COMPARISON OF RADON MONITORING TECHNIQUES, THE EFFECTS OF THERMOELASTIC STRAINS ON SUBSURFACE RADON, AND THE DEVELOPMENT OF A COMPUTER OPERATED RADON MONITORING NETWORK FOR EARTHQUAKE PREDICTION

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ANNUAL TECHNICAL REPORT

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Contract awarded for period 12/15/78 through 12/14/80, in the amount of $120,299

Pasadena, California 91125
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Abstract

During FY80 the Caltech automated radon-thoron monitoring network was expanded to include new sites at Pacoima Dam, Lake Hughes Forestry Station, Sky Forest Ranger Station, and Ft. Tejon State Historical Park. Among the technical improvements to the system during this period have been the incorporation of bi-directional telephone communication with the new monitors, improved capability for the control and monitoring of external instrumentation, and the installation of water level monitoring equipment at new sites. At the Pacoima site, in collaboration with Gulf Research, we have installed an automated gas chromatograph for the measurement of hydrogen and helium from the borehole.

Improvements also have been made in the software for routine data analysis which permit the more rapid dissemination of radon data updates to other investigators. In addition to the conventional time series presentation of the data, we now carry out spectral analysis of radon and other data on a regular basis in an attempt to better define anomalous patterns.

In collaboration with visiting scientists from the China, an expanded program of hydrogeological field work and geochemical analysis has been undertaken with the aim of determining hydrological and geochemical profiles of existing and future monitoring sites.

The large radon anomalies that were observed at the Kresge and Dalton Canyon sites during the second half of FY79 subsided during the early part of FY80 then reappeared in early summer and have continued to the present. In addition, there has been a substantial change in the level and character of data from the Stone Canyon Reservoir site during much of FY80. Data from the other sites appear to be following normal seasonal trends. The 1979 radon anomalies coincided with several other anomalous geochemical, geophysical, and geodetic data, and it now appears likely that these phenomena were caused by a regional strain event to which the 6.6 M Imperial Valley earthquake may have been related.

The reappearance of the substantial radon anomaly coincides with a return to tensional strain across the San Andreas as determined by laser geodimeter and VLBI techniques. This, together with continued high levels of seismicity throughout California, would suggest that the strain event which began in 1979 is continuing. Examination of historical seismicity data suggests that such events occur sporadically, typically are of about two years duration, and are accompanied by relatively high levels of seismicity.

Several intense rainstorms occurred in southern California during the first half of FY80. Although difficult operating conditions were encountered during the winter, the automated radon-thoron network collected data with very few interruptions. As a result, the response of several sites in the system to major changes in hydrology has been determined reasonably well. The 1980-81 winter has been very dry to date. This has allowed us to continue site development and to collect data without weather related problems.

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Appendices

I. Introduction

Data recorded by the Caltech automated radon-thoron monitoring network during FY80 indicate that the pattern of anomalous radon levels at Kresge and Dalton, which began in mid-1979, is continuing. In addition, it appears that a substantial change has taken place in the radon level at Stone Canyon Reservoir. At the same time, data from the Lytle Creek monitor appear to be repeating a seasonal pattern which is not anomalous. The anomalous radon observations seen during the second half of 1979 were accompanied by anomalies in a variety of other geochemical, geophysical, and geodetic measurements. This pattern of anomalies, together with a substantial increase in seismicity in southern California which included the 6.6 M Imperial Valley earthquake, has lead to the suggestion that a wide spread strain event began in southern California during 1979. The relationship of our radon data to this possible regional strain event has been discussed in detail in Shapiro et al. [1].

The onset of the radon anomaly at Kresge in 1979 was characterized by a very rapid increase in the levels and then a tapering off over several months. The pattern during 1980 has been considerably different. There has been a gradual increase in the average levels accompanied by substantial fluctuations. However, by the end of FY80 the levels had approached the maximum values observed during July of 1979. At present, there is not a substantial amount of recent data available from other investigations; however, geodetic data from the laser geodimeter program of Savage and the VLBI program at JPL do indicate that strain is again tensional across the strike of the San Andreas fault in southern California. While the geodetic data do not have the time resolution of our radon measurements, there is a remarkable similarity in the temporal development of both the radon anomalies and the geodetic anomalies.

The character of the anomaly at Dalton Canyon during 1980 is similar to that of 1979, namely occasional spike-like excursions along with a very gradual rise in level. At Stone Canyon Reservoir (west Los Angeles), there has been a substantial increase in the level of radon observed during much of 1980 along with substantially larger long and short-term variations.

The correlation of the anomalous radon data with continued unusual geodetic variations would suggest that the strain event that began in 1979 is continuing. The continued high level of seismicity in California appears to be characteristic of such a strain episode. Because of the nature of the data, our highest priorities during 1980 have been the expansion of the network and the collection and dissemination of data.

Automated radon-thoron monitoring sites developed during 1980 included Pacoima Dam, Lake Hughes Forestry Station, Sky Forest Ranger Station, and Ft. Tejon State Historical Park. The Pacoima site is located on granite within a few kilometers of the epicenter of the 1971 Sylmar earthquake, the Lake Hughes Forestry Station site is located on a pre-Cambrian formation about 3 km from the San Andreas fault, and the Ft. Tejon site is located on granite about 7 km north of the intersection of the Garlock and San Andreas faults. These three sites form the northwesterly running leg of our network of radon-thoron monitors. The Sky Forest site is located on granite about 2 km south of Lake Arrowhead.

A number of improvements have been made in the version of the monitor that is now being deployed. The most significant changes include the capacity for bi-directional telephone communication with the monitors, expanded capability for the control of external sensors and equipment, and provisions for measuring water level in the borehole at each site. At the

Pacoima site a fully automated gas chromatograph (provided by Gulf Research) is being controlled by the radon-thoron monitor, and data from the chromatograph are being stored in the on-board computer of the radon-thoron monitor and are transmitted to Kellogg Radiation Laboratory along with the other data from the monitor. The bi-directional communication capability of the monitor permits us to change the operating program of the monitor at will from the laboratory. This is essential for the operation of the gas chromatograph which requires monthly recalibration.

The winter of 1979-80 in southern California was characterized by a series of intense rainstorms separated in time by two to three weeks. Near record amounts of rainfall were recorded at our southern California monitoring sites. At four of these five sites, the radon data during this stormy period were dominated by the large hydrological changes that were taking place. A preliminary analysis of these results was included in the semi-annual technical report [2] and a brief summary is included below.

During FY80 the comparison experiment at San Juan Bautista was completed and our radon-thoron monitor was removed from that location. Although this particular site was not ideal for monitoring purposes owing to the geological setting and hydrological factors, there was reasonably good agreement between results obtained with the Caltech instrument and the other two continuous monitors at the site.

The severe weather encountered during the first half of FY80 together with some difficulties in obtaining permits caused delays in the siting of new monitors; however, by the end of the year most of the site work was back on schedule. This was helped to a great extent by dry weather during the fall and early winter. Our new sites are in somewhat more remote locations which has added to the delays that were experienced during FY80.

The gas chromatograph experiment (in collaboration with Gulf Research) at Pacoima is now in full operation. Generally, the instrument has worked well. However, it requires much more maintenance than the radon-thoron monitors. At present it is not clear that this is the best type of device for automated remote gas monitoring. While the baseline data for hydrogen and helium at Pacoima is still quite short, it does appear that there was a noticeable change in level before a nearby earthquake. There also was a change in radon level at the same time, although of lesser magnitude.

The work on the Gulf Research instrument has been supported by Gulf Oil Corporation and has been at no direct cost to the U.S.G.S. contract.

During FY80 we have spent considerable effort on improving software for data analysis and presentation. In addition to writing programs which have reduced the time needed to prepare data updates, spectral analyses and cross-correlation analyses have been carried out. Fourier transforms of the radon time series data have shown substantial changes in frequency content during some anomalous periods preceding local earthquakes. However, there does not appear to have been a change in frequency content during the major anomaly of 1979. Rather, a fourfold increase in power occurred at all frequencies. During 1980 data from several of our sites showed a pronounced increase in power at the one day period. At present this is not well understood.

II. Progress during the first half of FY80

A. Comparison of Different Radon Monitoring Techniques

Approximately 16 months of data were taken at San Juan Bautista in the side-by-side comparison between the Caltech automated radon-thoron monitor, the LBL continuous gamma-ray radon daughter monitor, and the Wakita continuous alpha counting radon-radon daughter monitor. During this period of operation the Caltech radon-thoron monitor worked well. Only a few interruptions in data collection occurred, and most of these were the result of external factors unrelated to instrument design. These included loss of flow to the holding tank on two occasions owing to breaks in the water line from the well, a premature failure of a backup battery, and the accidental shutoff of flow to the holding tank on one occasion. Because of the distance involved, repairs to the San Juan Bautista instrument could not be carried out as rapidly as repairs to units in southern California have been. Nevertheless, more than sufficient data were accumulated to carry out the comparisons.

Data from the LBL instrument were telemetered through our instrument directly to Kellogg Laboratory, which facilitates comparison. Inspection of the data sets from the two instruments indicated good qualitative agreement. The LBL instrument employs a much larger holding tank than our unit, and thus tends to time average the radon levels to a greater extent. This results in a somewhat lowered sensitivity to fast changes in the radon level for the LBL instrument compared to our instrument.

C.Y. King has supplied segments of data from the Wakita instrument that also was in operation at the San Juan Bautista site. While there was generally good qualitative agreement between the data sets, from time to time it appeared that changes in the opposite direction were being recorded on both instruments. It is believed that this may have been due to flow rate problems in the lines from the pumped well. Samples of typical data from the three instruments are shown in Figure 1.

In general, the San Juan Bautista site did not provide the necessary conditions for a good side-by-side test. The well at this site is in alluvium and is near other wells that are pumped for irrigation and water supply purposes. During much of the study period the data were smooth and featureless, providing little opportunity for a detailed comparison. In addition, plumbing problems which often resulted in clogged filters and variations in flow rate complicated interpretation of the data. Nevertheless, the experience gained at San Juan Bautista proved valuable in the design of a similar system for the Ft. Tejon site.

B. Study of Environmental Effects on Subsurface Radon

To date we have identified three environmental factors which can affect data from the automated radon-thoron monitors. The first of these is a temperature dependent wall effect which causes the plating out of radon daughters on the interior surfaces of the instrument vault before they can be captured on the filter paper for counting. This is a common problem in continuous radon monitors of different designs. The effect is somewhat dependent on the wall materials and temperature fluctuations encountered at the field sites. We have found empirically that over the temperature ranges usually encountered, a simple linear correction is sufficient to eliminate this factor from the data. At sites where large diurnal swings are encountered, extra insulation is added to the monitor vault. This step is sufficient to reduce the temperature fluctuations to the point where the linear correction is adequate.

The second factor which appears to affect the subsurface radon is thermoelastic strains. The diurnal temperature wave does not penetrate to much more than 1 meter beneath the surface. Since all of our field units monitor radon from much greater depth, the diurnal thermoelastic strains are of little consequence. However, the annual temperature cycle does penetrate to depth sufficiently to produce moderately large thermoelastic strains at sites where the topography is severe. Annual cycles in the data appear to be present at Kresge and Dalton Canyon. Both of these units are located in small canyons with steep walls. There appears to be an annual cycle in the data from Lytle Creek; however, this may be driven more by hydrological factors than by thermoelastic strains. Because of the heavy rains this past winter and the anomalous data during the latter part of FY79, it has not been possible to learn much more about the effects of thermoelastic strains at the various sites. Hopefully, more normal environmental conditions will prevail during the coming year.

During 1980 we have observed an increase in the magnitude of the diurnal variations in radon data at several of our sites for the greater part of the year. Cross-correlation of the data with ambient temperature, however, does not indicate a much stronger temperature dependence than was observed during previous years. In addition, one of the sites for which a reasonably long data set is available--Lytle Creek--shows little or no change in the intensity of diurnal fluctuations. Since the daily temperature variations at this particular site are larger than at most of the other sites on the system, it does not appear that the increased diurnal cycle is a temperature driven wall effect.

It is possible that daily thermoelastic strain may be partly responsible for the increased diurnal fluctuations in radon level at several of our sites. The past three winters have been marked by well above average precipitation in southern California, and the hydrological head is now higher at most of the sites. To some extent this means that radon closer to the surface is being sampled, and there is some possibility that these near surface radon concentrations are affected by the diurnal thermoelastic strains.

The heavy winter rains did give us the opportunity to observe the system while it was being driven dominantly by the large changes in hydrology that were taking place. The winter weather was characterized by a series of intense storms, each of several days duration and each separated by two to three weeks. Thus each storm can be viewed as providing a sudden pulse input to the aquifer at each site. At four of the five southern California sites, well defined responses were observed to these input pulses. At the remaining site (Dalton Canyon), the response to the rainfall was much less pronounced.

A detailed discussion of our results was given in our semi-annual technical report which is available as USGS Open File Report 80-896 [Ref. 2]. Here we present only a brief summary:

Of the five monitoring sites in operation in southern California during this period, only one--Dalton Canyon--did not exhibit marked response to the intense rainfall. At the other sites--Stone Canyon, Kresge, Santa Anita, and Lytle Creek--there were well-defined, short-duration increases in the radon level. For each site, once the capacity of the overburden had been exceeded (about 8 cm of rain), the response would take place after a characteristic delay time.

At Stone Canyon the delay time was about 4 to 6 days, which corresponded to flow velocities of 2 to 3 m/day under conditions of heavy influx. At this site there was no discernable change in the thoron levels during this period, which suggests that much of the increase at Stone

Canyon was the result of "washdown" of radon from the overburden. At Kresge the delay time ranged from 5 to 9 days corresponding to flow velocities of 3 to 6 m/day. At Kresge there was a strongly correlated increase in thoron at the same time, which would indicate that changes in the subsurface flow rates were at least as important as "washdown" at this site. At the Santa Anita site there was an aliasing problem in the analysis of the data. As a result, two possible delay time ranges were obtained. The shorter interval ranged from 2 to 11 days, and the longer from 20 to 25 days. These would correspond to flow velocities of from 1 to 6 m/day or from 0.5 to 0.6 m/day. At the Santa Anita site there always appears to be a strong correlation between radon and thoron which would suggest that flow velocity has a major influence on radon level at this location. At the Lytle Creek site there also was an aliasing problem, with the result that delay time ranges of 2 to 6 days or 18 to 25 days were consistent with the observed data. These time ranges corresponded to downward flow velocities of 2.5 to 7.5 m/day and 0.6 to 0.8 m/day. The correlation between radon and thoron levels during this period was quite strong, which would indicate that flow velocity is an important factor affecting the radon levels at this location.

Figures 2 through 9 present the data obtained during this period of heavy rainfall.

C. Development of a Radon Data Collection Net for Earthquake Prediction

1. Field Installations and Related Work

The heavy winter weather together with problems in obtaining permits delayed the schedule for deployment of additional monitors. However, during FY80 it was possible to complete nearly all the necessary site work for units at Pacoima Dam, Ft. Tejon State Historical Park, Lake Hughes Forestry Station, and Sky Forest Ranger Station. The Pacoima monitor has been in operation for several months, and the monitor at Lake Hughes Forestry Station was recently brought on line. The installations at Sky Forest and Ft. Tejon are nearing completion.

At Pacoima, special reinforcing was added to the standard prefabricated shed used to house the monitors in order to protect the instruments from damage from rock falls. The radon-thoron monitor at this location began operation during the first week of August 1980, and the gas chromatograph was installed about a week later. Except for a few minor start-up problems, the radon-thoron monitor has produced usable data since then. The gas chromatograph, however, has been prone to minor difficulties. Because most of our field efforts have been devoted to site work for the new radon-thoron monitors and to maintenance of the existing units, the chromatograph sometimes has been out of operation for periods of a week or so as a result of these minor problems.

Since the borehole at Pacoima was completed just prior to the onset of the winter rains, it was available for testing the water level monitoring device which is being interfaced to the radon-thoron monitors. Tests were carried out in which the bubbler tube from one of the standard monitors was lowered to a measured depth and the output of the pressure sensor on the bubbler line was measured during the bubbling cycle and shortly after the cessation of bubbling. Very little difference was noted between the two readings, and the monitors in operation at Pacoima and Lake Hughes record pressure readings only during bubbler operation.

Typical water level data from the Pacoima borehole are shown in Figure 10. Generally, changes in water level of a few mm are noticeable. The water level data usually show diurnal variation; however, we do not yet have enough data to determine if the variations correspond to tidal periods. One minor problem that has arisen in the water level measurements has been the tendency of the plastic bubbler tubing to twist and stretch in the borehole. While the total amount of motion is small, it is sufficient to make the location of the bubbler tube below the surface uncertain by as much as 10 cm. To remedy this situation we will replace the plastic tubing for the bubbler either with stainless steel tubing or with rigid PVC tubing.

The installation at Lake Hughes Forestry Station has followed our past practices. The borehole, however, was drilled to a depth of 150 feet below the surface in order to be well below the water table. The borehole was cased through the overburden with solid PVC pipe that was securely cemented into the rock. At several depths in the borehole, cores were obtained. Rock samples from these cores will be measured for radon and thoron progenitors. Water level in the borehole at Lake Hughes is being measured with the same type of pressure sensor that was installed at Pacoima.

At Sky Forest a concrete walled instrument vault was constructed at the request of the Forest Service in order to properly withstand the heavy snow loading experienced at this location. A cored borehole was drilled to a depth of approximately 100 ft. at this site, and cased in the same manner as the borehole at Lake Hughes. The rock is granite that is well consolidated with some large fractures. The water table at this site is quite high (within 10 feet of the surface), and we are taking precautions to protect the monitor if artesian flow should take place during the rainy season. The radon-thoron monitor for Sky Forest has been constructed and bench tested. Deployment of this unit occurred on January 8, 1981.

The Ft. Tejon unit will monitor radon and thoron levels in the water of the supply well for the ranger's house at the park. This is a naturally artesian well that is drilled and cased to a depth of more than 200 feet into a granite formation. While the well is artesian, a pump is operated occasionally to lift water to a storage tank. Based on our experience at San Juan Bautista, an improved filter system is being installed to prevent our flow regulators from clogging, and logic is being designed to shut off the flow to the holding tank while bubbling is taking place. This will ensure that a fixed size sample of water is being stripped of radon during each run, and will greatly reduce the sensitivity of the system to flow rate variations. In addition, the monitor will be equipped to sense when the pump is in operation, and this data will be transmitted to Kellogg along with the other information.

During the past twelve months the existing field units have operated for long periods of time with little need for field service. Some outages occurred during the exceptionally heavy rains that were experienced early in the year, but remarkably few days of data were lost. The engineering data from each unit is scanned almost daily, and as a result most problems have been picked up before data was lost. Again the most frequent reason for field trips for maintenance has been battery failure. We have tried a variety of lead-acid batteries from different manufacturers, and we now are using a deep cycle, recreational vehicle battery that appears to provide a minimum of 8 months of service. We also have obtained a number of surplus 480 amp-hour stationary 2 volt cells. Several of these have been reconditioned and placed in service at some of our more remote sites. This type of cell is designed for very long-term float charge service.

In addition to our collaboration with Gulf Research, we have made our installation at Dalton Canyon available to SRI for use in their atmospheric electric field measurements. Their field mill is located on the roof of our aluminum utility shed. Data from the field mill is recorded on magnetic tape cassettes in an electronics package located inside our instrument shed. Our field technician changes the tapes and mails them to SRI on a regular basis.

Growing experience with the network during the past year suggests that those monitors located on crystalline basement rock somewhat removed from nearby fault zones tend to show the greatest sensitivity to tectonic strains. Thus in our search for additional sites, we now are devoting greater effort to pre-selection site investigation. Mr. P.B. Larson from the Division of Geological and Planetary Sciences was very helpful in carrying out geological investigations of a number of potential sites during the first half of the year. An initial field investigation of possible sites near the San Jacinto fault zone also was carried out during FY80 in cooperation with Lamarr and Merrifield.

During the first part of FY80 one of our visitors from the PRC, Professor Qiu, completed the absolute calibration of a large volume (65 cm^3), high resolution Ge(Li) counter in the low background counting facility at Cal State-Fullerton for non-destructive determination of radium and thorium content of rock samples, and for the direct determination of radon emanation rates. The calibration which Professor

Qiu carried out corrects for the finite geometry and self-absorption of samples cut from borehole corings.

To date, samples from the boreholes at Santa Anita and Pacoima have been measured. Two samples from Santa Anita averaged about 3.7 ppm U-238 and about 4 ppm Th-232. Two samples from Pacoima averaged about 2.1 ppm U-238 and about 3 ppm Th-232. The low background counting facility at CSUF is being used for this work on a time available basis at no cost to the contract. During FY81 additional samples will be tested.

2. Automatic Data Collection and Analysis Software

In May of 1980 a new 1200 baud modem with autodialing capability was added to the Kellogg Laboratory LSI-11 data collection computer. This eliminated the intermediate microprocessor previously utilized for calling and collecting data from the field monitors, thereby allowing more reliable and efficient software to be implemented. The previous computer programs which called each of the field monitors, received the data, automatically retried on errors, stored the data on floppy disc, and created formatted printouts, have been upgraded to operate through this new modem.

In addition, a completely new software system has been written to match the more powerful on-board software of the version 3 radon-thoron monitors which have been deployed at Pacoima, Lake Hughes, and Sky Forest (and which will be deployed shortly at Ft. Tejon). This system of software implements bi-directional communications with the version 3 field units, reduces the amount of time needed for data transfer from the field, and eventually will have all the features needed to handle all the routine data analysis and preparation of weekly updates. The new software system also maintains log files of all communications with the field units which include descriptions of any communication errors and the recovery actions taken automatically by the computer.

3. Upgraded Field Monitor Development

A number of improvements were incorporated into the Caltech radon-thoron monitor during 1980, culminating in the version 3 monitors which have been deployed at Pacoima, Lake Hughes, and Sky Forest. A version 3 monitor also is scheduled for deployment at Ft. Tejon during January, and three additional monitors of this type will be deployed at sites along the San Jacinto fault zone later in FY81. The five version 2 monitors operating at Stone Canyon Reservoir, Kresge, Santa Anita, Dalton Canyon, and Lytle Creek are scheduled for upgrading to version 3 on a gradual basis during FY81.

The new hardware features of the version 3 monitor include:

(1) an interface so that the radon-thoron monitor can read any of up to 256 analog inputs as part of its automatic operation sequence. At each site these inputs will be used to measure monitor vault and ambient temperature, water temperature and water level in the borehole, AC line condition, and voltage of the computer backup battery. On individual monitors, additional inputs can be used to record other quantities, such as the output of instruments external to the radon-thoron monitor. In section 4 we describe the recording of data from a gas chromatograph which monitors hydrogen and helium levels in the borehole.

(2) an interface so that the radon-thoron monitor can control eight on-off voltage levels as part of its automatic operation. These outputs are provided for automatic control of external instrumentation by the radon-thoron monitor.

(3) Circuitry to shut down the operation of the radon-thoron monitor and disconnect it completely from the AC line/charger/battery system if a dangerously high voltage transient appears on the computer power line, or if the computer backup battery voltage becomes so low -- because of extended loss of AC power or battery failure -- that it would be damaging to draw further power from it.

(4) circuitry to restore power if the unit has powered down for some reason, and to restart the computer program on the radon-thoron monitor, whenever the monitor fails to answer an incoming phone call after 4 rings. This allows remote restarting of the monitor after it has shut down because of an extended AC power loss which has depleted the computer battery. The circuitry which carries out this function is always on. It is very low power and causes negligible battery drain. Another part of this circuitry restarts the computer if the phone remains off hook for more than 2048 seconds. This provides remote recovery for the case of a radon-thoron monitor program failure during a telephone call which holds the phone off hook and which, thereby, prevents a new phone call which could restart the monitor.

The new software features of the version 3 monitor include:

(1) Interpretation of a much more elaborate set of automatic operation sequence commands, thereby allowing many more operation sequences to be stored in the limited memory available in the on-board computer than was possible previously.

(2) compacting of the data before storage in the on-board computer, allowing typically 30% more words of data to be stored. With new more elaborate operation sequences, only 4 days of data could be stored in the current monitor without data compacting. This rises to approximately 6 days with data compacting.

(3) a counter to time how long the field monitor has operated since the last time it was started up.

(4) storage of identifiers, error codes and times whenever the monitor is started or halts by reason of a telephone call instruction or an error in a program sequence that it is trying to execute.

(5) bidirectional telephone communication. Previous radon-thoron monitors simply answered the phone, dumped all of their data, and hung up. The new version answers the phone and then responds to commands sent by an operator or an automatic data collection program running in a Kellogg Laboratory computer. These commands may be one or more of

(a) dump part of memory, including programs and/or data;

(b) halt the currently running program;

(c) load a new operation sequence into the field monitor (this sequence can call on permanently stored operation sequences as sub-operation sequences -- "subroutines");

(d) start running any particular operation sequence, either one of the permanently stored sequences or one of the new sequences loaded as described in (c) above.

The hardware and software improvements described in this section are all oriented towards more flexible remote data acquisition, collection of a larger variety of data from internal radon-thoron monitor sensors and from external sensors and instruments, and elimination of field trips previously required to restart monitors after power outages.

Figures 11 through 14 diagram the important features of the version 3 monitor. A paper describing the improvements incorporated in version 3 was given at the Fall 1980 A.G.U. meeting (see Appendix B).

4. The Radon-Thoron Monitor Controlled Gas Chromatograph Experiment

A cooperative project with Gulf Oil Corporation to monitor hydrogen and helium at the Pacoima Dam radon-thoron monitor site was initiated during the early part of 1980. Gulf supplied a technician and a gas chromatograph instrument. With some assistance from Kellogg Laboratory personnel, the chromatograph was upgraded to the stability needed for field operation and was provided with a battery backup power system. The upgraded Kellogg radon-thoron monitor was equipped with a hardware interface and specialized software to:

(1) cycle the gas chromatograph once every 8 hours;

(2) run a calibrated gas sample through the gas chromatograph once every 24 hours;

(3) on instruction from Kellogg through the telephone callup system, to halt the current operation sequence, to cycle the gas chromatograph and collect data from which a graph of the output (gas crossing the thermal sensor) as a function of time could be constructed, to load a new operation sequence which takes into account any drift in the time that the hydrogen and helium peaks came through on the graph, and to restart automatic operation.

After considerable testing in the laboratory, the gas chromatograph was deployed at Pacoima shortly after the radon-thoron monitor was installed there. This instrument is complicated mechanically, and requires more calibration and adjustment than the radon-thoron monitors. Occasional minor malfunctions of the gas chromatograph have put it out of action for several periods of a week or so. However, some data have been collected and they showed a possible precursor before a nearby 3.2 M earthquake. This consisted of a gradual increase in the hydrogen level which then decreased just prior to the earthquake. There also was a suggestion of a radon anomaly at Pacoima during this period (Figure 15.) It should be emphasized, however, that only very limited baseline data is available at Pacoima for comparison.

We recently have installed a chart recorder at the field site to check that the on-site readings are consistent with the computer automated data collection system which employs discrete windows to sample the hydrogen and helium peaks as well as background. Gulf Research also is supplying parts which will permit the substitution of a known standard gas for the borehole sample. This will then allow us to evaluate the stability of the instrument under actual field conditions.

5. Site Hydrogeology and Geochemistry

During the second half of FY80 a hydrogeologist, Fong-liang Jiang, and geochemist, Gui-ru Li, from the PRC joined our group for a year long visit. Both of these scientists have been active in the earthquake prediction program in China, and are familiar with the geochemical monitoring techniques in use there. Since coming to Caltech they have been carrying out geological and hydrological investigations at sites where we have radon-thoron monitors in operation, and they have participated in field trips undertaken for the purpose of selecting new sites. They have collected rock and water samples for eventual analysis in the laboratory.

They have begun to set up apparatus to carry out a variety of geochemical tests on the samples that have been obtained so far. Some of the rock samples have been cut into cubes for use in experiments designed to measure the effects of stress on radon release from the rocks in the vicinity of our monitoring sites. A stainless steel pressure vessel has been constructed for these experiments, and a system for the laboratory measurement of radon is being constructed.

Our visitors also have prepared two papers in English which summarize much of the field work that has been carried out in China for the routine monitoring of radon and other suspected geochemical precursors, as well as describing tests under more controlled conditions to find some of the causes of the variations in these parameters. These papers have been distributed as W.K. Kellogg Radiation Laboratory preprints LiAP-37 and LiAP-39, and summaries were presented at the fall 1980 A.G.U. meeting. Abstracts of this work are included in Appendix C.

D. Preliminary Analysis of Data Acquired During FY80

During FY80 Caltech automated radon-thoron monitors were in operation at Stone Canyon Reservoir just north of U.C.L.A. in west Los Angeles, at Kresge Seismological Laboratory in northwest Pasadena, near Santa Anita Canyon Dam north of Arcadia, at Big Dalton Canyon dam north of Glendora, at Lytle Creek Ranger Station north of Fontana, and at Pacoima Dam northeast of Pacoima. At each of these sites, the monitor is coupled to the casing of a static borehole that has been drilled into bedrock for the specific purpose of measuring the radon levels in the groundwater on a near real-time basis. The boreholes range in depth from 80 to 150 feet. Each has been cased with solid plastic pipe for depth of 30 feet or more. The solid casing has then been cemented to the rock to reduce the inflow of radon from the overburden and to reduce the effects of atmospheric variations. At some of the sites perforated casings have been used below the solid casing to hold the borehole open while permitting the flow of water through the borehole. At the remaining sites the lower part of the borehole is uncased.

The Stone Canyon site is located on a sedimentary formation just north of the Santa Monica fault and a few miles to the east of the

Newport-Inglewood fault terminus. Kresge is located in the granites of the San Rafael Hills near the Verdugo fault zone and the western end of the Raymond Hill fault. Santa Anita is located about 13 km to the east of Kresge in the hard granite of the San Gabriel mountains near the intersection of the Sierra Madre fault and the eastern end of the Raymond Hill fault. Dalton is located about 16 km to the east of Santa Anita in weathered granite and granodiorite close to the Sierra Madre and Cucamonga faults. The Lytle Creek monitor lies between two major fault zones, the San Jacinto and the San Andreas. The unit is sited on a small granite intrusion in rock that is mostly gneiss and sandstone.

Figure 16 shows data from the six southern California sites that were in operation during FY80. The monitor at Kresge began to produce usable data in April of 1977. During the first two years of operation, the data from Kresge exhibited a weak annual cycle that is believed to be the result of thermoelastic strains and hydrological effects. Except for some excursions that resulted from the heavy rains of the 1978-79 winter, the data during this time were relatively smooth--with only a small temperature induced diurnal cycle and a few minor excursions from the general trend which were associated with earthquakes in the Transverse Ranges (discussed in Shapiro et al. [3]).

Starting about the end of June 1979, a major change in the magnitude and character of the radon signal was noted at Kresge and also at the Dalton Canyon monitor about 30 km to the east. The data from the Lytle Creek monitor showed a steady increase during this period but none of the large fluctuations seen at the other two sites.

The data from Kresge and Dalton Canyon were considered highly anomalous, and were watched very closely during the summer and fall of 1979. Finally, during the week of October 15, 1979 the 6.6 M Imperial

Valley earthquake occurred, followed in the same week by a 4.2 M event off Malibu and 4.1 M event within 5 km of the Lytle Creek monitor.

At the time it seemed unlikely that radon anomalies in the Transverse Ranges some 290 km to the northwest of the Imperial Valley could be related to that earthquake. However, as time passed it became apparent that several other anomalies were being recorded in the Transverse Ranges coincident with our observations of anomalous radon. These included: significant anomalies in the levels of radon and helium in the waters of Arrowhead Hot Springs as measured by Craig et al. [4], a gravity anomaly of about 50 microgals reported by Whitcomb [5], a relatively large shift in the direction of the apparent electrical resistivity tensor in the region just to the north of the "big bend" in the San Andreas fault reported by Lienert et al. [6], changes in magnetic field measurments over a wide portion of the Transverse Ranges reported by Williams and McWhirter [7], but most striking were geodetic changes observed both by the laser geodimeter techniques of Savage et al [8]. and the radio interferometric techniques of MacDoran et al. [9].

All of these anomalies point to the occurrence of a rather wide spread strain event taking place in southern California during 1979. If indeed such a strain event did occur, then some very interesting questions can be raised regarding the implications for earthquake prediction. For example, why were most of the anomalies observed at scattered sites in the Transverse Ranges, while other monitoring both in the Transverse Ranges and closer to the epicenter of the Imperial Valley earthquake showed nothing unusual? Furthermore, if the anomalies preceding a large earthquake are spread over such a wide area, how can the impending epicenter be pinpointed? Finally, did the occurrence of the Imperial Valley earthquake signal the end of the strain event or is it still continuing?

The data which we have collected through the end of FY80 would suggest that the strain event has not yet terminated. During January and February of 1980, southern California experienced a series of very intense rainstorms (as discussed above), and the radon spikes that are present in the data from many sites (Figure 16) during this period reflect the very heavy recharge. Following the cessation of the rains, the radon level was close to the "normal" level for early spring at most sites except for larger than usual diurnal fluctuations at some sites and some minor variation with about a 10 day period at Kresge and Dalton. During the late spring, the data from most sites were normal except for occasional spikes at Kresge and Dalton. An exception was Stone Canyon which showed a step increase in the radon level in April for no apparent reason.

Beginning in June a gradual increase in radon level with considerable diurnal variation and some spikes was noted at Kresge and Dalton, and unusual changes at Stone Canyon continued. While the magnitude of the anomalous data is somewhat less than in the second half of 1979, the fluctuations during the last few weeks of 1980 have been quite large in the absence of any significant precipitation. In contrast, the data from Lytle Creek essentially are repeating the pattern of the previous year with no increase in diurnal swing. The unusual character of the data from Kresge, Dalton, and Stone Canyon coincide with a return of tensional strain across the strike of the San Andreas as reported by both the laser geodimeter group and ARIES.

A study of historic seismicity in California by McNally and a similar search of the catalog by Hutton suggests that strain events characterized by clusters of larger magnitude earthquakes happen episodically. These events typically seem to last about two years, and are interspersed with periods of seismic quiesence that ofter are considerably longer. With that in mind, and with the available seismic, geodetic, and geochemical data, it would seem prudent to operate under the assumption that a strain event is continuing and that higher than average seismicity can be expected in the near future.

A preliminary study of Fourier transforms of radon time-series data from our monitors has yielded some interesting information. In general, the power spectra show a 1/f dependence typical of the noise expected in a geophysical measurement, together with a peak at a period of one-day corresponding to the diurnal variations mentioned above. At times, however, there is a marked departure from the 1/f dependence. Before some nearby earthquakes an enhancement is noted in the 5 - 20 day cycles, and during periods of heavy rainfall cycles in the 1 - 5 day range become prominent. Interestingly, the large anomalies of the past 18 months do not show up in the power spectra as enhancements in any particular frequency range, but rather the power at all frequencies is increased by a factor of about four. Figures 17 through 19 show typical power spectra of data from the Kresge site.

III. Projected Course of the Project During FY81

A. Comparision of Different Radon Monitoring Techniques

With the permission of the U.S.G.S., the data taking phase of the comparison measurement at San Juan Bautista has been completed and the Caltech instrument has been removed for refurbishing and installation at Ft. Tejon. A second LSI-11 computer system now is in operation at Kellogg Laboratory. This will facilitate completion of the analysis of the San Juan Bautista data, and we expect to have the results prepared for publication soon.

B. Study of Environmental Effects on Subsurface Radon

As noted in previous sections, the hardware and software has been completed to permit the addition of water level monitoring and water temperature monitoring at the field sites. The presently exisisting sites will be upgraded to include these features one unit at a time in order to minimize the loss of coverage during the upgrading work. The water level measuring devices already are in operation at Pacoima and Lake Hughes Forestry Station, and additional pressure sensors are on order for the other monitors. A low cost ground water temperature probe is under development.

We also are working on improved short term temperature corrections for each of the sites. Using fast Fourier transform techniques cross-correlations of radon data with surficial temperature are being carried out with the hopes that some of the combined effects of thermoelastic strains and instrument wall effects can be removed more effectively.

C. Extension of the Radon Data Collection Net for Earthquake Prediction

During the first part of FY81 the remaining site work at Sky Forest and Ft. Tejon will be finished. Then attention will focus on siting three monitors along the San Jacinto fault zone between Riverside and Anza (Anderson has pointed out the existence of a significant seismic gap in the vicinity of Anza). As with our previous sites, we will attempt to find outcrops of igneous basement rock--preferably granite-- for the location of our boreholes.

D. Planned Further Improvements in Field Monitor Capability

The newly developed version of the Kellogg radon-thoron monitor (see section II.C.3 above) has every feature included in the original conception of the field instrument, plus several additional ones that have come out of the very fruitful collaboration with Gulf Oil Corporation. The latter features allow for remote operation and calibration of an instrument external to the radon-thoron monitor utilizing the radon-thoron monitor microcomputer and telephone call-up system. It has become clear to us during the course of this development work that the radon-thoron monitor, besides providing automatic radon data collection, is very useful as a general purpose remote experiment controller. When combined with the telephone callup computer in Kellogg Laboratory and the data handling software being developed, it will provide a framework for rapid implementation of future remote experiments and handling of the resultant data.

The new version of the radon-thoron monitor will include various environmental sensors (water level, air and water temperature) as described in II.C.3 above. In the future, other environmental sensors can be provided at each field site, such as monitors of barometric pressure humidity, air flow, rainfall, and water chemistry, without any modification of the radon-throron monitor control system.

If the number of monitors to be built after 1980 warrants it, we may implement some additional electronic improvements beyond those in the version 3 monitor. These include the use of a commercial microcomputer board which takes advantage of new technology to provide more memory and also to reduce overall power consumption by 50 to 70%, a lower cost 1200 baud modem, and a new custom designed interface board to include all the features currently provided on the radon-thoron monitor. These changes would make possible the following improvements with no change in the electromechanical system and very minor software changes:

(1) increase in the number of days of data that can be stored on board from 6 days to 25 or 50 days, depending on the kind of memory chips provided on the microcomputer board;

(2) the ability to count input pulses at rates up to 4 MHz instead of the 10 KHz limit now required;

(3) the ability to store longer and more numerous program sequences;

(4) the ability to recognize simple anomalies in data (such as exceeding a maximum or falling below a minimum), or incipient failures (such as loss of AC power, battery failure, and filter paper depletion) and to call a succession of phone numbers until an answer is obtained in order to alert the investigators to the condition of concern.

IV. Publications and Talks

During FY80 the following papers were published or distributed as preprints:

M.H. Shapiro, J.D. Melvin, N.A. Copping, T.A Tombrello, and J.H. Whitcomb, Automated radon-thoron monitoring for earthquake prediction research, in Natural Radiation Environment III--DOE Conf-780422 (Vol. 1) 1980 p. 137.

M.H. Shapiro, J.D. Melvin, T.A. Tombrello, and J.H. Whitcomb, Automated radon monitoring at a hard-rock site in the southern California Transverse Ranges, J. Geophys. Res., 85, 3058, 1980.

M.H. Shapiro, J.D. Melvin, T.A. Tombrello, M.H. Mendenhall, P.B. Larson, and J.H. Whitcomb, Relationship of the 1979 southern California radon anomaly to a possible regional strain event, J. Geophys. Res., in press. (W.K. Kellogg Radiation Lab. preprint LiAP-36, 1980).

Jiang Fong-liang and Li Gui-ru, The application of geochemical methods in earthquake prediction in China, W.K. Kellogg Radiation Lab. preprint LiAP-37, 1980.

Jiang Fong-liang and Li Gui-ru, Experimental studies of the mechanisms of seismo-geochemical precursors, W.K. Kellogg

Radiation Lab. preprint LiAP-39, 1980.

M.H. Shapiro, Comparison of radon monitoring techniques, the effects of thermoelastic strains on subsurface radon, and the development of a computer operated radon monitoring network for earthquake prediction, U.S.G.S. Open file report 80-896, 1980.

Abstracts of these papers appear in Appendix C of this report.

The following contributed paper was presented at the Spring 1980 meeting of the American Geophysical Union in Toronto, Canada:

M.H. Shapiro, J.D. Melvin, T.A. Tombrello, P.B. Larson, and J.H. Whitcomb, Rainfall induced changes in subsurface radon levels, Eos, 61, 573, 1980.

A copy of the abstract is included as Appendix A.

The following contributed papers were presented at the Fall 1980 meeting of the American Geophysical Union:

Li Gui-ru and Jiang Fong-liang, Experimental studies on the mechanisms of seismo-geochemical precursors, Eos, 61, 1032, 1980.

Jiang Fong-liang and Li Gui-ru, The application of geochemical methods in earthquake prediction in China, Eos, 61, 1032, 1980.

J.D. Melvin, M.H. Mendenhall, A.R. Rice, Improvements to the Caltech automated radon-thoron monitoring system network, Eos, 61, 1033, 1980.

M.H. Shapiro, J.D. Melvin, M.H. Mendenhall, and T.A. Tombrello, Recent data from the Caltech automated radon-thoron monitoring network, Eos, 61, 1033, 1980.

M.H. Mendenhall, M.H. Shapiro, J.D. Melvin, and T.A. Tombrello, Preliminary spectral analysis of near real-time subsurface radon data, Eos, 61, 1033, 1980.

Abstracts of these papers appear in Appendix B.

V. Acknowledgments

The work reported herein was facilitated greatly by excellent assistance from the staffs of the U.S.G.S., the Seismological Laboratory at Caltech, the Los Angeles County Flood Control District, the Los Angeles City Department of Water and Power, the U.S. Forest Service, and Gulf Research. The dedicated assistance of our own Kellogg Radiation Laboratory staff also is gratefully acknowledged.

During the FY80 the following persons have been involved in this project either on a paid or volunteer basis:

Katherine Chesick

Philip Grove

Jiang Fong-liang

Peter Larson

Li Gui-ru

Jon Melvin

Marc Mendenhall

Alan Rice

Mark Shapiro

Tom Tombrello

Qiu Yunxan

Appendix A. Abstract of the talk given at the AGU spring meeting.

Toronto, May, 1980.

RAINFALL INDUCED CHANGES IN SUBSURFACE RADON LEVELS*

M.H. Shapiro+
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P.B. Larson (Div. of Geology and Planetary Sci., Caltech)
J.H. Whitcomb (C.I.R.E.S., Univ. of Colorado Boulder, CO 80302)

The W.K. Kellogg Radiation Laboratory of Caltech presently operates a system of 6 fully automated radon-thoron field monitors for earthquake prediction research. Five of these monitors are sited along the frontal faults of the Transverse Ranges of southern California. At one of the sites radon and thoron data have been collected continuously for more than 3 years, and at the others from 3 months to one year. During the past year anomalous radon data have been recorded at two of the southern California sites (Kresge and Dalton Canyon) and possibly anomalous data have been recorded at a third intermediate site (Santa Anita Canyon).

A series of intense rainstorms during January and February, 1980 (total rainfall approx. 100 cm) has given us the opportunity to examine the response of the monitors to changes in hydrology. All of the southern California instruments recorded increases in radon which appeared to correlate well with the rainfall, although the degree of response varied from one site to another. From the delays observed between the onset of heavy rain and the changes in radon levels, estimates have been made of vertical flow velocities in the vicinity of each site. These ranged from 0.6 to 3 m/day. At 3 of the 5 sites, changes in thoron level coincident with the radon changes also were observed, suggesting that increased flow rather than washdown caused the increases in radon levels.

*Supported in part by USGS contract #14-08-0001-17734.
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Appendix B. Abstract of talks given at the AGU fall meeting.

San Francisco, December, 1980.

EXPERIMENTAL STUDIES ON THE MECHANISMS OF SEISMO-GEOCHEMICAL PRECURSORS

Li Gui-ru
Jiang Fong-liang (Institute of Geology, State Seismological Bureau, Beijing, China and W. K. Kellogg Radiation Laboratory, Caltech, Pasadena, California 91125)
(Sponsor: Mark. H. Shapiro)

We describe several aspects of modeling experiments on the seismo-geochemical precursors of earthquakes including: (1) gas emission during stress loading and rupture of rock in the laboratory, (2) explosion tests in the field, (3) aquifer mixing experiments using test boreholes, and (4) experiments on the physico-chemical processes caused by stress events. We have drawn the following conclusions:

1) The stage of elastic deformation of rocks under stress loading before an earthquake is thought to be responsible for long-term seismo-geochemical anomalies. The stage of plastic deformation appears to correspond to short-term anomalies, and the spike-like anomalies observed before an earthquake appear to correspond to the stage of shear displacement of the rock.

2) Anomalous changes in the chemical composition of groundwater as well as soil gas may result from rock fracturing which opens up pathways for the upward migration of deep-seated, confined aquifers and for gas flow from the deeper crust.

3) Increasing stress on rock in the region surrounding the epicenter may induce chemical reactions which may be responsible for the changes in chemical composition of groundwater which have been observed before large earthquakes.

THE APPLICATION OF GEOCHEMICAL METHODS IN EARTHQUAKE PREDICTION IN CHINA

Jiang Fong-liang
Li Gui-ru (Institute of Geology, State Seismological Bureau, Beijing, China and W. K. Kellogg Radiation Laboratory, Caltech, Pasadena, California 91125)
(Sponsor: Mark. H. Shapiro)

Those geochemical anomalies observed before the Haichen, Longling, Tangshan, and Songpan earthquakes and their strong aftershocks are presented. They include changes in groundwater radon levels; chemical composition of the groundwater (concentration of Ca^{++}, Mg^{++}, Cl^-, $SO_4^=$, HCO_3^-, AND F^- ions); hardness and conductivity; pH and dissolved solids; and dissolved gases such as H_2, CO_2, SO_2, etc. In addition, anomalous changes in water color and quality were observed before large earthquakes. Before some events gases escaped from the surface, and there were reports of "ground odors" being smelled by local residents.

The large amount of radon data can be grouped into long-term and short-term anomalies. The long-term anomalies have a radon emission build up time of from a few months to more than a year. The short-term anomalies have durations from a few months to a few hours or less.

It is suggested that a precursor field appears to be governed by a stress field related to the impending earthquake. It is reasonable to expect that geochemical anomalies may have a close association with the regional seismic activity on one hand, and on the other hand geochemical anomalies may vary with different focal mechanisms for the impending earthquake and may take different forms for different tectonic structure, geological history, geochemical environment, and hydrogeological conditions within a given seismic region.

IMPROVEMENTS TO THE CALTECH AUTOMATED RADON -THORON MONITORING NETWORK

J.D. Melvin
M.H. Mendenhall
A.R. Rice (all at W.K. Kellogg Radiation Laboratory, Caltech, Pasadena, CA 91125)

During the past three and one-half years, several improvements have been incorporated in the Caltech radon-thoron monitoring network. The prototype field monitor deployed in 1976 was fully automated under microprocessor control, but did not provide for telemetry of the data. In 1977 and 1978 monitor versions (2) and (3) were developed which incorporated "dial-up" telemetry for remote readout of the data, a simplified electromechanical system, a printed circuit version of the on-board microcomputer, and improved transient protection for the battery charger power lines and telemetry telephone line.

Version (3) of the monitor was upgraded during 1979 and 1980 to add overvoltage and undervoltage protection, automatic restart by telephone after a prolonged loss of power, an improved external interface which permits measurements from up to 256 external sensors and control of up to 8 external instruments, and greatly improved software. The new software allows for greater flexibility in data collection, and permits bi-directional telephone communications so that alternate programs for the monitor can be sent from the central laboratory computer.

An upgraded version (3) monitor now in operation at Pacoima Dam is used to control a gas chromatograph and to collect water level information in addition to radon and thoron data. In the coming year, similar improvements will be added to monitors at other sites.

RECENT DATA FROM THE CALTECH AUTOMATED RADON-THORON MONITORING NETWORK

M.H. Shapiro*
J.D. Melvin
M.H. Mendenhall
T.A. Tombrello (all at W.K. Kellogg Radiation Laboratory, Caltech, Pasadena, CA 91125)

The Caltech automated radon-thoron monitoring network includes monitors at Stone Canyon Reservoir, Kresge, Santa Anita Canyon, Dalton Canyon, Lytle Creek, and Pacoima in the Transverse Ranges of southern California. New units are being added near Lake Hughes, at Ft. Tejon, and near Lake Arrowhead. The data accumulated from several of the southern California stations during 1980 appear to have different characteristics than were observed previously. Following sharp hydrological responses at several sites to intense winter rains, most stations returned to levels comparable with previous early spring data. However, diurnal variations of greater magnitude and regularity became noticable at several sites. In addition as the summer progressed, the average values of the radon levels at some of the stations have risen to higher than "normal" levels.

During the past three years, rainfall was well above average while during the previous three years drought conditions prevailed in southern California. In addition, after several years of rather low seismic activity, there has been a much higher level of seismicity during the past 18 months. These factors complicate the interpretation of the radon data.

*Also California State University, Fullerton

PRELIMINARY SPECTRAL ANALYSIS OF NEAR REAL-TIME SUBSURFACE RADON DATA

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M.H. Shapiro*
J.D. Melvin
T.A. Tombrello (all at W.K. Kellogg Radiation Laboratory, Caltech, Pasadena, CA 91125)

The thrice-daily sampled radon levels of several wells of the Caltech radon monitoring network were subjected to Fourier transform spectrum analysis to determine what regular cycles appear. The resulting information can be used to identify and remove periodic variations in the radon levels that result from daily and monthly tides, weather cycles and any other extraneous fluctuations that may drive the radon levels. Also, it appears that the power spectra of the radon levels at some sites have changed substantially before some nearby earthquakes. Much more of the power tends to be concentrated in the 10 - 20 day cycles before these earthquakes than at other times. This change is also visible in the time series but is far easier to quantify when the data is represented in the form of a power spectrum.

The power spectrum analysis also seems to be capable of distinguishing rainfall induced radon changes from other variations. During periods of rainfall, the power spectrum resembles a white noise spectrum with a great deal of power in the high frequency (short period) cycles. At other times the only substantial high frequency variations are the daily fluctuations that appear at some sites, while during periods of rainfall cycles in the 2 - 5 day range become prominent.

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Appendix C. Abstracts of radon group papers and preprints--FY80.

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 85, NO. B6, PAGES 3058-3064, JUNE 10, 1980

AUTOMATED RADON MONITORING AT A HARD-ROCK SITE IN THE SOUTHERN CALIFORNIA TRANSVERSE RANGES

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Abstract. Data are presented from 20 months of near-real-time (three samples per day) radon monitoring at a hard-rock site in the Transverse Ranges of southern California. An annual cycle is evident in the data which is attributed to thermoelastic strains in the vicinity of the borehole site. Between April 1, 1977, and October 31, 1978, there were 11 earthquakes with magnitudes ≥2.0 within 25 km of the monitoring site. Three of these events appeared to be preceded by precursory signals, four were preceded by 'possible' precursory signals, and four were not preceded by any apparent precursors. Before the 4.6 M Malibu earthquake of January 1, 1979, a possible precursory signal sequence of 40-45 days' duration was observed.

Automated Radon–Thoron Monitoring for Earthquake Prediction Research

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ABSTRACT

This paper describes an automated instrument for earthquake prediction research which monitors the emission of radon (^{222}Rn) and thoron (^{220}Rn) from rock. The instrument uses aerosol filtration techniques and beta counting to determine radon and thoron levels; a programmable microcomputer that controls mechanical operations, collects data, and monitors the condition of key components; and a call-up telemetry system to transmit data to a central location over standard telephone lines. Data from the first year of operation of a field prototype suggest an annual cycle in the radon level at the site which is related to thermoelastic strains in the crust. Two anomalous increases in the radon level of short duration have been observed during the first year of operation. One anomaly appears to have been a precursor for a nearby earthquake (2.8 magnitude, Richter scale), and the other may have been associated with changing hydrological conditions resulting from heavy rainfall.

RELATIONSHIP OF THE 1979 SOUTHERN CALIFORNIA RADON ANOMALY TO A POSSIBLE REGIONAL STRAIN EVENT

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Abstract. During the second half of 1979, anomalously high emanation of radon was recorded at two stations of the automated radon-thoron monitoring network operated by the W. K. Kellogg Radiation Laboratory of Caltech. The two stations exhibiting major anomalies, Kresge and Dalton Canyon, are located approximately 30 km apart on the frontal fault system of the Transverse Ranges of southern California. At Kresge the anomaly began on June 21, 1979 and continued through December 1979. At Dalton Canyon the anomaly started about three weeks later and also continued through December 1979. At both sites the anomalous levels of radon decreased (but did not return entirely to normal values) shortly before October 15, 1979. During the week of October 15, 1979 a 6.6 M earthquake occurred about 290 km to the southeast of the two stations, and later in that week earthquakes of magnitude 4.2 and 4.1 occurred at Malibu and Lytle Creek. The latter two events were within 60 km of the monitors. A radon-thoron monitor at Lytle Creek recorded no long term anomaly, but did record a sharp spike-like decrease in the radon level on October 13, 1979. Coincident with our observations of anomalous radon levels, other investigators have reported anomalies or suspected anomalies in several other geodetic, geophysical, and geochemical signals from the same general region. The rapid temporal development of several of the anomalies together with the large area over which they were observed suggest that a large-scale strain event took place which may have been responsible both for the widespread anomalies and for the seismicity that occurred in the region subsequent to the onset of the anomalies.

EXPERIMENTAL STUDIES OF THE MECHANISMS OF SEISMO-GEOCHEMICAL PRECURSORS

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ABSTRACT

The following aspects of modeling experiments on seismo-geochemical precursors are described: (1) gas emission during laboratory stress loading and rupture of rocks, (2) field measurements with explosion sources, (3) aquifer mixing tests in the field, (4) experimental studies of physico-chemical processes caused by stress events. From these studies, three conclusions have been drawn:

(1) Long-term seismo-geochemical anomalies appear to be related to the stage of elastic deformation of rocks under stress loading prior to a seismic event. Short-term anomalies appear to be related to the plastic deformation of rock, and spike-like anomalies appear to be related to shear displacement before an earthquake.

(2) Anomalous changes in chemical composition of groundwater and the escape of gases from the ground appear to result from rock fracturing which opens up pathways for the upward migration of water from deep, confined aquifers, and for the upward migration of gases from the deeper crust.

(3) Chemical reactions induced by increasing stress in the epicentral region may result in the anomalous changes in chemical composition of groundwater observed before some large earthquakes.

THE APPLICATION OF GEOCHEMICAL METHODS IN EARTHQUAKE PREDICTION IN CHINA

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ABSTRACT

Geochemical anomalies observed before the Haichen, Longling, Tangshan, and Songpan earthquakes and their strong aftershocks are presented. They include changes in groundwater radon levels; chemical composition of the groundwater (concentration of Ca^{++}, Mg^{++}, Cl^{-}, $SO_4^{=}$, HCO_3^{-}, AND F^{-} ions); hardness and conductivity; pH and dissolved solids; and dissolved gases such as H_2, CO_2, SO_2, etc. In addition, anomalous changes in water color and quality were observed before these large earthquakes. Before some events gases escaped from the surface, and there were reports of "ground odors" being smelled by local residents.

The large amount of radon data can be grouped into long-term and short-term anomalies. The long-term anomalies have a radon emission build up time of from a few months to more than a year. The short-term anomalies have durations from a few hours or less to a few months.

It is suggested that a precursor field appears to be governed by a stress field related to the impending earthquake. It is reasonable to expect that geochemical anomalies may have a close association with the regional seismic activity and may vary with different focal mechanisms for the impending earthquake and different tectonic structure, focal mechanisms, geological history, geochemical environment, and hydrogeological conditions within a given seismic region.

References

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change near Palmdale, California, Science, 211, 56, 1981.

[9] P. MacDoran, Private communication, 1980.

Figure Captions

(1) Comparison of radon data from the Caltech, LBL, and Wakita instruments at San Juan Bautista.

(2) 72-hr running averages of radon and thoron data from Stone Canyon (every third run plotted) from October 1979 to April 1980.

(3) 72-hr running averages of radon and thoron data from Kresge (every third run plotted) from October 1979 to April 1980. The radon data have been temperature corrected.

(4) Correlograms for Kresge radon vs. Kresge thoron for the rainy period Jan.-Feb. 1980 and the dry period Oct.-Nov. 1979.

(5) 72-hr running averages of radon and thoron data from Santa Anita (every third run plotted) from Nov. 1979 to April 1980.

(6) Correlograms for Santa Anita radon vs. Santa Anita thoron for the rainy and dry periods.

(7) 72-hr running averages of radon and thoron data from Dalton Canyon (every third run plotted) from October 1979 to April 1980. The radon data have been temperature corrected.

(8) 72-hr running averages of radon and thoron data from Lytle Creek (every third run plotted) from October 1979 to April 1980. The radon data have been temperature corrected.

(9) Correlograms for Lytle Creek radon vs. Lytle Creek thoron for the rainy and dry periods.

(10) Typical water level data from the Pacoima radon-thoron monitor.

(11) RTM-3 Radon-thoron monitor components (version 3).

(12) RTM-3 Radon-thoron monitor electromechanical system (version 3).

(13) RTM-3 Radon-thoron monitor control system: power supply and GM Tube circuitry (version 3).

(14) RTM-3 Radon-thoron monitor control system: microcomputer (version 3).

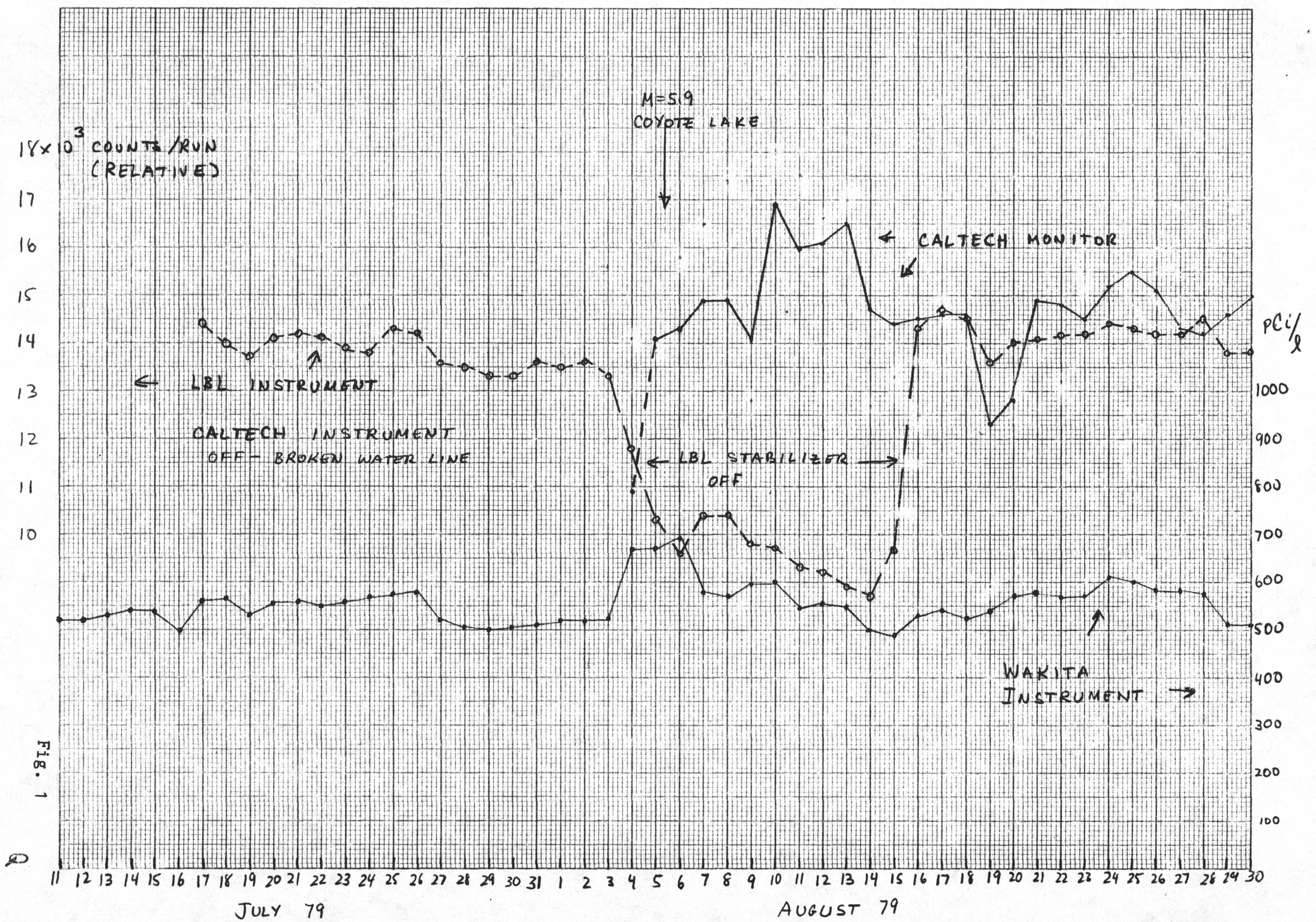
(15) Pacoima radon data at the time of a local earthquake (3.5 M within 5 km of the monitoring site.)

(16) Complete radon archive for monitors in operation during FY80. 24-hr running averages of the raw data are presented.

(17) 1/f normalized power spectrum of Kresge radon data during a quiet (non-anomalous) period.

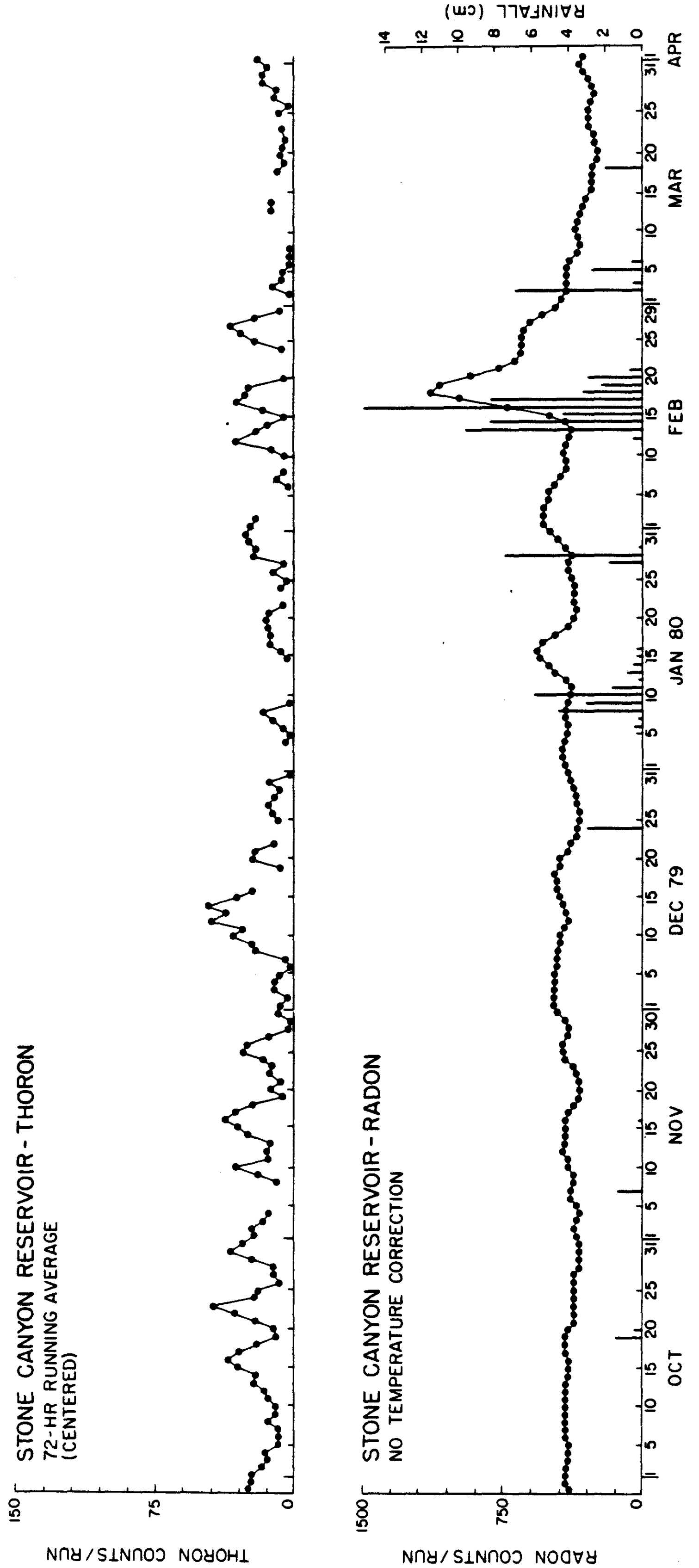
(18) 1/f normalized power spectrum of Kresge radon data during the period when a small local earthquake occurred (3.0 M within 13 km of the site on 20-Dec-1977).

(19) 1/f normalized power spectrum of Kresge radon data during the anomalous period that commenced in June of 1979.



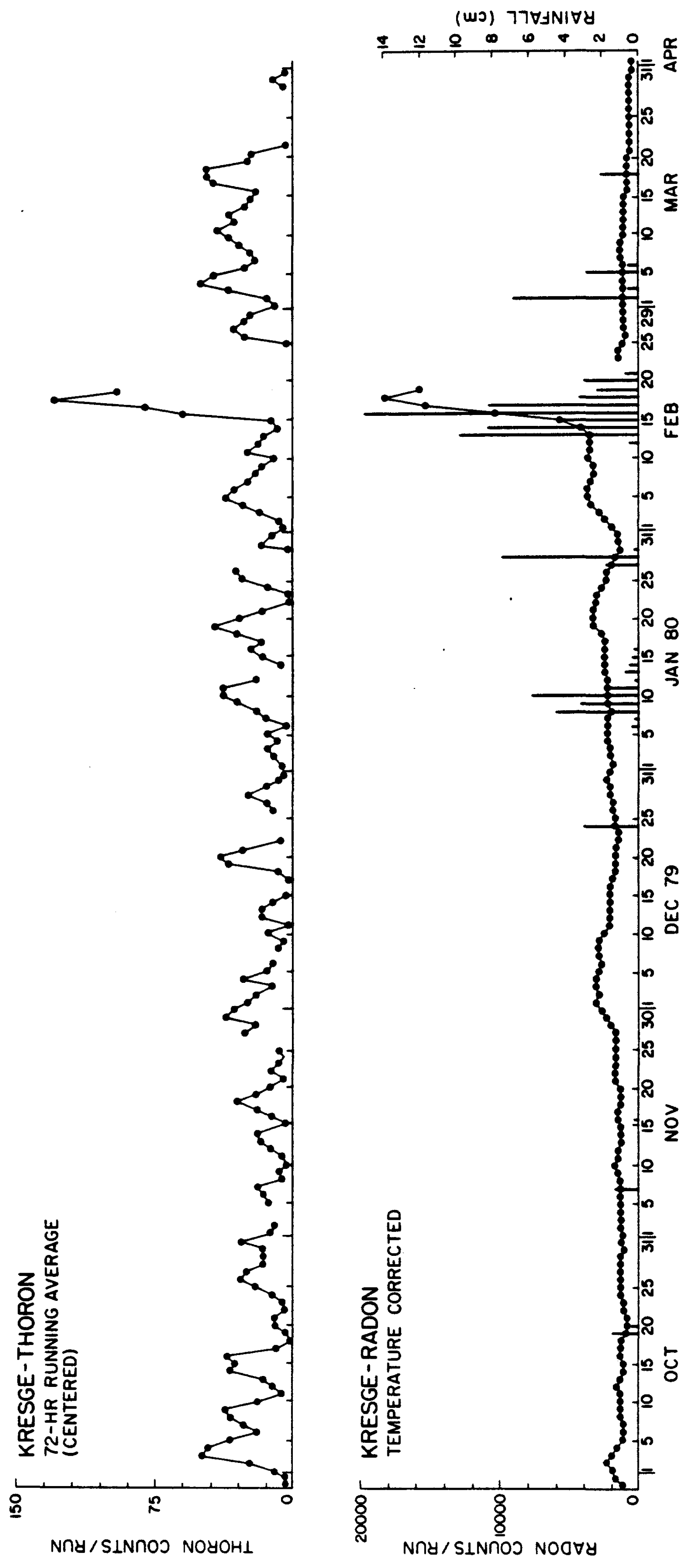
18x10³ COUNTS/RUN (RELATIVE)
17
16
15
14
13
12
11
10
LBL INSTRUMENT
CALTECH INSTRUMENT OFF - BROKEN WATER LINE
M=5.9 COYOTE LAKE
LBL STABILIZER OFF
CALTECH MONITOR
WAKITA INSTRUMENT
pCi/l
1000
900
800
700
600
500
400
300
200
100
11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30
JULY 79
AUGUST 79

Fig. 1



STONE CANYON RESERVOIR - THORON
72-HR RUNNING AVERAGE
(CENTERED)
THORON COUNTS/RUN
150
75
0
STONE CANYON RESERVOIR - RADON
NO TEMPERATURE CORRECTION
RADON COUNTS/RUN
1500
750
0
RAINFALL (cm)
14
12
10
8
6
4
2
0
OCT
NOV
DEC 79
JAN 80
FEB
MAR
APR

Fig. 2



KRESGE-THORON
72-HR RUNNING AVERAGE
(CENTERED)
THORON COUNTS/RUN
KRESGE-RADON
TEMPERATURE CORRECTED
RADON COUNTS/RUN
RAINFALL (cm)
OCT
NOV
DEC 79
JAN 80
FEB
MAR
APR

Fig. 3

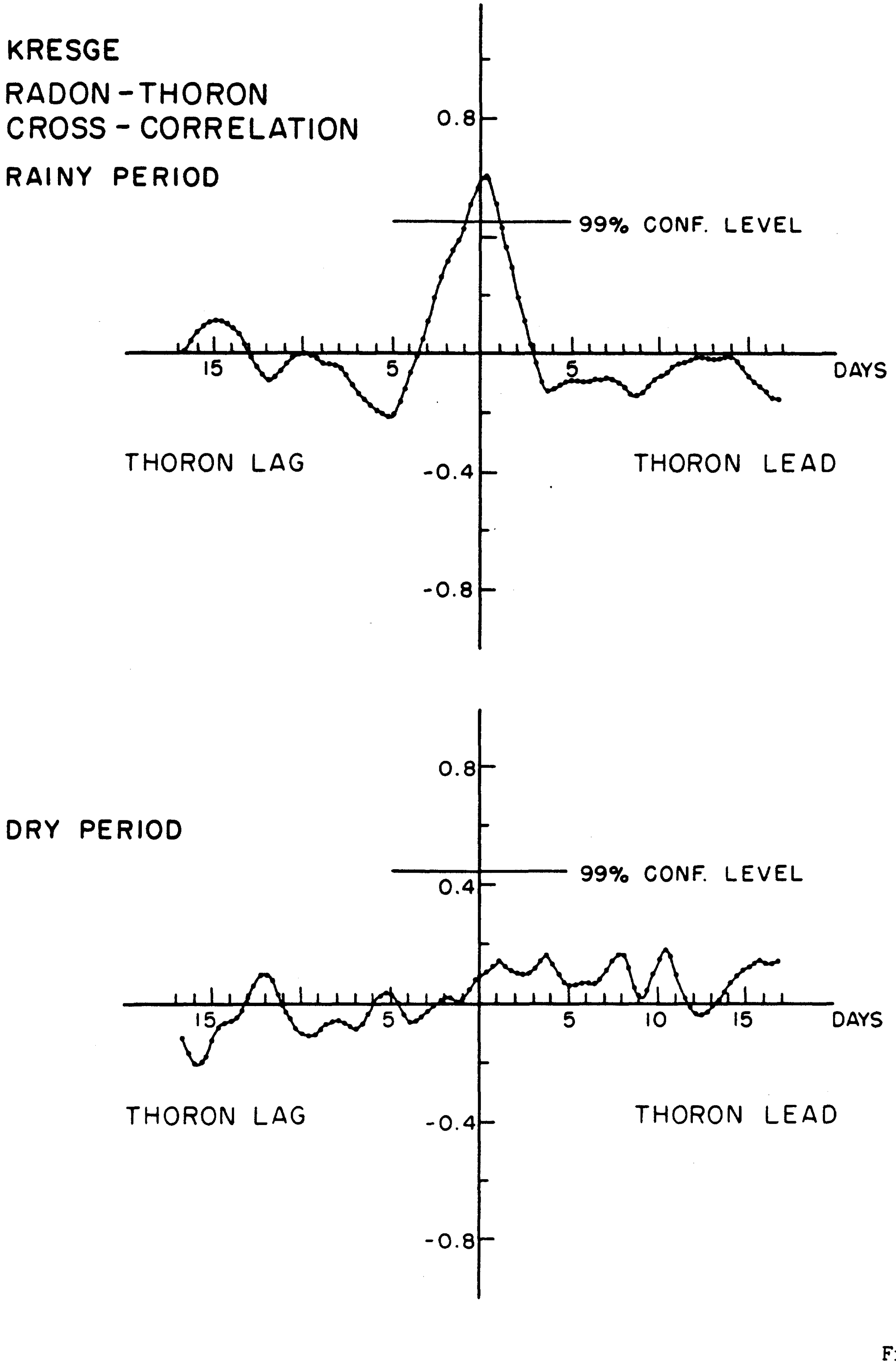

KRESGE
RADON - THORON
CROSS - CORRELATION
RAINY PERIOD
0.8
99% CONF. LEVEL
15
5
5
DAYS
THORON LAG
THORON LEAD
-0.4
-0.8
DRY PERIOD
0.8
99% CONF. LEVEL
0.4
15
5
5
10
15
DAYS
THORON LAG
THORON LEAD
-0.4
-0.8

Fig. 4

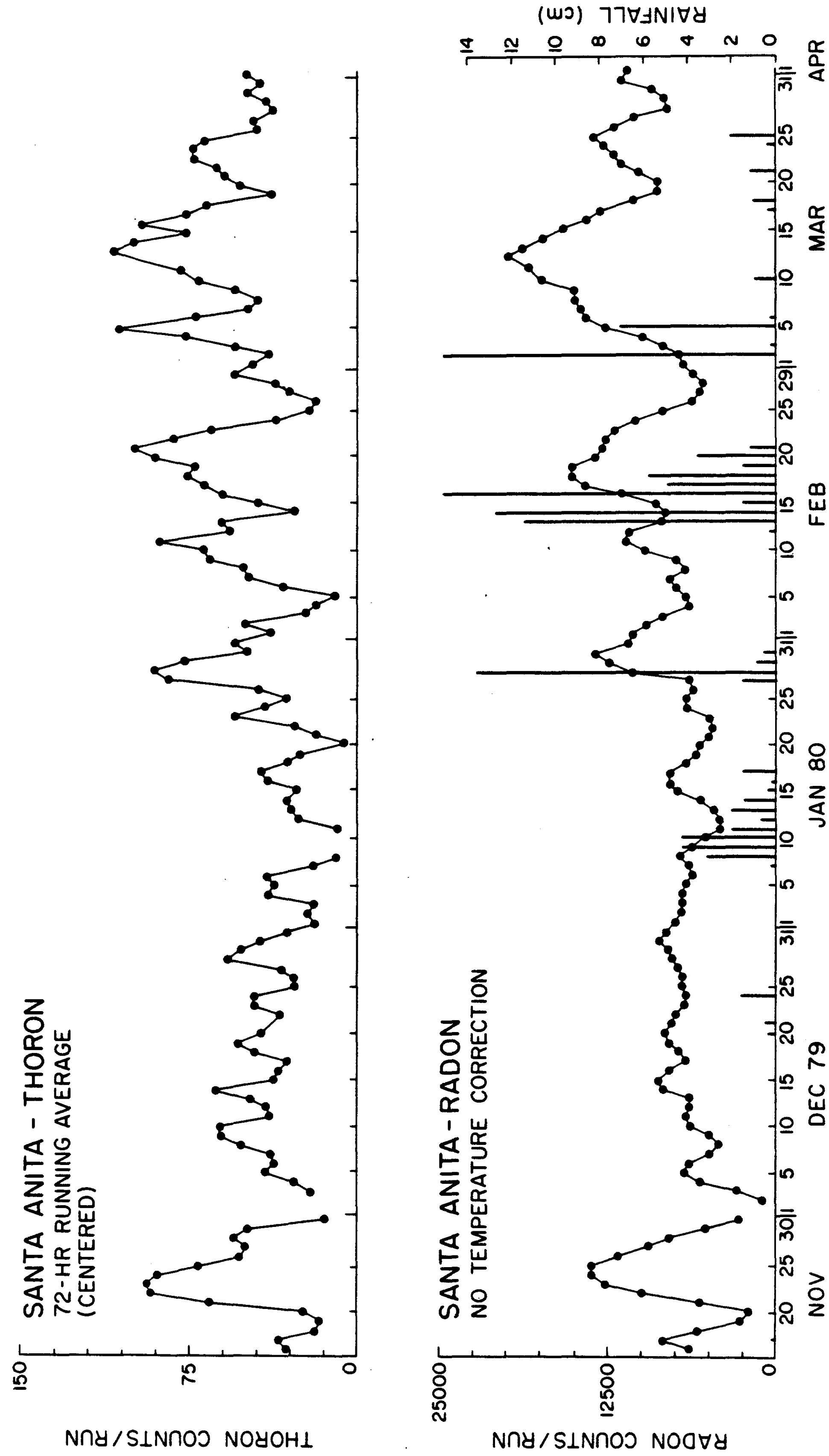
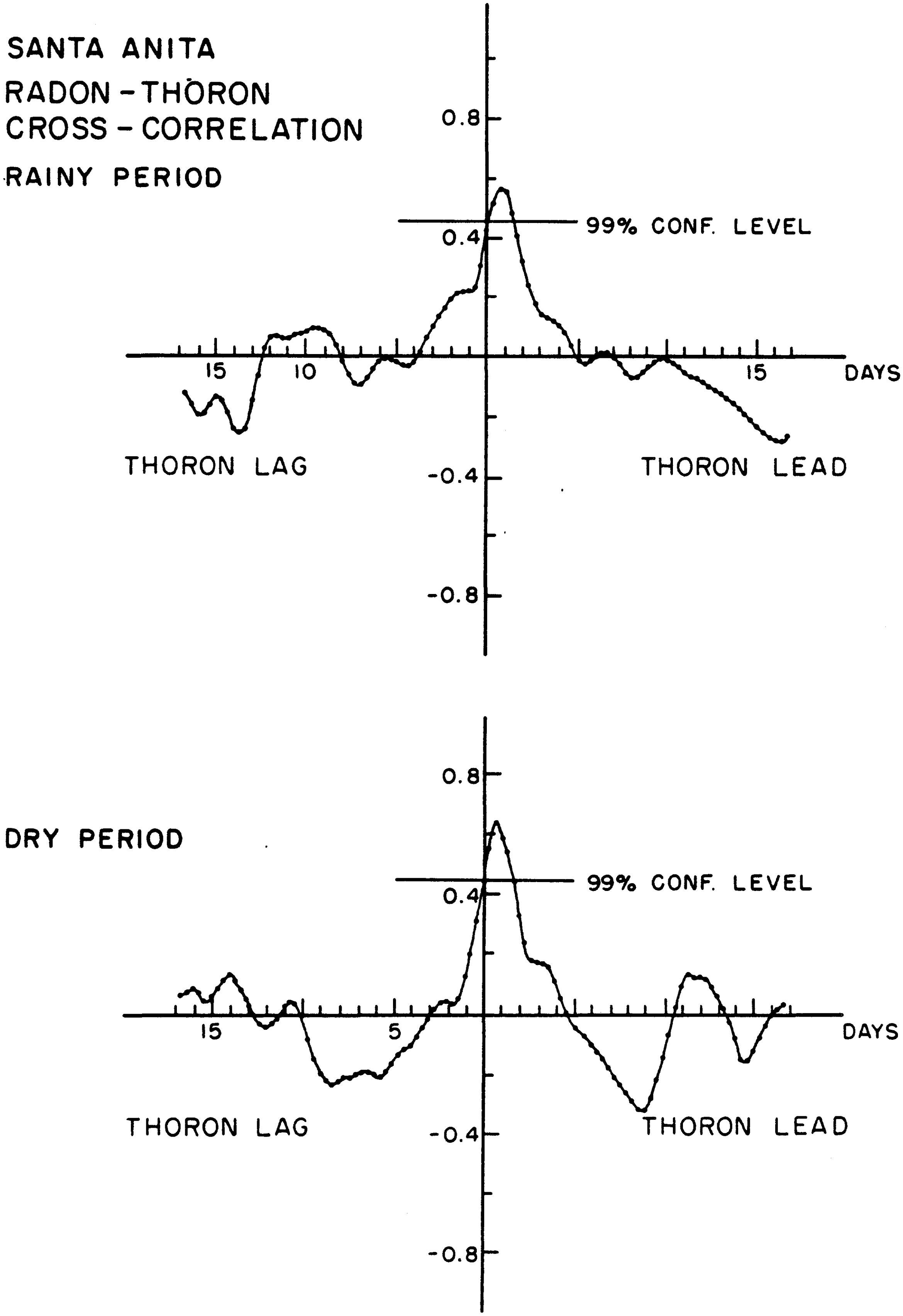

SANTA ANITA - THORON
72-HR RUNNING AVERAGE
(CENTERED)
THORON COUNTS/RUN
SANTA ANITA - RADON
NO TEMPERATURE CORRECTION
RADON COUNTS/RUN
RAINFALL (cm)
NOV
DEC 79
JAN 80
FEB
MAR
APR

Fig. 5



SANTA ANITA
RADON - THORON
CROSS - CORRELATION
RAINY PERIOD
0.8
0.4
-0.4
-0.8
99% CONF. LEVEL
15
10
15
DAYS
THORON LAG
THORON LEAD
DRY PERIOD
0.8
0.4
-0.4
-0.8
99% CONF. LEVEL
15
5
DAYS
THORON LAG
THORON LEAD

Fig. 6

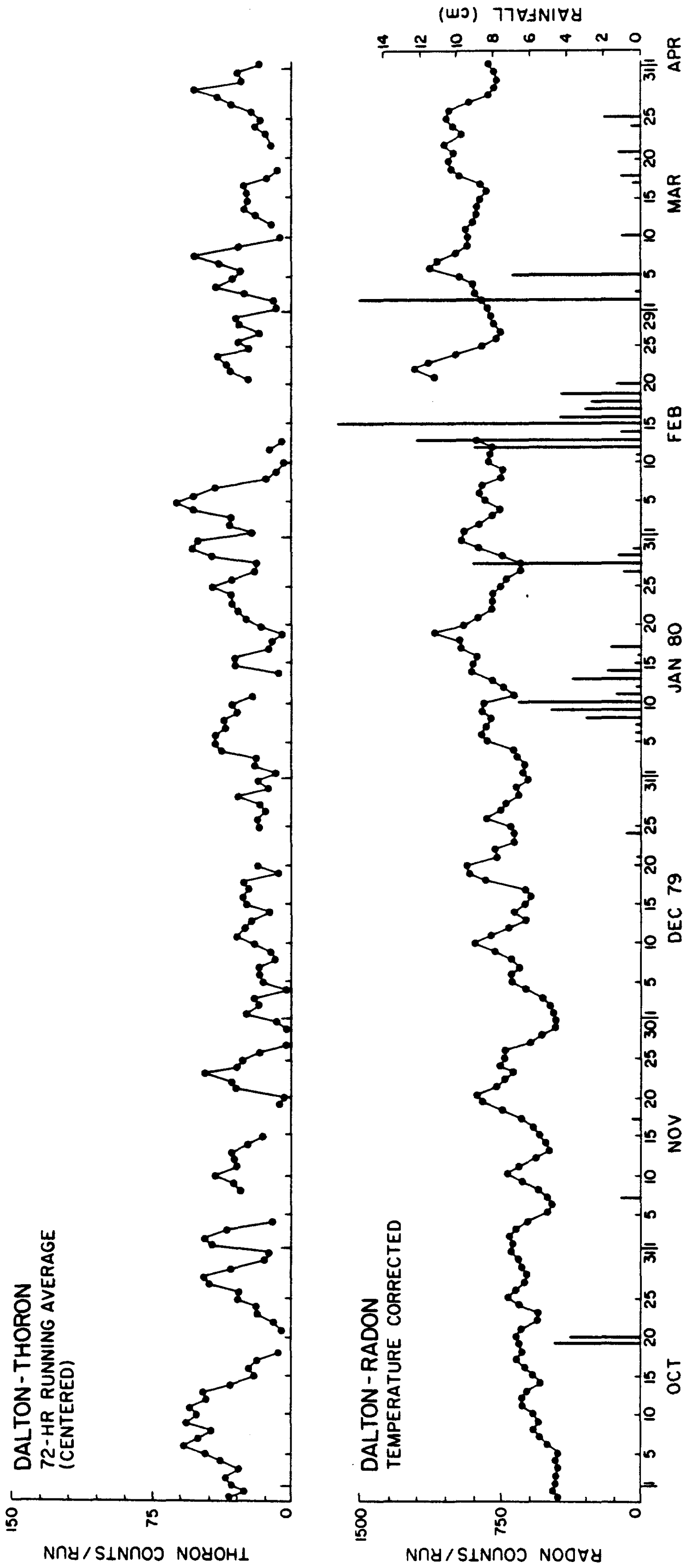

DALTON-THORON
72-HR RUNNING AVERAGE
(CENTERED)
THORON COUNTS/RUN
150
75
0
DALTON-RADON
TEMPERATURE CORRECTED
RADON COUNTS/RUN
1500
750
0
RAINFALL (cm)
14
12
10
8
6
4
2
0
OCT
NOV
DEC 79
JAN 80
FEB
MAR
APR

Fig. 7

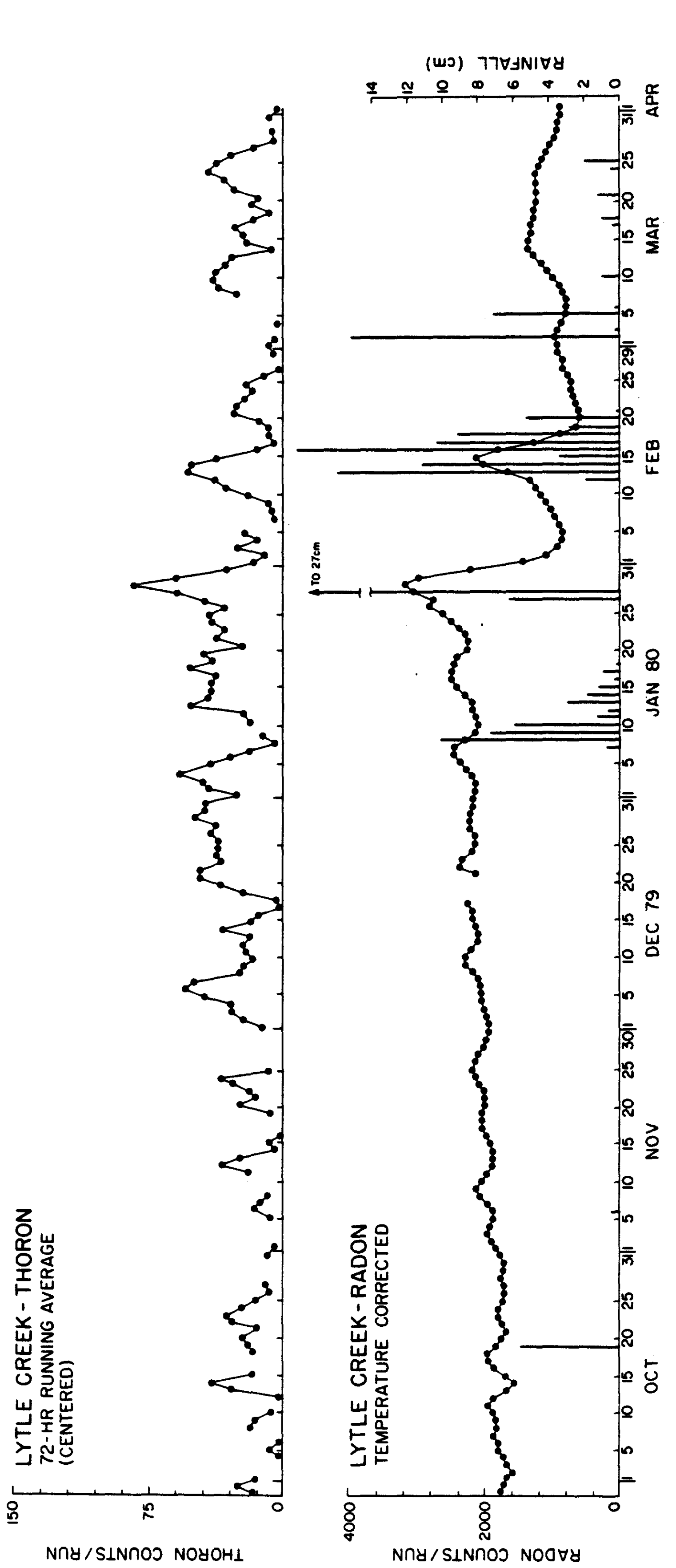

LYTLE CREEK - THORON
72-HR RUNNING AVERAGE
(CENTERED)
LYTLE CREEK - RADON
TEMPERATURE CORRECTED
THORON COUNTS/RUN
RADON COUNTS/RUN
RAINFALL (cm)
TO 27cm
OCT
NOV
DEC 79
JAN 80
FEB
MAR
APR

Fig. 8

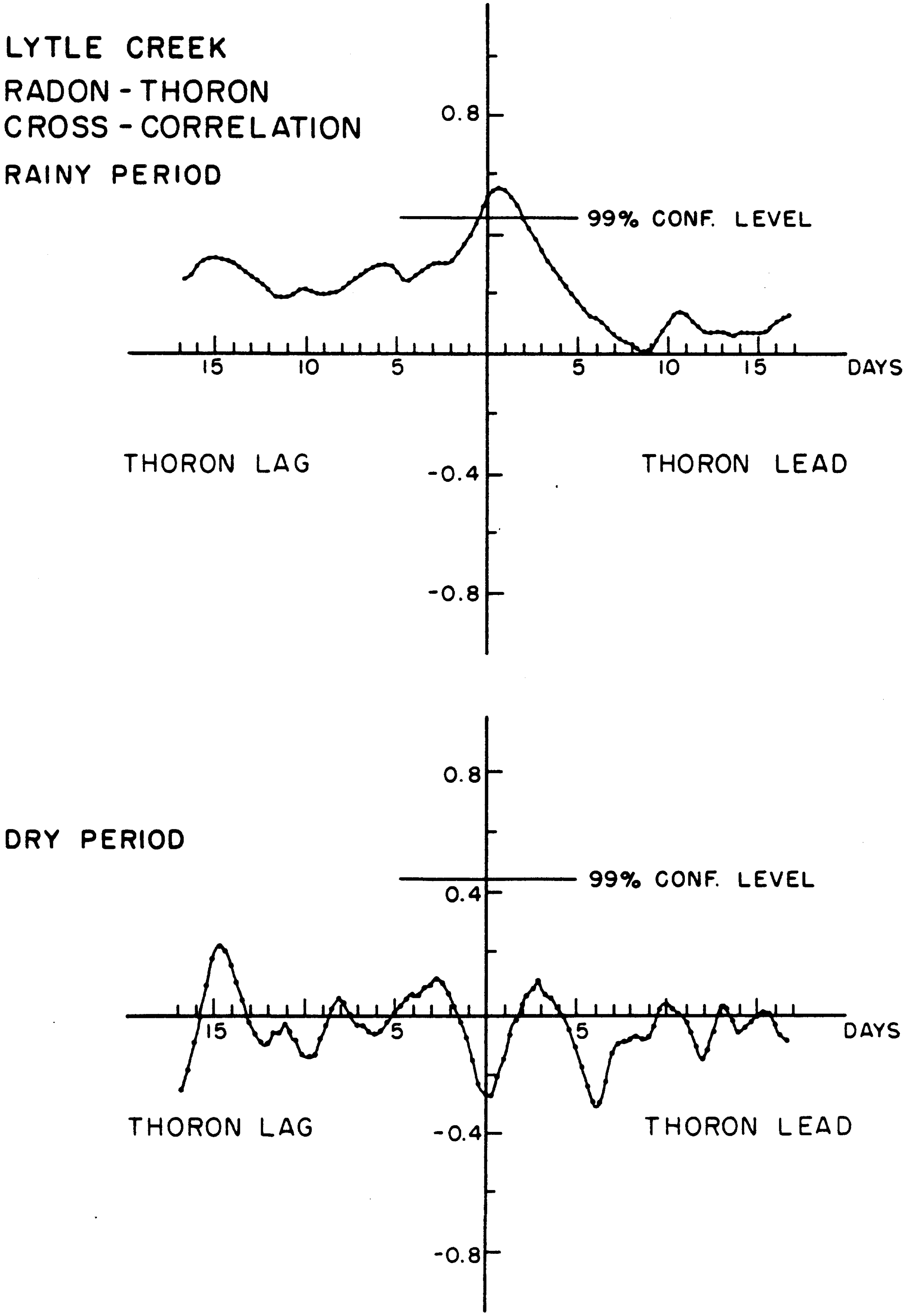

LYTLE CREEK
RADON - THORON
CROSS - CORRELATION
RAINY PERIOD
0.8
99% CONF. LEVEL
15
10
5
5
10
15
DAYS
THORON LAG
-0.4
THORON LEAD
-0.8
DRY PERIOD
0.8
99% CONF. LEVEL
0.4
15
5
5
DAYS
THORON LAG
-0.4
THORON LEAD
-0.8

Fig. 9

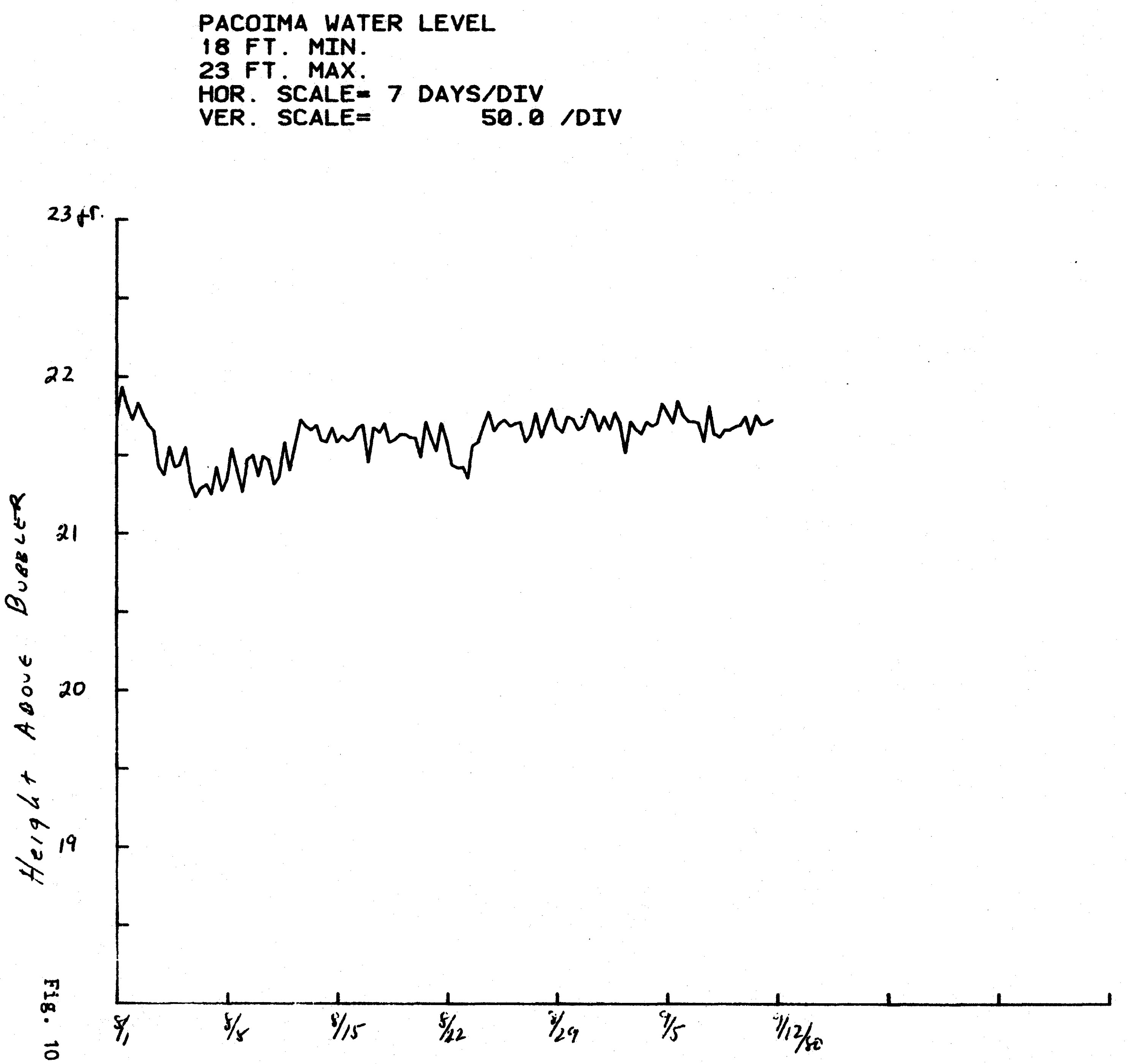
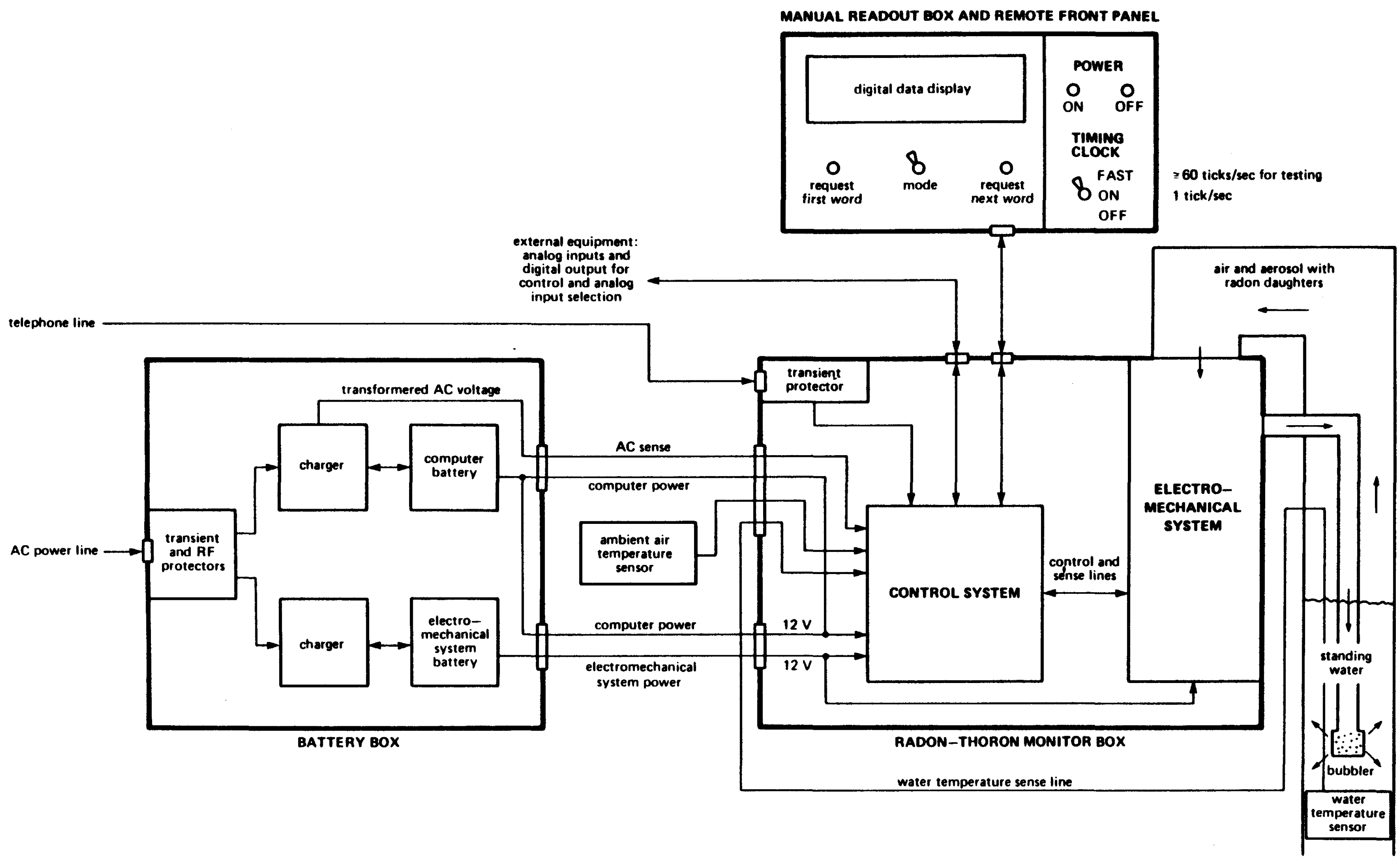
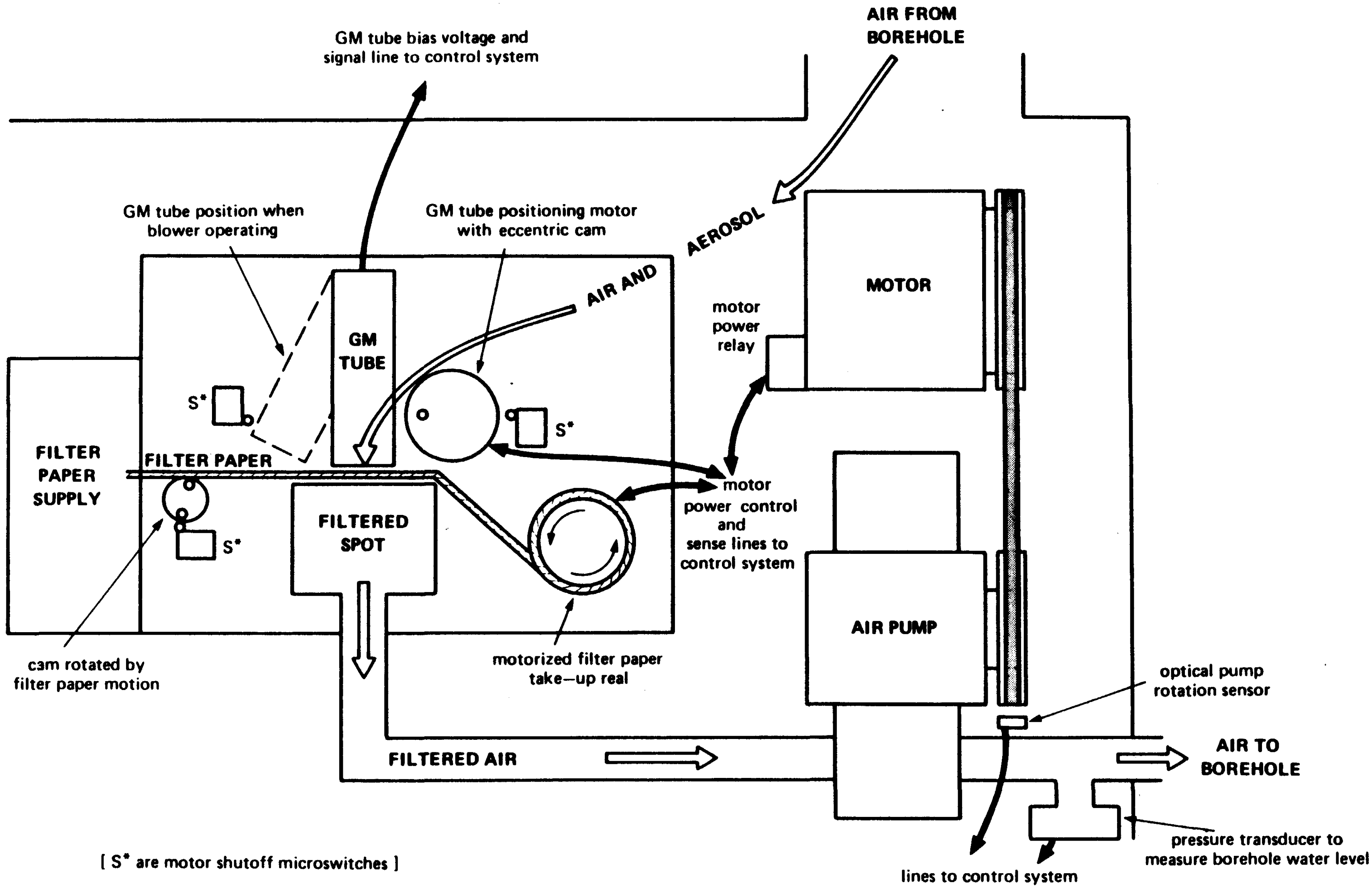

PACOIMA WATER LEVEL
18 FT. MIN.
23 FT. MAX.
HOR. SCALE= 7 DAYS/DIV
VER. SCALE= 50.0 /DIV
23 ft.
22
21
20
19
Height Above Bubbler
8/1
8/8
8/15
8/22
8/29
9/5
9/12/80

Fig. 10



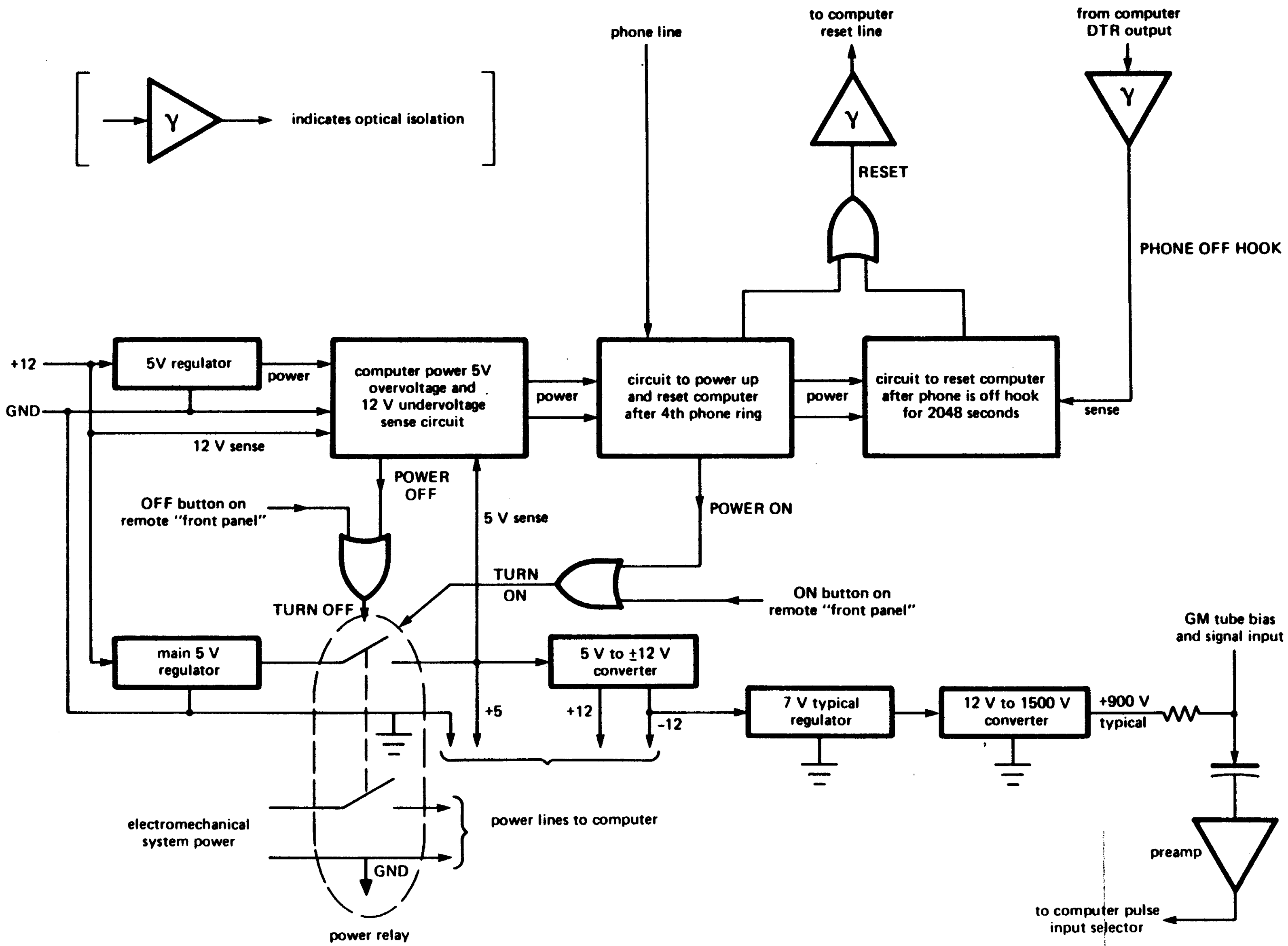
RTM–3 RADON THORON MONITOR COMPONENTS

Fig. 11



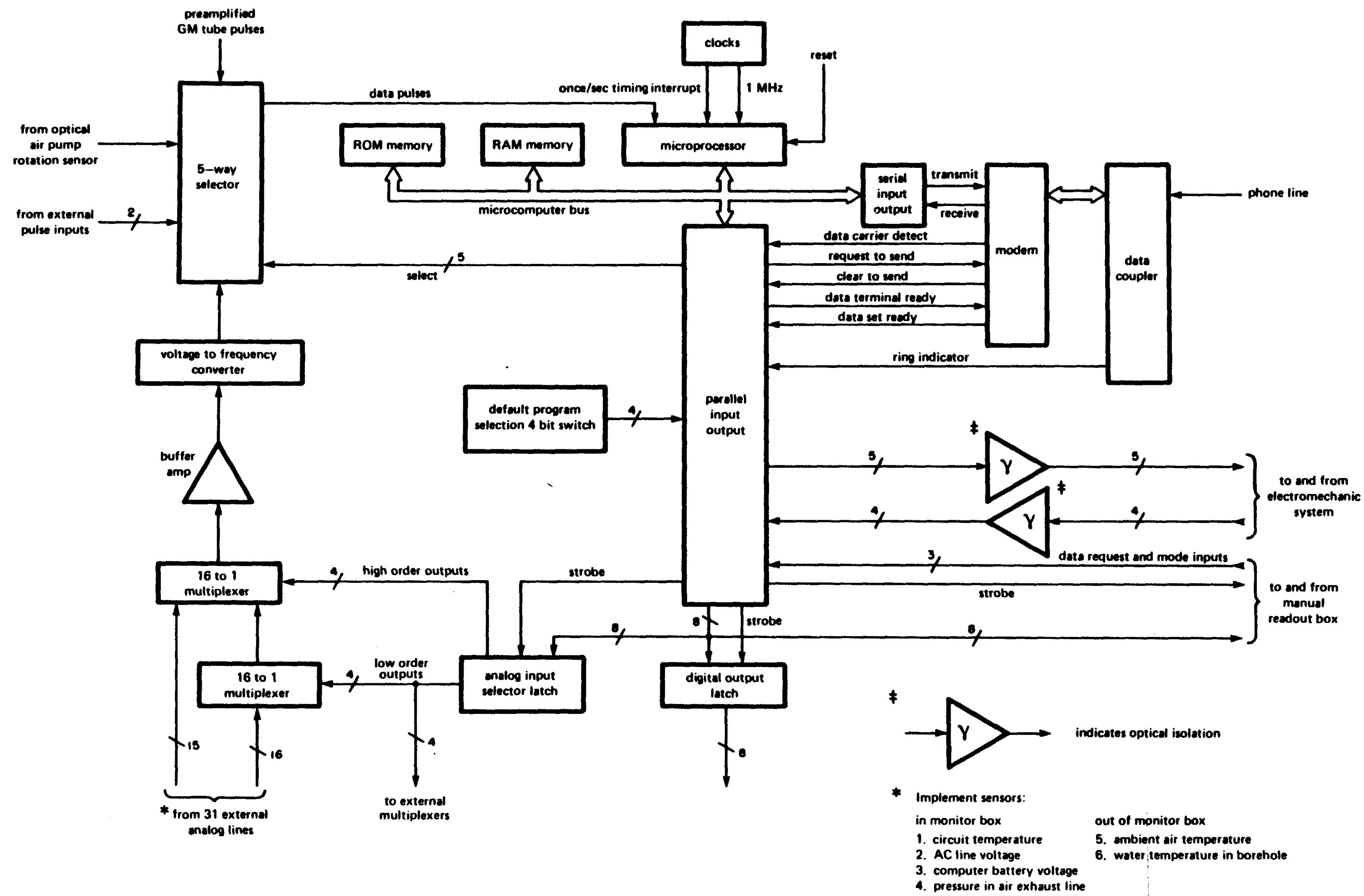
RTM–3 RADON THORON MONITOR ELECTROMECHANICAL SYSTEM

Fig. 12



RTM–3 RADON THORON MONITOR CONTROL SYSTEM: POWER SUPPLY AND GM TUBE CIRCUITRY

Fig. 13



RTM–3 RADON THORON MONITOR CONTROL SYSTEM: MICROCOMPUTER

Fig. 14

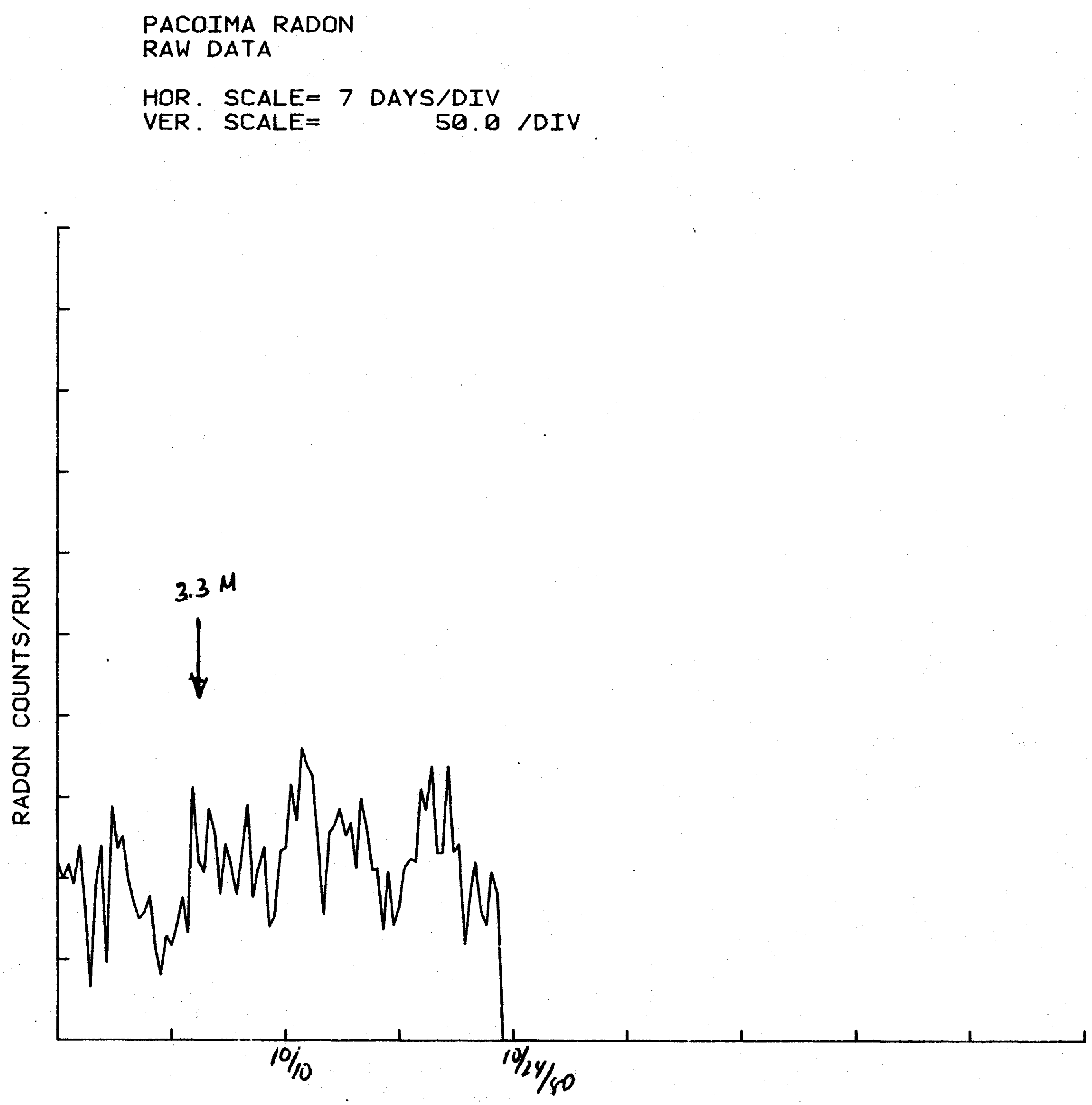

PACOIMA RADON
RAW DATA
HOR. SCALE= 7 DAYS/DIV
VER. SCALE= 50.0 /DIV
RADON COUNTS/RUN
3.3 M
10/10
10/24/80

Fig. 15

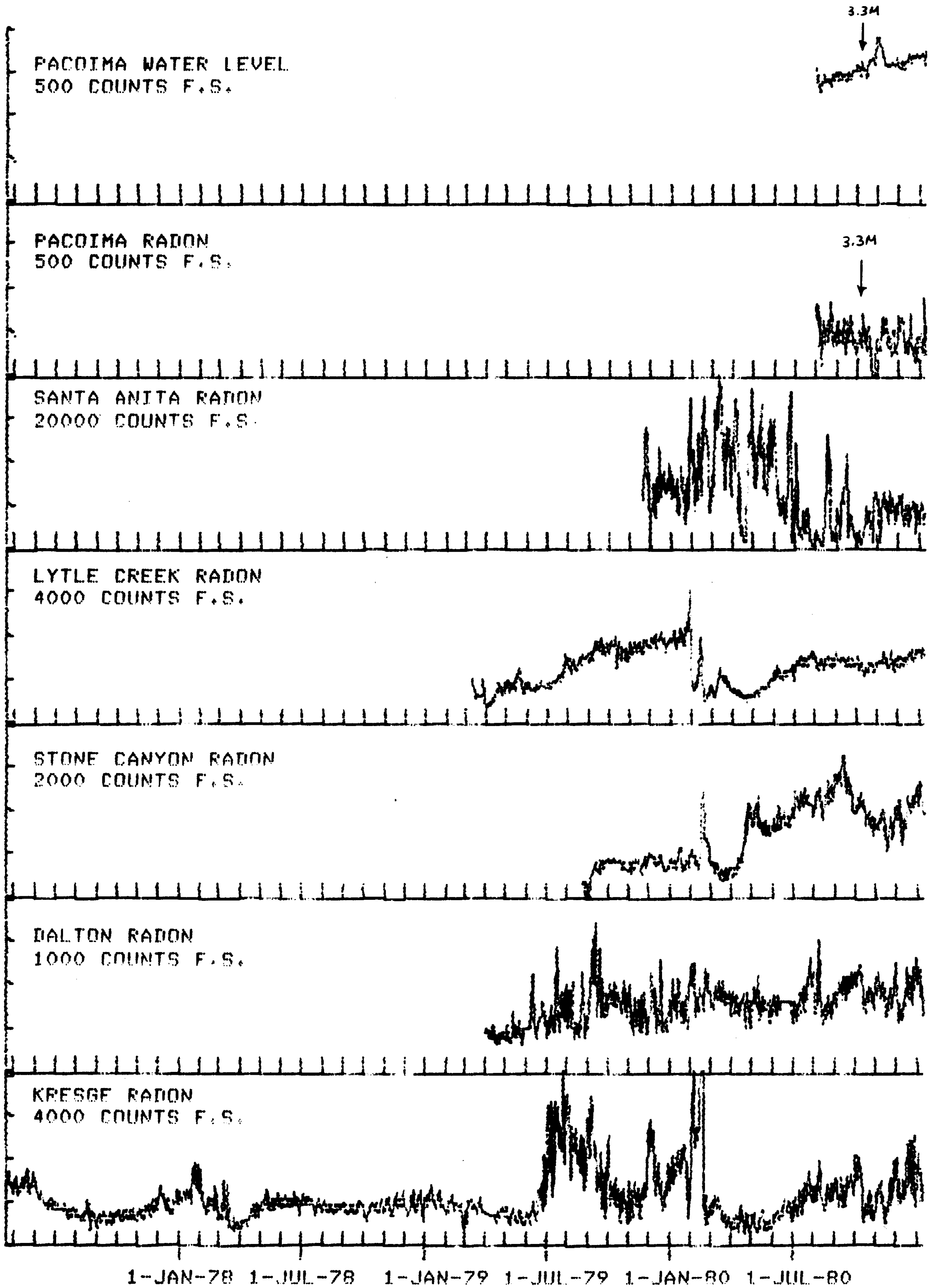

3.3M
PACOIMA WATER LEVEL
500 COUNTS F.S.
PACOIMA RADON
500 COUNTS F.S.
3.3M
SANTA ANITA RADON
20000 COUNTS F.S.
LYTLE CREEK RADON
4000 COUNTS F.S.
STONE CANYON RADON
2000 COUNTS F.S.
DALTON RADON
1000 COUNTS F.S.
KRESGE RADON
4000 COUNTS F.S.
1-JAN-78
1-JUL-78
1-JAN-79
1-JUL-79
1-JAN-80
1-JUL-80

Fig. 16

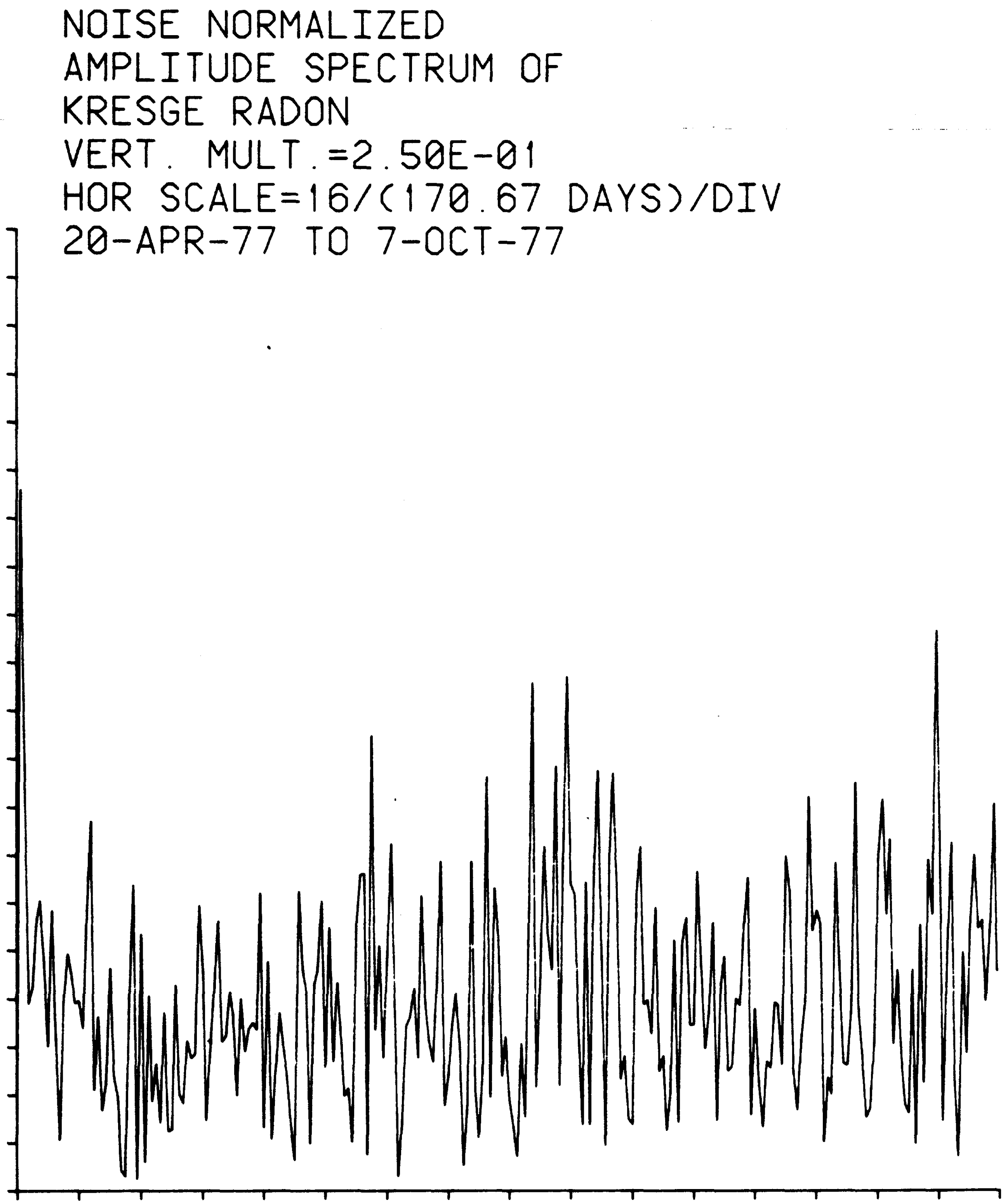

NOISE NORMALIZED
AMPLITUDE SPECTRUM OF
KRESGE RADON
VERT. MULT.=2.50E-01
HOR SCALE=16/(170.67 DAYS)/DIV
20-APR-77 TO 7-OCT-77

Fig. 17

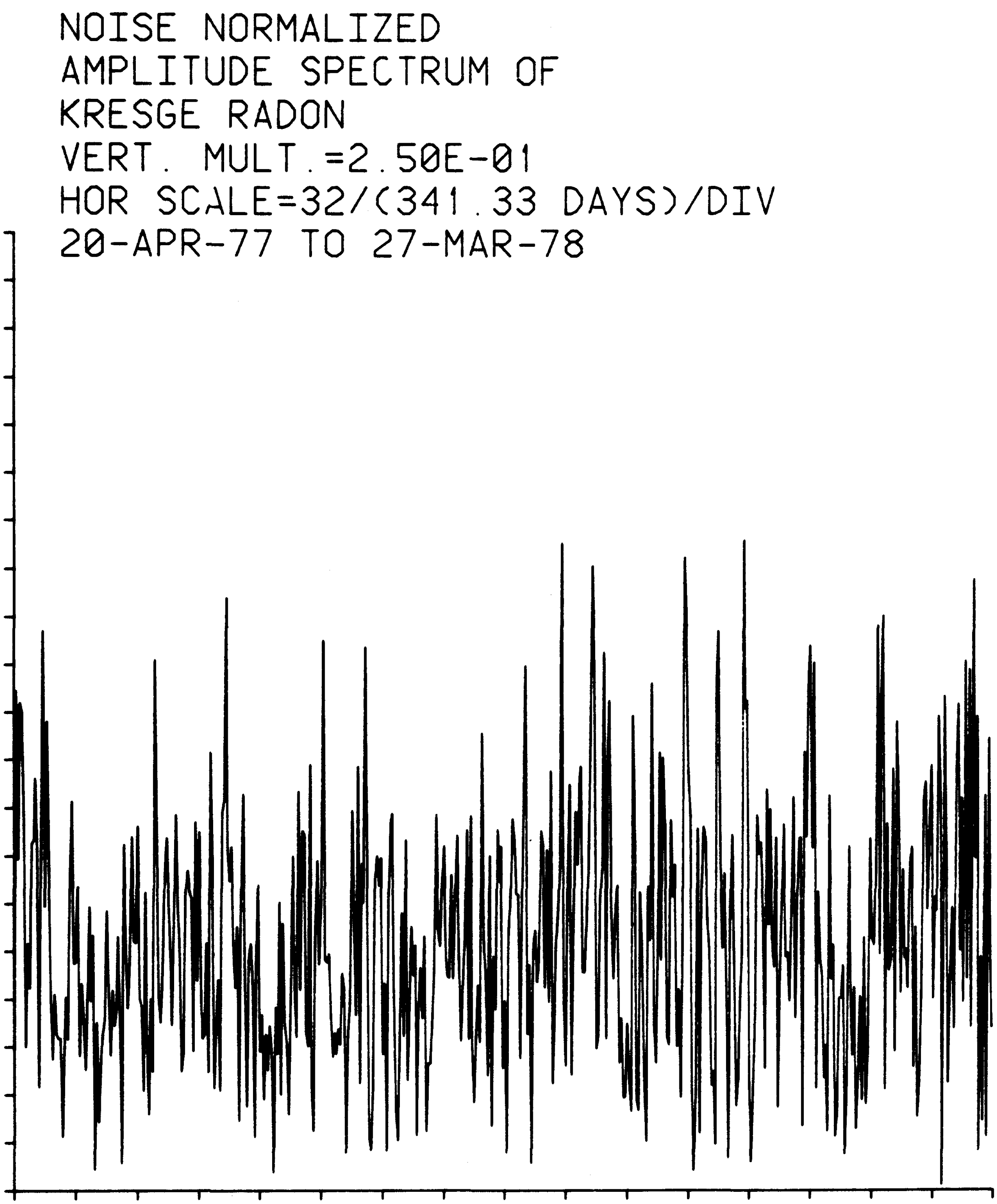

NOISE NORMALIZED
AMPLITUDE SPECTRUM OF
KRESGE RADON
VERT. MULT.=2.50E-01
HOR SCALE=32/(341.33 DAYS)/DIV
20-APR-77 TO 27-MAR-78

Fig. 18

NOISE NORMALIZED
AMPLITUDE SPECTRUM OF
KRESGE RADON
VERT. MULT.=1.00E+00
HOR SCALE=16/(170.67 DAYS)/DIV
1-JUN-79 TO 18-NOV-79

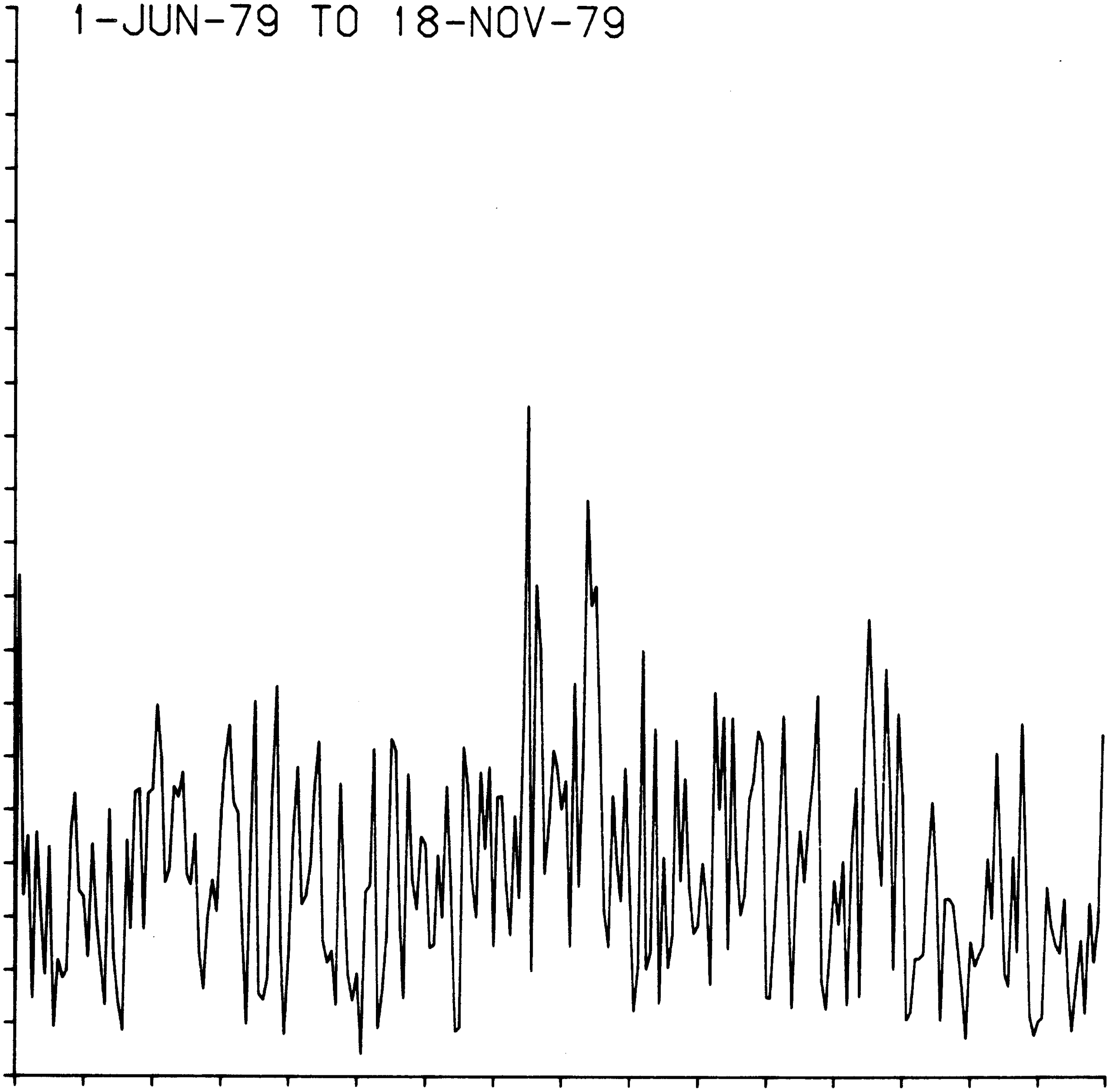


Fig. 19

RELATIONSHIP OF THE 1979 SOUTHERN CALIFORNIA RADON ANOMALY TO A POSSIBLE REGIONAL STRAIN EVENT†

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ABSTRACT

During the second half of 1979, substantial radon anomalies were recorded at two stations of the automated radon-thoron monitoring network operated by the W. K. Kellogg Radiation Laboratory of Caltech. The two stations exhibiting major anomalies, Kresge and Dalton Canyon, are located approximately 30 km apart on the frontal fault system of the Transverse Ranges of southern California. At Kresge the anomaly began on June 21, 1979 and continued through December 1979. At Dalton Canyon the anomaly started about three weeks later and also continued through December 1979. At both sites the anomalous levels of radon decreased (but did not return entirely to normal values) shortly before October 15, 1979. During the week of October 15, 1979 a 6.6 M earthquake occurred about 290 km to the southeast of the two stations, and later in that week earthquakes of magnitude 4.2 and 4.1 occurred at Malibu and Lytle Creek. The latter two events were within 60 km of the monitors. A radon-thoron monitor at Lytle Creek recorded no long term anomaly, but did record a sharp spike-like decrease in the radon level on October 13, 1979. Coincident with our observations of anomalous radon levels, other investigators have reported anomalies or suspected anomalies in several other geodetic, geophysical, and geochemical signals from the same general region. The rapid temporal development of several of the anomalies together with the large area over which they were observed suggest that a large-scale, dynamic strain event took place which may have been responsible both for the widespread anomalies and for the seismicity that occurred in the region subsequent to the onset of the anomalies.

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†Supported in part by USGS contract [14-08-0001-17734] and the National Science Foundation [PHY79-23638].

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ONE OF THE LIME AID PREPRINT SERIES IN NUCLEAR GEOPHYSICS & COSMOCHEMISTRY

September 1980

Introduction

Since the 1965 Tashkent earthquake there have been a number of reports of radon anomalies preceding moderate or large earthquakes from the U.S.S.R. [Sadovsky et al., 1972], China [Li et al., 1975], and Japan [Wakita et al., 1980]. Almost all of these reports have been based on the observation of changes in radon levels in groundwater. More recently in the United States several groups have been monitoring radon in soil gas [Mogro-Campero et al., 1980; King, 1980; Birchard and Libby, 1980] and in groundwater [Shapiro et al., 1980a; Talwani et al., 1980; Teng, 1980] in an attempt to observe precursory changes in radon levels. While several of the reported precursory radon anomalies have been recorded within a few tens of kilometers from the subsequent epicenter, there have been a number of reports of precursory radon anomalies at large distances from subsequent epicenters. For example Teng [1980] tabulated data from the Kutzan station in China where in a four year period radon spikes of short duration were observed several days before 8 earthquakes ranging in magnitude from 5.2 to 7.9. All of these earthquakes occurred on a Y-shaped fracture zone. The nearest event with a precursory anomaly was 54 km from the station, while the furthest occurred 345 km from the station. During the same period one radon spike was observed with no subsequent earthquake, and for one 6.5 M earthquake 420 km distant on the same fracture zone no precursory anomaly was observed.

Such reports of supposedly precursory radon anomalies at great distance from subsequent earthquakes often have been received with considerable skepticism, particularly in the United States, since the half-life of a radon atom is too short (3.8 days) to permit its movement more than several tens of meters from its point of production even if active subsurface transport mechanisms are invoked [Tanner, 1978]. In addition, during the short history of the radon monitoring effort in the United States there have been only a few previous reports of precursory radon anomalies, and generally these have been associated with nearby earthquakes. In this paper we report the observation of a radon anomaly which coincided with several other geophysical and geochemical anomalies, and which appears to have been associated with an earthquake some 290 km from the site of the radon anomalies. These observations are discussed with reference to two recently proposed models which would account for much of the anomalous data observed in southern California during 1979.

Experimental Procedure

A full description of the automated radon-thoron monitors used in the California Institute of Technology radon monitoring program has been given in Melvin et al. [1978]. Radon data from the Kresge site, which is located in the San Rafael Hills of Pasadena (34.089 N, 118.103 W), have been obtained from two monitors. The first prototype unit monitored radon and thoron from a 24.1 m deep static borehole in granite from April 1977 to March 1979. Data from this period of operation have been discussed in Shapiro et al. [1980a]. A few apparently precursory changes in radon level were observed before some local earthquakes. The largest of these was a 5.0 M event which occurred on January 1, 1979 off the coast at Malibu about 54 km west of the monitor. For about 45 days prior to the earthquake a series of positive spikes were observed in the radon data [Shapiro et al., 1980a]. The prototype monitor was replaced with a more advanced unit which incorporated dial-up telemetry in April 1979. The new unit was coupled to the same borehole as the prototype, and within a few days after start-up the radon levels observed with the new monitor were essentially the same as those observed from the prototype shortly before the changeover.

Monitors of the new type began operation over static boreholes of similar depth at Dalton Canyon (34.102 N, 117.486 W) and Lytle Creek (34.140 N, 117.287 W) in April 1979 and March 1979, respectively. At all three sites the boreholes are cased through the overburden, and the monitor vaults are coupled directly to the casing to reduce atmospheric environmental effects. The Kresge and Dalton Canyon boreholes both are located in small, steep canyons where the rock which is penetrated is heavily fractured. At Kresge the rock is granite, while at Dalton Canyon it is granodiorite. At Lytle Creek the borehole is located on a terrace near an outcropping of weathered granite. The overburden is relatively thin at Kresge and Dalton Canyon (less than 5 m), while at Lytle Creek it is about 13 m deep at the borehole location. The monitors strip radon from the boreholes every eight hours. The on-board microcomputer stores--in addition to radon and thoron data--a background count, instrument temperature and ambient temperature, and a number of engineering parameters. The background count serves as a sensitive check on instrument stability. The temperature data are used to correct radon data for instrument wall effects as described in Melvin et al. [1978]. The temperature corrections are applied to 24-hr and 72-hr running averages of the data; however, the difference between raw radon data and temperature corrected data is not significant when large scale features of the data are examined.

Radon Observations

Complete sets of radon data (without temperature corrections) from the Kresge, Dalton Canyon, and Lytle Creek stations from the inception of monitoring at each site are shown in Figure 1. The Kresge data set is considerably longer than the other two, and provides a baseline against which the anomalous data recorded during the latter half of 1979 can be compared. During the first two years of operation, the data from Kresge exhibited a weak annual cycle that is believed to be the result of thermoelastic strains and hydrological effects [Shapiro et al., 1980a]. Heavy winter rainfall has been observed to cause increases of short duration in the radon levels at several of our monitoring sites [Shapiro et al., 1980b]. The winter of 1979-80 was characterized by a series of four unusually heavy rainstorms, and the large peaks that are seen in the radon data from Kresge and Lytle Creek during January and February of 1980 are responses to rapid recharge. The fluctuations in the Kresge radon level during the first three months of 1978 also were associated with heavy winter rainfall. During the first two years of monitoring at Kresge, the radon levels during the late summer and fall months generally were free of large fluctuations, and during the late summer months were near a minimum.

The radon data sets from Dalton Canyon and Lytle Creek are not as extensive as the Kresge data set. As a result, it is not possible to determine the "baseline" levels for these sites with as much confidence. However, it appears that the data from the Lytle Creek site exhibit an annual cycle that is driven predominantly by hydrological factors, namely the annual recharge and draining of the alluvial overburden on the terrace and in a nearby side canyon. The data from the Dalton Canyon site do not show as obvious an annual cycle as those recorded at Kresge and Lytle Creek.

The most striking feature of the data shown in Figure 1 is the large increase in the radon level at Kresge which began in late June of 1979 and persisted throughout the remainder of the year. The data obtained during this period from the Kresge, Dalton Canyon, and Lytle Creek stations is replotted with an expanded time scale in Figure 2. Large radon spikes started to appear in the Kresge data beginning about June 21, 1979, and within two weeks the average levels of radon being measured at Kresge exceeded any that had been measured at this site during the previous two years. The character of the radon signal also was considerably different from the previous data. In addition to the general increase in the radon level, large and rapid fluctuations occurred, lasting from less than one day to a few days. Several checks were carried out to ensure that the monitor was operating properly. The background count (taken before each run) and the thoron levels were found to be within normal limits, and none of the engineering data were abnormal.

About three weeks after the data became anomalous at Kresge, large radon spikes also were observed in the data from the Dalton monitor. While baseline data from previous years did not exist at the Dalton site, the data trend at Dalton had been reasonably smooth from the start of monitoring through early July except for a short time in early June that immediately followed a period when the monitor vault had been opened for service. Therefore, the radon spikes at Dalton were considered anomalous.

During the same period, the data from the Lytle Creek monitor was free of the large fluctuations seen at Kresge and Dalton. However, one and one half days before the Imperial Valley earthquake, there was one run with substantially lower than normal radon. Inspection of the engineering data from that run indicated that the air pump of the monitor did not operate for its usual full eight minute cycle. This behavior has been observed occasionally as a symptom of incipient battery failure. In the case of battery failure this condition becomes progressively worse. However, in this instance normal pump operation took place for several runs before and after the one with low radon. A routine maintenance check six weeks after the low run revealed that the electromechanical system battery, which is operated in a float charged configuration, was operating with a dead cell. In this condition, the battery still had sufficient capacity to operate the monitor air pump for a full eight minutes. We now speculate that the increased back pressure on the air pump from a temporary increase in water level could have accounted for a short air pump cycle, and thus one run with low radon count. Our experience with the field monitors has indicated that an eight minute air pump cycle is more than sufficient to fully strip radon from the borehole. Thus the low radon reading probably did not result from incomplete stripping. The thoron count from the run in question was normal, which would further support this interpretation.

Other Anomalies

During the same time period in which the large radon anomalies at Kresge and Dalton Canyon were observed, there also were several other anomalies reported in southern California. Savage et al. [1980] report the results of laser geodimeter strain measurements near Palmdale that were repeated frequently during the period from 1971 to 1980. These measurements indicate that in addition to a uniform right-lateral shear strain (0.35 micro-rad/yr engineering shear) across the San Andreas fault, a 1 microstrain contraction perpendicular to the fault accumulated gradually during 1974 to 1978. Several measurements taken during 1979 indicate that essentially all of this contraction was released without local seismicity between February and November 1979, then about half the contraction was recovered between November 1979 and March 1980.

In addition to the laser geodimeter work of Savage et al. [1980], the ARIES very long baseline radio interferometry program [Resch, 1979] has provided independent geodetic data from southern California since August 1974. Repeated measurements of the baseline between Goldstone and Pasadena (JPL) during that time period appear to show two episodes of rapid strain which is interpreted as sudden plate motion during 1975 and 1978-79 [Whitcomb, 1980]. Temporal changes in deformation during 1978-80 as deduced from the ARIES data are in good agreement with the results of Savage et al. [Niell, 1979; MacDoran, 1980]. For both the laser geodimeter data and the Aries data, the period of most rapid strain change in southern California coincides quite closely with the period during which the large radon anomaly was observed.

During the same period, Whitcomb [1979] reported a decrease in gravity for the Pasadena area and Lytle Creek relative to Goldstone of 50 micro-gals, and the same change in absolute gravity was confirmed during this period at Lytle Creek [Goodkind, 1980]. In addition, Lienert et al. [1980] report a relatively large shift in the direction of the apparent electrical resistivity tensor in the region just to the north of the "big bend" in the San Andreas fault, and Williams and McWhirter [1979] reported changes in magnetic field measurements extending over a substantial part of the transverse ranges during 1979.

That part of the frontal fault system of the Transverse Ranges on which the Kresge and Dalton Canyon stations are located has been relatively quiet seismically from the inception of instrumental monitoring in 1932 until 1970. A general increase in the seismicity in this region has been noted in the past decade; however, there were no particularly unusual changes in seismicity along the frontal faults during the period of the anomaly [Hutton, 1980]. However, during the past two years there has been a general increase in the seismicity of southern California [Whitcomb, 1980]. Prior to the start of the radon anomaly all of the earthquakes of M_L = 5.0 or greater that were part of this increase had been in the Transverse Ranges. The most obvious anomaly in the seismicity of southern California during the period of the radon anomaly was the sharp reduction in Imperial Valley seismicity prior to the 6.6 M Imperial Valley event. There was a 40% reduction in the number of earthquakes in the Imperial valley during the 15 week period preceding the Imperial Valley earthquake [Johnson and Hutton, 1980]. This coincides quite closely with the period of increased radon at the Kresge and Dalton sites.

In addition to these geodetic and geophysical anomalies, Craig et al. [1980] reported significant anomalies in the radon and helium levels at Arrowhead Hot Springs. This site is located about 20 km to the east of our Lytle Creek Station, and is near the San Andreas fault zone north of San Bernardino. This spring had been sampled at approximately monthly intervals since 1975. While these grab sample data do not have the time resolution of our near real-time radon data, the temporal development of the anomalies at Arrowhead Hot Springs was quite similar to the Kresge data with the exception that the increase began about a month earlier. Craig et al. [1980] attribute the Arrowhead Hot Springs anomalies to an earthquake swarm at Big Bear Lake which occurred in June and July of 1979 (M_L = 4.8) some 32 km east of the site; however, the six month duration of the anomalies extends well past the time of the Big Bear swarm, which would suggest that they were related to the other southern California anomalies.

Discussion

The geodetic, geophysical, and geochemical anomalies observed in southern California during 1979 are striking because of their variety, the size of the area over which they occurred, and their correlation in time. Of particular interest, is the rapidity with which the anomalies developed. The availabilty of the near real-time radon data provided an important impetus for increasing the frequency of the laser geodimeter and VLBI surveys so that the rapid geodetic changes could be observed with reasonable time resolution.

At this point the interpretation of the anomalies is not completely clear. The major geodetic and geochemical anomalies and the geophysical anomalies, with the exception of seismicity, appear to have been limited to the vicinity of the Transverse Ranges, while the major anomaly in the seismicity of southern California occurred more than 200 km to the southeast in the Imperial Valley. The seismicity anomaly indeed was followed by a relatively large earthquake, and the correspondence in the temporal development of the seismicity anomaly with the anomalies which occurred in the Transverse Ranges suggests a possible connection between the Imperial Valley earthquake and all of the southern California anomalies.

During the week following the Imperial Valley earthquake, two smaller seismic events occurred in the Transverse Ranges. However, it seems unlikely that these events (4.2 M near Malibu and 4.1 M near Lytle Creek) would be preceded by anomalies of such an extensive nature. However, it is possible that the sharp radon decrease observed at the Lytle Creek station was associated with the 4.1 M Lytle Creek event since the epicenter for this event was only 5 km from the monitor.

Because of the wide area covered by the anomalies and the variety of parameters which exhibited anomalies, it seems unlikely that non-tectonic environmental factors were responsible. Rather, the data suggest that some type of regional strain event was occurring in southern California during this period. Two quite different models have been proposed to explain the anomalies. Savage et al. [1980] employ a dislocation model in an attempt to explain their geodetic data. On their model the upper part of the crust slips over a horizontal plane of detachment. The line of dislocation is presumed to be moving from the northeast to southwest across the strike of the San Andreas fault in the "big bend" area. An interesting feature of the model is the prediction of a relatively rapid compressional phase following the dilatation observed during 1979. The model is essentially local, and would not directly explain the Imperial Valley seismicity.

Whitcomb [1980] has suggested that episodes of rapid plate motion occur along the boundary of the Pacific and North American plates. These episodes are expected to be marked by a general increase of seismicity throughout California. He also suggests that in the region of the "big bend" of the San Andreas fault a substantial amount of crustal shortening is required to accommodate the plate motion. This, in turn, leads to creep at depth on the thrust fault systems in the Transverse Ranges. As evidence for this view, Whitcomb [1980] cites the coincidence of periods of high seismicity in California during 1975 and

1979-80 with ARIES data which indicate accelerated plate motion and crustal shortening. Whitcomb's picture qualitatively explains both the Imperial Valley seismicity and the major anomalies in the Transverse Ranges as separate manifestations of the the same event.

An interesting feature of both models is the requirement of creep at depth on the thrust fault systems of the Transverse Ranges. This would require increased loading on some of these thrust faults nearer the surface, and would suggest that an increased hazard exists along the heavily populated regions where these faults outcrop.

While the existing data appear to be insufficient to validate either model, it does appear that they have delineated a strain event that developed quite rapidly in time. The observation of a number of such events in the future should provide the data necessary to refine models of crustal behavior for southern California. To this end it is essential that regular monitoring of geodetic, geophysical, and geochemical parameters continue in the region. Where possible, the monitoring should be on a real-time or near real-time basis.

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Figure Captions

Fig. 1. Radon levels recorded at Kresge, Dalton Canyon, and Lytle Creek stations from the inception of monitoring at each site. The full scale count for each time series is noted in the legend. Missing data have been patched with smooth line segments.

Fig. 2. Radon levels recorded at Kresge, Dalton Canyon, and Lytle Creek stations during 1979. The times at which the Imperial Valley (6.6 M), Malibu (4.2 M), and Lytle Creek (4.1 M) earthquakes occurred are denoted by the symbols A, B, and C respectively. The full scale count for each time series is noted in the legend. Missing data have been patched with smooth line segments.

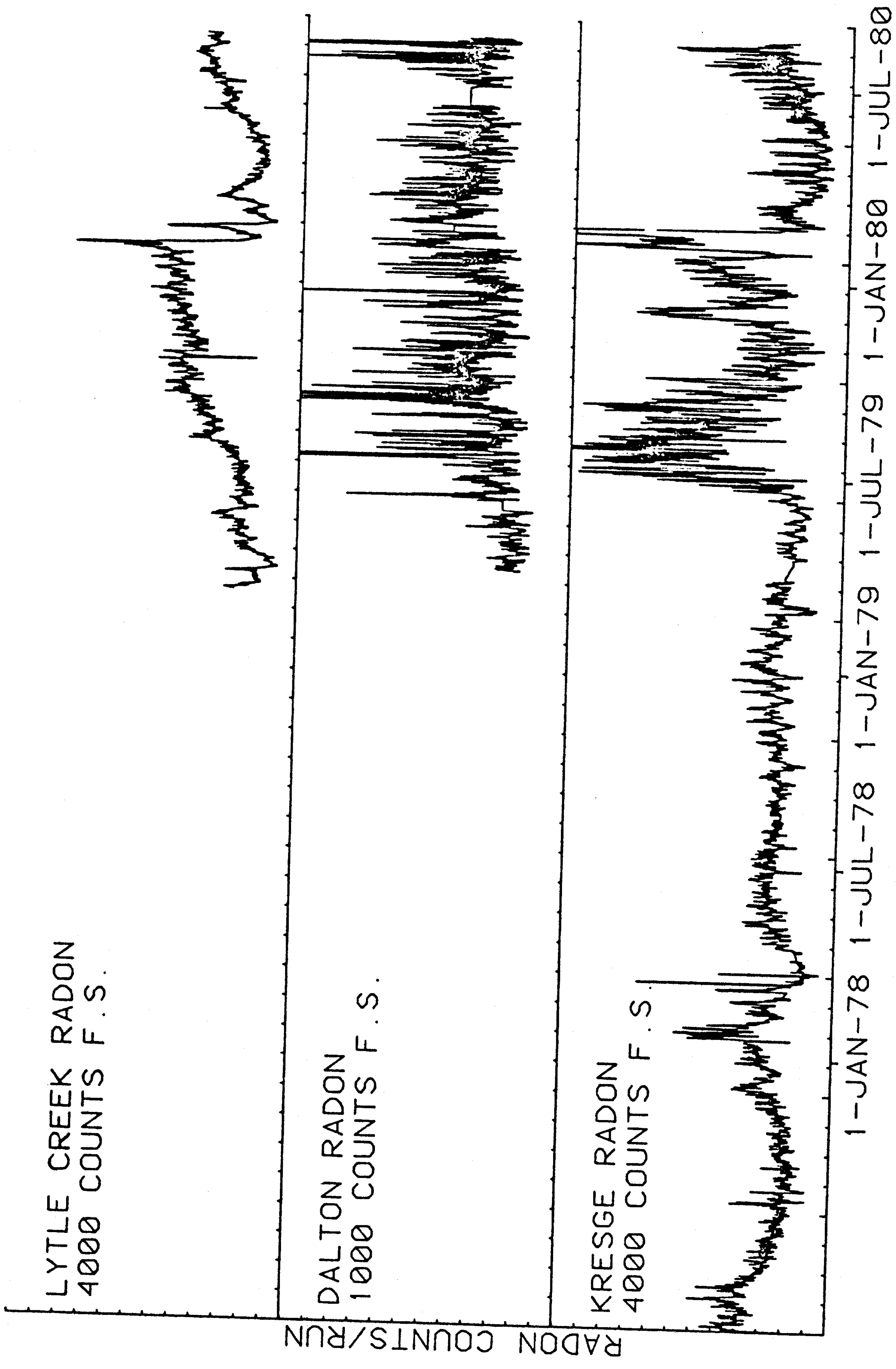
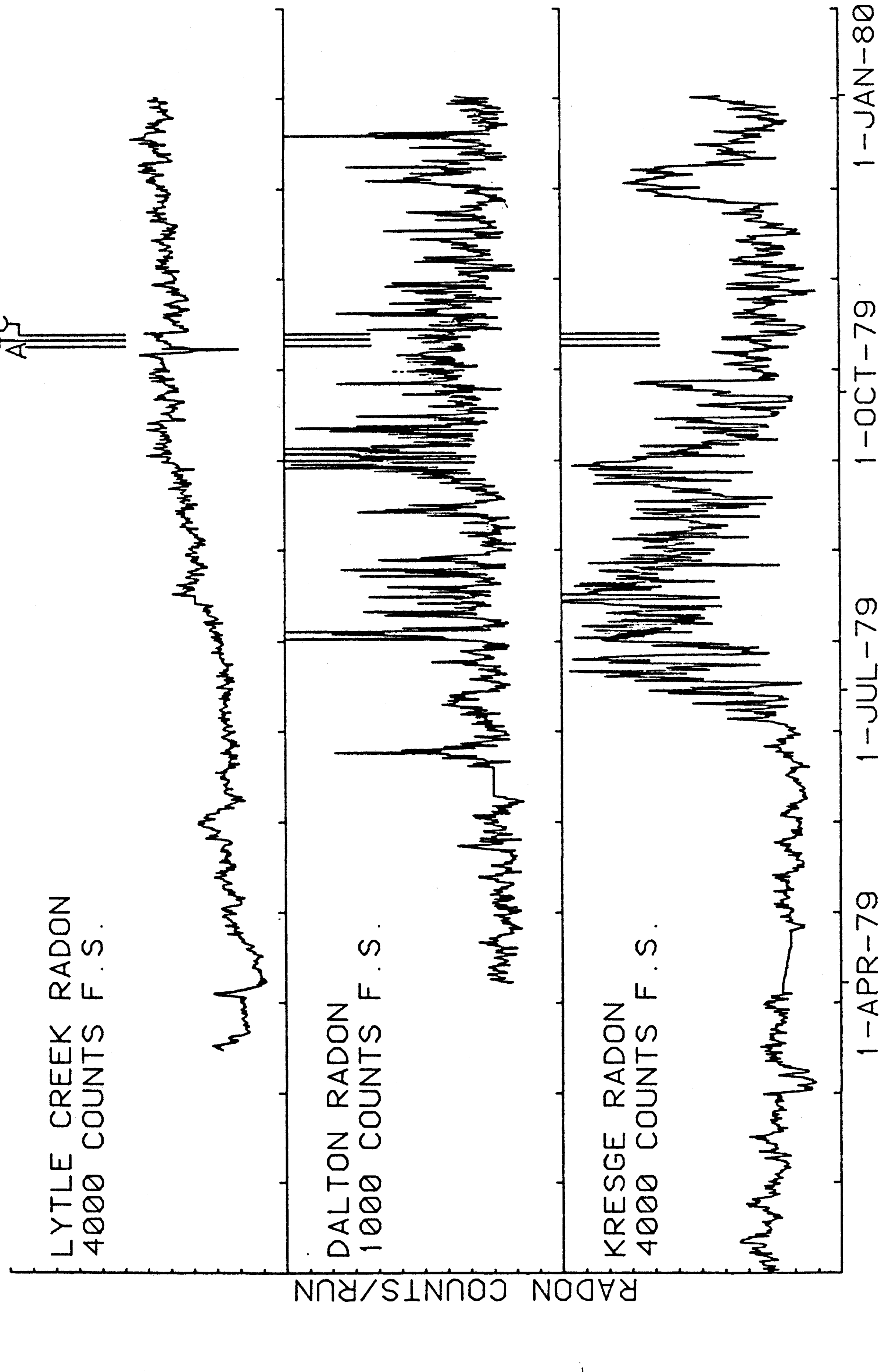

LYTLE CREEK RADON
4000 COUNTS F.S.
DALTON RADON
1000 COUNTS F.S.
KRESGE RADON
4000 COUNTS F.S.
RADON COUNTS/RUN
1-JAN-78
1-JUL-78
1-JAN-79
1-JUL-79
1-JAN-80
1-JUL-80

Fig. 1



LYTLE CREEK RADON
4000 COUNTS F.S.
DALTON RADON
1000 COUNTS F.S.
KRESGE RADON
4000 COUNTS F.S.
RADON COUNTS/RUN
1-APR-79
1-JUL-79
1-OCT-79
1-JAN-80
A
B
C

Fig. 2