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SUBSIDENCE AT THE GEYSERS GEOTHERMAL FIELD: RESULTS AND SIMPLE MODELS

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1 Abstract

A series of repeated first order leveling surveys across The Geysers geothermal field were carried out during the 1970's. The results revealed that the region was apparently subsiding. Between 1973 and 1977 a maximum subsidence of some 0.19 m was observed at, what was then, the centre of steam production activities. During 1996 many of the leveling monuments were reoccupied using GPS receivers and their locations measured to a typical accuracy of $\sigma_H \approx$ 0.006 m, $\sigma_V \approx$ 0.02 m, where σ is one standard deviation and the subscript refers to horizontal, H, or vertical, V, measurements. Comparison of GPS to leveling heights is complicated by the fact that the GPS measurements are located within an ellipsoidal reference frame, in this case the WGS84 model, whilst leveling heights are relative to a geoid based reference frame, in this case NGVD29. The data were transformed to the same co-ordinate system using a high precision geoid model, GEOID96, plus some further datum corrections. These transformations add approximately 0.03 m of uncertainty to the results but allow direct comparison of measured heights over a 20 year period. Subsidence is clearly observed between the 1977 and 1996 surveys, throughout The Geysers, with a maximum of 0.9 $\pm$ 0.05 m. The subsidence can be closely modeled using a small number of simple dilatational point sources (Mogi sources). We note that the location of the best fitting sources corresponds to the mapped steam pressure lows within the reservoir.

2 Introduction

The Geysers geothermal field is situated in the coast ranges of northern California. It is the largest producer of geothermal power in the world. At its peak, in the mid-1980's, some 2 GW of power were generated here, entailing the extraction of vast quantities of steam. Power production has since declined due to falling steam pressure within the reservoir. The steam producing reservoir itself is a highly fractured volume of Franciscan greywacke and Quaternary silicic intrusives, the latter known as the felsite. It is capped by a 1-3 km layer of, low permeability, metamorphic melange [Thompson, 1992].

The region is presently deforming as evidenced by the fact that it is one of the most seismically active regions in northern California [*e.g.,* Hill *et al.,* 19901. Vertical surface deformation was measured, during the 1970's, by a series of first order leveling surveys across The Geysers The land surface above the geothermal reservoir was observed to be subsiding. The maximum relative subsidence with respect to a chosen fixed site, located some 20 km from the reservoir, was 0.19 $\pm$ 0.02 m between 1973 and 1977; a rate of approximately 0.05 m/yr. The greatest subsidence appeared to be centred on the area of most active steam extraction from the reservoir during that time.

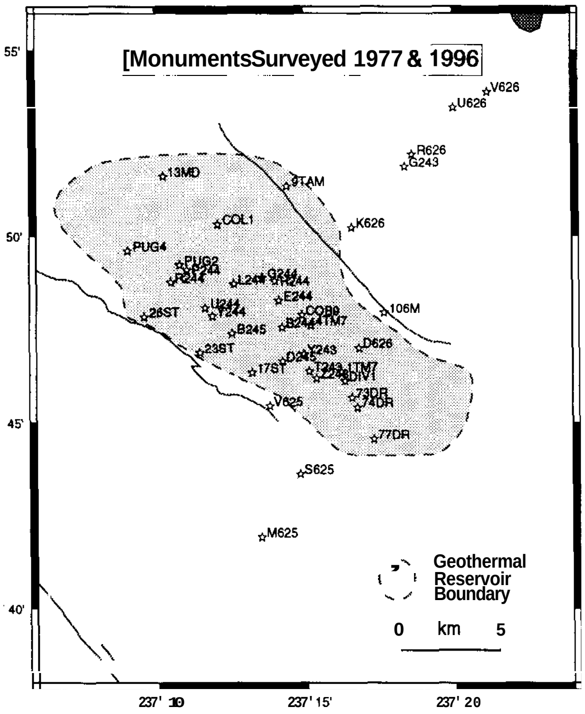

Figure 1: Monuments surveyed in both the 1977 leveling and 1996 GPS surveys.

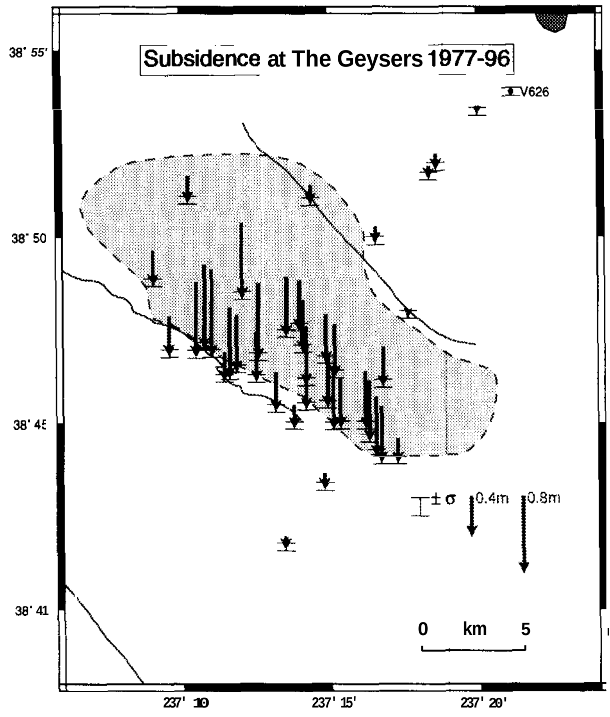

Figure 2: Subsidence between the 1977 leveling and 1996 GPS surveys, holding V626 fixed.

3 Resurveying with GPS Receivers

In **1996** a number of existing leveling monuments were reoccupied using GPS receivers. Figure **1** shows those monuments measured in both the **1977** and **1996** surveys and it's these we shall consider in this paper. However, GPS and leveling survey heights are not directly comparable. Leveling measures elevation with repect to a geoid based, orthometric, datum, whereas GPS measurements are with respect to an idealised ellipsoidal reference frame. In this instance the **1977** leveling survey data were adjusted to the NGVD 29 datum. The GPS heights were determined relative to the WGS **84** reference ellipsoid. For comparison to be made between the leveling and GPS results they first have to be transformed into the same coordinate system.

The problem of converting geodetic reference frames is the subject of ongoing research at the National Geodetic Survey (NGS). The present state of the art geoid model is GEOID **96** [Milbert and Smith, **19961,** this refers the height of the NAVD **88** geoid with respect to the NAD **83** ellipsoid and so allows conversion between these two reference frames. An additional transformation from NGVD 29 to NAVD 88 coordinates is required for the Geysers leveled data and is achieved by applying NGS's VERTCON model. The final transformation between the NAD **83** and WGS **84** ellipsoids is insignificant compared to the errors in the data, which are of the order 0.01 m, and this step is therefore not necessary. It should be noted that, in themselves, the GEOID96 and VERTCON transformations are inexact and for the short baselines considered here introduce, in combination, a more or less constant error of **0.03** m to each height.

4 Subsidence Between 1977 and 1996

The height changes between **1977** and **1996** are shown schematically in figure **2.**

The vertical arrows indicate the magnitude of height change, subsidence is shown as southward pointing arrows, the error bars are for f l a . The monument V 626, the furthest monument to the north-east, is held constant. This we justify by noting that it is the site furthest from the geothermal field of those monuments surveyed in both 1977 and 1996 and that little significant motion was observed at this point during the 1970's surveys. The region subsiding appears to be well bounded by the known extent of the geothermal reservoir. Little elevation change is observed for sites to the south-west of the reservoir while our fixed point is to the north-east. The maximum measured subsidence was 0.90 $\pm$ 0.04 m, consistent with a rate of 0.047 $\pm$ 0.002 m/yr. This was for monument P(1)244 approximately **2** km north of the site of maximum subsidence observed between 1973 and 1976 (T1244 not surveyed in 1996, hence not shown in figure 1).

5 Modeling the Subsidence

Subsidence is consistent with volume contraction within the reservoir. It appears appropriate, therefore, to attempt to model the surface deformation with volume change at depth. We built our model from idealised point sources of volume change, generally referred to as Mogi sources [Mogi, 1958]. These give a good approximation to roughly equidimensional bodies, within the crust, undergoing uniform strain. The location and intensity of the Mogi sources was found by optimising the fit of the predicted subsidence with that observed using the random cost approach described in Murray *et al.*, [1996]. In reality, the volume contraction is distributed throughout the reservoir. The point contraction/dilatation sources serve simply to identify the locations of maximal volume change.

It was observed that a single Mogi source achieved a poor fit with the data and would have to be located far deeper than would be expected if the source was associated with the geothermal reservoir. Increasing the number of point sources to two gave a far better fit to the data and achieved a large decrease in the normalised sum of squared residuals. The residual refers to the difference between observed and predicted elevation change for a monument. The normalised sum of squared residuals, provides a general measure of how well we fit all the data. Both

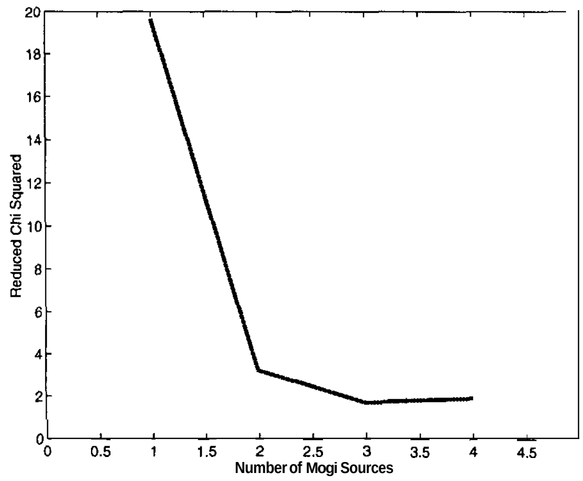

Figure 3: Reduced χ^2 as a function of number ***of*** ***op-**timal* ***Mogi*** *sources, note increase from 3 to 4 sources*

of the sources, for the optimal two source model, were located at much shallower depths than the single source, consumate with their corresponding to volume changes within the reservoir.

The significance of the reduction in sum of squared residuals versus the increase in complexity due to the addition of an extra Mogi source was measured via an F - test. For the case of going from one to two sources a significance greater than the 99th percentile was found. Similarly the addition of a third Mogi source yielded an improvement with a probability greater than the 95th percentile. The addition of a fourth Mogi source caused an increase in the reduced χ^2 value (see figure **3)** indicating that no significant improvement was achieved.

Figures **3** is a plot of the change in reduced χ^2 with increasing complexity of model. Note the large reduction in going from one to two sources and the slight increase with going from three to four sources. Table **1** gives the normalised sum of squared residuals and reduced χ^2 for the best fitting one, two, three or four Mogi source models. The location and volume reduction of each of these sources are also given.

Figure 4 shows the residuals for the best fitting, three Mogi source, model.

The Mogi source "epicentral" locations are shown as circles, the radii of the circles scaling with the cube root of the volume reduction. Note that the residuals are, in general, comparable to the combined measurement and conversion errors in the observed sub-

Source	"N	"W	Depth (m)	Volume Change (m^3)
Mogi 1	38.80630	122.79267	9820	
Mogi 1	38.82182	122.80485	4120	$-7.06 \times 10^7 \pm 0.21 \times 10^7$
Mogi 2	38.76708	122.73396	3760	$-3.45 \times 10^7 \pm 0.16 \times 10^7$
3 Mogi Sources: SSQR = 44.63, Reduced χ^2 = 1.7165				
Mogi 1	38.8227	122.80645	3900	$-6.42 \times 10^7 \pm 0.14 \times 10^7$
Mogi 2	38.76216	122.72742	2570	$-1.55 \times 107 \pm 0.07 \times 10^7$
Mogi 3	38.78693	122.75764	2540	$-9.53 \times 10^6 \pm 0.75 \times 10^6$
Mogi 1	38.82401	122.80907	3930	$-7.10 \times 107 \pm 0.25 \times 10^7$
Mogi 2	38.76217	122.72743	2570	$-1.55 \times 107 \pm 0.07 \times 107$
Mogi 3	38.78723	122.75808	2590	$-9.82 \times 10^6 \pm 0.78 \times 10^6$
Mogi 4	38.83669	122.82857	1010	$+6.05 \times 10^6 \pm 2.09 \times 10^6$

Table 1: Location and intensity of the Mogi sources for the optimised cases of 1, 2, 3 or 4 sources and the associated normalised sum od squared residuals, SSQR, and the Reduced χ^2.

sidence, *i.e.*, are about the same as the error bars in figure 2. That the residuals are roughly equal to the errors in the data, indicates that this best fitting Mogi source model does a good job at explaining the data. It should be noted though that these solutions are non-unique and that we have not explored more complex source types.

6 Conclusions

The average subsidence rate between 1977 and 1996 is 0.047 ± 0.003 m/yr, consistent with that measured in the leveling surveys of the 1970's, indicating the veracity of this earlier work. This subsidence is best modeled by three Mogi sources shown in figure 4, which gives a close fit to the observed height changes. The total volume change required by this model is some 2×10^9 m^3. In support of this conclusion, figure 6 shows the measured pressure lows that had developed by 1987 [Williamson, 19921 superimposed on a representation of the best fitting Mogi sources.

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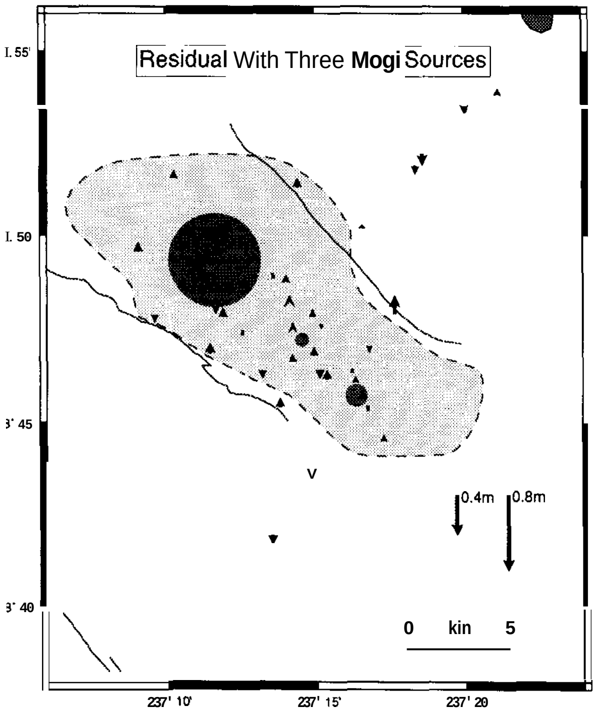

Figure 4: The best fitting Mogi source model and associated residuals. The mapped Mogi source radii are proportional to the cube root of the source volume change.

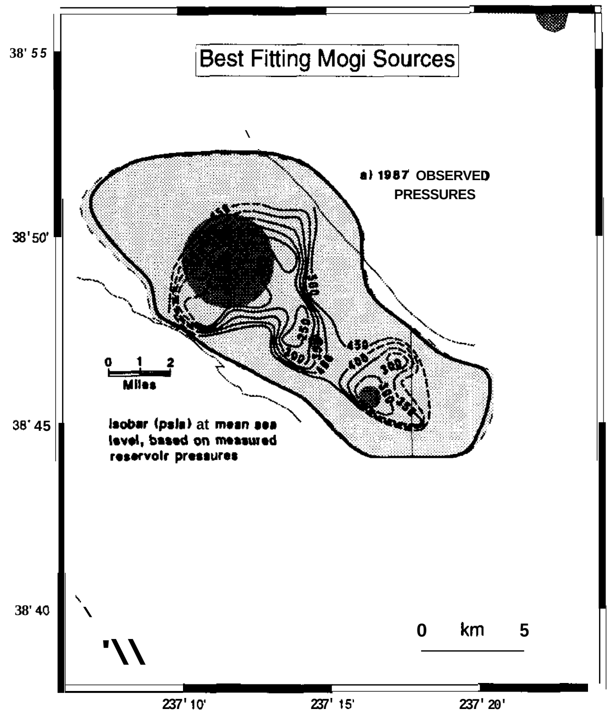

Figure 5: The best fitting Mogi sources with superimposed, measured, pressure lows as of 1987 [Williamson, 1992].

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