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FINAL REPORT

NASA NSG-5331

John M. Goodkind, Principal Investigator
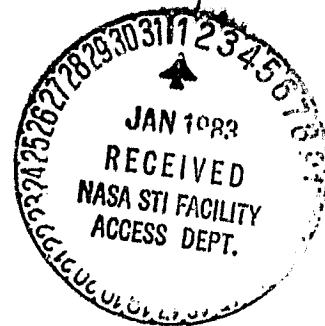
I. INTRODUCTION

The superconducting gravimeter was simultaneously developed and applied to field measurements by this investigator and coworkers through an arduous decade of work. The unprecedented stability of the instrument yielded the highest precision measurements of the earth tides ever attained. It revealed details about the effect of the atmosphere on gravity when that effect had not yet been observed with other instruments. The most recent work was dominated by attempts to measure secular variations in gravity and to measure the stability of the instruments by comparing records from co-located instruments. These efforts have resulted in substantial reductions in the noise level at very low frequencies so that the peak differences between two instruments at the same location can now be reduced to 0.1 μgal.

II. HISTORY OF DEVELOPMENT AND DEPLOYMENT OF THE SUPERCONDUCTING GRAVIMETERS

Data from the first field-operational superconducting gravimeter was obtained in 1973 at Piñon Flat, California. It was used to study the tides of the solid earth.[1] The precision of the measurements was ten times better than had been possible with any other instrument. The data also demonstrated the capability of the instrument for measurement of long term changes in gravity. It was for this application that major funding was obtained from NASA to build five instruments. In addition the geothermal division of the USGS provided funds for construction of a sixth new instrument. Thus the major thrust of our work became the measurement of secular variations of gravity. By December of 1977, five new instruments were built. At that time we were also developing microcomputer controlled data acquisition systems, a minicomputer facility in the laboratory, and the extensive software needed for both. The data systems are still more flexible and powerful than anything available commercially. Also at that time we were continuing to operate an instrument at Piñon Flat and a detailed analysis of the tides[2,3] and of the influence of the atmosphere on gravity was completed.[4]

The first of the new instruments and the new data systems was deployed at Otay

Mountain in San Diego in December 1977. The lessons learned from this installation caused us to spend most of 1978 testing and modifying the remaining instruments. In December of 1978 a second instrument was placed at Lytle Creek, California. Early in 1979 instruments were installed at Boulder, Colorado, at The Geysers in northern California, and at Goddard Space Flight Center in Maryland. These instruments continued to display behavior which had not been observed on the original ones so that we were forced to continue diagnostic experiments in the laboratory. We also developed tilt stabilized platforms since it was clear that tilt was responsible for very large spurious signals at Lytle Creek and was the major source of noise at all sites. At the same time we were servicing all of the instruments in the field, archiving and partially analyzing the data.

At this time funding for the work began to decrease and we felt that our most critical need was to undertake laboratory testing of instruments operating simultaneously so that we utilized the remaining NASA funds to run 2 or 3 instruments in the laboratory. We also took advantage of the presence of the instruments in the laboratory to obtain a small grant from the Physics Division of the NSF to test the gravitational inverse square law at 1 meter distance to within a few parts in 10^4. The data for that experiment are in the final stages of analysis.

The testing and analysis of the instruments revealed some subtle causes of low frequency noise which were corrected as they were discovered. Details are presented in Section IV. The best results obtained before funding ran out revealed peak differences between instruments at 0.3 μgal (see Fig. 1) over a one-week record. If the records were high passed above 4 cycles per day, the peak differences were 0.1 μgal (see Fig. 2). The 0.1 μgal limit can be obtained for arbitrarily long records if all of the techniques which we have learned are implemented. This means that the device is stable to one part in 10^{10} and it can measure a vertical displacement of 1 mm. Below this level a wide variety of phenomena could produce observable signals so that a very substantial research effort would be required to further improve performance.

Having obtained this laboratory proof of the capabilities of the instruments we felt ready to make a new generation of measurements which would utilize their full potential. We began by running an instrument in Del Mar, seven kilometers from the laboratory while

two instruments were still operating in the laboratory. Differences between the records (high passed above 4 cycles per day) from the two locations were only slightly greater than the differences between two instruments in the laboratory, namely between 0.1 and 0.2 µgal. (See Fig. 2.)

At this point our funding was nearly exhausted so that we turned off all of the instruments to eliminate the expense for liquid helium. With the time remaining we turned our attention to the large amount of data which has not been fully exploited.

III. DATA

A. Log of all Data

A log of all of the data obtained since January 1978 is shown in Figure 3. As indicated, some of this data has been examined for long term trends. None of it has been used to study tides or atmospheric effects or for low frequency resonances. Some of the data has not been examined at all since it suffered many interruptions and offsets which were too time consuming to remove with the software available at the time. We now have hardware and software which could enable us to salvage this worst data (principally from The Geysers and Goddard). A sampling of results which nave been obtained are presented in the following paragraphs.

B. Atmospheric Pressure Effects

In order to obtain long term trends from the records, tides and atmospheric effects are removed. For the data at Boulder and The Geysers we found that the admittance between gravity and pressure was less stable than at other locations. The problem was compounded at Boulder by the fact that the pressure variations were also larger than elsewhere. The gravity effect of the atmosphere depends on the size, shape and motion of the pressure cells as they pass the gravimeter. This accounts for the variability in the admittance. An Illustration of this is shown in Figure 4 where two instruments in the laboratory measured a change of 3 µgal over 7 hours. This was apparantly caused by the atmosphere but the pressure change evolved more slowly and largely after the gravity change. Events such as this are common so that, on the time scale of 12 hours or less, fitting pressure to gravity without lags fails to reveal much of the causal relationship.

On the other hand we also have evidence that some of the short term changes in pressure

have very little effect on gravity since the pressure change takes place over a very small area. This is illustrated in Figures 5, 2, and 6. These records were high passed above 4 cycles per day. They show 2 instruments in the laboratory (SG5 and SG7) and one at Del Mar (GWR), seven kilometers from the laboratory. Figure 5 shows the 3 individual gravity records. Figure 2 shows the difference between the 2 lab instruments and the difference between one of them and Del Mar. It demonstrates that Del Mar is almost as well correlated with the lab as are the two instruments in the lab with each other. Figure 6 shows the pressure at Del Mar and the pressure difference between Del Mar and the laboratory. It shows pressure differences which would have produced observable gravity differences if the scale of the pressure change had been as large as 7 km. We conclude that a portion of the observed pressure variation results from phenomena of scale smaller than 7 km and has very small effect on gravity.

C. Low Frequency Modes

Figures 7 and 8 show power spectra from simultaneous records at La Jolla and Boulder. Both show significant peaks very close in 0.5 cycles/hour. A subsequent time period continued to show the peak at La Jolla, but not at Boulder. This may have been due to an increase in the barometric pressure noise at Boulder which then overwhelmed the signal. Data from adjacent time segments at both locations is now being examined.

D. "Silent" Earthquakes

Figure 9 illustrates commonly observed "wiggles". In this case it contains spectral components with periods between about 60 and 700 seconds. In a few cases where these were observed at La Jolla the simultaneous records at Boulder were examined, but no corresponding signal was found. The possibility that such events represent very low frequency seismic events could be tested by simultaneous records.

E. Long Term Correlation Between Instruments

Most of our work during the past 2 years was directed toward detecting and eliminating long term drifts in the instruments. Gravity residuals obtained previously from isolated instruments in the field are shown in Figures 10, 11, 12, 13, and 14 for Piñon Flat, Otay, Boulder, The Geysers, and Lytle Creek. The only variations which seem to demand explanation are the events observed at The Geysers and the steady drift at Lytle Creek. The instrument

from Lytle Creek was operated in the laboratory after it was returned from that station.

It exhibited a decaying drift rate immediately after turn on, but no steady drift. We

have not observed a steady drift like this under any other circumstances. Events like

those at The Geysers have not appeared on other records so that we assume they resulted

from activity in the geothermal reservoir. Drifts observed in the laboratory by means of

simultaneous records have shown decaying rates due to the transfer of adsorbed helium gas

between the test mass and the walls of the gravimeter. The decay is not a simple exponential,

but equivalent time constants have ranged between tens of hours and tens of days. In all

cases the decays are smooth so that the investigations proposed here will be unaffected by

instrument drifts.

IV. MEASUREMENTS OF INSTRUMENT CHARACTERISTICS

A. Possible Causes of Instrumental Noise and Drift

The Brownian noise limit of these instruments is 0.01 μgal/Hz$^{1/2}$. The observed

noise level using a filter of 100 second time constant is of order 0.01 μgal and there-

fore about 10 times larger than the Brownian noise. Over periods longer than a few hours

the peak excursions are 0.1 to 0.3 μgal. For this reason we

attempted to identify the sources of noise in the various frequency domains of interest.

In many cases an attempt to prove the presence of an assumed source resulted in proving

that it was not present. In all cases the measurements were time consuming since we were

concerned with frequencies between 10^{-2} and 10^{-5} Hz.

1. Electronic Circuit Stability.

The stability of the electronic circuits themselves had been tested at an early stage

of the work on a dummy capacitance bridge. Its noise level at the output was known to be

at least 10 times smaller than the output noise when the gravimeter was functioning.

However, the in-situ noise level with the cryogenic portion of the circuits connected

needed to be measured independently. For example, the coaxial cables for the capacitance

bridge are at 4°K at one end and room temperature on the other, and the temperature profile

varies with time.

In order to test for such problems the gravimeter was operated with a very large

force gradient (stiff spring) so that the circuit noise dominated the output. In this way we identified and eliminated several problems with ground loops and stray capacitance. Ultimately the output, with the large force gradient, was reduced to uniform, random noise from the input stage of the capacitance bridge preamplifier.

The capacitance of the cryogenic stainless steel coaxes was found to vary with the pressure inside the Dewar and with the flow rate of He gas out of the Dewar. The effect of this capacitance variation was eliminated by reduction of the source impedance of the bridge.

2. Temperature Stability.

Our earliest work on these instruments demonstrated that the levitation force depended on temperature. Measured coefficients have ranged between 16 and 37 μgal/mK. Thus, stability of 10^{-2} μgal would require temperature regulation to better than 1 μK. Temperature was measured by germanium resistance thermometers. The overall temperature regulation was tested by attaching two independent thermometers to the gravimeter. One was used to control the temperature while the other would measure how well it was being controlled. The two were then interchanged. In this way the stability of the resistance thermometers as well as of the measuring circuits was ascertained. The fluctuations in the measured temperature were such that they could cause apparent changes in gravity at the 0.01 μgal level. However, no correlation was found between the gravimeter output and the temperature as a function of time. This is probably due to the complexity of the dependence of the gravimeter signal on the temperature of various parts of the instrument. Improved temperature regulation remains a possible means for reducing the instrument noise in the frequency domain above 10^{-4} Hz.

The temperature dependence is apparently an intrinsic property of the superconducting materials in the gravimeter which is related to the temperature dependence of the penetration depth. We know that changes in temperature of the magnetic shield, the support magnets and the levitated sphere all have an independent effect. However, further study of this problem will require construction of an instrument which would allow quantitativ measurement of each of the three temperature coefficients independently.

The temperature of the sphere could increase in the presence of high frequency mechanical noise as a consequence of dissipation by normal electrons flowing with the induced alternating currents. If this happened there would be an apparent decrease in gravity during periods of large microscisms. Several different kinds of tests failed to reveal any heating of the sphere either from high frequency motion or from directly applied alternating magnetic fields.

In principle, the temperature dependence could be reduced by either operating at lower temperature or by using a superconducting material with a higher critical temperature. In practice, neither is realistic. The simplest means of improvement can best be obtained by better temperature regulation.

3. Gas Pressure inside the Test Mass Chambers.

The levitated sphere is hollow and has a hole at its top to allow the gas pressure inside and outside to equilibrate. Nonetheless, there is a buoyant force from the low pressure helium gas which is left inside the test mass chamber in order to maintain thermal contact between the sphere and the temperature regulated body of the instrument. This force amounts to 2 µgal per micron of gas pressure at a temperature of 4 K. It will remain constant as long as the volume of the chamber remains constant. This is not the case if a pump-out tube is attached to the chamber and passes out of the apparatus to a room temperature valve. Changes in the temperature profile of this tube will cause gas to move back and forth between it and the chamber. For this reason the instruments are normally sealed with a predetermined density of helium gas and have no pump-out tube.

However, even in this case the gas pressure affects the operation of the device as a consequence of the adsorption and desorption of gas from the levitated sphere. In some cases, the time constant for the desorption effect was found to be many days. It was observed as follows. An instrument with a pump-out line was used to allow sudden increases or decreases in the gas pressure. The effect of a sudden increase of pressure was an immediate upward displacement caused by the increase in the buoyant force. This is followed by a slow downward displacement as the increased pressure leads to an increase of the adsorbed mass. The time constant for this increase in mass was of the order of one hour. However, when the pressure was decreased suddenly, the subsequent desorption of the

gas could have a time constant as long as a month.

For our 1" diameter sphere with a mass of about 5 grams, a monolayer of ^{4}He on the inside and outside surfaces corresponds to a force of about 500 μgal. The rate of change of the gravity signal after decreasing the pressure was about 10 μgal/day so that it corresponded to only about 2% of a monolayer per day.

4. Drift of the Magnetic Field.

In principle, the magnetic field produced by a superconducting persistent current is perfectly stable, but, it was not known at the beginning of this work if long term stability of a part in 10^9 to 10^{10} could be achieved in practice. Indeed, by making measurements with a superconducting magnetic flux detector (now called a SQUID) we were able to measure a decrease in the field from a single coil which was proportional to the logarithm of the time. In addition, the field was found to be a function of the temperature of the coils.

These problems were effectively eliminated by adding stabilizing coils on the inside and outside of the main magnet coils. These are persistent current loops with a switch such that they are allowed to persist only after the magnetic field has been established. Therefore, initially they carry no current, but if the current in the main magnet coil decreases by a small amount it will be compensated by a small current in the stabilizing coil. In this way the drift in the field is reduced below the level where it can be measured with a SQUID and below the level where it can have a measureable influence on the gravimeter. The temperature dependence is also reduced to a level such that regulation of the temperature is adequate as described in Section 2 above.

5. Flux Jumps.

In addition to the continuous variations in field described above, there can also be discontinuous changes known as flux jumps. This is a sudden avalanche of quantized flux lines which are trapped, metastably in the body of the superconducting wire, shielding, or sphere. These result in sudden offsets of the gravimeter output. They are easily recognizable since they are instantaneous on the time scale of our geophysical measurements. They can be removed from the data but they complicate the software required to reduce the data. They also add to the time required for analysis and, at some level, introduce errors into the results. Identifying and eliminating the causes of these was difficult and

time consuming since we were unable to build instruments specifically designed to diagnose such problems. However, we have shown that the quality of the superconducting lead on the sphere and the niobium in the coils is crucial.

The niobium wire must be annealed for best results but we have found with unannealed wire that the frequency and magnitude of the offsets can be substantially reduced by cooling very rapidly through the superconducting critical temperature.

After the magnets are energized and the sphere is levitated, the offsets could also be reduced by temporarily raising the temperature of the gravimeter about 0.1 K above its normal operating temperature.

6. <u>Pressure inside of Dewar</u>.

Several mechanisms were found for the influence of the gas pressure inside the Dewar on the gravimeter output. The most significant was the pumping of gas in and out of the gravimeter chamber as the temperature of the liquid helium bath changed. This is discussed in section 3 above and was eliminated by eliminating the pump-out tube.

In addition, the change in bath temperature could result in a change in temperature of parts of the gravimeter. Good thermal contact between the superconducting shield and the rest of the gravimeter is essential. The large surface area of the shield means that it has significant thermal contact to the bath either by conduction through the small residual pressure of He gas or directly through radiation.

A change in pressure can also cause the instrument to tilt inside of the Dewar. For this reason the tiltmeters, which are used to control the tilt, must be mounted inside of the Dewar rigidly attached to the gravimeter.

The capacitance of the coaxial cables for the capacitance bridge is somewhat sensitive to the pressure inside the Dewar. In some configurations of the gravimeter with electro-static feedback, this was a source of noise. In normal operation with magnetic feed back the effect is far below the mechanical ground noise level.

7. <u>Variation in Electric Charge on the Sphere</u>.

In electrostatic feedback a change in the electric charge on the sphere would lead to an apparent change in gravity. In magnetic feedback it could also result in a change in force if there are geometrical asymmetries in the capacitance bridge, or if the charge is

not uniformly distributed over the surface. The charge was determined by applying a bias voltage as shown below such that there was no force on the sphere when the potential was applied to the end plates.

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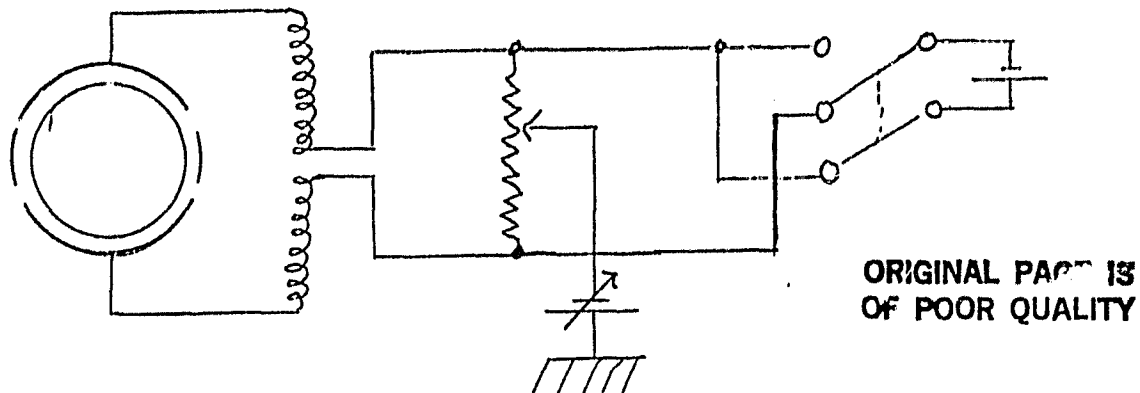
It was found that the charge on the sphere did drift after the instrument was set into operation. The drift rate was equal to that expected from the production of ion pairs by cosmic rays in the low pressure He gas in the gravimeter chamber. One instrument was measured every four days for one month as it approached equilibrium. The rate decreased from 2000 electron charges per hour to 500 during that period. It was found that the charge on the sphere could not be changed by touching it to the capacitor plates unless they were raised to a potential of some tens of volts. It was also shown that the observed change in charge had no effect on the gravimeter when it was operated in magnetic feedback (no potential applied to the end plates). This also demonstrated that thermoelectric and contact potentials in the gravimeter circuit have no effect on it in magnetic feedback.

8.   Normal Modes of the Instrument.

Ideally a gravimeter would have only one degree of freedom; along the axis of the instrument which is to be aligned with the vertical. In our instrument, the restoring forces in the horizontal direction are normally 10 to 100 times larger than in the vertical direction, but this still allows for motion in the horizontal plane which can either result in vertical motion or can unbalance the capacitance bridge and thus appears to be vertical motion. For slow tilts or small horizontal accelerations this is compensated by the tilt control system. Rapid motions would normally average to zero at small amplitudes. However, there is a normal mode associated with the horizontal motion which, if highly excited, can interfere with the measurements. The frequency can be between about 7 and 70 cycles/hour.

The motion consists of a translation of the center of mass of the sphere around an orbital path. This is demonstrated by the fact that the damping of the mode is controlled by the gas pressure in the test mass chamber. With hard vacuum in the chamber the mode rings for many days with very little decay in amplitude. The effect of viscous damping would be much smaller than observed if the mode consisted entirely of rotation of the sphere about its own axis.

Additional evidence was provided by the excitation of the mode by a standard tilt pulse along a fixed direction. By rotating the instrument with respect to this direction, an orientation was found in which the mode was not excited. This demonstrated that the motion is analogous to sliding around a circular groove in a plane which is tilted. If the plane is already tilted down along the direction in which the tilt pulse will be applied, no oscillations will be excited. Also consistent with this model is the fact that the frequency of the mode increases as the instrument's axis is tilted away from the vertical.

The mode frequency when the instrument is aligned along the vertical can be increased by deliberately trapping magnetic flux in the system. This is done by leaving a fraction of the field of the earth on the instrument as it is cooled through the superconducting transition temperature of lead. Since trapped flux in the horizontal direction breaks the cylindrical symmetry, this is also consistent with the above model. In principle it is desirable to clamp the mode more tightly (increase its frequency). However, clamping it by this method degrades performance in other ways by introducing an asymmetry into the tilt coefficient (see below).

9. <u>Ambient Magnetic Fields</u>.

Since the test mass is suspended by a magnetic field, the magnetic field must be stable to the same percentage that the measurements of gravity are to be made. The levitating field is approximately 200 Gauss so that the variations of 10^{-3} Gauss in the earth's field would render the device useless. For this reason it is enclosed inside of a superconducting shield which is in turn shielded by a μ metal container. With this shielding we measured artificial signals 0.3 μgal/Gauss for an axial field and 0.1 μgal/ Gauss for horizontal fields. Thus only in relatively large man-made environments would field changes be significant. In such cases we have simply added another layer of μ metal

shielding .

10. <u>Tilt.</u>

Any gravity meter invented thus far measures force only along one axis. If its
axis deviates from the vertical by an angle θ, then the component of gravity along the
axis decreases as cosθ, or $1 - \frac{1}{2} \theta^2$ for small angles. This amounts to 1 μgal if the
instrument tilts by 45 μradians.

In our instrument the tilt effect is of the same magnitude but of the opposite sign.
That is, if the axis of the instrument is tilted away from the vertical, the apparent force
of gravity increases rather than decreases. This is a consequence of the specific form of
the magnetic levitation. A minor modification of the coil geometry could reverse the sign
of this coefficient or reduce it to zero for small tilts. A special instrument would have
to be built to test for the optimum configuration and resources have, thus far, not been
available for the purpose.

This peculiar tilt property of the instruments also makes it sensitive to ambient flux
trapped in the lead shield and the levitated sphere. The horizontal components of this
flux result in an asymmetric tilt coefficient and excessive noise due to tilt. The symmetry
of the tilt coefficients is used as a measure of the expected quality of the signal during
initial setup of the instrument. If it is not symmetric the system is warmed up above the
critical temperature and recooled after demagnetizing the μ metal shields.

Tilts of cement piers in our laboratory have been as large as 100 μradians over
periods of a few months. In field conditions they have been as much as 10 times larger.
For this reason we built simple pendulum type tiltmeters to mount rigidly on the gravimeters
in the cryogenic environment. The output for these meters is fed back to hold the tilt
angle constant. The feedback has been accomplished through the use of thermal expansion
columns of two different types. The first used a teflon bar confined in an aluminum tube.
The second used oil inside of a metal bellows. The second had larger dynamic range and a
shorter time constant. Using these devices, tilt is completely eliminated as a source
of spurious signals.

11. <u>Damping.</u>

The adjustment of feedback for optimum operation depends on the open loop response

function of the instrument. This is determined by the force gradient and the damping.

The instrument has always been operated as an overdamped oscillator. The damping is predominantly electromagnetic. As the sphere moves in the magnetic field gradient which supports it, flux lines are displaced through the capacitance plates. The induced currents in the plates will decay with a finite time constant and therefore introduce damping of the motion at low frequencies. At high frequencies the currents will not have time to decay, but will create a negative feedback force which will reduce the motion of the sphere.

This feedback is desirable since it is passive, inherently stable, and helps to restrict the motion of the sphere to the range of linearity of the instrument. For this reason tests were made using copper capacitance plates of much higher conductivity than the normal aluminum ones. The time constant was increased to about approximately 100 seconds, but the noise level was also increased. The noise was at too high a level to come from the Brownian motion and resources were not available to pursue the question. Other researchers have found evidence of charge trapping on the surface of copper which could lead to this effect, in which case a thin coating of gold on the copper could eliminate it.

A closer examination of the damping with aluminum plates revealed that it was not simply proportional to the relative velocity of the sphere and capacitor plates. Even with active feedback the motion due to ambient microseismic background noise was sufficiently large to reveal non-linear damping. This was confirmed by measurements, without feedback, of the transcient decay time as a function of the spring constant. The product of decay time and spring constant was not constant as it would be for linear damping. The observed functional dependence of the product on spring constant could only be characterized by non-linear dependence on the velocity.

V. CONCLUSIONS

Our work on the superconducting gravity meter has allowed us to make measurements of gravity as a function of time at seven different locations in the United States. A cumulative total of more than 15 years of data have been obtained with the instruments. Definitive new results concerning the tides and the influence of the atmosphere on gravity have been obtained. Upper limits on the variation of gravity were set at 1 to 10 µgal at four locations. Gravity "events" were observed at The Geysers and a long term drift was observed only at

Lytle Creek. Critical testing of colocated instruments has demonstrated that variations between 0.1 and 0.3 µgal can be measured with the instruments.

The data contain evidence of phenomena such as large scale crustal motion, sub-surface mass redistribution and very low frequency seismic events. However, in order to confirm such interpretations more data must be analyzed and it will probably be necessary to obtain additional data with the greater precision which is now available.

The development and field testing of these instruments which was made possible by this NASA grant has led to an instrument with stability and resolution which is rare in physical measurements. Much work remains to be done to realize the full potential of the instruments in the wide variety of applications where they could produce important new results. Unfortunately all sources of funding for the work have now terminated. As of April 1983 the only superconducting gravity meters operating anywhere in the world will be the two which were built for research groups in Belgium and Germany.

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SG5 - SG2
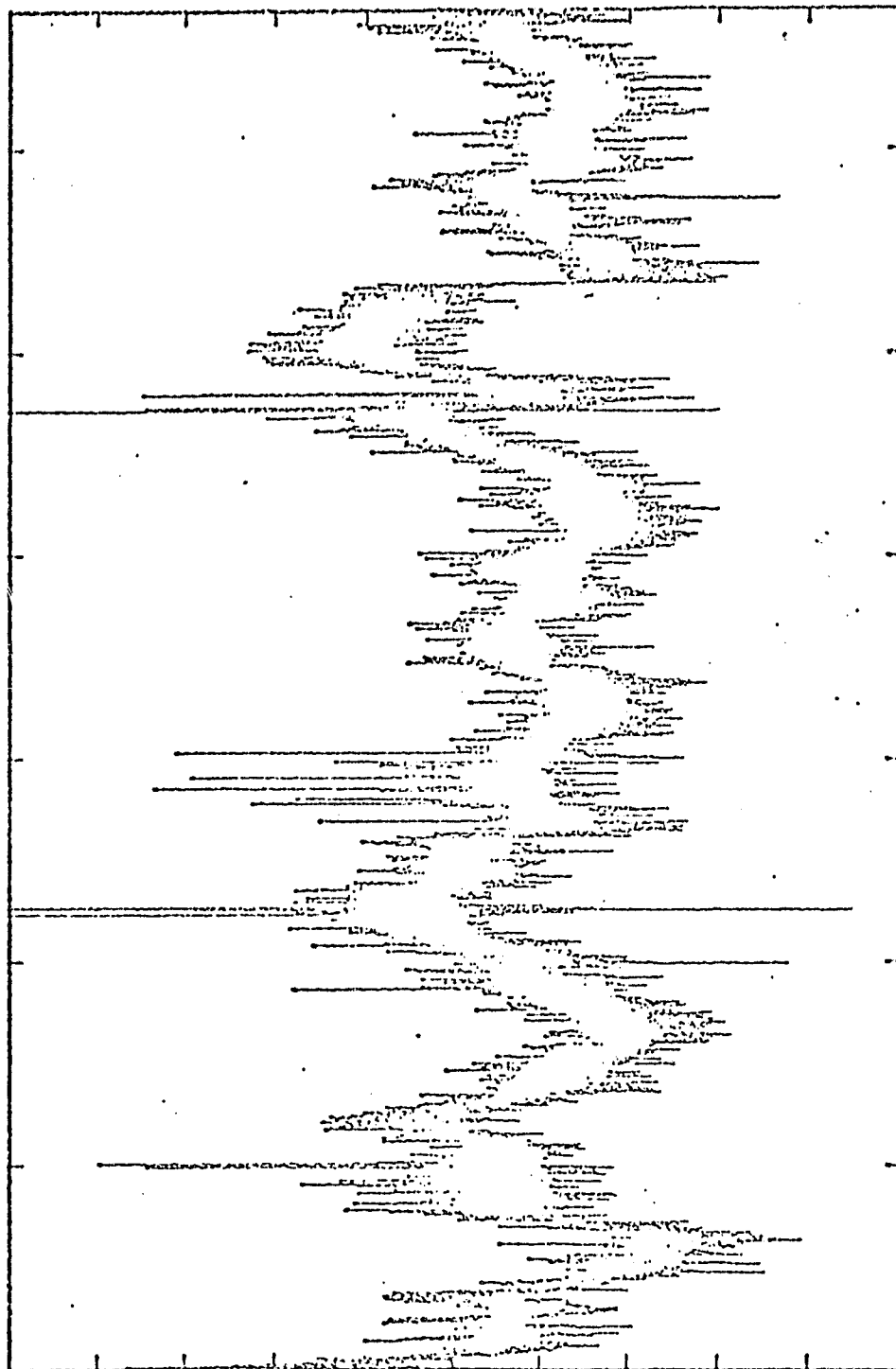
0.1 µgal/div

1-day/div

Figure 1

Difference between signals from two instruments in the lab over a 6-day period. Long period noise sources still exist at the level of 0.5 µgal.

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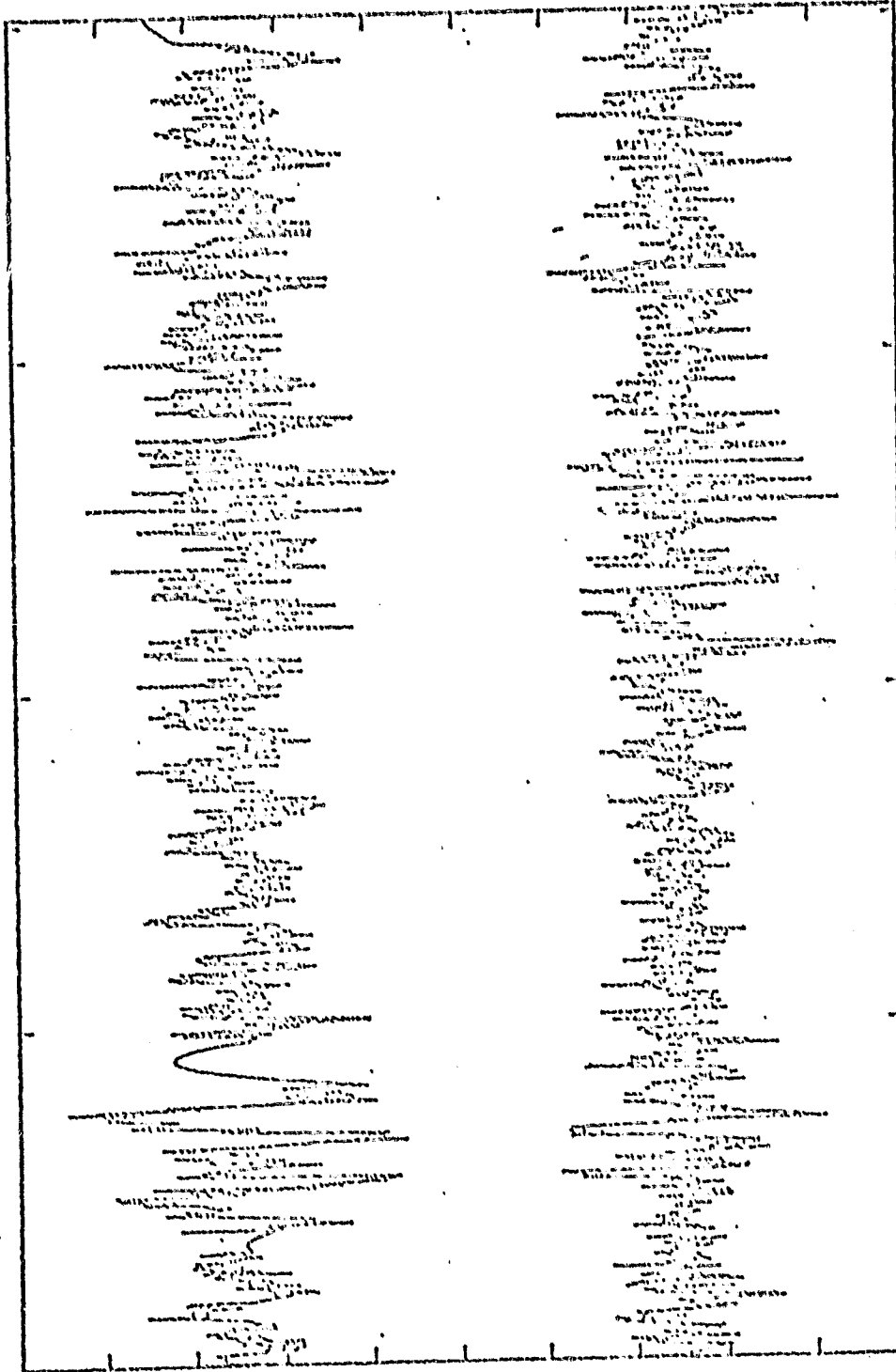
Figure 2

High-passed differences.
Differences between the two records of Figure 7 in the lab (SG7-SG5) and between Del Mar and the lab (GWR-SG5).
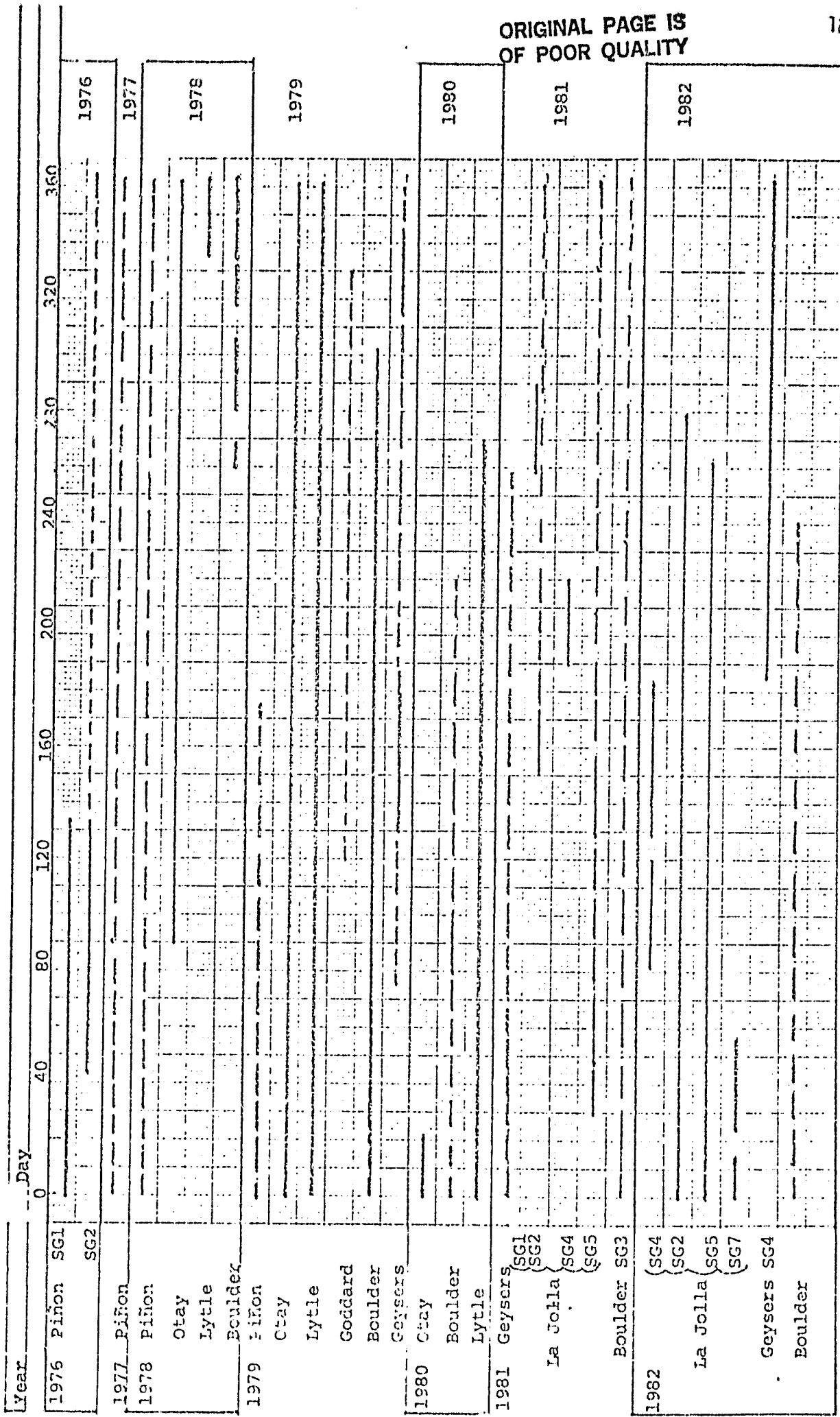
Figure 3. Log of all data obtained since 1976. Solid lines represent data which has been processed and detided to obtain the long term variations. It is ready to be examined for long period modes or for tides. Dotted lines represent data for which only short segments have been processed.
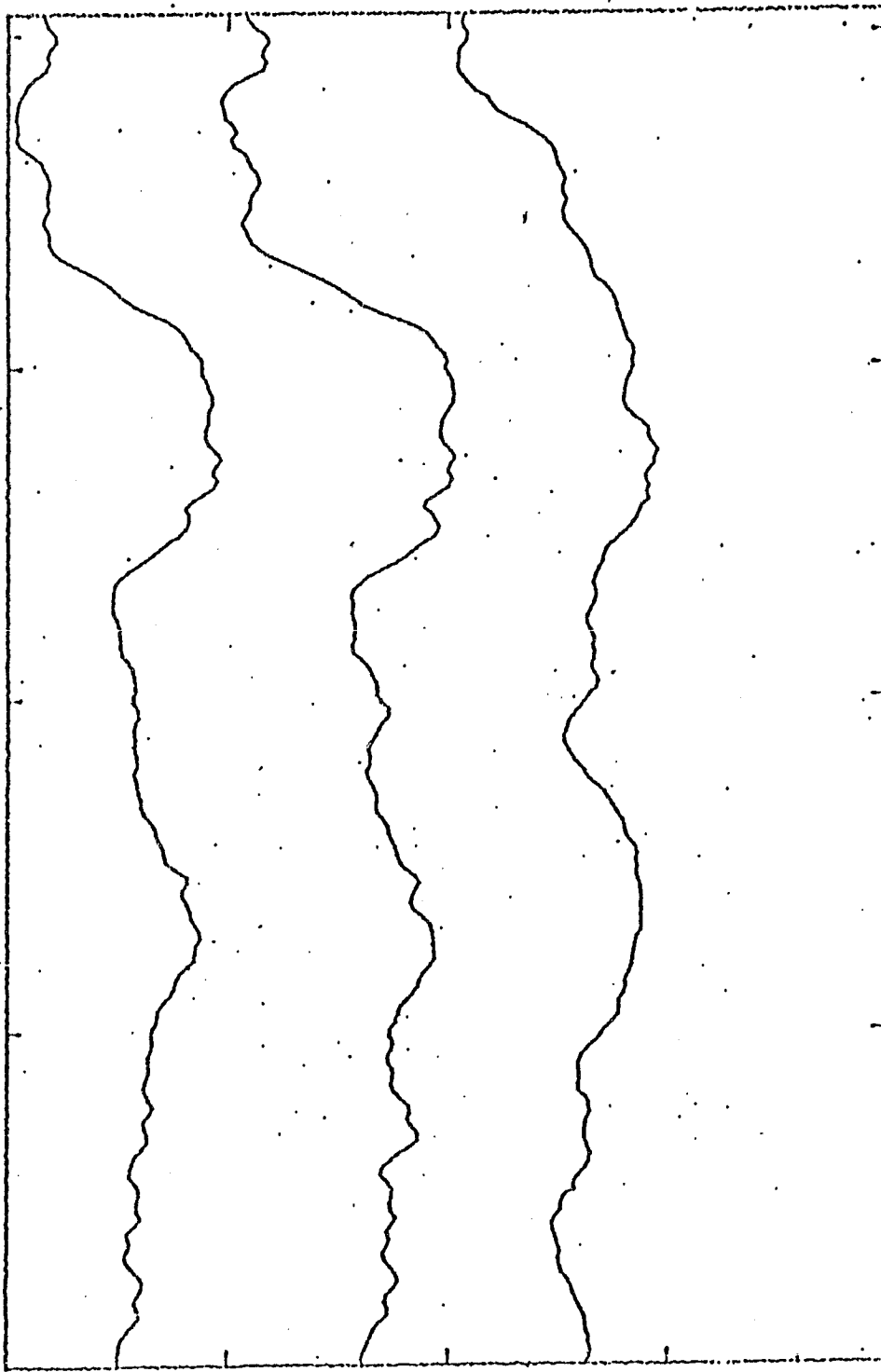
SG5-theory
4 ugal

SG2-theory
4 ugal

Pressure
12 mbar

1 day per Division

Figure 4

The same records as Figure 1, but also showing the atmospheric pressure.

GWR (Del Mar)
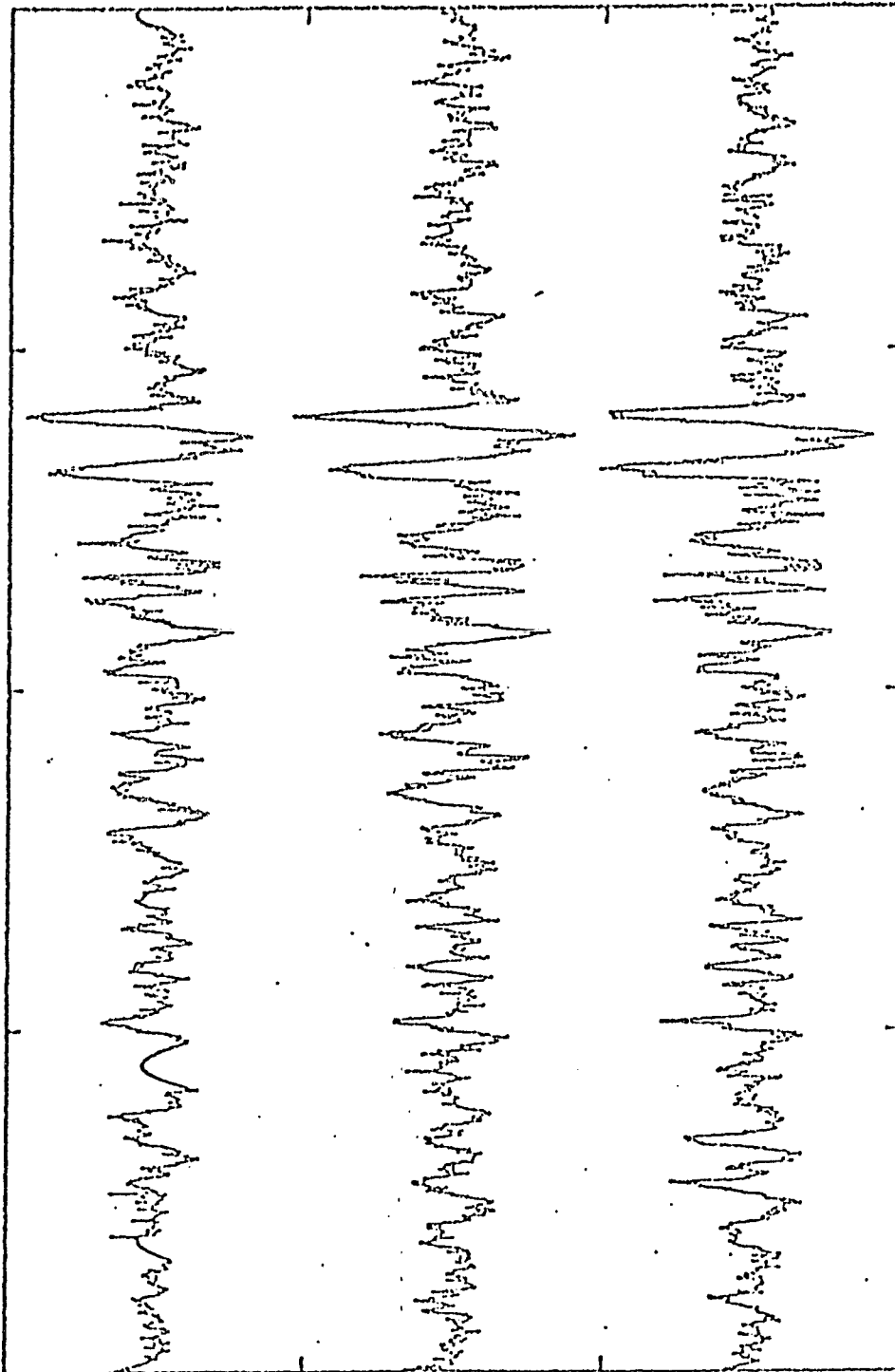
SG7 (La Jolla)

1 μgal/div.

SG5 (La Jolla)

1 day/div.

Figure 5

4 - day record

High passed records from SG5 and SG7 in the lab and from a third instrument in Del Mar, about 10 Km away.
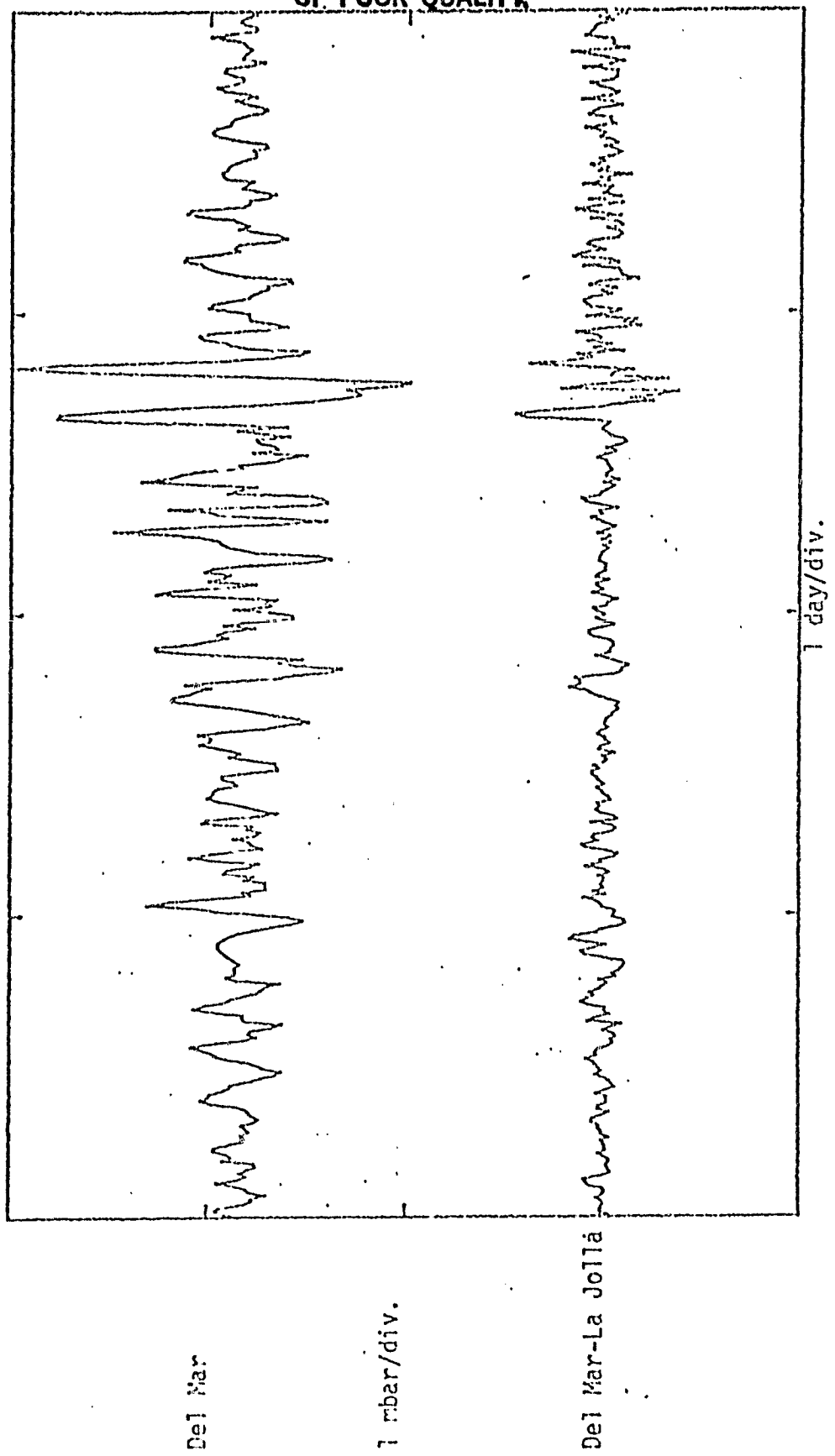
Figure 6

4 - day record. Barometric pressures.

Barometric pressure at Del Mar and the pressure difference between the lab and Del Mar for the same period of time as Figures 7 and 8.
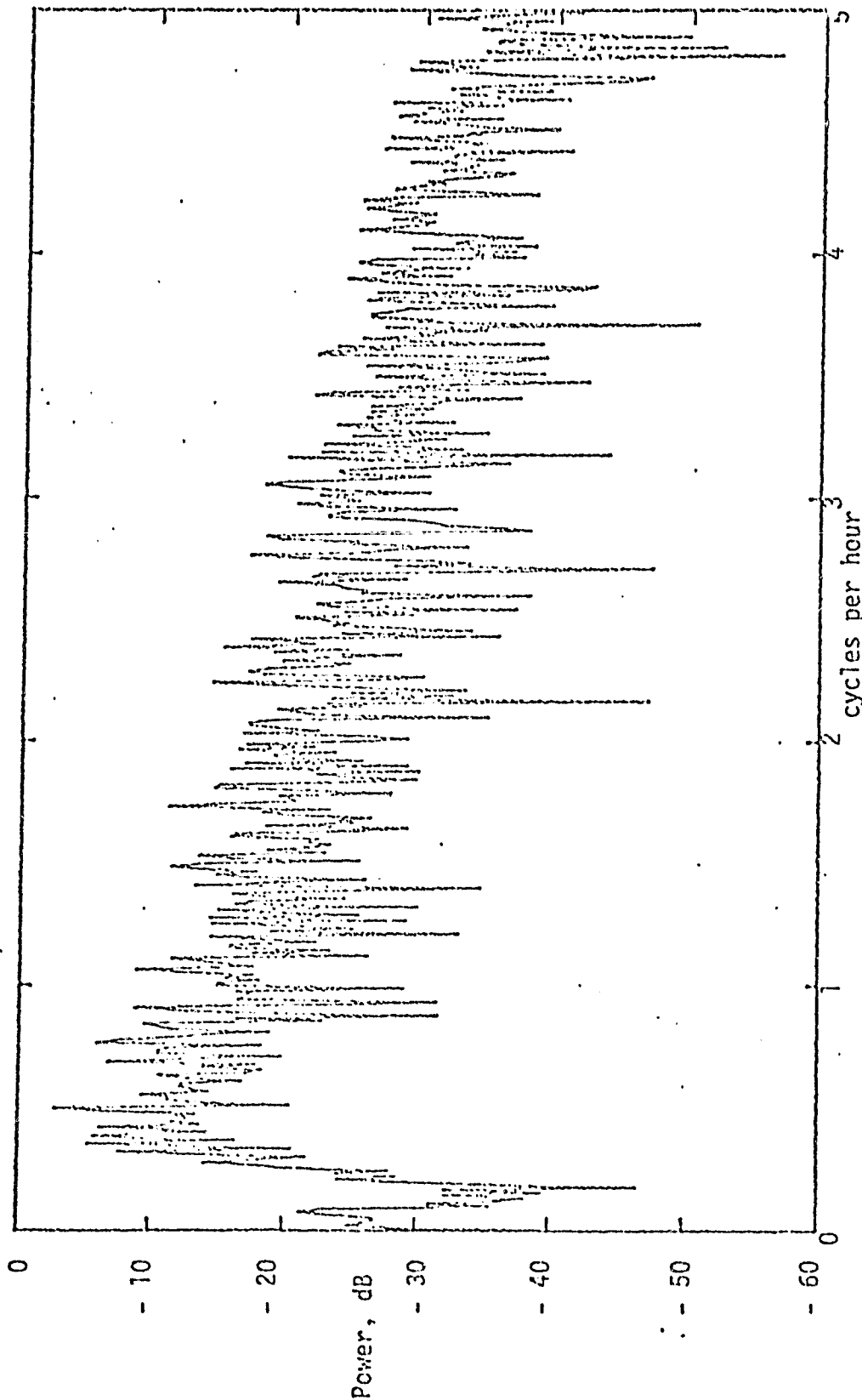
Figure 7

Averaged time series of SG2, 5, 1. 1981 day 330 to 334. Data is high passed above 4 cycle/day. The peak close to 1/2 cycle/hour also appears in Figure 5.
Power spectrum from the averaged signal from three instruments in the lab.
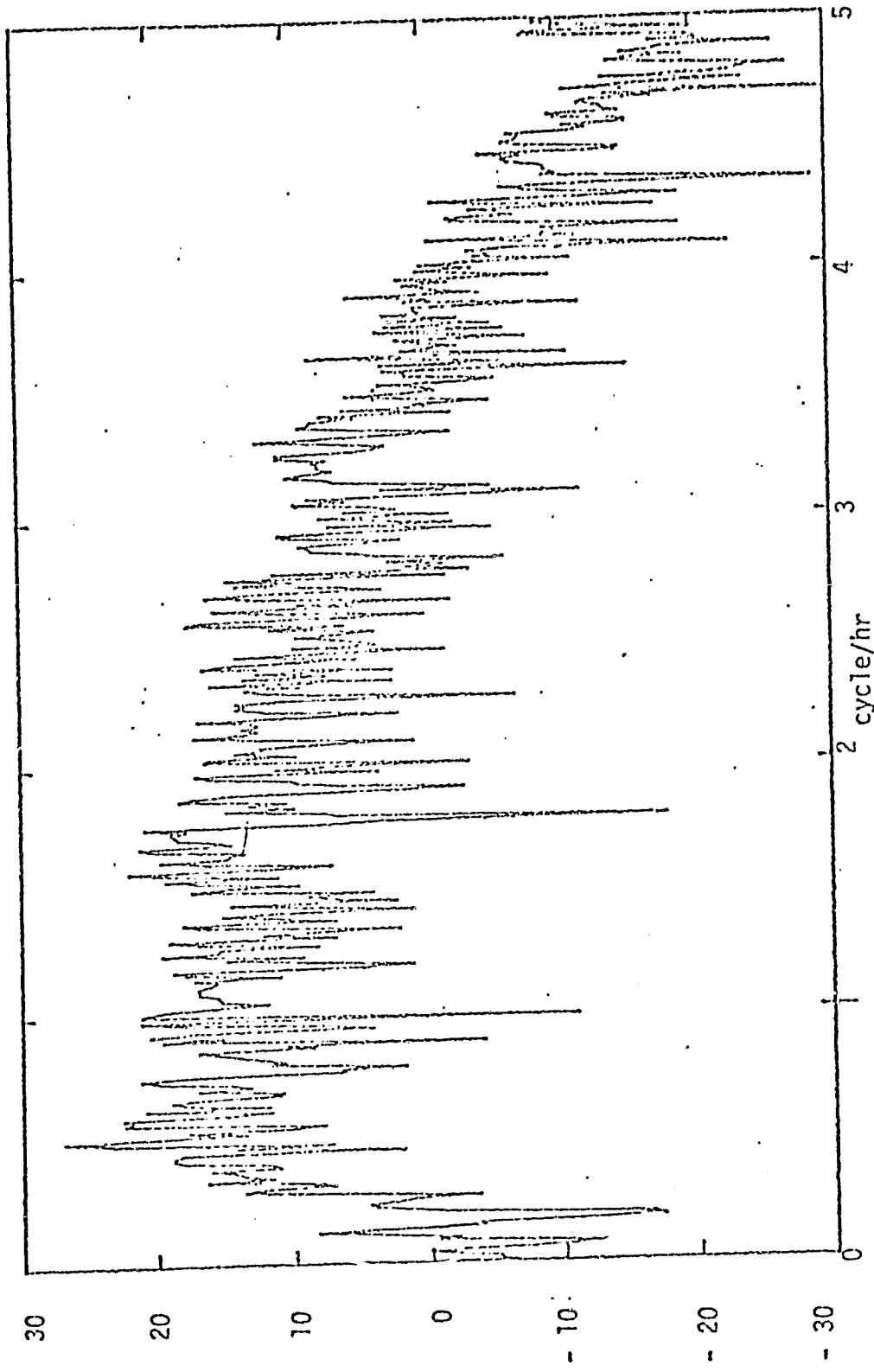
Figure 8

Power spectrum from Boulder for the simultaneous period and treated in the same way as Figure 4. Boulder, 1931, 4 days, treated in the same way as Figure 4. Peak close to 1/2 cycle/hour is identical in frequency and intensity with that of Figure 4.
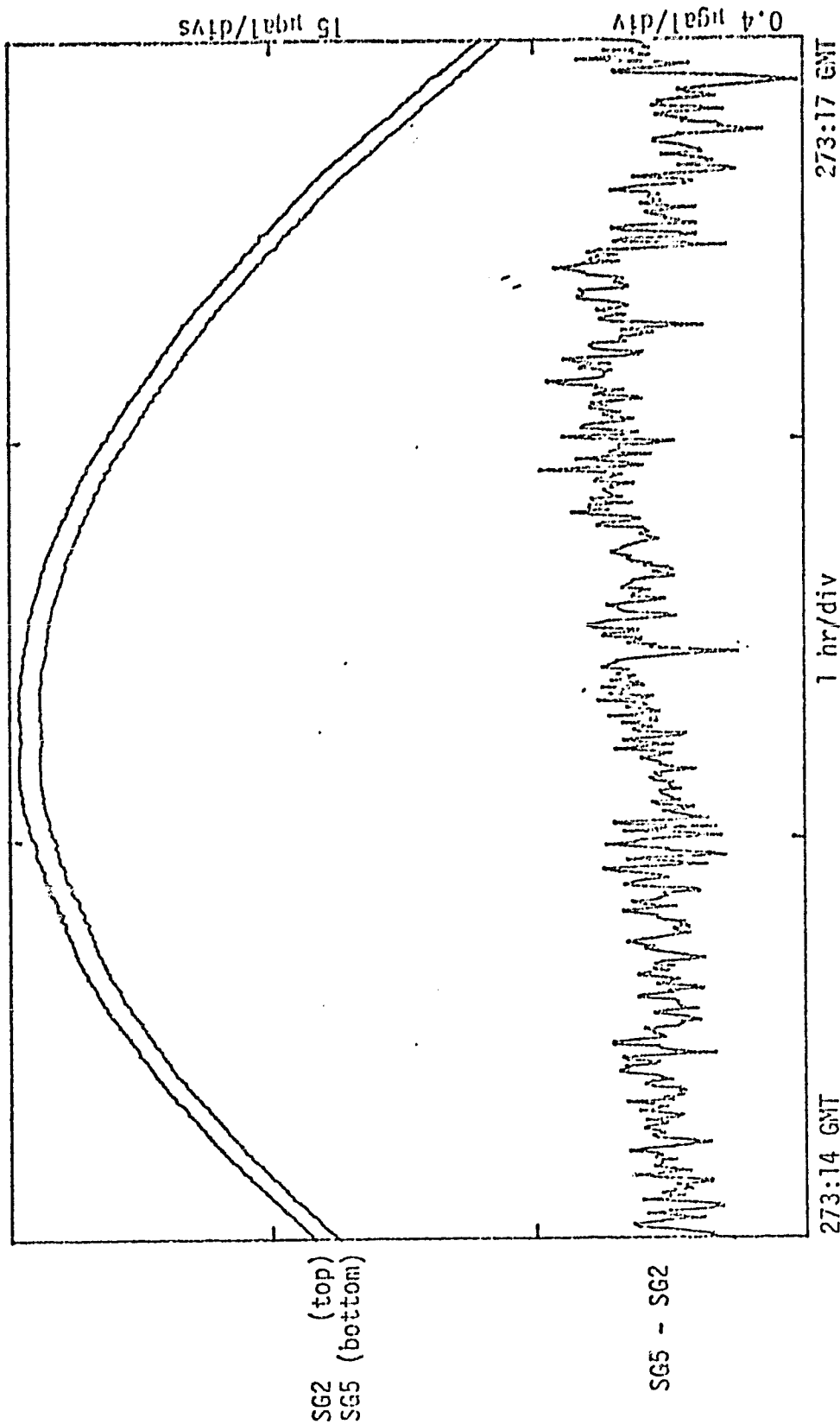
Figure 9. Raw signals from SG2 and SG5 showing signals on top of tide. Lower trace is the difference between the two plotted with 0.1 µgal per division.
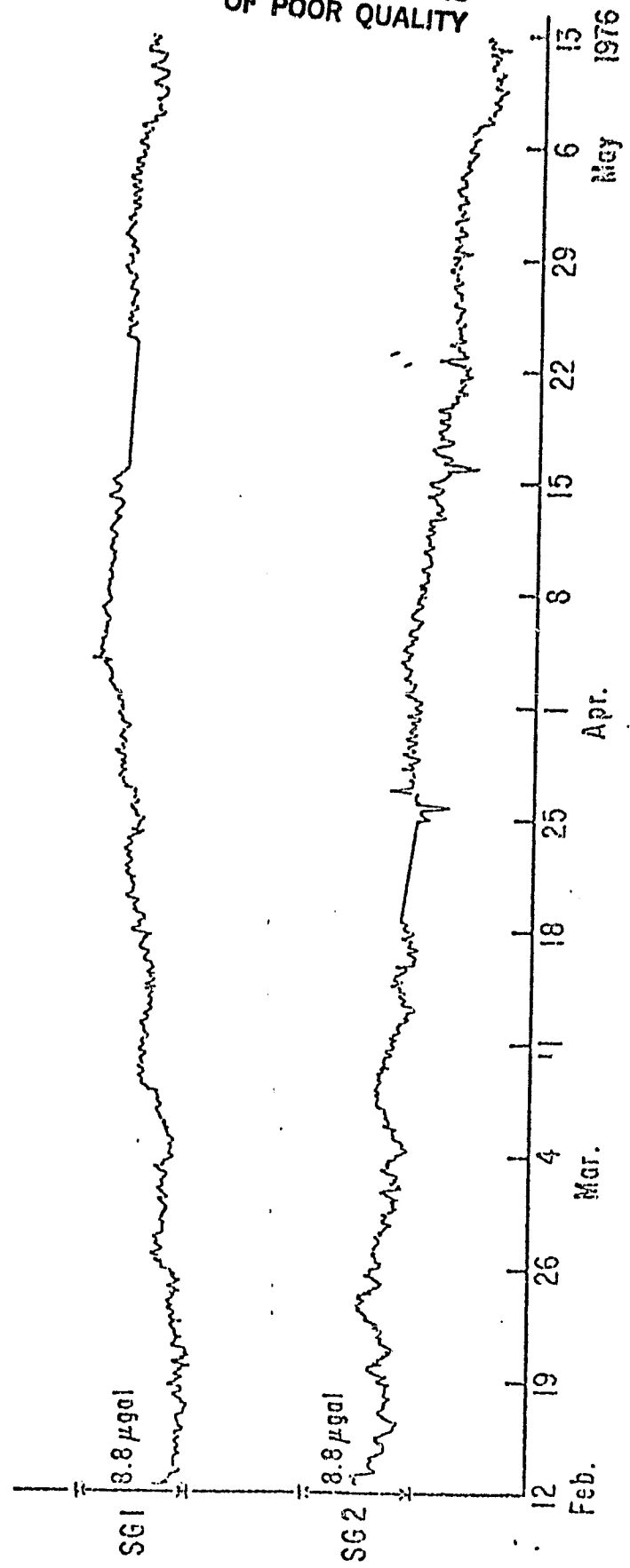
Figure 10

Gravity residuals for SG1 and SG2 at Pinon Flat Observatory after subtraction of the effects of atmospheric pressure. Gravity increases towards the top of the graph. SG1 was known to be drifting in the direction of increasing gravity due to flux creep in the magnet. This effect was eliminated by the addition of superconducting stabilizing coils to all instruments.
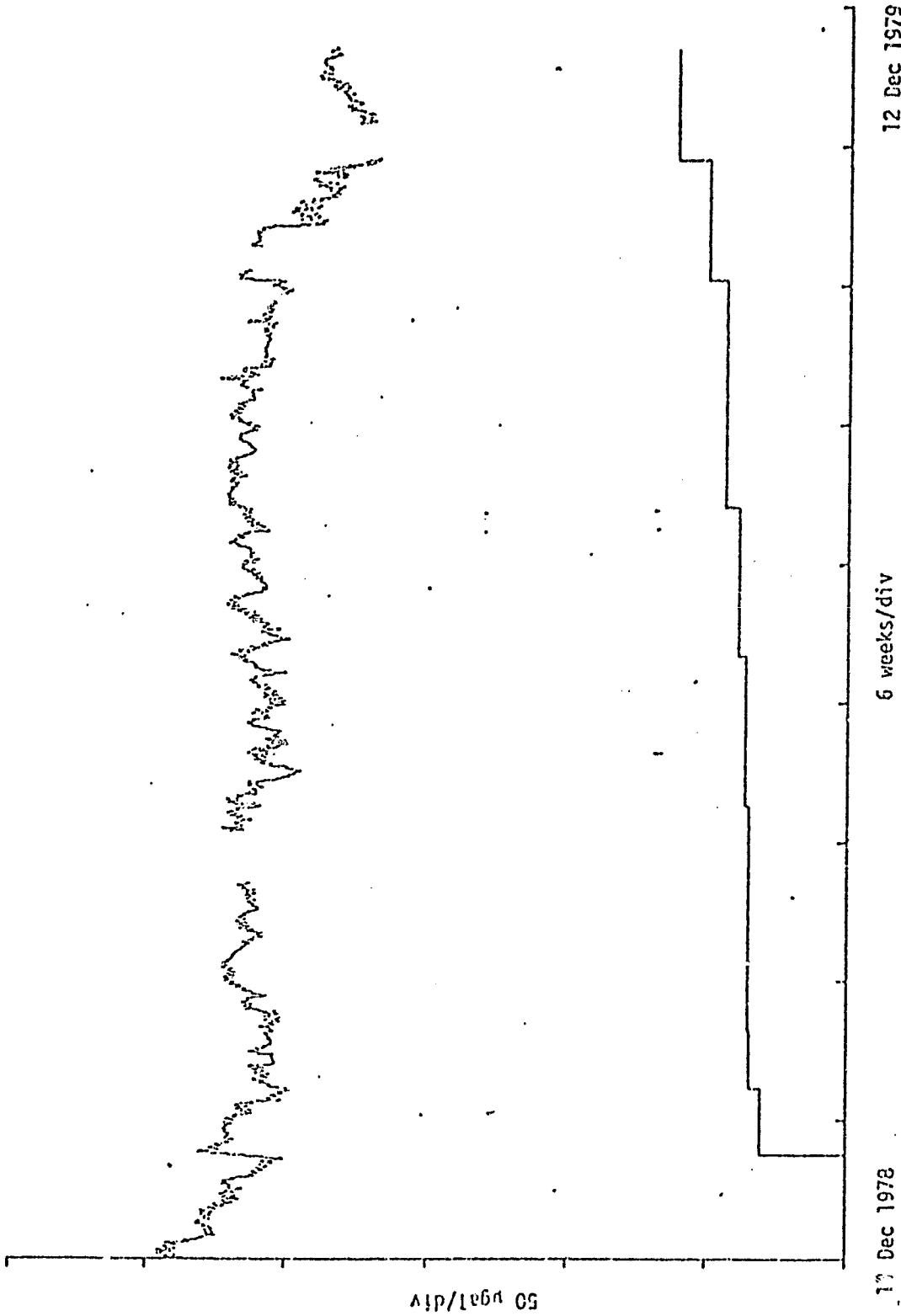
Figure 11

One year of data from Otay Mountain, CA. The bottom trace shows the required gravity correction for tilt as determined by periodic relevelings of the instrument. The top trace is the gravity residual after application of this correction. Exclusive of the winter months, where the tilts are greatest, the signal shows no monotonic drift.
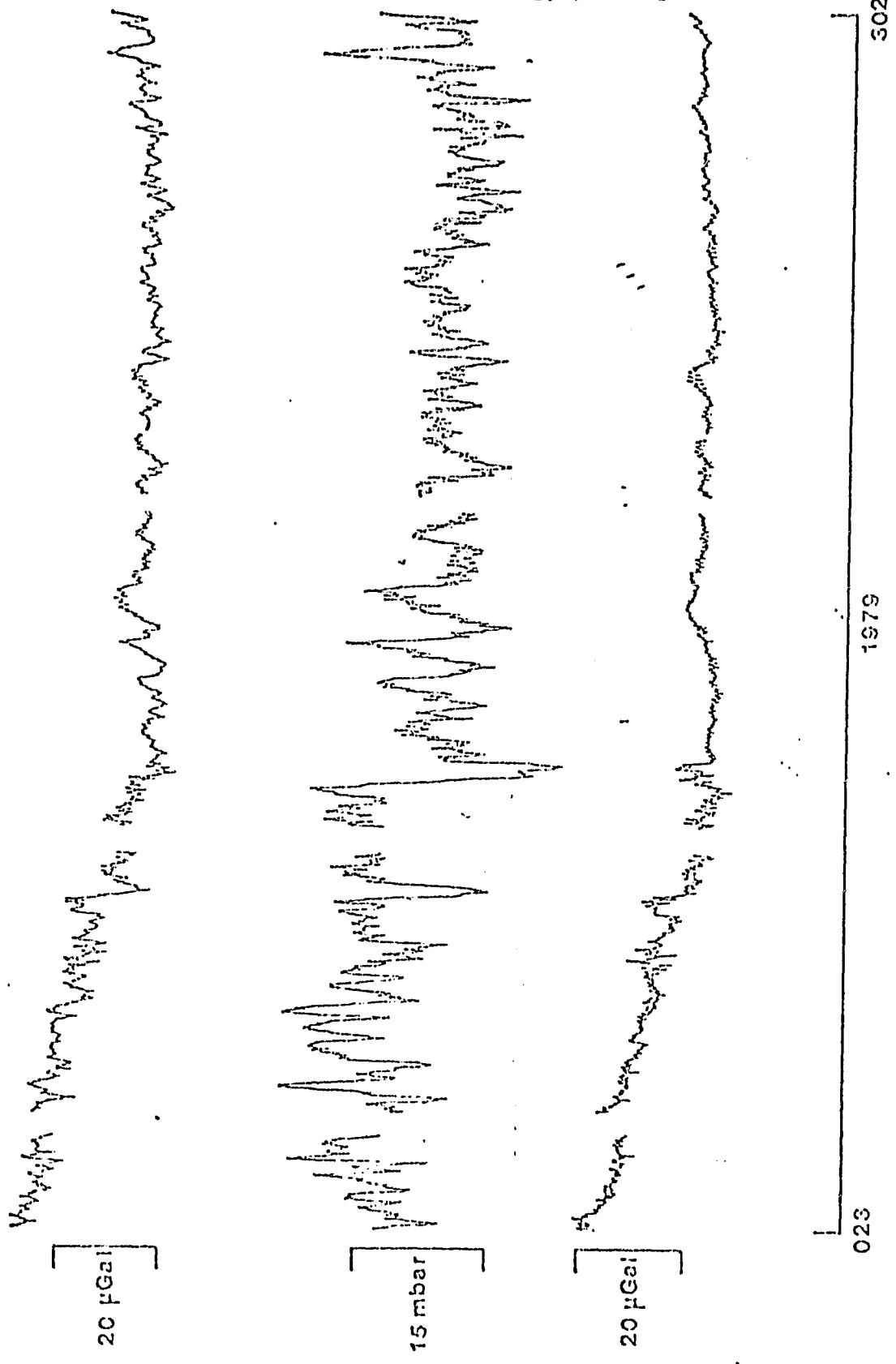
12 Dec 1978   6 weeks/div   12 Dec 1979

50 μgal/div

Figure 12.

A 270-day record from Boulder, CO. The top trace is gravity after removal of the tides, the second is the barometric pressure, and the third is the residual gravity after removal of the pressure effect.
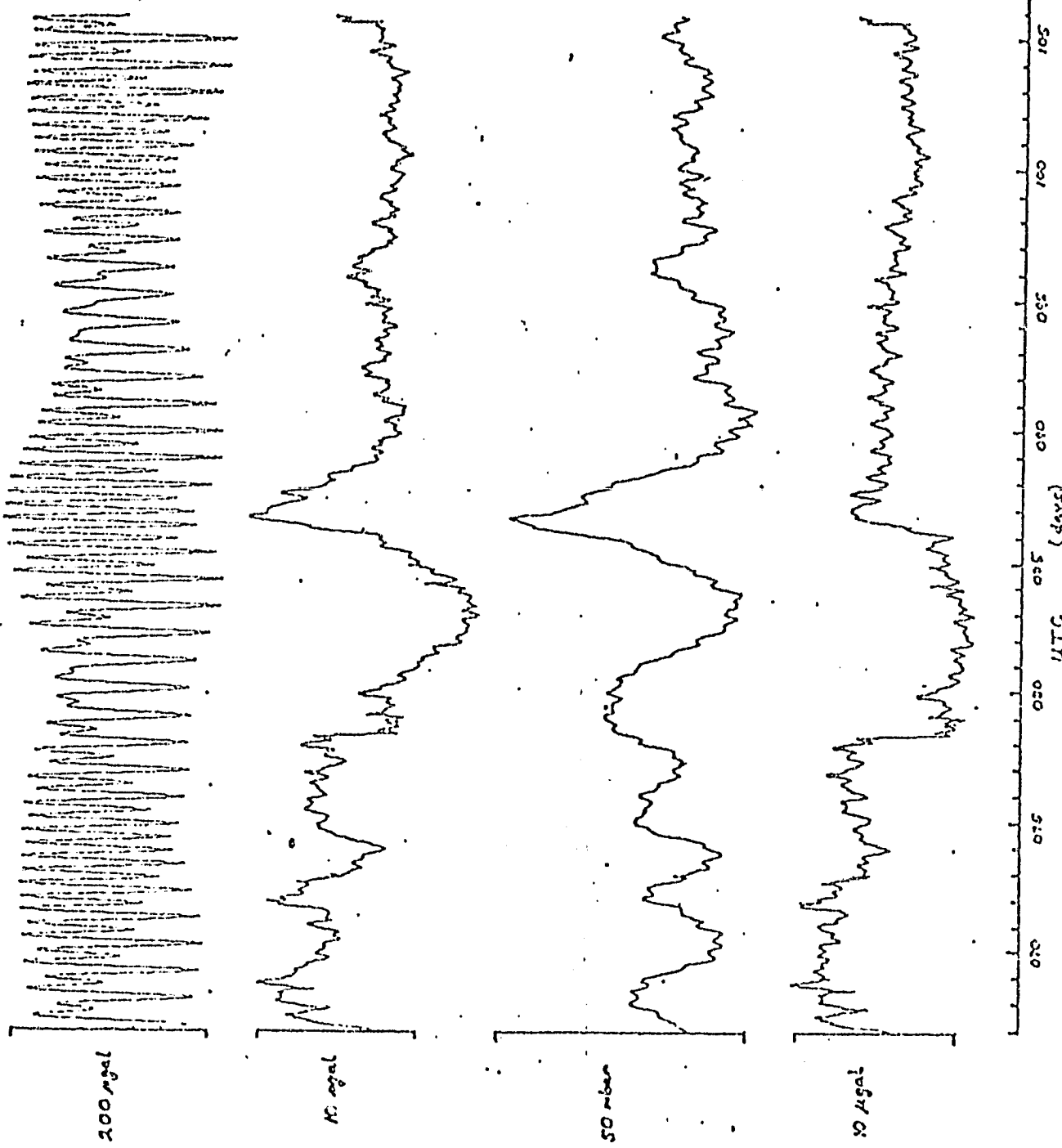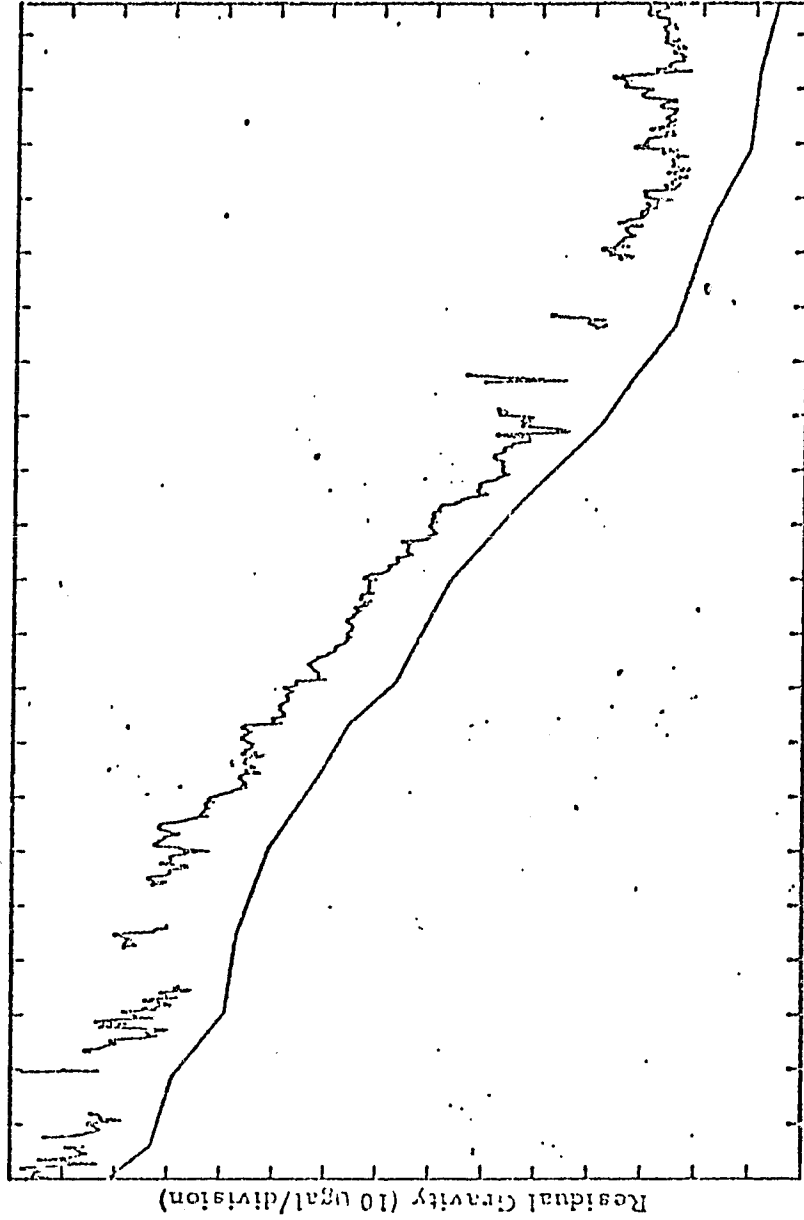
Figure 13. A 38-day data segment from The Geysers, illustrating the extraction of a barometrically adjusted residual gravity signal from the raw gravity and barometric pressure signals.

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Figure 14. Gravity residual from 647 days at Lytle Creek,
California. The top curve represents all of the avail-
able residual. The bottom curve is a linear interpola-
tion of the gravity residual between the times the
instrument was known to be aligned with the vertical.