# CHAPTER ONE: Introduction

## Chapter 1.1.1 : Introduction

The three earthquake sequences being observed are March 31st, 2020 Stanley sequence, the April 2014-May 2017 Challis Sequence, and the September 2nd Sulphur Peak sequence. The Stanley event took place in remote central Idaho near the town of Stanley, ID (Figure 1). The event took place within 15km of two prominent earthquakes, the 1944 M6.1 and 1945 M 6.0 seafoam earthquakes. The mainshock may have initiated along the Sawtooth fault, but there is a lack of visible rupturing at the surface; this coupled with a preliminary aftershock sequence analysis, suggests that there may be a complex interplay of active and unknown faults (Liberty et al., 2020), (Pollitz et al., 2020).

The Sulphur Peak earthquake sequence consisted of a series of events occurring from September to October in 2017, near Sulphur Peak, Idaho. The normal faulting Mw 5.3 main shock occurred on September 2nd, 2017 and was felt in Idaho, Utah, and Wyoming. The following month consisted of a series of energetic aftershocks, over 1,000, that reached magnitudes >= 4.0 Ml. The mainshock occurred about 12km east of Soda Springs, Idaho at a depth of 9.5km

In April 2014, after approximately 20 years of relatively low seismicity an energetic earthquake sequence, maximum Ml 4.8, began 25km northwest of the 1983 Ms 7.3 Borah Peak earthquake ( Pang et al. 2018). The rupture occurred close to the town of Challis, Idaho and the sequence ended sometime in the fall of 2014. In the following months, beginning sometime in January 2015, another energetic sequence of earthquakes began, but this time the events were occurring ~20km to the southeast, with the largest event being a Ml 5.0. The earthquakes are believed to have been a continuation of energy release from the 1973 Borah Peak earthquake, which would mean that this is an unusually long aftershock sequence.

Through a machine learning (ML) algorithm we detect aftershocks of the three sequences to contribute to each earthquake catalog with aim to contribute to the observations regarding fault geometry and cause of seismicity for each region. The neural network will assist in the monitoring of low magnitude seismicity, helping determine the cause of earthquakes and the risk associated with potential unknown active faults in the area. Traditional detection methods have a large signal-to-noise ratio threshold, meaning they often miss smaller aftershocks (e.g. M<2.5).

After a preliminary aftershock analysis completed by researchers Lee Liberty and co., an after-slip pattern was detected (Liberty et al., 2020). The after-slip pattern was opposite of the direction of dip of the Sawtooth fault, which is unexpected (Liberty et al., 2020). Coincidentally, the temporal spatial distribution of aftershocks resembles the previous aftershock sequences of the two other sequences mentioned in this study. Each sequence is characterized by a normal-faulting earthquake, a similar southward migration of aftershocks from the mainshock, and a temporal distribution that occurs opposite the direction of the dipping fault plane (Liberty et al., 2020), (Pang et al., 2018), (Koper, 2019). The relationship between these fault planes and the conjugate fault network may be a key to deciphering the origin of these unique seismic events and a critical step to understand hazards associated with similar faults located in the intermountain west.

In conjunction with machine learning we began our aftershock analysis by employing traditional methods used to enhance the location of detected events, such as relocating hypocenters. When observing previous research regarding seismicity in central Idaho, Dewey (1983) showed that by relocating hypocenters he was able to improve the concentration of events compared to the USGS catalog of the event; in hand, enhancing their understanding of the source region associated with the Borah Peak earthquake. Based on research involving swarm behavior in Reno, Nevada, we used local stations, in conjunction with regional networks, to assist our aftershock analysis and help determine fault geometry near seismicity (e.g., Ruhl et al., 2016). We relocated hypocenter locations and depths by comparing multiple velocity models for each sequence and decrease residual errors accompanying event location.

The most pertinent question seismologists struggle to answer is where an earthquake is most likely to occur and when. The answer to this question relies heavily on the characteristics of the geologic environment and the nature of the potential earthquake. Aftershock sequences can provide vital information regarding why these earthquakes occur and where they may occur in the future. Earthquakes do not happen without cause; whether it be fault movements, fluid pressure, or even another earthquake (i.e. a triggered event) (Koper et.al, 2018). Aftershock analysis can show migration paths of earthquakes over time (e.g., Ruhl et al., 2016). Detecting aftershocks enables researchers to determine what physical drivers are causing the earthquake. Following the temporal history of an earthquake gives insight into faults and the amount of time expected between events which are important pieces of information when assessing the seismic risk associated with a given area (Pang et al., 2018).

Figure 1: Map of central Idaho showing mapped faults and locations of events for each sequence

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# CHAPTER 1.2.1: Geologic Background

The geologic setting for Challis, Stanley, and Sulphur sequences lies within the greater extent of Basin and Range extension that host both the centennial tectonic belt and Idaho seismic belt. The nature of basin and range extension is a 750km wide extensional tectonic province with Miocene-Holocene fault activity (Thackray, 2013). The intermountain seismic belt (ISB) and centennial tectonic belt (CBT) of Idaho are two regions well known for their seismic hazards. The Sulphur Peak sequence of southeastern Idaho, located within the ISB, is not the only notable earthquake to occur within this diffuse band of seismicity that stretches from northwestern Arizona to northwestern Montana (Koper, 2017). The widely felt Draney Peak Sequence of 1944 (Brumbaugh, 2001) also occurred in the Southeastern Idaho portion of the ISB and like the Sulphur Sequence, was highly energetic. (Koper, 2017). The CBT of Idaho is another region characterized by large amounts of seismicity that spans central Idaho and extends to southwestern Montana (Stickney and Bartholomew, 1987). The CBT is known for other historic earthquakes apart from the Challis and Stanley sequences, such as the 1983 Ms 7.3 Borah Peak earthquake that ruptured along the Lost River fault. The three sequences can be better characterized by their geographic location about the Snake River Plain, which intersects the Challis and Stanley sequence from the Southeastern Sulphur Peak sequence. The Challis and Stanley sequences can be referred to as the Western Sequences (WS) and the Sulphur Peak sequence can be referred to as the Eastern Sequence (ES).

2.2.2 : ES Geologic Background:

 The mainshock of the Sulphur Peak earthquake occurred about 12km east of Soda Springs, Idaho at a depth of 9.5km. The mainshock, and following aftershock sequence, were located within the ISB and to the southeast of CBT (Koper et. al, 2018). The 2017 Sulphur Peak event appears to be a repeat of two earlier seismic events, one in the summer of 1960 and the other in the fall of 1982 (Koper et. al , 2018). The zone of seismicity occurred in the northern extent of the Basin and Range province (Payne, 2013). The eastern extent of the Snake River Plain encompasses Late Tertiary silicic volcanic centers that represent the NE-trending track of the Yellowstone hotspot (Pierce and Morgan, 1992). The mafic intrusion into the midcrust caused partial melting of the crust surround Sulphur Springs and produced large-volume silicic eruptions in the area from ca. 10 MA to 4 Ma (Kunts et al., 1986). The CBT host late Quaternary northwest striking normal faults and extend into the proposed Centennial shear zone at the southeast termination of the normal faults (Payne, 2013). Current bedrock structural features inferred from gravity and seismological data suggest that fault offset does not extend into the SRP (Mabey, 1987, Jackson et al., 2006). Further to the south of the Snake River plain near the town of Soda Springs resides the northwest trending East Bear Lake Fault (EBLF) within a margin of northeast trending right-stepping normal faults that occurred in response to east-west Neogene extension superimposed on Cretaceous to early Tertiary folds and thrust faults (Marith et al., 2009). A notable characteristic of the earthquake is that it occurred to the east of the west dipping northern section of the EBLF, which bounds the Aspen range to the north where most aftershocks are occurring in the footwall of the fault (Koper, 2018). The significant thinning of the crust due to mafic intrusion in the area is apparent in preliminary aftershock locations and motivates research to determine the depth of the seismogenic zone.

2.2.3 : WS Geologic Background:

Within the northeastern corner of the basin and range province includes several active faults that have caused Pleistocene to Holocene ruptures including the forementioned Borah Peak earthquake (Thackray, 2013). The sawtooth mountains expose Cretaceous granodiorite, Eocene granite, and metamorphosed Paleozoic wall rocks and roof pendants (fisher et al., 1992). The local province named, CBT, consists of subparallel northwest-striking normal faults that contain Precambrian and Paleozoic sedimentary and metamorphic rocks (Stickney and Bartholomew, 1987). There are three primary normal faults in the WS region, and they are the Lost River, Lemhi, and Beaverhead Fault, which initiated about 16 Ma (Liberty, 2020). Each of these faults accommodates significant vertical displacement of the crust and exhibit clear geomorphic expression along six segmented boundaries (Crone and Haller, 1991). Prior paleoseismic and geomorphic indicators indicate Quaternary activity in the central segments of these three faults (Scott et al., 1985). Southwest of these three faults lies the Sawtooth Fault, another normal fault that accommodates significant vertical displacement and forms a dramatic high relief range front towards the Northeast side of these mountains (Liberty, 2020). The sawtooth fault extends approximately 60km to the northwest, but the totality of its length is debated due to the lack of fault scarping to the northwest. Preliminary results and aftershock locations suggest that the fault extends past what is currently mapped. Previous research documents the faults scarp using limited light detection and ranging topographic 4-9 meter high scarps displacing 11-14 ka glacial deposit, and around 2-3 meter high scarps in the Holocene alluvial deposits (Thackray et al., 2013). Based on these observations it is noted that two or three postglacial surface rupturing events have occurred, suggesting that there are two discrete fault segments (Thackray et al, 2013). Using these observations, Thackray et al., estimated Holocene slip rate of 0.5-0.9 mm/yr, higher than the long-term Quaternary slip rate estimate of <0.2mm/yr (Crone et al., 2010). The length-magnitude scaling relationships (Wells and coppersmith, 1994) and the 2-3 m displacement, if this occurred in a single segment, suggest that the sawtooth fault may have moved with similar movement release as the Borah Peak (Liberty, 2020). The total extent of the Sawtooth Mountains consists of mostly Cretaceous granitic rocks of the Idaho Batholith, they produce about 1300m of relief across the fault with an uplifted horst block that hosts 57 peaks higher than 300m above sea level (Liberty, 2020). The current termination of the Sawtooth Fault terminates near its intersection with the Trans-challis-faults (TCFS), similarly to the Challis sequence that occurred on the Lost River Fault. The area to the southeast of the TCFS is recognized as graben and synvolcanic basin that accommodated Eocene extension and subsidence which extends southwest to the Sawtooth fault and north to the town of Challis (Kiilsgaard et al., 1986). While there is no direct evidence for active motion on faults that lie within the graben, the N60E alignment of some Stanley earthquakes and the northern limit of the 2014-2017 Challis earthquake sequence, all lie at the northern boundary of this graben (Pang, et al., 2018).

Northeast of Stanley lies Challis region, residing on the eastern edge of the Idaho batholith. The Challis region is composed of a suite of volcanic rock that is associated with an extensive Eocene volcanic belt in the Pacific Northwest (Moye et al., 1988). The extent of the volcanic group makes up approximately 25,000 square km and forms the largest subregion of Eocene volcanic rock in the northwestern Unites States also home to the Eocene TCFS that terminate the northwestern region of seismicity for Challis and Stanley (Moye et al., 1988). In central Idaho a significant portion of seismic activity occurs near the active northwest-striking extensional faults north of the Snake River Plain, eg. Lost River, Lone Pine, Lemhi, and Beaverhead. The fault responsible for the Ml 7.3 Borah Peak earthquake was the Lost River fault (Stein and Bucknam, 1985). The trans-challis fault system has been characterized by significant seismicity that tends to last for a few weeks to months at a time, the sequences originated along sub parallel segments of the Lost River fault, and in the case of the 1984 Devil Canyon sequence, along the northeast-dipping conjugate Lone Pine fault (Payne et al., 2004).

For more detail regarding the tectonic and geologic structure surrounding events occurring in the Basin and Range province see research provided by Pang et al., Liberty et al., and Pollitz et al. The Pang and Koper studies provide extensive interpretations regarding prior seismicity in for Challis and Sulphur Peak, whereas the Pollitz and Liberty papers provide preliminary aftershock analysis for the March 31st Stanley earthquake.

Chapter 1.3.1**:** Seismic History Challis:

Seismicity in Challis did not begin again until April 2014, nearly 20 years later. The energetic sequence of earthquakes began in April 2014 and continued through the fall of 2014 only to resume in January 2015 and continue through May of 2017 (Pang et al., 2018). While the second sequence of events started in 2015 occurred southeast of the first sequence, all earthquakes were occurring to the northwest of the Borah Peak rupture area (Pang et al., 2018).

The seismicity from April - October 2014 was recorded using an array of seven seismographs. Only one of these stations remained active through July 2015. The deployment of these stations was a joint effort among the University of Utah, the Montana Bureau of the Mines and Geology, and Geology, Idaho National Laboratory (INL), the Idaho Geological survey, and the U.S. geological survey (Pang et al., 2018). In 2015 the INL installed a new permanent seismometer about 20km southeast of Challis, before the installation of this seismometer the nearest three-component broadband seismometer was located about 120km south of Challis near Hailey, Idaho. Using the temporary seismic networks in conjunction with 90 permanent stations, both sequences exhibited migration from the northwest to the southeast over time (Pang et al., 2018). The depth control for these events was enhanced by the addition of a local network. The observed depth of the events seemed to decrease the farther north the event took place. *Pang et al.,* suggest that the trend in depth could be a result of a conjugate zone or fault network adjacent to the northern tip of the Lost River fault. One other possibility is that the resulting increase in depths to the southeast could be due to the better coverage of seismic events to the north and therefore a result of inadequate depth control for hypocenters to the southeast. We are motivated by the possibility that increasing the catalog of aftershocks for the Challis event may enable us to determine whether the resulting change in depths is due to inadequate quality of event hypocenters or a conjugate zone of faulting to the north of Challis.

1.3.2: Sulphur:

During the event in 1960 the USGS geodetic survey reported instrument locations for 17 earthquakes in southeast Idaho (Talley & Cloud, 1962). The locations were precise only to 0.1 or 0.5 degrees but there were spoken confirmations regarding the events (Koper et al., 2018). During the sequence that occurred in 1982 the largest earthquake recorded was Ml 4.7 and was recorded on a network of 19 seismic stations deployed near the epicentral region and approximately 2,000 earthquakes were recorded in 11 days (Smith et al., 1983).

Research previously conducted using a hypocentral relocation technique on 219 of the best recorded earthquakes from 1960-1982, shows that the 2017 sequence overlaps the epicentral zone of those 219 recorded earthquakes (Arabs & Julander, 1986). The Sulphur peak sequence occurred beneath the Aspen Range to the east of the west-dipping northern section of the East Bear Lake fault (EBLF), this fault bounds the range and is like other normal faults in the ISB that exists within realms of active or historic seismicity.

Characteristics of the Sulphur Peak event suggest that the aftershock sequence is much too energetic to be consistent with an expected mainshock aftershock relationship. Within 10 days of the mainshock 16 of 17 earthquakes had occurred that exceeded the predicted maximum magnitude of an aftershock determined by Bath’s law (Bath, 1965), (Koper et al., 2018). Southeastern Idaho might be a region with slow slip or creep events (Peng & Gomberg, 2010).

1:3:3 Stanley

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# Methods CHAPTER 2. 1 : Machine Learning Approach (Overview)

The approach used for signal detection and phase picking was the automated Artificial Intelligence algorithm, EQTransformer (EQT). The algorithm simultaneously detects events while picking P and S wave phase arrivals. The algorithm is built with hierarchical architecture that is designed specifically for earthquake signals (Mousavi, S.M, Ellsworth et al., 2020). The program was designed using the python coding language. In overview, the algorithm is a multi-task deep neural network. The program functions by consisting of one deep encoder and three separate decoders (detector, P-picker, and S-picker branches) each with attention mechanisms (Mousavi, S.M, Ellsworth et al., 2020). The attention mechanisms in neural networks are inspired by a human’s visual attention, like how a seismologist would pick an earthquake signal from within a waveform. A seismologist focuses on a certain region of an image with high resolution while perceiving the surrounding image at low resolution, adjusting the focal point over time. EQT emulates this using two level of attention mechanisms in the hierarchical structure as mentioned before: the first at the global level for identifying an earthquake signal in the input time series, the second at the local level for identifying separate seismic phases within that earthquake signal. The algorithm then proceeds to distinguish local characteristics from global (full waveform) features using two levels of self-attention. The model is the first hierarchical-attentive model specifically designed for earthquake signals; contains 56 activation layers, is the deepest network that has been trained for seismic signal processing, has multi-task architecture that simultaneously performs the detection and phase picking – using separate loss functions – while modeling the dependency of these task on each other through the hierarchical structure, it provides output variations based on Bayesian inference, the model is trained using a globally distributed training set of 1.3 M local earthquake observations, and lastly it consists of both convolutional and recurrent neurons (Mousavi, S.M, Ellsworth et al., 2020).

The algorithm is trained using the Stanford Earthquake Dataset (STEAD) (Mousavi, S.M, Ellsworth et al., 2020). This dataset is a large-scale global dataset of labeled earthquake and non-earthquake signals. In order to train the program 1million earthquake and 300 thousand noise waveforms (including both ambient and cultural noise) were recorded by approximately 2600 seismic stations with epicentral distances up to 300km (Mousavi, S.M, Ellsworth et al., 2020). Many of the earthquake waveforms being used are smaller than M 2.5 and have been recorded within 100km from the event epicenter (Mousavi, S.M, Ellsworth et al., 2020).

In order to test the viability of the program’s ability to locate and pick earthquake waveforms and signals, EQT’s high generalization ability was tested on five weeks of continuous data recorded during the 2000 Mw 6.6 western Tottori, Japan earthquake by the Japan Meteorological Agency (JMA) (Mousavi, S.M, Ellsworth et al., 2020). The JMA’s analyst picked 279,104 P and S arrival times on 57 stations, EQT was able to pick 401,556 P and S arrivals on 18 of those stations (Mousavi, S.M, Ellsworth et al., 2020). Rather than solely relying on the program creator’s quality assurance test we replicated their experiment by utilizing the preliminary results and detected events from the March 31st, 2020, Stanley sequence. I, Blaine Bockholt, Dylan Mikesell, and Kristinia Rossavik picked P and S arrivals for all aftershocks >M 2.5. The catalog consisted of approximately 2k hand-picked events. Using the parameters: 41.46 to 47.46 degrees latitude and -117.636 to -112.636 degrees longitude, an event must be found on six stations to be considered an earthquake, an overlapping window of 0.3 seconds for template matching, a P wave probability amplitude threshold of 0.1, S wave probability amplitude threshold of 0.1, and probability detection threshold of 0.3 for the hierarchical attentive processing of EQT we constructed a catalog of ~74,000 events.

*Figure Showing EQT Events on Map with Stations*

Following similar methods used by Mousavi & Ellsworth, the P and S wave arrivals from the Stanley Earthquake were compared to the hand-picked arrivals using the regional network and 15 temporary stations. The origin time for each event was matched by finding the minimal difference in time between events so that only 1,996 hand-picked events were being compared to the corresponding event detected by EQT.

*Place figure here that shows the P and S wave arrival differences, origin time differences.*

**Methods Overview 2.2.1:**

Each sequence required that EQT be parameterized to accurately detect events and utilize available regional and temporary stations. The order of processes required to automate event detection and location can be generalized into three phases.

**2.2.2 Station Array:**

The first phase involved determining the boundary that should be used to encapsulate the mainshock and expected aftershock distribution. The prominent factor used in determining the azimuthal bounding box for this parameter was the station array. There are multiple approaches to modeling seismic sources: such as teleseismic, regional, or near-source models. Teleseismic modeling is advantageous when modeling events globally and the earthquake source magnitude is 5.5 and larger, but this does not provide much more than point-source parameters. Regional distance modeling can produce a more rapid-assessment of earthquake source properties but tends to be complicated by complex wave-propagation. Near-source modeling has the potential for detailed imaging of source properties; however, earthquakes tend to occur in regions without sufficient instrumentations to allow this detailed modeling approach (Beroza, 1995). The methods used in modelling the three sequences is a combination of near-source and regional modeling with a modern approach. Rather than relying on hand picks we can ignore the complexity of picking stacked events by hand and rely solely on our automated detection method. The ability to utilize regional and near source models with the benefit of machine learning motivates the research and hypothesis that near source modeling is potentially the best approach to constructing seismic arrays.

In order to effectively capture a seismic sequence, the location of an event is best determined when occurring within the bounds of a network array to help eliminate geographic bias. Seismic detection bias can occur as a seismic signal is detected locally by one station and again on a station much farther away. Utilizing linear velocity models to approximate earthquake hypocenters can lead to inaccurate arrival time estimations of earthquakes due to changing lithology as seismic waves travel outside the main region of seismicity (Dewey, 1985). The three-dimensional location of an earthquake is estimated by minimizing the sum of squares of weighted residuals:

Where stands for an error factor of both the modelling and measurement, *ti* is the measured arrival time of a seismic wave group (usually P waves) at the *i*th station, *t0* is the origin time, is the distance between the epicenter (projected hypocenter to the global surface from the Earth’s center) and the distance between the epicenter (projected hypocenter) and the *i*th station, *h* is the focal depth, and the nonlinear function (*T(* is the predicted travel time obtained from the standard travel time tables (Ogata et al., 1998). Therefore, despite the signal being a true seismic event, the relocation is may be inaccurate due to lack of radial symmetry surrounding the event. The bounds for each sequence were determined by the distance to nearest regional station in each direction from the mainshock. Each sequence being studied did have a temporary local array but the density of stations for each sequence varies (see parameter *table* #? for number of stations, bounding box, timeline for each sequence, and local station deployment).

**2.2.3 Machine Learning Script**

The preprocessing involved in preparing the machine learning event detection algorithm is outlined in the machine learning approach. The necessary bounding box must be set using latitude and longitude in decimal degrees. The start and stop time of the event must be designated to provide a time window for the algorithm retrieve data from. The hierarchical neural network works by applying a designated model, the model used for all three sequences was designed by the EQT program designers and trained using the STEAD network. The algorithm retrieves data from the IRIS (Incorporated Research Institute for Seismology) Client. The IRIS data servers provide raw waveform miniseed data with the pertaining network, station, and origin time of the collected data. The program then segments the waveforms into 1-minute windows to begin template matching outlined in the previous section. The output of the algorithm are three folders: an association, detection, and phase association folder; within the association folder exists a phase file which can then be read into the Hypoinverse relocation algorithm to assist in hypocenter relocation and event quality measurement.

**2.2.4 Velocity Model Approach:**

The location of each sequence is heavily affected by the surrounding geology. When constructing an aftershock catalog the decision must be made to either incorporate a suggested velocity model for the region, utilize a general crustal velocity model such as the ak-135 model that provides a decent fit to a broad range of phase arrivals, or utilize the difference in arrival times for single events to determine the speed of the P and S wave associated with an event. The latter of three is an inverse method that requires a significant amount of computation compared to the linearized approach of using a 1-D velocity model. Each sequence was tested using the accepted ak-135 velocity, a localized velocity model, and a gradient approach to the ak-135 model rather than definitive steps in p and s wave velocities. The models were tested by comparing the hypocenter locations horizontal, vertical, and travel time residual error for each event and the standard deviation associated with each specific model. The relocation algorithm used was Hypoinverse, a Fortran program for seismic event relocation and magnitude (Klein, 2002). The scope of this research did not involve magnitude assessment, so the presented catalogs omit this parameter. The input into Hypoinverse was the output of EQT. A general workflow can be found below.

*Figure: showing general workflow of scripting input 🡪 output and final catalog*

**2.2.5 Quality of Events**

The event comparison is an essential step in determining the quality of our chosen machine learning algorithm and whether it will be a valuable tool in detecting low magnitude events and P and S wave phases for each event. The output of the relocation algorithm is a summary file that contains, latitude, longitude, travel time residuals, vertical/horizontal error, depth, origin time of the event, and a quality rating. The quality assessment is determined to assess whether the location detected by EQT is an actual event and whether the phase arrivals are picked correctly on the waveform.  Hypoinverse uses several parameters: root-mean-squared travel time residual (RMS) ERH (horizontal location error), ERZ (vertical location error), NWR number of weighted station reading phases, MAXGAP (maximum angular gap in degrees between azimuthally adjacent stations, the earthquake depth, and the minimum distance to the closest station. Using these parameters Hypoinverse applies a quality rating that is an average of two quality ratings.

The first quality rating is based on errors and goodness of fit.

1. RMS < 0.15 sec and ERH ≤ 1.0 km and ERZ ≤ 2.0 km
2. RMS <0.30 sec and ERH ≤ 2.5 km and ERZ ≤ 5.0 km
3. RMS < 0.50 sec and ERH ≤  5.0 km
4. Worse than above

The second quality rating is based on station geometry:

1. NWR ≥ 6 and MAXGAP ≤ 90 and either DMIN  ≤ DEPTH or DMIN ≤5.0
2. NWR ≥ 6 and MAXGAP ≤ 135  and either DMIN ≤ 2\*DEPTH or DMIN ≤10
3. NWR ≥ 6 and MAXGAP ≤ 180 and DMIN ≤ 50
4. Worse than above

The distance from the event to the nearest station is weighted using a krigging approach. The ideal-distance weighting scheme allows for reducing the weight of the distant stations when an event is detected within the interior of a seismic network (Survey, G. 2002). The HYPOINVERSE distance weighting function is 1.0 for near stations, 0.0 for far stations, and for those in-between it follows a cosine taper as follows:

Diagram

Description automatically generated