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AN ASSESSMENT OF PRECISE SURFACE GRAVITY MEASUREMENTS FOR MONITORING THE RESPONSE OF A GEOTHERMAL RESERVOIR TO EXPLOITATION

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R. B. Grannell

Department of Geological Sciences
California State University
Long Beach, CA 90840

J. H. Whitcomb

Cooperative Institute for Research
in the Environmental Sciences
University of Colorado
Boulder, CO 80302

P. S. Aronstam

Department of Geological Sciences
California State University
Long Beach, CA 90840

R. C. Clover

Department of Biology
California State University
Long Beach, CA 90840

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Lawrence Berkeley Laboratory
University of California
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SUMMARY AND CONCLUSIONS

This study constitutes an assessment of the utility of repetitive gravity measurements in monitoring elevation and mass changes due to production in a geothermal field.

Elevation changes occur in the form of subsidence. Its major cause is an increase in effective stress in producing zones due to fluid withdrawal and loss of buoyant support. This subsidence may not occur immediately, and may be triggered by earthquakes. Subsidence of lesser magnitude may be due to thermal contraction. Regardless of the source, subsidence causes an increase in gravity values.

Mass changes occur because of fluid withdrawal in the absence of natural or artificial recharge, or from changes in density due to local solution or precipitation of minerals, or from phase changes in the system with consequent repositioning of mass. Fluid withdrawal, the most important mass change, causes a decrease in gravity values.

The effectiveness of the gravity method is a function of two variables: (1) the precision which can be attained using conventional gravity meters; and (2) the magnitude of the expected gravity changes. At present, only two types of meters are capable of high precision, the stationary cryogenic gravity meter, which is expensive in both construction and maintenance, and the portable mechanical meters manufactured by LaCoste and Romberg (models D and G), which are moderately priced and relatively inexpensive to use. The former meter can achieve one microgal precision (standard deviation) and continuous monitoring in one location, but is not adapted to comprehensive surveys over a wide area. The latter meters can achieve four or five microgals precision under the most favorable circumstances, and will be more extensively used because of portability and lower cost. Further discussion

will thus be limited to the LaCoste and Romberg meters.

The LaCoste and Romberg D model gravity meters are somewhat more precise than G meters, with reported values for standard deviations from the literature ranging from 5 to 25 microgals for the D meter, whereas G meters range from 8 to 24 microgals. Since precision is a function of field procedures as well as meter type, we performed a G meter evaluation on Vancouver Island, repeating stations established by the Canadian government using D meters; nearly identical field procedures were utilized. Our average precisions were 8 to 10 microgals, whereas the reported Canadian values for the D meter were 5+ microgals. Precisions of 8 microgals or less could be consistently achieved with the G meter, but only with a larger number of repetitions, allowing exclusion of imprecise values. For both meters, the use of a "leap frogging" technique (with several ties between adjacent stations) to establish a network of values with redundant ties (a station tied to more than one other station) allows distribution of error and increased precision over the values cited above. The "looping" technique, with several stations tied to a base (with the loop repeated to achieve higher precision) is less precise, but also less expensive and time consuming.

In many geothermal situations, gravity changes are likely to be significant and measurable by means of current instrumentation and field techniques. Two studies at geothermal fields (Wairakei and The Geysers) reported gravity changes one magnitude or more greater than achievable precisions in repetitive gravity surveys. Modeling studies which we performed, using a disk model and reasonable parameters for consolidation and initial conditions, verify this conclusion.

Several precautions will have to be observed in performing a precise repetitive gravity survey. It will be necessary to conduct a contemporaneous second-order spirit leveling, so that the effects of mass and elevation can be separated. Both types of measurements are concerned with potential fields and neither yields a unique result without the other; i.e., elevations determined without accompanying gravity values will not be true geometric elevations unless the effects of mass changes are removed. Monitoring by both gravity and leveling should be initiated on permanent monuments prior to production, and repeated at least once, to identify non-geothermal changes such as those due to tectonic activity and weather effects. The greatest detriment to high precision is transport of the gravity meter over rough roads; special transport cases, increased repetitions, the use of heavier cars, and/or avoidance of the rough areas (for instance, by walking) should be employed to mitigate this problem. Likewise, high temperatures and wind conditions, or ground vibration from seismic shaking, geothermal production, and heavy traffic, are also deleterious.

A repetitive gravity survey seeks to establish changes in the differences in observed gravity between stations located in the production zone and stable reference base(s) located outside the zone, preferably on bedrock. The calculation of these differences is straightforward, involving only calibration, removal of tidal and drift effects, and averaging reduced values at stations and bases. However, for best results, calibration differences among meters must be resolved through establishment of a calibration loop, and tidal monitoring may be needed to establish values of the tidal constants for reduction purposes. Barometric pressure variations can be neglected, since the effects are insignificant and may be partially removed through station repetition and dedrifting. Data reduction, including statistical analysis, should be performed in the field with a pocket calculator and tide tables.

This will allow additional data to be collected which can substitute for imprecise values; changes can also be made in field procedure, if needed.

Based on the foregoing assessment, we have included recommendations for carrying out surveys which achieve 15, 10 and 5 microgal precisions. Achieving the smaller standard deviations will require more field effort and will be more costly. For a 60 station survey, at commercial rates in 1981, typical costs are estimated to be $20,000, $26,000 and $35,000 respectively, for data collection, reduction and interpretation. These figures exclude instrument purchase or rental.

Finally, we evaluated 20 geothermal areas in the western United States which might be suitable for precise repetitive gravity monitoring. The evaluation criteria included capability for subsidence on a geological basis, estimated electrical production, environmental impact, and anticipation of production in the near future. We feel that the most promising areas in order of priority are (1) the Salton Sea field, California; (2) Valles Caldera, New Mexico; (3) The Geysers-Clear Lake; and (4) Westmorland, California; (5) Roosevelt Hot Springs, Utah; and (6) Heber; (7) Brawley; and (8) Long Valley, California.

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I. PREFACE AND ACKNOWLEDGMENTS

This assessment of the surface gravity method and its applicability to monitoring changes in a producing geothermal regime is the product of four separate authors. Each of us bore the responsibility for different sections and tasks, as follows: (1) Grannell - Sections I, II, IIIA, B and C, IV, VI and Appendices A and B; (2) Whitcomb - Section IIID; (3) Aronstam - Assistance with field work and input of numerous ideas and calculations in Grannell's sections; (4) Clover - Statistical evaluations used in Section IIIB.

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II. INTRODUCTION

Within recent years, geothermal areas have become an increasingly important target for the development of alternate energy. These areas produce hot water and/or steam from porous and permeable aquifers, or from natural or artificially induced fractures in otherwise impermeable rocks. In either case, exploitation removes mass from the system which may or may not be returned in the form of injected waste water or natural recharge. The removal of hot water in either the liquid or the gas phase can cause several identifiable changes within the reservoir; one of the most serious, due to the damage which can result, is subsidence of the ground surface due to compaction of the depleted zone. Substantial subsidence has been identified in New Zealand at the Wairakei field (Hatton, 1970) and, to a lesser extent, at The Geysers in California (Grimsrud _et al_, 1978). Because of possible important economic consequences, programs for predicting and monitoring subsidence should be implemented in susceptible areas. It has already been well established that repetitive spirit leveling and tiltmeter observations conducted at the surface are useful techniques for monitoring subsidence (ibid); this report explores the feasibility of utilizing a less known but promising supplemental technique, namely, precise repetitive surface gravity observations.

The classical use of gravimetry has been in the detection and interpretation of _spatial_ variations in gravity, after reduction of field data to Bouguer anomaly values. More recently, this use has been augmented by precise, repetitive measurements of observed gravity which are utilized to document _temporal_ variations in the gravity field. This augmentation

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The classical use of gravimetry has been in the detection and interpretation of *spatial* variations in gravity, after reduction of field data to Bouguer anomaly values. More recently, this use has been augmented by precise, repetitive measurements of observed gravity which are utilized to document *temporal* variations in the gravity field. This augmentation has been facilitated by improvements in field techniques and instrumentation, as well as by a greater ability to understand and mathematically model earth processes. In consequence, temporal studies have been applied to measurement of earthquake deformation and processes (Barnes, 1964; Oliver et al, 1975; Kisslinger, 1975), pre-earthquake predictive monitoring (Jachens and Roberts, 1977; Lambert et al, 1979) pre-eruption studies of Kilauea volcano in Hawaii (Gordon Eaton, U.S.G.S., personal communication, 1976) and groundwater withdrawal in sedimentary basins (Strange and Carroll, 1974). In addition, similar studies have been conducted or are underway in geothermal regimes (Hunt, 1970; Isherwood, 1977; Cook and Carter, 1978; and Grannell et al, 1978), where they may be useful in documenting both ground subsidence and net-mass changes due to exploitation. However, the application of precise gravity methods to geothermal areas has not yet been fully assessed.

In his assessment of the use of precise spirit leveling for monitoring geothermal areas, Van Til (1979) listed the following reasons for such monitoring:

1) "The satisfaction of legal requirements for monitoring instituted by governmental authorities with jurisdiction in the area.
2) The protection of environmental features, such as streams, parks, forested areas, wildlife habitat, etc., which may be adversely affected by subsidence.
3) The protection of man-made structures, such as irrigation or drainage canals, dams, power plants, buildings, power lines, communication towers, roads, railroads, etc., which may be damaged by subsidence.
4) The collection of evidential data for enforcement purposes.
5) A check of engineering design features intended to minimize the

effects of subsidence.

6) Research, for example, in the development of monitoring techniques, or operational aspects of the geothermal field, including between rate of subsidence and rate of fluid withdrawal, rate of subsidence vs. rate of fluid reinjection and relationships between subsidence and temperature regime changes."

Precise gravity monitoring would also satisfy these reasons, and serve other important functions related to net-mass changes, such as:

1) The detection and monitoring of natural recharge for the purpose of estimating reservoir life (Isherwood, 1977).
2) The calculation of gravity corrections which must be made to leveling data because of the dependency of these data on a reference equipotential surface; this equipotential surface is in turn sensitive to mass changes in the subsurface (Whitcomb, 1976).
3) Calculations of the total amount of mass removal, such as have been performed for the Wairakei geothermal field in New Zealand (Hunt, 1970).

III. ASSESSMENT OF THE GRAVITY METHOD

A. TECHNICAL DISCUSSION

If a precise gravity survey were to be conducted and repeated over a producing geothermal field, the gravity values could theoretically have changed with time due to both subsidence in the field (an elevation effect) and to mass changes. And if precise (second order or better) leveling accompanied the gravity effort, the elevation effects per se could theoretically be calculated and removed, thus isolating the combined mass changes.

Subsidence could arise from three separate causes during the exploitation process. The following summary is derived primarily from Van Til (1979):

1) Most of the subsidence is expected to be caused by loss of pore space due to compaction following fluid withdrawal. The theory of effective stress states that the effective downward stress carried by earth materials equals the geostatic pressure (weight of overlying rock and interstitial water) minus the pore fluid pressure. A decrease in fluid pressure during exploitation results in increased effective stress and leads to the compaction of the layers from which geothermal fluids were removed. Compaction may be transmitted to the surface through subsidence of the overlying layers and eventually the ground surface. The effect will be greatest where the pore space is intergranular and contains hot waters; lesser effects will be observed where the interstitial fluid is steam (because of initially low fluid pressures and high compressibilities) and where fracture pore space characterizes the reservoir, although experiments on rock core samples indicate that an increase in effective stress in this case may nevertheless produce volume decreases. Subsidence from this cause could probably be detected in short time spans of 1-3 years, depending upon the production rates in the reservoir and its geology.
2) Thermal contraction of reservoir rocks due to cooling may contribute to subsidence. This effect would probably be minor, because of the small decreases in average temperature which result during production, and because of the very low coefficients of thermal expansion of rocks. Thus temperature-induced subsidence would probably be effective (and

thus detectable) only over long time spans of some tens of years. Order of magnitude calculations by Finnemore and Gillam (1976) show that the uniform cooling by 20^{o}C of a 1 km thick reservoir could produce 20 cm of shortening. These values may be exceeded locally; for instance, cooling may be more pronounced in the vicinity of cold water recharge.

3) Subsidence could also be caused by seismic activity, since earthquake shaking can contribute to the compaction of unconsolidated materials (through rearrangement of the constituent grains). This effect has been observed at the Wilmington oil field (Poland and Davis, 1969) where the rate of ground subsidence increased temporarily by several centimeters annually in response to two moderate earthquakes. According to Atherton et al (1976), "Since most geothermal areas are located near the boundaries of major crustal plates ... geothermal areas as a group are more likely to experience seismic shaking than other fluid resource areas." Active fault zones are a geological component of nearly all the major geothermal resource areas in the western United States. In addition, subsidence from other sources may cause minor earthquakes, augmenting that subsidence. Subsidence due to seismic activity is not yet predictable in terms of either magnitude or frequency of occurence. Such subsidence has been observed in the Cerro Prieto geothermal field, with elevation decreases of more than one foot, as a consequence of the 1980 Victoria earthquake.

Several net-mass changes could also conceivably result from the exploitation process. These include the following:

1) Mass is withdrawn from the reservoir when production occurs. This

effect may be offset by natural recharge and/or by reinjection of geothermal brines. If reinjection is used for brine disposal, the liquids may not necessarily be returned to the same part of the reservoir from which they originated. In the absence of natural recharge and reinjection, net mass losses could be detectable in a time interval as short as one to a few years, depending on production rate and depth to the reservoir, among other factors.

2) The subsurface chemical/thermodynamic environment may be altered, such as by cooling, with consequent densification due to mineral precipitation in pores and fractures. Thermal metamorphism and cap rock precipitation are common occurences in geothermal environments (e.g., Elders _et al_, 1978), and deposition of surface minerals precipitated from cooling brines near wellheads has been observed to occur over a short time span in the Cerro Prieto geothermal field. These processes may be altered in the subsurface, yielding mass changes, but no data apparently exist on reaction rates. It is surmised that such alterations might produce measurable mass changes over long time spans, but probably not in the short term.

3) Changes in liquid saturation within the reservoir may occur; i.e., boiling may occur because of lowered fluid pressure caused by production. This transition would affect not only subsidence (through an increase in effective stress), but could cause migration of mass in the form of mobile and less dense steam to a higher part of the reservoir. Because of the inverse square law nature of gravity, such spatial changes in the mass regime without the removal of mass would also affect gravity values measured at the surface. This mass change is

liable to be detected only over a longer time frame.

These statements do not, however, take into account the fact that non-geothermally caused subsidence and mass changes are also possible in a geothermal environment, and can substantially augment, or even mask, geothermally-induced gravity changes. This background "noise" may arise from both cultural and natural causes. As an example, temporal effects of up to 17 microgals have been observed in Canada (H. Dragert, personal communication, 1978), and may be due to such factors as local changes in the water table from precipitation or drought, formation of ice at the expense of water, and thermal contraction or expansion of the ground surface. Similarly, artificial ground water recharge in southern California has caused gravity changes of 35 - 40 microgals (Evernden, 1981). Other causes could include:

1) changes in the levels of nearby surface water bodies such as lakes or canals;
2) withdrawal of groundwater, oil or gas from the subsurface;
3) local erosion and quarrying;
4) slope creep and landslides;
5) hydrocompaction;
6) oxidation of organic soils; and
7) tectonically-induced elevation changes and tilting such as have been observed in the Imperial Valley of California (Lofgren, 1974).

A further complication is the dependence of the leveling process on density distributions within the earth. Elevation variations obtained by means of leveling do not represent true geometrical changes if the spatial distribution of mass within the reservoir is altered during production.

Fortunately, if both gravity and leveling studies are carried out, and if the dimensions of the region being subjected to density variations are known or small, then the density changes can be calculated using appropriate equations (Whitcomb, 1976). Any models of mass changes (in liquid, gas, or host rocks) which manifest themselves as changes in ground elevation, gravity, and gravitational potential or geoid distortion need to include a consideration of the differences between geometric and orthometric (leveling) elevation changes.

The feasibility of conducting a precise gravity monitoring program in a geothermal regime depends essentially on the interrelationship of two major factors: (1) the magnitudes and rate of occurence of the expected changes, as discussed above; and (2) the precision of the instrumentation and field techniques available to detect those changes. In the remaining parts of this section, we will examine the questions of the precision of available instrumentation and the magnitude of the expected gravity changes as determined by actual observation in geothermal fields and modeling studies; the modeling studies incorporate considerations concerning orthometric versus geometric elevations. Since non-geothermally induced gravity changes are best handled by monitoring prior to development, a discussion of this topic will be deferred to Section IV.

B. PRECISION OF MEASUREMENT WITH STATE-OF-THE-ART GRAVIMETERS

Basically, two types of gravity meters are currently being used to monitor gravity changes in producing geothermal fields: a) extremely precise meters which are monitored continuously in one particular location, as exemplified by cryogenic gravity meters; and b) less precise but portable mechanical meters which are used for monitoring multiple stations at regular time intervals.

The cryogenic gravity meter "differs from conventional gravity meters in that mechanical springs and levers are replaced by magnetic fields generated from persistent currents in coils of super-conducting wire. These fields support a one-inch-diameter superconducting sphere (the gravimeter's only moving part) with a force that does not significantly diminish with time... Thus the cryogenic gravimeter does not exhibit the instrumentally produced signal drift which is characteristic of conventional gravimeters" (Olson and Warburton, 1979). These instruments are very precise, their precision limited only by noise from "known sources such as earth and ocean tides and atmospheric density variations". These effects can be subtracted out, yielding a precision of measurement of approximately one microgal (ibid). Precisions of this order of magnitude and the capability for continuous measurements are a distinct advantage when it is necessary to detect changes in elevation and mass over time intervals as short as a month, such as those observed at The Geysers (ibid). However, the lack of portability, coupled with high instrument cost (as much as $80,000 at present - Norman Goldstein, personal communication, 1979) and large installation and monitoring costs, make them unusable in situations where wide spatial coverage at substantially lower cost is desired. In addition, cryogenic meters may occasionally exhibit tare-like behavior. Evernden (1981) has interpreted the 300 microgal change observed over a month-long interval in a cryogenic meter installed at Lytle Creek (southern California) as being instrumental in origin; this lessens one of the clear-cut advantages of this type of meter. Therefore, it is presumed that most gravity monitoring in the near future will be performed with the less precise portable meters. Thus, the remaining part of this section will be restricted to discussions involving these gravity meters.

It is generally recognized that the meters manufactured by LaCoste and Romberg are the state-of-the-art instrumentation for carrying out high precision, repetitive gravity surveys. Two models are currently available, the G and D models, each characterized by low drift rate, consistent performance, and portability. Achievable standard deviations under optimum conditions, as reported in the literature and through personal communication, range from 8 to 15 microgals and 5 to 10 microgals, for the G and D models, respectively. We have thoroughly examined the literature, discussed precision problems with various persons involved in temporal gravity variation studies, and conducted field tests in western Canada, southern California, and northern Mexico to ascertain the instrumental and field technique requirements for repetitive gravity surveys in producing geothermal areas. This section presents the results of this study, and outlines recommendations for conducting gravity surveys at differing levels of precision.

a. Comparison of the LaCoste and Romberg G and D Model Gravimeters from Previous Studies

Several precise, repetitive gravity studies and/or instrumental evaluations have been carried out within recent years which have provided information concerning achievable levels of precision with both G and D model LaCoste and Romberg gravity meters. Brein et al (1977) conducted studies in Europe to examine problems associated with the G model meters; their work indicated that the achievable standard deviation for a tie between two gravity stations is 10 to 15 microgals. Grannell *et al* (1978, 1979, and 1981) have achieved variable results from repetitive surveys at the Cerro Prieto geothermal field, Mexico, over a three-year period with two G model meters. The median standard deviations were 15 and 10 microgals for the first and second years, respectively. Ranges for both years (for 90% of the ties) lie between 4 and 25 microgals; this excluded ties which had been subjected to obvious tares, probably occasioned by transport problems (in other words, long distances of travel by car over washboard roads with no suspension system available to damp out excessive vibrations). During the third year of repetitions, pooled variance calculations for the entire survey yielded a standard deviation of 8 microgals. Use of G meters by U.S. Geological Survey personnel and other researchers in various repetitive surveys has yielded the following estimates of precision:

1) Eleven microgals was reported by Jachens and Roberts (1977) for work performed on the Palmdale Bulge;
2) A precision of 9 microgals was considered achievable in meter tests in 1974 and 1975 (Howard Oliver, personal communication, 1975); and
3) Four to 24 microgals were reported by Cook and Carter (1978) in repetitive studies at Roosevelt Hot Springs.

G meter results have also been evaluated by personnel from the Bureau of Energy, Mines and Resources, Canada, with the most precise ties yielding standard deviations of about 8 microgals (H. Dragert and J. Liard, personal communication, 1979). The conclusion reached from the above information is that, with reasonable care, gravity ties made with G meters should expectably be characterized by precisions averaging approximately 10 microgals.

Less published information is available for the D model gravity meter. The initial conclusions from the literature suggest that D meters can attain approximately twice the precision of G meters. Tests by personnel from the U.S. Geological Survey indicate precisions of 4 microgals are achievable with the D meter (Howard Oliver, personal communication, 1975). However, continuing tests by the U.S.G.S. also show that the D meter is most precise only when the range is restricted to a few milligals; when the range is extended beyond approximately 10 milligals, the precision deteriorates and becomes comparable to that of the G meter, or perhaps worse (Steve Robbins, personal communication, 1979). A U.S.G.S.- funded study involving several gravity lines established across the San Andreas Fault indicates a lower precision for two D meters, with a standard deviation from 17 to 26 microgals (Evernden, 1981). In another test, a precise set of data obtained in several locations in Canada over a two or more year interval has been studied (Lambert et al, 1979; H. Dragert and J. Liard, personal communication, 1979). According to this study, precisions of 8 microgals or less are nearly always attained, and adjustment of errors through a network of ties yields final precisions for all ties of approximately 5 microgals.

Two major problems exist in using values from the literature to establish precisions:

1) No published and extensive comparative data exist which directly compare D and G meter data obtained under exactly comparable

circumstances; and

2) The surveys reported by various workers were based on different field techniques, and the precision is liable to be affected by the type of field technique employed.

Because of these two deficiencies, we felt that field tests were mandatory, which would compare data taken by both kinds of meters utilizing a standardized field technique.

b. Field Procedures and Tests

Basically, two major types of field procedures can be employed for precise, repetitive gravity work, "looping" and "leap frogging".

1) In the "looping" technique, a base station is occupied, followed by occupation of several stations, and then followed by a return to the base within a short time interval (3-4 hours) so that instrumental drift is minimized and tares are detected.
   Data are reduced and then the differences between each station and the base are found. To enhance precision, multiple readings may be taken at the time of each occupation, and the entire loop may be repeated several times. This was the technique used by Grannell _et_ _al_ (1978) and Chase _et_ _al_ (1978) at Cerro Prieto and by several workers occupying earthquake prediction lines and various calibration loops established in California (e.g., the Palm Desert line). A variation on this technique which generally eliminates the need to calculate tidal drift was first published by Roman (1946), in which drift segment slopes can be calculated and drift removed on a short term basis, because of the order in

which stations are occupied. If a series of stations are named A, B, C, D, E, F, G, etc., the order of occupation is: AB, ABC, ABCD, BCDE, CDEF, DEFG, etc., so that triple ties within the loop are made at each station occupation to improve precision. The calculations for producing the drift segments are somewhat tedious, but tidal corrections are not needed if ties are kept short. This method has been used in repetitive surveys at Roosevelt Hot Springs, using G meters (Cook and Carter, 1978). The major problem with these two looping techniques is that tares occurring within the loop must be treated as linear drift although they are non-linear in nature, and consequently sizeable errors may affect significant portions of, or all of the stations in, a particular loop. Other errors, such as those due to high temperatures, have the same effect, and in some instances, entire loops must be rejected, and thus repeated.

2) A "leap frogging" technique can be utilized, in which the order of repetition of stations is analogous to procedures used in precise leveling, with backsights and foresights. Repetitive ties are made between a base and a station, until the gravity difference between the two is well established. The station thus established is then treated as the new base, and tied in to another station. Continuing in this fashion a chain of stations is obtained, all tied carefully to the original base. If the chain is completed at the original base, closure errors can be distributed over the chain. If ties are made to individual stations from several different stations, then errors can be distributed over the network even more precisely, analogous to the distribution of error in a triangulation

network. This procedure has been utilized successfully by Canadian personnel (Lambert et al, 1979), but is not commonly used in the United States. Because of the sequencing of observations, individual gravity differences out of the set that make up a tie can be rejected due to lack of precision, rather than an entire loop (or portion thereof). But the method is expensive, in terms of manpower, and, if numerous successive ties are made in a chain configuration, errors may accumulate within the network at a rate of $X\sqrt{N}$, where X is the error of an individual tie, and N is the number of ties. The removal of error by a linear distribution process, as discussed above, might be less effective in removing the error in cases where many stations are involved than when only a few successive ties are made. No published G meter data exist, to our knowledge, using this technique.

Because of the lack of comparative data between G and D meters, and because of the lack of G meter data using the "leap frogging" technique described above, we decided to occupy a group of gravity stations established by Canadian personnel on Vancouver Island for the purpose of monitoring a major active fault zone. Our field procedures were identical to those used in the original survey, except that three G meters were utilized rather than two D meters. Basically, the procedures were as follows:

1) Eight ties were made between two stations, starting initially at the "base" station, and returning to it at the end. Nine readings were obtained, with only one reading taken for each occupation. Four minutes exactly were allowed to elapse between the

unclamping of the meter and the actual reading, so that hysteresis problems could be minimized.

2) The data were reduced to observed gravity values in the field, using tide correction tables which had been previously generated on the computer, and by multiplying by the appropriate calibration constants. The gravity differences for successive ties were then calculated, and standard deviations were obtained for these differences.

3) Exclusion criteria were applied if individual differences were outside two standard deviations of the mean calculated for the 8 sets of differences. Additional field work then commenced to substitute for the rejected differences. Canadian procedure at this point allows up to 4 additional ties, and if the final data set does not have a standard deviation of 8 microgals or less, the entire set is rejected, and the ties between the two stations must be repeated in their entirety (Dragert, personal communication, 1979).

Using three G meters (G300, G423, and G395), we established a total of 17 ties in the area around Sproat Lake near Port Alberni in central Vancouver Island. Transport of the meters was in special spring-mounted boxes so that road vibrations could be eliminated, and the meters were kept shaded during occupations to reduce instrument leveling errors. The meters were always returned to the same position at the same orientation, to eliminate magnetization effects, and no base plate was used so that the elevation of the center of mass of the meter was virtually identical for each occupation of a single station.

For the 17 ties, we obtained standard deviations ranging from 4 microgals to 18 microgals, with a median value of 8 microgals. Thus, using Canadian exclusion principles, half of the ties would have been acceptable, and approximately twice as much work would be needed to meet their particular exclusion criteria. The results of the work are summarized in Figure 1 on the next page. Some of the results suggest that fewer data would need to be excluded under normal circumstances. For instance, the extreme value of 18 microgals was obtained by an operator suffering from food poisoning, and the anomalous readings in that data set might have been due to operator error rather than to instrument noise. Also, there were differences among the meters: G300 registered a median standard deviation for all ties of 7 microgals, G395 produced a median value of 8 microgals, and G423, 10 microgals. The latter instrument was having internal difficulties, and under field conditions in a geothermal area, the instrument would not have been used once such a problem was identified. Finally, we plotted standard deviations as functions of both time, and distance between stations. Figure 2 on page 20 shows that the standard deviations improved with time. Either the meter stabilized after the long trip to Canada, or the operators became more experienced. Both reasons are likely, since (1) transport is known to cause errors, and (2) one drawback of the G meter is that parallax effects in reading the central value of the needle with the electronic readout are an order of magnitude greater than with D meters. The latter problem, which can add 3 to 4 microgals of error, can be reduced by means of magnification of the dial, or a mirror mounted beneath it, or the use of an external galvanometer with a large scale. It is also clear that experienced personnel are mandatory, and that in a longer field session

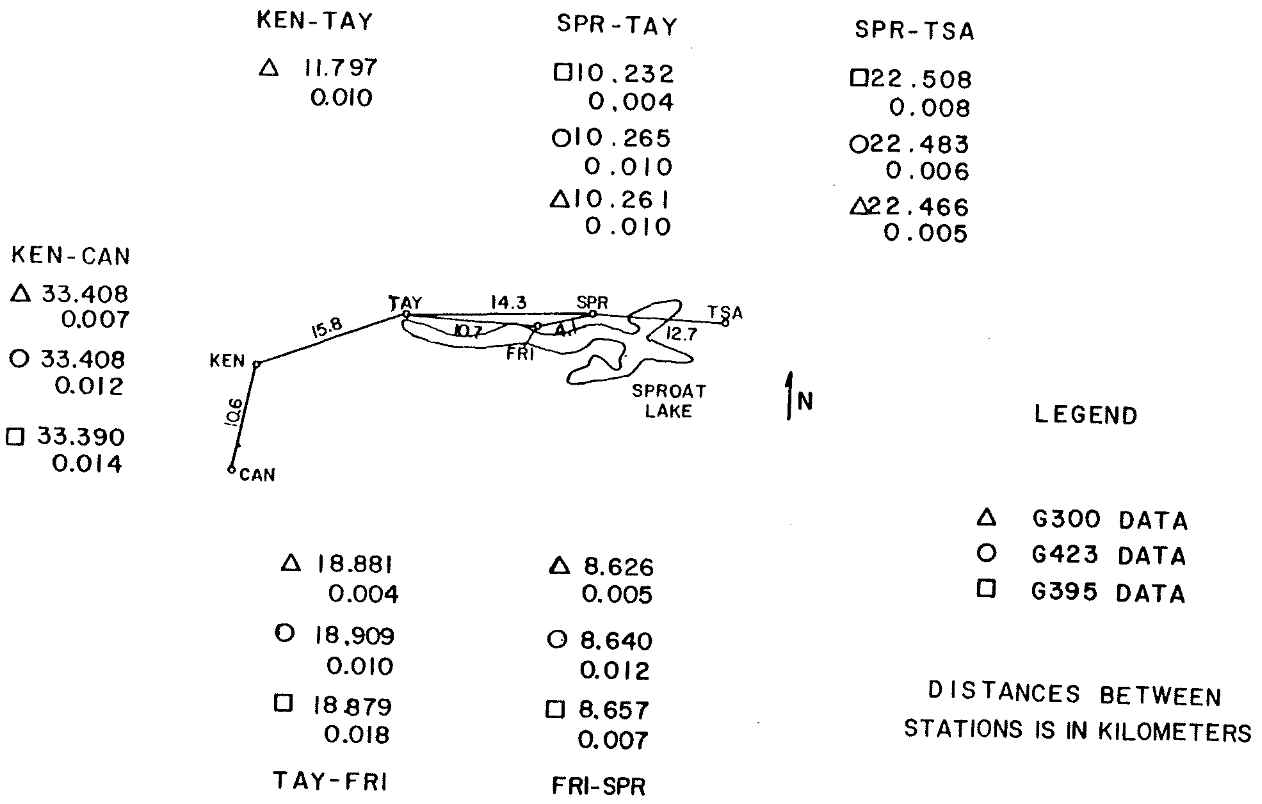


Figure 1. Map of the Sproat Lake area near Port Alberni on Vancouver Island, B.C., showing the location of gravity stations in the Canadian precise gravity network and distances between adjacent stations. The mean value for all ties with a particular meter is shown to the right of the meter symbol (refer to legend); the standard deviation is given below the mean value, with all values in milligals. The discrepancies among tie means is partially a function of calibration factor differences.

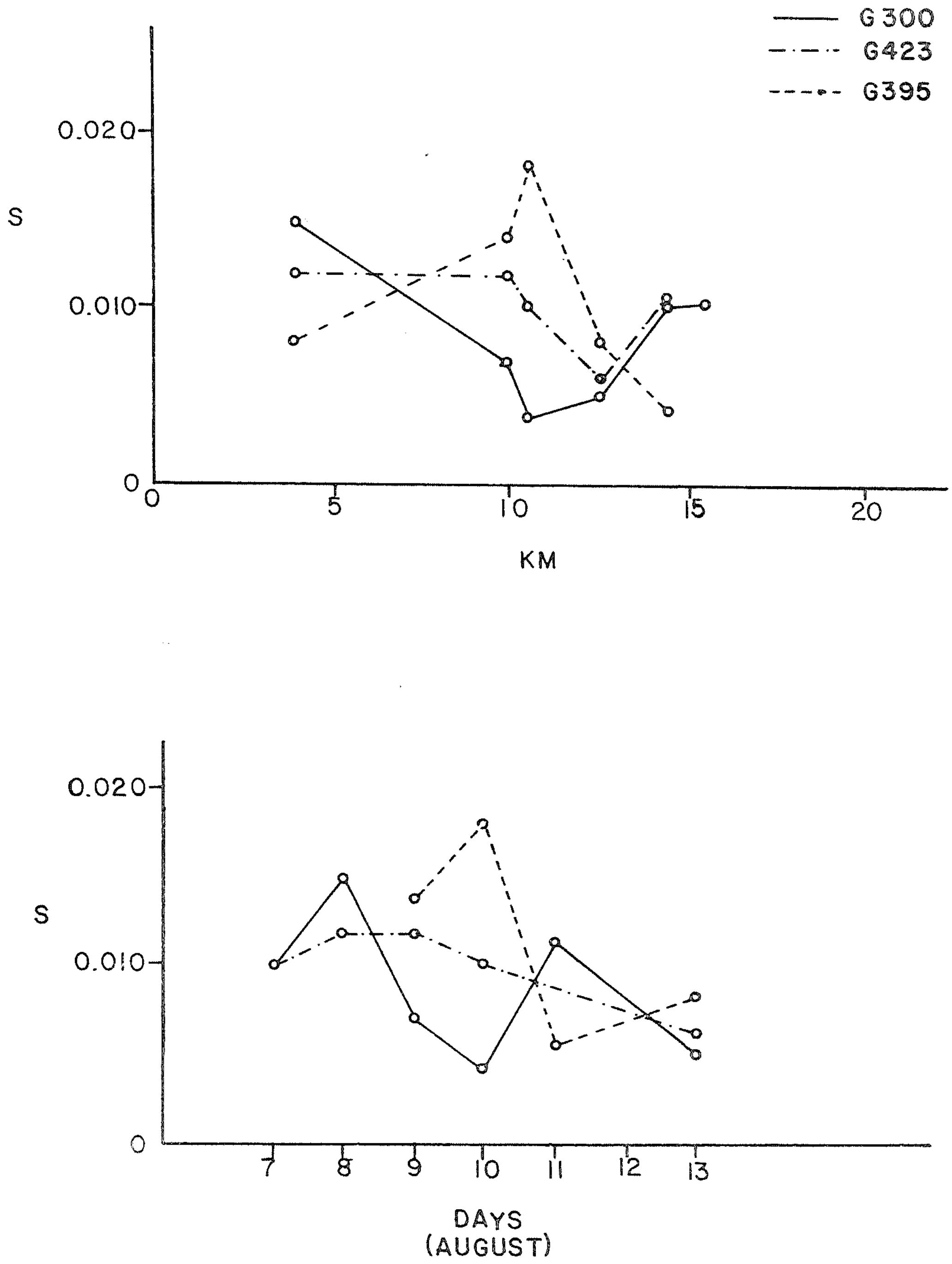


Figure 2. Plots of the standard deviation for gravity ties versus distance of travel (upper graph) and versus total time in the field (lower graph). There seems to be no correlation between precision and distance of travel, as seen in the upper curve, at least over the short distances encountered in this study. In the lower curve, the precision generally improved with time, with increased operator experience and meter stabilization.

with qualified people, fewer data sets would have to be rejected, using the above field techniques and applying the same exclusion principles. We feel that 70-75% of G meter data could be utilized, with fewer repeated ties thus needed, and that precisions of 8 microgals (reduced to 5 microgals with network error distribution) can be attained with about 130% of the effort with D meters. Apparently, as indicated on Figure 2, the distance among stations were similar enough that distance of transport during the station occupations was not an apparent factor.

A transport system which damps out road vibrations seems to be an effective mechanism for improving precision. The road between stations Tsawassen and Sproat (TSA and SPR), normally paved, was reduced to a rugged washboard dirt road during installation of a sewer pipe. The road conditions were similar to those which were encountered by the senior author in work at Leach and Kyle Hot Springs, Nevada, which caused instrumental drift of up to 0.1 mgal daily, approximately 10 times the normal drift of 1/4 to 1/2 mgal per month. In addition, the car used for transport was small and overloaded by the combined load of meters and lead weights used for ballast, and the shock absorbers had grown ineffective with time. Nevertheless, over this segment of the road (occupied toward the end of our stay), we recorded some of our best tie values (refer back to Figure 2, p. 20), and the transport problems seem to have been minimized.

Based on our experience with the "leap frogging" method in Canada, we felt that some modifications in field procedure were in order; these would be implemented for both G and D meter surveys:

1) The established procedure calls for occupation of stations A and B in a sequence as follows: A B A B A B A B A. Differences

are then calculated for A to B, then B to A, etc., so that 8 differences are available for the total occupation of 9 stations. This data reduction technique has some problems in that all the intermediate values (BABABAB) enter into the calculations twice, first as the second value of the forward tie, and then as the first value of the backward tie, whereas the end stations at the base (A and A) enter into the calculations only once; this procedure thus has the effect of weighting intermediate stations twice as much as end stations (put another way, any error in an intermediate station affects both the forward and backward ties into which it is incorporated). We feel that it would be an improvement in statistical procedure to repeat the intermediate values, as follows:
AB BA AB BA AB BA AB BA. This involves no more transportation, and adds only four more minutes to each occupation, but then makes all the ties independent of each other. Differences are calculated within the 8 groupings, as depicted above.

2) With the G meters, additional replicability may improve the precision, so that the station sequencing would appear as follows:
AABB BBAA AABB BBAA AABB BBAA AABB BBAA. Again, differences are calculated within the groupings depicted, with the mean of the A readings being subtracted from the mean of the B readings.

3) We observed that the data for all meters exhibit "excursions" to a certain extent, either cyclical variations with a long period, or minor tares of 0.01 or 0.02 milligals (a typical data set is shown on the following page, as Figure 3), where one or two of the differences are more extreme in their variation from the mean within each

G300
8/11/79
RBG

STA		TIME*	MTR RD	COR. Mgal	ΔG
SPR	1	23.07	4456.729	4715.502	
TSA	2	0.35	4477.953	4737.964	22.462
	1	8/12 1.08	4456.742	4715.486	22.478
	2	1.38	4477.963	4737.949	22.463
	1	2.03	4456.778	4715.500	22.449
	2	2.41	4478.013	4737.973	22.465
	1	3.10	4456.794	4715.488	22.485
	2	3.38	4478.022	4737.959	22.472
	1	4.09	4456.811	4715.485	22.474

$\bar{X} = 22.469$

$s = .011$

$\bar{X}_1 = .492$

$s = .008$

$\bar{X}_2 = .961$

$s = .010$

* Greenwich

bumpy road - construction -

Figure 3. This is an actual copy of reduced data from the field notes, for the tie SPR to TSA in Canada. The cyclical behavior of the gravity meter is indicated in the last column to the right, where extremes are found, one low and one high. The total range in this case is 36 microgals.

tie. Both positive and negative extremes seem to be reached in a data set with several ties, so that the mean is not affected by these extremes, even though the standard deviations for individual sets of ties might be considerably larger.

To test the sets of premises outlined above, we conducted a second field test in Long Beach, where we took multiple sets of ties at three stations separated by a distance up to 10 km, using the station occupation scheme described in (2) above. All these tests were run with G300, and 7 ties were made over two different runs. The three stations chosen were probably similar to those which would be located in a geothermal environment, in that two of the stations were located on unconsolidated sediments, and one was located within 0.2 km of several actively pumping oil wells. Unlike a geothermal area, paved roads could be utilized exclusively, and traffic noise was severe in the Long Beach urban environment. The same precautions were followed as were used in the Canadian work; concrete pads were used as stations, the meter always occupied the same position and orientation, no base plate was used, transport was accomplished between stations, in most instances, with the special spring-mounted box, the meter was continually shaded, and readings were taken four minutes apart after picking up the meter and releveling between observing individual values at a station.

The results of this work show some improvement in precision over G300 values obtained in the Canadian work. The individual standard deviations of the ties were 5, 6, 7, 8, 5, 10, and 15 microgals, respectively. When a pooled variance for the meter was calculated, and the standard deviation calculated from it (as the square root of the variance), the resulting value was less than 3 microgals. The results of this work are summarized in Table I on the following page.

The calculation of a pooled variance in this case is analogous to the calculation of a standard error (another commonly calculated statistic) which can be viewed as being equivalent to the standard deviation of several means. The standard error can also be predicted mathematically and is then based on the number of observations and the standard deviations associated with individual ties. In comparing the two standard error values, the mathematically predicted value is somewhat larger than the value actually calculated from the data by the pooled variance technique. This suggests to us that occupation of stations over a several hour interval tends to even out the "cyclical variations" or "excursions" which are seen in the data, that errors are not truly normally distributed, and that the standard error should be used as the measure of error for precision gravity studies in a geothermal environment in cases where means of repetitive values are used. Unfortunately, no standard error determinations for repeated sets of gravity observations are available for D meters.

Only one standard deviation value on Table I exceeded 10 microgals: the last value for the tie from COLO to EL DOR was 15 microgals. There was an identifiable source of error for this tie, in that part way through the data collection, a heavy road grader drove over the station, which was located on a sidewalk overlying unconsolidated soil. Initially, the gravity value became 20 microgals too high (in comparison with other data) suggesting compression of the soil; later, the value became too low, suggesting reexpansion and then overcompensation. Ultimately, deformation had occurred. The cyclical variation mean of the eight ties still yielded a value (16.267) which lay within the range of values (16.272 to 16.266) obtained for the other three

TABLE I. SUMMARY OF WORK, LONG BEACH TIES

COLO - STATE TIE SET

	Meter	$\overline{x}$ (mgals)	S (mgals)
1.	G300	7.892	.005
2.	G300	7.888	.006
3.	G300	7.888	.010

$\overline{s}$, all 7 ties,
= .008 m gals

without value 7,
$\overline{s}$ = .007 mgals

COLO - EL DOR TIE SET

	Meter	$\overline{x}$ (mgals)	S (mgals)
4.	G300	16.272	.008
5.	G300	16.266	.005
6.	G300	16.266	.007
7.	G300	16.267	.015 (road grader problems)

STANDARD ERROR CALCULATIONS
(derived from data summarized above)

No. of ties in set	Standard Error
8	.0026
6	.0028
4	.005

sets of ties.

It is clear that the procedure used in the Long Beach study involves more work than the Canadian effort. We were able to complete the same number of ties per day (two) as we had done in Canada, probably because multiple readings per station occupation eliminated the necessity for excluding differences, and only the minimum number of ties per set were needed. But each replicated tie set involves an extra half-day. In an attempt to cut the work down, we evaluated our data set again, this time using the data from only the first six ties, and then again using only the first four ties. These results are also included in Table I. The following conclusions can be inferred from these results:

1) The loss in precision in using six ties, rather than eight, is negligible.
2) The loss in precision in using four ties per set is measurable, but still small.
3) If only the manpower for a total of one set of eight ties is fiscally feasible, it is better to perform two sets of occupations with four ties each, rather than one set of eight; the same effort is involved, but the former procedure permits the calculation of standard errors. An alternate (but less recommended) procedure is to collect one set of eight ties, and then divide the data into two sets of four for evaluation purposes.

C. ADDITIONAL CONSIDERATIONS IN ACHIEVING HIGH PRECISION IN REPETITIVE GRAVITY SURVEYS

There are additional considerations for assessing the use of the gravity method in geothermal regimes: (1) calibration effects; (2) transport problems; (3) barometric pressure variations; (4) tidal corrections; and (5) data reduction procedures.

(1) Calibration errors are the cause of mismatches among gravity meters. Figure 1 (on page 19) shows that, while standard deviations for values taken with a single meter may be small, the mean value for a set of ties can vary considerably from one meter to the next. This is shown, for instance, by the tie SPR-TSA, in which the largest standard deviation is 8 microgals, but the range in means, between G300 and G395 data sets, is 42 microgals. This mismatch is a function of imprecisions in the calibration tables provided by the manufacturers. The source of these imprecisions appears to be a combination of screw errors (due to nonlinearity in the screw with which gravity differences are measured) and too few data used in establishing calibration tables and constants. Screw errors may cause up to 70 microgal variations in G meters (R. Jachens, personal communication) and 30 microgal variations in D meters (H. Dragert, personal communication). The solution to this problem lies in establishing a detailed calibration loop over the range of the projected survey in a stable area. Reference gravity stations on this loop should be 10-20 milligals apart in value, and all the meters which are used in the survey must be calibrated, using one of the meters as a reference. This should greatly reduce inconsistencies among meters.

(2) Transport problems have been previously alluded to in the text as being detrimental to data quality. This problem cannot be overemphasized. Tares and non-linear drift have been artificially induced in LaCoste and Romberg gravity meters in the laboratory by placement on a platform vibrating at the

frequency of common carriers (Hamilton and Brule, 1967), and have been frequently observed in the field as well. An unprotected gravity meter transported over rough roads can experience more than .1 milligal of drift per day, which cannot be effectively removed in the data reduction process. We have repeatedly observed this effect during our surveys at Cerro Prieto geothermal field, where transport over a cobblestone road to the base on Cerro Prieto volcano, a distance of one mile, has caused .04 mgal drift in one hour of monitoring immediately after transport of only one mile distance. This drift is non-linear and unpredictable; it is usually toward high values, but is sometimes in the opposite sense as meters apparently occasionally recover some of the drift. The drift apparently also may "store" for some time, and then appear as a large sudden tare at an unpredictable time. Indeed, most of the drift seen in mechanical meters may be due to a succession of small tares which are vibration induced. Control of transport problems is multi-faceted, and can include the following:

a. Use of spring-mounted or air-compression transport cases or the use of mechanical isolators, which are designed to damp out vibrations in the 10-100 Hz range (the most damaging frequencies which are imparted by vehicular vibrations), may be quite effective. In the absence of a transport case, keeping the meter off the vehicle floor and use of extra padding on a car seat near the center of mass of the vehicle may prove helpful.

b. Selection of stations to avoid problematic roadways is recommended. If stations where no adequate access is possible must be used, then more repetitions of these stations and/or access to the station on foot may be effective. These considerations are especially crucial in the selection of a base station, since its value affects the value of every station in the loops referred to it. This is clearly indicated by a set of comparative data for Cerro Prieto geothermal field presented on Table II on the following page. During the course of that study, we first occupied a valley base located close to a paved road, then a station high on Cerro Prieto volcano (reached by three miles of dirt road and then one mile of cobblestone road), and finally a lower base on the volcano, which eliminated the cobblestone portion. The necessity for a bedrock reference base dictated the latter two choices, but from the standpoint of precision alone, the best choice was the valley station. Judicious selection of an appropriate base station, on the basis of both stability and transport difficulties, cannot be overemphasized.

c. Positioning in a vehicle and type of vehicle can be crucial. Heavy vehicles may be more effective in reducing drift than light ones (H. Dragert, personal communication), also shown by studies at Cerro Prieto. The field data there showed considerable upward drift, but it was more linear than with a small vehicle, yielding improved precision. Location in the vehicle may also be crucial (see Table II), since some of the highest-quality data in comparative studies were obtained with the meter midway in the car rather than at the rear (this may vary from one vehicle to the next).

(3) Barometric pressure variations are an error source which must be removed in conducting extremely precise gravity surveys, such as monitoring geothermal production with cryogenic gravity meters (Olson and Warburton, 1979). The influence of barometric pressure variations on gravity has been extensively studies by Warburton and Goodkind (1977). Based on their work, we have calculated that barometric pressure effects will usually cause errors in the 1 to 2 microgal range, and can be neglected in most geothermal repetitive gravity surveys. For the most part, the effects of barometric pressure will

TABLE II. COMPARISON OF GRAVITY SURVEY RESULTS UNDER A VARIETY OF TRANSPORT CONDITIONS AT CERRO PRIETO GEOTHERMAL FIELD

Gravity Meter Used	Period of Occupation	Approximate No. of Occupations Used in Statistical Analysis	Field Conditions	Standard Deviation (mgals)*
G300	1977-78, Winter	75	No transport case, small car, meter on seat, relatively inexperienced operators, valley base used.	.007
G423	1977-78, Winter	90	No transport case, small car, meter on seat, inexperienced operators, valley base used.	.025
G300	1978-79, Winter	120	No transport case, small car, meter on seat, valley base used.	.012
G300	1979-80, Winter	120	Transport case located center of medium-sized car, volcano base introduced.	.008
G300	1980-81, December and January	40	Transport case located in back of small car, volcano base used exclusively.	.011
G300	1981, February and March	32	Upgraded transport case located in back of heavy car, auxiliary volcano base used.	.007
G300	1981, January and March-April	41	Upgraded transport case located center of small car, auxiliary volcano base implemented (lower elevation), access to base over rough road on foot.	.011
G300	1981, March	6	Base ties over rough road only by walking in morning, meter stabilized overnight.	.008

* This is the standard deviation of all the individually measured standard deviations, i.e., 68% of the standard deviations fall within this tabulated value.

be eliminated by repetitions of gravity values at different times, and by removal of meter drift, as is performed with the looping methods. Under normal circumstances, then, no correction needs to be made for barometric pressure effects, even with D meters operating at five microgal precisions, since the effect is not significant.

(4) Tidal changes do form a substantial portion of the observed gravity variations seen over short time periods at individual stations, and must be removed from the gravity values either by appropriate field procedures or by post-field processing. The magnitude of tidal changes can far exceed those associated with geothermal production, and thus mask the values being sought, with changes of ± .2 milligals being commonly observed. Roman's method (Roman, 1946), as described earlier, is a variation of the looping techniques which allows the gravimetrist to ignore tidal corrections by dedrifting, using the data obtained in successive occupations of stations within the loop. With enough ties in a set, the use of the "leap frogging" technique would also theoretically permit one to avoid tidal corrections, since the tidal effects would be averaged out. This would result in similar mean values for sets of ties, but much larger standard deviations within the sets. We do not recommend either of the above field procedures, unless data reduction must be done entirely by hand. The calculation of tidal corrections, once an extremely tedious task by hand, is very straightforward and rapid on high speed computers, using algorithms such as those developed by Longman (1959). Furthermore, the extra data occupations needed to remove tidal effects by field procedures (rather than computationally) are far more expensive in terms of manpower and money. However, the use of Roman's

method to evaluate and remove drift after tidal effects have been removed from the data may enhance data precision and thus justify the extra cost of conducting such a survey; it must be realized that some of the occupations in this type of work will be for drift evaluation and thus will not constitute additional independent gravity values which can be used to measure the precision. The use of Roman's techniques to enhance precision by drift evaluation has never been studied.

To use tidal corrections of the correct magnitude, the value of two empirical constants must be determined. According to Chase et al (1978):

> The first of these, the so-called lag time, reflects the difference in time between the passage of the sun and the moon and the distortion of the earth's surface. Normally, a zero lag time is assumed. The other constant is a proportionality constant, which brings conformance between the theoretical calculated tidal corrections and the observed tidal changes. The latter are usually larger, and the calculated values are normally multiplied by 1.16 to obtain the appropriate tidal correction. However, there is some measured variability in this value.

If these tidal constants are unknown for the area being studied, they can be measured in the field by two or three days of continuous gravity monitoring (either by using a strip chart recorder attached through the electronic jack on the side of the meter, or by taking readings manually every 10-15 minutes throughout the recording period). These values can then be incorporated into a tidal correction computer program. Separate values may be needed for the calibration loop, if this is located at some distance from the gravity survey area.

(5) Data reduction procedures are simple and rapid when the reduced quantity sought is observed gravity values, as is the case in precise, repetitive surveys. The following steps are usually taken:

a. The meter readings are multiplied by the appropriate calibration factors, to convert the readings into milligals and parts of milligals.

b. Tidal corrections are applied to all the values in a loop or a set of ties, using appropriate values for the lag time and conformance factor.

c. If the looping method is used, the accumulated changes which are not removed by the tidal corrections can be treated as drift, and removed by distributing the error which occurs between adjacent base station occupations to the intervening stations, assuming linear changes. This is effective if loops are kept short, and if drift changes are small (.01 to .02 mgal over a five or six hour period).

d. Once all the stations in a loop or set of ties have been completed, gravity differences can be calculated between the base and the station(s), using mean values of the readings obtained. The object of a precise repetitive gravity survey is the detection of temporal changes in the differences between individual stations and some stable reference base located outside the field area.

e. Finally, when loops are repeated, or a set(s) of ties completed, standard deviations and/or standard errors should be calculated. This allows an estimate of the precision of the survey, and thus the isolation of gravity variations which are significant.

Ideally, data reduction should be carried out in the field as the data are collected. This will allow the exclusion of imprecise data and the collection of replacement values, and will allow timely modification of field procedures, if necessary, such as selection of an alternate base station due to transport difficulties. Smaller tares can also be identified and dealt with if data are reduced immediately. With the exception of the tidal corrections, whose programming demands large storage space in the computer, all of the reduction procedures can be carried out with a sophisticated pocket calculator. The recommended procedure is to pre-calculate the tidal corrections, printing them as a set of tables which cover the interval of time in which data will be collected; a ten-minute interval between adjacent values is adequate, since intermediate corrections can be interpolated. These are then carried to the field, allowing full reduction of data as they are collected.

An alternative to hand calculations is to use a microprocessor system which will not only assist in the data collection process by appropriate interfacing, but will produce data reduction in real time. This permits immediate identification of tares if the system has some means of visual display, and will allow the identification of (and elimination of) hysteresis effects, which may sometimes exist in the first five or ten minutes of occupation at a particular station. Such a unit could also store previous gravity data and make comparisons with those data, for immediate identification of significant changes. Furthermore, a microprocessor system will allow the collection of many more data in a given time span, allowing a fuller understanding of gravity meter behavior, and thus enhancement of precision by using optimum field procedures. A suitable interfaced microprocessor system has been described by Bajwa _et al_ (1978; 1979).

D. MAGNITUDE OF EXPECTED GRAVITY CHANGES: MODELS OF GRAVITY AND GEOID CHANGES DUE TO WATER WITHDRAWAL AND AQUIFER COMPACTION

a. Introduction

Although high precision can be obtained by the use of appropriate gravity meters and field techniques, use of the gravity method also depends on whether or not the expected change can be detected with the availabile precision within a reasonable time frame. Results from the literature suggest that the use of precise gravity surveys in geothermal regimes is indeed feasible; Isherwood (1977) detected changes of more than 0.1 mgal at The Geysers over a few-year-interval and Hunt (1970) reported a 0.5 mgal change at Wairakei in six years. We have augmented these measured magnitudes with modeling studies to estimate possible magnitudes for several different conditions of water withdrawal and aquifer compaction.

b. Technical Discussion

In this section we estimate the effect of water removal and compaction on gravitational acceleration, termed "gravity," and potential fields during the large-scale production of geothermal fluids. Because the affected area is sometimes equidimensional and the distribution of the affected porous materials in the shallow earth's crust is sometimes tabular in shape, a horizontal circular disk is used for estimating changes in the earth's gravitational acceleration and potential. Changes in the latter parameter affect estimates of vertical ground movement based on leveling, a procedure which assumes that the potential surface, or geoid, remains fixed in time. Other, less simple three-dimensional distributions of porous materials can be modeled with more complex, and costly, three-dimensional calculations if necessary. If only gravity is needed, two-dimensional calculations can be used, but for geoid estimates, two-dimensional models lead to infinite potential because of the infinite mass distribution in the third dimension. This limitation is, of course, also a characteristic of one-dimensional slab models.

The major factors that will affect the gravity and potential above the geothermal-production disk model are 1) mass removal due to fluid withdrawal, 2) density increase due to compaction of porous rocks as a result of reduced pore pressure and increased effective stress, 3) vertical movement of subsurface mass away from or toward the observing station on the earth's surface, and 4) vertical motion towards the earth's center of mass of the observing station itself due to compaction which leads to subsidence at the earth's surface. Pressure- and temperature-dependent changes in the density of water are neglected as being too small to significantly affect the results.

Computations of the gravity potential and apparent tilt (the horizontal spatial derivative of the change in geoid elevation) fields over the entire surface above the disk-shaped reservoir have been made. The maximum effect in gravity and potential change is above the center of the disk and maximum change in apparent tilt is above the edges of the disk. Figure 4 shows three basic types of geodetic elevation measurements that attempt to determine the shape of the ground surface. Leveling measures the distance between a reference equipotential surface and the ground surface. This measurement involves gravity corrections, and the resultant measurement, if it is referred to the geoid, is called the orthometric height. In this paper these corrections are assumed to be done perfectly, and heights measured by leveling are assumed to be true orthometric heights. Geometric methods measure the distance relative to some external frame of reference, represented here by a distant star. In practice, both leveling and geometric methods measure elevation relative to another point on the ground surface, so that the elevation measurements shown on Figure 4 should be accompanied by measurements for some distant

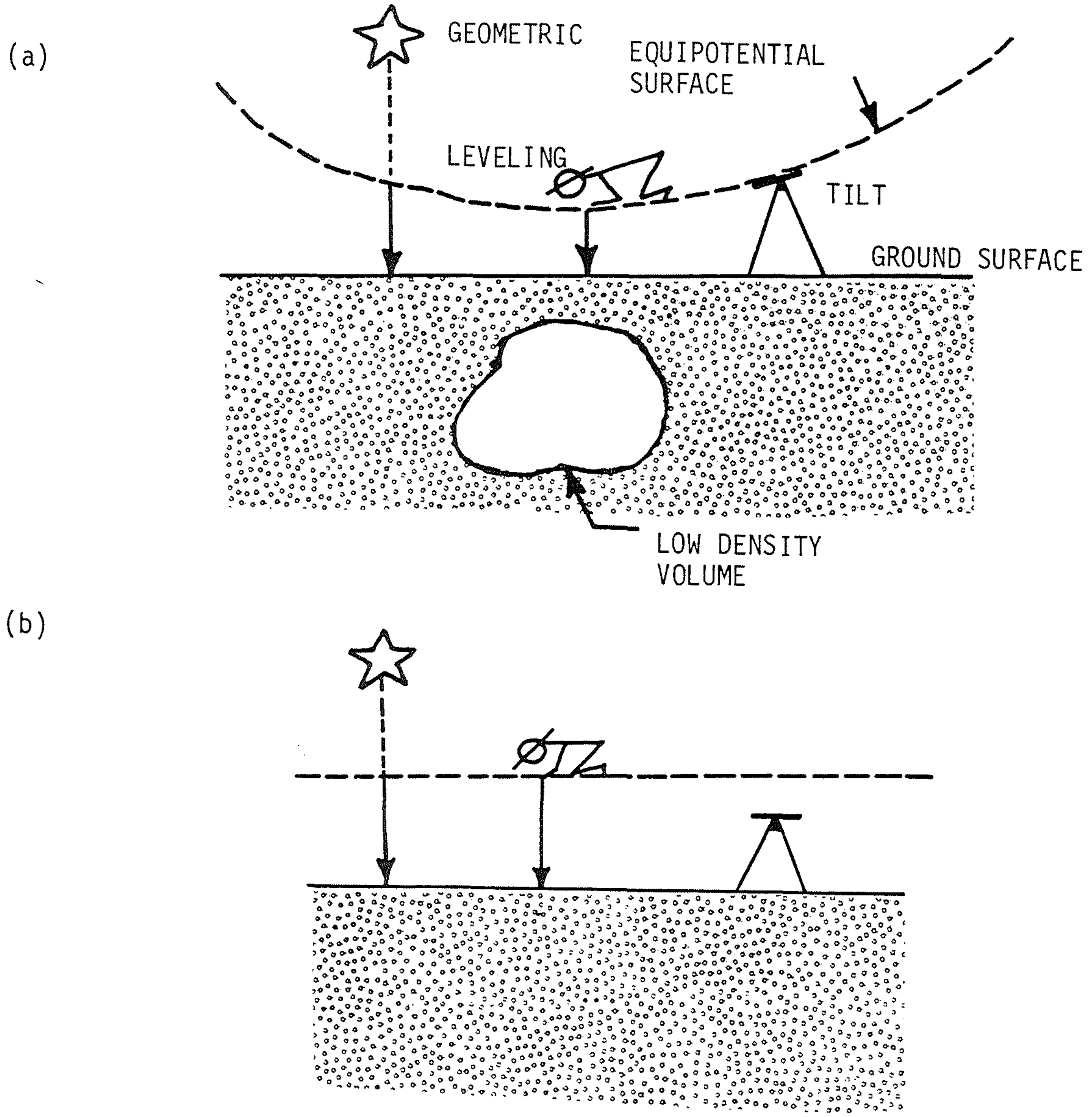


Figure 4. Schematic drawing illustrating the relations among leveling, tilt, and geometric methods of measuring ground surface shape for a half space. (a) Low density inclusion. (b) Homogeneous density distribution. In (a), leveling and tilt measurements would indicate a bulging ground surface, whereas the geometric measurement indicates a flat surface. A transition from (a) to (b) would show a ground elevation decrease from leveling and tilt readings, but not from geometric measurements. After Whitcomb (1976).

point with the same reference systems.

Figure 4a shows what will happen when an anomalous mass, here a lower-density volume in a homogeneous half space, is present just beneath the surface. Both the leveling and the tilt measurements would indicate that the ground surface has a bulge, even though it is geometrically flat. The geometric measurement is unaffected by mass distributions and faithfully follows the geometric ground shape.

Now suppose that the low-density volume of Figure 4a is eliminated by the transferral of mass from some distant source, so that the subsurface is homogeneous, as is shown in Figure 4b. The change in mass distribution will cause a decrease in elevation as measured by leveling and tilt, but the geometric measurement will register no change.

A disk model is used here to estimate the various gravitational parameters of the models including gravity, potential, and geoid tilt. By using the expansion of gravitational potential for a thin disk in terms of Legendre Polynomials, the desired parameters can be calculated at all points in space. Cylindrical bodies can be treated by separating them into several disks in order to avoid edge effects. For a more complete discussion, see Whitcomb (1976).

c. Model Analysis

Case 1. The first model represents a relatively shallow geothermal production field such as those described by Lippmann et al (1977). Reservoirs with horizontal radii of one to five kilometers, consolidation formation thicknesses of 100 to 200 meters, and consolidations of 0.1% are typical in this paper. The consolidation formation is not always the production formation, but this has negligible effects on the calculations here. The burial depths of the models in Lippmann et al are not given because the calculations in that paper assume that all distortion is vertical. This assumption implies a shallow depth of burial. This will not be a limitation in these gravity calculations, however. The model production formation is assumed to have a radius of 5 km, a thickness of 200 meters, a burial depth (to the top of the formation) of 200 meters, an initial porosity of 0.1, an initial density of 2.44 gm/cm^3, and a consolidation of 0.1% yielding a surface subsidence of 20 cm. Water is assumed to fill the pores both before and after subsidence. Table III shows the results for Case 1 as a function of horizontal distance from the surface point above the disk model. The first column is distance in kilometers; the second is change in gravitational potential in cm^2/sec^2, the third is change in orthometric elevation (potential divided by the free-air gradient of potential 981 cm sec^{-2}), the fourth is change in gravity in mgals, the fifth is apparent free-air elevation change in cm (gravity divided by the free-air gravity gradient 3.08 x 10^{-6} sec^{-2}), and the sixth is the geoid tilt (the horizontal gradient of the geoid height change).

Here, as in all cases that follow, there is little significant difference between the orthometric change, that is, the elevation change as measured by leveling, and the geometric elevation change which is 20 cm in this case.

The gravity change is 0.0538 mgal at the center of the model, decreasing to 0.0528 mgal one km from the edge. At a distance of 1 km beyond the edge of the disk the gravity change is less than 0.001 mgal.

The free-air elevation change of -17.45 cm is a relatively good estimate of the geometric elevation change of -20 cm in this case. It will be seen in

TABLE III. Case 1.

Distance (KM)	Potential (CM2/SEC2)	Orthometric Elevation (CM)	Gravity (MGAL)	Free Air Elevation (CM)	Tilt (MICRORAD)
0.0	19616.	-20.00	0.0538	-17.45	0.0
1.00000	19616.	-20.00	0.0537	-17.44	0.00
2.00000	19616.	-20.00	0.0536	-17.42	0.00
3.00000	19616.	-20.00	0.0534	-17.35	0.00
4.00000	19617.	-20.00	0.0528	-17.14	0.00
5.00000	0.	0.0	0.0	0.0	0.0
6.00000	-2.	0.00	0.0008	-0.27	0.00
7.00000	-1.	0.00	0.0003	-0.10	0.00
8.00000	-1.	0.00	0.0002	-0.06	0.00
9.00000	-1.	0.00	0.0001	-0.03	0.00
10.00000	-1.	0.00	0.0001	-0.02	0.00
11.00000	-1.	0.00	0.0000	-0.02	0.00
12.00000	-1.	0.00	0.0000	-0.01	0.00
13.00000	-1.	0.00	0.0000	-0.01	0.00
14.00000	-1.	0.00	0.0000	-0.01	0.00
15.00000	-1.	0.00	0.0000	-0.01	0.00
16.00000	-1.	0.00	0.0000	-0.00	0.00
17.00000	-1.	0.00	0.0000	-0.00	0.00
18.00000	-0.	0.00	0.0000	-0.00	0.00
19.00000	-0.	0.00	0.0000	-0.00	0.00
20.00000	-0.	0.00	0.0000	-0.00	0.00

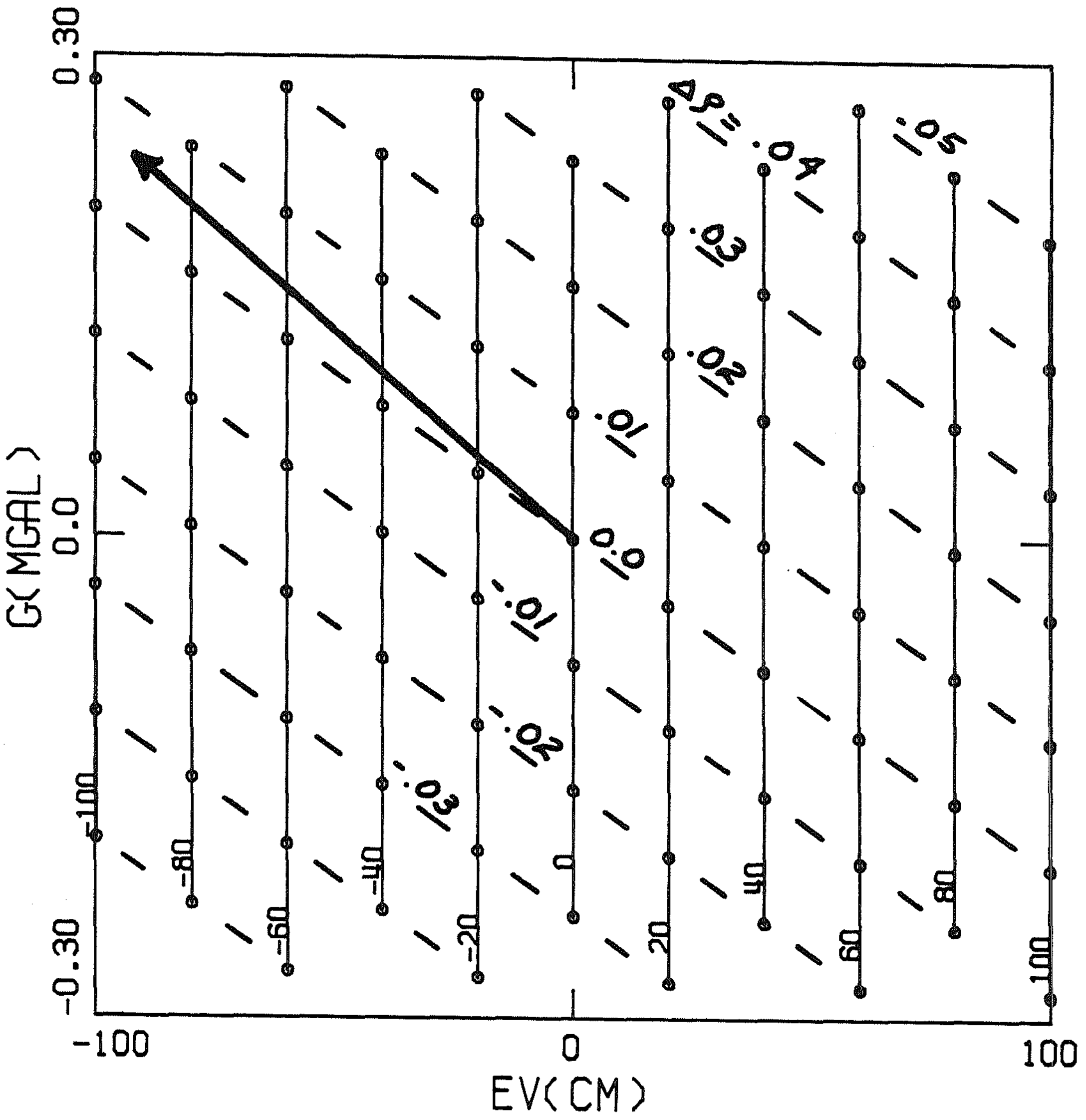
later examples, however, that free-air elevation computed from gravity data alone does not provide a good estimate of elevation change and that elevation must be measured separately.

Tilt anomalies in this model are small, less than 0.005 microradians.

At any point on the earth's surface above this same disk model, it is possible to construct the behavior of the parameters for an arbitrary consolidation in the three-dimensional gravity, elevation, and bulk density change space. For the given geometry of 5 km radius, 200 m thickness, and 200 m burial depth, the specification of any two of the parameters of change in gravity, elevation, or bulk density uniquely determines the third. Figure 5 illustrates such a plot for Case 1 relating all three parameters at the surface above the center of the disk model. Lines of equal gravity are horizontal, lines of equal elevation are vertical, and lines of equal density are diagonal across the plot.

Case 2. In this model, all parameters are identical to those of Case 1 with the exception that the production/consolidation formation is at the deeper burial depth of 2 km. The results are shown in Table IV (for an explanation of the table, see Case 1). Little change from the results of Case 1 in Table III is seen, with the exception that the maximum gravity change in Case 2 is reduced to 0.0494 mgal compared to 0.0538 in Case 1.

Case 3. The next two models are intended to investigate more extensive regional aquifers than those of Cases 1 and 2. Major geopressurized geothermal reservoirs in deep sedimentary formations exist in the Gulf Coast states of the U.S. If these reservoirs are exploited, the large continuous lateral extent of the aquifers could mean that the subsidence effects might extend to a radius of 50 km or more. For this model, a disk formation was used



RAD= 5.00
THICK= 0.20, DEPTH= 0.30
DEN1= 2.44000
DEN2= 2.390000 2.490000 0.010000

RADPLT= 0.0

Figure 5. Plot in the three-dimensional space of gravity (mgals), elevation (cm), and bulk density (gm/c^3) at the surface above the center of the disk geothermal fluid production model for Case 1. The model's parameters are: radius = 5 km, thickness - 200 m, and burial depth (depth to the top of the disk) = 200 m. The heavy line with an arrow starting at the origin indicate the path that would be followed by increasing consolidation of the production formation.

TABLE IV. Case 2.

Distance	Potential	Orthometric Elevation	Gravity	Free Air Elevation	Tilt
(KM)	(CM2/SEC2)	(CM)	(MGAL)	(CM)	(MICRORAD)
0.0	19614.	-19.99	0.0494	-16.03	0.0
1.00000	19614.	-19.99	0.0492	-15.99	0.00
2.00000	19614.	-19.99	0.0489	-15.87	0.00
3.00000	19615.	-19.99	0.0481	-15.63	0.00
4.00000	19615.	-20.00	0.0469	-15.23	0.01
5.00000	0.	0.0	0.0	0.0	0.0
6.00000	-2.	0.00	0.0025	-0.82	0.01
7.00000	-2.	0.00	0.0015	-0.49	0.00
8.00000	-1.	0.00	0.0009	-0.31	0.00
9.00000	-1.	0.00	0.0006	-0.20	0.00
10.00000	-1.	0.00	0.0004	-0.14	0.00
11.00000	-1.	0.00	0.0003	-0.10	0.00
12.00000	-1.	0.00	0.0002	-0.08	0.00
13.00000	-1.	0.00	0.0002	-0.06	0.00
14.00000	-1.	0.00	0.0001	-0.05	0.00
15.00000	-1.	0.00	0.0001	-0.04	0.00
16.00000	-1.	0.00	0.0001	-0.03	0.00
17.00000	-1.	0.00	0.0001	-0.03	0.00
18.00000	-1.	0.00	0.0001	-0.02	0.00
19.00000	-0.	0.00	0.0001	-0.02	0.00
20.00000	-0.	0.00	0.0000	-0.02	0.00

with a radius of 50 km, a thickness of 1 km, a burial depth of 1 km, an initial porosity of 0.1, an initial density of 2.44 gm/cm^3, and a consolidation of 0.1% yielding a surface subsidence of 100 cm. Water is assumed to fill the pores both before and after subsidence. Table V shows the results for Case 3 as a function of horizontal distance from the surface point above the disk model (for an explanation of the table, see Case 1).

The difference between the change of 100 cm geometric elevation and orthometric elevation change in Table V is 0.2 cm, which is not significant in light of the accuracy of leveling. The gravity change is 0.2708 mgal at the center of the disk, and decreases to 0.2651 mgal at a position 5 km from the edge. Outside the disk radius, gravity changes are 0.005 mgal or less.

Figure 6 is a three-dimensional gravity, elevation, and bulk density changes plot for an arbitrary consolidation of the model in Case 3. Again as in Case 1, the solid line going towards the upper left from the origin of the plot is the path that would be followed by increasing formation consolidation due to water withdrawal where remaining pore space is filled with water.

Case 4. In this model, all parameters are identical to those of Case 3 with the exception that the production/consolidation formation is put at a more realistic and deeper burial depth of 4 km. The results are shown in Table VI (for an explanation of the table, see Case 1). The major differences from the Case 3 results are that the gravity change at the center of the structure is reduced by 0.004 mgal and the gravity 5 km outside the disk radius is increased by 0.007 mgal.

Case 5. This model was chosen to show the effect of removal of liquid with no recharge, or of a liquid-to-vapor transition in an aquifer. These can be accomplished by a lowering of a water table near the surface by some

TABLE V. Case 3.

Distance	Potential	Orthometric Elevation	Gravity	Free Air Elevation	Tilt
(KM)	(CM2/SEC2)	(CM)	(MGAL)	(CM)	(MICRORAD)
0.0	97914.	-99.81	0.2708	-87.91	0.0
5.00000	97914.	-99.81	0.2708	-87.91	0.00
10.00000	97916.	-99.81	0.2707	-87.89	0.00
15.00000	97918.	-99.81	0.2706	-87.86	0.01
20.00000	97921.	-99.82	0.2705	-87.82	0.01
25.00000	97926.	-99.82	0.2703	-87.75	0.01
30.00000	97931.	-99.83	0.2699	-87.65	0.01
35.00000	97938.	-99.83	0.2694	-87.46	0.02
40.00000	97947.	-99.84	0.2683	-87.10	0.02
45.00000	97959.	-99.86	0.2651	-87.07	0.03
50.00000	0.	0.0	0.0	0.0	0.0
55.00000	-94.	0.10	0.0049	-1.59	0.03
60.00000	-83.	0.08	0.0021	-0.69	0.02
65.00000	-75.	0.08	0.0012	-0.40	0.01
70.00000	-68.	0.07	0.0008	-0.26	0.01
75.00000	-63.	0.06	0.0006	-0.19	0.01
80.00000	-58.	0.06	0.0004	-0.14	0.01
85.00000	-54.	0.06	0.0003	-0.11	0.01
90.00000	-51.	0.05	0.0003	-0.08	0.01
95.00000	-48.	0.05	0.0002	-0.07	0.01
100.00000	-46.	0.05	0.0002	-0.06	0.01
105.00000	-43.	0.04	0.0001	-0.05	0.00
110.00000	-41.	0.04	0.0001	-0.04	0.00
115.00000	-39.	0.04	0.0001	-0.03	0.00
120.00000	-38.	0.04	0.0001	-0.03	0.00
125.00000	-36.	0.04	0.0001	-0.03	0.00
130.00000	-35.	0.04	0.0001	-0.02	0.00
135.00000	-33.	0.03	0.0001	-0.02	0.00
140.00000	-32.	0.03	0.0001	-0.02	0.00
145.00000	-31.	0.03	0.0000	-0.02	0.00
150.00000	-30.	0.03	0.0000	-0.01	0.00
155.00000	-29.	0.03	0.0000	-0.01	0.00
160.00000	-28.	0.03	0.0000	-0.01	0.00
165.00000	-27.	0.03	0.0000	-0.01	0.00
170.00000	-26.	0.03	0.0000	-0.01	0.00
175.00000	-25.	0.03	0.0000	-0.01	0.00
180.00000	-25.	0.03	0.0000	-0.01	0.00
185.00000	-24.	0.02	0.0000	-0.01	0.00
190.00000	-23.	0.02	0.0000	-0.01	0.00
195.00000	-23.	0.02	0.0000	-0.01	0.00
200.00000	-22.	0.02	0.0000	-0.01	0.00

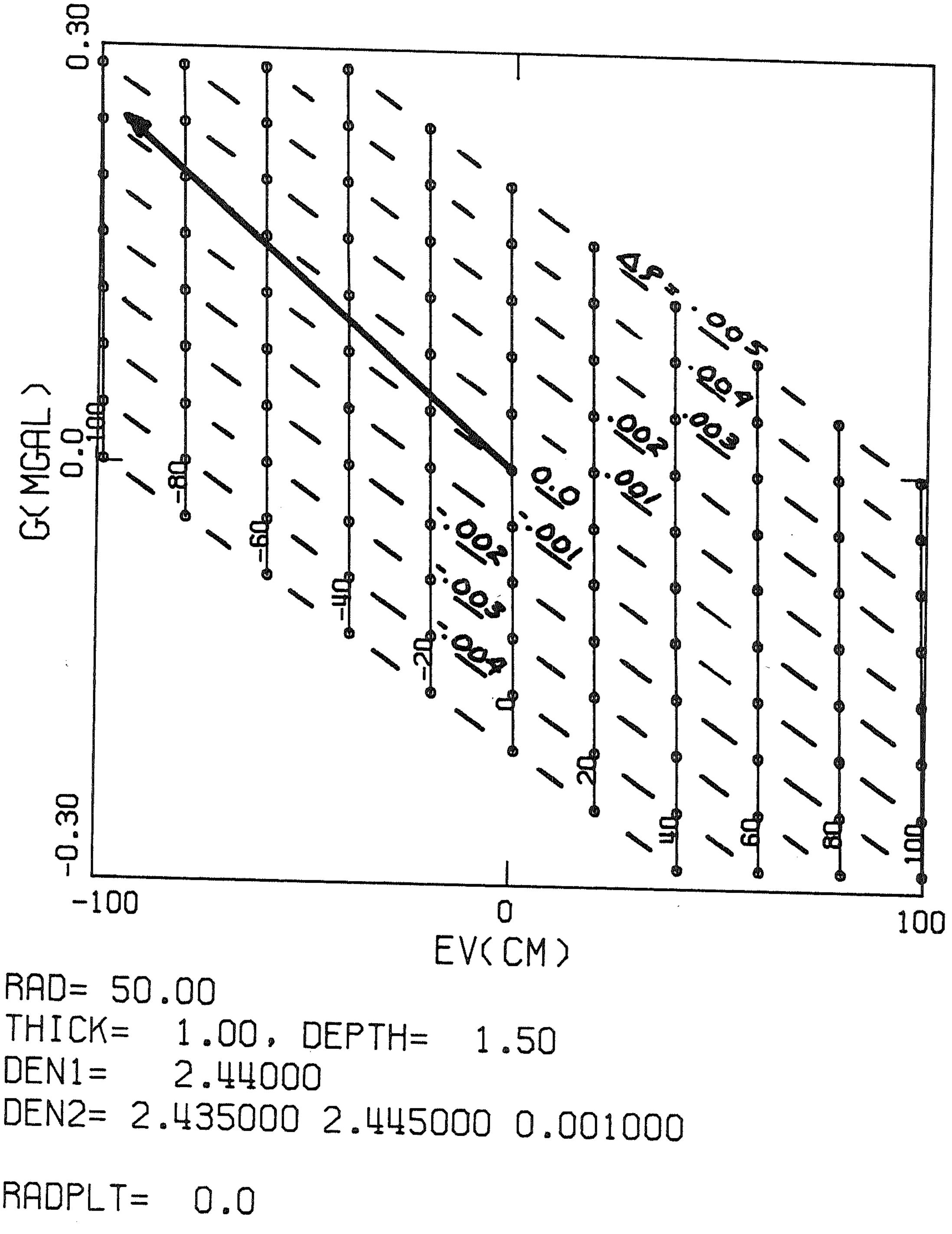


Figure 6. Plot in three-dimensional space of gravity (mgals), elevation (cm) and bulk density change (gm/cm^3) at the surface above the center of the disk geothermal fluid production model for Case 3. The model's parameters are: radius = 50 km thickness = 1 km, and burial depth = 1 km. The heavy line with an arrow starting at the origin indicates the path that would be followed by increasing consolidation of the production formation. The equi-elevation change contours are not vertical here because of the distortion of the geoid by the consolidation. The contours are the geometric change in elevation and the horizontal axis of the plot represents orthometric elevation change (as measured by leveling).

TABLE VI. Case 4.

Distance (KM)	Potential (CM2/SEC2)	Orthometric Elevation (CM)	Gravity (MGAL)	Free Air Elevation (CM)	Tilt (MICRORAD)
0.0	97895.	-99.79	0.2668	-86.61	0.0
5.00000	97895.	-99.79	0.2667	-86.60	0.00
10.00000	97897.	-99.79	0.2666	-86.55	0.00
15.00000	97899.	-99.80	0.2663	-86.47	0.01
20.00000	97902.	-99.80	0.2659	-86.34	0.01
25.00000	97907.	-99.81	0.2653	-86.15	0.01
30.00000	97913.	-99.82	0.2644	-85.84	0.01
35.00000	97920.	-99.82	0.2628	-85.33	0.02
40.00000	97930.	-99.83	0.2598	-84.37	0.02
45.00000	97943.	-99.84	0.2530	-82.14	0.03
50.00000	0.	0.0	0.0	0.0	0.0
55.00000	-96.	0.10	0.0119	-3.87	0.03
60.00000	-84.	0.09	0.0059	-1.92	0.02
65.00000	-75.	0.08	0.0035	-1.15	0.02
70.00000	-69.	0.07	0.0024	-0.77	0.01
75.00000	-63.	0.06	0.0017	-0.55	0.01
80.00000	-59.	0.06	0.0013	-0.41	0.01
85.00000	-55.	0.06	0.0010	-0.32	0.01
90.00000	-51.	0.05	0.0008	-0.25	0.01
95.00000	-48.	0.05	0.0006	-0.20	0.01
100.00000	-46.	0.05	0.0005	-0.17	0.01
105.00000	-43.	0.04	0.0004	-0.14	0.00
110.00000	-41.	0.04	0.0004	-0.12	0.00
115.00000	-39.	0.04	0.0003	-0.10	0.00
120.00000	-38.	0.04	0.0003	-0.09	0.00
125.00000	-36.	0.04	0.0002	-0.08	0.00
130.00000	-35.	0.04	0.0002	-0.07	0.00
135.00000	-33.	0.03	0.0002	-0.06	0.00
140.00000	-32.	0.03	0.0002	-0.05	0.00
145.00000	-31.	0.03	0.0001	-0.05	0.00
150.00000	-30.	0.03	0.0001	-0.04	0.00
155.00000	-29.	0.03	0.0001	-0.04	0.00
160.00000	-28.	0.03	0.0001	-0.03	0.00
165.00000	-27.	0.03	0.0001	-0.03	0.00
170.00000	-26.	0.03	0.0001	-0.03	0.00
175.00000	-25.	0.03	0.0001	-0.03	0.00
180.00000	-25.	0.03	0.0001	-0.02	0.00
185.00000	-24.	0.02	0.0001	-0.02	0.00
190.00000	-23.	0.02	0.0001	-0.02	0.00
195.00000	-23.	0.02	0.0001	-0.02	0.00
200.00000	-22.	0.02	0.0001	-0.02	0.00

means (not necessarily directly related to the geothermal activity) or by the reduction of pore pressure causing a liquid-to-vapor transition during geothermal fluid production. In this model the affected formation has a radius of 1 km, a thickness of 100 m, a burial depth of 250 m, and a porosity of 0.1. Table VII shows the results for Case 5 (for an explanation of Table VII, see Case 1).

Again, the orthometric elevation change is small, only 0.03 cm. However, the gravity change is large and negative owing to the absence of a free-air effect due to consolidation and related lowering of the observing station. The free-air apparent elevation change computed from the gravity is 97 cm at the center of the structure, clearly showing that gravity is not a good measure of elevation change, which in this case is zero.

While the actual geometric tilt is zero, the tilt of the geoid (that which would be measured by a tilt meter) is the largest of the cases considered here, being as much as 0.16 microradians 200 m from the edge of the disk model.

d. Conclusions

1. Gravity variations to be expected from typical geothermal production zones can be expected to be of the order of 0.050 mgal or larger as seen in Cases 1 and 2. This is certainly well-resolvable with current state-of-the-art gravimeters.

2. Both gravity and elevation measurements must be made in order to evaluate the nature of distortion in a geothermal production area. Gravity alone cannot be used as a measure of vertical surface motion, and leveling surveys cannot give estimates of subsurface density changes.

TABLE VII. Case 5.

Distance	Potential	Orthometric Elevation	Gravity	Free Air Elevation	Tilt
(KM)	(CM2/SEC2)	(CM)	(MGAL)	(CM)	(MICRORAD)
0.0	-31.	0.03	-0.2989	97.05	0.0
0.20000	-31.	0.03	-0.2958	96.04	0.04
0.40000	-30.	0.03	-0.2853	92.64	0.08
0.60000	-28.	0.03	-0.2632	85.44	0.12
0.80000	-25.	0.03	-0.2191	71.14	0.16
1.00000	0.	0.0	0.0	0.0	0.0
1.20000	-18.	0.02	-0.0751	24.37	0.16
1.40000	-16.	0.02	-0.0398	12.91	0.12
1.60000	-13.	0.01	-0.0234	7.58	0.09
1.80000	-12.	0.01	-0.0150	4.86	0.07
2.00000	-11.	0.01	-0.0102	3.32	0.06
2.20000	-10.	0.01	-0.0073	2.38	0.05
2.40000	-9.	0.01	-0.0054	1.77	0.04
2.60000	-8.	0.01	-0.0042	1.35	0.03
2.80000	-8.	0.01	-0.0033	1.06	0.03
3.00000	-7.	0.01	-0.0026	0.85	0.02
3.20000	-7.	0.01	-0.0021	0.69	0.02
3.40000	-6.	0.01	-0.0017	0.57	0.02
3.60000	-6.	0.01	-0.0015	0.47	0.02
3.80000	-6.	0.01	-0.0012	0.40	0.02
4.00000	-5.	0.01	-0.0010	0.34	0.01

3. Varying groundwater levels, because of their large effect on gravity as seen in Case 5, must be monitored and removed from gravity data in order to avoid the masking of deeper bulk density changes.

IV. IMPLEMENTATION OF REPETITIVE GRAVITY SURVEYS IN GEOTHERMAL REGIMES

A. SUMMARY

Based on the foregoing work, we can make a series of recommendations concerning the conduct of a precise repetitive gravity survey over a producing geothermal field. The recommendations fall into two categories: 1) those which apply to all gravity surveys, irrespective of the level of precision desired; and 2) three sets of specific recommendations for maintenance of 15, 10, and 5 microgal standard deviations, respectively. Both categories are presented in detail in Appendix A, together with the rationale for the recommendations, as appropriate; here the recommendations will be summarized.

For all gravity surveys, the following are recommended:

1) The gravity stations should be permanently established on flat concrete piers, with permanent positions for the meter feet with identical orientations at all stations. Station locations should have minimal cultural noise and be protected from possible long-term damage.
2) Deleterious environmental conditions must be minimized or avoided. These include rough transport, sunlight on the level bubbles, high external temperatures, and strong winds.

3) More than one meter should be used, and all meters should be frequently calibrated relative to each other on a stable, permanent, precisely-established calibration loop.

4) Data reduction should be completed coincident with data collection, and statistical evaluation carried out. This is facilitated through use of a pocket calculator and tidal correction tables for the interval of the gravity survey. If necessary, tidal monitoring with a gravity meter precedes the gravity survey, and is used to calculate appropriate tidal constants. Field reduction of the data permits identification of tares, exclusion of poor quality values, and the acquisition of replacement data.

5) The gravity survey should be accompanied by a precise (second order minimum) leveling survey. This is needed to separate the effects of mass and elevation changes, since both types of changes will occur during geothermal production. Both the gravity and leveling surveys must include one or more stations which serve as stable references, preferably located on bedrocks. Gravity and elevation differences can be assessed with respect to these reference points. Neither method gives unequivocal results without the other.

If maintenance of a specific precision is desired, either D or G meters may be used, and either the tie or looping technique followed, but more data will have to be excluded, and repeated, as precision requirements increase. Table VIII summarizes our recommendations for 15, 10 and 5 microgal requirements.

TABLE VIII. RECOMMENDATIONS FOR 15, 10 and 5 MICROGAL PRECISION REQUIREMENTS FOR REPETITIVE GRAVITY SURVEYS

Precision Level	Meter Type	Field Method	Comments
15 microgals	G or D LaCoste-Romberg	Looping or Leapfrogging	G meter and looping method will be sufficient and less costly. Two occupations of a station in separate loops will suffice, but will not permit calculation of standard error directly from field data.
10 microgals	G or D LaCoste-Romberg	Looping or Leapfrogging	G meter and looping method will be sufficient and less costly, but a few data may have to be rejected. Three occupations of a station in separate loops will suffice; four will permit calculation of standard error directly from field data (yielding two sets of two occupations).
5 microgals	D LaCoste-Romberg; G model in some circumstances	Leapfrogging	Two sets of six ties each are preferred to tie in stations; a comprehensive survey may need internal bases. Some stable G meters could be utilized. Extra precautions will be necessary to maintain this level of precision for both types of meters.

Note: A full discussion of precision maintenance starts on page 65.

B. RECOMMENDATIONS FOR FURTHER WORK

The following four tasks should still be carried out, to further enhance recommendations for maintenance of precision.

(1) Comparative studies should be carried out between D and G meters in an actively producing geothermal environment. The advantages of the D meter may lessen for high precision surveys in this harsh environment.

(2) An evaluation of screw errors between G and D meter types should be systematically evaluated.

(3) A comprehensive study comparing different transport case types should be undertaken.

(4) Roman's (1946) method of tidal and drift correction removal by field observations should be thoroughly evaluated for its possible role in improving precision.

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V. SITE SELECTION FOR IMPLEMENTATION OF A PRECISE SURFACE GRAVITY STUDY IN A GEOTHERMAL REGIME

The third task carried out in this geothermal assessment study was the evaluation of several active or potentially active geothermal regimes for the possible implementation of a precise, repetitive surface gravity study. The sites evaluated in this report are all located in the western United States, since most of the development of geothermal resources in the near future is scheduled for this region.

Initially, we examined the tabulated characteristics of all the geothermal resources listed in Circular 790 -- Assessment of Geothermal Resources of the United States - 1978 (Muffler, 1979) and selected several geothermal areas which seemed amenable to carrying out successful repetitive gravity surveys. The principle criteria used in the site evaluation process were:

a. The reservoir could be producing by 1990, but should not currently be producing (with the exception perhaps of test wells), and/or should be a potential large scale electrical producer (a minimum production of 300 MW over a 30 year interval was selected as the cutoff). This mostly limited the possible sites to those with potentially large reservoir volumes and temperatures above 150°C.

b. Ideally, the geologic and hydrologic characteristics should be understood with some confidence, as deduced from field mapping, surface geophysical and geochemical studies, and test wells. These data should be readily available (in non-proprietary form). It is understood that these conditions would only rarely be met.

c. The site should be capable of undergoing measurable gravity changes in a short time interval of a few years, due to subsidence and/or mass removal. The criterion of gravity changes due to mass removal may be more readily realized, since many geothermal terranes may not yield significant subsidence because production would be limited to fractured bedrock (examples are The Geysers, several Basin and Range geothermal systems, and hot dry rock areas). The site may or may not be characterized by non-geothermal gravity changes, due to tectonic, cultural, or seasonal causes; if these are present, they should be identifiable, and should be monitored to establish magnitude and range of values prior to exploitation.

d. The site should be characterized by less-than-favorable conditions, e.g., should include elevation extremes and rough roads; if precise gravity work must be restricted to only the most favorable conditions, and the method cannot thus be widely applied, then it could not be considered feasible. In general, most geothermal regimes fit this criterion.

e. Ideally, the site should be located close to a stable region, such as a bedrock block, which is not liable to undergo differential elevation changes during the course of the study. Measurements over the stable area should be incorporated into the gravity study to serve as the reference for all the measurements in and near the geothermal field, since the gravity values to be utilized are relative rather than absolute. The stable area should also be accessible so that a calibration loop could be established for the comparison of gravity meter characteristics.

On the basis of the foregoing criteria, the following areas were selected for evaluation: (1) several Imperial Valley, California sites, i.e., the

Salton Sea area, Brawley, Westmoreland, East Mesa and Heber; (2) two volcanic areas in eastern California, namely Coso Hot Springs and Long Valley Caldera; (3) Surprise Valley, in northeasterly California; (4) the Clear Lake Volcanic Field in northern California (and, nearby, The Geysers field, for comparison); (5) the Crane Creek-Cove Creek area in Idaho, and the Bruneau-Grandview area in the same state (the latter resource is of lower temperature than is desirable, but occupies an exceptionally large volume); (6) Steamboat Springs, Stillwater, Desert Peak, and Dixie Valley, all in Nevada; (7) the Valles Caldera in New Mexico; (8) three areas in Oregon; namely, Newberry Caldera, Vale Hot Springs and the Klamath Falls area; and (9) Roosevelt Hot Springs and Cove Fort-Sulfurdale in Utah. The evaluation of these regimes was carried out both by a thorough literature review, and through personal contact with persons working in these areas.

The areas are discussed individually in Appendix B, which encapsulates the salient characteristics of each regime, and presents the pros and cons of conducting a gravity study over each of them. Table IX on the following pages summarizes the discussions and presents the geothermal regimes with a priority ranking for conducting a gravity survey, and appropriate reasons.

TABLE IX. SITE SELECTION FOR PRECISE REPETITIVE GRAVITY SURVEYS

Priority	Area	T (^{o}C)	V (Km^{3})	Power (MW)	Comments
1	Salton Sea, Ca.	323	116	3400	Largest system in U.S., power plant soon on line, environmentally sensitive area, subsidence likely.
2	Valles Caldera, N.M.	273	125	2700	Power plant soon on line, some subsubsidence likely.
3	The Geysers, Ca.	237	1167	1610	Largest operational system in world, minor subsidence noted, gravity effective in mass removal and recharge studies, should be continued.
	Clear Lake, Ca.	190	83	900	Hot water system adjacent to The Geysers, subsidence likely, gravity survey at The Geysers should be extended to cover this environmentally sensitive area. Power plant soon on line.
4	Westmorland, Ca.	217	123	1710	May be extension of Salton Sea field, same constraints, gravity survey should be extended to cover this nearby area.
5	Roosevelt Hot Spr., Ut.	265	47	970	Power plant soon on line, some subsidence likely, gravity survey initiated.
6	Heber, Ca.	175	71	650	Power plant soon on line, subsidence likely, environmentally sensitive area, gravity survey under way and should be repeated.

TABLE IX - Continued

Priority	Area	T (^oC)	V (Km^3)	Power (MW)	Comments
7	Brawley, Ca.	253	34	640	Power plant planned soon, subsidence likely, environmentally sensitive area.
8	Long Valley, Ca.	227	136	2100	Large system even with removal of eastern half of caldera, subsidence likely, power plant not imminent.
9	Desert Peak, Nev.	221	52	750	Subsidence minor, little environmental damage, power plant not imminent.
10	Newberry, Ore.	230	47	740	System could yield considerable power, but still relatively unknown, power plant not imminent.
11	Surprise Valley, Ca.	152	210	1490	Large system, but marginal temperatures, no electrical users for market, power plant not developed soon, may go to low-temperature use, subsidence likely.
12	Coso Hot Spr., Ca.	220	46	650	System may be low permeability, little subsidence, may be used for Navy power source for facility at China Lake, could impact agriculture.
13	Vale Hot Spr., Ore.	157	117	870	Moderately large, but poorly known, power plant not to be developed soon.

Priority	Area	T (^{o}C)	V (Km^3)	Power (MW)	Comments
14	Stillwater, Nev.	159	59	450	Smaller system, marginal temperature, close to medium-sized town (Fallon), development in environmentally sensitive area, subsidence likely.
15	East Mesa, Ca.	182	36	360	Small system, some subsidence, power plant planned, environmentally sensitive area.
16	Steamboat Spr., Nev.	200	29	350	Small system, close to Reno and Carson City, no major subsidence expected, power plant not planned soon.
17	Crane Creek, Ida.	171	39	340	Area little known, power plant not planned soon.
18	Cove Fort-Sulphurdale, Ut.	167	39	330	Small system, poorly known, power plant not planned soon.
19	Klamath Falls, Ore.	111	114	None	Low temperature resource now providing space heating and other low temperature uses. The use of heat exchangers and reinjection of hot waters make substantial subsidence unlikely.
20	Bruneau-Grandview, Ida.	107	1830	None	Large, low temperature system, very poorly known, development seems remote at present.

TABLE IX - Continued

Priority	Area	T (^oC)	V (Km^3)	Power (MW)	Comments
21	Dixie Valley, Nev.				Unknown system with some apparent steam production, little probable capacity for subsidence, may be small volume (fault-controlled), power plant not imminent.

VI. APPENDICES

APPENDIX A. RECOMMENDATIONS FOR CARRYING OUT REPETITIVE GRAVITY SURVEYS IN GEOTHERMAL REGIMES

Based on the foregoing work, we can make a series of recommendations concerning the conduct of a precise repetitive gravity survey over a producing geothermal field. The recommendations fall into two categories: 1) a set of techniques which apply to all gravity surveys in which high precision is desired; and 2) a set which is provided for maintaining 15, 10 and 5 microgal standard deviations, respectively.

a. Recommendations for all Gravity Surveys

1) The gravity stations should be permanently established on concrete piers or existing structures which are sufficiently large to accommodate the gravity meters used, and penetrating deeply enough to be stable. The top surfaces must be flat. Stations on bedrock need not use concrete piers if the rock is solid, and the position of the station can be affixed directly into it. Stations should not be established near sources of ground noise (vibration from traffic or geothermal production), or where erosion or human activities can modify the gravity value or degrade the monument. The station locations should also be selected with regard to access for other monitoring techniques (seismic or electrical resistivity) and with adequate visibility for a concurrent leveling operation. The gravity station network must include two or more reference bases on stable ground, to which the survey can be referred; a single base station has too high a probability for destruction. The gravity stations must also be areally (rather than linearly) distributed,

since the potential calculations which allow separation of elevation and mass effects must be for three-dimensional models. The stations must be well described, for recovery by others.

2) Several environmental conditions can affect gravity meters deleteriously. These include transport over rough roads, high external temperatures, high wind conditions, seismic activity, traffic noise and direct sunlight on the meter which affects the leveling. These conditions must either be minimized or avoided. Transport problems can be minimized through the use of special transport cases; 3 types are available: 1) boxes mounted on heavy duty stiff springs selected to dampen the vibrational frequencies of the vehicle (10-100 Hz), b) mechanical isolation systems, or c) boxes on an air-compression mount. In the absence of transport boxes, keeping meters off the floor and on the seats with excess padding, secured with the seat belt, will be helpful. The use of heavier vehicles, avoidance of especially bumpy routes, and cautious driving may be beneficial to the precision, as will location of the meters in the center of the vehicle, rather than toward the rear. If transport continues to affect precision after these measures are taken, alternatives include walking over the roughest terrain, and performing additional repetitions so that the most imprecise values can be deleted, following exclusion principles.

Tents or awnings with short installation times can provide both shade and windbreaks, but must be vented to prevent accumulations of heat. Under heavy wind conditions, tests will be inadequate (or even dangerous) and no readings should be taken. Under high temperature conditions (>90^{o} or 100^{o}F) readings should not be taken at all, unless air conditioned vehicles can be used and exposure to high temperatures can be kept to short intervals of time. An alternative is to work at night with a flashlight; the lighting system of some gravity meters may disturb thermal equilibrium and should not be used. If traffic poses a problem near highways or in urban areas, the affected stations should be occupied when traffic is minimal, e.g., on weekends or during off-peak hours. Traffic effects are especially critical when stations are located on fill material or poorly consolidated sediments, and heavy vehicles pass by at high velocities. The meter should always be clamped when this situation seems imminent. Similarly, the survey should be discontinued when the passage of earthquake waves makes meter readings either unattainable or less replicable; the association of geothermal regimes with tectonic activity in the western United States and other parts of the world makes this source of disturbance common enough.

3) It is recommended that LaCoste and Romberg meters be used because of their low drift rates, and that more than one meter be used in the conduct of a precise, repetitive gravity survey. The meters used should be calibrated against each other on a well-established calibration loop, using one meter as a reference standard. All meters used should be calibrated annually or bi-annually to account for any internal changes. This is particularly crucial with the G meters, which cannot be reranged to accommodate changes due to instrumental drift and tares.

The calibration loop should be established as close as possible to the geothermal field under study, should be established on stable ground such as a coherent bedrock block (no active faulting within the block) so that no gravity changes are liable to occur among stations in the loop, and should have a sufficient number of stations that the entire range expected in the actual survey is exceeded by 20-30 mgals, at each end. The station values should be 10-15 mgals apart. The calibration loop stations should be monumented in exactly the same way as the stations in the survey; the additional recommendations for carrying out a 5 microgal survey should be followed in the monumenting procedures (see page 70). The values on the calibration loop should be established to a precision of 5 microgals or better.

Any new meters brought into a continuing survey must first be calibrated, and any D meters using a different part of their range must also be recalibrated, to avoid screw error contributions to data imprecision.

Under ideal circumstances, the calibration loop will contain one or two stations which can serve both as reference base stations for the gravity survey, and as stations within the loop. If the calibration loop must be located too far away (because of the unsuitability of the local geology, access, and/or gravity field), the reference bases should be established closer to the geothermal field.

4) If the values of the tidal constants are unknown for the area to be studied, three days of continuous tidal monitoring with the gravity meter should be conducted and evaluated prior to the initiation of the gravity survey. This may have to be repeated in the area of the calibration loop if the latter is located more than 50 miles away. The barometric pressure correction may be ignored for all surveys, provided the recommendations for specific precisions are followed.

5) The data collection process should be designed with sufficient redundancy to allow calculation of statistical parameters and distribution of error, if needed. Although specific recommendations for section b., which follow on page 69, are for standard deviations (because of the

familiarity of this term), the design should allow calculation of standard errors, since means of gravity values are utilized (rather than isolated values). The significance of any change in gravity differences can then be established by obtaining the square root of the added variance (the squares of the standard deviations or standard errors); a change must exceed 1.4 or $\sqrt{2}$ of this value to be significant, since two data sets of approximately the same precision are being utilized.

6) Data reduction should be completed in the field on a daily basis as data are collected. Tide corrections are too cumbersome for the present generation of calculators, but they may be precalculated and tabulated at 10-minute intervals over the entire anticipated duration of the field work. Data should be reduced to observed gravity values, the differences between (or among) stations calculated, and statistics obtained as soon as is feasible (after second replication of an entire loop, or after completion of a set of ties, as the case may be). The results of the statistical evaluation should be utilized to exclude data and to modify the conduct of the survey, as necessary.

b. Recommendations for Gravity Surveys with 15, 10 or 5 Microgal Precision, Respectively.

1) 15 microgal precision. For this level of precision, either D or G model gravity meters may be used. The looping technique should be adequate, with two occupations of each station (in separate loops), provided the foregoing recommendations are followed. Few or no data should have to be excluded. The cost of a 60 station survey, at 1981 commercial rates, should be about $20,000, excluding instrument cost and maintenance, or

rental.

2) 10 microgal precision. For this level of precision, either D or G model gravity meters may be used. The looping technique should be adequate, with three occupations of each station, in separate loops, provided the foregoing recommendations for all gravity surveys are followed. Several data may have to be excluded, and some loops repeated. The cost of a 60 station survey, at 1981 commercial rates, should be about $26,000, excluding instrument cost and maintenance, or rental.

3) 5 microgal precision. For this level of precision, additional constraints exist on the gravity survey. Monuments should include permanent positions for the meter feet (chisel or brass disks) so that the meter(s) used can always be positioned in the same place on the pier and with the same orientation (set in with a Brunton Compass) for all piers. The base plate should not be used, and gravity values should be obtained by holding one meter leg fixed (if possible) so that the height of the meter remains essentially constant. The use of D meters may be mandatory, although certain G meters may yield higher precision than normal, and thus be utilized. Exclusion criteria should be established, and values rejected and repeated as necessary. The "leapfrogging" field procedure should be utilized. To avoid long distance of transport in an areally distributed gravity survey, a system of internal bases can be established, with multiple sets of ties among them; all of the stations can then be tied to one of these bases in a network of triangles, so that error can be distributed both among the bases and among the station triangles. This type of field scheme is illustrated on the following page as Figure 7.

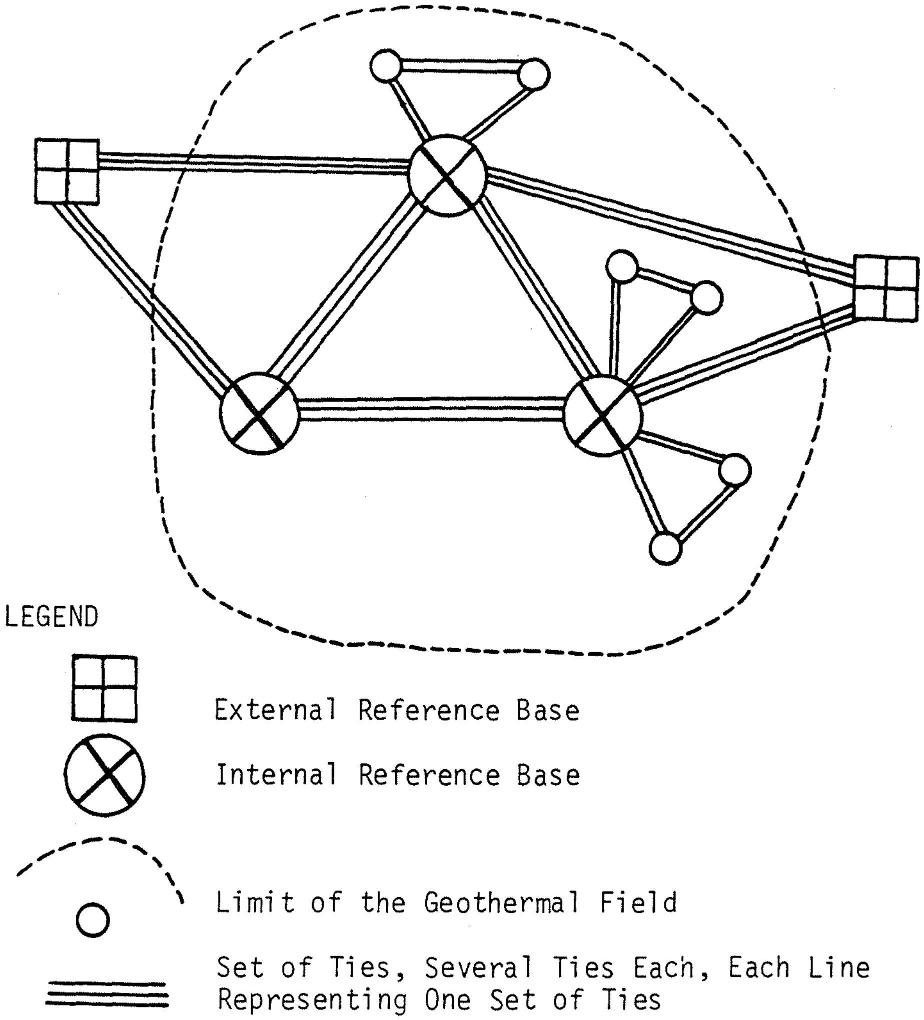

Figure 7. Diagram for station occupation scheme for implementing a 5 microgal precision gravity survey.

The precision of individual stations need only be seven or eight microgals, since the error distribution process will reduce that value to about five microgals. The values among the internal bases, and to the external reference bases, will, on the other hand, have to be extremely well established. Three sets of ties with six ties each are recommended for the bases, while stations may be established with two sets of four to six ties each, for each gravity meter used (two are recommended); the procedures discussed beginning at the bottom of page 21 should be followed.

APPENDIX B. EVALUATION OF SELECTED GEOTHERMAL AREAS FOR SURFACE GRAVITY MONITORING

(1) The Imperial Valley

Six separate hot water hydrothermal convection systems, with temperatures estimated at greater than 150°C, are located in the Imperial Valley of California: a) Salton Sea area; b) Westmoreland; c) Brawley; d) East Mesa; e) Border; and f) Heber. The combined electrical energy output estimated for a 30 year period is estimated at approximately 6800 MW (Brook et al, 1979), or more than four times that estimated for The Geysers. This fact, based on estimated and/or measured temperatures ranging from 160° to 340°C and large reservoir volume, makes it potentially the most valuable geothermal resource region in the western United States. Of the six individual systems mentioned above, only the Border system is minor in size and will not be further considered; the others have estimated individual electrical productions ranging from 360 MW (East Mesa) to 3400 MW (Salton Sea).

These fields are located in the northern and central parts of the Salton-Mexicali structural trough; the Cerro Prieto system, which is actively producing 150 MW of electricity 35 km south of the Mexican border, is located in the southern end of this major structural depression. The trough is both bounded by, and contains, several major strike-slip faults, including the San Andreas, Imperial, San Jacinto, and Elsinore Faults; large vertical displacements exist beneath the valley alluvium (McNitt, 1963). These faults have caused intense folding and compression of Tertiary sediments (Elders et al, 1972), and bound at least three postulated pull-apart basins. These basins are characterized by young volcanics and high heat flow values, and are intimately related to the presence of some of the known geothermal prospects (ibid). The Salton-Mexicali trough is presumed to be an active "spreading center" which has resulted in both crustal thinning and accumulations of more than 6000 m of young sediments, on the basis of geophysical studies (Biehler et al, 1964). Consequently the maximum principle stress is horizontal in this area, and the region is characterized by high seismicity and active surface faulting.

The reservoirs for these geothermal prospects are located in permeable Tertiary sedimentary material of predominantly continental origin at depths ranging from 0.7 to 4 km (Brook et al, 1979). High temperatures and fluids have produced local metamorphism which creates densification of the sediments (Muffler and White, 1969) and local positive gravity anomalies (Biehler, 1971). Removal of fluids during production presumably would cause gravity changes which would result primarily from both subsidence and mass removal, and secondarily (only over long time periods and to a lesser magnitude) from precipitation of minerals and metamorphism; the effects are expected to be large (in tenths of milligals) unless secondary recharge of geothermal fluids is initiated. The measurement of gravity in this area is complicated by the documented subsidence of 1 to 2 cm/year in the trough region associated with continuing tectonic deformation, which is reflected also in tilting and horizontal distance changes; the subsidence has been documented by precise first and second order leveling data obtained repeatedly since 1972 (Lofgren, 1978). Subsidence from any source is of more than passing interest, since any variations in elevation of the flat valley floor will affect the extensive canal network which supplies irrigation water for the intensely developed agriculture in the region.

Four areas presently seem to be slated for commercial development in the near future, and power facilities of 50 MW each are presently in the planning stages. These are Heber, East Mesa, the Salton Sea field, and Brawley. Since the anticipated total electrical production at Heber and Brawley appears to be twice that of East Mesa, and the Salton Sea field appears ten times as large (Brook et al, 1979), East Mesa is perhaps a less favorable target for precise, repetitive gravity surveys at this time. All four sites have accessible bedrock areas in the vicinity; in the case of the Salton Sea field, Heber, and Brawley, these are the Laguna, Inkopah and Jacumba Mountains to the west (Strand, 1962) which, while located uncomfortably far away (45-50 km) and across several active fault zones, could serve nevertheless both as bedrock reference ties and as gravity calibration range areas. East Mesa is located 25 miles west of the Cargo Muchacha Mountains, which are the locus of first order leveling benchmarks located on bedrock. The Heber area is perhaps slightly more favored for gravimetric monitoring than the other areas since it is little affected by tectonically-related subsidence at present; changes over a two year period across the entire valley parallel and adjacent to the Mexican border totalled 13 mm (Robert Estes, Imperial County Public Works Department, personal communication, 1980). This small a magnitude value is not liable to be detected gravimetrically over the same time interval, and makes the Heber area appear more stable. However, the status of federal funding for the Heber project is now questionable, and repetitive gravity surveys in the Salton Sea field should thus receive the top priority. The Westmorland field, while not slated for immediate production, is second in size only to the Salton Sea field, and may be a continuation of it. It, therefore, should undergo repetitive gravity surveys together with the Salton Sea field.

(2) Coso Hot Springs and Long Valley Caldera, Eastern California

Coso Hot Springs and Long Valley Caldera are two geothermal areas characterized by recent volcanism, located approximately 200 km apart (in a north-south direction) and east of the Sierra Nevada Mountains in eastern California. Of the two, Long Valley Caldera is estimated to have a greater electrical potential (2100 MW for 30 years as opposed to 650 MW); the mean reservoir temperatures of the two systems are quite similar, an estimated 230°C (Brook et al, 1979). In spite of the similarities in the age of the volcanism, the reservoirs of the two geothermal systems are located in differing rock types (with, consequently, different gravity signatures expected from repetitive temporal surveys); thus the two areas will be discussed separately below.

Coso Hot Springs is located at the southern end of the Owens Valley, southeastern California, within a United States Navy facility. This KGRA is situated in the Coso Mountains, at the southwestern extremity of the Basin and Range province, which is bounded by the east-west trending Garlock fault 75 km to the south. Four rock types underlie the Coso KGRA: 1) Pre-Late Cretaceous intermediate to mafic metamorphic rocks; 2) Post-metamorphic quartz latite porphyry and felsite; 3) Late Cretaceous (?) granite and allied intrusive rocks, presumably related to the emplacement of the Sierra Nevada batholith; and 4) Late Cenozoic volcanic and subordinate sedimentary rocks (Hulen, 1978). The latter group of rocks contains two main groups: 1) intermediate to basic volcanics and associated sediments of Late Pliocene age (3.42 to 2.20 m.y., K-Ar ages); and 2) Pleistocene basalts and rhyolite domes, ranging from 1 million years to 41,000 years in age (ibid). Some workers have suggested that the Coso area is an incipient caldera, based on an apparent ring fracture system bounding the area and the presence of young rhyolitic rocks (K. Austin, personal communication). Duffield (1975) and Galbraith (1978) have described the regional faulting, consisting of Pliocene ring fractures, a north-northeast tensional fault system, and a west-northwest trending, possibly left-lateral dip-slip system. Many young, northerly trending faults offset older faults and show evidence, such as scarp development in alluvium, of recent normal displacement; the rocks at Coso are frequently fractured into blocks averaging 1/3 to 1 m on a side, and brecciated and gouge zones associated with the faults are common (Hulen, 1978). No evidence of deep permeable aquifers exists, and the geothermal reservoir is apparently developed in, and confined to, secondary fracture porosity associated with the younger set of faults, and particularly where they intersect older fault systems (ibid and Galbraith, 1978). Thus little or no subsidence can be expected, unless horizontal or low-angle cracks are volumetrically important, or solution channels are quantitatively important. The major part of any temporal gravity variation is expected to be due to mass removal.

Presently, a precise level line extending approximately halfway across the geothermal area is being monitored (W. Duffield, personal communication, 1977). If this area were to be the subject of a temporal gravity survey, the benchmarks from the level line should be incorporated into the gravity station network. Temporal gravity observations could conceivably be affected by two non-geothermal factors: 1) tectonically-caused variations in elevation, since this is a seismically active area; and 2) subsidence at the western margin of the area near Highway 395, due to withdrawal of groundwater for agricultural purposes. Two other constraints on a possible gravity survey should be mentioned. First of all, it may be difficult to establish an appropriate calibration loop and set of reference stations; although substantial bedrock is exposed to the west in the Sierra Nevada, accessibility is a problem. And, no changes can be expected to occur until late in the next decade, when the first power plant is expected to go into production.

The Long Valley Caldera is located in central-eastern California approximately 50 km north of the town of Bishop; the resort town of Mammoth Lakes is located at its western margin, at the east base of the Sierra Nevada Mountains. The caldera is elliptically shaped, 32 km on the east-west axis and 17 km on the north-south, covering an area of about 450 km^2 (Bailey et al, 1976). The caldera lies at an elevation of approximately 2100 m in a highy scenic area, and the structure is well-defined by steep walls on nearly all its sides. The pre-Tertiary basement, in which the structure was formed, consists of Paleozoic and Mesozoic metamorphic rocks which have been intruded by the Jurassic and Cretaceous granitic rocks of the Sierra Nevada batholith. These are overlain uncomfortably by Tertiary volcanic rocks (3.2 to 2.6 m.y., K-Ar ages) of basaltic, andesitic, and rhyodacitic composition, some of which extend well into the caldera area (ibid). These early volcanics appear not to be directly related to formation of the caldera, which is younger in age. Caldera formation was initiated with thick (1000+ m) accumulations of domes, flows, and shallow intrusions and associated pyroclastic deposits, spanning a million year interval from 1.92 to 0.9 m.y. (K-Ar dates). This sequence (the so-called rhyolites of Glass Mountain) was followed by eruption and deposition of the 0.7 m.y.

old Bishop tuff, which covered an area of approximately 1100 km^2, and originated from vents within the present caldera structure. The total volume of ash is on the order of 500 km^3, some two-thirds of which accumulated within the caldera, which subsided and collapsed contemporaneously as the magma chamber partially emptied (ibid). The tuff provides a low-density fill material which forms prominent gravity lows (Pakiser, 1961; Pakiser _et al_, 1964; Kane _et al_, 1976), and is now located some 800 m lower in elevation than similar materials on the rim (Bailey, _et al_, 1976). Eruption of the tuff and subsidence were followed by further rhyolite eruptions and doming within the caldera, eruption of rhyodocites on the rim, and late basaltic and Holocene rhyolitic volcanism (ibid). Contemporaneously, the depression of the caldera was filled with water to form the Pleistocene Long Valley Lake (Mayo, 1934) in which lacustrine and glacial sediments were deposited (Bailey _et al_, 1976). The caldera has been substantially affected by later Basin and Range faulting (primarily the Hilton Creek fault), and most of the hot spring activity is localized along these fault zones (Rinehart and Ross, 1964). Earthquake activity in 1973 (Bailey _et al_, 1976) and 1979 altered the hydrothermal regimen, causing increased temperatures and relocation of surface expressions.

The Long Valley heat source is presumed by many workers to be a still-molten magma chamber 10 or more kilometers below the surface. Hot springs occur where fault systems permit the ascent of waters to the surface; other possible conduits become blocked by the "self-sealing" process of dense hydrothermal alteration. Presumably, much of the reservoir consists of tuffaceous materials with primary porosity, although some of the reservoir could be located in fractured basement. Drill holes in the eastern half of the caldera encountered no substantial reservoir in Tertiary rocks, since temperature inversions were reached at depth (Frank Olmsted, personal communication). Some subsidence could be expected in the western half of the caldera, from which production is likely to occur, and could be developed even at some distance from the hot springs area, as was experienced in New Zealand (Hatton, 1970). In spite of the reduction in estimated reservoir volume because of the disappointing drill hole results in the eastern half of the caldera, the anticipated electrical production is still a high 2000 MW (Brook et al, 1979).

No difficulty would be encountered in setting up a calibration line in this area, since access to bedrock areas is quite good. The western half of the caldera is readily accessible for a detailed gravity survey. The eastern half has fewer roads and would be more difficult to cover in detail. The major cultural features which would be affected by subsidence would be the Highway 395 system and scattered buildings; Mammoth Lakes presumably would undergo less disturbance due to its location at the caldera margin. No power plant is scheduled for the next few years.

(3) Surprise Valley

Surprise Valley is a Basin and Range geothermal prospect in northeastern California, located 80 km from both the Nevada and Oregon borders. The area contains four main groups of thermal springs and eight wells in a zone about 20 km long; the estimated electrical energy output over a 30 year period is about 1500 MW, based on moderate temperatures (150°C) combined with a sizeable reservoir (200 km^3) according to Brook et al, 1979.

Lower temperature resources are also present (ibid; and Sammel, 1979). Surprise Valley is bounded on the west by the Warner Mountains, which contain a bedded sequence of Tertiary Miocene volcanics and volcanically derived sediments, the so-called Cedarville series, which have been intruded by numerous east-west trending dikes and tilted westward by Basin and Range faulting; the rock types, which range in age from 8 to 40 m.y. (Slosson, 1974), are typical of those found in the Modoc Plateau province. The valley is a complex faulted, rectangular graben, which has been displaced downward from the Warner Mountain block along the Surprise Valley fault. The fault is presumed to be active on the basis of a fault-line scarp in the southern part of the valley which has a fresh physical appearance suggestive of Late Pleistocene-Holocene tectonic activity (ibid). This fault zone is the locus of numerous hot springs, and deep circulation of geothermal waters, which may have their source in the Cedarville series, is inferred to exist within the Surprise Valley and subsidiary faults (Sammel, 1979; Woods, 1974). The resource may thus be located within fractures and aquifers in the Cedarville "basement", within fault zones and fracture systems, and/or within overlying valley fill deposits; a possible magmatice source with depth is suggested (Sammel, 1979), but no corroborating evidence currently exists.

Production of electricity in the Surprise Valley area will probably be delayed past 1983, for several reasons outlined by Frederickson (1977): 1) Because of the lower temperature of the resource (150-160°C), binary technology will probably be required, which will not be available until 1981; 2) drilling is quite expensive in this area, which makes electrical production non-competitive at present costs; and 3) the area is isolated, with only a small market for the power generated at present. Frederickson (ibid) suggests, however, that 300 MW can be on line by 1990. Establishment of a calibration line will present no problems in the area, because of the paved highway which crosses the Warner Mountains, linking Alturas with Cedarville. A repetitive gravity survey would likely show variations due both to mass removal and to subsidence, depending on what part of the resource is tapped. Tectonic changes may well be affecting the area (which would affect temporal gravity surveys), but no precise, repetitive leveling data are currently available. Such leveling should be initiated with a gravity survey.

(4) The Geysers and the Clear Lake Volcanic Field

The Geysers and the Clear Lake Volcanic Field occur in similar geological terranes in northwestern California. At present The Geysers, a vapor-dominated system, is the largest geothermal power producer in the world with more than 900 MW annual production, and an anticipated possible output of 1610 MW over a 30 year period. The mean temperature of the reservoir is 237°C, while its volume is estimated at 1200 km^3 (Brook *et al*, 1979). Electrical energy at the nearby Clear Lake Volcanic Field, which is a currently undeveloped hot water system, may be somewhat less than at The Geysers (estimated at 900 MW), based both on an estimated lower reservoir temperature (190°C) and volume (less than 100 km^3) according to Brook *et al* (ibid).

Three major rock types underlie the region: the Franciscan assemblage, the Great Valley sequence, and the Clear Lake volcanics (McLaughlin, 1977). The Franciscan assemblage, of Late Jurassic to Late Cretaceous age in this area, consists of "mildly to moderately metamorphosed sandstone, conglomerate and argillite, subordinate basaltic volcanic rocks (greenstone) and chert, and minor limestone, blue schist, antigoritic serpentinite, amphibolite, and ecologite." These rocks are preserved in "imbricate thrust slices varying in degree of deformation from coherent interbedded sequences to chaotic melanges" (ibid). The Great Valley sequence "strata consist of mafic breccias...overlain by mudstone and minor basaltic sandstone of probably Late Jurassic (Mid-Tithonian) to Early Cretaceous age" (ibid). Only a few patches of basal Great Valley sequence are present at the surface in The Geysers-Clear Lake area, but relatively chloride-rich waters and low resistivity indicate that it underlies an extensive area beneath the Clear Lake volcanics (ibid). The Clear Lake volcanics are Late Pliocene to Holocene in age, and rest on both of the above-cited Mesozoic rock types; the volcanic field is the youngest and most northerly of several volcanic centers (Donnelly et al, 1977). The main part of this volcanic field occupies the southern part of the Clear Lake topographic basin, and consists primarily of basalt, andesite, dacite, and rhyolite in the form of domes and flows with minor pyroclastics (ibid). The volcanics, as well as the heat source for both The Geysers and Clear Lake, appear to be derived from a magma chamber with an estimated diameter of some 6 to 8 km, and depth of 10 km beneath the surface (ibid). The existence of the magma chamber is indicated by gravity surveys, which show a circular 25 mgal gravity low some 20 km in diameter, centered in the south-central part of the volcanic field (Chapman, 1975; Isherwood and Chapman, 1975). Resistivity lows, possibly due to fluids at elevated temperature and salinity above a heat source at depth, are coincident with the gravity low (Stanley et al, 1973), as are teleseismic P-wave delays (Steeples and Iyer, 1976; Iyer and

Hitchcock, 1975).

The Geysers reservoir occurs solely in secondary fracture porosity, induced both by episodes of thrusting which occurred in Early Tertiary, and by superposition of later faulting which is predominantly normal, with some right lateral strike-slip components. The later faulting may be at least partially active, since earthquake epicenters are located close to some of the fault centers (Bufe et al, 1976), and faults show evidence of recent movement in drainage offsets and other features (Donnelly et al, 1977). These young faults generally parallel the northwesterly trending San Andreas system. Not only are the faulting episodes crucial in the development of reservoir porosity in The Geysers field, but two of the younger faults (the Mercuryville and the Collayomi) constitute its eastern and western boundaries (McLaughlin, 1977). The Collayomi fault additionally functions an an impermeable boundary, separating the low-pressure (with regard to hydrostatic head) steam field of The Geysers from the high-pressure hot water regime which exists to the northeast beneath the Clear Lake Volcanic Field (ibid). The difference between the two regimes is thought to lie primarily in the amount of recharge, which is minimal in The Geysers area, presumably because of low permeabilities (thus inducing a low pressure environment of steam underlain by boiling brines at greater depth); in the Clear Lake area, numerous volcanic vents may provide funnel-like collecting areas which could produce extensive recharge, thereby preventing the development of the low-pressure conditions needed to induce and maintain a vapor-dominated system (ibid). Repetitive gravity studies by Isherwood (1977) support the notion of little recharge in The Geysers area, since changes in gravity can be explained wholly by the measured mass removal.

Repetitive gravity surveys in The Geysers should primarily show the effects of mass removal, since a low-pressure vapor regime should largely be confined to relatively competent rocks; only a modest amount of buoyancy can be expected from the underpressured steam. Precise leveling and horizontal control measurements between 1972 and 1978 indicate maximum ground subsidence of about 13 cm in the area of maximum fluid withdrawal and horizontal ground movement of up to two centimeters annually (Grimsrud et al, 1978). This vertical motion is much lower in magnitude than that in other geological terranes, but would be measurable, with a precise gravity effort, after about two years (estimating a subsidence rate of 2 cm/year). However, corrections need to be made to the subsidence values using Whitcomb's equations (1976); the true geometric subsidence may differ because of the interdependence between leveling and mass changes, but removal of mass should still be the principal source of gravity changes in this area, as was interpreted by Isherwood, 1977. The nature of the reservoir rocks in the Clear Lake area is less well known, due to lack of drilling, but presumably porosity could be both primary (in the Great Valley sequence) and secondary (in the Franciscan assemblage as well as in the Great Valley sequence). If the large volume of Great Valley strata does indeed exist beneath the Clear Lake volcanics, as inferred by Donnelly et al (1977), both subsidence and mass removal could produce gravity changes with time. Repetitive gravity measurements in the Clear Lake area would be complicated by active deformation, including local subsidence from probable tectonic causes within the volcanic field and Clear Lake structural basin (ibid). Repetitive gravity studies in The Geysers area have so far not been extended to Clear Lake. Establishment of an adequate calibration line and reference stations should be possible in the nearby

Coast Ranges, in a stable area. Development of large power plants using hot water in the Clear Lake area is being initiated with the construction of the Bottle Rock plant, in spite of certain environmental concerns which exist for the region.

(5) Crane Creek - Cove Creek and Bruneau - Grandview Areas, Idaho

Two areas have been selected for further evaluation in the State of Idaho. The first of these, the Crane Creek-Cove Creek area, was selected because it is the only sizable system in the State which has temperatures high enough for possible electrical production; temperatures there average a postulated 170°C, and an anticipated energy of 340 MW is projected over a 30 year period (Brook et al, 1979). The Bruneau-Grandview area was selected because of its great size, with an estimated reservoir volume of more than 1800 km^3, which gives it an exceptionally large beneficial heat rating (27×10^{18} joules) in spite of the low estimated mean temperature of only 107°C (ibid). Both of these resources are located toward the western end of the Snake River Plain; an arcuate, young geological feature which includes several other areas with significant geothermal potential, most notably the Yellowstone and Island Park areas at its eastern end, at the Wyoming border; the better-known Raft River geothermal area is located just south of the plain in south-central Idaho. The Snake River Plain is a region of extensive Neogene and Quaternary volcanism. The geology of the western end of this area is not well-known, and reservoir assessment by personnel from the U.S.G.S. is currently underway; few drill holes exist to characterize the area geologically, and at present the continuity of the hydrothermal systems beneath the plain is not known, so that resource assessment is so far quite tentative (ibid). The geology of the Snake River Plain has been synthesized by Hill et al (1961):

> The highlands immediately to the north and south of the plain are composed mainly of silicic volcanic rocks of Early Pliocene age, and of granite of Cretaceous age. A veneer of basalt flows of Middle Pliocene age covers the silicic volcanic rocks in the lower elevations. The western Snake River Plain is a graben filled with Pliocene and Pleistocene sedimentary rocks and interbedded basalt flows to a depth of at least 3000 feet below the surface (H.E. Malde and H.A. Powers, written communication, 1961). Subsidence of the graben took place along a series of faults trending northwest. The most prominent fault zone forms a sharp escarpment along the northern edge of the Snake River Plain. Malde (1959) estimates that the aggregate throw along this zone is at least 9000 feet.

Extensive gravity work by the above authors has led them to believe that large magnitude (30+ mgal) and areally extensive Bouguer anomalies are due to the possible combination of two mechanisms: (1) "The plain is a graben bounded by faults with large vertical displacements. Volcanism has accompanied the subsidence. The resulting lava flows filled the depression, yielding thick accumulations of basalt"; and (2) "Crustal stresses have caused large en echelon fissures under the Snake River Plain. These fissures have been injected with basalt or basalt-like material" (ibid).

The Crane Creek-Cove Creek area consists of two groups of springs about 11 km apart with similar water chemistries which may or may not be interconnected at depth. The springs are located in a zone of sinter deposits and mercury mineralization (ibid). The geothermal waters may come from a deep source because of high temperatures (249°C) as estimated from the sulfate-water isotope geothermometer (ibid). The estimated depth to the top of the reservoir is 1000 m, with the cap rock made up of young alluvium and medium-hard rocks of the Idaho Group (Trehan et al, 1978). Since reservoir assessment is not yet complete, the geology is still poorly understood and the potential for subsidence is thus unknown; a power plant will not be constructed until at least 1985 (ibid). This area does not appear promising at present for a detailed and repetitive gravity survey, although such a survey would be logistically feasible in the future.

The above conclusion must also be reached for the Bruneau-Grandview area. Although two 3000 m holes have been drilled through the volcanic section, which in one case reached permeability zones, the existence of a commercially viable power reservoir must still be proven, and a power plant is thus not expected to be on-line until 1987 (ibid); the potential for subsidence is likewise unknown and apparently far removed in time.

(6) Nevada Geothermal Systems

Several promising hot water geothermal resources may ultimately be developed within the Basin and Range province in the state of Nevada. These include the following, which were chosen for further evaluation primarily because of their potential for electrical production: a) Steamboat Springs, in west-central Nevada near the California border; b) Desert Peak, located approximately in the center of the triangle formed by the towns of Lovelock, Fernley and Fallon (the smaller Brady's Hot Springs resource is located less than 19 km to the northwest); c) Stillwater, located 30 km east of Fallon; and d) Dixie Valley, located across the Stillwater Range to the east of Stillwater. With the exception of Dixie Valley, all of the above resources will each generate at least 350 MW over a 30-year interval, and reservoir temperatures range from an estimated minimum value of 160^{o}C to a maximum of 220^{o}C (Brook *et al*, 1979). Dixie Valley is included because of the recent possible discovery of a steam field, which now makes the area more attractive as a prospect than its original moderate temperature (140^{o}C) status in the U.S.G.S.

geothermal resource assessment (ibid).

The above-cited hydrothermal systems all share several features in common: a) they are associated with the steeply dipping, large displacement Basin and Range faults, which apparently localize the geothermal fluid, especially at fault intersections where fracturing is particularly intense; b) deep circulation of meteoric waters in these fault zones produces the geothermal resource; and c) secondary fracture porosity is predominantly responsible for storage in the reservoirs, rather than primary porosity from sedimentary materials.

Steamboat Springs consists of several springs discharging from an extensive sinter apron (ibid), which consist of heated meteroic water recharging largely from the Carson Range to the east (White, 1968); this geothermal area is strategically located between two of the major cities in Nevada, namely Reno and Carson City. The reservoir is located in fractured and faulted Mesozoic metamorphic and granitic rocks of low permeability overlain by a 300 m cover of shallow sedimentary and volcanic rocks (ibid); this shallow reservoir depth with its thin rock cover is an attribute favorable for development (Trehan *et al*, 1978). The springs emerge from the northeastern part of Steamboat Hills, a small positive structural area located within a chain of structural basins located between the Virginia and Carson Ranges. Volcanic rocks in the area range from Middle Tertiary to Early Quaternary age, and may be derived from a large (100 km^3) hot magma chamber (White, 1968). The area is extensively faulted by the presence of three well-defined fault systems of varying trends; some individual faults displace Middle Pleistocene alluvium and sinter (ibid). A 50 MW power plant will probably be constructed by 1985, provided the resource is proved to be large enough for power production (Trehan, et al, 1978). Although not much subsidence is expected in this area, since large, low angle permeable channels which could collapse are not likely to exist (White, 1968), the shallow nature of the fractured reservoir should yield an especially good site for studies of mass removal. The area is easily accessible, and favorable locations for a calibration loop and reference base will be easily attained on nearby bedrock.

The Desert Peak area is a newly discovered resource (Benoit, 1978) which is located in the Hot Springs Mountains north of Fallon, Nevada. Unlike most "basins" in the Basin and Range, the area where the first successful wells were drilled is located a few hundred meters above the present valley floor. The underlying geology consists primarily of Tertiary and Quaternary tuffs, tuffaceous sediments, and volcanic flows which are locally several thousand feet thick. The reservoir seems developed primarily in underlying fractured metamorphic basement rock of pre-Tertiary age, since fractured greenstones were brought up during drilling (ibid); at least one of the wells is located in a major fault zone, characterized by an unusually steep gravity gradient (Grannell, 1977). Although some aquifers contain hot water, the primary production will be from a deeper, fracture-controlled reservoir. The reservoir may be extensive, since intense faulting characterizes the area, and structures are quite complex (Voegtly, personal communication), but individual production zones may not be continuous with each other, and several separate reservoirs of smaller size may be present. High temperatures at depth may be partially due to deep circulation, but an overlying cap rock of altered tuffaceous rock, with a low thermal conductivity, may be helpful in producing reservoir temperatures in excess of 220°C.

Little subsidence may occur when the area goes into production (at a currently unknown date), unless fractures or channels are sizeable, horizontally oriented, and capable of callapse upon withdrawal of geothermal waters. The system is located in an especially arid area, and high recharge rates for the reservoir are unlikely, since the high elevation of the area prevents any recharge except from local precipitation (Grannell, 1977); thus gravity changes in a temporal survey would largely reflect mass removal alone. There may be some logistical difficulties with conducting a survey in this area, since access is currently limited, and some stations might have to be established on foot. A location for a calibration loop will also not be readily available. Tectonic changes can be expected if some of the faults are active, which seems likely; these could affect repetitive gravity surveys.

The Stillwater area is located on the eastern side of the southern Stillwater Range (the town of Stillwater is located over the resource). Hot waters are encountered in sedimentary materials which form the valley fill (together with Tertiary basalt flows), but temperature inversions are present in drill holes and the main resource has not been located (Olmsted et al, 1975). Geophysical evidence suggests the presence of major faulting in the subsurface, and the trace of the fault which generated the moderate Fallon earthquake of 1954 passes through this area; since fractured bedrock at depth is thus likely, this area may follow the typical Basin and Range characteristic of the resource being confined primarily to secondary porosity in metamorphic basement. The temperatures at Stillwater are not too far above the electrical cutoff temperature of 150°C (they average 160°C), indicating that a binary plant would be needed, and probably would not be on-line until after 1985. A repetitive gravity survey would primarily reflect mass removal from the basement, but some subsidence could also be expected if overlying aquifers are also utilized. Some interesting non-geothermal gravity variations would likely be produced by changes in water levels in the numerous lakes in the Wildlife Refuge and gun club located nearby, and tectonic changes are also expectable in this seismically active area. A calibration line could be established some 15 km to the southeast along a major access into the southern Stillwater Range, although tectonic activity could affect the elevation of the range.

The Dixie Valley area is located in a wide basin bounded on the west by the Stillwater Range; it grades northward into Jersey Valley, and is bounded eastward by the Augusta Mountains. These valleys contain numerous hot springs of unknown temperature, which are likely controlled by intersecting fault trends. Newly discovered resources in Dixie Valley appear to yield fracture production (J. Noble, personal communication). Major subsidence is not likely from geothermal production, although it may occur from agricultural drawdown in parts of the valley. Mass removal would likely be detectable gravimetrically, but the changes may be small because of possible great depth to the resource (a characteristic of many Basin and Range systems). The valley will present normal access problems for Nevada basins, in that the existing roads are rough, they will not provide complete coverage, and a four-wheel drive vehicle will be required. Establishment of a calibration network should present no problems, with the exception of possible tectonic activity affecting elevations. It is not known when and if electrical production from hot water (and/or steam) will be initiated.

(7) Valles Caldera, New Mexico

The Valles Caldera is located 80 km northwest of Santa Fe, New Mexico in the center of the Jemez Mountains, and is Pleistocene in age. The estimated electrical energy output of 400 to 2700 MW over a 30 year period makes it the largest potential geothermal resource in New Mexico, and one of the most promising in the western United States (second only to the Imperial Valley); the estimated electrical production is based on a moderate reservoir size of 125 km^3, as well as on reservoir temperatures with a mean value of approximately 275°C (Brook et al, 1979), for the 2700 MW value.

The caldera is roughly circular to elliptical in shape with an approximate mean diameter of 13 km. It was formed in pre-existing Late Tertiary volcanic rocks resting on a Precambrian through Tertiary igneous, sedimentary, and metamorphic basement complex (Smith et al, 1961). In early Pleistocene time, catastrophic eruptions occurred in the center of the Tertiary volcanics, with the ejection of some 250 km^3 of rhyolitic pyroclastic rocks in the form of ash flows; these formed 300 m thick sheets of welded tuff, which comprise the major part of the so-called Bandelier tuff (ibid). The emptying of the magma chamber caused collapse of the roof to form the Valles Caldera (ibid). Subsequent to its formation, the Bandelier tuff within the caldera has been overlain, or intruded by, younder sedimentary rocks and post-subsidence rhyolites; the main magma chamber is still presumed to be molten. The center of the caldera has undergone intensive faulting and fracturing, as a result of doming which resulted in an areal tilt away from a centrally-formed, northeasterly trending graben (ibid).

The Valles Caldera is the major geothermal resource in the Rio Grande rift which, other than the caldera, consists of a rather small identified resource base (Brook _et al_, 1979); however, high heat flow values throughout the region, and geophysical anomalies suggestive of buried magma bodies near Socorro (Sanford _et al_, 1977; Chapin _et al_, 1978), imply that many undiscovered (although less spectacular and less easily identifiable) hydrothermal areas exist along the rift region (Brook _et al_, 1979). The caldera itself consists of a hot water reservoir (ibid). The resource is developed in rocks which are largely volcanic, and the permeability is secondary in origin, developed in indurated rocks (Trehan _et al_, 1978); the presence of some aquifers in the sedimentary materials cannot be completely discounted, however.

Subsidence in the Valles Caldera will be dependent on the nature of the reservoir which is tapped for production. Subsidence will be minimal to moderate if the reservoir lies primarily within fracture porosity developed in indurated volcanic rocks; it may be more sizeable if aquifers in sedimentary materials exist and are drawn down, or if the creation of secondary channels by solution has created high porosity zones. Gravity effects due to mass changes may well dominate the magnitudes of the gravity changes expected here, and may be measurable in a few year interval, since a 50 MW power plant is planned in the near future (Brook _et al_, 1979). The area should present no logistical difficulties, and an adequate calibration loop should be feasible in the nearby mountains.

(8) Oregon Geothermal Systems

Three areas in Oregon seem to be suitable for evaluation because of their geothermal potential: 1) Newberry Caldera; 2) Vale Hot Springs; and 3) Klamath Falls area. The first two areas are characterized by high temperatures (230°C and 157°C respectively) and moderate volumes (47 km^3 and 117 km^3 respectively), so that each area should yield approximately 800 MW of electrical energy over a 30 year period (Brook et al, 1979). The third area, Klamath Falls (which actually includes three KGRA's -- Klamath Falls, Klamath Hills, and Olene Gap) is considerably lower in temperature (111°C - 124°C), but contains an unusually large amount of beneficial heat (approximately 2×10^{18} joules), and low-temperature uses of the resources in the area for space-heating and greenhouse operations are common (ibid). Thus this area is included because development is likely to continue for these low temperature purposes, and further evaluation of certain parts of the region may reveal higher temperature resources, although their existence is currently speculative (Stark et al, 1979).

Newberry Caldera is a young (0.6 m.y. and younger) volcano which is located in central Oregon south of the town of Bend on the boundary between the High Cascades Volcanic Province and the Basin and Range Province (MacLeod et al, 1975); it is the youngest and most northwesterly of 34 rhyolitic domes and related volcanoes which are found in southeastern Oregon, all of which, as a general rule, become older in an easterly direction (ibid). Newberry Volcano is a 20 X 40 km basaltic shield volcano with a summit caldera in which both basaltic and rhyolitic rocks have been erupted (Higgins, 1973). Many of the caldera rocks, including ash and pumice flow tuffs, air fall tuffs, and obsidian flows, are only 2000-7000 years old (ibid). The emplacement of the caldera was probably controlled by faulting along three regional fault systems, with magma being periodically released by the faulting process. The caldera is probably underlain by several thousand feet of Pliocene-Pleistocene volcanic and volcaniclastic rocks, the same kinds of materials as those making up the caldera. Little is known about the geothermal environment at Newberry Caldera (for instance, temperatures have been estimated from similar Quaternary volcanoes rather than by geothermal or direct measurements), and no production is slated for the near future. Some subsidence could be expected, and in particular would be associated with volcaniclastic rocks making up the reservoir. However, a gravity monitoring effort would be hampered by the presence of two large bodies of water (Paulina Lake and East Lake) which cover approximately one-third of the caldera area; fluctuations in water levels in these lakes could contribute significant non-geothermal gravity changes, if existent. Local and recent faulting might make establishment of a calibration loop difficult, requiring that one be established in some other area.

The Vale Hot Springs area is located in eastern central Oregon, near the Idaho border. It lies in proximity to the Vale fault zone (defined by Lawrence, 1976), which is one of four identified west-northwesterly trending strike-slip fault zones which (a) break rocks of Pliocene age, (b) separate areas of normal faulting, and (c) form the transition between the main Basin and Range province of Nevada and the largely unfaulted Columbia River Plateau basalts (ibid). The area is located along the southern boundary of the Snake River Plain structural trend where it crosses from Idaho into Oregon (Hill _et al_, 1961), an area underlain primarily by lavas of Pliocene age, with graben materials of Pliocene and Pleistocene sedimentary rocks and interbedded basalt flows underlying the plain itself. Although little apparently has been published on this hydrothermal convection system, a large area is suggested by an audio-magnetotelluric survey (Long and Kaufmann, 1980), and a high heat flow anomaly (Brook _et al_, 1979). At present, no production is planned. Subsidence should be expected if production is primarily from volcaniclastic rocks, a likelihood. Any problems with conducting a precision gravity survey or establishing a calibration loop are currently unknown.

The Klamath Falls area is located in south-central Oregon, within the Klamath Basin, which is bounded by the High Cascades to the west, the Medicine Lake Highlands to the south (in northermost California), and high desert country to the east (Stark _et al_, 1979). The basement rocks consist of Pliocene basalts, which are unconformably overlain by the Pliocene Yonna formation, a sequence of tuffaceous siltstones and sandstones, and diatomaceous lacustrine sediments, which contain maars, tuffs and thin basalt flows; the Yonna formation is overlain by Late Pliocene and Pleistocene basalt flows with volcaniclastic interbeds. All the formations have been broken into grabens and horsts by northwesterly trending normal faults, with as much as 1600 feet vertical displacement; less prominent are north and northwest-trending cross faults which truncate or offset topographic features (ibid). Fault scarps seem to control at least some of the distribution of subsurface hot waters (ibid). This area shows the same potential for subsidence as the two areas mentioned above, and hot water is currently being produced and discharged, although some users utilize heat exchangers to conserve the resource (Lund _et al_, 1975). In some areas, gravity work would prove difficult because of the presence of large water bodies (Klamath Lake and Swan Lake); no difficulty is anticipated in establishing a calibration loop locally.

(9) Roosevelt Hot Springs and Cove Fort - Sulfurdale, Utah

The Roosevelt and Cove Fort-Sulfurdale KGRAs are located in southwestern

Utah (northeast of the town of Milford), near the eastern margin of the Basin and Range province. This area has been characterized by repeated igneous activity in the last 30 m.y., and the associated rock types are high silica rhyolite, and basalt or basaltic andesite, a bimodal association which is typical of the Late Cenozoic volcanism which is common along this edge of the Basin and Range (Ward et al, 1978). The province edge is coincident with a major structural feature, the so-called Intermountain Seismic Belt, a 1300+ km long, 100 km wide zone of seismicity which separates it from the Colorado Plateau-Middle Rocky Mountains; this northerly trending belt is characterized locally by regions of high heat flow and geothermal features (Smith and Sbar, 1974). These two KGRAs, together with the lower temperature Thermo KGRA (located some 30 km southwest of Roosevelt Hot Springs), are located near the intersection of the Intermountain Seismic Belt with a 200 km east-westerly trending zone of seismicity, which extends from southwestern Utah through southern Nevada and bounds the southern Great Basin (ibid). This latter belt is spatially coincident with the Pioche-Beaver-Tushar mineral trend, a significant tectonic feature which crosscuts the northerly trending Late Cenozoic fault features of the eastern Great Basin (Ward et al, 1978). Roosevelt Hot Springs has an estimated mean reservoir temperature of 265°C, a mean volume of 47 km^3, and an expected electrical energy output of 970 MW over a 30 year period; the values for the same parameters at Cove Fort-Sulfurdale are 167°C, 30 km^3, and 330 MW (Brook et al, 1979).

Roosevelt Hot Springs is located on the western margin of the Mineral Mountains, whose geology consists primarily of a young Tertiary granitic pluton which has intruded older sedimentary rocks and is associated with

Tertiary volcanic rocks and Quaternary rhyolite flows, domes and ash deposits; the pluton is the largest (250 km^2 area) and youngest (10^{-14} m.y. by K-Ar ages) in Utah (Ward et al, 1978). The volcanic rocks were formed in repeated episodes of volcanism, starting 20 m.y. ago and continuing until the most recent episode of Quaternary basaltic eruptions (ibid). The hot springs are associated with the intersection of two major faults, the northeasterly trending Opal Mound fault and, perpendicular to it, the Hot Springs fault; numerous faults parallel the Hot Springs fault (ibid). The geothermal system is structurally controlled, based on the correlation between exceptionally high heat flow values and identified faults; the heat may "be supplied by steady state conduction from a source at a temperature near the granite solidus having lateral dimensions of the Mineral Mountains pluton at a depth of 7 km" (ibid). Partial melting (and/or intense fracturing) is suggested both by low velocity raypaths and a low Q transmission path (ibid). Low heat flow values in the central Mineral Mountains, east of the main geothermal prospect located along the Opal Mound fault, "are likely associated with a recharge region" for this hot water system.

The main hot water production seems to be from fracture porosity associated with the extensive faulting found in the Roosevelt Hot Springs area. Low to moderate amounts of subsidence are thus expected over a several year period, and particularly if recharge rates are low, as may be anticipated in this type of geology. Mass removal may also be measurable with time, and particularly since some production may be from higher levels in the reservoir; producing wells are located at depths as shallow as 382 m (Brook et al, 1979). A 55 MW power plant is planned for the near future (ibid), so that initiation of monitoring is desirable at this time. Previous repetitive gravity and leveling surveys have already been conducted in this area (Cook and Carter, 1978) and could be resumed.

Less detailed geological information seems to be currently available for the Cove Fort-Sulfurdale area, which seems to be characterized by the same regional geologic framework as the Roosevelt area. This area does have a higher level of seismic activity than Roosevelt Hot Springs, and an argument can be made that "the close spatial association of...earthquake swarms with the nearby Quaternary basalts suggests that the potential exists for a geothermal source related to Holocene volcanism" (Ward et al, 1978). Since the hydrothermal regime is likely to be similar to that at Roosevelt Hot Springs, but (a) the reservoir temperature, volume and power production are currently estimated to be lower, (b) the state of geological and geophysical knowledge is less, and (c) no power plant is planned for the near future, this area appears to be a less viable prospect for gravity monitoring at the present time.

No logistical difficulties (other than the avoidance of high temperatures in the summer months) are expected in either of these KGRAs, and there should be no problem with the establishment of calibration loops at appropriate bedrock locations.

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