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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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Geothermal Subsidence Research Management Program

June 1981

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Prepared for the U.S. Department of Energy under Contract W-7405-ENG-48

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Printed in the United States of America
Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161
Price Code: A06

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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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June 1981

This work was supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Renewable Technology, Division of Geothermal and Hydropower Technologies of the U.S. Department of Energy under Contract No. W-7405-ENG-48 with Lawrence Berkeley Laboratory through Subcontract No. 4502410.

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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.

This assessment could not have been carried out without the assistance of several individuals and organizations, to whom we wish to extend credit. Ing. Alfredo Mañon M. and his staff of the Comisión Federal de Electricidad of Mexico facilitated our field work at the Cerro Prieto geothermal field. Norman Goldstein and Ernie Majer critically reviewed the manuscript and provided helpful comments. Sally Foster, Barbara Tanizawa and Elizabeth Clarke typed intermediate and final versions of the text. Robert Leggewie carried out much of the literature search, particularly for Appendix B. Rosemary Wyman did some computer analysis and provided considerable moral support as well as technical comments. Paul Knox drafted some of the figures. To all these persons and agencies, we wish to express our gratitude.

We are especially grateful to Herbert Dragert of the Pacific Geoscience Centre on Vancouver Island. He not only provided logistical support, but also many invaluable technical discussions.

This work was supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Renewable Technology, Division of Geothermal and Hydropower Technologies of the U.S. Department of Energy under Contract No. W-7405-ENG-48 with Lawrence Berkeley Laboratory through Subcontract No. 4502410 under the Geothermal Subsidence Research Program. The program was administered under the technical direction of Norman Goldstein. Mr. H. A. Todd was the contract administrator for Lawrence Berkeley Laboratory.

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

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°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 monitor-

ing 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

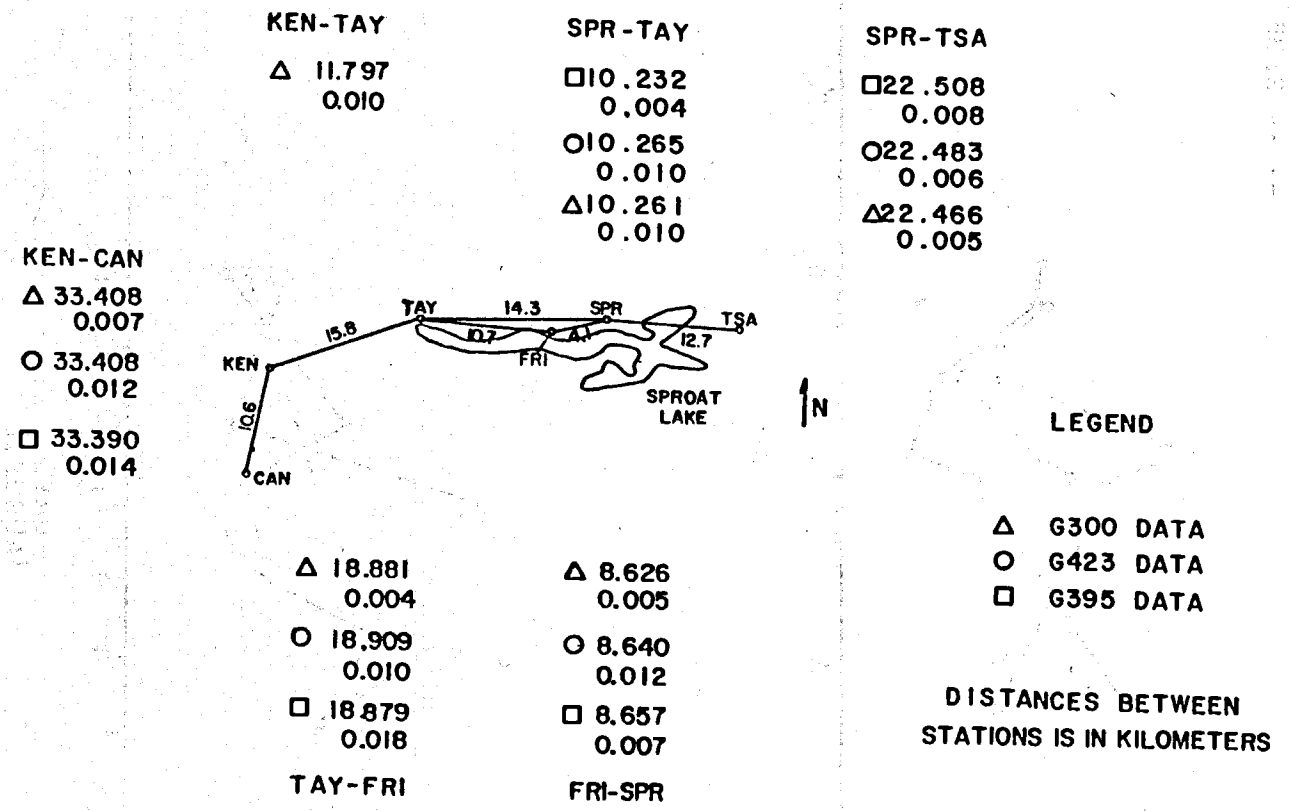

Figure 1. Map of the Sproat Lake area near Port Alberni on Vancouver Island, B.C., showing the location of gravity stations in the Canadian precise gravity network and distances between adjacent stations. The mean value for all ties with a particular meter is shown to the right of the meter symbol (refer 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.

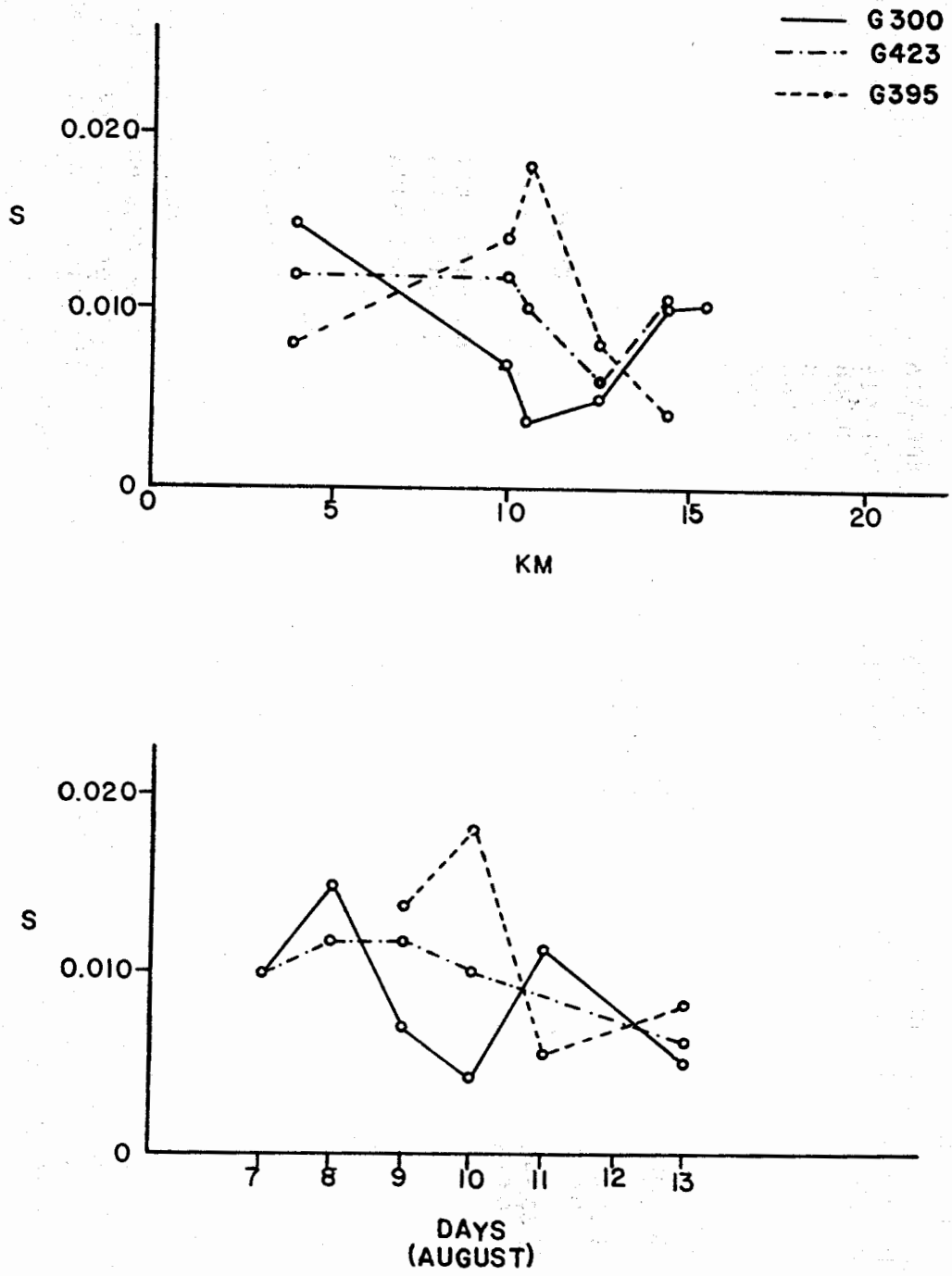

Figure 2. Plots of the standard deviation for gravity ties versus distance of travel (upper graph) and versus total time in the field (lower graph). There seems to be no correlation between precision and distance of travel, as seen in the upper curve, at least over the short distances encountered in 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 μgal	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
				$\bar{X}_1$ = .492	$\bar{X}$ = 22.469
				s = .008	s = .011
				$\bar{X}_2$ = .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	$\bar{x}$ (mgals)	S (mgals)
1.	G300	7.892	.005
2.	G300	7.888	.006
3.	G300	7.888	.010

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

COLO - EL DOR TIE SET

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

	Meter	$\bar{x}$ (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

LBL-12910
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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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June 1981

This work was supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Renewable Technology, Division of Geothermal and Hydropower Technologies of the U.S. Department of Energy under Contract No. W-7405-ENG-48 with Lawrence Berkeley Laboratory through Subcontract No. 4502410.

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 $\pm$ .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

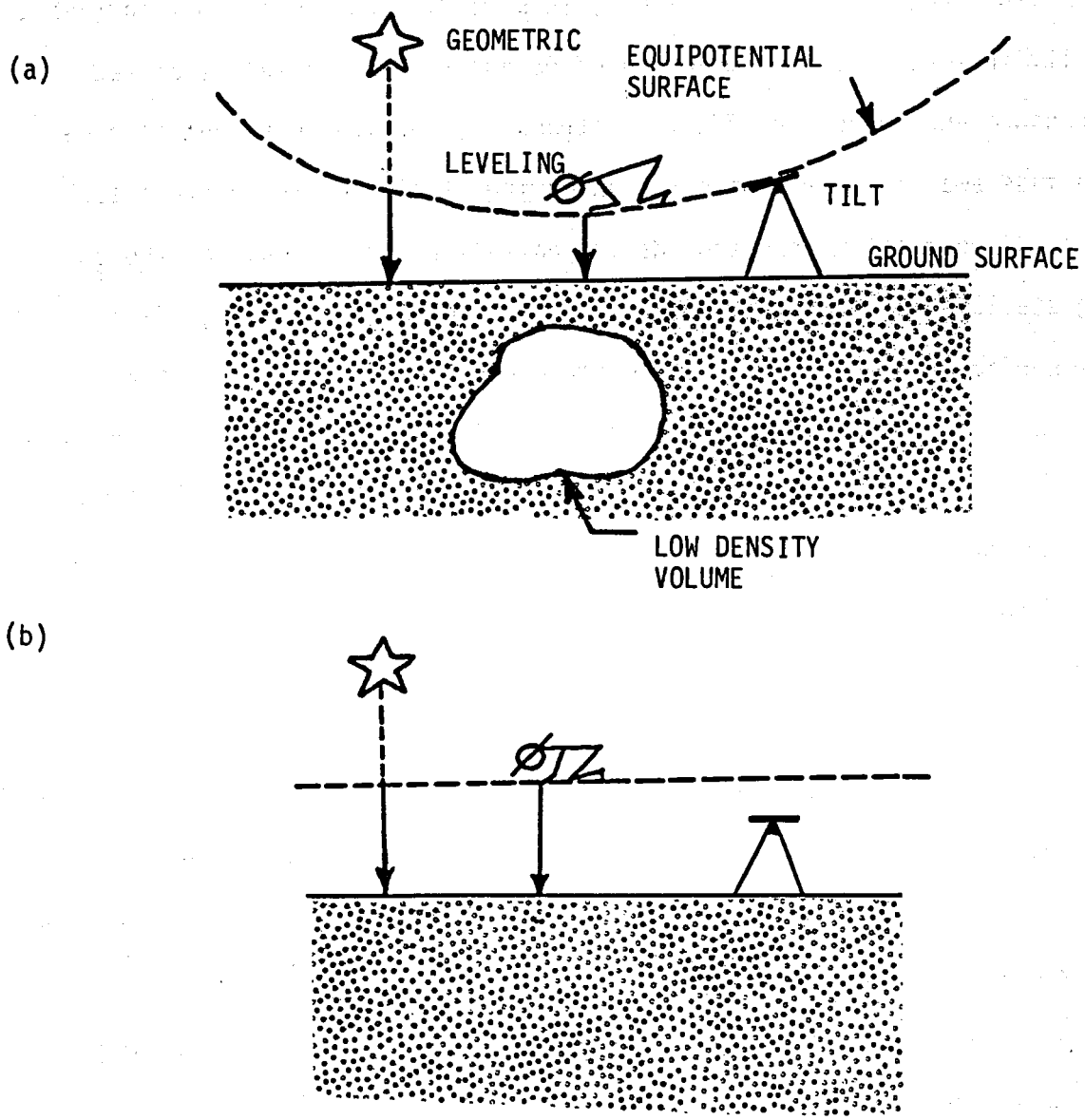


Figure 4. Schematic drawing illustrating the relations among leveling, tilt, and geometric methods of measuring ground surface shape for a half space. (a) Low density inclusion. (b) Homogeneous density distribution. In (a), leveling and tilt measurements would indicate a bulging ground surface, whereas 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 3.08×10^{-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 gecmetric 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	Potential	Orthometric Elevation	Gravity	Free Air Elevation	Tilt
(KM)	(CM2/SEC2)	(CM)	(MGAL)	(CM)	(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

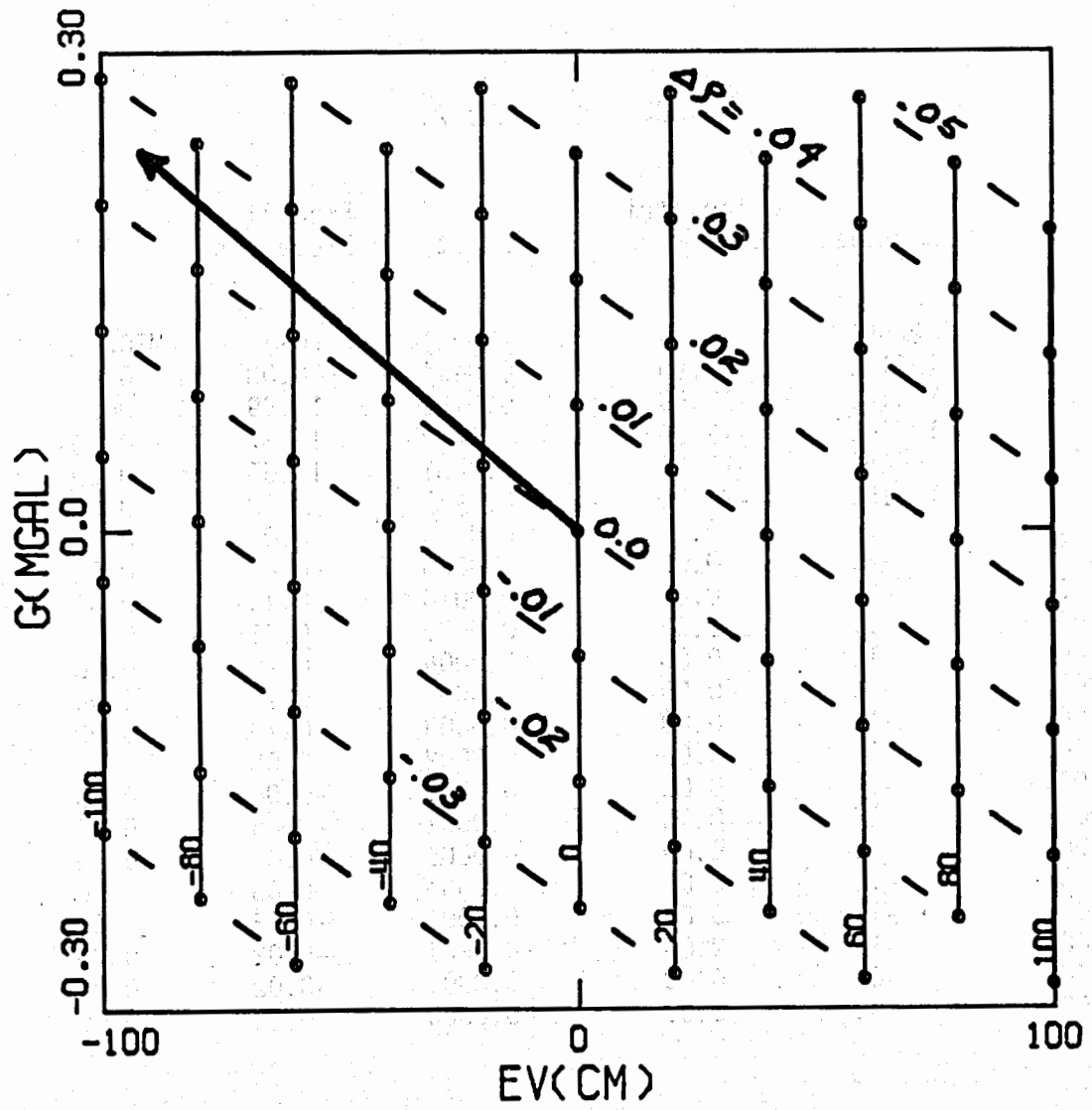
later examples, however, that free-air elevation computed from gravity data alone does not provide a good estimate of elevation change and that elevation must be measured separately.

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.

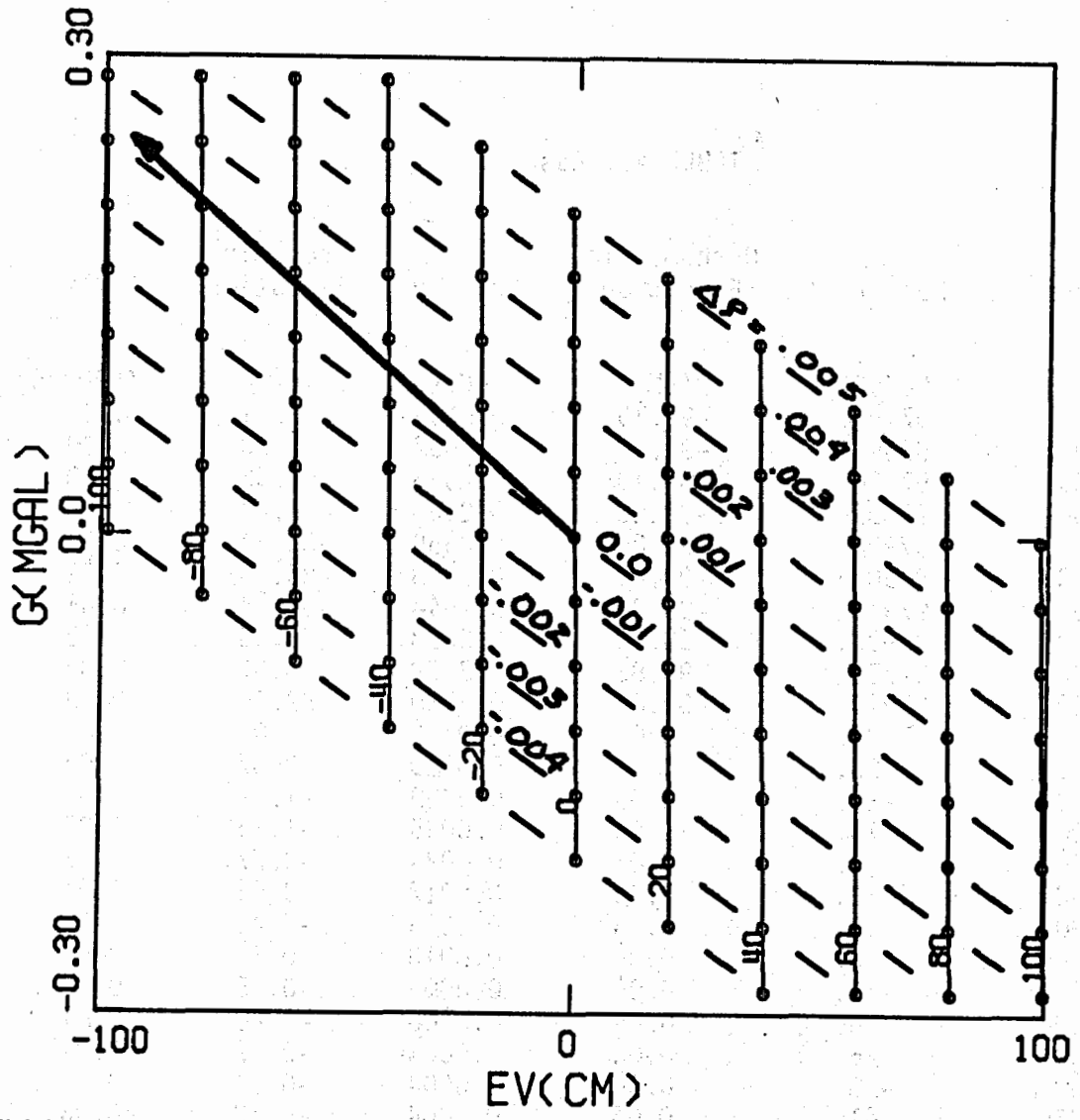
Figure 6 is a three-dimensional gravity, elevation, and bulk density changes plot for an arbitrary consolidation of the model in Case 3. Again as in Case 1, the solid line going towards the upper left from the origin of the plot is the path that would be followed by increasing formation consolidation 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	0.00
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



RAD= 50.00
THICK= 1.00, DEPTH= 1.50
DEN1= 2.44000
DEN2= 2.435000 2.445000 0.001000

RADPLT= 0.0

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	Potential	Orthometric Elevation	Gravity	Free Air Elevation	Tilt
(KM)	(CM2/SEC2)	(CM)	(MGAL)	(CM)	(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.