as parent template	Capture signal coda
lowcut	filter lowcut (Hz)	1	dependent on network	Discussed above in table (A), see fmin and fmax.
highcut	filter highcut (Hz)	10		
filomin	lower bound of on low frequency window (Hz)	1	dependent on catalog	Discussed above in table (A)
filomax	upper bound of on low frequency window (Hz)	2.5		
fiupmin	lower bound of on low frequency window (Hz)	5		
fiupmax	upper bound of on upper frequency window (Hz)	10		
tolerance	factor above median trace amplitude for boxcar removal	4 x 10^4	depends on data	Discussed above in table (B)

F) Parameter recommendations for calculate_relative_magnitudes() (optional function to calculate magnitudes for detections obtained from associated templates)				
Parameter Name	**What it controls**	**Default Value**	**Recommended Value**	**Remarks**
noise_window	time window to calculate noise amplitude (s, s)	-	(-20s, -prepick)	Note that the time window is relative to each pick time. Select a sizable time window before the pick, up until prepick.
signal_window	time window to calculate signal amplitude (s, s)	-	(-prepick, -prepick+length)	Note that the time window is relative to each pick time. Select a time window for the signal, taking into account pick uncertainty.
min_cc	minimum cross-correlation coefficient to calculate relative magnitude	0.6	0.6 or more	If cc is set to a higher value (e.g. 0.7 or above), the user can be more confident in the relative magnitude determination, as waveforms look more alike. That said, keeping it at a lower value (such as 0.6) will maximize the number of events that are permitted for magnitude calculation.
min_snr	minimum signal-to-noise to calculate relative magnitude	1	1 to 5 (depends on network)	Increasing the minimum SNR will provide better confidence in the calculated magnitudes. However, having it too high will lead to a significant number of low amplitude template events getting discarded.
shift_len	length of time shift to find max cc between each event pair (s)	1.5	3 or less	Finding the maximum cc between a detection and its parent template does not require a big shift.
resampling_frequency	for resampling traces prior to final merge (Hz)	50	comply with station with lowest sampling rate	Discussed above in table (C)
lowcut	filter lowcut (Hz)	1	dependent on network	Discussed above in table (A), see fmin and fmax.
highcut	filter highcut (Hz)	10		
tolerance	factor above median trace amplitude for boxcar removal	4 x 10^4	depends on data	Discussed above in table (B)
use_s_picks	option to allow S-picks to contribute to magnitude calculations	False	False	-

G) Parameter recommendations for generate_dtcc() (wrapper to use EQcorrscan's write_correlations to construct the dt.cc file)				
Parameter Name	**What it controls**	**Default Value**	**Recommended Value**	**Remarks**
prepick_actual	prepick time (s)	0.15	the correlated segment should be less than 3s long	The correlated segment should be short and focused on the phase arrival. It should avoid incorporating coda, as it risks incorporating other phases present in the full signal.
length_actual	length of phase segment (s)	2.66		
prepick_excess	prepick time in excess for waveform retrieval (s)	1	greater than pre_pick + shift_len	the data pulled should account for the correlated segment and time shift (shift_len)
length_excess	length of phase segment in excess for waveform retrieval (s)	4	greater than length + shift_len	
shift_len	length of time shift to find max cc between phase arrivals (s)	0.4	0.4 or less	For good quality picks, this time shift can go as low as 0.2s.
lowcut	filter lowcut (Hz)	1	dependent on network	Discussed above in table (A). See fmin and fmax.
highcut	filter highcut (Hz)	10		
min_cc	minimum cross-correlation coefficient to retain differential time	0.7	0.6 or more for sparse networks, as low as 0.4 for dense networks	Having a minimum cc of 0.7 or more generally provides confidence for good waveform similarity, but significantly lower cc thresholds have been used at densely instrumented study areas (down to about 0.4)
min_link	minimum number of differential time observations for an event to be paired	3	3 or more (ideally 8 or more)	When relocating events, we usually want strong links between each event pair, which is typically defined by eight or more differential time observations (one observation for each degree of freedom). However, at sparse volcanic networks, we often have to forego strong links and store as many differential time observations as possible. That said, having less than 3 differential time observations would be far too few. Note that if the dt.cc file is used in GrowClust, these links control clustering as well, and erroneous clusters might form if min_link thresholds are too relaxed.
max_sep	maximum separation between event pairs (km)	100 (correlate all)	dependent on relocation tool used	If hypoDD is being used for relocation, this parameter should be set to a high value such that no event pairs are discarded due to distance. This is because hypoDD imposes a distance condition within itself (see WDCC in hypoDD.inp)
weight_func	function to be applied on raw cross-correlation coefficient squared value computed by write_correlations()	None	depends	A more sophisticated weighting scheme can be used (e.g., penalizing observation weights if there is a high chance of cycle-skipping)
by_cluster	option to only correlate within EQcorrscan parties and across EQcorrscan templates (detections made by different templates are not correlated with one another)	False	False	Storing as many cross-correlation differential times as possible will create a denser "mesh" across all observed events, making relocations more robust.
make_s_picks	option to make theoretical S picks from P picks using an vp/vs ratio of 1.73 before constructing dt.cc	False	False	Certain applications have found relocation improvements when pseudo S picks are made to better anchor the templates using horizontal channels.

H) Parameter recommendations for ph2dt.inc (controls array dimensions for ph2dt)				
Parameter Name	**What it controls**	**Default Value**	**Recommended Value**	**Remarks**
MEV	Maximum number of events	12000	-	The inc file is used to compile ph2dt and allocate sufficient memory for the subsequent run. Scale the numbers to fit the problem as necessary. The numbers under the 'Default Value' column are recommendations from the HypoDD manual.
MSTA	Maximum number of stations	2600	-	
MOBS	Maximum number of phases (P&S) per event	1000	-	

I) Parameter recommendations for ph2dt.inp (controls the creation of the dt.ct file)				
Parameter Name	**What it controls**	**Default Value**	**Recommended Value**	**Remarks**
MINWGHT	Minimum pick weight	0	0	Include all picks. At sparse seismic networks (e.g., Alaska volcanoes), we generally cannot afford to exclude poor quality picks.
MAXDIST	Maximum distance between event pair and station (km)	120	High enough to include local stations being used	Include all local stations
MAXSEP	Maximum hypocentral separation between event pairs (km)	10	10 or less	For the double difference assumption of similar path effects to hold, we need the event pair distance to be significantly smaller than the event-station distance. This is particularly important if the observed seismicity is dispersed on the scale of event-station distances.
MAXNGH	Maximum number of neighbors per event	10	10	-
MINLNK	Minimum number of links required to define a neighbor	8	8 or less if need be	When constructing the dt.ct using ph2dt, we want to consider only strong links with 8 or more differential time observations (one observation for each degree of freedom). That said, this might need to be lowered if the network is sparse or impaired, as it might limit the number of observations saved in the dt.ct file.
MINOBS	Minimum of links per pair saved	8	8 or less if need be	
MAXOBS	Maximum number of links per pair saved	20	As high as it needs to be	Definitely save all ct links

J) Parameter recommendations for hypoDD.inc (controls array dimensions for hypoDD)				
Parameter Name	**What it controls**	**Default Value**	**Recommended Value**	**Remarks**
MAXEVE	Maximum number of events	S: 1,000 / L: 20,000	-	The inc file is used to compile hypoDD and allocate sufficient memory for the subsequent run. Scale the numbers to fit the problem as necessary. The numbers under the 'Default Value' column are recommendations from the HypoDD manual (S: small dataset / L: large dataset).
MAXDATA	Maximum number of differential time observations	S: 20,000 / L: 3,000,000	-	
MAXEVE0	Maximum number of events used for SVD (2 = LSQR used)	S: 20 / L 215	-	
MAXDATA0	Maximum number of differential time observations used for SVD (1 = LSQR used)	S: 2,000 / L: 100,000	-	
MAXLAY	Maximum number of velocity model layers	S: 30 / L: 50	-	
MAXSTA	Maximum number of stations	S: 100 / L: 400	-	
MAXCL	Maximum number of clusters	S: 200 / L: 200	-	

K) Parameter recommendations for hypoDD.inp (controls hypoDD relocation iterations)				
Parameter Name	**What it controls**	**Default Value**	**Recommended Value**	**Remarks**
IDAT	Data Type; 1: cc only, 2: ct only, 3: cc & ct	3	3	If HypoDD is used for both ct and cc iterations, set to 3. If GrowClust is used for cc iterations, set to 2. Set to 1 only if the user is evaluating the influence of cc on hypocenter convergence (we find that using ct data is particularly important for volcanic settings)
IPHA	Phase Type; 1: P only, 2: S only, 3: P & S	3	3	Keeping both is preferred. Can be set to 1 or 2 if the influence of S-phase differential times needs to be evaluated.
DIST	Maximum distance between cluster centroid and stations (km)	50	50	Treating the entire catalog as one cluster is reasonable for volcanic settings. As such, we set the maximum acceptable distance and azimuth gap to be as high as it needs to be, and require no minimum cc/ct links per cluster. The cutoff thresholds and event separations defined in the iteration sets will control convergence directly.
OBSCC	Minimum number of cc links for cluster, out-of-box: 0	0	0	
OBSCT	Minimum number of ct links for cluster, out-of-box: 8	0	0	
MINDS	Min distance between individual event pairs and stations (-999: not used) (km)	-999	At least 2 times the distance between event pairs	For the double difference assumption of similar path effects to hold, we generally require event pair distances to be significantly smaller than the event-station distance. A good rule of thumb is to have the minimum distance set as a factor multiplied by the event pair distances observed in the input catalog. Users are recommended to test different multiplication factors for each seismic network used. Setting a condition on azimuthal gap may help address the azimuthal bias in instances where the network is poorly distributed around the observed event pair, or if the observations are too few. This controls the dt observations quantity vs quality tradeoff, but users should exercise caution when imposing this control especially if the number of dt observations are already low to begin with.
MAXDS	Max distance between individual event pairs and stations (-999: not used) (km)	-999	-999	
MAXGAP	Max azimuthal gap between individual event pairs and stations. (-999 or 365: not used) (degrees)	-999	depends	
ISTART	Initial locations; 1: start from centroid, 2: start from catalog locations	2	2	When evaluating the HypoDD solution, the user can select 1 and start from the centroid, allowing for more iterations to arrive at a stable solution. This can help evaluate the extent of damping.
ISOLVE	Least squares solution: 1: SVD, 2: LSQR	2	2	In general, volcanic earthquake catalogs consist of too many events to solve for a solution using SVD. A subset of events can be relocated using SVD to evaluate HypoDD error. More details are provided the HypoDD manual.
IAQ	Keep (0) or Remove (1) air quakes	0	0	Keep air quakes. At volcanic settings, it is common to have earthquakes relocating above the sea level.
NSET	Number of sets of iteration specifications following (i.e. if NSET=3, the follow variables should be 3 element lists)	5	4 or more	Here we recommend that there at least be 4 sets of iteration specifications: 2 for ct data and 2 for cc data, or more for each. For each data type, the first set will be used for the initial shifts over larger length scales, and the following sets will use more conservative parameters to converge the hypocenters to smaller scale features.
NITER	Number of iterations for the set of weighting parameters that follow	[10, 10, 10, 10, 10]	8 or more iterations per setting	We find that 8 or more iterations allow for sufficient convergence per setting.
WTCCP	Weight for cc P wave (-9: omit)	[0.01, 0.01, 0.10, 0.50, 1.00]	-	Let cc-heavy iterations follow ct-heavy iterations. Consider providing a lower weight to S wave differential times due to greater pick uncertainty.
WTCCS	Weight for cc S wave (-9: omit)	[0.01, 0.01, 0.10, 0.50, 1.00]	-	
WRCC	Cutoff threshold for outliers located on cc tails (-9: no outlier removed)	[10, 10, 10, 6, 6]	-	Lower the cutoff threshold as hypocenters converge.
WDCC	Maximum event separation for cc data (-9: not activated) (km)	[4, 4, 4, 2, 2]	-	Start off with large event separation, and lower it after the initial few iterations. CC event separation should be lower, as we use a colocation assumption to give matched-filter detections a starting location.

WTCTP	Weight for ct P wave (-9: omit)	[1.00, 1.00, 1.00, 0.10, 0.01]	-	Let cc-heavy iterations follow ct-heavy iterations. Consider providing a lower weight to S wave differential times due to greater pick uncertainty.
WTCTS	Weight for ct S wave (-9: omit)	[1.00, 1.00, 1.00, 0.10, 0.01]	-	
WRCT	Cutoff threshold for outliers located on ct tails (-9: no outlier removed)	[12, 6, 6, 6, 6]	-	Lower the cutoff threshold as hypocenters converge.
WDCT	Maximum event separation for ct data (-9: not activated) (km)	[10, 5, 2.5, 2.5, 2.5]	-	Start off with large event separation, and lower it after the initial few iterations.
DAMP	Damping (only for LSQR, ISOLV=2)	[200, 200, 200, 200, 200]		Higher damping results in lower condition numbers. The HypoDD manual suggests that condition numbers between 60 and 120 are desirable for these iterations, but our tests have shown that condition numbers that exceed those values (up to 200) can still provide reasonable relocations. Evaluate the extent of damping by plotting out the relocated hypocenters and comparing them with their original locations. Repeating the relocation process while perturbing the starting location of events might reveal if the algorithm is over or under damped.

NOTE: It is strongly recommended that users run numerous iterations of HypoDD using different dt.ct and dt.cc files generated from different settings and using a range of damping values. Understanding how each setting affects the relocation output of your dataset is crucial for obtaining a high confidence result.

* For recommendations on GrowClust parameters, we refer readers to the GrowClust User Guide available on the public GrowClust Github repository: https://github.com/dttrugman/GrowClust