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PRELIMINARY INVESTIGATION OF AN ASEISMIC 'DOUGHNUT HOLE' REGION IN THE NORTHWEST GEYSERS, CALIFORNIA

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ABSTRACT

The Geysers Geothermal Reservoir experiences thousands of seismic events each month; some of these events are associated with recent coldwater injection and steam production within the Geysers basin. The greatest injection volume rate occurs in the Northern Geysers, and it is here that a flattened spheroidal region of relatively low seismic density, called the Doughnut Hole, has become visible within the last 20 years. The Doughnut Hole is preliminarily defined as a region of low seismic density (normalized number of earthquakes per unit volume) surrounded on all sides by a region of higher seismic density. This study is in its preliminary stages; we have collected and processed the data, but are in the early stages of analysis. This study seeks to determine the true 3-D extent of the Doughnut Hole, to image concurrent changes in the local velocity structure, and to describe its origins. The dataset is comprised of over 87,000 events detected in the Geysers by the Lawrence Berkeley National Laboratory seismic array, and located using a new automated phase-picking, locating, and processing system.

INTRODUCTION

Geological Setting

The Geysers geothermal reservoir is located just south of Clear Lake, nested between the Southwest-bounding Mayacama fault and the Northeast-bounding Collayami fault (McLaughlin, 1981) in a region of complexly blended strike-slip and thrust faulting. Historic subduction of the Farallon plate beneath the North American plate led to Pliocene-Holocene volcanism which left enough heat to metamorphose the graywacke of the overlying Franciscan melange to biotite (Moore, et.al, 1995). Felsite from a Quaternary magmatic intrusion is non-uniform in extent along the reservoir's length, reaching up to shallower elevations in the Southeast Geysers, but residing between 1 and 2 km depth, relative to sea level, in the Northwest Geysers (Thompson, 1989). Heat for the reservoir has been thought to originate from a large, silicic magma body just North of the steam field (Stimac, et.al, 1992), previously percolating groundwater through the natively low-permeability Franciscan melange when fractures opened due to local faulting. The Geysers was historically fluid-dominated (Sternfeld, 1989; Moore and Gunderson, 1995), but increased fracture volume due to crustal extension has been implicated in the formation and sustained presence of the vapor-dominated conditions that exist today (Allis & Shook, 1999).

Production and Injection History

Industrial production of steam from the Geysers began in 1960, and coldwater injection followed shortly thereafter. Small-magnitude seismicity has a well-documented relationship with both injection and production, but when increased seismicity was first noted following the start of production and injection, the temporal and spatial relationship was unclear. Where seismicity was observed, the most probable explanations included cooling-based volumetric contraction which triggered nearby faults (Eberhart-Phillips & Oppenheimer, 1984), aseismic creep being converted to seismic slip due to increase in effective rock pressure, and dehydration of clays and fault gouge that caused increased friction along fault surfaces (Allis, 1982; Eberhart-Phillips & Oppenheimer, 1984). Spatial relationships between production/injection and seismicity were noted in 1995 (Romero, et.al), with production-based earthquakes appearing in the steam production zone, and injection-based events occuring much deeper, clustered around well heads; few events occurred deeper than 3km presumably due to the near-ductile

state of rocks at this depth, although the rocks could become brittle in the presence of cool injectate. Later, temporal relationships between injection and seismicity were found to be somewhat predictable and injection-induced earthquakes were found to be of generally low magnitude (1.5<M<3.0). Though earthquakes of higher magnitudes have increased in number since reservoir stimulation began, the increase could not be temporally associated with injection (Majer & Peterson, 2007). Several source mechanisms have been suggested, however injection-based seismicity is likely due to cooling-induced shear-slip along fractures (Rutqvist & Oldenburg, 2008) and production-based seismicity is likely due to temperature and pore-pressure decline (Denlinger & Bufe, 1982).

First Observation of the Doughnut Hole

The Doughnut Hole (DH) was first expressed by Beall et.al (2010 as an anomalous 'de-coupling' of injection rate and induced seismicity in the Northwest Geysers, the area of highest volume injection. A strong relationship between deep seismicity and injection in the Northwest Geysers has been associated with the "High-Temperature Zone" (HTZ) underlying the main reservoir (Stark, 2003), but in 2007 the injection-induced seismicity relationship for the HTZ began to change: in certain regions, injection rates no longer induced seismicity in a predictable manner. A plot of deep seismicity and cumulative coldwater injection in the Northwest Geysers (below) reveals the DH at depth, although it remains unclear whether the DH resides within the HTZ without knowing its true 3D extents; this study will ultimately define the DH in 3-dimensions, and will report its spatial association with the HTZ.

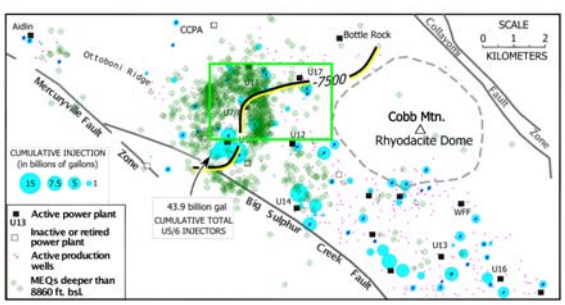


Figure 1. (Borrowed from Beall et.al, 2007). Deep seismicity in the Northwest Geysers co-plotted with aggregate coldwater injection in blue circles, with circle radius representative of injection amount.

If seismic activity in the Northwest Geysers is related to thermal contraction, then de-coupling of injection and induced seismicity in the DH region could represent accumulation of injectate as plumes within the reservoir (Beall et.al, 2009).GEYSERS DATA

In order to formulate a comprehensive description of the DH via seismicity, we confirmed its appearance in two separate catalogs based on distinct seismic monitoring arrays, picking algorithms, and location methods. The Northern California Earthquake Data Center (NCEDC) utilizes USGS monitoring stations and locations, and its 2003-2010 catalog provided good lateral constraints on the DH region, enabling us to define a study area to investigate more deeply with the LBNL-Geysers array.

NCEDC Catalog

The NCEDC catalog reports a total of 80616 earthquakes in the Geysers region from Apr 22, 2003 to Dec 1, 2010, with an approximate catalog b-value of 1.08 from a least-squares fit of the completeness range for the entire catalog.

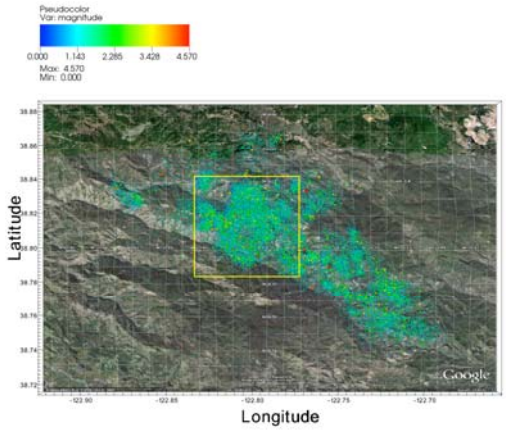


Figure 2. NCEDC catalog for Apr 22, 2003 – Dec 1, 2010 in The Geysers.

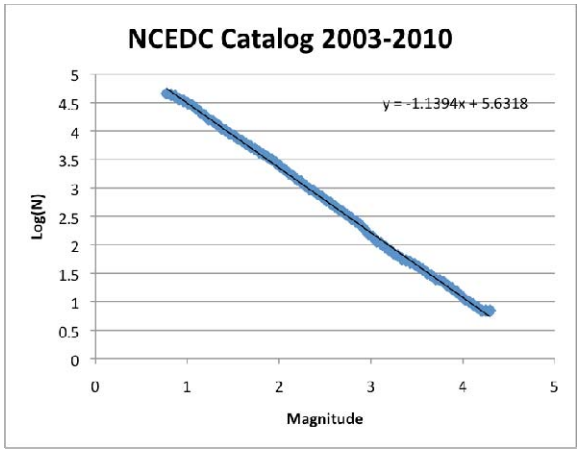


Figure 3. NCEDC catalog b-value.

This catalog was used as a base for corroborating the distribution of seismicity reported in the Lawrence Berkeley National Laboratory (LBNL) catalog,

generated from 33 three-component stations distributed in the Geysers area.

LBNL Catalog

The LBNL Rapid Geothermal Reservoir Assessment Program (RGRAP) registered 273602 triggers in the Geysers region during the period of April 2003 to Nov 23, 2010. Of these triggers, 87,467 were selected for detailed imaging of the DH region based on the following quality criteria: RMS travel-time residual less than 0.20s, vertical and horizontal location errors of 1 km or less, and a minimum of 8 phase picks (any combination of P- and S- picks). The resulting catalog and b-value curve are shown below. The b-value curve exhibits a peculiar slope change at around Mw = 2.5, which needs to be investigated further. The catalog appears complete above Mw = 0.84, but may be unreliable for Mw > 3.8, perhaps highlighting the need for long-period instruments in addition to the current array.

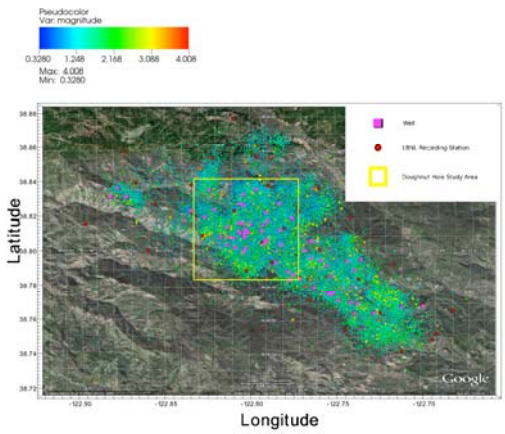


Figure 4. RGRAP catalog for 2003-2010, with injection wells and LBNL monitoring stations.

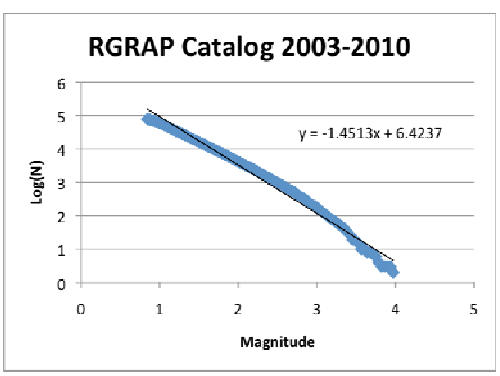


Figure 5. RGRAP catalog b-value, for the entire Geysers with least-squares linear regression to estimate b.

Further query into the 'b-value bend' shows a time-dependence, which may be indicative of monitoring capabilities at the time, or transient geomechanical phenomena related to injection and production. A plot of the b-value base curve for the 2003 events only (including regions beyond the catalog completeness) shows a noticeable bend in the entire curve, although the slope of the most linear region (Mw = 1.61 – 2.99) is identical to the aggregate NCEDC b-value of 1.08. In a plot of the 2005 events alone, the completeness range exhibits a linear magnitude-frequency relationship between Mw = 0.91 and Mw = 2.98, but is much higher, at b = 1.26.

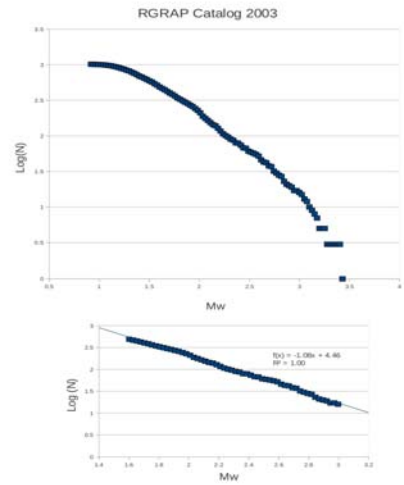


Figure 6. RGRAP Geysers catalog b-value for 2003 with entire catalog (top) and linear fit of catalog completeness region (bottom).

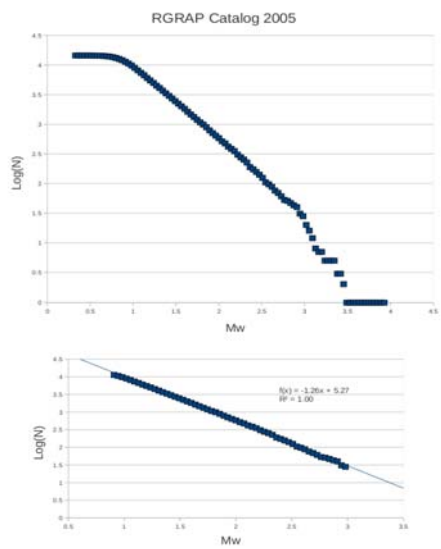


Figure 7. RGRAP Geysers catalog b-value for 2005 with entire catalog (top) and linear fit of catalog completeness region (bottom).

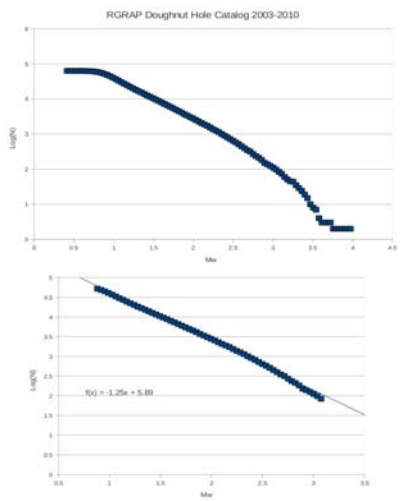


Figure 8. RGRAP Doughnut Hole b-value for 2003 to 2010, with entire catalog (top) and linear fit of catalog completeness region (bottom).

The DH study area, which lies between longitudes -122.8335 and -122.77255, and latitudes 38.78313 – 38.84145, has a lower b-value (b = 1.25) than that computed for the entire Geysers (b = 1.45). The overall high b-values are representative of an oversampling of small events, which are typical of geothermal and enhanced geothermal sites. Further investigation of the b-value behavior will include the temporal and spatial subsets and correlations with reservoir stimulation.

Comprised of a subset of 63443 events from the RGRAP catalog, the DH study area represents 72.5% of the entire Geysers' recorded seismicity.

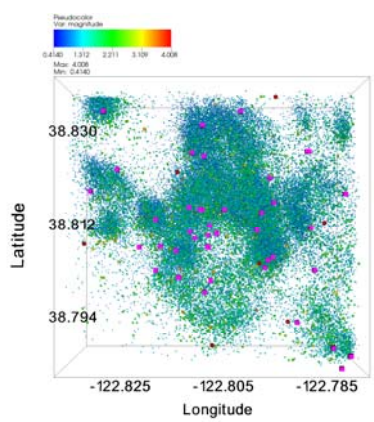


Figure 9. Seismicity in the Doughnut Hole study area from the RGRAP catalog for years 2003-2010, outlined in yellow in Figure 4. Pink boxes represent injection wells, and red spheres represent LBNL network recording stations.

The DH is not immediately apparent in map-view because it is a three-dimensional feature; not all seismic clusters from Figure 6 are part of the DH (or of the "Doughnut" of seismicity surrounding it). In the plots below, one can see that the majority of the Northernmost events are higher in elevation than the ring and hole which comprise the DH feature.

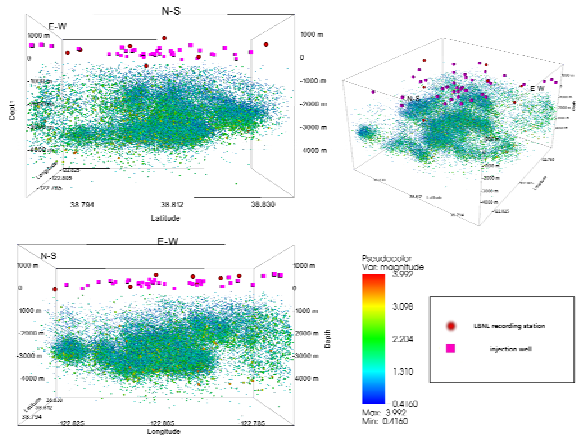
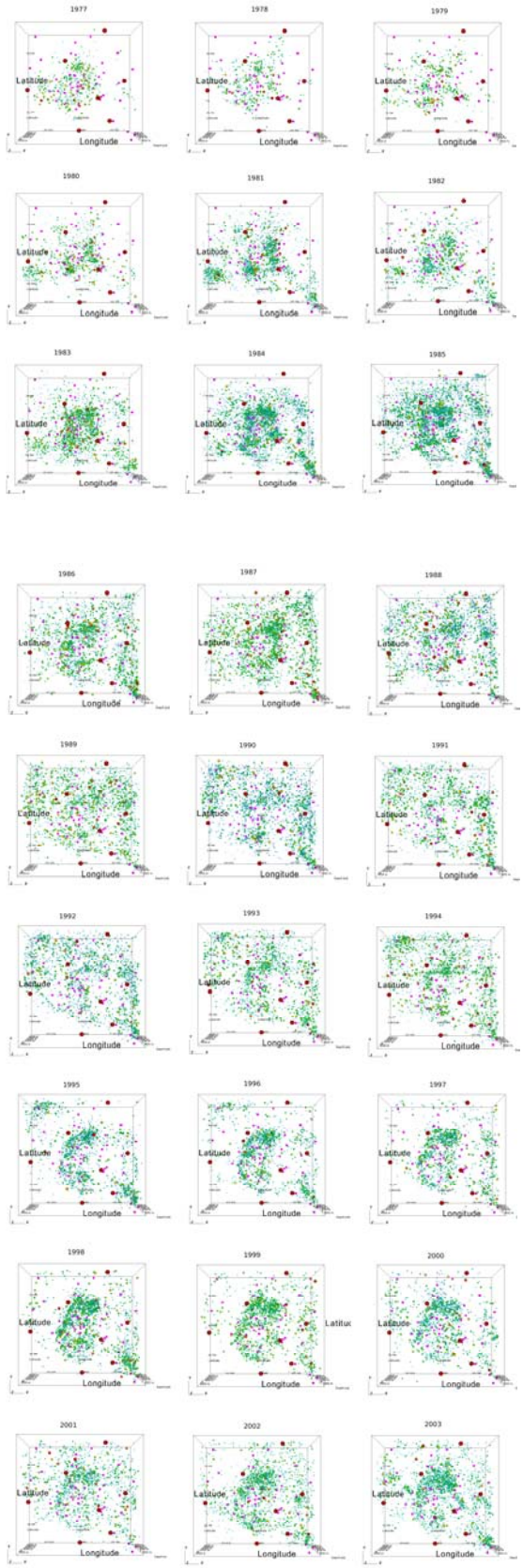


Figure 10. 3-dimensional plots of RGRAP catalog hypocenters in the DH region.

CHALLENGES IN DEFINING THE DOUGHNUT HOLE

The Doughnut Hole cannot be defined from hypocentral locations alone. In fact, several factors undermine precise definition of the feature. First, the first appearance of the DH cannot be clearly constrained in time. The LBNL seismic monitoring array was set up in 2003, and prior to this date, seismic catalogs come from two sources: 1. Calpine Corporation's local monitoring array (data still being processed), which was set up in 1999, and 2. the NCEDC catalog, which is sparse prior to 2006. An attempt to catch the first appearance of the DH using the limited NCEDC data is inconclusive, but it does raise interesting questions about whether the DH is relatively aseismic, or whether the region around it is highly seismic. In the plots below, a circular region of relatively high seismicity appears around 1982, presumably associated with increased injection rates in the center of the future DH. However, by 1988, the seismicity in the study area is more-or-less uniform, and until reservoir data has been processed we cannot describe the seismicity in terms of injection or production activity. A visible cluster of seismicity in the study area reemerges in 1995, but now the seismicity is concentrated around the edges of the circular region, and over time the seismicity rates increase markedly around a pocket within which the rates remain relatively constant.



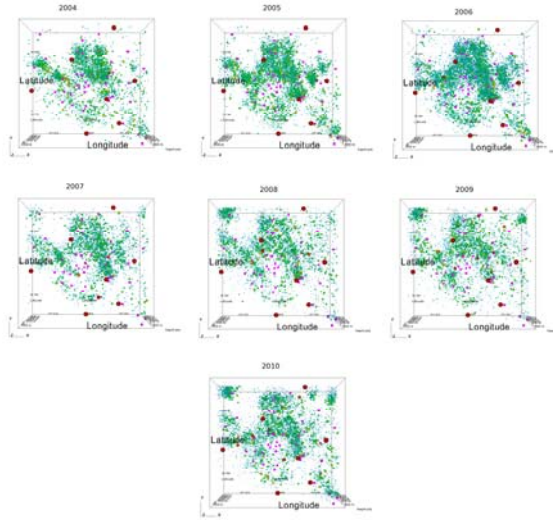


Figure 11. NCEDC seismicity in the Doughnut Hole region displayed year-by-year for all of 1977 to 2010.

The second consideration in defining the DH is that it is not truly aseismic—there is, in fact, scattered seismicity throughout the study area, but in the DH it is, on average, lower and less-clustered in distribution. Third, resolution of the DH edges is limited to the accuracy of the earthquake catalog. Fourth, the DH is a three-dimensional feature that must be defined (and imaged) in three dimensions, and is not visible from a map view alone. Fifth, the center of mass of the low-seismicity region changes slightly from year to year because of its randomly distributed seismicity, and this may be accompanied by simultaneous changes in the local velocity structure. Therefore, a comprehensive definition of the DH must be time-dependent, expressed with respect to hypocentral location uncertainty, accommodate changing velocity structure, and it must be truly 3-dimensional.

One method of describing the low-seismicity anomaly is through seismic density—the number of earthquakes per unit volume. If the volume is defined based on the average location uncertainty for the entire catalog, then it is reasonable to report the number of hypocenters per grid volume as an empirical description of 'seismicity,' with the assumption that uncertainties due to hypocenters on the edges of gridblocks will cancel each other out across the entire area. Further, taking horizontal slices using the same average location uncertainty moving downward through the study region will generate a 3-D image based on location uncertainty.

To obtain a rough estimate of this method's usefulness, we chose to make the density gridblock size equal to the average RMS travel-time residual for the entire catalog multiplied by a P-velocity of 5

km/s (taken from a depth of 2.0 km with our initial coarse 1-dimensional P-velocity model). An example of seismic density for the year 2005 data is shown below. The DH would be defined by contiguous low-seismicity gridblocks surrounded in all 4 horizontal directions by high-seismicity gridblocks, and plots such as these would be stacked in the z-direction to describe the 3-D extent of the feature.

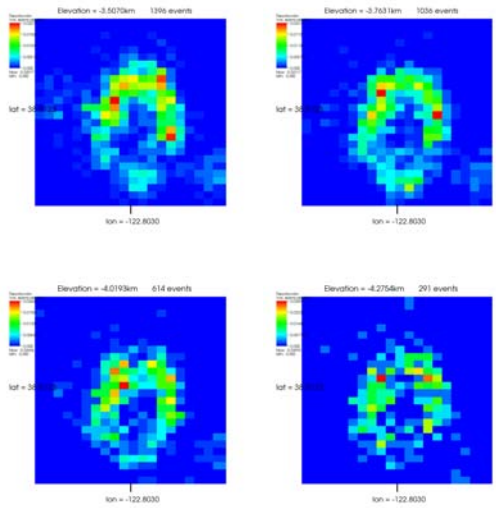


Figure 12. Four vertically sequential seismic density (number of hypocenters per unit volume determined by the average catalog location uncertainty) images for 2005 data from the RGRAP catalog.

CONCLUSIONS

The DH is a 3-dimensional feature visible in both hypocentral 'dots in a box' plots and plots of normalized seismic density (number of earthquakes per unit volume), visually estimated to reside at around 3.5 km depth in the Northwest Geysers. Its relationship to injection and production in the Northwest Geysers is under investigation, as are correlations with geomechanical changes in the area, 3-D velocity structure, and variations in temperature and pressure. These issues will be addressed in future work.

We are currently refining the seismic density grids using double-difference relocation via the tomoDD code (Zhang &Thurber, 2003) to gain a higher-resolution of the DH boundaries. We expect the tomoDD catalog to have a lower RMS travel-time residual, and thus to reduce the density gridblock size. An example of seismic density grid refinement using tomoDD relocations is shown below. Note the low-elevation, suggesting possible spatial overlap with the Northwest Geysers HTZ. Seismic density grids will be taken at sequential horizontal slices through the DH feature, and then stacked vertically to extend the low-seismicity region into the third dimension. Using an empirical definition of 'aseismicity' as a normalized seismic density that is 1/3 of that of surrounding gridblocks, the boundaries of the DH will be traced out in 3D, and its center of mass and rough shape will be estimated.

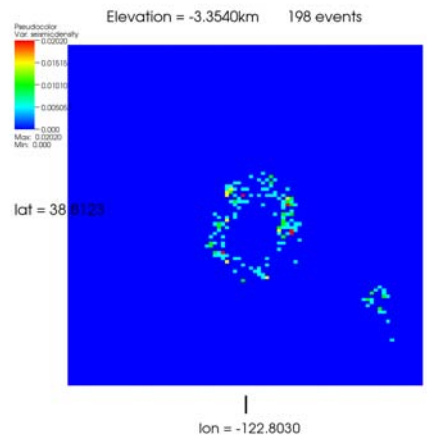


Figure 13. Seismic density for a horizontal slice of the DH using relocated hypocenters from tomoDD.

We are also using tomoDD (Zhang & Thurber, 2003) to update the velocity structure year-by-year, for the purpose of generating time-dependent velocity models that can be associated with reservoir and geomechanical phenomena. An example of a 3-dimensional velocity model generated with 2004 Geysers data is displayed below.

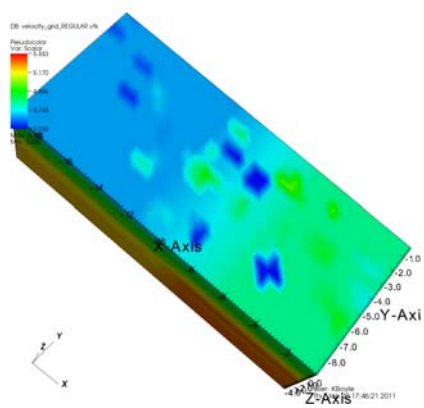


Figure 14. Vp model for the entire Geysers region produced with tomoDD using 2004 data from The Geysers. The lower right portion of the model corresponds to the Southeast Geysers, while the upper left, lower-velocity region corresponds to the Northwest Geysers.

This model was generated using a coarse-resolution model taken from Julian et.al (1996), although the velocity structure is changing rapidly in time (Foulger, et.al, 1997; Gunasekera, et.al, 2003), and we expect the most definitive information to come from hypocenter relocations and the corresponding changes in velocity inversion meshes output by tomoDD.

We will also be investigating source mechanisms for earthquakes in and around the DH over time, and hope to explain the deviation from a predictable injection-seismicity relationship in the depths of the Northwest Geysers.

ACKNOWLEDGMENTS

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