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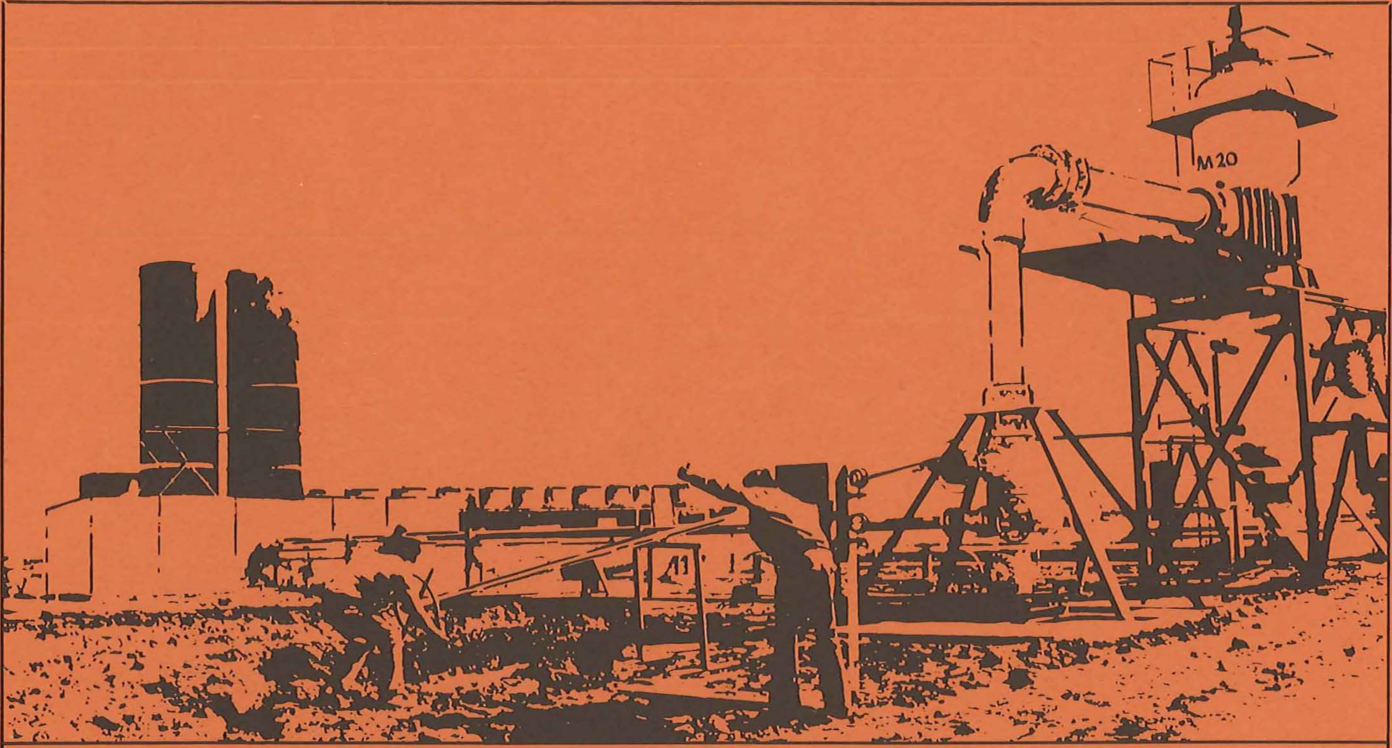
MEXICAN-AMERICAN COOPERATIVE PROGRAM AT THE CERRO PRIETO GEOTHERMAL FIELD



REPETITIVE PRECISION GRAVITY STUDIES AT THE CERRO PRIETO AND HEBER GEOTHERMAL FIELDS

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September 1982

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Prepared for

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by

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SUMMARY

The Salton-Mexicali structural trough, located in southeastern California and Baja California, is an elongated deep Tertiary basin characterized by young volcanics and high heat flow values. In consequence, the geothermal production on the California side of the border with Mexico could potentially be the greatest in the United States, although currently only 20 MW are being produced. South of the border, 150 MW are being produced at Cerro Prieto, and considerably greater potential exists in nearby areas. The production throughout the Salton-Mexicali trough is from permeable zones in metamorphosed sediments, and subsidence due to fluid withdrawal is likely if no recharge occurs. Subsidence is already documented and widespread from tectonic causes.

To study subsidence and mass removal, a precise gravity network was established on 60 permanent monuments in the Cerro Prieto geothermal field in early 1978, and repeated annually through early 1981; the survey was tied to two bedrock sites outside the limits of the current production zone. The looping technique of station occupation was utilized, in which occupation of the base was followed by occupation of several stations, followed by a return to the base. Use of two LaCoste and Romberg gravity meters, and replication of values within loops as well as entire loops, enhanced precision such that the median standard deviations of the base-to-station differences, reduced to observed gravity values, ranged from 7 to 15

microgals for individual surveys. The smaller values were obtained as field and data reduction techniques were improved and experience was gained.

A similar survey was initiated in the Heber area just north of the Mexican border in early 1980. It too was established on permanent monuments, was tied to bedrock stations outside the geothermal area, and used multiple repetititions of values with two meters to achieve high precision. A variation of the Canadian tie method was used, in which each individual station was tied directly several times to one of three base stations within the geothermal field; the gravity differences among these bases were well established by a total of 108 ties. The precision of the reduced gravity differences for the entire survey was 8 microgals for one of the meters, and 11 to 17 microgals for the other.

The entire Heber gravity network has not yet been repeated. However, the base station network and its set of ties to the two bedrock stations were repeated during the winter of 1980-81, commensurate with the first order releveling of the Imperial Valley following the October, 1979, Mexicali earthquake. Except at one base, no significant variations were observed.

Supportive technical and geophysical work for these two projects consisted of the following:

(1) Continuous tidal gravity monitoring on Cerro Prieto volcano for a period of three days to establish values for the conformance factor and lag time (necessary for making tidal corrections).

(2) First and second order leveling carried out by the Comisión Federal de Electricidad of Mexico coincidentally with the gravity surveys, for the purpose of separating elevation from mass effects in any observed temporal gravity variations. Leveling was already available at Heber due to industry and government efforts.

(3) Gravity ties made in both early 1980 and 1981 between the Cerro Prieto and Heber bases, to integrate the two gravity surveys.

(4) Establishment of a precise gravity calibration network on stable bedrock in the Santa Ana Mountains, Orange County, California (in the same gravity range as the Heber and Cerro Prieto surveys) for reconciliation of the two gravity meters used at Heber both with each other and with meters to be used in future years. This was not needed for the third meter used at Cerro Prieto, since no significant calibration differences were observed in its use. The calibration network was established using the Canadian tie method on stations located at 15-20 milligal intervals; the resulting precisions were 6 microgals standard deviation and 3 microgals standard error for one meter, about double that for the other.

Significant temporal gravity changes occurred in the northern part of the Cerro Prieto area during 1979, and changes of up to 80 microgals also occurred throughout much of the central and southeastern part of the same field during 1980. These variations are interpreted as being respectively due to the Mexicali earthquake of October, 1979, and to the Victoria earthquake of June, 1980; both seismic events were greater than magnitude 6 on the Richter scale, and caused observed ground deformation. Smaller positive gravity variations near the limits of precision may be attributed to ground subsidence due to geothermal production. Due to the lack of a repeated full survey, no variation in gravity was observed in the Heber geothermal field, with the exception of one base value (out of five repeated bases).

I. INTRODUCTION

The Salton-Mexicali structural trough straddles the United States-Mexico border in southeastern California and northeastern Baja California. The trough is bounded by, and contains, several major active strike-slip faults, including the San Andreas, Imperial, San Jacinto, Elsinore, Cerro Prieto, and Cucupa faults; large vertical displacements are also present beneath the valley alluvium (McNitt, 1963). These faults have caused intense folding and compression of Tertiary and Quaternary sediments (Elders and others, 1972), and bound at least four postulated pull-apart basins. These basins are characterized by young volcanics and high heat flow values, and are directly related to the presence of known geothermal prospects (Elders and others, 1972). The Salton-Mexicali trough is presumed by many workers to be an active "spreading center;" the spreading process has resulted in both crustal thinning and accumulation of more than 6000 m of young marine and terrestrial sediments, on the basis of geophysical studies (Biehler and others, 1964). In the Imperial Valley of California, six hydrothermal convection systems with tempertures greater than 150°C at depth have been identified: (a) Salton Sea area; (b) Westmorland; (c) Brawley; (d) East Mesa; (e) Border; and (f) Heber. These areas constitute the largest known geothermal resource in the United States, with an estimated possible electrical output four times as large as at The Geysers (Brook and others, 1979). At present, only two 10 MW demonstration plants, at East Mesa and Brawley, are operating but permits have been issued for the construction of larger plants at Heber and the Salton Sea. Across the border in Mexico, the Cerro Prieto field is currently producing 150 MW, and its output will soon be doubled. Nearby areas such as Tule Check (Diaz, 1978) also show potential for possible geothermal development. These areas are shown on Figure 1 below.

The reservoirs for the above-named geothermal prospects are located in permeable Tertiary sedimentary material of predominantly continental origin at depths ranging from 0.7 to 4Km (Brook and others, 1979). High temperatures and fluids have produced shallow metamorphism which densifies sediments (Muffler and White, 1969; Elders and others, 1978); the actual production is from

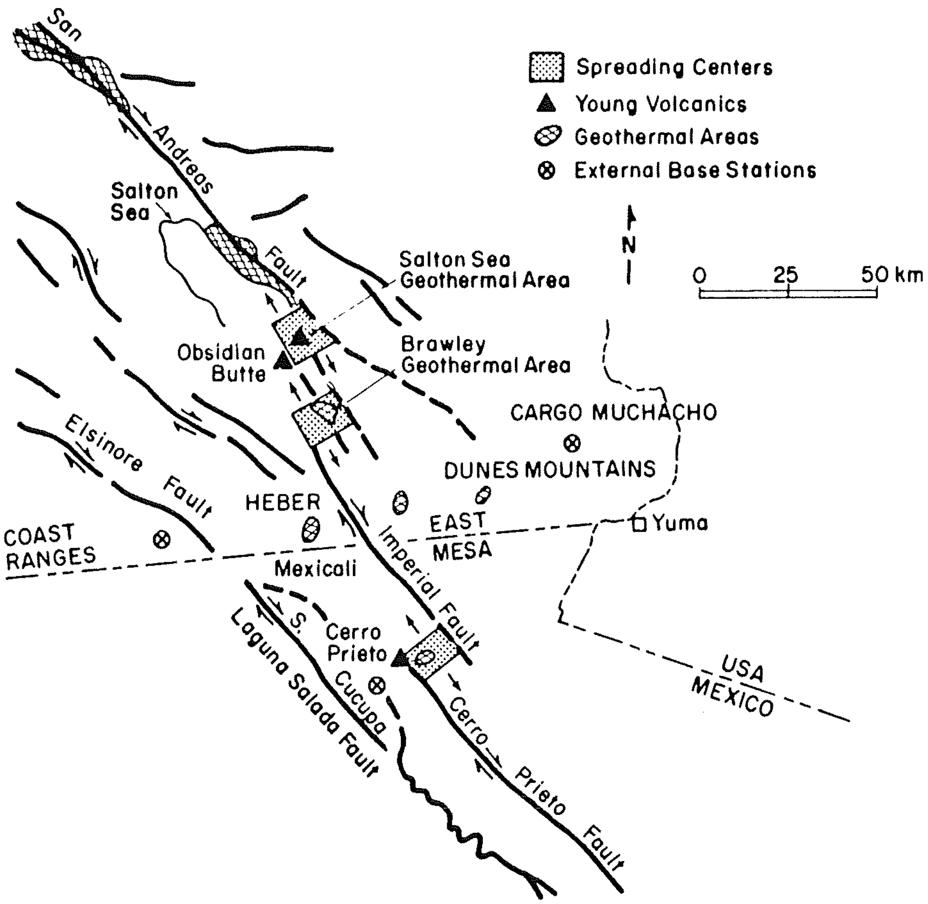

Figure 1. Index map, Salton trough area, showing Cerro Prieto and Heber geothermal fields.

permeable zones within these altered areas. Removal of fluids during production would cause subsidence, net mass removal, precipitation of minerals, phase changes, and reservoir cooling. Of these reservoir changes, the most quantitatively substantial is subsidence, unless recharge accompanies fluid withdrawal. Net mass removal would also be quantitatively important in the short term. In addition to the possibility for geothermally-induced subsidence, there is documented subsidence of 1 to 2 cm/year in the trough region which is due to continuing tectonic deformation (Lofgren, 1978); this is accompanied by both horizontal distance changes (Massey, 1978) and tilt variations (Lofgren, 1974). Most of this ground deformation is aseismic in nature, but discrete seismic events such as the Mexicali (Imperial Valley) earthquake of October, 1979, have also resulted in substantial variations. Subsidence from any source is crucial, since changes in the gradients of the relatively flat Imperial-Mexicali valley floor will affect the extensive canal network which supplies irrigation water for the intensely developed agriculture in the region. Steepening of the gradients of streams, canals, and drains, and increased storage area for the Salton Sea (with consequent inundation of croplands at the south end) has already been documented by precise geodetic surveys (Lofgren, 1978).

A surface gravity survey, established with a precision of a few microgals on permanent markers within and adjacent to producing geothermal fields and repeated at regular intervals, should be capable of detecting short-term changes due to both subsidence and mass removal. The variations could be on the order of tenths of milligals, as has been observed in other areas (Isherwood, 1977; Hunt, 1970). If repetitive leveling of first or second order accompanies the gravity work, the individual effects of mass and elevation changes can be separated, using mathematical procedures based on potential theory (Whitcomb, 1976). Consequently, two gravity case studies were initiated in the Salton-Mexicali trough.

Between January and May of 1978, a precise gravity network was established in the area of the Cerro Prieto geothermal field, Baja California, Mexico. The stations in the network were reoccupied on an annual basis each winter through early 1981. A similar study was initiated at the Heber geothermal field in the Imperial Valley of California in the late winter and spring of 1980, with repetition of base station values in the early months of 1981. Additional supportive gravity work was performed in the Santa Ana Mountains of California in late spring, 1980, to establish a calibration loop for instruments used at Heber and Cerro Prieto.

The purpose of the precise, repetitive gravity surveys conducted to study these geothermal areas was threefold: (1) Reduction of the data to observed gravity values would allow the interpretation of any temporal variations in terms of elevation changes and/or mass removal. These variations could occur from production of the fields, tectonic events and "noise" such as cultural disturbances and weather effects.

(2) Further reduction of the data to Bouguer anomaly values would permit evaluation of the spatial distribution of the gravity field. When coupled with lithologic and density information, an estimate of the controlling structure and volume of the reservoirs could be obtained from a three-dimensional model of the subsurface geology of the field.

(3) Analyses of the data collection process and the precision of measurement of reduced data would permit an assessment of the use of the surface gravity method in monitoring changes due to geothermal production. If these analyses were to be conducted simultaneously with the gravity surveys, enhanced precision could result from both refinement of the field methods used and collection of additional data as needed.

As a consequence of this third objective, changes in field procedure during the course of the survey were implemented to incorporate new findings from the literature, or to test alternate methods of conducting precise work. While this led to an "unevenness" in technique and data quality, it also promoted considerable improvement with time. The procedures used at Cerro Prieto were quite different than those used at Heber and to establish the calibration network; the various surveys are thus treated separately in succeeding sections, following a discussion of previous work.

II. PREVIOUS WORK

No attempt will be made here to discuss the history of the development of either the gravity method in this particular application or of the Heber and Cerro Prieto geothermal fields. Rather, a few comprehensive review and state-of-the-art articles will be emphasized.

The methodology, precision, and utility of the gravity method for the monitoring of certain geothermally-induced reservoir changes has been summarized in detail by Grannell and others (1981a); this article includes a complete bibliography on the use of repetitive gravity. Two additional recent articles are those by Dragert and others (1981) and Whitcomb and others (1980); both of these emphasize the use of gravity in monitoring pre-earthquake crustal deformation, but much of the content is appropriate to the geothermal situation. A technical discussion of the interrelationships between gravity and leveling, without which proper interpretation cannot be accomplished, was presented by Whitcomb (1976).

For an up-to-date discussion on the geology, development and geochemical and geophysical exploration of the Cerro Prieto geothermal field, the proceedings volumes (Lawrence Berkeley Laboratory, 1978; Coordinario Ejecutiva de Cerro Prieto, 1979; and Lawrence Berkeley Laboratory, 1981) are especially valuable. Articles on the gravity effort at Cerro Prieto are included in these volumes, authored by Chase and others (1978), Grannell and others (1979), and Grannell and others (1981b). No comparable references exist for the Heber area, although the Imperial Valley, including Heber, is evaluated, with a partial bibliography, in Grannell and others (1981a, Appendix B).

Repetitive ground deformation studies have been carried out in the Salton-Mexicali trough by various government and industrial organizations on an average semi-annual to biennial basis (depending on the area) at both first and second order level since the early 1970's; representative articles include those by Garcia (1979), Massey (1978) and de la Peña (1981) for the Cerro Prieto area, and Lofgren (1974 and 1978) for the Imperial Valley.

III. CERRO PRIETO GRAVITY SURVEY

A. FIELD TECHNIQUES FOR OCCUPYING THE GRAVITY NETWORK

Fifty-five gravity stations, as well as several alternates, have been established over an area of approximately 500 Km^2 centered on the Cerro Prieto geothermal field. The 55 stations consist of permanent concrete monuments with deep footings and flat concrete tops which are large enough to accommodate the gravity meters; the first 40 were established prior to the initial gravity survey in early 1978, and the remaining 15 toward the end of that particular survey. The alternate stations were established throughout the course of the project (from 1978 through early 1981) for three purposes: (1) to replace stations destroyed by construction; (2) to provide stations with better accessibility (some stations, for instance, were inundated several times a year by mud); and (3) to extend the areal coverage of the gravity network. Alternate stations in categories (1) and (2) were located very close to the original stations (or their previous sites) and consequently were given the same numerical designation, but with the suffix "bis" (Spanish for "alternate") after the number. Alternate in category (3) received new numbers, with values in the hundreds. The alternate stations were either monumented like the regular stations, or were established on existing concrete structures such as bridge foundations. Both stations and alternates are shown on Figure 2 on the following page.

Two "bedrock" localities were used to establish relatively stable reference bases outside the production zone of the field. Stations 1 and 1bis were established on granitic rock outcrops in the Cucupa range 15 Km west of the geothermal power plant, and stations 20 and 20bis were established on the eastern flank of the rhyocdacitic Cerro Prieto volcano 10 km northwest of the plant. Tectonic changes could conceivably affect the elevation differences between these two locales, but they are probably less susceptible in the short term to such variation than the remaining stations in the network, which are located on thick sedimentary deposits of largely fluvial origin.

A final base which was established for another purpose was station number 23, located approximately five kilometers east of Cerro Prieto volcano and about one kilometer east of the main road paralleling the railroad tracks between the

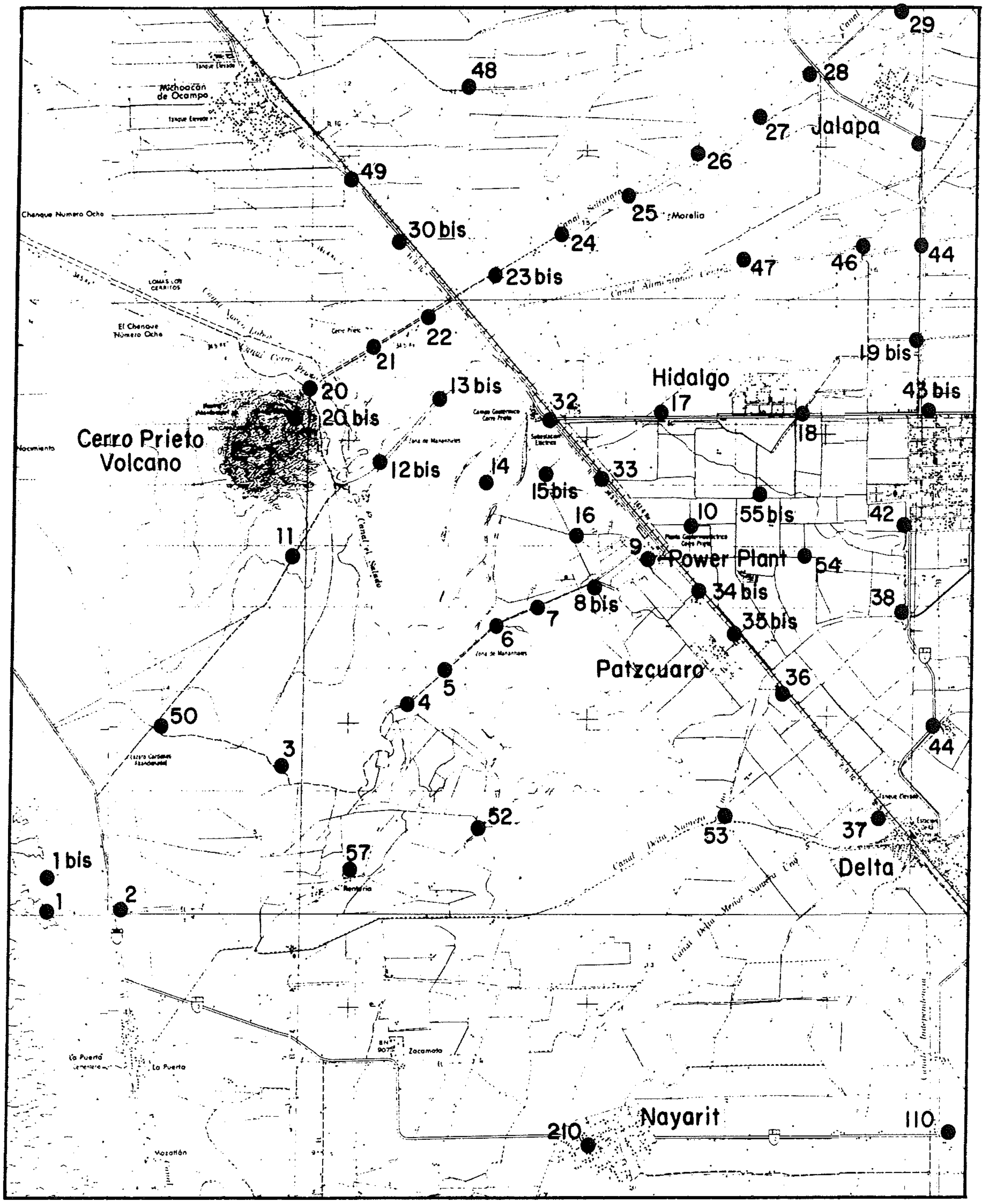

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Figure 2. Gravity station location map, Cerro Prieto geothermal field.

towns of Michoacan de Ocampo and Delta. This station was used for drift and tare control in the gravity readings on a daily basis, since access to the reference bedrock bases was more difficult because of distance and rough road conditions (these factors contribute substantially to imprecision). Station 23 was chosen because its off-the-highway position substantially reduced traffic disturbances, although some vibration was experienced with the passage of occasional trains. On the other hand, its central location provided rapid access. Thus, time was saved in returning to the base, and the individual loops used in the survey could usually be kept to durations of from three to five hours (base to base time).

Throughout the course of the survey, every attempt was made to evaluate and minimize tares, which are small jumps or accelerated drift in the data, and other imprecisions. External temperatures greater than 100°F were avoided, as were high winds and intervals of seismic activity. Stations were either located away from heavy traffic, or were occupied at times when traffic was light, as on weekends, since the ground vibrations caused great difficulty in obtaining readings. Transportation over bumpy dirt roads was accomplished with careful driving, and as much protection for the instruments as possible was provided.

The occupation of individual gravity stations followed a set routine which was used to enhance the precision of the field data. The looping method was employed, in which a base station is occupied, followed by the sequential occupation of several stations and then a return to the base station. Each station was usually occupied from two to four times in separate loops, and during each occupation, a minimum of four readings was obtained, with the meter being picked up and releveled before every reading so that possible leveling errors could be distributed.

Two LaCoste and Romberg gravity meters were used during the first two years of the survey (the initial occupation in early 1978, and the first repetition during the winter of 1978-79); these were G300, owned by California State University at Long Beach, and G423, belonging to California State Polytechnic University, Pomona. Prior to the third year, G423 developed mechanical problems which precluded its further use, and the remaining two annual surveys were performed solely with G300.

In addition to the instrument change mentioned above, other procedures were modified in an attempt to either enhance precision, or reject those which had a negligible effect on data quality. The following changes were made:

(1) Initially, the four readings at a particular station were made two apiece by two different operators. However, once persons are well trained in reading the instruments, there are no significant variations from one operator to the next, and adherence to this technique was no longer required. Some entire loops were run by only one person, and at other times, persons would alternate between stations. Four repetitions at each station were not always made in the last two surveys, to minimize costs.

(2) At first, to minimize transport problems, the gravity meters were carried on the seats of small cars padded with foam. This procedure, used during the first two years, was apparently somewhat effective in reducing the magnitude, duration, and occurrence of tares. During the third year, a transport box mounted on springs with the appropriate characteristics for damping out vibrations in the 10-100 Hz frequency range was introduced, based on a Canadian design (Herbert Dragert, personal communication, 1978). This transport case was upgraded in the fourth year. Also, during the third and fourth years larger cars were used for part of the work. Both of these strategies proved to be partially effective in increasing precision, although the precision gains were partially negated by the necessity of using a different base, discussed below.

(3) The daily field base used during the first two years was station number 23, with a normal number of ties being made to stations 1 and 1bis (distance and lack of accessibility made additional replications unfeasible); extra ties were made to station 20bis on Cerro Prieto volcano. It was early recognized that the use of one base for field work and others for reference on bedrock created an additional imprecision, a facet which will be discussed in detail in section III-E (on data reduction). Consequently, during the third field season, the individual loops referred to station 23 contained occupations of station 20bis, and the emphasis gradually changed to using station 20bis as both a field and reference base. The gravity difference between these two bases thus became well established by extra repetitions.

Prior to the fourth field season, station 23 was destroyed by a bulldozer, leaving 20 bis as the only viable alternative, in spite of access problems over a cobblestone road. During the fourth year, in early 1981, a final base shift was made, to avoid the use of the cobblestone access to 20bis (movement over this road was identified as being a significant source of error, frequently producing tares with magnitudes in the hundredths of milligals). Station 20, farther down the volcano, could be reached by a combination of dirt road driving and a half-kilometer walk. This was then used as the permanent base station; the gravity difference between 20 and 20bis was established by several ties made on foot in early 1981.

(4) In order to test its possible efficacy in reducing imprecisions due to nonlinear instrumental drift, a variation of the looping technique introduced by Roman (1946) was employed during part of the fourth field season. In this method, intermediate stations are frequently reoccupied during the course of the day; these then serve as auxiliary bases, and their repetition allows the construction of more carefully controlled drift curves during the data reduction phase of the work.

During the first year, the gravity network was tied several times to an external base in Mexicali established by the National Oceanic and Atmospheric Administration. This base is located in a noisy traffic circle, with less precise readings than those obtained during the course of the main gravity survey. Likewise, during the second year, the gravity network was tied to a local base in the Cerro Prieto geothermal field, used by personnel from Comisión Federal de Electricidad in establishing their regional gravity survey of the area (this base was subsequently destroyed). At both these locations, the Bouguer anomaly value was known, so that the Bouguer anomaly values in absolute terms could be evaluated for the survey described in this paper.

There were two other types of field studies which were carried out to support the gravity effort at Cerro Prieto; these were accompanying second order leveling, and tidal monitoring. These are discussed in sections B and C below.

B. LEVELING STUDIES AT CERRO PRIETO

In order to separate elevation changes from mass changes in the reduced gravity data, second order leveling was performed at Cerro Prieto on a biannual basis, approximately coincidentally with the four gravity surveys. This leveling, conducted by the Comisión Federal de Electricidad (CFE), used the same monuments as utilized in the gravity survey.

First order leveling was also performed. This leveling network was initially established by DETENAL (Direccion General de Estudios del Territorio Nacional Mexico) in 1977 and 1978, and was repeated in 1980-81 by CFE. This network follows two main lines from Mexicali to the Cerro Prieto field, and is restricted in coverage (for the most part) to the major highways.

However, the lines coincide with the second order coverage and the gravity survey both along the dike road from Cerro Prieto volcano to gravity station number 28 to the east near Jalapa, and from the intersection of this road with the main highway south to Delta (coincidental with the line occupied by gravity stations 31 through 37; refer back to Figure 2). The first order leveling network has been tied in to the United States first order network through occupation of a portion of the U.S. leveling line in Calexico and other points to the east.

C. TIDAL MONITORING

Before reduction to observed gravity values could be completed for the Cerro Prieto data, it was necessary to verify through field measurements the values of two constants which are used in making tidal corrections to gravity data. These two corrections are summarized by Chase and others (1978):

> "The first of these, the so-called lag time, reflects the difference in time between the passage of the sun and 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."

The determination of these constants for a particular area is accomplished by taking frequent readings of gravity at one location for a long time interval.

Two intervals of tidal monitoring were carried out at

Cerro Prieto, at station 20bis on the volcano; this locality was selected because it is relatively stable and vibration-free, and is partially protected from wind gusts. The first interval covered 24 hours in April, 1978, but severe winds overrode the protection available, making part of the data unusable. Eight hours of that interval were considered to be of adequate quality for analysis. The reduced field data were plotted with the inverse of the calculated tidal corrections (i.e., actual tidal changes) on a graph of gravity versus time. These data suggested that the lag time was indeed zero, since the minima were approximately coincidental, but they were of insufficient length to provide an adequate estimate of the conformance factor.

Because of the short interval of usable data obtained, a second set of tidal data were obtained in the same location in the late winter of 1979. Gravity meter G300 was set up on the concrete slab at 20bis, and read continuously, using a strip chart recorder inserted into the electronic jack, for three days. Protection from the wind was provided by a heavy canvas shelter erected around three sides and over the top of the site. To maintain high precision, the leveling of the meter was checked every 15 minutes and adjusted, if necessary. Barometric pressure variations were also recorded.

The data from this second tidal monitoring were also reduced to observed gravity values (through multiplication with the meter calibration constant). No significant barometric pressure variations were observed during the course of the monitoring, so that no correction was made for this factor. The reduced data were again plotted together with values calculated using Longman's (1959) algorithms on a graph depicting changes of gravity with time (shown on Figure 3 on the following page). As a result of comparing the two curves, the values of zero lag time and 1.16 for the conformance factor were presumed to be reasonable, and used in making tidal corrections to the calibrated data (see next section).

D. DATA REDUCTION

The first phase of data reduction at Cerro Prieto was the conversion of raw meter readings into observed gravity values; to do this, the following steps were taken:

(1) The meter readings were multiplied by the appropriate calibration factors (supplied by the manufacturer) for the meters used. This process converted the readings into milligals; values were rounded off to thousandths of milligals, reflecting the expected precision level.

(2) Tidal drift was removed from each of the calibrated values by using computer-generated corrections based on Longman's (1959) formulas; because of the results of the tidal monitoring, a lag time of zero and a conformance factor of 1.16 were used. In late 1981, a small discrepancy in the tide program was discovered. All the Cerro Prieto

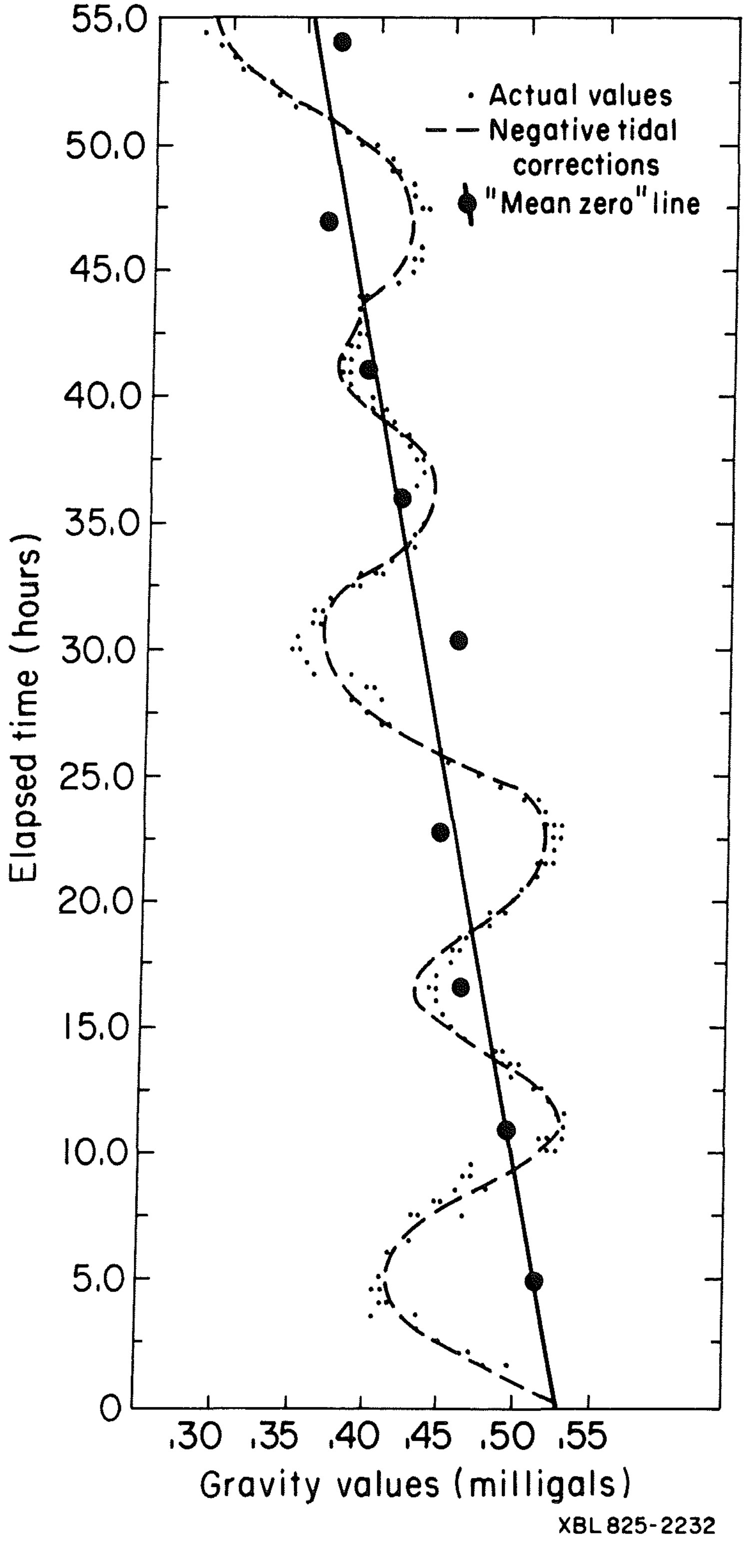

Figure 3. Graphs of tidal monitoring values and tidal corrections. The negative tidal corrections were superimposed on the actual gravity values after construction of the "mean zero" line, a line of zero corrections which is slanted because of drift in the strip chart recorder used for monitoring.

data had already been reduced by this time, but the 1977-78 and 1978-79 data sets were recalculated with the new values. Because this error was usually small in magnitude and could be partially removed with the drift (step (3) below) it had no substantial effect on the magnitude of individual values or on precision. Consequently, the data from later surveys were not recalculated.

(3) Because the tidal corrections did not remove all of the accumulated changes which occurred between base station occupations, additional drift corrections were also employed. For the first three occupations, and about half of the last year, the looping technique of station occupation was utilized, and drift removal for such stations presumed a linear change with time. Thus the nontidal change between the two base station values at the ends of a loop was distributed linearly to all the intervening gravity values. This change is not linear, but a linear approximation resulted in improved data quality. Midway through the last year, a variation on the Roman (1946) method of drift removal was adopted to test its efficacy in improving drift corrections and thus precision; this involves repetition of intervening stations which then act as both stations and auxiliary bases. Figure 4 on the following page is a sample drift reduction carried out for one day's worth of work. The order of station occupation is also indicated on this figure. In essence, several drift curves are constructed

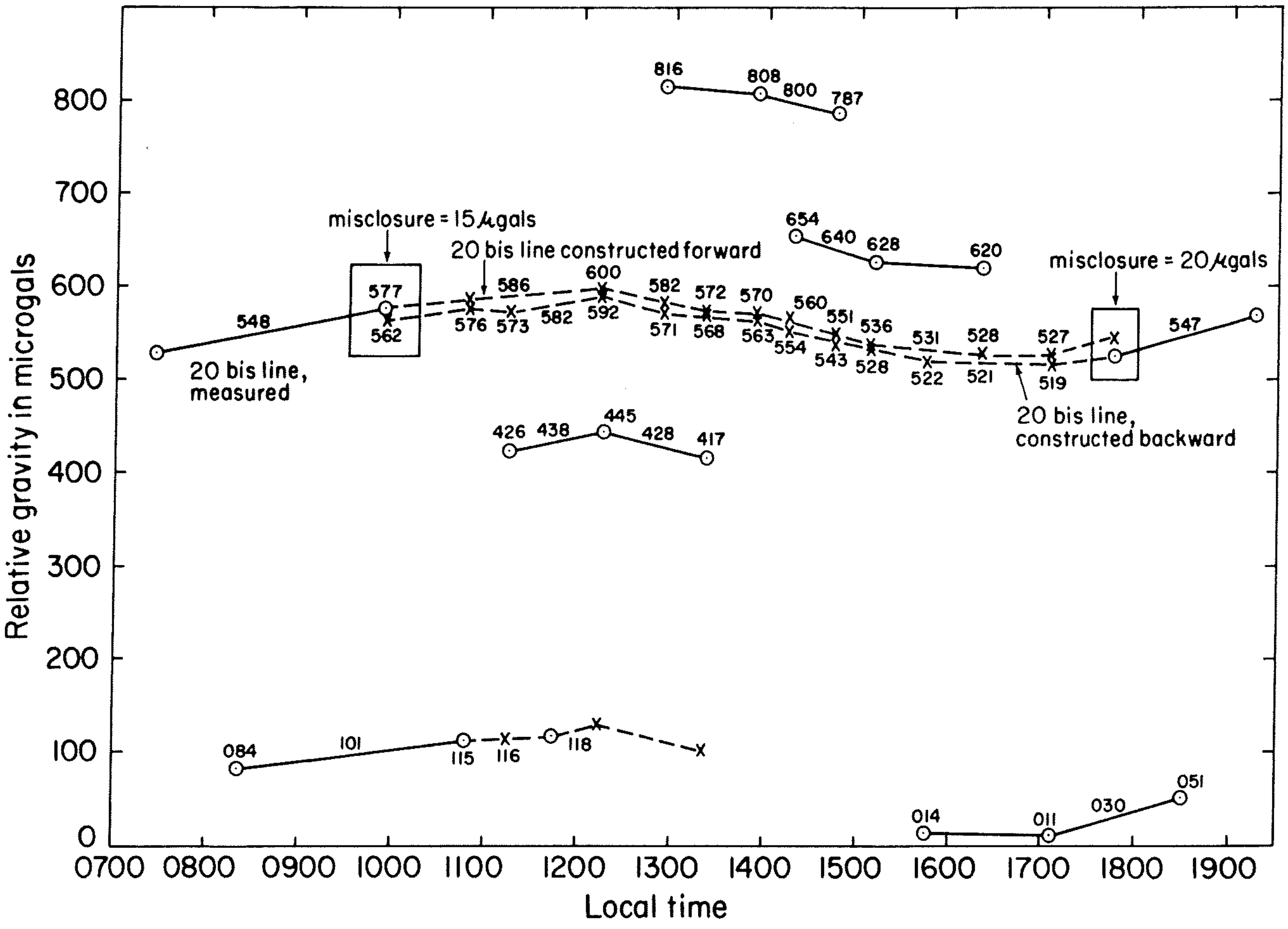

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Figure 4. Sample drift reduction for one day's worth of work. The order of station occupation is also shown.

through segments of the loop; these overlap, and permit integration of drift changes for the entire loop.

Since systematic long-term upward drift in mechanical gravity meters is inevitable and cannot be removed in the reduction process, it was not possible to compare the actual repeated values of gravity taken at any particular station. The crucial parameter, however, is not the gravity value itself but rather the difference in gravity between a station and a selected reference point or base. Consequently, all the station data obtained in each gravity loop were subtracted from the base value established at the beginning of that particular loop, yielding an array of gravity differences which were then comparable. During the first two surveys, station 23 was used for this purpose. Station 20bis was utilized for the third and part of the fourth surveys, while station 20 was used for the remainder of the fourth survey. The result of the subtraction process was a series of individual station values for four different surveys referred to one of three bases. Two further processes were carried out on these values. First of all, the mean values of the multiple-base to station differences for each station in each survey were calculated. Also, to make the data completely comparable, it was necessary to refer these mean values to a common base. Thus, the values referred to stations 23 and 20 were converted to values with station 20bis as a reference by algebraically adding the differences 23 to

20bis and 20 to 20bis respectively. These differences were well-known because of the additional repetitions of the gravity ties which established their values.

The quantity sought as a result of a repetitive gravity survey is a change with time in the differences between the stable reference base outside the producing field and the individual stations. Such changes can only be presumed significant if, among other criteria, the values consistently exceed the possible error or imprecision inherent in the measurement techniques. Consequently, some statistical evaluation is necessary as part of the data reduction process. The following procedures were carried out (and are discussed more fully below): (1) calculation of standard deviations for individual stations; (2) calculation of standard errors for individual stations; (3) calculation of the standard deviation for entire surveys, or parts of surveys, as appropriate; and (4) calculation of the standard errors of stations mathematically referred to station 20bis, when the base station occupied in the field survey was 20 or 23.

(1) The standard deviation for all the replications at a station relative to a particular base was calculated for every station in each survey. The formula used was the following:

$$S = \left[\frac{1}{n=1} \sum_{i=1}^{n} (X_i - \overline{X})^2 \right]^{1/2} ,$$

where S is the standard deviation, n is the number of observations, X_i is an individual reading, and $\overline{X}$ is the mean of the readings for that particular station. The number of replications for an individual station usually ranged from two to four; for a few stations in individual years, only one value could be obtained, and standard deviations could not be calculated.

(2) The standard error for all the replications at a station relative to a particular base was also calculated for every station in each survey. The formula used is given by

$$S.E. = S/\sqrt{n},$$

where S.E. is the standard error, and the other symbols have already been defined in (1) above. This is an estimate of the precision of the mean of the sample rather than of the individual values, at the 68% confidence level. Calculations of twice the standard error yield limits on precision at the 95% confidence limit, and were used as the measure of significance in this paper.

(3) The standard deviation of an entire or partial survey was calculated according to the following formula:

$$S_p^2 = \sum_{i=1}^{K} \sum_{u=1}^{n_i} \left(Y_{iu} - \overline{Y}_i\right)^2 \bigg/ \left[\left(\sum_{i=1}^{K} n_i\right) - K\right] .$$

This is the square root of the pooled variance formula which is used to calculate the variance of a pooled population which has an uneven distribution of data (for instance, varying numbers of replications at the stations occupied). In this formula, S_p is the pooled standard deviation, Y_{iu} is the uth reading at the ith station, Y_i is the mean of the n_i readings at the ith station, and K is the number of stations in the survey.

(4) In the cases where stations were referred in the field to either base 20 or 23, and then referred mathematically to station 20bis, the precision of the final result is a function of the precision of both the individual base-to-station value, and of the base-to-base difference. An estimate of the total precision involved is based on the addition of the squares of the standard errors, as follows:

$$S.E._r = \sqrt{S.E._{bs}^2 + S.E._{bb}^2} \, .$$

Here $S.E._r$ is the standard error of the referred value, $S.E._{bs}$ is the standard error of the base-to-station difference, and $S.E._{bb}$ is the standard error of the base-to-base difference. Since the values added algebraically were the means of these differences, it was appropriate to use the standard errors rather than the standard deviations. Squared values were added (and the square root of the sum utilized) since only variances are additive.

The calculation of the various statistics above allowed an assessment of the quality of the survey, both on an overall basis, and at the individual station level. Some of the data reduction (including statistical analysis) was performed in the field during the third and fourth surveys, when precalculated tidal correction tables were readily available during the field effort. This allowed additional reoccupations of stations characterized by inadequate precision, time permitting. For all four sets of station occupations, the completed reduction process allowed culling of selected imprecise values. This culling was carried out, for the most part, for the first two surveys, when inexperience in the first year led to some data being collected in weather that was hotter than permissible for adequate meter performance, and in both years when lack of adequate transport caused the presence of moderate and, in one case, massive tares!

Rather than rejecting data from loops with tares out of hand, these loops were salvaged by identifying the location of the tare, if stable loops with minor drift containing the same stations were available. Rather than dedrifting these tared loops linearly (which imparts substantial error to all the stations), the tare was treated as a discontinuity. All stations taken prior to the tare were referred to the first base occupation, and all those afterward to the base reoccupation at the end of the loop. No internal drift could be calculated, but even without drift corrections, the resulting data were substantially improved. Indeed, I suspect that drift is a step-like process, and that such steps, when small, can be approximated by linear changes; when large, drift removal compounds the problem rather than solving it.

The reduced and statistically evaluated data are listed on Table I on the following three pages. This table summarizes the complete gravity effort at Cerro Prieto. It presents the mean of the values taken each year at all of the stations, and double the standard error calculated for each mean gravity difference. All of the values have been referred to station 20bis on Cerro Prieto volcano, and the culling process has removed a few imprecise values. Individual values, for which no statistics could be calculated, are indicated by an "S" in the standard error column, and stations which could not be occupied in particular years (because they did not exist, could not be temporarily located, or had been destroyed) are indicated by horizontal lines. In some cases, these latter stations were only occupied in one year, and their values thus have no bearing on an assessment of possible gravity changes at Cerro Prieto. These values are included because they provide some measure of both the impermanence of the monuments established for the gravity works, and the precision maintained throughout the entire research effort.

A statistical table summarizing the precisions typifying the entire gravity survey is presented as Table II following Table I. Included on this table are (1) the range and the median of the individual station standard deviations; (2) the pooled standard deviation value(s) for the annual survey; and (3) the number of values used to calculate the pooled standard deviation values. The values

TABLE I. SUMMARY OF CERRO PRIETO GRAVITY DIFFERENCES AND PRECISIONS IN MICROGALS

Station	First Year	2S.E.	Second Year	2S.E.	Third Year	2S.E.	Fourth Year	2S.E.
1	20,852	18	20,847	11	20,844	6	20,871	16
1bis	19,071	10	19,064	12	19,057	4	19,075	8
2	17,402	11	17,400	11	17,400	1	17,401	10
3	9,844	19	9,815	12	9,802	6	9,824	8
4	13,808	15	13,818	9	13,821	4	13,836	17
5	16,369	8	16,369	11	16,385	2	16,396	14
6	18,696	15	18,706	13	18,705	1	18,751	9
7	19,725	17	19,753	11	19,758	5	--	--
7bis	--	--	--	--	19,777	6	19,828	14
8	21,035	8	21,043	11	21,040	8	--	--
8bis	--	--	--	--	--	--	21,114	7
9	21,479	16	21,499	11	21,502	11	21,544	9
10	20,564	8	20,567	10	20,566	6	20,632	15
11	15,059	7	15,049	11	15,055	3	15,068	7
11bis	18,649	8	--	--	--	--	--	--
12	20,810	13	20,828	12	20,814	0	20,851	26
12bis	21,498	13	21,525	14	21,509	4	21,533	18
13	23,501	7	23,513	12	23,516	10	23,513	21
13bis	24,089	11	24,114	13	24,107	4	24,132	18
14	21,883	13	21,899	10	21,907	8	--	--
14bis	--	--	22,095	15	22,102	8	22,127	7
15	22,633	11	22,647	10	--	0	--	--
15bis	--	--	--	--	22,634	3	22,651	8
16	22,185	16	22,202	11	22,203	1	--	--
17	21,370	10	21,389	9	21,399	13	21,463	18
18	19,605	11	19,640	13	19,618	7	19,674	17
19	17,970	25	17,991	10	17,990	1	18,010	21
19bis	--	--	--	--	17,874	1	17,882	7
20	18,545	20	18,537	11	18,537	10	18,544	7
20bis	000	--	000	--	000	--	000	
21	24,985	10	24,977	12	25,000	3	25,006	21
22	25,396	16	25,399	16	25,406	0	25,402	13
23	21,613	7	21,622	8	21,623	3	--	--

TABLE I. (continued)

Station	First Year	2S.E.	Second Year	2S.E.	Third Year	2S.E.	Fourth Year	2S.E.
23bis	22,301	12	--	--	--	--	--	--
23bisbis	--	--	22,254	11	--	--	22,271	6
24	19,220	13	19,215	11	19,237	4	19,231	7
25	17,500	8	17,487	9	17,502	8	17,501	15
26	15,907	10	15,905	14	15,914	5	15,914	13
27	14,826	10	14,828	11	14,831	6	14,855	17
28	14,259	13	14,265	9	14,273	1	14,279	17
29	14,503	18	14,505	9	14,532	8	14,541	10
30	25,531	15	25,534	11	25,539	5	25,543	8
30bis	--	--	25,103	16	25,107	16	25,124	5
31	24,284	13	24,282	11	24,288	10	24,294	12
32	23,554	8	23,572	14	23,579	7	23,587	16
33	22,621	8	22,629	9	22,650	0	22,671	16
33bis	22,343	7	22,347	14	--	--	--	--
34	18,994	8	19,011	11	--	--	--	--
34bis	--	--	18,903	9	18,919	23	18,966	9
35	16,424	9	16,445	S	--	--	--	--
35bis	--	--	16,404	9	16,426	3	16,443	14
35bisbis	--	--	--	--	--	--	15,974	13
36	13,352	9	13,360	11	13,371	3	13,445	7
37	9,146	11	9,137	9	9,143	3	9,201	23
38	13,178	17	13,205	11	13,212	8	13,258	13
38bis	--	--	12,755	16	12,768	4	12,797	S
39	11,419	33	11,427	11	11,434	5	11,467	10
39bis	--	--	9,307	15	--	--	--	--
40	12,563	7	12,599	11	12,596	5	12,598	15
41	10,160	15	10,158	11	10,142	7	10,234	8
42	16,175	15	16,175	19	16,182	0	16,210	11
43	18,059	11	--	--	--	--	--	--
43bis	--	--	17,930	11	17,919	2	17,942	8
44	16,906	12	16,921	11	16,917	5	16,932	11
45	15,408	7	15,420	14	15,425	6	15,431	8
46	16,789	7	16,804	8	16,799	11	16,821	17

TABLE I. (continued)

Station	First Year	2S.E.	Second Year	2S.E.	Third Year	2S.E.	Fourth Year	2S.E.
47	17,609	20	17,618	19	17,623	12	17,624	7
48	20,658	S	20,648	10	20,646	11	20,644	1
49	27,123	8	27,106	10	27,104	8	27,131	12
50	13,069	8	13,082	9	13,075	5	13,091	9
51	7,763	S	7,811	9	7,811	1	7,792	10
52	11,604	S	11,652	11	11,650	0	11,647	10
53	13,028	S	13,031	11	13,041	0	13,041	11
54	16,991	S	17,000	16	17,000	1	17,020	S
55	19,915	S	19,928	14	--	--	--	--
75	--	--	23,742	12	--	--	--	--
110	--	--	9,307	15	9,323	9	9,327	21
906	--	--	22,796	11	--		--	--
210	--	--	--	--	--	--	11,565	18

NOTE: Station 39bis, measured in the second year, is identical to station 110. This value is thus duplicated twice in the tables.

TABLE II. COMPARISON OF PRECISION VALUES FOR GRAVITY DIFFERENCES AT CERRO PRIETO GEOTHERMAL FIELD

OCCUPATION INTERVAL	APPROXIMATE NUMBER OF OCCUPATIONS	COMMENTS	RANGE	MEDIAN S	S FOR ENTIRE SURVEY
1977-78, winter	75	No transport case, small car, valley base used with G300			7
1977-78, winter	90	No transport case, small car, valley base used with G423			25
1977-78, winter	165	Combined meters, valley base used, no transport case, small car	1-28 1-23*	9 8*	16
1978-79, winter	200	Combined meters, valley base, no transport case, small car	1-17 1-17*	8 8*	12
1979-80, winter	200	G300, volcano base, transport case, medium car	0-16	5	8
1980-81, winter	100	G300, volcano base, small car	1-18	8	11
1981, spring	32	G300, upgraded transport case, volcano base, heavy car	1-15	5	7
1981, spring	6	Base ties on volcano by walking, meter stabilized overnight, G300			8

Note: All values in the 3 columns to the right are in microgals. Last column was computed by the pooled variance calculation for all the values in the survey; other two columns contain values calculated by comparing the standard deviations of the individual stations, asterisks indicate values remaining after rejection of extremes.

are given for both culled and unculled data. Comments are also listed in a separate column, as appropriate, so that identifiable factors affecting the precision could be included.

One final reduction process which was carried out was the reduction of the observed gravity values to Bouguer anomalies. This process was performed on the unculled means of the values obtained during the first year, in conjunction with the leveling data and an available small-scale topographic map. The free-air, latitude, and Bouguer corrections were applied, the latter using a density value of 2.67 gm/cm (approximately the density of granitic rocks underlying station 1 in the Cucupa Mountains). Because of the flat topography, terrain corrections were not made. Thus, some error (not exceeding 2 mgals) can be expected for the bedrock stations located in topographically steep areas. Some valley stations were located adjacent to, or on, dikes located along the canal network, and the lack of terrain corrections in these instances could reach error values as large as .15 mgal. In both cases, the resulting Bouguer anomaly value would be too small. The anomaly values have been contoured at a 1 mgal interval (Figure 5 on the following page); for convenience in preparing the figure, station 1 was arbitrarily assigned a value of zero mgal, and all station values were referred to this station. The Bouguer values are tabulated in Table III, on page 33.

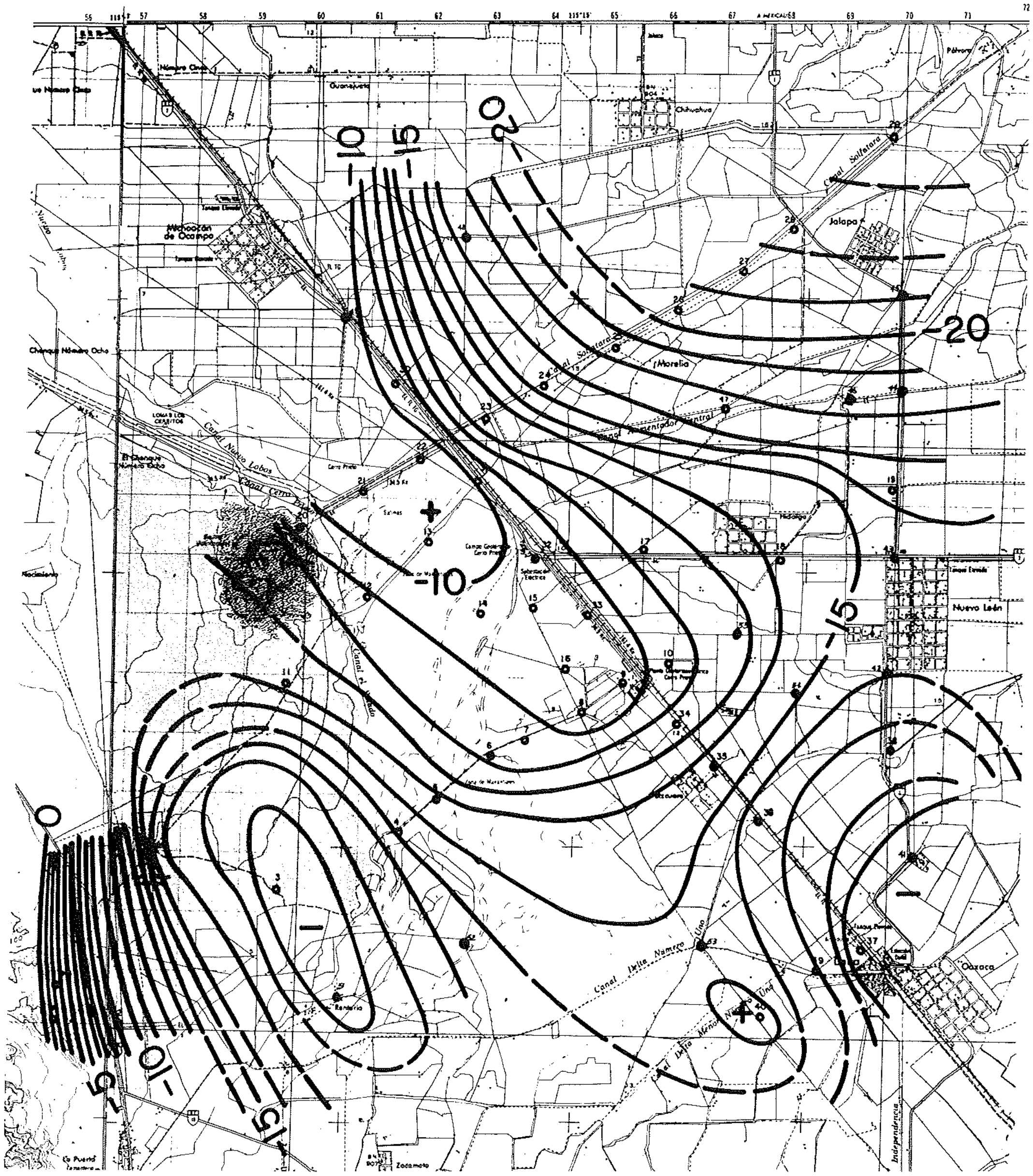

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Figure 5. Bouguer anomaly map of the Cerro Prieto geothermal field. Contour interval is 1 mgal. All values are referred to station 1 in the Sierra Cucupa (southwest corner of map).

TABLE III. CERRO PRIETO BOUGUER ANOMALY VALUES

STATION	ELEVATION (IN METERS)	LATITUDE (IN DEGREES)	LONGTITUDE (IN DEGREES)	BOUGUER ANOMALY VALUES (IN MGALS, RELATIVE TO STATION 1	BOUGUER ANOMALY VALUES (IN MGALS, ABSOLUTE)
Mexicali	8.699	32.615	115.439	-23.59	-57.4
1	46.516	32.348	115.343	0.00	-33.8
1bis	56.201	32.354	115.342	-0.38	-34.2
2	20.066	32.348	115.330	-8.66	-42.5
3	13.932	32.368	115.304	-19.05	-52.9
4	13.262	32.378	115.282	-16.05	-49.9
5	12.065	32.383	115.274	-14.13	-47.9
6	12.533	32.389	115.265	-11.98	-45.8
7	12.232	32.391	115.258	-11.42	-45.2
8	10.969	32.397	115.248	-10.85	-44.7
9	9.698	32.401	115.241	-10.94	-44.7
10	10.645	32.403	115.232	-11.61	-45.4
11	26.837	32.400	115.302	-13.94	-47.7
12	15.268	32.413	115.288	-11.56	-45.4
12bis	12.623	32.413	115.288	-11.40	-45.2
13	15.033	32.421	115.276	-9.56	-43.4
13bis	12.614	32.421	115.276	-9.44	-43.2
14	12.427	32.411	115.267	-10.83	-44.6
15	11.214	32.411	115.258	-10.34	-44.1
16	9.753	32.402	115.251	-10.37	-44.2
17	11.531	32.420	115.238	-12.29	-46.1
18	10.736	32.418	115.213	-14.06	-47.9
19	11.700	32.429	115.193	-16.42	-50.2
20	37.575	32.424	115.299	-10.29	-44.1
20bis	89.520	32.420	115.302	-18.32	-52.1
21	11.052	32.429	115.288	-9.48	-43.3
22	11.476	32.434	115.277	-9.36	-43.2
23	13.533	32.440	115.267	-13.31	-47.1
23bis	10.723	32.440	115.267	-13.17	-47.0
24	13.438	32.446	115.255	-16.14	-49.9
25	14.005	32.451	115.242	-18.23	-52.0
26	14.274	32.457	115.231	-20.25	-54.1
27	14.330	32.462	115.220	-21.74	-55.5
28	14.458	32.469	115.210	-22.81	-56.6
29	14.867	32.484	115.193	-23.68	-57.5
30	9.670	32.445	115.283	-10.53	-44.3
31	12.361	32.430	115.268	-10.04	-43.8
32	9.979	32.419	115.258	-10.68	-44.5
33	9.831	32.410	115.247	-10.69	-44.5
34	10.318	32.394	115.232	-12.79	-46.6
35	11.854	32.386	115.225	-14.42	-48.2
36	12.694	32.379	115.217	-16.72	-50.5
37	10.404	32.359	115.198	-19.73	-53.5
38	13.463	32.390	115.195	-17.59	-51.4
39	12.957	32.356	115.206	-16.72	-50.5
40	13.275	32.349	115.216	-14.95	-48.8

TABLE III. (continued)

STATION	ELEVATION (IN METERS)	LATITUDE (IN DEGREES)	LONGTITUDE (IN DEGREES)	BOUGUER ANOMALY VALUES (IN MGALS, RELATIVE TO STATION 1	BOUGUER ANOMALY VALUES (IN MGALS, ABSOLUTE)
41	11.933	32.373	115.190	-19.61	-53.4
42	12.099	32.403	115.194	-15.93	-49.7
43	11.900	32.419	115.190	-15.46	-49.3
44	13.079	32.443	115.192	-18.29	-52.1
45	13.283	32.459	115.194	-21.05	-54.9
46	13.079	32.444	115.202	-18.54	-52.3
47	12.679	32.443	115.223	-17.66	-51.5
48	10.919	32.469	115.272	-17.09	-50.9
49	10.271	32.455	115.292	-9.76	-43.6
50	12.288	32.375	115.323	-16.74	-50.5
51	13.597	32.353	115.292	-19.98	-53.8
52	13.268	32.361	115.269	-16.82	-50.6
53	12.975	32.361	115.226	-15.45	-49.3
54	12.054	32.399	115.212	-14.85	-48.7
55	12.497	32.408	115.220	-12.56	-46.4

E. DISCUSSION OF RESULTS AND INTERPRETATION

Three facets of the reduced data need further discussion; these are (1) the Bouguer anomaly values; (2) the precision attained in the survey, and (3) the temporal changes in gravity which were observed.

(1) The results of the Bouguer anomaly data reduction are shown on Figure 5. This map shows several distinct anomaly patterns. The most prominent feature on the gravity map is a northwesterly trending gravity high with 5 to 10 mgals of expression relative to adjacent negative anomalies. As noted by other workers, the Cerro Prieto geothermal field is located near the southeasterly termination of this high, which has been interpreted by Puente (1978) as a basement horst bounded by faults with several hundred meters of vertical displacement. Alternately, this positive gravity feature could be partially or wholly attributed to significant densification of reservoir rocks due to hydrothermal alteration from geothermal fluids, such as that documented by Elders and others (1978), and the interpretations of Wilt and others (1978) for several Schlumberger and dipole-dipole resistivity profiles show no necessity for a highly resistive basement uplifted into horst. To the northeast, southeast, and southwest of the gravity high are areas of low gravity, presumably located over thickened alluvial and deltaic deposits located in fault-controlled troughs. The depression to the southwest is bounded on the west by the Sierra Cucupa, a mountain range of uplifted, relatively dense granitic rocks (a southerly continuation of the Peninsular Ranges batholithic structures); a steep gravity

gradient (15 mgals/km) characterizes this nearly vertical, fault-controlled boundary between alluvial fill and exposed basement rocks. A gradient this steep is nowhere else repeated on the Bouguer anomaly map, although moderate gradients (6 to 7 mgal/km) of the same trend bound all three flanks of the gravity high. These northwesterly trending graduents are associated with the Cucupa, Cerro Prieto, and Imperial faults, from west to east, respectively; these are shown on Figure 1 on page 2.

Puente (1978) has identified a second set of faults, called the Volcano system, which trend normally to the above-mentioned major faults. One of these has been identified as passing through the area of Cerro Prieto volcano. This fault, however, bounding a posulated pull-apart basin (see Figure 1), has no significant gravity expression, probably because of the lack of notable vertical displacement coupled with obliteration of its expression by the prominent subsurface hydrothermal alteration. Cerro Prieto volcano itself lacks any significant gravity expression, due to (a) few values on and around its vicinity, (b) lack of terrain corrections on the volcano itself, and (c) masking of its values by the gradient bounding the west flank of the gravity high. If information about anomalous masses in the volcano were needed, a detailed gravity survey in its vicinity, coupled with regional-residual separation and suitable mathematical filtering techniques, would have to be performed. A more significant northeast-trending gravity feature is the abrupt termination of the gravity high south of the Cerro Prieto geothermal field, between the power plant and the town of Delta. Presumably, this feature is another "fault" of the Volcano system, which is expressed as the southern boundary of the pull-apart basin mentioned previously. If hydrothermal alteration defines both positive gravity values and possible future production zones, then areas south of this postulated pull-apart basin might be unfavorable for future development. However, the lobe-like southerly extension of the gravity high west of Delta and Oaxaca could be a promising target area.

One final distinctive anomaly pattern is the change in direction of isogal anomaly lines from northwest to east-west in the northeast corner of the Bouguer anomaly map, near the town of Jalapa. The contour lines, which become more negative to the north, probably define an area of deeper sedimentary fill. However, the reason for the orientation change to an anomalous direction is unknown.

(2) Estimates of the precision of the annual gravity surveys are indicated on Tables I and II. These two tables are apparently inconsistent in their values; the discrepancy exists because Table II contains measured values with standard deviations to the appropriate base station, whereas Table I contains values which have all been mathematically referred to a single base (20bis), and precisions are listed in terms of twice the standard error. The values in Table II are thus at the 68% confidence level, and indicate the estimated precision for the mean gravity differences. There are also variations from year to year shown on both tables. The measured precisions on Table II include both culled and unculled values, and the changes in value also reflect the type of vehicle used, the introduction of the transport case, and the particular reference

base station occupied. In general, precision increased as values were culled, experience was gained, a heavier car was utilized, and the transport case was implemented and then improved; precision deteriorated, however, as the valley base (23) was abandoned and 20bis and 20 were employed instead. On Table I, the variations in precision come about primarily as the contrast between referred stations versus directly measured stations. For the first and second years, the higher standard error values reflect the fact that all the stations were measured relative to base 23; to convert to 20bis, the differences between the two had to be added, and the double standard error values for these two mean differences were 7 microgals for the first year and 8 microgals for the second year. In the third year, all of the measurements were made relative to station 20bis with a larger car and transport case, and the standard error values are consequently much lower. In the fourth year, station 20 was partially used, and the difference between 20 and 20bis was characterized by a 7 microgal double standard error. Also, many fourth year station means included only two or three repetitions, which increased standard error values. Consequently, the precision of measurement, after culling of values, averaged 7 to 11 microgals for all four years, with a range from 0 to 19 microgals. The double standard error values ranged from 0 to 33 microgals, with median values of 11, 11, 5, and 11 microgals for the first, second, third, and fourth years respectively.

From these data, it is clear that referring data to one base while measuring directly to another does cause a reduction in data quality. This can be offset by establishing the difference between the two bases especially well (with about 30 repetitions); this reduces the double standard error value to about 2 microgals, and the effect of a second base will then become negligible, and particularly when combined with larger standard deviation values. An alternate method for maintaining precision at Cerro Prieto is to use a large car and continue the use of 20bis. A third tactic which could be employed is to use both volcano bases, as appropriate; the difference between the bases can be bypassed if individual stations in later years are always measured with respect to the same base (either 20 or 20bis) as that to which they were originally referred. In looking for significant changes in the gravity differences with time, the particular base won't matter, provided that the difference between the two stations does not itself change with time. So far, the reported means between these two base stations for all four years lie within a range of only eight microgals, and no systematic variation can be seen in these values. Consequently, the relative difference between 20 and 20bis appears to be constant with time, and the third procedure discussed above could be employed.

The Roman method did not apparently affect precision significantly for the better, probably because at the microgal level, drift is no longer linear. The use of Roman's method (1946) requires extra occupations of stations which serve only to control drift and cannot be used as independent measurements. The time spent using this method would be better spent taking extra independent values for less precisely measured stations, at least under the conditions prevailing at Cerro Prieto. It is probably essential that at least four separate occupations be made at each station, to enhance the double standard error values, and this is a higher priority than a marginal improvement in individual occupation values by a method such as Roman's.

(3) Marginal to significant temporal gravity variations at Cerro Prieto have been observed. The most important set of changes seen to date is that associated with the Victoria earthquake of late spring, 1980. These changes (referred to station 20bis) are plotted on Figure 6 on the following page, and consist of the variations in gravity which occurred between the third and fourth repetitions (1979-80 and 1980-81). The most substantial changes are in the southeastern section of the geothermal field, where changes greater than 80 microgals were observed, but significant changes also are found in the older part of the field, between the power plant and Cerro Prieto volcano. The pattern of the gravity changes shows a spatial association with both the geothermal field and two of the faults in the area, the Cerro Prieto fault and the Hidalgo fault; the association with the Cerro Prieto fault is more pronounced, in that the fault separates a zone of no apparent change to the west from the prominent changes to the east. This separation is, however, somewhat artificial, in that the magnitude and sign of the observed anomalies are partially a function of the reference base chosen. The present map indicates positive values (consistent

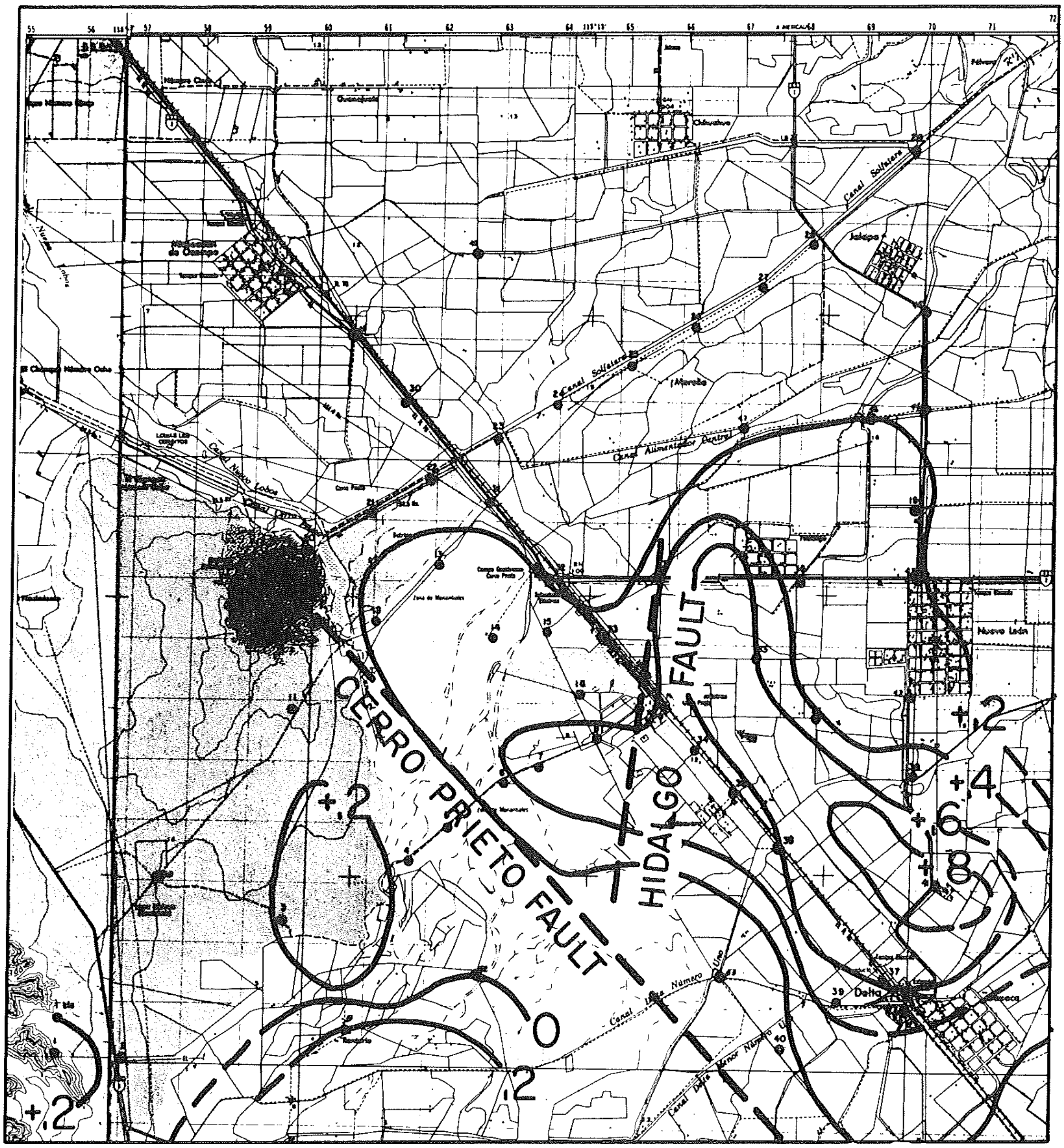

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Figure 6. Gravity changes at the Cerro Prieto geothermal field between the 1979-80 and 1980-81 repetitions, believed to be associated with the 1980 Victoria earthquake. Numbers indicate tens of microgals; contour interval is 20 microgals. All values are referred to station 20bis on Cerro Prieto volcano.

with subsidence) of 80 microgals and more, and positive values (consistent with uplift, and observed in the western and southwestern parts of the map) of more than 20 microgals. Had stations 1 and 1bis in the Sierra Cucupa been used as the reference bases instead, much of the area could be interpreted as having subsided, but not Cerro Prieto volcano. This distinction concerning reference bases is crucial, since it affects one's preceptions concerning the nature of the subsidence.

Three possible mechanisms could account for the observed subsidence in the Cerro Prieto area: (1) liquefaction and consolidation of surficial material; (2) collapse at depth of layers from which geothermal fluids have been removed and which have not been fully recharged; and/or (3) tectonic subsidence due to widening of the Salton trough both seismically and aseismically. The first alternative was favored by many workers after the Victoria earthquake, but I believe substantial components of subsidence came from mechanisms (2) and (3) as well, and that collapse of geothermal layers may be the most dominant mechanism. The reasons for this lie predominantly in the pattern of ground deformation, and its relationship to the production zones of the geothermal field. The pattern shows an apparent closure in the direction of the epicentral region of the earthquake, although this pattern is not as closely controlled as it should be. Unless there is a marked change in surficial lithology to the southeast, with more competent beds prevailing, the deformation should increase in that direction (rather than decreasing, as it appears to do). Furthermore, production of the field should have produced more subsidence than has been observed to date; gravity changes between the first and second, and second and third repetitions are only marginally significant, small in value, and not necessarily spatially associated with the field. It appears from electrical resistivity changes (Wilt and others, 1981) that the field is being recharged to a certain extent by supposedly colder but more saline waters, which yield lower resistivities on the flanks of the producing zones. However, some of the wells have now undergone some boiling, indicative of a pressure drop and lack of full recharge. The geothermal reservoir is located in metamorphosed, dense materials which might not subside immediately upon removal of buoyant support because of inherent strength in the rock layers; subsidence might instead be triggered by seismic activity.

I feel that there is also a tectonic component to the subsidence. If the Sierra Cucupa can be presumed to be stable, then nearly all of the valley in the vicinity of the Cerro Prieto field east of the Cerro Prieto fault underwent subsidence; the area west of this fault either underwent no change, or was uplifted. There was a relative change of 20 to 30 microgals between the Sierra Cucupa and Cerro Prieto volcano, with the volcano becoming relatively more negative, indicating uplift. If this uplift is real, the most logical cause is tectonic activity. The same kinds of changes are seen in the second order level data obtained from CFE and summarized on Table IV.

TABLE IV. CHANGES IN ELEVATION (IN MM) AT CERRO PRIETO GEOTHERMAL FIELD

STATION	CHANGE, 1977-79	CHANGE, 1979-81	TOTAL CHANGE, 1977-81
1	-17	+67	+50
1bis	-24	+74	+50
2	-7	+65	+58
3	+19	+62	+81
4	+28	+49	+77
5	+19	+12	+31
6	+4	-37	-33
7	-3	-160	-163
8	-15	destroyed	---
9	-31	-132	-163
10	-15	-186	-201
11	+38	-60	-22
12	+23	-32	-9
12bis	+22	-22	0
13	+14	-13	+1
13bis	+3	-3	0
14	+8	-61	-53
15	+27	rebuilt	---
16	+14	-91	-77
17	+14	-240	-226
18	+16	-167	-151
19	+4	-49	-45
20	+25	+29	+54
20bis	not measured, 1979		+158
21	+28	+22	+50
22	+25	+26	+51
23	+9	destroyed	---
23bis	+26	+10	+36
24	+4	+2	+6
25	-7	-1	-8
26	+6	+18	+24
27	+5	-11	-6
28	-7	-6	-13
29	-2	-33	-35
30	+21	+17	+38
31	+35	+15	+50
32	+20	-67	-47
33	+10	-91	-81
34	rebuilt	-168	---
35	rebuilt	-162	---
36	-5	-254	-259
37	-13	-257	-270
38	-9	-101	-110
39	+2	+40	+42
40	-155(?)	+80	-75
41	-11	-128	-139
42	+16	-72	-56
43	destroyed	---	---
44	+15	-42	-27

TABLE IV. (continued)

STATION	CHANGE, 1977-79	CHANGE, 1979-81	TOTAL CHANGE, 1977-81
45	+9	-27	-18
46	+19	-71	-52
47	+13	-36	-23
48	+16	+5	+21
49	+24	+16	+40
50	+16	+93	+109
51	+48	+38	+86
52	+30	+29	+59
53	+16	+26	+42
54	+6	-173	-167
55	-12	destroyed	---

The tabulated elevation changes are difficult to compare directly with the gravity changes, since they are referred to a different base station, and this elevation base appears to be subsiding relative to Cerro Prieto volcano; from 1977 to 1979, station 20 became (relatively) 25mm higher, and from 1979 to 1981, another 29mm higher. It was not possible, with available information, to convert the elevation changes to become relative to 20 or 20bis; however, some trends in spite of this difficulty can be observed. The relative change upward of the volcano relative to the Sierra Cucupa can be seen (in 1980), as can the subsidence over much of the geothermal field. Perhaps only larger trends of this type will ever be observed in the elevation data, since there is a question of data quality at some of the farther stations, most notably at station 20bis, which changed (apparently) some 10cm with respect to station 20 over a four year interval; this is in contradiction to the gravity data, which indicate no significant change at all. Until problems with the elevation data are reconciled, low magnitude changes cannot be either recognized or trusted.

The Victoria earthquake created large enough gravity changes in the Cerro Prieto area that subsidence from geothermal production cannot be recognized in the data from the third gravity repetition conducted in early 1981. Such changes must be sought in previous years, and apparently can be recognized. For the most part, no significant variations can be recognized on an annual basis (since they are quantitatively small), but if one compares the gravity values taken in early 1978 with those taken in the winter of 1979-80 nearly two years later, then small positive changes, only a little larger than the level of significance at the 95% confidence interval, become apparent at several stations. From north to south, these occur at stations 21, 13, 17, 14, 33, 9, 7, 38, and 36 - refer back to Figure 2 on page 9. These stations are not completely contiguous, but intervening stations (such as 15, 16, 8, 32, 34, and 35) all had problems either of larger standard error values masking possible changes, or of station destruction with some determining values lacking. In general, the observed changes over a two year interval averaged 15 to 30 microgals, all in a positive (subsiding) sense. Most of the stations with significant changes also showed some consistency in undergoing small positive changes each year, becoming gradually larger, and this tendency was often repeated at the intervening stations which lacked significant changes.

The pattern of gravity changes over the two year interval described is approximately elliptical, with the major axis oriented in a northwest-southeast direction. The outline of this area is shown on Figure 7 on the following page. The orientation indicates the possibility of some structural control, due to alignment (but not coincidence) with known northwesterly trending faults; there may be an anisotropy of permeability which precludes much recharge parallel to the structural grain. Within the limits of precision, no subsidence can be inferred outside the zone marked on Figure 7. Since the precision of the gravity survey is on the order of 16 to 20

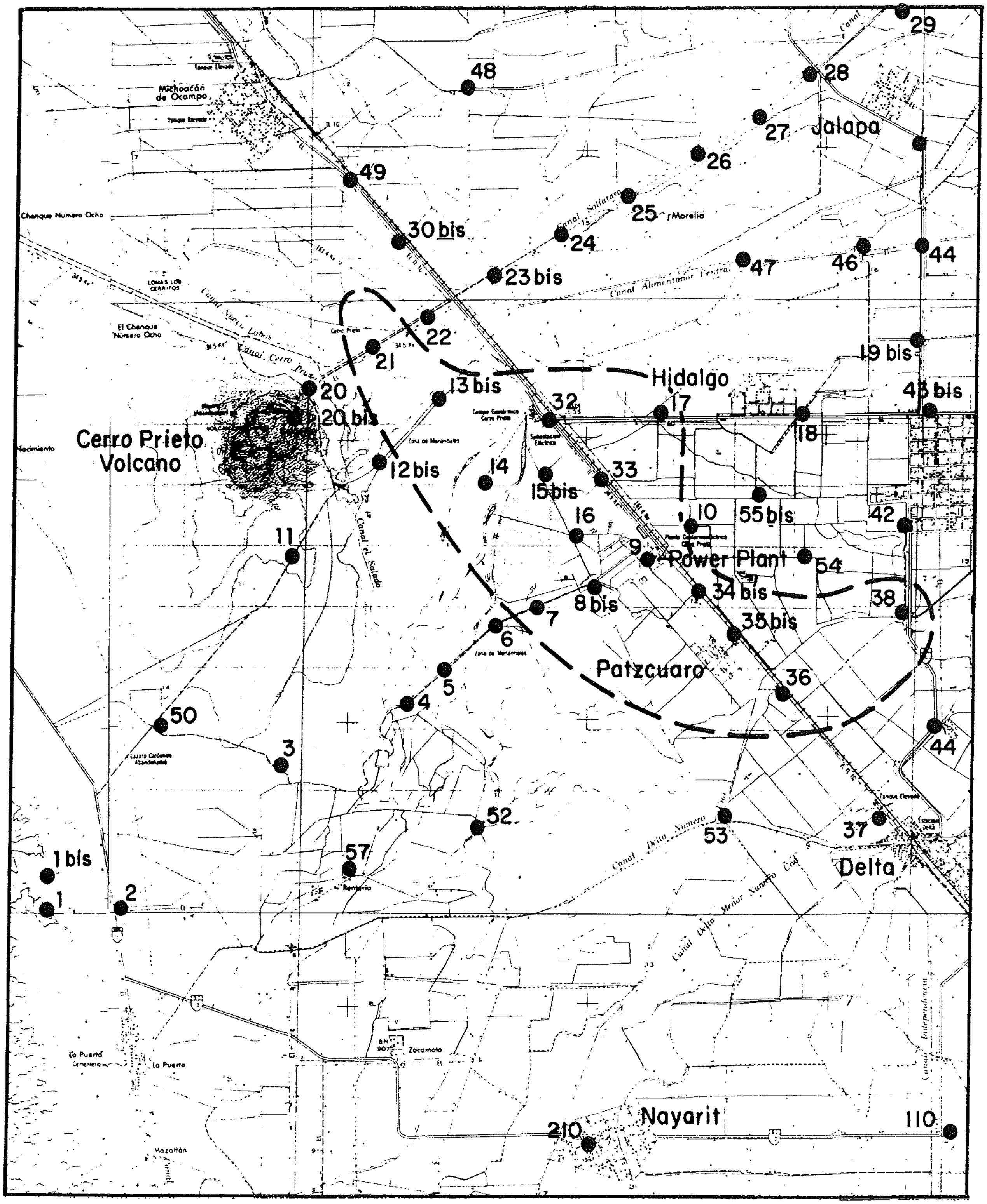

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Figure 7. Area of significant geothermally induced positive gravity changes at Cerro Prieto. The dotted line depicted on the map is not a contour line, but rather a boundary of the subsiding area. Significant values within the bounded area range from +15 to +34 microgals, and all the changes are positive. The changes occurred between spring 1978 and spring 1980.

microgals when two gravity differences are compared, major net changes in mass and elevation due to production are precluded outside the outlined area. The concept of no significant gravity variations in these "outside" regions to the east and the west is consistent with the model proposed by Wilt and others (1981) for resistivity changes in these same areas; their model suggests recharge of colder, more saline water to explain decreases in resistivity. Although the origin of such water is somewhat difficult to explain, three sources are possible:

(1) Dewatering of shale or clay beds has been observed in areas of groundwater withdrawal, and has been proposed as a mechanism in geopressured geothermal areas (Samuels, 1979). This water is enriched in electrolytes, and thus is highly saline.

(2) Connate water of originally high salinity trapped in stagnant aquifers in structural depressions (such as that seen on the Bouguer anomaly map, Figure 5, and located west of the geothermal field) could be drawn out as pressures decrease in the production zone. Waters of above normal salinity currently exist in certain lagoonal areas in Baja California (P. J. Fritts, personal communication), and are likely to have existed in the past, becoming more saline upon burial and stagnation. The observed salinities for inner lagoon waters range from 40 to 80 parts per thousand, with an average of about 50 parts per thousand.

(3) The Colorado River has become increasingly more saline during the last several decades (from continued use and reuse

upstream), with values as high as 80 ppt observed locally. Slow migration of this water would result in further salinity increases with time.

The northeastern part of the gravity survey area, near the town of Jalapa, also appears to have subsided. At stations 29 and 45, significant changes occurred between early 1978 and 1980, perhaps associated with the October, 1979 Mexicali earthquake. These two stations are located closer to the Imperial Fault (which broke as far north as Brawley) than other parts of the field. Neither station underwent significant subsidence during the Victoria earthquake the following year.

The term "significant" has been used extensively in preceding paragraphs. With regard to the gravity data, three criteria were sought in estimating significance: (1) changes whose magnitude exceeded the combined precisions of values from the two individual data which were compared for particular stations; (2) those which were generally observed at several adjoining stations; and (3) changes which were consistent in sign for several adjoining stations. The gravity variations discussed in this section have all met these criteria.

IV. SANTA ANA MOUNTAINS CALIBRATION LINE

A calibration line to support the gravity work in the Salton trough was established in the Santa Ana Mountains of southern California (east of the town of San Juan Capistrano) to solve three basic problems: (1) three gravity meters were used during the course of the Salton trough surveys, and two of these were miscalibrated (each yielded precise values when replicated, but the gravity differences each measured were not comparable); (2) the Salton trough gravity network could potentially be repeated over many years, during which interval new meters might be introduced, or the original ones might become characterized by changed calibration constants; and (3) the calibration constants provided by the manufacturer not only can cause slight miscalibration problems, but only operate at 100 milligal intervals, whereas variations of lesser magnitude may typify meter behavior.

Normally, a calibration network would be established in the vicinity of the gravity survey it was meant to support. However, the overriding considerations in choosing an appropriate area are that it be stable (so that the gravity differences among the stations in the network do not change with time) and that it occupy the same range of gravity values as the survey itself. This latter criterion could not be met in close proximity to the Salton Trough region, either in the Coast Ranges to the west, or to the east in the bedrock areas adjacent to the Arizona border. The elevations in the Salton trough are low enough, and the crust beneath it dense enough, that the bedrock densities in adjoining areas do not raise the gravity values sufficiently, in spite of the thick, low-density sediments filling the trough. Consequently, a calibration area had to be sought farther north where increasing latitude coupled with granitic basement densities raised the gravity to appropriate values. Although no area in California may be completely stable over time intervals exceeding hundreds of years, due to ongoing tectonic activity, it was felt that the bedrock portion of the Santa Ana Mountains between the Elsinore and the Cristianitos-Aliso fault systems would be suitable. The area proved to be in range with the Salton trough (unlike a previously established calibration loop in the San Jacinto Mountains), was easily accessible to the author's headquarters, and its location on the coastal-facing slopes of the Santa Ana Mountains provided a mild climate for year-round occupation. Aside from extensive weekend traffic, restricting favorable measurements to weekdays, and the presence of a one-mile long dirt segment which could cause unfavorable local transport conditions, the area seemed very suitable for a permanent, stable gravity network.

Eight stations were established at permanent markers along the Ortega Highway (California Highway 74) and connecting spur roads in Cleveland National Forest in May and June of 1980; the locations are shown on the index map (Figure 8 on the following page). Three of the stations were located on concrete bench marks with large concrete piers, three on permanent stonework, and two on bedrock outcrops.

The two LaCoste and Romberg gravity meters which were used to establish the Heber gravity network, G300 and G465, were also utilized for the calibration loop. The Canadian

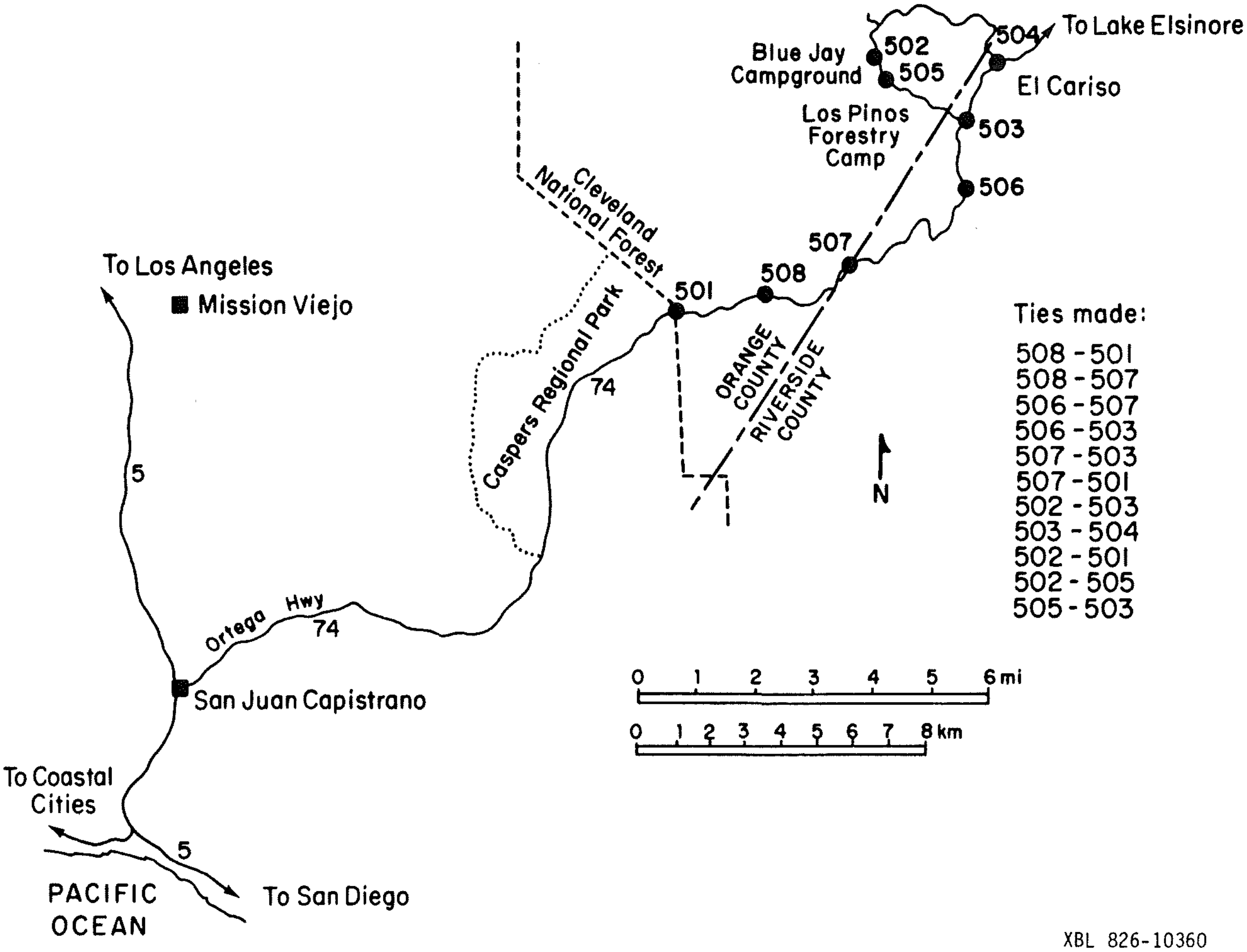

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Figure 8. Location map and gravity tie sequence, Santa Ana Mountains calibration line.

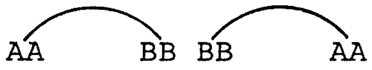
tie technique was used, with ties established linearly up the Ortega highway, so that all adjacent stations were connected by sets of ties, usually eight per gravity meter between each two adjacent stations. In addition, the last station (number 502) was tied directly back to the first and lowest elevation station (number 501). Finally, three additional sets of cross-ties were made as a precision check, which resulted in a chain of three sets of interlocking triangles. The eleven sets of ties which were established are shown on Figure 8 and on Table V(p.57). A sequence of station occupation for a triangle is depicted in the three lines below, in which each separate letter represents a station, and its repetition indicates the number of replications; each horizontal line represents one set of ties, and each tie is the difference between the means of two adjacent values for two stations, e.g., (B+B)/2 - (A+A)/2), using the values between adjacent slashes:

AA BB/BB AA/AA BB/BB AA/AA BB/BB AA/AA BB/BB AA
BB CC/CC BB/BB CC/CC BB/BB CC/CC BB/BB CC/CC BB
CC AA/AA CC/CC AA/AA CC/CC AA/AA CC/CC AA/AA CC

Both the large number of ties and the extra replications were designed to enhance precision; indeed, when data were inconsistent in the field, extra replications or extra ties were performed.

The stations in the network were located as few as 10, and as many as 30, milligals apart, but most of the stations were 20 milligals apart; the total range was 154 milligals, which greatly exceeded the 40 milligal range found for the data set taken in the Cerro Prieto and Heber region, and also encompassed the bedrock stations in the Coast Ranges and Cargo Muchacho Mountains. For the most part, the Salton trough gravity values are concentrated near the lower end of the calibration network range, so that substantial upward drift for many years should not take the meters out of range.

The collected data were reduced to observed gravity values by the standard procedures discussed earlier in this paper. Gravity differences were then calculated, using mean values of replications according to the formula presented on the previous page. This technique treated the four usual replications at an intermediate station as belonging half to the previous station, and half to the next station, so that the values were partitioned before means and differences were obtained. Thus, two ties could be obtained from the three station occupations depicted below, as indicated:



Some drift removal was attempted, but the noise sources are apparently erratic, and drift corrections did not improve the precision. The mean and the standard deviation of all the differences were then obtained for a set of ties. These data were examined, and if an individual datum was more than either two standard deviations, or, in some instances, 20 microgals from the mean, it could be rejected or culled. This process had to be restricted to clearly extreme values, however, since excessive rejection in poorer quality data sets may not improve the standard error, unless great improvement in the standard deviation offsets the decreased number of values. Rejection of more than two values was thus not permitted except in two instances where the data set was larger than normal. New means and standard deviations were calculated from the revised data sets (following rejection), and single and double standard errors were then obtained; the latter, expressing a value within whose limits the mean has a 95% chance of ocurring, is used as the level of significance for the reduced data.

The data are presented on Table V on the following page. This table is a summary of the mean reduced values obtained for both gravity meters, and shows the means, standard deviations, number of values used in the standard error calculations, and the single and double standard error values for all the ties retained; no rejected data are included. In addition, the directly measured cross-ties are compared with the individual added legs which make up the alternate routes of arriving at more distant stations (for instance,the direct measurement from 501 to 502 is compared with the sum of the individual ties 501-507, 507-503 and 503-502). This comparison provides a check on the precision, in that the difference between the two final values should lie (with 95% confidence) within the combined double standard error values for the two routes. Standard errors of summed legs were obtained by calculating the square root of the summation of the squares of individual

TABLE V. SUMMARY OF CALIBRATION DATA, SANTA ANA MOUNTAINS

STATION TIE	METER INTERVAL G300 (MILLIGALS)	G300 VALUE & S.D. (MICROGALS)	NO. OF VALUES	S.E. (MICRO-GALS)	2x S.E.	METER INTERVAL G465 (MILLIGALS)	G465 VALUE & S.D. (MICROGALS)	NO. OF VALUES	S.E. (MICRO-GALS)	2x S.E.
508-501	3249-3270	20,866± 5	8	1.8	3.5	3182-3203	20,875±11	8	3.9	7.8
508-507	3249-3230	19,147± 6	8	2.1	4.2	3182-3163	19,159± 9	9	3.0	6.0
506-507	3199-3230	30,504± 6	8	2.1	4.2	3132-3163	30,488± 8	7	3.0	6.0
506-503	3199-3177	22,027± 9	8	3.2	6.4	3132-3110	22,074± 7	5	3.1	6.2
507-503	3230-3177	52,523± 5	7	1.9	3.8	3163-3110	52,542±18	6	7.4	14.7
507-501	3230-3270	40,002± 6	6	2.4	4.9	3163-3203	40,028±11	8	3.9	7.8
502-503	3116-3177	61,756± 6	8	2.1	4.2	3048-3110	61,755±13	8	4.6	9.2
503-504	3177-3167	10,079± 7	7	2.6	5.3	3110-3100	10,051±11	10	3.5	7.0
502-501	3116-3270	154,284± 7	8	2.5	4.9	3048-3203	154,326±12	6	4.9	9.8
502-505	3116-3136	20,362±10	6	4.1	8.2	3048-3069	20,323±10	6	4.1	8.2
505-503	3136-3177	41,405±10	8	3.5	7.1	3069-3110	41,436±16	6	6.5	13.1

COMBINED TIES, G300*

Combined Values (Microgals)	Ties	Direct Values (Microgals)	Tie
40,013± 5	507-501 ↓ +501-508	40,0002± 5	507-501
52,531± 8	506-507 +506-503	52,523± 4	507-503
61,767±11	502-505 +503-505	61,756± 4	502-503
154,281± 8	507-501 +507-503 +502-503	154,284± 5	502=501

COMBINED TIES, G465*

Combined Values (Microgals)	Ties	Direct Values (Microgals)	Tie
40,034±10	507-501 ↓ +501-508	40,028± 8	507-501
52,562± 9	506-507 +506-503	52,542±15	507-503
61,759±15	502-505 +503-505	61,755± 9	502-503
154,325±19	507-501 +507-503 +502-503	154,326±10	502-501

* Values reported for precisions under these two headings are for twice the standard error.

standard errors.

In reviewing the data obtained from the data reduction process, it is clear that one of the meters was more reliable in yielding precise data than the other; that in spite of this mismatch in precision there was a definite miscalibration; and that consequently a calibration curve relating the two meters should be constructed. I shall examine these conclusions individually.

There are several criteria one can use to compare instruments. Among these are the sets of standard deviations one obtains. From the reduced individual gravity ties, the following standard deviations were obtained for each meter, listed sequentially in ascending order for the eleven sets of ties:

G465: 9, 11, 11, 11, 12, 16, 17, 22, 23, 24, and 34 microgals.
G300: 5, 6, 6, 6, 6, 9, 9, 10, 10, 13, and 17 microgals.

The smallest, median, and largest values for these unculled data are all about half as large for G300 as for G465. The revised data sets, with standard deviations recalculated without the rejected values, show somewhat the same pattern:

G465: 7, 8, 9, 10, 11, 11, 11, 12, 13, 16, and 18 microgals.
G300: 5, 5, 6, 6, 6, 6, 7, 7, 9, 10, and 10 microgals.

Another measure for comparison is the total range found in an individual set of ties. The following are unculled data:

G465: 27, 30, 30, 33, 36, 49, 53, 57, 69, 79, 116 microgals
G300: 15, 15, 16, 20, 22, 24, 28, 30, 32, 39, 54 microgals

Again, the performance of G300 yields half as much error. G465 had been damaged in a fall of several feet some ten months earlier. Although it had been sent in for repair and revision of the calibration table, some of the instability had not yet worked out. Consequently, it was subject to considerable hysteresis, and a data point taken four minutes after unclamping the meter often did not compare favorably with one taken after eight minutes. In addition, erratic persistent fluctuations were frequently encountered which made individual ties extreme in value. This problem was partially recognized in the field, and many additional replications were performed with the meter, both at an individual station, and with extra ties. Nevertheless, more data rejection was required for G465 (15 tie values rather than five for G300), with ultimately lesser precision. Although G465 could perform quite well at times, other data from this interval of time (and perhaps afterward) are suspect unless replication documents the precision. It is particularly crucial, if the looping technique is used, that loops be independently repeated; otherwise errors due to fluctuations could be concealed within the loops. As a general practice, replicate values at a station are needed also, with rejection of hysteresis values implemented; this may not be necessary with G300, although the practice was followed in all the surveys described in this paper.

In spite of the precision problems encountered with G465, it was clear from the culled data (means and standard errors) that a significant miscalibration existed between the two meters. In general, this is expressed (on Table V) as a .02-.04 mgal discrepancy between means for the same station differences. Normally, G465 gave a larger value, but this was not inevitably true; consequently the simple multiplication of the pertinent meter calibration constants by appropriate correction factors would provide some relief (and improve comparability), but would not remove all of the mismatch. To further enhance the comparability, a calibration curve with G300 as the reference had to be constructed on a segment by segment basis, using a varying calibration factor. The construction of this curve was complicated by the fact that the two meters are operating approximately 60 units apart on their respective scales (about 60 milligals). The calibration curve is shown as Figure 9 on the following page; the numbers depicted on it were used to revise the G465 data obtained at Heber.

One final comment can be made concerning the data collection process, based on the Santa Ana Mountains results. In looking at the data from G300, I observed that the standard deviation deteriorated with time. If the data collection interval is divided up roughly into quarters, the following average standard

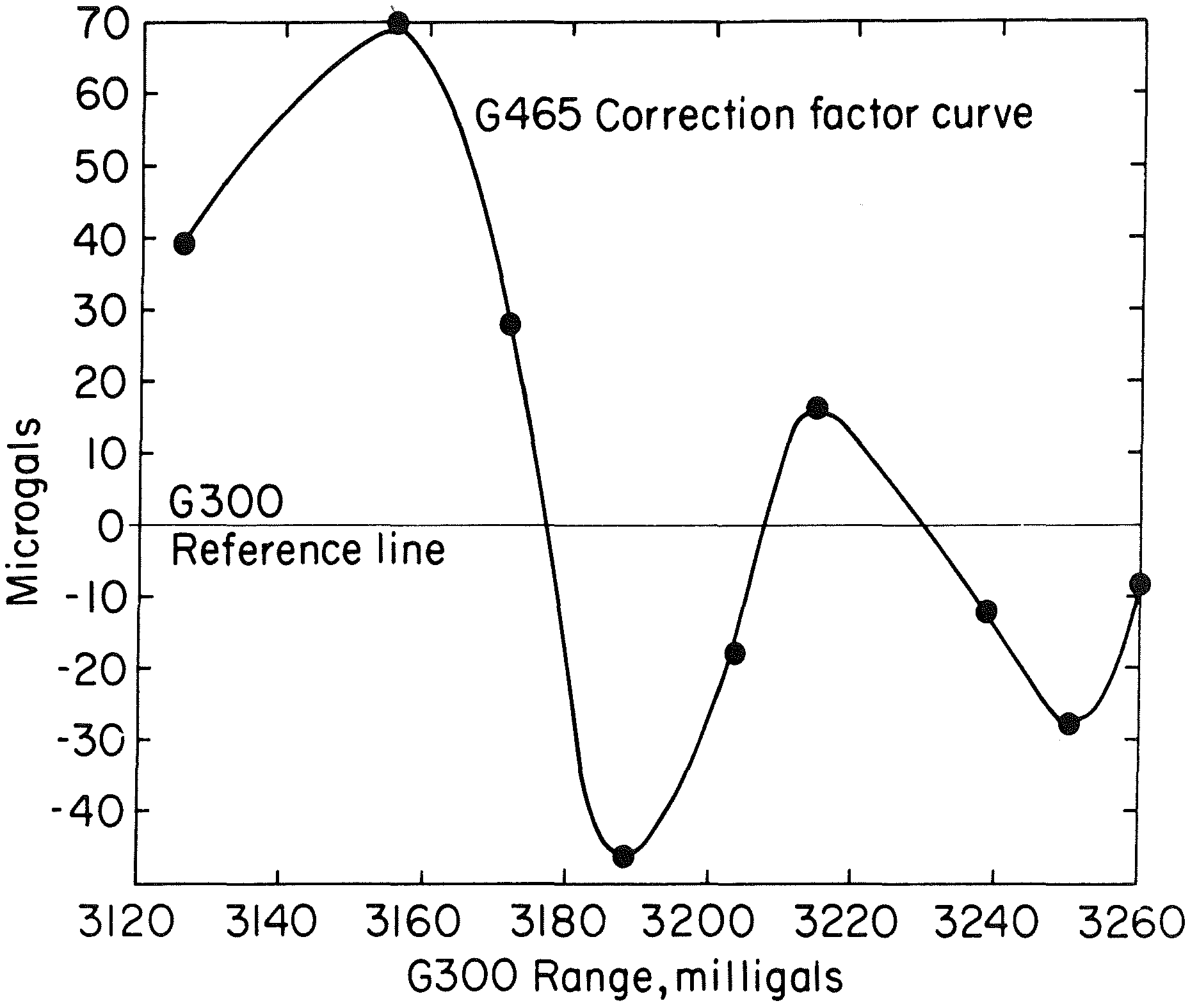


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Figure 9. Calibration correction curve, to bring conformity to G465 data relative to G300. The points on the curve were obtained by plotting the negative values of the discrepancies listed in Table V at the midpoints of the appropriate G300 gravity intervals. The horizontal scale is given in reduced (milligal) values rather than in meter units. A correction can be made to a G465 gravity difference by finding the midpoint of the equivalent G300 interval and then reading the intersection of that point with the plotted curve. The value is added algebraically to the G465 datum.

deviations are obtained for the unculled data:

1st 3 ties: 5.67 microgals
2nd 3 ties: 8 microgals
3d 3 ties: 9.67 microgals
last 2 ties: 13.5 microgals

The gravity meter was used steadily for eight days to collect these data, with only one day of down time, and an average of 200 miles was driven on each day of operation over (mostly) paved roads. Although the transport case was used for much of the work to minimize the effect of vibrations, it appears as if the meter can store residual deleterious vibrational effects which increase slowly with increased use, leading to greater instability. To achieve very high quality work, it may be necessary to remain in the field area overnight to minimize the amount of driving, to find new methods of transport which will be somewhat more effective in isolating the meter, to replicate the occupation of stations additional times, and/or (if feasible) to separate field days with resting days (perhaps two days of operation alternated with one or two days of rest) so that the meter can stabilize. It was frequently observed in Mexico that the meter underwent changes overnight, so that some readjustment while the meter is not in operation does occur, and may be beneficial.

No similar trend was observed for the G465 data set, but the fluctuations in the values may have obscured time-dependent effects.

V. THE HEBER GRAVITY NETWORK

A. FIELD PROCEDURES

The gravity survey at the Heber geothermal field was established over a region of about 100 square miles centered approximately over the identified area of highest heat flow, generally south of El Centro and west of Heber, California. The approximate boundaries for the survey (see Figure 10 on the following page) are Highway 111 and LaBrucherie Road on the east and west, respectively, and Highway 98 and McCabe Road respectively, to the south and north; individual stations extend beyond these boundaries, and particularly into El Centro, where a base from the California gravity base station network (Chapman, 1966) was occupied, as well as two other benchmarks from a first order level line. Altogether, 68 stations were occupied. Of these 68, two served as external bases, and were located 40 to 50 miles away, one to the east, and one to the west of the Heber field. These external bases were selected because they are reference bedrock bench marks in the first order leveling network across the Imperial Valley (Robert Estes, Imperial County Public Works Department, personal communication); one is located in the Coast Ranges between Ocotillo and Mountain Springs, and the other in the Cargo Muchacho Mountains northeast of Ogilby (see Figure 1). These two stations are stable, and over a two year interval changed only 11 mm relative to one another (equivalent to about two microgals of gravity change).

Three more of the stations established served as internal bases within the Heber geothermal field. The major reason for

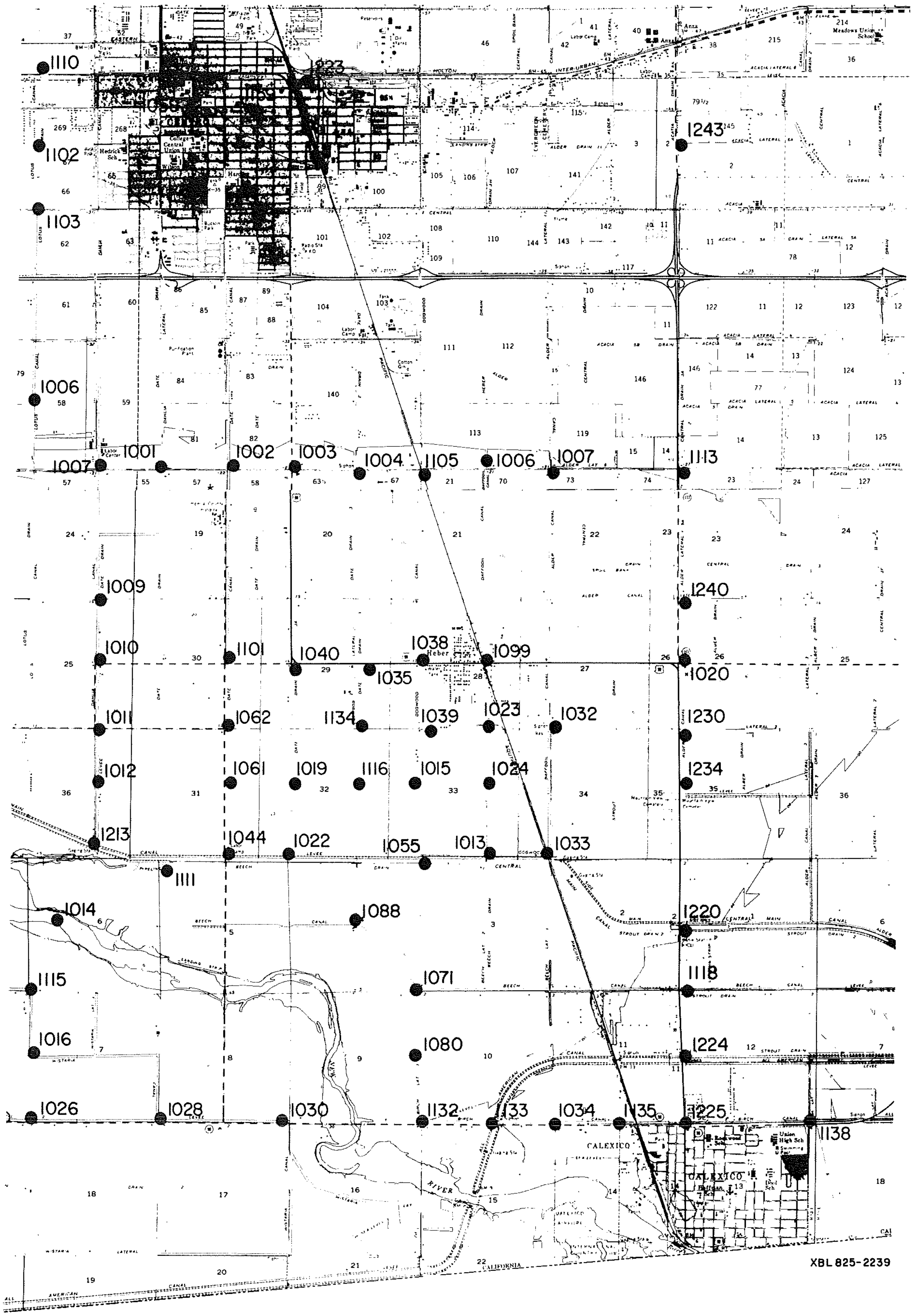

Figure 10. Location map of gravity stations in the Heber area.

locating three bases in a triangle approximately 5-10 miles apart was to always provide a base station within short driving distance of every gravity station in the network, to minimize transport distance (and with it, imprecisions and extra cost). In addition, one of the bases (in Calexico) was located in an area currently undergoing little subsidence (Robert Erickson, Standard Oil Company of California, personal communication), and another was protected from the wind, so that some work could selectively be scheduled on the many windy days in the later spring season.

The remaining 63 stations constitute the gravity network covering the Heber geothermal field. They, and the five bases already discussed, are all located at permanently monumented sites. These consist primarily of benchmarks established by government agencies for first and second order leveling to detect aseismic and seismic ground deformation throughout the Imperial Valley, as well as second order benchmarks established by private industry for semiannual monitoring of possible geothermally-related subsidence. Additional sites were established to extend the coverage on permanent concrete structures such as concrete pads, culverts, and canal weir gate abutments.

The station occupation scheme is depicted schematically on Figure 11 on the following page. A variation of the Canadian tie method was used. The tie method per se was discussed in Section IV, but is, in summary, a method in which the difference between two adjacent stations is well established by several

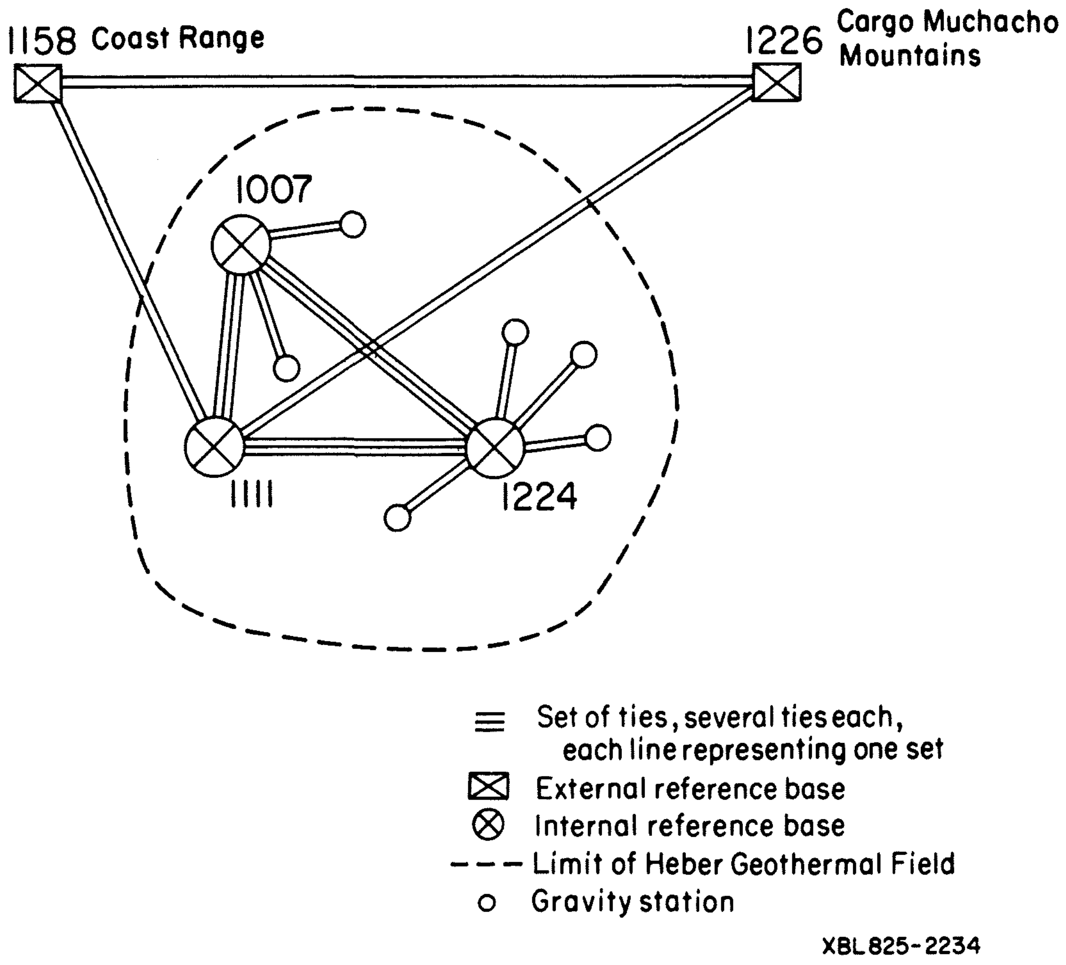

Figure 11. Gravity station occupation scheme, Heber geothermal field. Each set of ties indicated normally contained six individual ties. The figure is schematic and not to scale.

"ties" back and forth between the two. When this gravity difference is well known, one of the two stations can be tied to a third, and that to a fourth, etc., akin to the process of leveling with its backsights and foresights. Error can propagate down this chain, and it is not appropriate without modification for a very long repetitive survey, as this one was. The modification consisted (at Heber) of tying each of the stations directly into one of the three bases with two sets of four ties apiece with each of two LaCoste and Romberg gravity meters (G300, owned by California State University at Long Beach, and G465, owned by James H. Whitcomb). Although this type of scheme does not permit error distribution throughout a network, the short tie distances should help minimize errors. Since three bases were used to establish the station ties, it was necessary to measure the differences among the bases very well, to make the station values comparable. In consequence, the three legs of the base station triangle were each measured with three sets of six ties by each gravity meter (36 ties total for each leg). In addition to the repeated ties, precision was enhanced by measuring replicate readings each time a station was occupied, by keeping the meters always oriented in the same position, by not using the base plate with its slightly curved surface, and by transporting the instruments as much as possible in special transfer boxes.

To tie the survey into the external bases, another triangular configuration of ties was established, the apices consisting of the two external bases and the most central internal base. Long distances along the three legs of 70 to 130 kilometers precluded as many ties for the external bases as were made for the internal bases, but each leg difference was measured approximately ten times by each meter, using the same procedure as was discussed in foregoing paragraphs. The initial occupation of the Heber area was started in February, 1980, and (due to the late arrival of high temperatures) was concluded in early May of the same year. The major leveling of the Imperial Valley following the 1979 Mexicali (Imperial Valley) earthquake was conducted in late 1980 and early 1981; to ensure that the relative differences among the stations probably had not altered in the six month or longer interval between the gravity and leveling efforts, the gravity ties among the five bases were repeated at approximately the same time as the first order leveling survey.

No tidal monitoring was performed in the Heber area. The distance from the central area of the Heber survey to Cerro Prieto volcano does not exceed 40 kilometers, and it was felt that no significant changes in the tidal constants were likely to occur over that small distance.

B. DATA REDUCTION AND STATISTICAL ANALYSIS

The raw meter data were processed through several reduction procedures:

(1) The raw values were multiplied by the calibration constants provided by the manufacturer. In the case of meter G465, an additional correction factor was applied, to correct for

miscalibration (see discussion in Section IV).

(2) Tidal corrections were made; after this step, the resulting values were observed gravity values.

(3) The means of replications at individual stations were obtained after dividing the observed gravity values into pairs (e.g., if four replications were made, the first two were averaged separately from the last two). These means were each subtracted algebraically from the adjacent mean value from the other station in the tie (a full discussion of this procedure was given in Section IV). This produced a single gravity difference for each subtraction, or tie.

(4) The means and standard deviations for all the ties between each station pair were calculated for each meter, and then for the combined values. After culling extreme values, new values of the means, standard deviations, and single and double standard errors were calculated, using the same procedures as were utilized for the calibration line in the Santa Ana Mountains.

The reduced data are presented in two tables on the next pages. The first table, Table VI-a, contains the final values obtained in 1980, and includes no rejected data. The tabulated values are the combined results of the work, using both meters. All of the station values have been referred, on this table, to bench mark Y-1224, the internal base station (of the three utilized) which has undergone the least, and only minimal, subsidence (Bob Erickson, personal communication), and the only one which is also part of the first order leveling network in the Imperial Valley. Stations

TABLE VI-a. SUMMARY OF HEBER GRAVITY VALUES, SPRING 1980

INTERNAL BASE STATION TIES, $\bar{X}$ AND 2 S.E.

STATION	G300 DATA (MICROGALS)	G465 DATA (MICROGALS)	G465 DATA, REVISED (MICROGALS)	COMBINED VALUES (MICROGALS)
1224 to 1007	3,155 ± 3.4	3,147 ± 8.4	3,142 ± 8.4	3,149 ± 4.4
1224 to 1111	5,067 ± 3.4	5,086 ± 12	5,079 ± 12	5,071 ± 4.8
1007 to 1111	1,914 ± 3	1,922 ± 8.6	1,917 ± 8.6	1,914 ± 4.0

EXTERNAL BASE STATION TIES, $\bar{X}$ AND 2 S.E.

STATION	G300 DATA (MICROGALS)	G465 DATA (MICROGALS)	G465 DATA, REVISED (MICROGALS)	COMBINED VALUES (MICROGALS)
1111 to 1158	-112,617 ± 5.7	-112,634 ± 14	-112,607 ± 14.3	-112,613 ± 6.9
1111 to 1226	-8,409 ± 5.7	-8,405 ± 13	-8,400 ± 12.3	-8,405 ± 6.6
1158 to 1226	104,193 ± 9.1	104,213 ± 33	104,232 ± 33.1	104,209 ±18.0

STATION TIES, REFERRED TO B.M. Y1224, $\bar{X}$ AND 2 S.E.

STATION	G300 DATA (MICROGALS)	G465 DATA (MICROGALS)	G465 DATA, REVISED (MICROGALS)	COMBINED VALUES (MICROGALS)
1001	4,222 ± 5.0	4,221 ± 10.6	4,206 ± 10.6	4,214 ± 6.1
1002	5,081 ± 5.2	5,087 ± 9.3	5,072 ± 9.3	5,077 ± 5.4
1003	6,088 ± 5.1	6,084 ± 12.3	6,069 ± 12.3	6,079 ± 6.1
1004	6,667 ±12.5	6,651 ± 20.8	6,636 ± 20.8	6,652 ±11.8
1005	7,575 ± 6.6	7,592 ± 10.2	7,575 ± 10.2	7,575 ± 6.8
1006	3,513 ± 7.8	3,503 ± 13.8	3,489 ± 13.8	3,502 ±10.9
1007	3,155 ± 3.4	3,147 ± 8.4	3,142 ± 8.4	3,149 ± 4.4
1009	3,492 ± 6.6	3,499 ± 10.9	3,485 ± 10.9	3,488 ± 6.4
1010	3,790 ± 7.6	3,793 ± 11.6	3,779 ± 11.6	3,785 ± 9.9
1010*		3,758 ± 12.3		

*The second column value tabulated in this row was taken six weeks after the value immediately above it, at the same location. The difference is 35 ± 17 microgals, which is clearly significant at the 95% confidence level.

All 1010 values were measured with respect to station 1007, and then referred algebraically to 1224; this procedure increased the double standard error values. The gravity difference is even more striking in the original measured values.

TABLE VI-a. SUMMARY OF HEBER GRAVITY VALUES, SPRING 1980 (continued)

STATION TIES, REFERRED TO B.M. Y1224, $\bar{X}$ AND 2 S.E.

STATION	G300 DATA (MICROGALS)	G465 DATA (MICROGALS)	G465 DATA, REVISED (MICROGALS)	COMBINED VALUES (MICROGALS)
1011	3,922 ± 5.7			3,922 ± 5.7
1012	3,794 ± 6.0	3,785 ± 13.8	3,771 ± 13.8	3,785 ± 9.9
1013	5,607 ± 5.4	5,623 ± 13.6	5,605 ± 13.6	5,605 ± 7.4
1014	5,942 ± 7.2			5,942 ± 7.2
1015	6,837 ± 6.6	6,834 ± 13.0	6,815 ± 13.0	6,830 ± 11.4
1016	3,731 ± 6.6			3,731 ± 6.6
1019	6,562 ± 8.7	6,587 ± 13.1	6,568 ± 13.1	6,563 ± 7.3
1020	7,436 ± 2.3			7,436 ± 2.3
1022	5,902 ± 6.6	5,920 ± 14.7	5,901 ± 14.7	5,899 ± 7.7
1023	7,397 ± 4.6	7,413 ± 12.8	7,394 ± 12.8	7,394 ± 8.2
1024	6,643 ± 5.6	6,660 ± 13.6	6,641 ± 13.6	6,639 ± 6.9
1026	4,190 ± 7.2	4,189 ± 12.0	4,181 ± 12.0	4,186 ± 6.9
1026*	4,192 ± 9.1	4,169 ± 16.2	4,155 ± 16.2	4,183
1028**	1,700 ± 5.5			1,700 ± 5.5
1030	142 ± 10.0			142 ± 10.0
1032	7,374 ± 6.0	7,391 ± 13.0	7,372 ± 13.0	7,373 ± 6.9
1033	5,396 ± 7.2	5,410 ± 13.8	5,392 ± 13.8	5,392 ± 7.9
1034	-90 ± 3.5	-84 ± 14.1	-82 ± 14.1	-86 ± 7.2
1035	7,384 ± 7.2	7,397 ± 14.5	7,378 ± 14.5	7,381 ± 6.8
1038	8,074 ± 6.0	9,000 ± 19.4	8,081 ± 19.4	8,076 ± 7.9
1039	7,335 ± 9.1	7,363 ± 14.5	7,344 ± 14.5	7,338 ± 7.5
1040	6,955 ± 7.2	6,969 ± 16.1	6,950 ± 16.1	6,955 ± 14.1
1044	5,563 ± 4.1	5,576 ± 13.6	5,558 ± 13.6	5,558 ± 7.2
1055		5,760 ± 18.4	5,734 ± 18.4	5,734 ± 18.4
1059	8,796 ± 5.4	8,840 ± 14.5	8,820 ± 14.5	8,805 ± 7.0
1061	6,090 ± 7.8	6,115 ± 12.1	6,098 ± 12.1	6,093 ± 6.4
1062	6,242 ± 8.7	6,268 ± 17.7	6,251 ± 17.7	6,245 ± 8.5
1071***	2,534 ± 6.4	2,552 ± 23.4	2,539 ± 23.4	2,537 ± 7.0
1072	8,332	only a single gravity value was obtained		
1077	9,108 ± 11.1	9,098 ± 10.1	9,082 ± 10.1	9,095 ± 8.7
1080		1,089 ± 15.0	1,075 ± 15.0	1,075 ± 15.0

*The values of 1026 in this row were measured relative to base 1111 (for G300) and to 1007 (for G465); both were converted algebraically to become relative to 1224. The values in the row above were measured directly, relative to 1224. The combined value in this row has a mean weighted between the revised value for G465, and the value for G300; no precision could be calculated, but it exceeds 20 microgals for 2 S.E.

**Eight ties were made with G300 for this station, four directly to 1224, and four to 1111 and then converted. The value for 2 S.E. has a somewhat different connotation from others listed in the table.

***The G465 values in this row are referred to two stations. The value for 2 S.E. has a different connotation than other tabulated values.

TABLE VI-a. SUMMARY OF HEBER GRAVITY VALUES, SPRING 1980 (continued)

STATION TIES, REFERRED TO B.M. Y1224, $\bar{X}$ AND 2 S.E.

STATION	G300 DATA (MICROGALS)	G465 DATA (MICROGALS)	G465 DATA, REVISED (MICROGALS)	COMBINED VALUES (MICROGALS)
1088	4,441 ± 9.0	4,457 ± 14.3	4,441 ± 14.3	4,439 ± 7.9
1088*	4,434 ± 6.4			4,434 ± 6.4
1099	8,382 ± 6.6	8,383 ± 15.5	8,365 ± 15.5	8,375 ± 10.0
1101	6,069 ± 8.4	6,096 ± 15.5	6,079 ± 15.5	6,072 ± 7.3
1102	6,439 ± 12.9	6,447 ± 15.2	6,433 ± 15.2	6,436 ± 9.7
1103	5,391 ± 5.2	5,401 ± 25.4	5,387 ± 25.4	5,390 ± 11.9
1106	8,491 ± 6.9			8,491 ± 6.9
1110	7,512 ± 11.5	7,508 ± 14.3	7,494 ± 14.3	7,504 ± 8.8
1111	5,067 ± 3.4	5,086 ± 12.0	5,079 ± 12.0	5,071 ± 4.8
1113**	10,119 ± 4.2	10,125 ± 11.4	10,110 ± 11.4	10,115 ± 4.7
1115	3,343 ± 7.2			3,343 ± 7.2
1116	6,726 ± 5.8			6,726 ± 5.8
1118	2,359 ± 6.4			2,359 ± 6.4
1132	3,021 ± 6.0	3,016 ± 13.4	3,003 ± 13.4	3,013 ± 6.5
1133	-679 ± 3.0	-690 ± 13.0	-692 ± 13.0	-686 ± 7.8
1134	7,100 ± 5.1			7,100 ± 5.1
1135***	-158 ± 4.9	-133 ± 9	-135 ± 9	-150 ± 7.8
1138	303 ± 9.0	309 ± 13.9	307 ± 9	305 ± 7.0
1159	9,200 ± 6.0	9,223 ± 15.6	9,203 ± 15.6	9,201 ± 6.9
1213	3,630 ± 8.1			3,630 ± 8.1
1220	3,367 ± 7.8	3,388 ± 5.0	3,382 ± 5.0	3,374 ± 6.9
1223	9,446 ± 5.2	9,486 ± 22.5	9,466 ± 22.5	9,454 ± 10.9
1225	446 ± 4.2	463 ± 10.0	461 ± 10.0	465 ± 4.4
1230	6,527 ± 7.3	6,527 ± 11.5	6,521 ± 11.5	6,525 ± 6.0
1234	5,535 ± 3.0	5,543 ± 10.0	5,536 ± 10.0	5,535 ± 3.8
1240***	8,679 ± 4.1	8,709 ± 6	8,702 ± 6	8,688 ± 8.1
1243	11,602 ± 4.2			11,602 ± 4.2

*This value of 1088 was measured directly; the ones above were referred through base 1111.

**The G300 data were measured directly, while the G465 were referred through base 1007. The double standard error for the combined data set is for the direct values combined with revised and referred individual G465 values.

***The discrepancy between G300 and G465 in this data set is significant both before and after calibration corrections to G465 values, at the 95% confidence level

TABLE VI-b. SUMMARY OF INTERNAL AND EXTERNAL BASE STATION VALUES WITH REPETITIONS, GRAVITY METER G300

TIE SET	SPRING 1980 MEAN AND 2 S.E. (MICROGALS)	WINTER-SPRING 1980-81 MEAN AND 2 S.E. (MICROGALS)	COMMENTS
INTERNAL			
1224 to 1007	3,155 ± 3.4	3,158 ± 5.4	January, 1981
		3,146 ± 7.2	April, 1981
		3,152 ± 6.6	combined
1224 to 1111	5,067 ± 3.4	5,071 ± 4.9	November, 1980
		5,066 ± 2.4	April, 1981
		5,069 ± 3.0	combined values
		5,068 ±17.0	post Cerro Prieto
1007 to 1111	1,914 ± 3.0	1,923 ± 8.2	November, 1980
		1,899 ± 3.3	April, 1981
EXTERNAL			
1111 to 1158	-112,617 ± 5.7	-112,619 ± 6.9*	
1111 to 1226	-8,409 ± 5.7	-8,420 ± 6.3*	
1158 to 1226	104,193 ± 9.1	104,195 ± 3.8	

*This double standard error value is higher than the previous spring, because fewer values were obtained. The standard deviation, as reported in the text, is lower.

which were not measured directly to this base have been converted algebraically, using the mean values for the base station ties, presented first on the table.

Table VI-a contains four columns of gravity values in addition to the station numbers on the left hand side. The first column contains the reduced mean values for G300, and the double standard error value for those means; the second column lists the same parameters for gravity meter G465. The third column lists the revised values for G465, after a calibration correction has been added algebraically. The double standard error value for this column is identical to that of the second column, but here it represents a minimal, rather than an actual value. The recalibrated values have some additional error built in because of uncertainty in the calibration correction, but this could not be readily assessed; thus the actual values should be somewhat larger than the reported values. The fourth column has means and double standard errors calculated for the combined values of actual G300 and revised G465 data. In future gravity surveys, comparisons from those future occupations to this survey should refer to the first column if only G300 is then used, to the second if only G465 is used, and to the fourth column if both meters are used.

Table VI-b lists the base station repetitions with G300 in the winter of 1980-81; the same values for spring 1980, for meter G300 only, are provided for comparison.

C. INTERPRETATION AND DISCUSSION

Little interpretation of the data is possible in terms of subsidence effects, due to the lack of repetition of any of the stations, with the exception of the base ties. Consequently, most of the discussion will focus on the precision of measurement.

In Section V, the precision differences between meters G300 and 465 were already noted. The same discrepancies were also observed in establishing the Heber network. For G300,85 sets of ties were established; within these sets, less than 6% of the individual ties were rejected, and the median standard deviation for the unculled and culled data sets was 8 microgals. The most extreme standard deviation before rejecting any values was 22 microgals, and 82% of the values were 12 microgals or less; half of the remaining values consisted of the long base station ties (minimum of 40 miles driving distance), which provides evidence in itself of the effect of transport on the gravity meters. Among the culled values, all but four of the tie sets (more than 95% of the values) were 12 microgals or less, and three of the four remaining values were from the long distance ties; the most extreme culled standard deviation was a value of 19 microgals, which was associated with ties made directly after returning across the Mexican border after long field days under rough road conditions.

For G465, the median standard deviation with no data rejection was 17 microgals, which is close to the 16 microgal value reported by Whitcomb and others (1980) for gravity work in Southern California using the same meter. For the culled values, after removal of more than 18% of the individual ties (more than three times as many as with G300), the median standard deviation was 11 microgals. However, the most telling difference comes with looking at extreme values. Among the unculled values, fully 25% were characterized by standard deviations greater than 20 microgals and 14% by values greater than 30 microgals; the most extreme value was 74 microgals (this was not operator error, since the value was repeated several times), more than three times greater than the largest value for G300. Basically, G465 is less reliable because of a succession of tares which occur in the data sets much more frequently; these are the sources of the erratic standard deviation values, and without serious repetitive work, the results from this meter are not trustworthy, there being too great a chance for undetected aberrant values. The tares usually are expressed as finite jumps in an overall upward drift, which yields one more comparison: the positive drift during use for G465 was .75 mgal/month, whereas that for G300 was one quarter that value. Distance of transport does affect meters deleteriously. In spite of the transport case, long ties yielded average standard deviations much larger than those for the short local ties. This effect was seen for both gravity meters, in that the unculled local median standard deviations were 8 and 16 microgals for G300 and G465 respectively, but 14 and 37 for the external base station ties, respectively. When the base stations were repeated with G300 in late 1980 and early 1981, an upgraded transport case was used, and the reduced data did show an improvement, apparently as a consequence of improved damping of transport-induced vibrations. The standard deviations for both occupation episodes are listed below for comparison, using unculled G300 data (including ties across the Mexican border to Cerro Prieto):

early 1980 - 14, 15, 14, 13
1980-81 - 12, 10, 5, 7

The data above are for four external ties; the values are paired vertically, so that each value beneath the upper value is the repetition of the same set of ties. The mean standard deviation for the first four sets is 14 microgals, whereas that for the second (and later) sets is 8.5, a considerable improvement for work under rather trying field conditions.

The meter discrepancies are also evident in the double standard error (D.S.E.) values listed on Table VI-a. Whereas the median value for the G300 data is 6 microgals, that for G465 is 14 microgals and for the combined value is 7 microgals. (The distribution is shown on Figure 12 on the next page). The latter value is somewhat larger than for G300 data alone; with the increased number of replications due to using both meters, the combined value should have decreased 30 or 40% (rather than increasing), had both meters yielded comparable precision. To offset this loss of precision, two tactics are possible: (1) increase the number of replications made with lesser quality instruments, until the D.S.E. values are comparable for both meters used (the standard deviations will never be comparable); or (2) use only the higher quality instrument. The first possibility means greatly in-

HISTOGRAM OF DOUBLE STANDARD ERROR VALUES, HEBER GRAVITY SURVEY, SPRING 1980

```
2 S.E. VALUES     NUMBER OF VALUES
 (MICROGALS)

      2           X

      3           XXXXXXX

      4           XXXXX
                  -----
      5           XXXXXXXX
                  o
                  ----
      6           XXXXXXXXXXXX    Median, G300
                  o
                  ---
      7           XXXXXXXXXXXX
                  ------------------    Median, Combined Values
      8           XXXX
                  o
                  --------
      9           XXXXXXX
                  oo
                  --
     10           X
                  ooo
                  ---
     11           XX
                  oo
                  --
     12           oooo
                  -

     13           X
                  ooooooo

     14           oooooooooooooo    Median, G465
                  -

     15           ooooo
                  -

     16           ooo

     17           ooooooo
    and           --
   larger
```

LEGEND

X	G300 Values
o	G465 Values
-	Combined Values

Figure 12. Histogram of double standard error values for gravity differences obtained at Heber during spring, 1980. Each symbol making up the horizontal rows represents one double standard error value. The range for G300 lies from 2 to 13, with a median of 6 microgals: the range for G465 lies from 6 to 33, with a median of 14 microgals; and the range for the combined values for both meters is from 4 to 20, with a median of 7 microgals. All values are rounded off to the nearest microgal.

creased costs; in the case of the Heber survey, a cost increase of 50-60% would be needed, since the number of G465 values would have to be more than doubled. The alternative case is somewhat risky in terms of temporal continuity, in that destruction or modification of this instrument, when its calibration has not been well documented in a calibration network, will result in a lack of comparability between data sets taken before and after the meter change.

The lower values of double standard errors in Table VI-a are associated with G300 values, values measured directly between base 1224 and the stations, and/or values characterized by larger (10+) numbers of replications. The maximum precision would be obtained in a repeated survey if all the stations were repeated in 10-16 ties with G300, and if 1224 could be used as the exclusive base. However, some tie means could deteriorate with the long distances used in this type of procedure. Alternatively, the internal base network of three stations could still be used, but with the replications among them increased to 30+ values; this would reduce the D.S.E. values to about 2.5 microgals, and the incorporation of such values would have a negligible effect (1 microgal or less) on station D.S.E. values of 3 and larger. Even if only one base were to be used in the future, a second base should be established especially well relative to the first base (and in a nearby area) because of the real possibility of destruction or substantive change. The destruction of the primary base without a well-established alternate would again create a loss of temporal continuity.

The only repeated values at Heber are those of the internal and external base station ties summarized on Table VI-b. There were no significant changes between spring 1980 and winter 1980-81 in these ties, indicating a lack of subsidence in this time interval. However, one rather interesting gravity change was observed during the 1980-81 repetition which apparently is significant at the 95% confidence level. Two sets of ties were occupied and reoccupied within this repetition on the same two days, both of them on November 27, 1980, and again on April 23, 1981; these were the internal base ties between stations 1224 and 1111, and 1111 and 1007. The former tie set showed no significant variation between the two occupations, whereas the latter did, a decrease in gravity of 24 microgals. Because only the latter tie was affected, it can be presumed that station 1007 underwent some change, it being present only in the varying tie and furthermore not being common to both sets. The third tie set of the triangular base configuration (from 1224 to 1007) is non-corroborative because it occurred over a shorter time interval, and the decrease of 12 microgals which was observed was only marginally significant at the 95% confidence level. There are several possible explanations for the changes observed at station 1007:

(1) The observed change could be tectonically induced. This part of the Heber geothermal field is subsiding more than areas to the south and east.

(2) It could be caused by irrigation of the surrounding fields, with resulting hydrocompaction and increased mass of near-surface water. The change in 1007 is positive and con-

sistent with this type of cause.

(3) The change could be due to variations in the amount of water carried by the canal network, since 1007, and many other Heber stations, are located on bench marks established on permanent canal structures.

Change (1) is tempting because of the geological history of the area, and particularly since the Westmorland (M = 5.5) earthquake occurred less than four days after the April 23, 1981, set of repetitions. However, three similar changes were observed within the occupations the previous spring (these are noted in Table VI-a), and these bear no spatial affinity to a tectonically changing region, which should produce gravity variations in a consistent way over a broad region. Changes at isolated stations are not easily ascribed to tectonic causes.

Change (2) is reasonable, but not quantitatively significant, and seems a less likely cause than change (3). It was observed that station 1007 is located at the edge of a catchment basin into which a major canal issues, and that sometimes this basin is suddenly depleted as waters are diverted. A reasonable change in water level was modeled by solving for the gravitational attraction of a parallelipiped 20' by 30' by 5' in dimension, whose top was located 5' below the gravity station. Addition of this quantity of water into the basin would produce a modelled gravity increase of 16 microgals, which is on the same order of magnitude as the change (24 microgals) actually observed, and the model could be too conservative in its dimensions. One of the three changes in spring 1980 involved a change in a tie to 1007; the other two changes, within tie sets taken near Calexico, are less easy to explain, but the stations involved are located on canals, which may be a contributing factor. Three conclusions can be based on these small (25-35 microgal) changes:

(1) Variations seen along canals should always be suspect, unless larger variations than those noted are seen, and corrections are made after careful field observations of water levels and waterway dimensions.

(2) Leveling data along canals may register small, false elevation changes as a consequence of water fluctuations. Changes in mass do distort the equipotential surface upon which leveling is based (Whitcomb, 1976) and may yield apparent changes which are not real. Caution should thus be used in interpreting canal station leveling changes.

(3) Because of the location of the catchment basin, 1007 was not a good choice for a gravity base station, and its use should be discontinued or deemphasized.

VI. INTEGRATION OF THE HEBER AND CERRO PRIETO GRAVITY SURVEYS

The Heber gravity survey was tied to the Cerro Prieto gravity survey by means of a set of ties made in April of 1980, and repeated again in the winter of 1980-81. During the first set of occupations, four values were obtained by setting up at Base 1111 in the Heber area, driving across the border, and occupying station 20bis on top of Cerro Prieto volcano; this process was repeated in reverse at the end of the day. The procedure was altered somewhat during the second set of occupations, in that seven ties were again made between 20bis and 1111, but in addition, four evening ties were made from 20bis to Heber station 1224, which is bench mark Y1224 of the United States first order leveling line; this bench mark was also included in the Mexican first order leveling effort carried out by DETENAL. The various tie data are depicted on Table VII on on the following page.

The data were reduced according to the procedures outlined in Section V, and standard deviations and double standard errors were calculated. Based on the statistics, no significant changes in gravity between the two locations were observed between spring of 1980 and winter of 1980-81. There were, however, two interesting observations concerning the data:

(1) The long-range ties underwent improvement in the Mexican set of data as well as in the external base ties at Heber; 20bis to 1111 was improved from a standard deviation of 13 microgals to one of 7 microgals, and, considering the 30 mile distance involved, the time delay encountered in crossing the border, and the mile of dirt road (which included a cobblestone portion at the end) needed to reach 20bis, the improved transport case seemed to be quite effective. By itself, the improvement noted for the Mexican ties could be happenstance, but it is part of a trend discussed in the last section, and the data presented here are included in the data set presented there for comparison of identical tie sets taken at different times.

(2) The evening ties, which were taken only on the repetition

TABLE VII. UNITED STATES TO MEXICO TIES FOR G300, SPRING 1980 AND WINTER 1980-81

SPRING 1980

TIES	VALUES (MICROGALS)		STATISTICS (MICROGALS)	COMMENTS
1111	4/25/80	4/26/80		
to	-39,808	-39,790	$\bar{x}$ and s = -39,808±13 (4)	
20bis	-39,818	-39,818	2 S.E. = 13	
	WINTER 1980-1981			
	11/30/80	1/03/81		
	-39,798	-39,795		
1111	-39,805	-39,798	$\bar{x}$ and s = -39,802± 7 (7)	
to			2 S.E. = 5	
20bis	12/31/80	1/15/81		taken in the morning, enroute to Cerro Prieto
	-39,813	-39,798		
	1/01/81			
	-39,808			
1224	12/31/80	1/03/81		
to	-34,737	-34,732	$\bar{x}$ and s = -34,735±15 (4)	
20 bis			2 S.E. = 15	
	1/01/81	1/15/81		taken in the evening, return from Cerro Prieto
	-34,717	-34,754		

in the winter interval, do not have as high precision; the standard deviation for these four ties was 15 microgals. If this one data set has any significance in comparison with the other, better quality long distance data, it indicates the presence of an adverse environment not affecting the other readings. I attribute the less desirable quality not to the time of day per se, or the route traversed in making the ties (which is nearly identical to that followed for the tie 20bis to 1111), but the fact that these ties inevitably followed a full day of field work in Mexico, with three round trips up and down the rough volcano road, as well as a considerable amount of time spent on washboard dirt roads. I feel that strain can accumulate in the meter, as was previously suggested in Section IV, and this can lead to a deterioration of quality over several days, or in a shorter interval if conditions are less favorable (as in Cerro Prieto). This strain begins to be released when the spring is unclamped to take a reading, but is not released fully for several tens of minutes. These episodes are more expectable, but are not always inevitable, during or after a long, hard field day. The occupation of 1224 in the evening was always followed by the occupation of 1111, and these ties showed an even larger standard deviation of 19 microgals. In terms of consistency of values, they are the worst data set collected in the entire Heber survey by gravity meter G300; overall, they are the second worst data set, exceeded only by one set of 22 microgal standard deviation which had seven very consistent value and one really wild value. I conclude that the effect of rough conditions not only accumulates, but persists in instability for some time after the causative environment is removed. Such long ties, and other crucial ones, should perhaps be performed only when the meter involved has not been subjected to deleterious transport; otherwise, lesser precision may have to be accepted, or more numerous ties obtained.

VII. CONCLUSIONS

The gravity method is quite effective in documenting small ground motions. At the attainable level of precision (6 to 10 microgals) for double standard errors, a comparison of two values will be significant if the magnitude exceeds 9 to 14 microgals. A value of 15 microgals change is equivalent to a 5cm elevation change if a free air gradient is assumed, and about 6cm if a Bouguer gradient can be assumed (with loss of water accounting for the density change). With increased precision, which is realistically attainable only with a substantially increased effort and/or modification of field procedures, these values could be improved to 3 and 4cm, or even less. Consequently, the gravity method should continue to be used in geothermal environments. The Cerro Prieto survey in particular was useful in documenting subsidence which could be presumed due to both fluid withdrawal, and to tectonic (seismic) events.

One surprising conclusion in comparing the Heber and Cerro Prieto gravity surveys is the very similar standard deviations which were obtained for the two different field procedures used. The final precision of measurement will thus be dependent only on the number of times a station is independently occupied, not on the field procedure, for the level of work accomplished here. However, the tie method (modified into some separate chain configurations which allow distribution of error) may still be more effective at maintaining high precision, and it certainly allows tighter control on tares. If the present level of precision is satisfactory, the cheaper looping technique can be utilized, provided that loops are replicated enough times.

Very little of the error found in these gravity surveys comes from operating the instruments. Once a person is well-trained and has several hours of experience in operating a meter, the error comes principally from the particular gravity meters used, and from field and transport conditions. Gravity meters which yield high quality results should be carefully treated, since they are ultimately capable of saving hundreds of manhours in excess repetitions if a certain precision must be maintained. Transport conditions and distance of travel are both crucial parameters in precision enhancement.

Gravity meters cannot be effectively used together unless the survey is specifically designed to maintain similar precisions (standard errors) on all of the instruments, both in the calibration process, and in establishing the gravity survey itself.

VIII. SUGGESTIONS FOR FURTHER WORK

Neither the Heber nor the Cerro Prieto surveys should be abandoned. The annual repetition at Cerro Prieto may be too frequent for the available funds, and a biennial repetition should prove adequate. Repetition at Cerro Prieto is especially crucial, since electrical production was only half its current value during the first two station occupations, and the two intervals between (a) the second and third occupation, and (b) third and fourth occupation, were both marked by moderate (M = 6+) earthquakes with documented ground deformation. Gravity and elevation changes relating to geothermal production have been verified, but marked as they are by tectonic disturbances, the conclusions remain sparse. Gravity changes are more likely to be noted at Cerro Prieto than at Heber, since no recharge from reinjection has so far occurred at the former locale.

The Heber field will soon be producing electricity commercially. A repetition there, coincidental with one of the leveling surveys, is also desirable prior to production to document any non-production changes in the region. That gravity repetition should, in turn, be repeated every two years.

Some interpretation is still possible for the Cerro Prieto data: (1) a full evaluation and interpretation of the Bouguer anomaly values; and (2) mathematical analysis and modeling using Whitcomb's techniques (Whitcomb, 1976) to relate mass and elevation changes to both seismic activity and reservoir production.

Particular attention should be paid to the relationship between the effect of the Victoria earthquake on the gravity values versus the effects seen in the previous two years. Three hypotheses have been advanced for the deformation associated with the earthquake: (1) tectonic deformation; (2) liquefaction of surficial material; and (3) subsidence of deep layers weakened by geothermal production. Some separation of these effects could be effected if it could be documented that pre-earthquake subsidence was adequate in magnitude to explain the amount of fluid produced so far, keeping in mind the probability of recharge. If modeling suggests that the subsidence has not kept pace with net mass loss (if some value can be presumed) then credence will be lent to hypothesis (3) above. Installation of extensometers in wells would also separate surficial effects from other types of effects in future earthquakes (Ben Lofgren, personal communication).

Comparison of the elevation with the gravity changes, assuring either a change along a free-air gradient, or alternately one along a Bouguer gradient, would help elucidate whether or not subsidence had been accompanied by mass changes at Cerro Prieto. For all of these modeling efforts, reconciliation and further evaluation of the elevation data is required. The elevation data must be referred to the same base as the gravity data.

If future data at either Heber or Cerro Prieto are collected by the Canadian tie technique, data reduction could be accomplished with a network analysis procedure, which would incorporate dedrifting and error distribution by a least squares procedure. Network analysis computer programs are readily available for evaluation of surveying networks, and have been used for the gravity case as well (H. Dragert, personal communication). One of these should be adapted for the Salton trough work, since this type of procedure should extract the maximum usable amount of information from the available data.

Finally, if greater precision is demanded, three routes are possible: (1) introduction of further improved transportation, especially necessary for ties such as that up Cerro Prieto volcano; (2) comparison of the D meter with the G under rugged conditions, to see if the reported advantages of this instrument over the G models persists in this type of measurement environment; and (3) incorporation of the suggestions made in previous sections for number of replications needed, use of base stations in an appropriate way, and intermixing of disparate gravity meters. Both the Heber and Cerro Prieto surveys should utilize one main base station, but a minimum of a second base will always be needed as a reserve to ensure continuity. The external base ties in both areas should also be maintained, in the Sierra Cucupa west of Cerro Prieto, and in the Coast Ranges and Cargo Muchacho Mountains west and east of Heber; Cerro Prieto volcano was apparently not stable during the Victoria earthquake, and the main Heber base at Calexico could also be problematical.

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X. AVAILABILITY OF FURTHER INFORMATION

Two types of detailed information concerning the work described here are available upon request from the Lawrence Berkeley Laboratory, Earth Sciences Division. The first consists of tables of original gravity differences (reduced and tidally corrected) with dates of station occupation, station of reference, and calculated means and standard deviations. Cerro Prieto, Heber, and Santa Ana Mountains values can be obtained. The second type of information available is lists of station descriptions for the same three localities.

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