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Locating Microearthquakes In The Salton Sea Geothermal Field, California

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Disclaimer

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LOCATING MICROEARTHQUAKES IN THE

SALTON SEA GEOTHERMAL FIELD, CALIFORNIA

by

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Lawrence Livermore National Laboratory

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ABSTRACT

We report the results of a 6-month microearthquake study of the Salton Sea Geothermal Field, California. This active geothermal field is also seismically active due to the flow of fluids through pre-existing fractures of rocks in the subsurface which can cause faults to slip. Locating these seismic events within the geothermal field enables researchers to determine whether the earthquakes are anthropogenic or tectonic from the nearby Brawley Seismic Zone. We analyzed November 2009 to April 2010 seismic waveform data retrieved from a network of continuously recording seismometers covering an area of 10 km^2. 2,271 microearthquake hypocenters were processed out of 2,609 total recorded events and their locations suggest the majority could be at approximately the same depth as the fluid injection wells.

TABLE OF CONTENTS

INTRODUCTION

The Salton Sea Geothermal Field is located in the Salton Trough near the border between the state of California and the country of Mexico. The field lies between the San Andreas Fault to the North and the East Pacific Rise spreading center to the South (Alles 2011). On a regional scale, the field is in a seismically active transition zone between strike slip movement to the North and a divergent boundary to the South. The Salton Trough is known as a graben structure where a block of Earth is bordered by two parallel normal faults that cause the center block to subside over time (Alles, 2011). Typically, this causes a major depression at the Earth's surface. However, in the Salton Sea, the Colorado River deposited sediments over millions of years at a rate equal to the rate of subsidence which created a heterogeneous environment.

Microearthquakes are classified as events that register magnitude values of less than 2 on the Richter scale. Locating these earthquakes is an inverse problem; we have the arrival time data but must solve for the location and origin time of the event. We determine the arrival times by picking the point in time when the P (primary) wave arrives at each of the seismometers. A P wave is defined as a compressional wave that moves radially away from the seismic source and shakes the ground back and forth in the same direction. These waves travel faster than S waves (shear waves) through the Earth's interior and are the first motion detected by a seismometer.

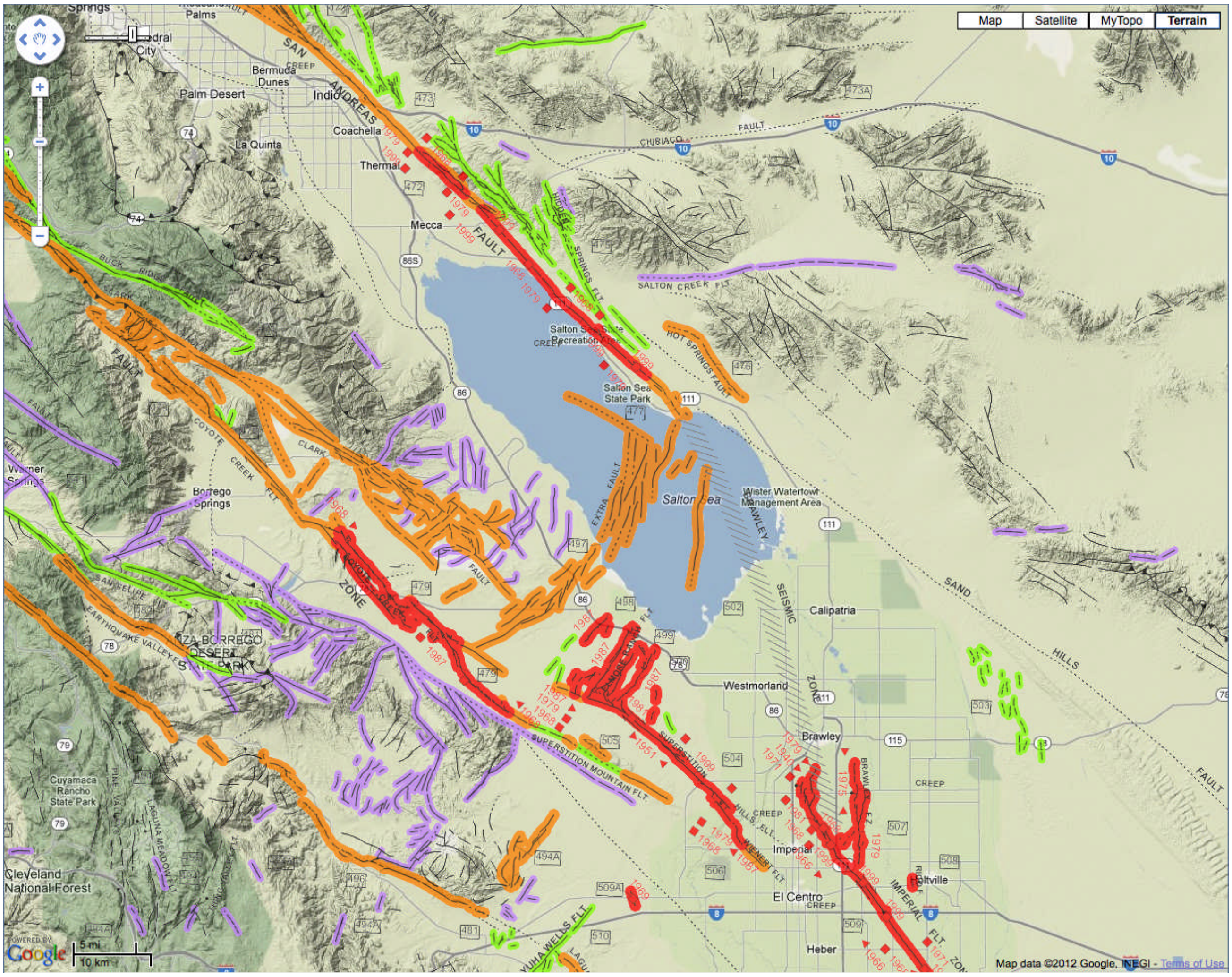

Figure 1: Location map of the Salton Sea, California, the Brawley Seismic Zone trends Northwest and Southeast through the geothermal field.

DATA AND METHODS

Seven 3-component digital seismograph stations operating in the Salton Sea Geothermal Field were used for this study. These stations continuously recorded seismic data over the entire 14-month study time period between November 2009 and December 2010. The Lawrence Livermore National Laboratory (LLNL) Matched Field Processing detection technique, altered for seismology applications by Dave Harris and Tormod Kvaerna, was applied to the continuously recorded data to detect microearthquakes (2010). The technique initially creates master templates of known and recorded seismic events from the earthquake catalog of the Southern California Earthquake Data Center (SCEDC) with a high Signal-to-Noise Ratio (SNR). Then, the master templates are matched against the continuously recorded seismic data to detect new events.

The goal of this project is to locate new seismic events identified by the MFP method in the Salton Sea Geothermal Field. The initial step is to download the SAC data of new seismic events identified by the LLNL Match Field Processing detection technique. The download list of data to be phase picked was prepared by Jingbo Wang. Download lists are organized by months that span the study time period of November 2009 to December 2010 and are titled download_newYYYYMM.txt. Each download list is composed of individual event download files with the following format:

```
WIND EN % % % 2009/11/7,4:35:58 2009/11/7,4:38:58
WIND EN % % % 2009/11/7,4:50:4 2009/11/7,4:53:4
WIND EN % % % 2009/11/7,4:54:23 2009/11/7,4:57:23
WIND EN % % % 2009/11/7,4:57:8 2009/11/7,5:0:8
```

WIND EN % % % 2009/11/7,5:17:35 2009/11/7,5:20:35

The format of the download file is to specify a time range within a certain seismic network and gather data from all stations in the specified network. In this study, we download data from the EN network. To download the SAC data, copy the file download_newYYYYMM.txt into a parent directory pick_newYYYYMM and a sub-directory download_newYYYYMM. The user must run the STP program in Unix and use the command: INPUT download_newYYYYMM.txt inside the sub-directory download_newYYYYMM. All seismic waveform data will be stored in the sub-directory download_newYYYYMM. Individual event .sac files cover 3 minutes of time; 1 minute prior to the actual event origin time and 2 minutes after the event origin time for each of the 3 components for the 7 stations used in the study. This was done to view the seismic noise prior to the start of an event as a way to better view the onset of the P wave compared to the background noise. The low frequency of the noise compared to the high frequency of an earthquake is another way of correctly identifying the P pick. Also, the increase in amplitude of the earthquake over the low amplitude of the background noise is another way to identify the P pick.

The next step is to organize the newly downloaded waveform data. The SAC files contain information from 7 different seismic stations and 3 different components (2 horizontal and 1 vertical) from each station totaling 21 individual files per event. The name of the waveform data (20091124003725.EN.ELM.EHZ.06.sac) needs to be formatted by removing (.06) to comply with the formatting requirements of the run_picks script. Execute script remove_characters inside of directory download_newYYYYMM. Then, copy the python script make_evt_dir2.py into the parent directory pick_newYYYYMM and execute the script. All of the files will be organized into individual directories with the format YYYYMMDDHHmmSS and will be referred to as "SAC directory names" in the parent directory pick_newYYYYMM.

Once the data is correctly organized for each month, the next task is to perform the P wave phase picking of individual seismic events. Input command "ssh –X claw" in Terminal before performing P picks so that graphics will appear on the user's home computer. Select a SAC directory name from the pick_newYYYYMM directory and copy the script run_picks into the command line (./run_picks "script") in the pick_newYYYYMM directory. Make sure the script arc_seconds is also in the pick_newYYYYMM directory. Execute run_picks and a seismogram of an event will appear.

The objective is to select the exact time the P wave arrives to 3 digits of accuracy on the vertical component (EHZ) of the stations. To zoom in, select an area of the seismogram using the "x" key, to zoom out use the "o" key, to display the timestamp anywhere in the seismogram use the "l" key and to make a P pick use the keys "up" or "dp" to indicate first motion up or down. All P pick times will be saved in the file P_picks_new_nov09.txt for example. The format of this file is:

```
20091124003725.EN.ELM.EHZ.sac      IPU0
2009328140733193388032140733193388070 26.92      103.7 M              C

   20091124003725.EN.ENG.EHZ.sac      IPU0
2009328140733193388032140733193388070 27.87      590.7 M              C

   20091124003725.EN.HAT.EHZ.sac      IPU0
2009328140733193388032140733193388070 26.93      570.9 M              C
```

```
  20091124003725.EN.OBS.EHZ.sac      IPU0
2009328140733193388032140733193388070 27.25      480.6 M             C
```

The first column contains the origin time of the event, the network code, the station code name, and the station component (EHZ represents the vertical component). The second column contains the motion of the P pick (up or down). The third column contains a string of information that may be corrupted and is not used in this study. The fourth column is the time of the P pick in seconds. The fifth column represents the amplitude of the P pick and the sixth column states the source of the pick "M" for a manual pick. The time of the P pick will be used in the input phase file for the Hypoinverse program.

The second output of run_picks is the input phase file for Hypoinverse that is titled "salton_new_nov09.arc". This output is formatted using script arc_seconds , which converts, for example, the fourth column of P_picks_new_nov09.txt to the correct input format for Hypoinverse.

```
ELM  EN  EHZ  PD0200911070613 4210
ENG  EN  EHZ  PD0200911070613 4245
HAT  EN  EHZ  PD0200911070613 4183
OBS  EN  EHZ  PU0200911070613 4251
RED  EN  EHZ  PU0200911070613 4201
YOU  EN  EHZ  PU0200911070613 4283
```

Each line of the .arc file contains the seismic station name, network code, component code, P wave indicated by letter "P", up or down first motion, weight code, and time of P pick (YYYYMMDDHHmm and seconds).

Next use the SCEC Community Velocity Model and GMT programs to generate a 1D homogeneous layered velocity model of the study area. The velocity model used in this study contains individual homogeneous layers at precise depth intervals selected by the author with a constant velocity throughout individual layers. Using GMT, plot a distribution of grid points that cover the study area to provide an accurate representation of the subsurface structure. Designate the depths of each grid point you are interested in imaging the velocities of. The input file (btestin) is formatted as follows:

```
240
33.135 -115.5867 0.0
33.135 -115.5867 500.0
33.135 -115.5867 1000.0
33.135 -115.5867 1500.0
33.135 -115.5867 2000.0
33.135 -115.5867 2500.0
33.135 -115.5867 3000.0
33.135 -115.5867 3500.0
33.135 -115.5867 4000.0
33.135 -115.5867 4500.0
33.135 -115.5867 5000.0
33.135 -115.5867 5500.0
33.135 -115.5867 6000.0
33.135 -115.5867 6500.0
33.135 -115.5867 7000.0
33.135 -115.5867 8000.0
33.135 -115.5867 9000.0
33.135 -115.5867 10000.0
33.135 -115.5867 11000.0
33.135 -115.5867 12000.0
```

The first line represents the total number of points in the file, the subsequent lines contain the latitude, longitude, both in decimal degrees, and depth in meters of a given grid point. Execute the SCEC Community Velocity Model with command: ./version3.0 in directory Version4_1. The format of the output file (btestout) is:

```
33.13500 -115.58670    0.00  1800.0   818.7  2149.2
33.13500 -115.58670  500.00  2328.2  1143.2  2232.6
33.13500 -115.58670 1000.00  2856.4  1491.1  2316.0
33.13500 -115.58670 1500.00  3384.6  1858.1  2399.4
33.13500 -115.58670 2000.00  3912.8  2241.2  2482.8
33.13500 -115.58670 2500.00  4441.0  2564.0  2566.2
33.13500 -115.58670 3000.00  4969.2  2869.0  2649.6
```

The first column is the latitude of the grid point, the second column is the longitude, the third column is the depth, the fourth column is the velocity of the P wave in meters per second, the fifth column is the velocity of the S wave in meters per second and the sixth column is the density in kilograms per meters cubed.

Next, calculate an average velocity for the 1D homogeneous layered velocity model of the velocity of each grid point at each specified depth. Use the script calculate_average_velocity to organize the final output of the velocity model.

```
SALTON SEA MODEL
1.80  0.00
2.53  0.50
3.26  1.00
4.00  1.50
```

The first line is the title of the model; the subsequent lines represent the P wave velocity in kilometers per second in the first column and the depth in kilometers in the second column.

Using this averaged 1D homogeneous layered velocity model, create the 1D linear gradient layered velocity model using the program TTGEN. Use the command: ./ttgen after creating the input file ttmod. as follows.

```
sal.PRT sal.   .1563
 .04  200  0.2  200   (48 MAX)
 0.5   15  1.0    10   (40 KM DEPTH MAX)
 0.5   25  1.0     0   (135 KM DIST MAX)
SALTON SEA
 1.80  0.00
 2.53  0.50
 3.26  1.00
 4.00  1.50
 4.63  2.00
```

```
4.72  2.50
4.90  3.00
4.92  3.50
5.01  4.50
5.10  5.00
5.36  5.50
5.62  6.00
5.72  6.50
6.22  9.00
6.64 12.00
```

The first line represents the title of the output file and the reducing velocity value in seconds per kilometer, and is approximately equal to the halfspace velocity of the model. The second line represents parameters for incrementing the independent parameter Q governing ray spacing, in this example the program starts with 0.0 then iterates 200 values at increments of 0.4 followed by 200 values at increments of 0.2. 2 sets of values and increments allow for various spacing intervals at different depths. The third line represents the parameters for incrementing the grid spacing in depth and follows the same format as line two. The fourth line represents the parameters for incrementing the grid spacing in horizontal distance and follows the same format as line two. For lines three and four, the values are in kilometers. The fifth line is the name of the model. The sixth and subsequent lines represent the values of the homogeneous velocity model with column one being velocity in kilometers per second and the second column being depth in kilometers.

The output of the linear gradient layered velocity model is in .crt format for use in Hypoinverse:

```
SALTON SEA        15  0.1563
 0.0  0.5  1.0  1.5  2.0  2.5  3.0  3.5  4.5  5.0  5.5  6.0  6.5  9.0 12.0
 1.8  2.5  3.3  4.0  4.6  4.7  4.9  4.9  5.0  5.1  5.4  5.6  5.7  6.2  6.6
 0.5000 25 1.0000  0
 0.5000 15 1.0000 10
```

0.0000 1.8000 2
-32000-31604-31230-30891-30594-30340-30125-29945-29796-29675-29576-29490-
29416-29353-29294
-29234-29175-29115-29056-28997-28937-28880-28822-28764-28707-28649
0.5000 2.5300 12
-31533-31499-31288-31051-30825-30622-30445-30294-30167-30062-29972-29893-
29825-29766-29707
-29648-29589-29530-29471-29412-29353-29294-29235-29176-29117-29060

The first line represents the model name, number of velocity points used for model, and the reducing velocity in seconds per kilometer. The second and third lines are the depths and velocities of points used in the model respectively. The fourth and fifth lines represent the parameters for incrementing grid spacing in depth and in distance respectively. The sixth line represents the depth, velocity, and value that resolves the ambiguity between up going and down going rays. The seventh line shows the reduced travel times at each grid point generated from lines four and five. Reduced travel times are given as integers in units of .0005 seconds minus 32000 to represent 0.0 to 32 seconds. Rename this .crt file to salvelocity.crt.

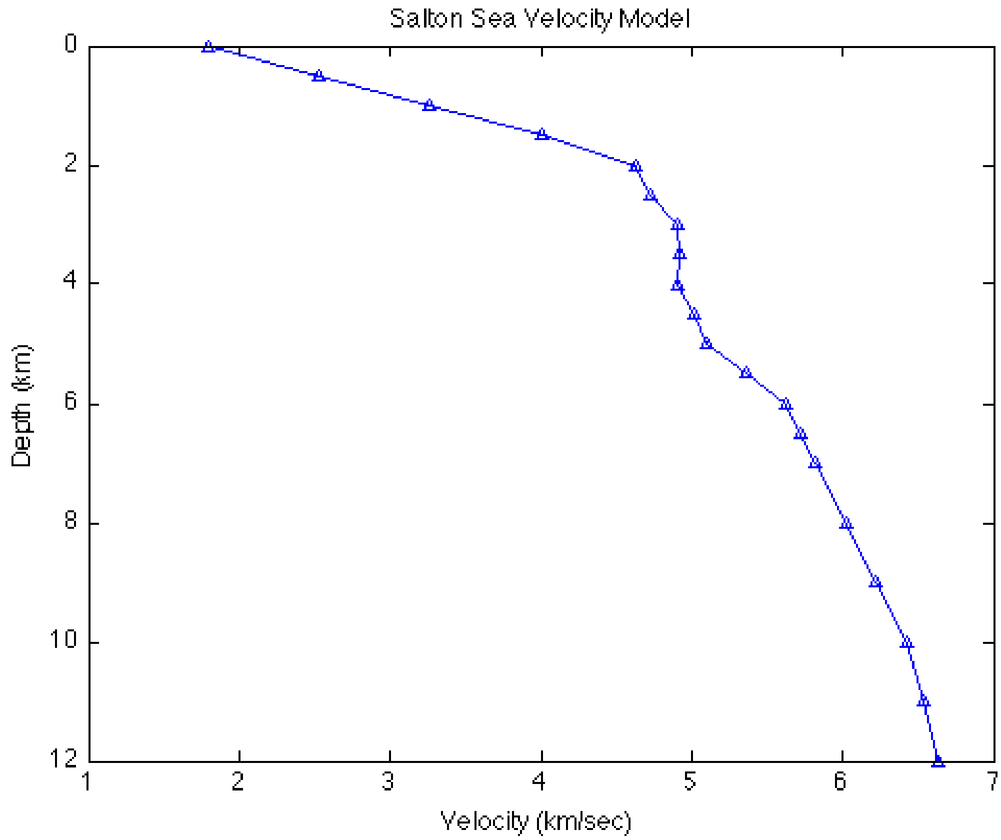

Figure 2: One dimensional P wave linear gradient layered velocity model profile created using TTGEN program

Finally, use the Hypoinverse program to locate the seismic event. The first input file is the station list titled salton.sta:

```
ELM   EN  EH2  33 10.6320 115 36.8040   -64.0   A 0.00  0.00  0.00  0.00 1  0.00
ELM   EN  EH3  33 10.6320 115 36.8040   -64.0   A 0.00  0.00  0.00  0.00 1  0.00
ELM   EN  EHZ  33 10.6320 115 36.8040   -64.0   A 0.00  0.00  0.00  0.00 1  0.00
ENG   EN  EH2  33  8.8620 115 32.6280   -64.0   A 0.00  0.00  0.00  0.00 1  0.00
ENG   EN  EH3  33  8.8620 115 32.6280   -64.0   A 0.00  0.00  0.00  0.00 1  0.00
ENG   EN  EHZ  33  8.8620 115 32.6280   -64.0   A 0.00  0.00  0.00  0.00 1  0.00
```

The first column is the station name, the second column is the network code, the third column is the component code, the fourth and fifth columns are latitude in degrees minutes.m, and the sixth and seventh columns are longitude in degrees minutes.m. The eighth column is the elevation of the seismic station in meters. The ninth column is an optional station remark field. The tenth and eleventh columns are P delays in seconds. The twelfth column is the amplitude magnitude correction. The thirteenth column is the duration magnitude correction. The fourteenth column is the instrument type code. The fifteenth column is the calibration factor.

The next file is the linear gradient velocity model with the title: salvelocity.crt.

The next file is the input phase file with title, for example: salton_new_nov09.arc. Start by copying the unformatted .arc file from Pick_Tyler directory to SALTON_SEA directory that contains the Hypoinverse program. To correctly format the input file, execute script make_sac_names_eid_new_nov09 in pick_new200911 directory to create the individual summary header lines for each event located in the file final_sac_names_eid_new_nov09 for example:

20091107043518 00000001

00000001

20091107044745 00000002

00000002

Each line contains the sac origin time followed by 2 numbers which both represent my creation of Event Identification Numbers. The latter number is in the correct position to be compatible with the Hypoinverse program and the first EID number is read over (skipped) by Hypoinverse. Manually copy and paste each summary header line with the correct P pick information for each individual event and insert a space between successive events.

```
20091107043518 00000001
00000001
ELM  EN  EHZ  PU0200911070436 1934
ENG  EN  EHZ  PU0200911070436 1971
HAT  EN  EHZ  PD0200911070436 1907
OBS  EN  EHZ  PU0200911070436 1982
RED  EN  EHZ  PU0200911070436 1929
YOU  EN  EHZ  PD0200911070436 2010

20091107044745 00000002
00000002
ENG  EN  EHZ  PD0200911070448 4703
HAT  EN  EHZ  PU0200911070448 4652
RED  EN  EHZ  PU0200911070448 4700
YOU  EN  EHZ  PU0200911070448 4744
```

The first line is the name of the event in YYYYMMDDHHmmSS format followed by the EID number and the EID number in the correct column/position. The first EID number is skipped over by Hypoinverse and does not affect the output of an event's location. The second line is the station name, network code, component code, P wave, up or down first motion, weight code, YYYYMMDDHHmm, seconds.

Place all of these files in a single directory along with the Hypoinverse program and sal_nov09.hyp script and execute the script: ./hyp followed by @sal_nov09.hyp.

The output will be the following:

Output archive file

```
200911240037260333 1078115 3606  272  0  6141  1   235171 11822211  65  0     44    0  64 112  6  00  00  0
0SAL      6    0 00   0 00        0   0  00   0  00  NC01
ELM  EN  EH2  PU0200911240037 2692   1100    0   0   0     0 0  0   0   0  1214900  0    0257  0  0 531   0     0
HAT  EN  EH2  PU0200911240037 2693  -2100    0   0   0     0 0  0   0   0  1614100  0    0130  0  0 683   0     0
```

The first line is a summary header line containing various pieces of data and information. The second line contains the same information as the input phase file but also includes the P travel time residual in the sixth column.

Output print file

Contains vast amount of information including data and information from input and output files and explanation of iterations to calculate location of earthquake.

Earthquake location

```
SEQ ---DATE--- TIME REMARK -LAT-  --LON-  DEPTH  RMS PMAG  NUM  ERH  ERZ  ID
  1   2009-11-24  0:37              33 11   115 36   2.72     0.02    0.0        6       0.6     1.1           0
```

Where depth is in kilometers, RMS is Root Mean Square travel time residual in seconds, ERH is error in the horizontal direction in kilometers, and ERZ is error in the depth in kilometers.

Copy all location outputs into a file titled initial_nov09_locations to create an earthquake catalog. After creating a file of earthquake locations, plot these locations and the coordinates of the 7 seismic stations used on a map of the study area using Generic Mapping Tools. First sort events according to quality rating based on errors and goodness-of-fit discussed by Klein (2000) using script quality_rating. The letter “A” denotes the best quality location. Assign four different colors to represent each quality: A (purple), B (green), C (red) and D (blue).

- A. RMS < 0.15 sec and ERH <= 1.0 km and ERZ <= 2.0 km
- B. RMS < 0.30 sec and ERH <= 2.5 km and ERZ <= 5.0 km
- C. RMS < 0.50 sec and ERH <= 5.0 km
- D. Worse than C.

Convert the latitude and longitude coordinates in the format of degrees minutes from output of Hypoinverse into the format of decimal degrees for the input into GMT. Create the hypocenter location map of November 2009 to April 2010 data by executing the script ./run_makemap.

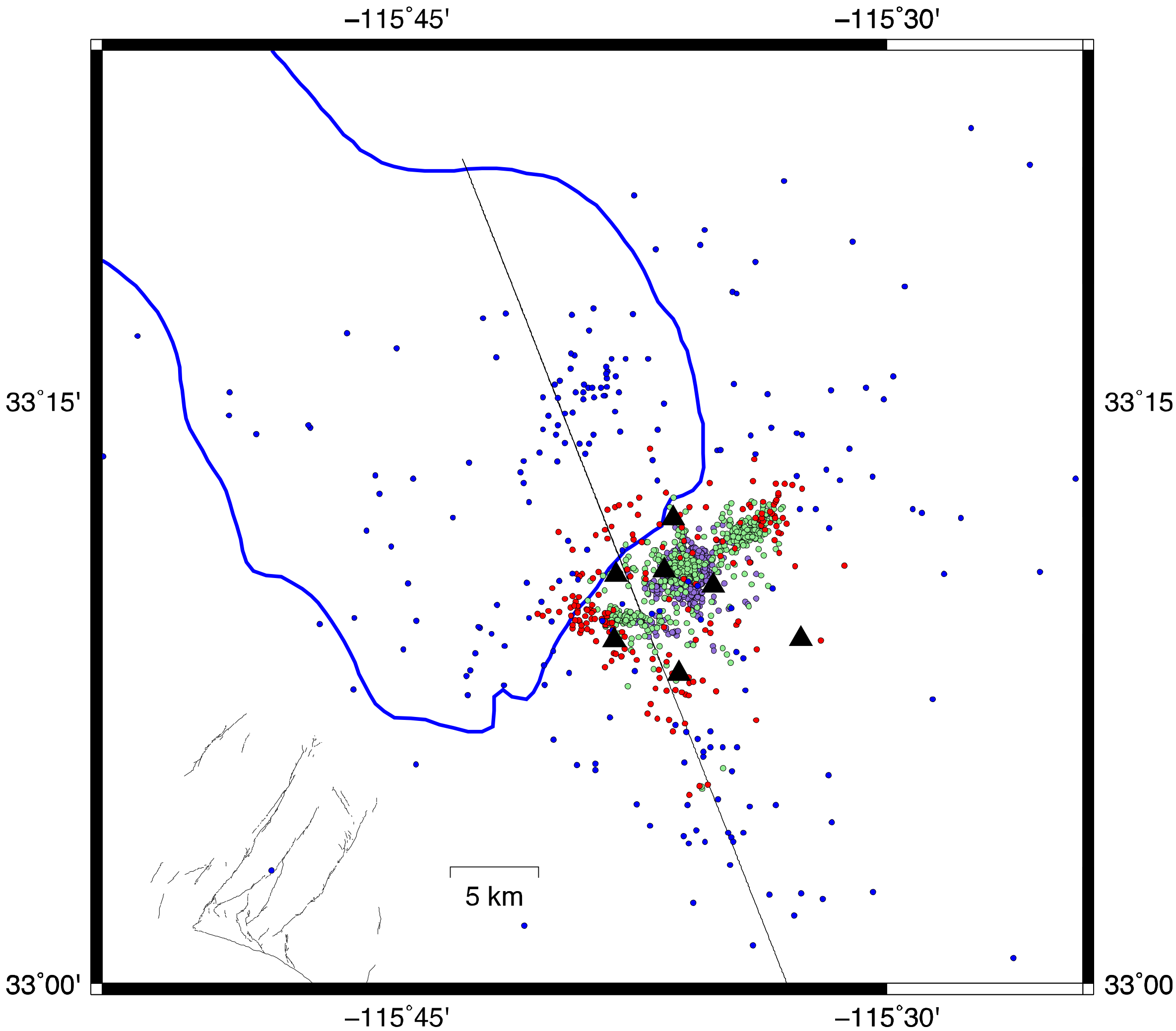

Figure 3: Hypocenter location map for November 2009 to April 2010 data

DISCUSSION

The primary objective of this study was to locate microearthquakes in the Salton Sea Geothermal Field using the program Hypoinverse. I successfully located 2,271 hypocenters out of a total of 2,609 events for the months of November 2009 to April 2010. The majority of depths I calculated are concentrated between 1 and 3 km; these results are shallower when compared to another relocated earthquake catalog by Egil Hauksson which reported depths between 2 and 4 km for the same study area (2011). The Hauksson catalog uses waveform cross correlation and a three-dimensional velocity model but also uses models that cover the entire area of Southern California. One explanation for my shallow depths could be due to the speed of my velocity model. If the velocity model is too fast, seismic waves will propagate through the model faster and can result in shallower depths. A slower velocity model may produce more accurate locations.

A few assumptions were also necessary to use the Hypoinverse program; the first issue is the scale of the study area. This study focuses on a small 10 km^2 area as opposed to the entire area of Southern California. Therefore, I expect my velocity model to have good resolution and return accurate locations because this model only covers and represents the study area. However, I am also using a homogeneous layered velocity model when the study area is a heterogeneous environment due to the deposition of different sediments over geologic time. I attempted to make my P arrival time picks with confidence but admit that some picks may not be accurate due to a low Signal-to-Noise Ratio waveform which made the event difficult to discern from the background noise.

Calculating hypocenter locations involves both measurement and modeling errors with respect to seismic arrival times, calculated travel times and the velocity model used (Husen and Hardebeck, 2010). I use a homogeneous layered velocity model when the study area is a heterogeneous environment due to the deposition of different sediments over geologic time. I also only use P wave arrival times for this study, which improves the accuracy of event locations but lowers the precision of locations. Finally, I attempted to make my P arrival time picks with confidence but some picks may not be accurate due to a low Signal-to-Noise Ratio waveform, which made particular events difficult to discern from the background noise.

Overall, the shallow depths do suggest that the majority of these events are located at approximately the same depth as the fluid injection wells of the geothermal field (Templeton, 2012). However, it is difficult correlate geothermal activity with causing microearthquakes because the companies do not release injecting and pumping data on similar time scales. Data from companies is on the order of months and would need to be daily or weekly to do a proper correlation between injection and seismicity rates. Therefore, the cause of microearthquakes in the Salton Sea Geothermal Field could be a combination of geothermal activity and natural tectonics from the Brawley Seismic Zone.

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Husen, S., and Hardebeck, J.L. (2010), Earthquake location accuracy, Community Online Resource for Statistical Seismicity Analysis, doi:10.5078/corssa-55815573.

Klein, F.W., User's Guide to HYPOINVERSE-2000 a Fortran Program to Solve for Earthquake Locations and Magnitudes, USGS Open File Report, Draft 5/19/2000.

Matzel, E., Personal communication, 08/01/2012.

Templeton, D., Personal communication, 08/01/2012.

PROGRAMS

Hypoinverse-2000, a Fortran program to solve for earthquake locations and magnitudes "hypoinv"

Seismogram Transfer Program (STP), Southern California Earthquake Data Center (SCEDC) program for retrieving waveforms and parametric data from the SCEDC archive "/opt/stp1.6/stp"

SCEC Community Velocity Model, a Fortran program that creates a 3D subsurface velocity structure model "Version4_1"

TTGEN, a Fortran program that generates a grid of travel times as a function of distance and depth to prepare a 1D linear gradient velocity model from a given velocity-depth function "ttgen_1"

GMT, program that generates map projections "GMT"

SAC, program used to analyze seismic events through plotting seismograms and performing P wave arrival time picking "SAC"