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TIME-DEPENDENT GRAVITY IN SOUTHERN CALIFORNIA, MAY 1974 - APRIL 1979

By

James H. Whitcomb

Wolfgang O. Franzen

Jeffrey W. Given

James C. Pechman

Larry J. Ruff

Seismological Laboratory
California Institute of Technology
Pasadena, California 91125

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ABSTRACT

The Southern California gravity monitoring project begun in May 1974, is intended to coordinate gravity measurements with the long-baseline three-dimensional geodetic measurements of the ARIES (Astronomical Radio Interferometric Earth Surveying) project which uses radio interferometry with extra-galactic radio sources. Gravity data from 28 of the stations, monitored on an approximately one- to two-month basis, have a single-reading standard deviation of 11 μgal which gives a relative single determination between stations a standard deviation of 16 μgal. The averaging of data reduces the uncertainty and, if gravity does not change during the averaging time, it appears that gravity at a station relative to the base can be determined with a standard error of 2 to 3 μgal. Where stations could not be placed on low-porosity bedrock, the effects of variable groundwater levels must be considered. The largest gravity variation observed, 80 μgal, correlates with nearby water-well variations and with smoothed rainfall. Smoothed rainfall data appear to be a good indicator of the qualitative response of gravity to changing groundwater levels at other supra-sediment stations, but frequent measurement of gravity at a station is essential until the quantitative calibration of the station's response to groundwater variations is accomplished. The largest earthquake to occur during the survey time near the gravity network was the August 13, 1978 Santa Barbara Channel event (M_L = 5.1-5.7, M_s = 5.6). The closest gravity station to this earthquake, 67 km east of the epicenter, also exhibits the network's largest gravity change that cannot be related to factors other than tectonic distortion. This change is a 50 μgal low occurring from mid-1975 to mid-1977.

INTRODUCTION

Changes in the acceleration of gravity at the surface of the earth are due to relative movement of mass within the earth, and to variation of the separation of the measurement point from the earth's center of mass. Atmospheric effects (discussed by Warburton and Goodkind, 1977) are significantly smaller than other uncertainties in local gravity surveys and, for our purposes, are not considered. Because the processes of tectonophysics can alter both density of subsurface rocks and the elevation of the ground surface, changes in gravity can be an important geophysical tool for understanding the forces and deformation of the earth's crust.

Gravity measurements are essential complements to measurements of elevation changes in order to interpert the sub-surface crustal distortion taking place in tectonically active regions. Elevation measurement programs now in progress measure either the geometric elevation change directly, as in the extraterrestrial methods such as Very Long Baseline Inferometry (VLBI), or they measure the orthometric elevation referenced to the geoid which itself may change (for a discussion, see Whitcomb, 1976). The program described here was begun in order to coordinate gravity measurements with VLBI project ARIES (Astronomical Radio Interferometric Earth Surveying) whose survey sites have spacings of 100-1000 km (see, for example, MacDoran, 1974). The gravity network was also densified to intermediate sites to provide better spatial resolution between the ARIES survey sites and to correlate with leveling data in the same regions.

One of the difficulties with most geodetic techniques is that their expense precludes high resolution in both spatial and temporal coverage of a region that is suspected of rapid tectonic distortion. Leveling surveys give detailed coverage along the line of survey but are generally repeated only every few years. Extraterrestrial techniques such as VLBI or laser ranging currently are most useful at station distances of 100 km or more and, with a few exceptions, are repeated yearly at best. Gravity meter surveys are relatively inexpensive compared to the above methods and therefore provide a means for bridging the temporal and spatial gaps left by widely-spaced or infrequent surveys to better define the time and extent of a crustal distortion event. To best complement other geodetic surveys, a gravity survey must therefore be both widespread to cover the spatial spread of extraterrestrial techniques and be frequent to cover the temporal gap left by surveys that are too expensive to repeat at short time intervals. These considerations have dictated the mode of the gravity survey described here. It was designed to cover a wide geographic range, to repeat every one to two months, to co-locate with as many geodetic and geophysical measurement sites as possible, and be cost effective.

The first consideration in the development of a time-dependent gravity monitoring program in tectonophysics is to determine the expected changes in gravity that are related to crustal distortion. The so-called "Palmdale Bulge" in Southern California (Castle et al., 1976) represents a broad elevation change of up to 45 cm over approximately

10-15 years. Much of this occurred during times at least as short as the interval between leveling surveys, of the order of 3 to 5 years. More recent evidence indicates elevation decreases of 17 cm over a period of two years or less north of Los Angeles. If all of this elevation change were to take place with no horizontal mass transfer, then the movement will be characterized by the free-air distortion gravity gradient of 3.08 μgal/cm. In this case, a 17 cm elevation decrease would give a gravity increase of 52 μgal and a 45 cm increase would give a gravity decrease of 139 μgal. Density changes within the earth's crust can also strongly affect gravity. Gravity and elevation data from the Matsushiro earthquake swarm in Japan (Kisslinger, 1975) show gravity changes of up to 80 μgals which had up to 40 μgals deviation from the free-air distortion gravity gradient. This combined gravity and leveling data indicated a $0.6\text{-}1.8 \times 10^{-4}$ dilatant volumetric strain within the crust (Whitcomb, 1976). During a 3 to 4 month period prior to the M = 7.8 Tangshan, China, earthquake, gravity changes were measured ranging from -90 to +167 μgals with the positive change occurring over the region of the future shock (Wang, 1979). Because no coincident elevation data were available, this 257 μgal range could have been the result of either elevation change or subsurface density change. For example, gravitational effects of this size are well within the estimated range of density variation. due to dilatancy models of a crust in preparation for a major earthquake (Whitcomb, 1976).

As will be shown here, the estimated standard deviation of a meter reading at a station is about 11 μgal. Since single gravity determinations in the survey are relative to a reference and are not absolute readings of gravity, each determination must consist of at least two readings, one for the station and one for the base. Thus, a single determination should have a combined standard deviation of 16 μgal. The averaging of repeat determinations can reduce the standard deviation to some extent provided that there are no systematic errors and that gravity does not change between readings. Two standard errors of the mean of a five-point moving average used here is calculated to be about 10 μgal, and this value is considered to be a reasonable estimate for testing the significance of a change of the moving average. If 10 μgal is translated into a free-air distortion elevation change, it would be equivalent to 3.3 cm of elevation change. If the 10 μgal is translated into a pure subsurface density change for a body similar to the size of the Matsushiro distortion, thickness of 5 km and radius of 5 km, it would be equivalent to about 3×10^{-5} dilatant volumetric strain (Whitcomb, 1976). The estimated accuracies of the gravity survey are indeed adequate to provide significant insight into tectonophysical processes.

The purpose of this paper is to describe the Southern California gravity survey and data reduction, show the temporal variation of gravity data since 1974, and show possible correlations with rainfall, well levels, and earthquakes in the region.

GRAVITY MEASUREMENTS

The gravity station network as listed in Table 1 and shown in Figure 1 has its highest density in the seismically active San Gabriel section of the Southern California Transverse Ranges and adjoining San Andreas Fault, with outlying stations at the radio telescope stations at Goldstone in the Mojave Desert and Owens Valley to the north. Both of the radio telescope stations are used as base stations for the ARIES long-baseline geodesy program. The base station of the gravity network is circled in the figure. Located at the California Institute of Technology in Pasadena, this station is the starting the ending point for al! surveys and all gravity values are directly referenced to this single point. This is the same base station used by Oliver et al. (1975) in their study of the 1971 San Fernando earthquake.

The gravity meters used for the survey are La Coste-Romberg Model G meters, G395 and G465, with electronic readout. The earlier part of the survey, from 1974 through 1976, made use of G141 which is the same type of meter without electronic readout. The model G is generally considered to be the state-of-the-art for portable gravity instrumentation with the possible exception of the La Coste-Romberg Model D. The Model D has increased sensitivity of the internal screw, one milligal per revolution versus 70 milligals for the Model G, at the sacrifice of dynamic range. The range of the Model D is 200 milligals versus 7000 milligals for the Model G, which is good for the entire earth's surface. In a side-by-side survey under the same conditions, the Model D appears to be superior only if the transport distance is short and the gravity range is less than 50 milligals (H. W. Oliver and S. L. Robbins, personal communication, 1975). Survey errors for the Model G meters used here appear to be dominated by non-linear changes in spring length or tares, and this is a characteristic that should be shared by Model D. These tares become more of a problem with increased severity of vibrations to the meter due to transport. For the type of survey used here, with substantial transport distances and ranges of gravity up to 440 milligals, the Model D does not appear to be advantageous to the Model G.

The method of survey is to begin at a base station, follow a broad loop of stations, and return to the base station within eight to ten hours for a measurement of closure. Because the long-term linear drift during this time is 0 to 15 μgals, depending on the meter used, linear drift should be a minor contribution to the uncertainty of the measurement. This method of measurement allows a broad geographical region to be tied directly to the value of gravity at the base station without accumulation of systematic errors as in the extension of a survey line by the joining of segments. The major benefit of this method is that it is the most cost-effective means to monitor gravity over a broad region. This factor allows more frequent measurements that help to establish the time of a rapid change of gravity, and provide a means to improve the accuracy through a combination of frequent repeated measurements.

Closure is the difference in reduced gravity at the base station between the measurements at the start and the end of a single survey. Statistics of individual meter closures show that two-thirds of the closures are less than the following values: G141 - 30 μgals; G395 - 25 μgals; G465 - 45 μgals. The high value for G465 is due to its young age and presumably will improve after its initial settling down period. Overall statistics show that 75% of the individual surveys have closures less than 40 gal. On the basis of this number and an observation of the general scatter of data with higher closures, 40 μgal closure is set as the limit of data acceptance. All data associated with higher closures is rejected.

Very large misclosure sometimes occurs and this often has been traced to a short episode, of duration less than travel time between stations, in which a tare has occurred. The behavior of the meter, as deduced from the stations' gravity values from previous and following surveys, appears to be normal immediately before and after the tare. In one such case during a survey in October 1978, G395 was accidentally struck which produced a tare of 637 μgal. Gravity values from the following stations in that day's survey showed no unusual deviation from the expected values except for the constant 637 μgal shift at the time of the accident. However, meter drift was abnormally accelerated for one month. It has been noted in this data set that when large misclosures occur, the scatter of individual station gravity values is often larger as comapared to moving averages of the data, even when the data reduction process assumes a single tare during the day's survey. This may suggest that tares tend to occur in groups of two or more, possibly as a result of unfavorable meter transport during that particular survey or the nature of non-linear drift characteristics of the meter's spring.

Distribution of the closure error is complicated by the fact that closure is sometimes larger and of opposite sign than what would be expected from the long-term linear drift of the gravity meters. Figure 2 shows the drift of G141, G395, and G465 at the base station. The amplitude is in dial turns which are approximately 1 milligal. The large shift in G465 in 1978 corresponds to a readjustment of the meter. Maximum linear meter drift is about 40 μgals per day and this would mean a 17 μgal misclosure over a 10 hour survey. Drifts for G141 and recent data from G395 are considerably below this at 4.6 μgal/day and -8 μgal/day, respectively. Another potential source of misclosure is from tares or non-linear changes in spring length over short time periods. In order to account for both linear drift and tares, the misclosure distribution is calculated in two ways. First, a linear drift with time is assumed; second, a combination of a single tare plus a linear drift with time is assumed. The distribution is chosen that produces the best fit, in a least squares sense, to the average values of the individual stations. In this manner, the added degree of freedom, a tare between stations, is allowed if the gravity values for that run are closer to the average station values. Thus, the extra degree of freedom in distribution of misclosure tends to minimize any deviation from the average values of the stations. This algorithm chose the simple linear distribution 25% of the time and the tare plus linear distribution for the remaining 75%.

Errors in the gravity data can be introduced by inaccurate estimation and removal of the tides, both solid-earth and ocean tidal components. While the solid-earth gravity tides are well known for the levels of accuracy needed here, the ocean-loading tides can be a problem in a region near the coast such as Southern California. In some cases errors up to 16 μgal are possible (Whitcomb, 1979). The gravity data here have had selected ocean-loading tidal components removed as will be described in a separate paper. It is estimated from comparison of our solid-earth and ocean-loading tidal calculations to observed tidal data that tidal uncertainties are less than ±1 μgal with somewhat higher errors within 50 km of the coastline.

In order to compare the results from one meter to another, the calibration factor of each meter must be defined more precisely than the values provided in the manufacturer's tables, which are at 100 milligal intervals and given to the nearest 10 μgal. After the tables are used, calibration can be done from the data themselves by computing the statistics for each station when multiple meters are used on the same survey. In this manner a separate calibration factor is computed for each station that minimizes the difference between the meters when they are used simultaneously on surveys. Only data with closures of 40 μgal or less are used to compute the calibration factors between meters. Because the meter G395 has the longest history and is the only meter with data coincident with both G141 and G465, it is used as the reference meter. The individual station results showing the difference between G395 and the other meters for each station are shown in Figure 3. Data points with no error bars, which are standard deviations, are computed with fewer than 4 observations for that particular station. All gravity data here is adjusted to be equivalent to readings on G395.

A potential source of error with a cyclical nature has been attributed to non-linearities of the internal screw of model G meters. The error has a period of approximately 70 milligals or exactly one revolution of the internal screw. For some meters, this error can be as much as 30 μgals peak-to-peak (R. Jachens, personal communication 1978). At the current drift rate of G141, a complete 70 milligal cycle would take about 41 years. THe last two years' drift rate on G395 would produce a 70 milligal cycle in about 20 years. The points in Figure 3 exhibit characteristics that might be this type of error but the data are not of a quality as yet to confirm this. When the phase and amplitude of the 70 milligal-period variation is calibrated, then the data can be corrected if necessary. Further study of this behavior is in progress.

Figure 4 shows the gravity data as a function of time for 28 stations of the Southern California area as shown in Figure 1. All gravity data here represent the gravity at the station minus the gravity at the Pasadena base station. Different symbols refer to the meter used for the reading; triangles for G141, squares for G395 and circles for G465. The station name and number along with its average gravity value are shown in each diagram. The average value has been subtracted from the data for each station so that the zero line represents the average. The error bars on individual points in Figure 4 are estimated solely from the closure. The total length of the error bar is the closure or 20 μgal, whichever is the larger. Thus, because the closure limit is 40 μgal, the error bars for a single point range from ±10 to ±20 μgal. Assuming that smaller misclosure implies a lower uncertainty for the data points associated with that survey, these error estimates are in good agreement with the 16 μgal standard deviations estimated below for all data.

The solid lines in Figure 4 represent ±2 standard errors of the mean of a moving, five-point weighted average of the individual data points shown in the same figure. The average itself, which is not plotted, is mideay between the solid lines. Weighting is done with the assumption that the error bar shown for each point represents that point's standard deviation. The ± 2 standard error range is used as a test of the significance of any change observed in the average.

Independent confirmation of the reality of gravity changes outside the ±2 standard error range is fortunately available for Station 22. Three independent gravity surveys have been made to this station by the National Geodetic Survey. Each survey consists of four to six determinations using meters different from those described in this paper. The data are shown as solid points for Stations 22 and 23 in Figure 4. The first two points show no change while the error range shows a significant increase during mid-1975 and then a return to the early-1975 values by the time of the second NGS point in mid-1976. When the moving error range again increased by about 35 μgal in early-1977, the NGS was able to repeat the determination and found the same increase in gravity. Thus the changes seen for Station 22 in Figure 4 of the order of 30 μgal are considered to be real and take place over periods of 6 months or less. It is clear that in order to avoid temporal aliasing of the data as occurred with the first two NGS data, measurements must be made at intervals significantly less than 6 months.

The scatter or standard deviation of individual gravity measurements can be estimated with two essentially independent methods. The first is to estimate the standard deviation of data for stations close to the base station under the assumption that their gravity relative to the base is not changing with time. At least two stations fulfill these criteria, Stations 16 and 24. The standard deviations of the data for Station 16 are as follows: G141 - 14 μgal, and G395 - 15 μgal (G465 does not have enough data). The standard deivations of the data for Station 24 are as follows: G141 - 15 μgal, G395 - 14 μgal, and G465 - 22 μgal. The readings for these stations are generally not done on the same day and therefore they should be independent data sets. The larger standard deviation of G465 is presumably due to the first year's instability of a new meter and a small sample. Because two readings are required for each point, the base station and the survey station, single-reading standard deviations for G141 and G395 would be 11 μgals and for G465, 16 μgals. A second method of estimation of a single-reading standard deviation is to use the comparison of two meter readings for the same station and survey, which should be identical after the meter calibration factor is removed. The standard deviation of 85 observations of G141 compared to G395 is 22 μgal. The standard deviation of 79 observations of G465 compared to G395 is 23 μgal. Each of these comparisons requires four single readings, one base station and one survey station for each meter. Thus, a single-reading standard deviation for each comparison is about 11 μgals, in agreement with the independent estimate above.

RESPONSE TO GROUNDWATER

Although every attempt has been made to place gravity stations at bedrock sites where near-surface porosity is low, it is not always possible to avoid sediment basins. This is due to factors such as the absence of bedrock at a tectonically important site, ease of access, and the fact that many survey bench marks are located in valleys along major roads. One half of the sites are situated on sediments. The gravitational effect of a varying level of groundwater can be significant but it depends on factors such as porosity and extent of the aquafer. The attraction due to an infinite horizontal slab of water is 0.419 μgals per centimeter of slab thickness. The general behavior of groundwater levels depends on the general rainfall of the region with modification by nearby pumping if present. The presence of pumping usually ensures a program of groundwater level monitoring that can be used to directly estimate the gravitational effect of level variations. However, because monitoring wells are usually not located immediately next to a gravity station, it is found that well levels do not always correspond to gravity variations at a station. For the station set, a search was made for monitor-well data close to all gravity stations located on sediments. The gravity data for these stations can then be correlated with their respective well data. In addition, data for all stations can be correlated with precipitation, the ultimate source of aquafer recharge.

Figure 5 shows monthly rainfall in Los Angeles (Station 716) after it has been passed through a low-pass exponential filter with a drop-off of 1/e in one year (the filter was started in 1959). Treated in this manner, the rainfall data is intended to resemble the behavior of an aquafer that is charged with water during the winter rain season in Southern Calfiornia and slowly drained either by lateral flow or by pumping. The average rainfall is 1.27 inches/month, but statistically, 76% of the rain comes in the months of December, January, February and March. The figure shows that rainfall in 1974-75 was average, 1976-77 was low, and 1978-79 was high.

The largest gravity change of the stations in Figure 4 is that of Station 28, which shows a 80 μgal increase in early 1978. If this is compared with the filtered rainfall data of Figure 5, a clear correlation is seen. During the heavy rains of early 1978, the closest monitored well to Station 28, Well 7128C, 100 meters away, showed a very large increase in level of nearly 16 meters. If this well data were to be converted to a gravity change with the assumption of a horizontal water table in an aquafer of porosity 0.13, it would closely fit the gravity data of Station 28 as shown in Figure 6. The zero level in Figure 6 is arbitrary. Thus, both the amplitude and the timing of the large gravity increase at Station 28 is readily explained by groundwater. However, for this station, the converted groundwater data of Figure 6 in 1975 are significantly higher than the measured gravity of Figure 4. This may be due to a different phase response of the aquafer under the gravity station compared to the well. For example, if the smoothed rainfall data of Figure 6 is compared to the gravity data, it can be seen that a slightly faster dropoff of the early 1975 rainfall charge could bring the late 1975 levels down to the 1976 levels, as is seen in the observed gravity. Thus, in the case of the highest gravity response to groundwater variations, smoothed rainfall appears to be a good indicator of the qualitative response of a gravity station to changing groundwater levels.

Figure 6 also shows the converted groundwater data for all other wells that are near sediment-basin stations and for which water level monitoring data has been found. The well number and corresponding gravity station name and number are shown for each data set. The well level changes were all converted to gravity change with the same assumptions of a horizontal groundwater slab in an aquafer of 0.13 porosity. Data from well 4076 is close to the base station (CALTECHL) and shows changes that would correspond to a drop of 20 μgals during 1976-78. Two closeby gravity stations, 16 and 24, are in sites that should have little groundwater effect and were installed to monitor the behavior of the base station. Gravity data for Stations 16 and 24 in Figure 4 show no increase in gravity during the 1976-78 period during the low of data from well 4076 or the low of the filtered rainfall. It is concluded that the base station has had no measurable response to nearby well data or rainfall as yet. Well 5873D close to Station 27 shows little change, yet the gravity data have a good correlation with the smoothed rainfall data of Figure 5. Well 8488A close to Station 29 shows a large water level variation that correlates fairly well with the rainfall data but the gravity data of Figure 4 does not agree. In this case the gravity data has a large variation but the low of the gravity data is a few months later than the low of both the rainfall and well data. It is possible that the gravity variation is due to groundwater but that the aquafer system under the gravity station has a different phase delay in response to groundwater recharge. Further rain cycles should resolve this. The wells 8695A and 8695B near Station 31 show little correlation with rainfall and their levels have been stable. The Station 31 gravity data has similar behavior with no significant change from 1975 through 1978. Well 8876 near Station 36 shows little variation in water level but the gravity data, which is scattered after 1978, has some correlation with filtered rainfall.

Some of the gravity stations are on sediments, but no nearby monitoring-well data have been found for comparison. However, the above analysis shows that the qualitative behavior of gravity response to groundwater can be estimated from correlation with the filtered rainfall data of Figure 5. Of the remaining suprasediment gravity stations, Stations 23, 43 and 46 show no rainfall response. Station 26 shows some response but the data are scattered. Station 44, located on a bridge benchmark over a stream channel in Wrightwood, California, shows correlation with the filtered rainfall data but the response to the high rainfall in early 1978 is delayed by 3 to 6 months. Further rainfall correlation study is needed for this station to determine its response. Station 47 shows some correlation with the rainfall but again the response is delayed.

Although more data is needed before an accurate analysis can be done, it appears that the gravity stations can be easily calibrated as to their response to local groundwater variations by correlation, perhaps with phase shifts, with a function constructed from filtered rainfall data. The groundwater response can then be removed from the gravity data. This analysis points to the need for frequent observation of stations in order to compute their gravity response to groundwater variations.

Station 45, on Table Mountain near Wrightwood, California, shows a possible correlation with the heavy rainfall of early 1978. Because this station is at a high elevation near the top of the mountain, heavy show accumulation is possible on the mountain during the cold winter and spring months followed by water saturated soils into late spring. Accumulations of precipitation equivalent to 36 cm of water, a reasonable estimate for heavy snow pack, that is distributed in a horizontal slab under the gravity station would increase the gravity by only 15 μgals. However, the effect of the downslope water distribution at a station on the top of a mountain will increase the vertical gravitational acceleration for the same thickness of accumulation. A simple calculation can be done to estimate the effect. Assume that a gravity station is at the apex of a circular cone as shown in Figure 7 with sides that slope at an angle $\underline{i}$ from horizontal, $\underline{R}$ is the down-slope distance, and $\underline{dA}$ is the element of cone area at distance R from the apex and horizontal angle $\underline{\Theta}$. The mass $\underline{dm}$ of a layer with surface density $\underline{\rho}$ at $\underline{dA}$ is: $\underline{dm} = \underline{\rho dA}$. The vertical gravitational attraction of the water layer is therefore:

$$\Delta g = G \sin i \int \frac{dm}{R^2} = G \rho \sin i \int \frac{dA}{R^2}$$

$$= G \rho \sin i \cos i \int_0^{2\pi} \int_{R_1}^{R_2} \frac{dRd\Theta}{R}$$

$$\Delta g = 2\pi G\rho \left(\sin i \cos i \ln \frac{R_2}{R_1}\right) \qquad (1)$$

where G is the gravitational constant (6.673×10^{-8} cm^3 g^{-1} s^{-2}). The first part of equation (1) is the familiar infinite slab formula so that the second part in brackets, $\sin i \cos i \ln R_2/R_1$, is the amplification factor due to the non-horizontal mass distribution of the cone. Equation (1) can now be applied to reasonable values for Station 45. If the slope $\underline{i}$ is 14°, R_1 is 50 cm, R_2 is 1.6 km, and the water layer is 36 cm thick, then the gravitational attraction is 29 μgals or 1.9 times the attraction due to a horizontal water slab of the same thickness. Half of the contribution of the 29 μgals comes from the first 30 meters of the down-slope distance R. Thus, relatively local distributions of snowpack downslope from a hilltop site can easily double the attraction compared to an equivalent amount of snowpack distributed horizontally. The value of 29 μgals compares well with the observed increased gravity in early 1978 at Station 45. One additional mountain site, Station 37, appears to have a similar effect although the site is on a mountain saddle instead of a peak, which reduces the amplification effect.

The sites along the Malubi coast, Stations 4 - 9, show no correlation with rainfall with the possible exception of Station 9 at the westernmost end along the coast. Station 9 shows a 50 μgal low beginning in late 1975 and ending in late 1977, a two year duration. This gravity low approximately coincides withe the filtered rainfall low of Figure 5 except that the gravity low terminates before the rainfall low. This would preclude the possibility of the gravity low being directly caused by rainfall induced groundwater effects. Other considerations also weigh against water-related effects. Station 9 is situated on a cement structure at the entrance to a highway culvert at an elevation above sea level of 3 meters. Because the ocean is nearby and the ground level is approximately 2 meters below the station on the side opposite the highway, there is little latitude for groundwater-level variation. Moreover, Station 8 is in a nearly identical situation and shows no correlation with rainfall. Therefore, it is concluded that the 50 μgal gravity low at Station 9 is not groundwater-induced.

CORRELATION WITH TECTONIC ACTIVITY

Table II and Figure 1 show the earthquakes that have occurred in Southern California of M_1 = 4.5 and larger from January 1974 through March 1979. Of the events of magnitude 5.0 or larger, only four are within 100 km of a gravity station. The first earthquake is a magnitude 5.1-5.7 (M_L) - 5.6 (M_s, USGS) that occurred on August 13, 1978 in the Santa Barbara Channel 67 km west-northwest of Station 9. As discussed above, gravity data for Station 9 show the only significant change among the entire network of stations for which no alternative explanation such as groundwater variations can be found. Gravity decreased by 50 μgals in 1975, increased again by 1978 after which the earthquake occurred as shown in Figure 4. Under the assumption that the gravity change at Station 9 is caused by tectonic distortion and that the tectonic distortion is related to the earthquake in the Santa Barbara Channel, it is interesting to compare the station-event separation distance with similar precursory distortion data from past events. Anderson and Whitcomb (1975) related the maximum observation distance for precursory distortion to the fault or aftershock dimension of the earthquake. The relationship closely follows the equation $\log_{10} (\ell/L^2) = -3$ where ℓ is the length of the earthquake fault dimension or aftershock zone and L is the length of the affected area of precursory distortion. For the Santa Barbara Channel event, the aftershock dimension was approximately 12 km. This then provides a length L of the distortion area of 110 km. Thus, the 67 km separation distance of the Santa Barbara Channel event from Station 9 is within that which has been observed for past precursory distortions.

If the gravity change observed at Station 9 is indeed a precursory tectonic response to the process of preparation for the August 13, 1978 Santa Barbara Channel earthquake, then the lack of a similar gravity change at Station 8 imposes stringent constraints on the distribution of the distortion area. As mentioned above, the stability of gravity at Station 8 provides support to the conclusion that the gravity change at Station 9 is not due to systematic errors for stations in the Malibu Coast loop or due to the effects of groundwater. However, because the stations are separated by only 8 km, the distortion area that gave rise to the gravity change at Sation 9 must be either a local effect or, if it extends west to the epicenter of the Santa Barbara Channel earthquake, its edge must be within a few km of Station 9. Either case is certainly an acceptable physical model, but the argument for association of the gravity change at Station 9 to the Santa Barbara Channel event is weakened by the fact that only one station clearly shows an anomaly that can be temporally related to the event.

The characteristic anomaly duration of earthquake precursors has been put into a relation relating the $\log_{10}$ T (days) to a linear function of magnitude by Tsubokawa (1969), Whitcomb et al. (1973), Myachkin and Zubkov (1973), Scholz et al. (1973), and Rikitake (1975). If the larger of the estimates of the magnitude of the Santa Barbara Channel earthquake were to be applied to these formulas, they would give anomaly duration times ranging from 240 to 420 days. The anomaly time of the data in Figure 4 for Station 9, as measured from the beginning of the anomaly to the event in August 13, 1978, is about 1,000 days. Thus the gravity anomaly duration is longer than that expected from the earlier formulas. However, these formulas will require considerable testing and probable modification before they can be applied confidently, especially for varying types of earthquakes and tectonic regions.

The next two events occurred close to one another in time and space on October 4, 1978, 50 km north of Stations 40 and 41. The first was a magnitude 5.8 (M_L) - 5.2 (M_s, USGS) and the second was 5.3 (M_L) within an hour of the main shock. The time of events is shown by arrows in Figure 4, Stations 40 and 41. Unfortunately, due to logistics problems, only four sets of gravity data were gathered for these stations so that temporal details of the behavior of gravity are not available. The latest points were obtained just after the earthquake, and show no consistent change from the data taken in 1975 and 1977. However, it is entirely possible that a change in gravity could have taken place during the 413 days between the survey in 1977 and the event in 1978.

The last larger event that is close to gravity stations is the January 1, 1979 magnitude 5.0 (M_L) earthquake in the Santa Monica Bay off Malibu. This event, as seen in Figure 1, is located approximately 17 km south-southwest of Station 5 and south-southeast of Station 6. Although some gravity change is seen prior to the time of the event in Figure 4, especially at Station 5, the changes are of short duration and are just outside the moving standard error bars.

SUMMARY

Gravity is a diagnostic indicator of the process of tectonophysics that can alter both density of subsurface rocks and the elevation of the ground surface. In order to interpret surface measurements in terms of tectonophysical distortion within the crust, both gravity and elevation measurements are necessary. The program described here was begun in order to coordinate gravity measurements with the long-baseline three-dimensional geodetic measurements of the ARIES project which uses radio interferometry with extra-galactic radio sources. Because gravity measurements are relatively economical, they can be used with greater density both spatially and temporally to increase the resolution of a tectonic event.

From past crustal distortions and actual gravity measurements in an active tectonic area, gravity changes of 50 to more than 200 μgal are likely. From the data here, the standard deviation of a single LaCoste-Romberg model G reading is 11 μgal which gives a relative determination between stations a standard deviation of 16 μgal. The moving average of five readings produces an estimate of 10 μgal for two standard errors of the mean which is taken to be a measure of this survey's resolution of a change in gravity at a typical station. The averaging of all data over the full time span of this survey results in an average value of gravity at a typical station with standard errors of 2 to 3 μgal . From these calculations, the accuracy of the gravity survey is deemed to be more than adequate for detection of tectonic distortion within the crust.

Although every attempt has been made to place gravity stations at bedrock sites in order to avoid the effect of variable groundwater levels, it is not always possible to avoid sediment basins. Where possible, water-well level data near the suprasediment gravity stations are used to estimate the effect of varying groundwater level. This analysis shows that smoothed rainfall data appears to be a good indicator of the qualitative response of gravity to changing groundwater levels at a station. The quantitative response, which depends on factors such as porosity and the shape of the water table surface, can be estimated from the correlation of gravity with smoothed rainfall over several rain seasons. Thus, water well data is not necessary for the calibration of a gravity station's response to groundwater, but frequent measurement of gravity at the station is essential until this calibration is accomplished.

It is found that most of the significant variations of gravity at the 28 stations described here are related to groundwater variations. Indeed, the largest gravity variation observed, 80 μgal , occurred at a station in a sediment basin and the gravity change correlates both with well level and rainfall data giving an estimate of porosity at that site of 0.13.

The largest earthquake to occur within or near the gravity network was the August 13, 1978 Santa Barbara Channel event (M_L = 5.1-5.7, M_s = 5.6). It is considered significant that the closest gravity station to this earthquake, Station 9 on the Malibu coast, also exhibits the network's largest gravity change that cannot be related to factors other than tectonic distortion. This change is a 50 μgal low occurring from mid-1975 to mid-1977. However, if the gravity change is relat d to the earthquake, which is 67 km to the west of the station, then the distortion area must be localized or its edge must be within a few km of Station 9. This reasoning follows from the lack of a similar anomaly at the next closest station which is 8 km to the east of Station 9. The separation distance of Station 9 from the earthquake, 67 km, is within past estimates of the size of precursory distortion areas. The anomaly duration, about 1,000 days, is longer than that calculated from previously published relationships relating the characteristic anomaly duration of earthquake precursors to the earthquake magnitude, 240 to 420 days.

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TABLE I. Gravity Stations

STATION	NO.	LAT.		LONG.		GRAVITY (milligals)
CIT1	4	34.	1.200	118.	30.330	25.564
CIT2	5	34.	2.220	118.	38.150	44.815
CIT3	6	34.	0.100	118.	48.350	53.185
CIT4	8	34.	3.200	118.	57.800	79.764
CIT5	9	34.	5.030	119.	2.300	96.271
LA CO BM	16	34.	12.350	118.	10.300	-52.246
GOLDST	22	35.	25.660	116.	53.300	-133.282
ECHO	23	35.	25.660	116.	53.300	-118.192
LVISTA	24	34.	10.579	118.	10.461	-10.271
TUJUNGA	25	34.	17.369	118.	21.957	-4[illegible].816
SFERND	26	34.	18.869	118.	29.118	-57.604
NEWHALL	27	34.	24.064	118.	32.547	-48.506
MINT	28	34.	24.999	118.	28.918	-50.501
SLEEPY	29	34.	31.251	118.	19.200	-96.838
RITTER	30	34.	30.668	118.	14.042	-124.991
PALM1	31	34.	32.315	118.	6.300	-126.917
BLOSSOM	36	34.	31.237	117.	55.354	-148.633
TIESUMIT	37	34.	23.361	118.	4.793	-363.452
LUCAS	38	34.	17.991	118.	9.133	-154.148
LACREST	39	34.	13.676	118.	11.080	-88.462
OVRO	40	37.	13.970	118.	16.870	-116.296
WESTGARD	41	37.	12.260	118.	14.510	-113.925
CLYDE R.	43	34.	19.440	117	33.828	-285.611

STATION	NO.	LAT.		LONG.		GRAVITY (milligals)
WRIGHTWD	44	34.	21.613	117.	38.130	-343.331
TABLE MT	45	34.	22.970	117.	41.080	-443.173
ANTV MT	46	34.	49.110	118.	29.820	-138.691
ANTV 138	47	34.	46.520	118.	36.280	-147.384
SKELTON	48	34.	11.800	118.	49.300	-2.011
OAK FLAT	49	34.	35.957	118.	43.187	-118.901

TABLE II Earthquakes in Southern California of M_L = 4.5 and larger, January 1974 to March 1979.

DATE			TIME			LAT.		LONG.		M_L
1974	3	9	0	54	31.91	34	23.93	-118	28.41	4.7
1974	12	6	12	13	8.31	32	42.50	-115	23.54	4.5
1975	1	12	21	22	14.84	32	45.39	-117	59.29	4.8
1975	1	23	17	2	29.43	32	57.11	-115	29.38	4.8
1975	5	13	0	21	35.58	34	59.97	-119	6.17	4.5
1975	6	1	1	38	49.23	34	30.94	-116	29.73	5.2
1975	8	2	0	14	7.73	33	31.19	-116	33.48	4.7
1975	11	15	6	13	27.62	34	18.22	-116	20.48	4.6
1975	12	14	18	16	20.09	34	17.38	-116	19.30	4.7
1976	4	8	15	21	38.07	34	20.81	-118	39.34	4.6
1977	8	12	2	19	26.08	34	22.78	-118	27.52	4.5
1978	8	13	22	54	52.33	34	17.31	-119	37.58	5.1
1978	10	4	16	42	48.63	37	31.68	-118	37.89	5.8
1978	10	4	17	39	2.87	37	35.06	-118	37.04	5.3
1979	01	01	23	14	38.90	33	56.70	-118	40.90	5.0
1979	03	15	20	17	50.80	34	18.30	-116	26.30	4.9
1979	03	15	21	07	16.50	34	19.50	-116	26.60	5.2
1979	03	15	21	34	25.50	34	20.80	-116	26.90	4.5
1979	03	15	23	07	58.90	34	19.60	-116	26.30	4.8

FIGURES

1. Map of the Southern California area showing gravity stations, major earthquakes of M_L = 4.5 or larger from January 1974 to March 1979, and major mapped faults in the region.

2. Drift of the LaCoste-Romberg gravity meters G141, G395, and G465 at the base station CALTECHL . The amplitude is in dial turns which is approximately one milligal.

3. Station calibration factors showing the difference between G395 and the other meters for each station as a function of the station's average gravity value. Data points with no error bars, which are standard deviations, are computed with fewer than 4 observations for that particular station.

4. Gravity data as a function of time for 28 stations of the Southern California area. Stations are shown in Figure 1. Triangles refer to meter G141, squares for G395, and circles for G465. All gravity values represent the gravity at the station minus the gravity at the base station CALTECHL. The station name and number along with its average gravity value are shown in each diagram. The average value has been subtracted from each point. The double lines represent plus and minus two standard errors of the mean of a five-point weighted moving average. Arrows indicate the time of nearby earthquakes. Solid points are independently determined values from the National Geodetic Survey.

5. Monthly rainfall in Los Angeles (Station 716) after it has been passed through a low-pass exponential filter with a drop-off of 1/e in one year (the filter was started in 1959).

6. Water-well level data converted to gravity change under assumption of an infinite slab of groundwater in an aquafer with porosity 0.13. The water well numbers are shown along with those of the gravity station that is nearby.

7. Right-circular cone with slope i used to estimate the gravitational effect of mountain snowpack on a mountaintop gravity station.

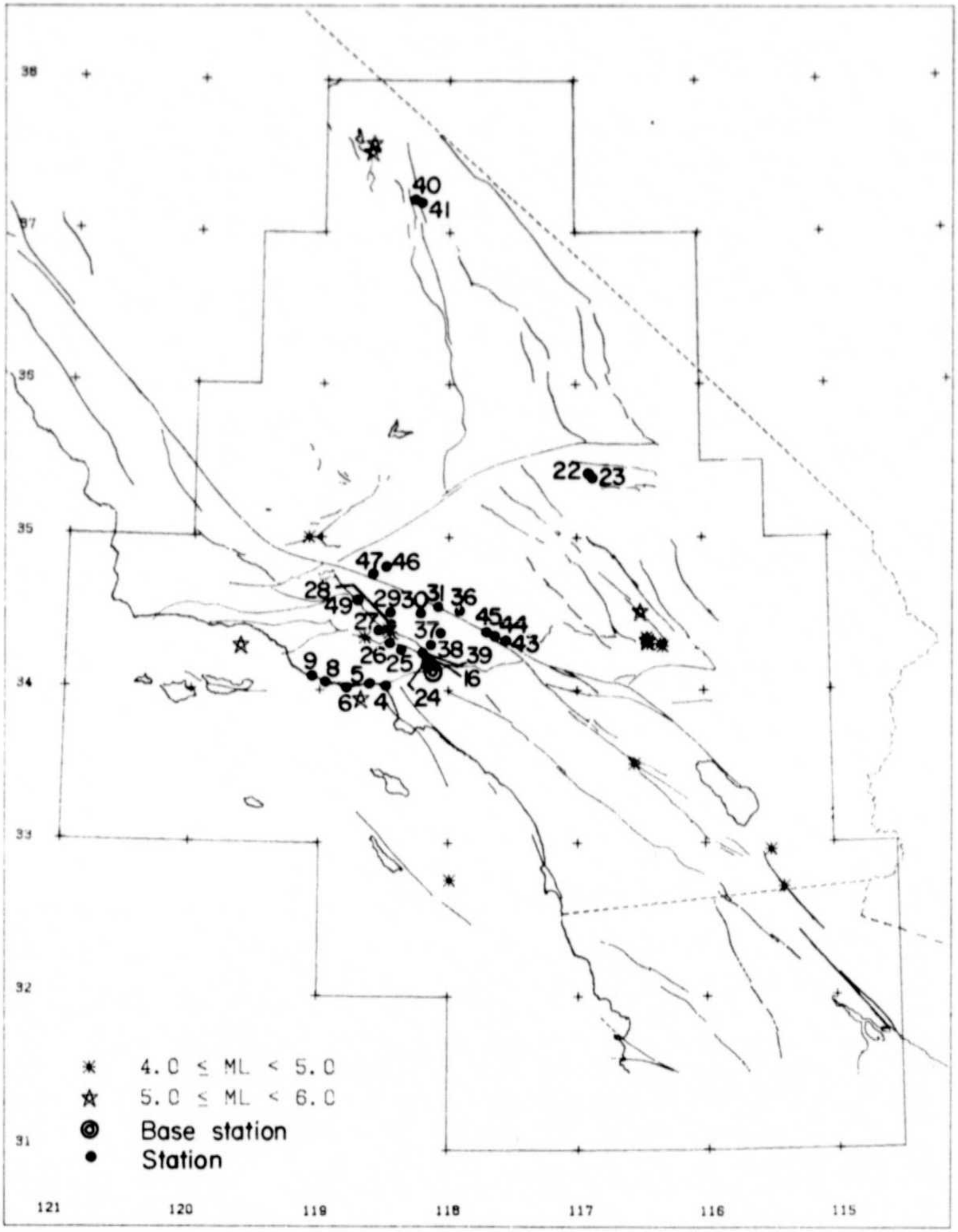
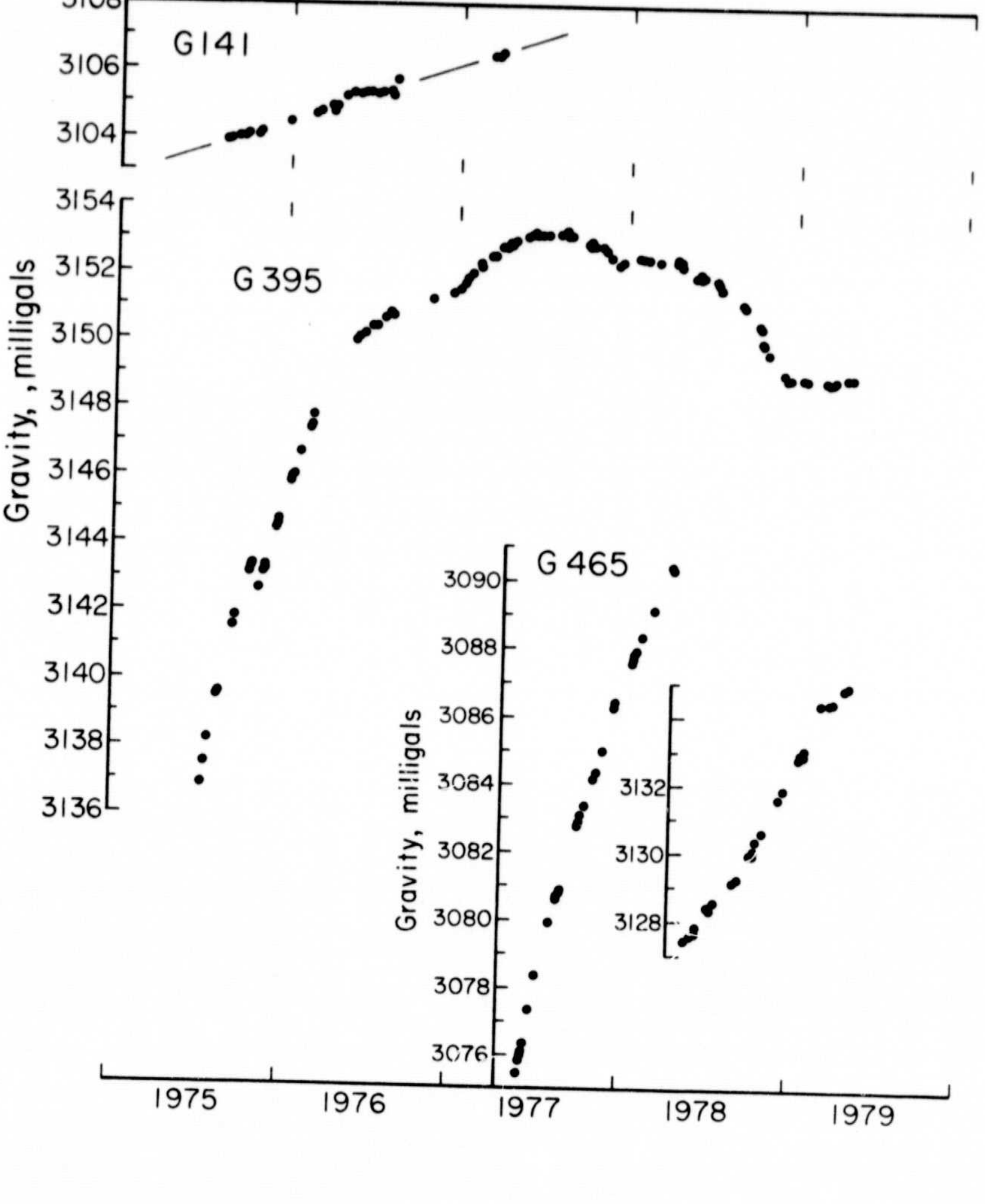

38
37
36
35
34
33
32
31
121
120
119
118
117
116
115
40
41
22
23
47
46
28
49
29
30
31
36
27
37
45
44
43
26
25
38
39
9
8
5
16
6
4
24
4.0 ≤ ML < 5.0
5.0 ≤ ML < 6.0
Base station
Station

Fig. 1



G141
G 395
G 465
Gravity, , milligals
Gravity, milligals
3108
3106
3104
3154
3152
3150
3148
3146
3144
3142
3140
3138
3136
3090
3088
3086
3084
3082
3080
3078
3076
3132
3130
3128
1975
1976
1977
1978
1979

Fig. 2

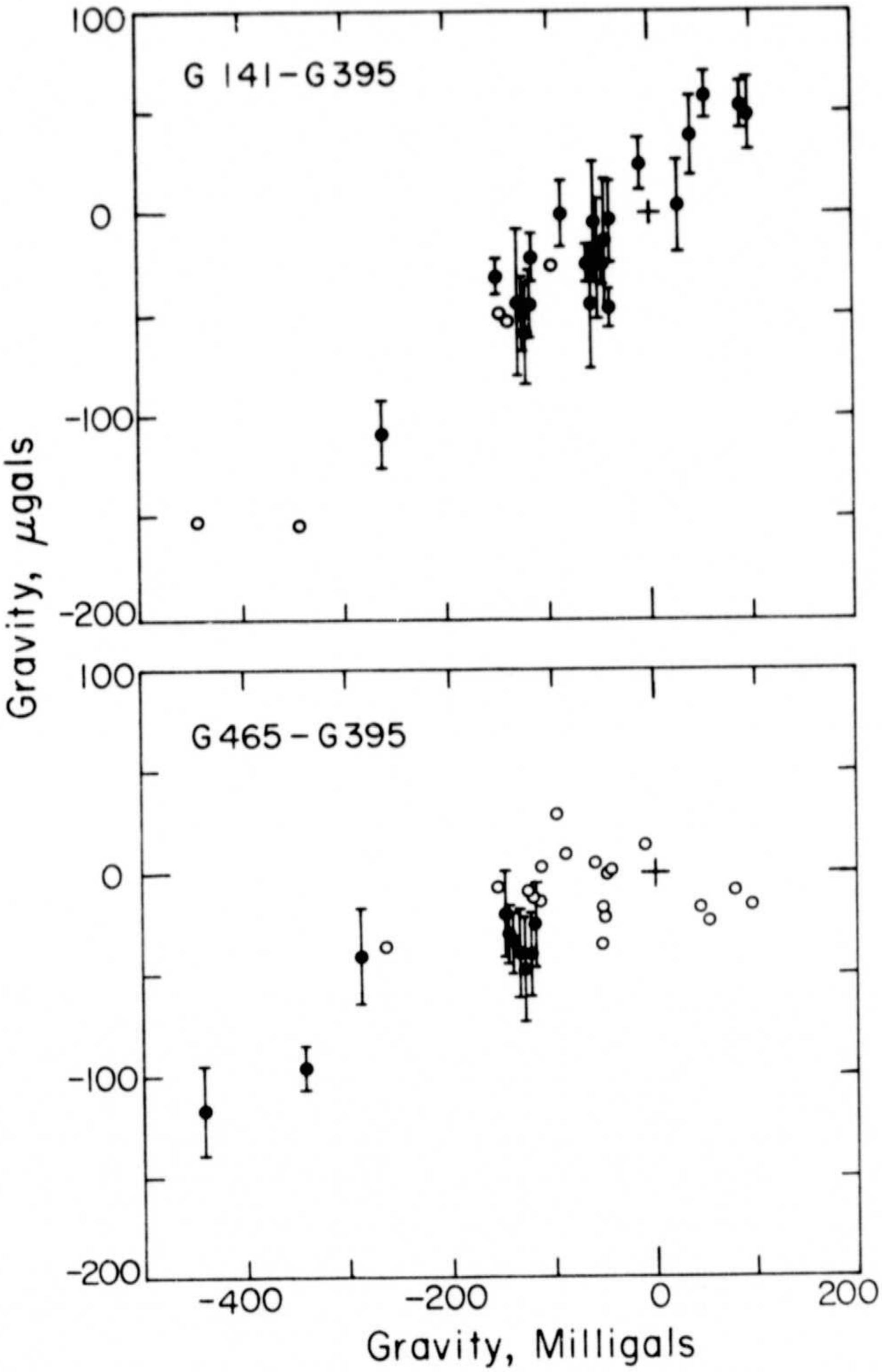
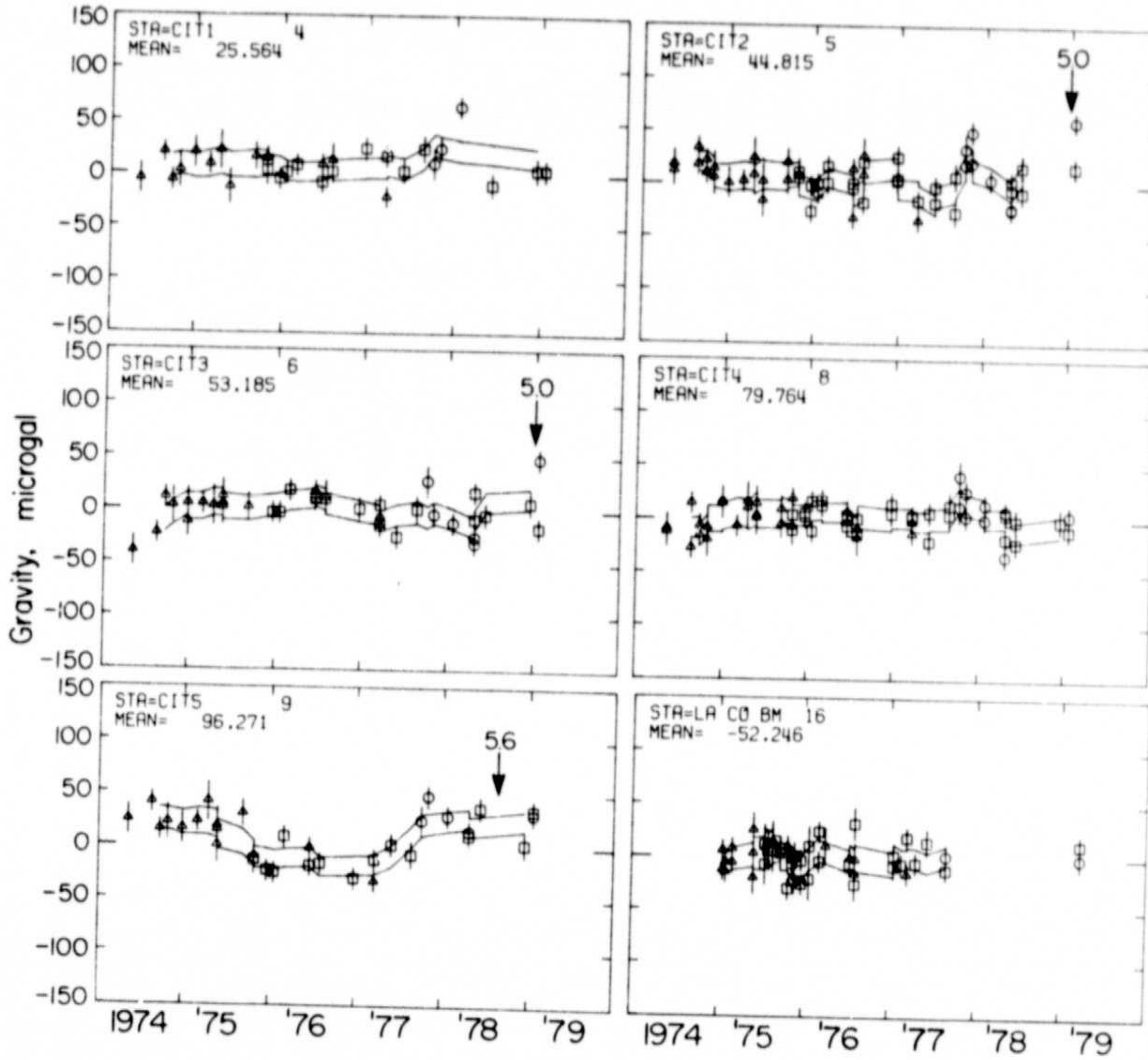
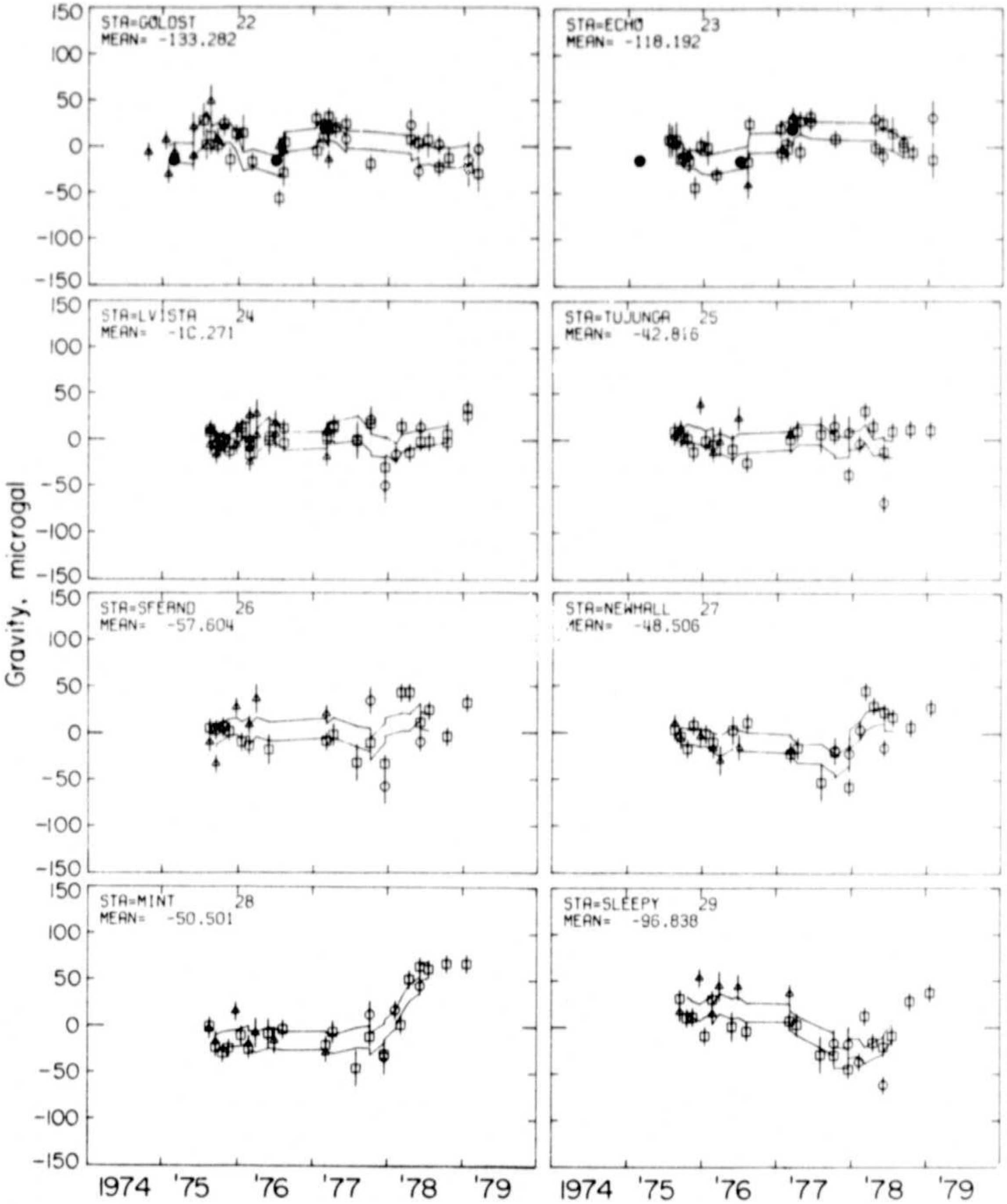

G 141-G 395
G 465-G 395
Gravity, μgals
Gravity, Milligals
100
0
-100
-200
-400
-200
0
200

Fig 3



STA=CIT1 4
MEAN= 25.564
STA=CIT2 5
MEAN= 44.815
5.0
STA=CIT3 6
MEAN= 53.185
5.0
STA=CIT4 8
MEAN= 79.764
STA=CIT5 9
MEAN= 96.271
5.6
STA=LA CO BM 16
MEAN= -52.246
Gravity, microgal
150
100
50
0
-50
-100
-150
1974
'75
'76
'77
'78
'79

Fig 4(a)



STA=GOLDST 22
MEAN= -133.282
STA=ECHO 23
MEAN= -118.192
STA=LVISTA 24
MEAN= -10.271
STA=TUJUNGA 25
MEAN= -42.816
STA=SFERND 26
MEAN= -57.604
STA=NEWHALL 27
MEAN= -48.506
STA=MINT 28
MEAN= -50.501
STA=SLEEPY 29
MEAN= -96.838
Gravity, microgal
150
100
50
0
-50
-100
-150
1974
'75
'76
'77
'78
'79

Fig. 4 (b)

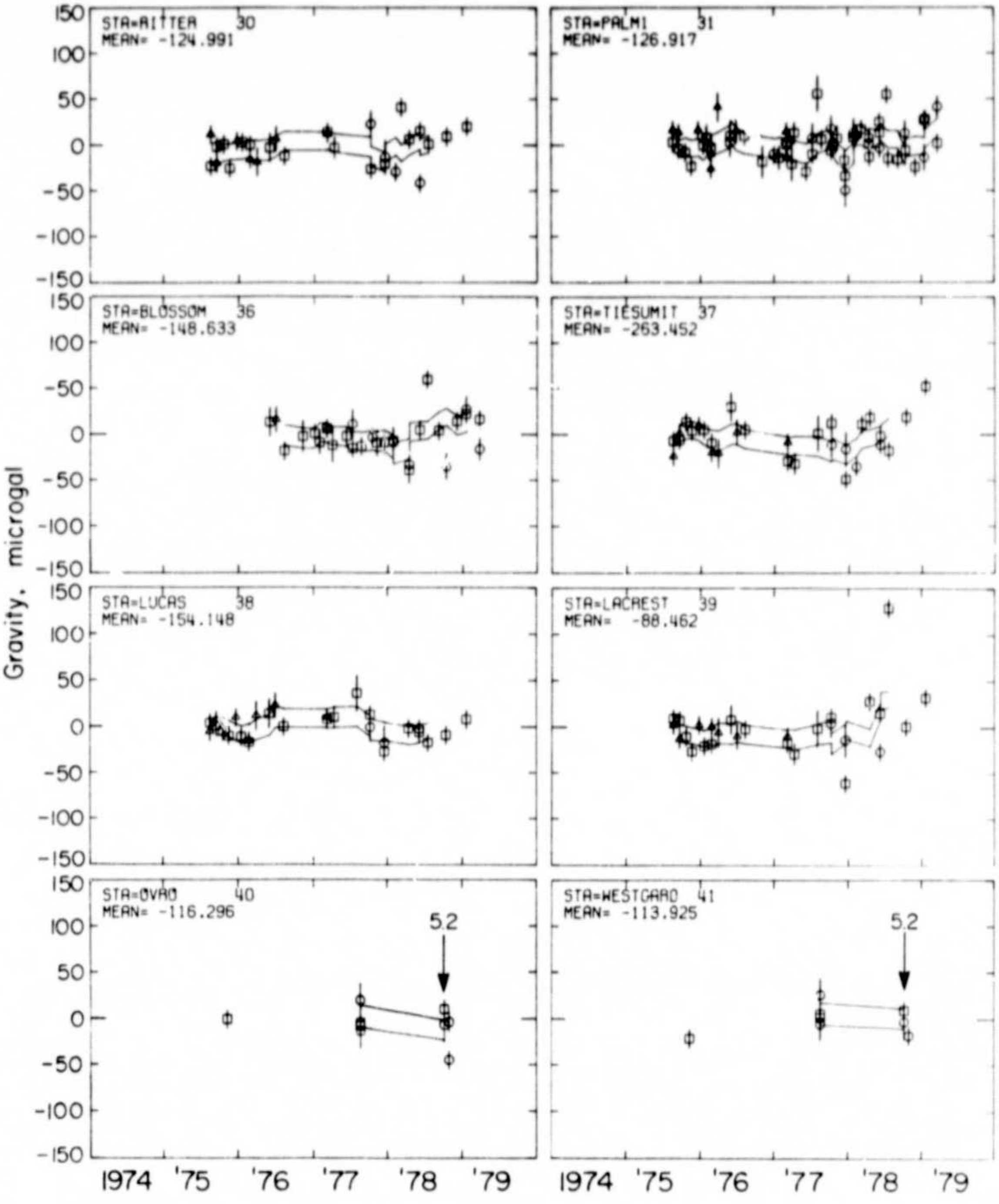
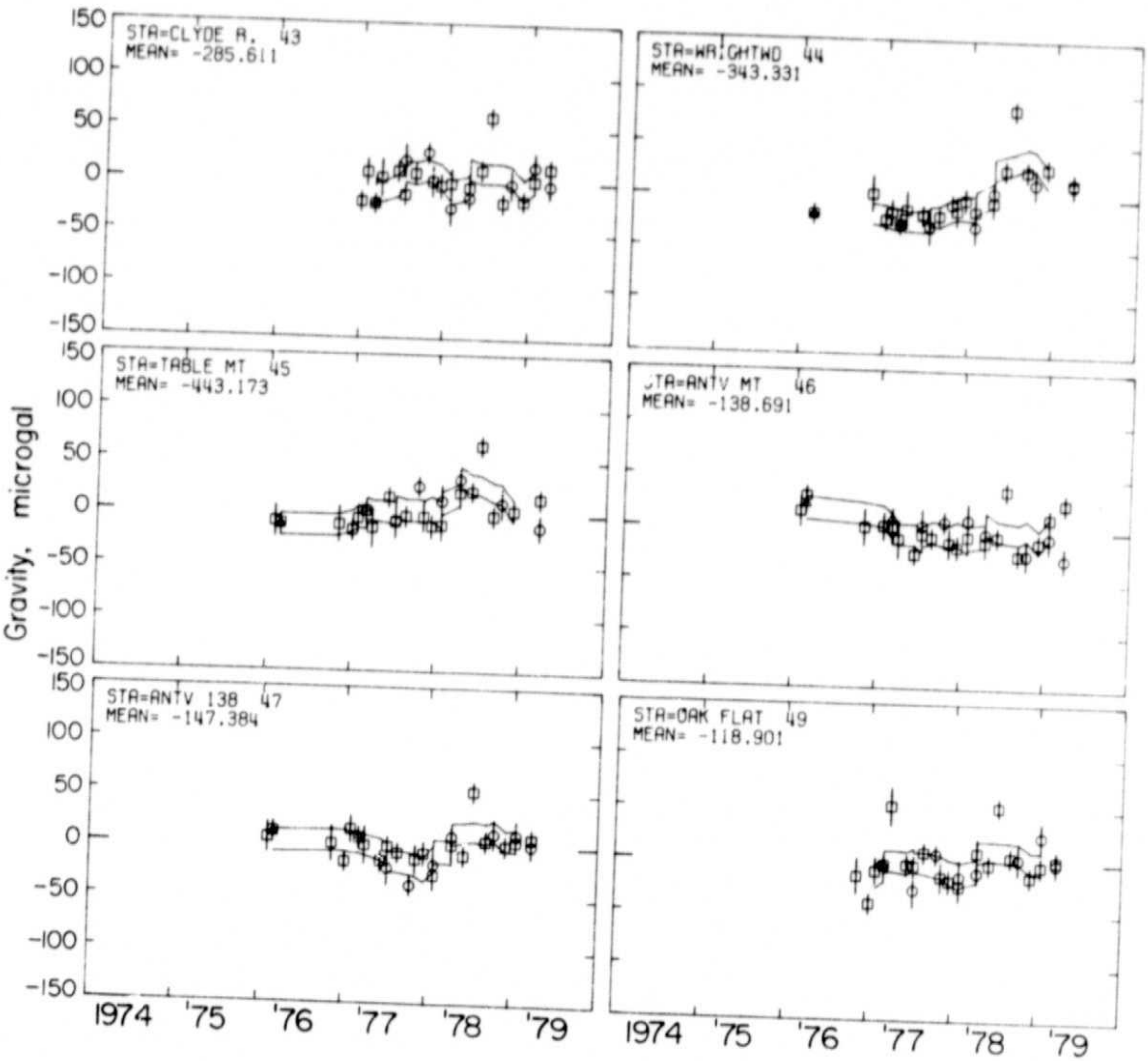
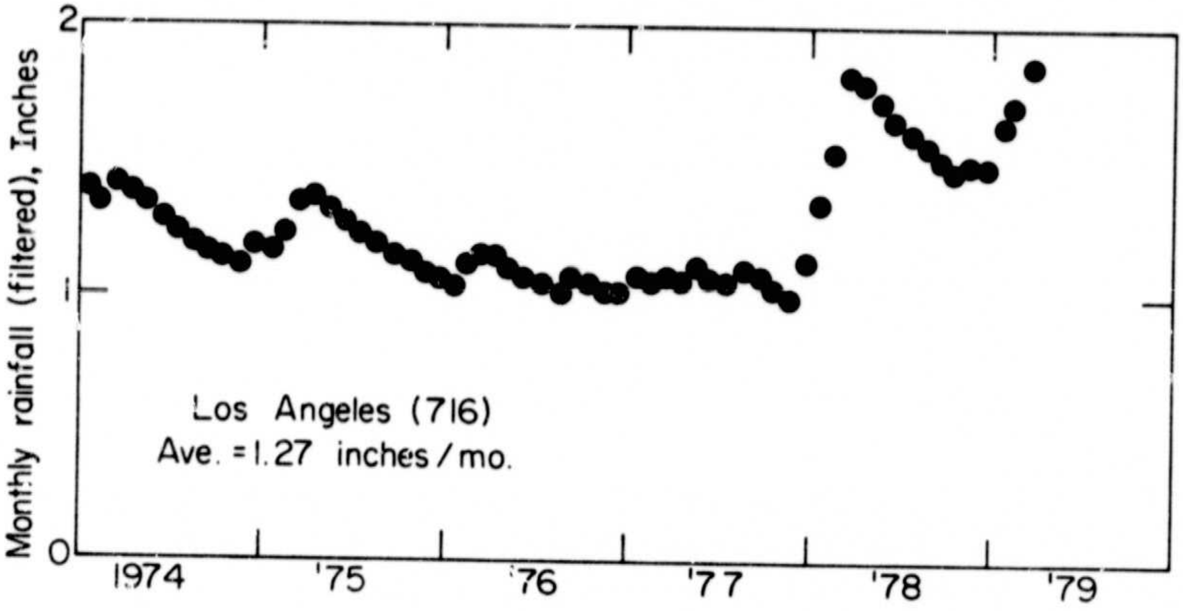

STA=RITTER 30
MEAN= -124.991
STA=PALMI 31
MEAN= -126.917
STA=BLOSSOM 36
MEAN= -148.633
STA=TIESUMIT 37
MEAN= -263.452
STA=LUCAS 38
MEAN= -154.148
STA=LACREST 39
MEAN= -88.462
STA=OVRO 40
MEAN= -116.296
STA=WESTGARD 41
MEAN= -113.925
5.2
5.2
Gravity, microgal
150
100
50
0
-50
-100
-150
1974
'75
'76
'77
'78
'79

Fig. 4(c)



STA=CLYDE R. 43
MEAN= -285.611
STA=WRIGHTWD 44
MEAN= -343.331
STA=TABLE MT 45
MEAN= -443.173
STA=ANTV MT 46
MEAN= -138.691
STA=ANTV 138 47
MEAN= -147.384
STA=OAK FLAT 49
MEAN= -118.901
Gravity, microgal
150
100
50
0
-50
-100
-150
1974
'75
'76
'77
'78
'79

Fig. 4(d)



Monthly rainfall (filtered), Inches
2
1
0
1974
'75
'76
'77
'78
'79
Los Angeles (716)
Ave. =1.27 inches / mo.

Fig. 5

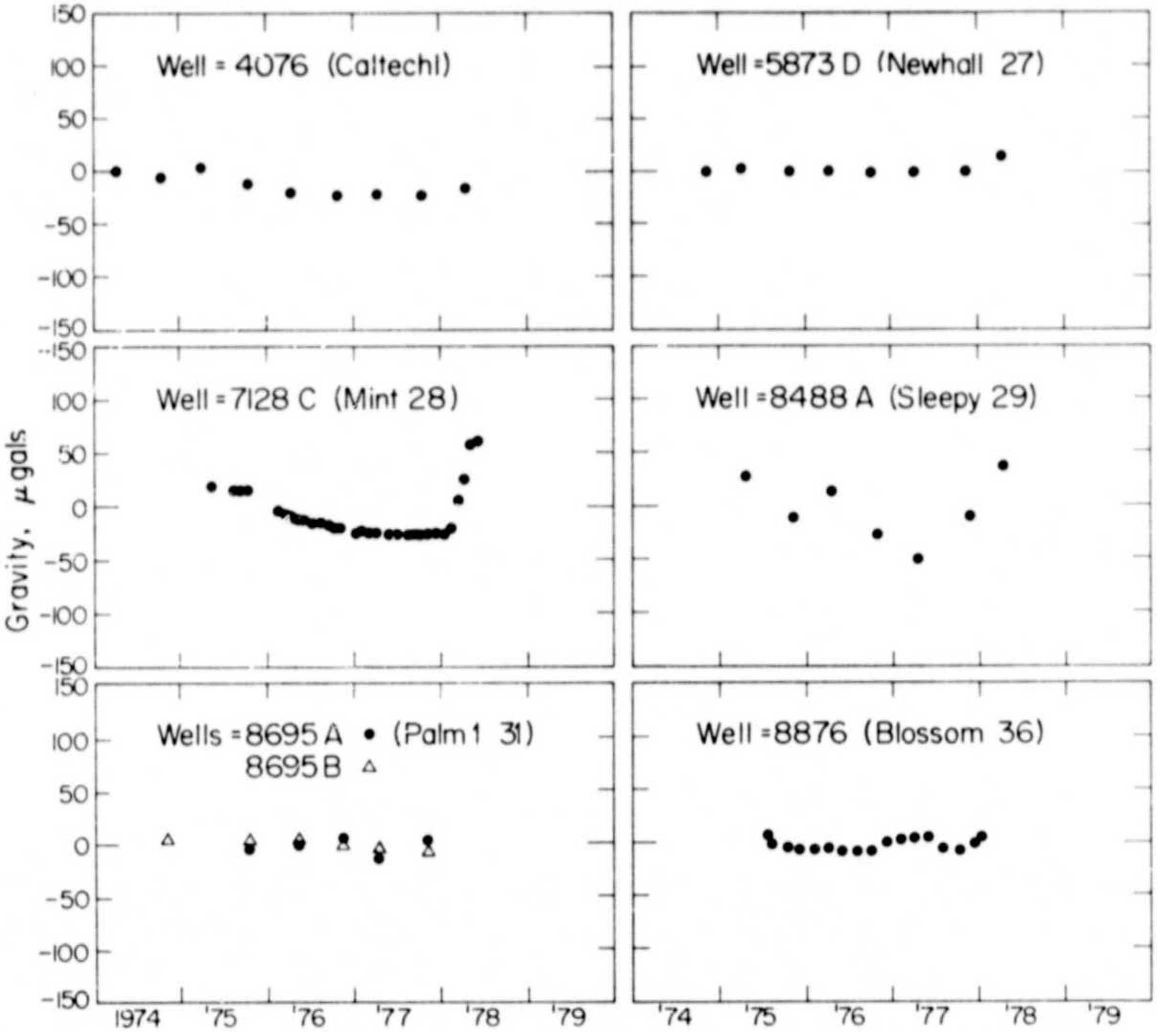

Well = 4076 (Caltech1)
Well = 5873 D (Newhall 27)
Well = 7128 C (Mint 28)
Well = 8488 A (Sleepy 29)
Wells = 8695 A • (Palm 1 31)
8695 B △
Well = 8876 (Blossom 36)
Gravity, μgals
150
100
50
0
-50
-100
-150
1974
'75
'76
'77
'78
'79
'74

Fig. 6

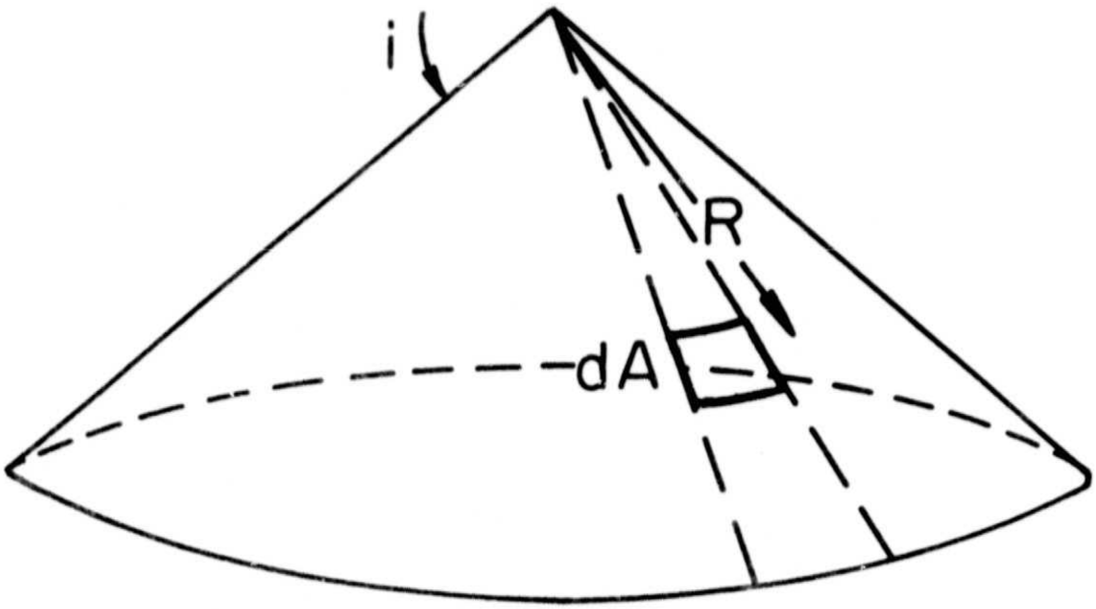


Fig. 7