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TESTS TO EXPLORE THE UTILITY OF GRAVITY ANOMALIES AND TOPOGRAPHIC DATA AS POSSIBLE PREDICTORS OF LOCATIONS OF SEISMICITY FOR TWO AREAS IN CALIFORNIA

By

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Tests to Explore the Utility of Gravity Anomalies and Topographic Data as Possible Predictors of Locations of Seismicity for Two Areas in California

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Abstract

Previous work in the U.S.S.R., in Italy, and in the U.S. has suggested the existence of correlations between gravity and topographic data and the locations of earthquakes. In particular, a combination of gravity and topographic data called the S-parameter has given promising results in the past. We have completed new tests to search for correlations in two study areas: a region in northern California centered around San Francisco and a region in southern California centered around Los Angeles. Results are promising, although questions remain as to how to quantify their statistical significance and how best to use the results for defining risk. In the northern area, for example, locations for which the isostatic residual gravity gradient is greater than 2.5 mGal/km occupy only 17 percent of the area but contain 38 percent of the $m \geq 4$ earthquakes from 1969-1990. Thus, $m \geq 4$ earthquakes have occurred in these high-gradient locations 2.9 times more often than elsewhere in the area over the past 20 years. This result makes geologic sense, because gravity gradients occur over changes in density at depth that can indicate the presence of structures and ongoing deformation. Additional work could be directed toward understanding the best ways of choosing the extent of the study area, the best ways of tuning the methods to a particular tectonic environment, and the best ways of evaluating the uncertainties for the numbers obtained. One useful by-product of the method is that it focuses attention on regions that may not have experienced recent seismicity, but which share characteristics with regions that have. In some cases, more detailed geologic and geophysical studies of such regions would seem appropriate.

Introduction

This report is a brief summary of joint research carried out by A. Sadovskii and R. Simpson during April-July 1990 under the auspices of the U.S.-U.S.S.R. cooperative program in earthquake research.

We have attempted to assess the usefulness of regional gravity data, topographic data, and a combination of the two called the S-parameter as predictors of earthquake location. Our two study areas (Figure 1) covered a part of northern California centered around San Francisco Bay (120°W-124°W, 36°N-39°N) and a large part of southern California centered on Los Angeles (115°W-122°W, 32°N-36°N).

A number of Soviet workers have previously reported success in correlating the locations of strong earthquakes in the Soviet Union, in Italy, and in California with Bouguer gravity and topographic data, and in particular with a combination called the S-parameter (Artem'ev and others, 1977; Caputo and others, 1983; Eaton and Sadovskii, 1985; Gorshkov and others, 1985).

Other workers in the United States and Canada, including McGinnis and Ervin (1974), Long (1976), Forsyth (1977), Kane (1977), and Simmons and others (1978), have pointed out apparent correlations of earthquake locations with features in the gravity field. Simpson and others (1981a,b; 1982), exploring possible correlations in the eastern United States, reported that earthquakes seemed to occur more often in proximity to ancient structures marked by gravity gradients, and less frequently in areas with low gravity gradients. Regions with a northeast grain to the residual gravity anomalies seemed to have more earthquakes than areas with other trends or with random patterns of anomalies.

Reasons for Expecting Correlations with Gravity and Topography

Some reasons for thinking that gravity and topographic data might predict the locations of earthquakes are as follows: the topographic data can provide information about the size and recency of crustal movements at the Earth's surface; the gravity data can provide crustal deformation information at shallow levels in the crust, for example, by defining sedimentary basins, and at deeper levels in the crust by revealing structures being formed by deformation.

Another reason for expecting correlations is perhaps most relevant to intraplate environments, but may also play a role in California. Sykes (1978) has suggested that much intraplate seismicity can be attributed to the reactivation of pre-existing structures. Such structures are not uncommonly defined by significant gravity anomalies and steep gravity gradients, which may serve to mark the ancient deformations that originally created these structures rather than the more recent deformations caused by reactivation.

In either case, gravity and topographic anomalies could serve as a guide to potential locations of seismicity.

S-Parameter

The S-parameter is calculated from a combination of Bouguer gravity and topographic data. The value of the S-parameter at a site is defined to be the maximum value of the Bouguer gravity (in milligals) within a window around the site plus a coefficient times the maximum elevation (in meters) within the same window (S = bmax + c*emax). Commonly, the coefficient is chosen to be 0.1 mGal/m, yielding an S-parameter with units of milligals. Because a simple Bouguer slab correction equals 0.1119 mGal/m, the choice of 0.1 for the coefficient makes the S-parameter a close approximation to the free-air gravity value in places where topographic is gentle and the non-slab part of terrain corrections is not extreme. For the investigations described here, the window was square, and its width was taken to be 5 km. The window provides some spatial smearing, but because maximum values are used within the window rather than an average value, the S-parameter field obtained is more discontinuous than either the free-air or Bouguer gravity anomaly fields.

The S-parameter appears to be especially sensitive to the vertical component of tectonic movements, and not so sensitive, perhaps, to horizontal movements except insofar as vertical movements are a by-product of large horizontal motions. The parameter cannot by itself give reliable information about the state of isostatic equilibrium in an area. It will not predict the locations of all earthquakes in an area, although previous tests seem to indicate that the majority of earthquakes will occur in places with high horizontal gradients of the S-parameter.

Previous studies have suggested that earthquakes might be expected to occur at sites of either large absolute values or large gradients (horizontal changes) in the S-parameter, depending on the tectonic environment. In compressive tectonic environments such as Italy or the Caucasus, seismicity seems to occur with large values of S-parameter, whereas in strike-slip environments, such as California, seismicity seems to correlate with zero-values or strong gradients of the parameter (Caputo and others, 1983; Eaton and Sadovskii, 1985; Gorshkov and others, 1985). In compressive tectonic environments, the tectonic movements are in large part vertical, creating new mountains and large downwarped sedimentary basins. In pure strike-slip environments, most of the motion is horizontal with perhaps only rather small uplifts and basins formed at bends in the strike-slip faults. These differences may explain why the S-parameter and seismicity appear to be differently related in the two environments.

Approach

Our approach has been to make color and contour maps of topographic, Bouguer gravity, isostatic residual gravity, S-parameter, and of the horizontal gradients of these quantities. Plots of earthquake epicenters have been overlaid on these maps to visually inspect for possible correlations between the locations of earthquakes and the values of the various quantities.

At the same time, histogram tables were prepared to quantify the visual impressions in a simple way. For example, if it appears that earthquakes are falling along high values of the gradient of the S-parameter, then we would print out the percent of earthquakes falling into incremental bins of different S-parameter-gradient values, and compare this distribution with the relative percent of the study area occupied by the respective bins.

One problem with this approach is that the quantitative results are strongly dependent upon the size and shape of the study area and whether or not it includes particular large gradients or unusual clusters of seismicity. Ideally, the boundary of a study area would be determined by geologic and tectonic features, but even then the interpreter must be constantly aware of the possibilities of biasing the results by the choice of the boundary.

Gravity and Topographic Data

The gravity data used were extracted from the compilation for California described by Snyder and others (1982). These data have been terrain corrected and are probably accurate to better than 1-2 mGal in most cases.

The topographic data came from 1-minute and 3-minute average elevation files for California prepared by the U.S. Geological Survey.

The gravity and topographic data were transformed into rectangular grids using a minimum curvature algorithm. For the northern California study area, a grid spacing of 1-km by 1-km was used. For southern California, the spacing was also 1-km by 1-km. A Lambert Conformal Conic projection was used to prepare the grids with standard parallels at 33 °N and 45 °N.

Two kinds of earthquake catalogs have been used. Catalogs of historic seismicity with magnitudes greater than about 6 for the past two centuries suffer from poor locations of earlier epicenters, but still offer a more complete picture of maximum expectable magnitudes in various regions. On the other hand, catalogs of network seismicity for the past several decades offer good epicentral locations, but because of the short time sampled probably do not offer a good overview of the distribution of seismic hazard.

The network catalogs used were the CALNET catalog of northern and central California seismicity maintained by the U.S. Geological Survey in Menlo Park for the years 1969-1990. For southern California, the California Institute of Technology catalog for years 1932-1985 was used. Most of the tests described below were made using earthquakes greater than magnitude 4 selected from these network catalogs.

Results for Northern California

Our Northern California study area is shown in Figure 2. For this region, we have found some apparent correlations of earthquake locations with gravity and topography. In this section, we will elaborate on two of these correlations: one with isostatic residual gravity gradients and one with lows in the isostatic residual gravity field.

High values of the horizontal gradient of isostatic residual gravity are shown in Figure 3. Histograms of gradient values are presented in Table 1 for the onland part of the study area. (Explanation of the terminology in the tables is given in Appendix A). The histogram shows values of isostatic residual gravity gradient sampled by magnitude ≥ 4 earthquakes over the time period from 1969-1990. Almost 38 percent of the earthquakes fall into regions exhibiting gradients greater than 2.5 mGal/km. Such high-gradient regions occupy about 17 percent of the onland data area. This suggests that, based on past experience, the regions in Figure 3 for which the isostatic residual gravity gradient is greater than 2.5 mGal/km are 2.8 times more likely to experience $m \geq 4$ earthquakes than onland areas with lower gradients.

We believe that this result makes tectonic sense. Gravity gradients occur over density contrasts at depth, such as might be produced by fault offsets. Thus the gradients will tend to lie along faults and around sedimentary basins caused by faulting. They may also define the boundaries of tectonic blocks. These are all locations along which earthquakes might be expected to occur.

Because the locations of many Bay Area faults are already known, this approach might not seem very useful. We think, however, that it can focus attention on areas that, though they may not be presently active, may nonetheless have a potential for seismicity in the long term. The result described in the preceding paragraph suggests that regions of high gravity gradient deserve careful scrutiny. Although some of these high-gradient regions can no doubt be explained by ancient structures or density contrasts not related to present seismic risk, others may indicate areas of risk that have not yet been recognized.

As mentioned in the last section, the correlation result is dependent to some degree on the size and extent of the chosen study area. A part of the Great Valley with low isostatic residual gravity gradients occupies a substantial fraction of the map area. If we redefine the study area by trimming it along the east side of the Coast Ranges to exclude the Great Valley and the Sierra Nevada, we find that regions of high gradient are 2.0 times (rather than 2.8 times) more likely to experience $m \geq 4$ earthquakes than areas with lower gradients.

If we further trim the study area to exclude the cluster of Coalinga aftershocks (the cluster of earthquakes in the southeast corner of Figure 3) with the idea that the large number of earthquakes in this aftershock sequence may bias the results, we find that regions of high gradients are 3.8 times more likely to experience $m \geq 4$ earthquakes based on 20 years of earthquakes.

A second correlation exists between lows in the isostatic residual gravity field and locations of earthquakes. Figure 4 shows locations with isostatic residual gravity values less than -20 mGal and earthquakes with magnitude ≥ 4. From Table 2, about 56 percent of earthquakes with magnitudes ≥ 4 fall into areas of isostatic residual gravity values less than -20 mGal that occupy only 31 percent of the onland part of the study area. This implies that earthquake are 2.9 times more likely in such areas of low isostatic gradient, based on past earthquakes. Also, although there are great uncertainties in the locations of some earlier earthquakes, using the best guesses for their locations only 3 of 17 large historic earthquakes appear to lie more than 10 km from regions of low gravity values.

For this correlation, the Coalinga aftershocks that lie in a region of low isostatic residual gravity along the edge of the Great Valley help the result considerably. If the study area is trimmed to exclude the Great Valley and the area of Coalinga aftershocks, then regions with isostatic residual gravity values less than -20 mGals are only 1.7 times (rather than 2.9 times) more likely to experience earthquakes than regions of higher gravity values.

A possible explanation for this correlation of earthquake locations with gravity lows is that many of the lows lie over sedimentary basins that have formed in areas of fault complexity. For example, basins can form at fault bends or offsets. This correlation has also been noted by V. Dubrovskiy who singled out the gravity low formed in the offset between the northern Hayward fault and the Rodgers Creek fault as indicative of fault geometry complexity and consequent seismic risk. Another low over the Livermore Valley region may be indicative of fault complexities. As with the gravity gradients, we feel that the gravity lows need to be investigated individually and evaluated on a case by case basis using all available geologic and geophysical information.

Results for Southern California

The southern California study area is shown in Figure 5. The tectonic complexity of this region is greater than that of the northern California San Francisco Bay region, because there are large domains of extensional tectonics (e.g., Salton Trough), and compressional tectonics (e.g., Transverse Ranges), as well as strike-slip. Although there are apparent correlations for the area as a whole, they tend to be weaker than for the San Francisco Bay region which is perhaps a more tectonically homogeneous area. For example, 22 percent of earthquakes with magnitude ≥ 4 fall in regions where the horizontal gradient of the S-parameter is greater than 10 mGal/km (Figure 6, Table 3). These regions make up 13 percent of the study area, so that there are about 2 times as many earthquakes in them as elsewhere.

It seemed that we might sharpen our results if we split out individual regions with more uniform tectonic fabric. In the southeastern part of the study area, the Salton Trough has low topographic relief and subdued gravity anomalies, but many earthquakes. The contrast between the Salton Trough and the Transverse Ranges in the amplitudes of topography and gravity and their gradients is striking.

Our first attempt along these lines involved separating out two rectangular sub-areas, one for the Transverse Ranges (117°W-122°W, 34°N-36°N) and one for the Salton Trough region (115°W-119°W, 32°N-34°N). For the Salton Trough region, results did not improve much, probably because the rectangle still contained a diversity of tectonic fabrics. Results for the Transverse Ranges area were somewhat sharper than those obtained for the region as a whole.

In our next attempt to sharpen results for different tectonic environments, we blanked out gradient values outside the Salton Trough area using the gradient map itself as a guide to the extent of this tectonic province. Because the area now contained only low values of gradients it was necessary to decrease the increment of gradient values used to construct the histogram table. The result was a fair correlation between high (for this region) S-parameter gradients ($\geq$1.5 mGal/km) and the locations of earthquakes (Figure 7, Table 4). Thus, it appears that the methods need to be tailored to some degree to individual tectonic regions to obtain the best results. One disadvantage is that by confining our study area to such a small region, the number of earthquakes is smaller and the results are less robust statistically.

We repeated this exercise for the Mojave Desert province and for the southern part of the Great Valley which are both regions of somewhat subdued gradients. The results for these areas were not very definitive, partly because of the relatively small numbers of earthquakes. Another explanation for the poor results may be that topographic and gravity anomalies have long lifetimes. It may take thousands or millions of years to build topographic features or gravity anomalies, whereas seismicity can presumably shift location on a much shorter timescale. Maybe our observation span for seismicity is too short, and the topography and gravity give a better indication of the locus of average tectonic movements over the last million years. Not all of these movements have necessarily been associated with seismic hazards; some may have occurred in a continuously creeping, aseismic mode.

Conclusions

Our tests indicate that correlations do exist between the locations of earthquakes and features defined by regional gravity and topographic data and by combinations thereof such as the S-parameter.

These correlations are not unexpected, because crustal movements associated with earthquakes can produce topographic features and gravity anomalies. For example, bends in a strike slip fault will often produce mountains and/or sedimentary basins and also generate highs, lows, and sharp gradients in the gravity field adjacent to the fault. It appears, for example, that earthquakes occur with greater frequency in regions of high gravity gradient, at least in our study areas. Also, old structures are commonly reactivated by present-day stress fields to produce earthquakes, and many of these old structures have well defined gravity anomalies and gradients.

Because gravity anomalies can be caused by bodies that are not related to present-day seismicity, apparent correlations should not be used to predict potential locations of seismicity without careful evaluation of all available geologic and geophysical data. Each predicted location needs to be evaluated individually. We anticipate, however, that such correlations may also help point to areas of seismic risk that have not been active in historic times.

More work could be done with the aid of computers to determine which parameter or combination of parameters gives the sharpest results. Important questions also need to be answered as to how the study area boundaries are best selected.

Future work in this area should include a study of how best to assign uncertainties to the numbers generated. It is not enough to say that earthquakes have occurred 3 times as frequently in areas of high gravity gradients without some indication of the statistical significance of the result. Unfortunately, because earthquakes tend to be clustered along faults rather than occurring at random and because there are definite patterns to gravity and topographic anomalies, traditional statistical method for assigning confidence levels may not be entirely appropriate. An alternate approach for determining significance levels might be to superpose earthquake locations from one region onto gravity anomalies of similar character from a variety of other regions. For example, because no meaningful correlation would be expected if earthquakes from the San Francisco Bay area were plotted on a map of southern California, such a juxtaposition might help to estimate the noise level in "real" correlations.

This work could be most usefully continued in a region such as the San Francisco Bay area where detailed regional studies of geology and geophysics are planned to aid in the assessment of seismic risk. Correlations of the sort described in this paper might then usefully focus attention on particular anomalies and areas, while a better understanding of the sources of all the anomalies could give new insights into the causes of the apparent correlations.

Acknowledgments

This research was carried out in Menlo Park, California from April to July 1990 during a visit of A. Sadovskii under the auspices of the U.S.S.R.-U.S. cooperative agreement in earthquake research.

References Cited

Artem'ev, M.E., Rotvain, I.M., and Sadovskii, A.M., 1977, Recognition of places of possible occurrence of strong earthquakes, VII. Investigation of Bouguer anomalies for California and adjacent regions, in, Pattern recognition and spectral analysis in seismology, Nauka, Moscow, Vychislitel'naya Seismologiya, n. 10, pp. 19-32.

Caputo, M., Marussi, A., and Sadovskii, A.M., 1983, Bouguer anomalies, topography, and seismicity of Italy, Dokl. AN SSSR, v. 272, n. 1, pp. 57-61.

Eaton, D. and Sadovskii, A.M., 1985, Gravity anomalies and epicenters of earthquakes with $M \geq 5$ in the zone of the central branch of the San Andreas fault system: Vychislitel'naya Seismologiya, n. 18, pp. 134-138.

Forsyth, D.A., 1977, Relationships between seismicity, free air gravity, and structure in Arctic and eastern Canada (abs.): Earthquake Notes, v. 48, p. 15.

Gorshkov, A.I., Niauri, G.A., Rantsman, E.Ya., and Sadovskii, A.M., 1985, Use of gravimetric data for recognition of places of possible occurrence of strong earthquakes in the Great Caucasus: Vychislitel'naya Seismologiya, n. 18, pp. 127-134.

Kane, M.F., 1977, Correlation of major eastern earthquake centers with mafic/ultramafic basement masses: U.S. Geological Survey Professional Paper 1028, p. 199-204.

Long, L.T., 1976, Speculations concerning Southeastern earthquakes, mafic intrusions, gravity anomalies, and stress amplification: Earthquake Notes, v. 47,. p. 29-35.

McGinnis, L.D., and Ervin, C.P., 1974, Earthquakes and block tectonics in the Illinois Basin: Geology, v. 2, p. 517-519.

Simmons, G., Tillson, D., Murphy, V., LeBlanc, G., Doherty, J., Sharp, J., and Roeloff, E., 1978, Gravity, stress, and earthquakes in Washington State and surrounding areas (abs.): 3rd International Conference on Basement Tectonics, 15-19 May 1978, Fort Lewis College, Durango, CO.

Simpson, R.W., Bothner, W.A., and Godson, R.H., 1981, Colored gravity anomaly and terrain maps of the northeastern U.S. and adjacent Canada: U.S. Geological Survey Open-File Report 81-560, 10 pp.

Simpson, R.W., and Godson, R.H., 1981, Colored gravity anomaly and terrain maps of the east Central United States: U.S. Geological Survey Open-File Report 81-846, 16 pp.

Simpson, R.W., Hildenbrand, T.G., Godson, R.H., and Kane, M.F., 1982, A description of colored gravity and terrain maps for the United States and adjacent Canada east of 104°: U.S. Geological Survey Open-File Report 82-877, 18 pp.

Snyder, D.G., Roberts, C.W., Saltus, R.W., and Sikora, R.F., 1982, Description of a magnetic tape containing the principal facts for 64,026 gravity stations in the state of California: National Technical Information Service Report PB-82-168-279, 30 pp. (Magnetic tape is available from U.S. Department of Commerce, National Technical Information Service, Springfield, VA 22152 as PB-82-168-287).

Sykes, L.R., 1978, Intraplate seismicity, reactivation of preexisting zones of weakness, alkaline magmatism, and other tectonism postdating continental fragmentation: Reviews of Geophysics and Space Physics, v. 16, p. 621.

APPENDIX A -- Explanation of Tables

Program = computer program used to make the table.

Grid = the name of the computer file containing the gridded data.
ID = identifier information for the grid.
ntot = total number of points in the grid.
ncol = number of columns in the grid.
nrow = number of rows in the grid.
xo, yo = coordinates of lower-left corner point of grid in kilometers.
dx, dy = spacing between grid points in kilometers.
xmax, ymax = coordinates of upper-right corner point of grid in kilometers.
projection = 4 = Lambert Conformal Conic projection.
ngood in grid = number of grid points not flagged for absence of data.
nblanks = number of grid points flagged for no data.

Eq file = name of the computer file containing the earthquakes.
neqs read = number of earthquakes read from the file.
neqs used = number of earthquakes that fell in areas of grid data.
neqs at blanks = number of earthquakes within the grid area, but falling at points with no data.

INTERVAL = a range of grid data values (mGal for gravity, mGal/km for gravity gradient).
Grid Pts (column 3) = number of grid points that had values within the specified range.
EQ No. (column 4) = number of earthquakes for which closest grid point had value in specified range.
Grid% (column 5) = Grid Pts from column 3 / ngood.
Eq% (column 6) = EQ No. from column 4 / neqs used.
GridCum% (column 7) = Cumulative percent from column 5 starting at 0% and adding.
EqCum% (column 8) = Cumulative percent from column 6 starting at 0% and adding.
GridCum% (column 9) = Cumulative percent from column 5 starting at 100% and subtracting.
EqCum% (column 10) = Cumulative percent from column 6 starting at 100% and subtracting.

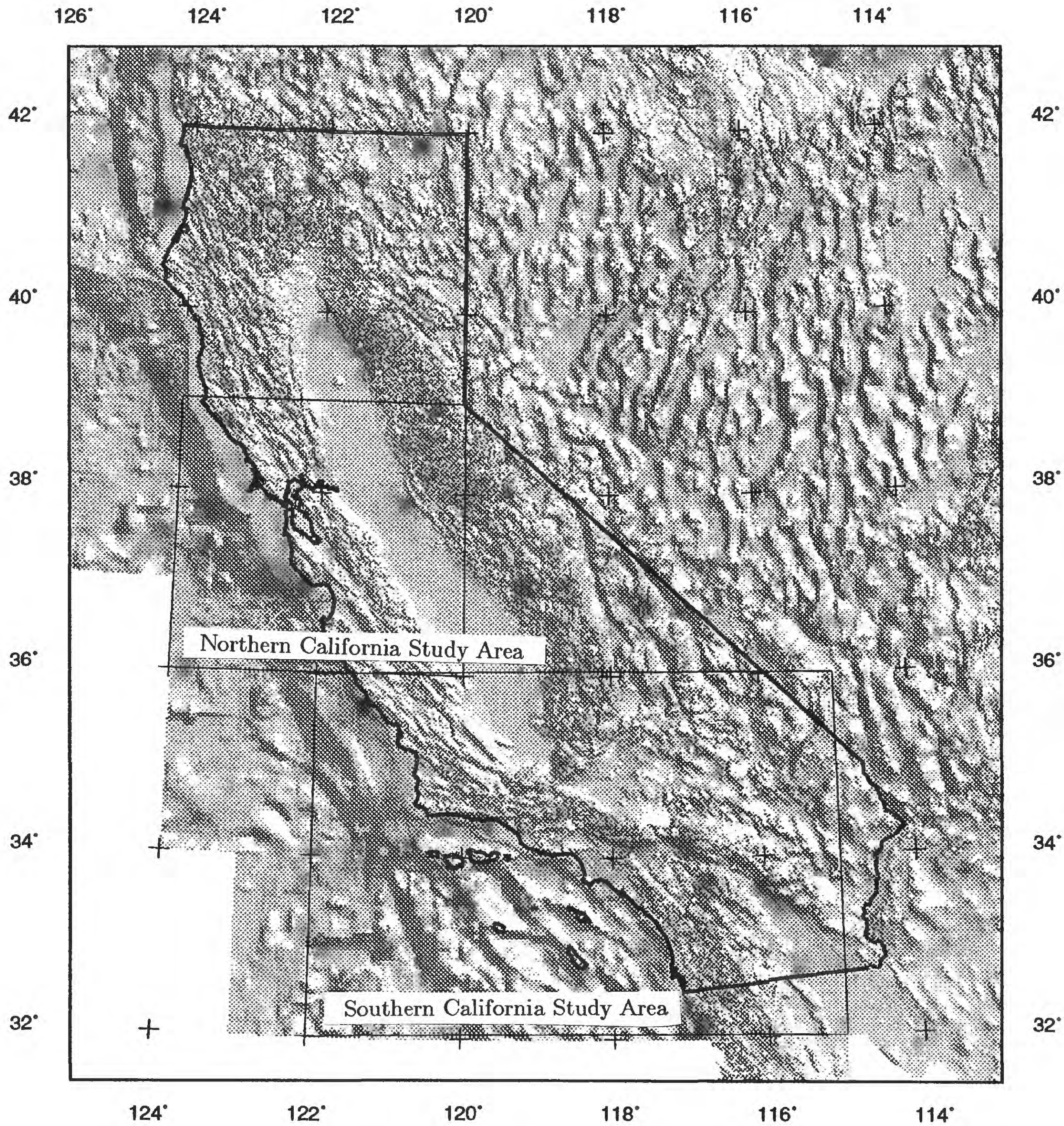

Figure 1. Location map showing outlines of Northern California and Southern California study areas.

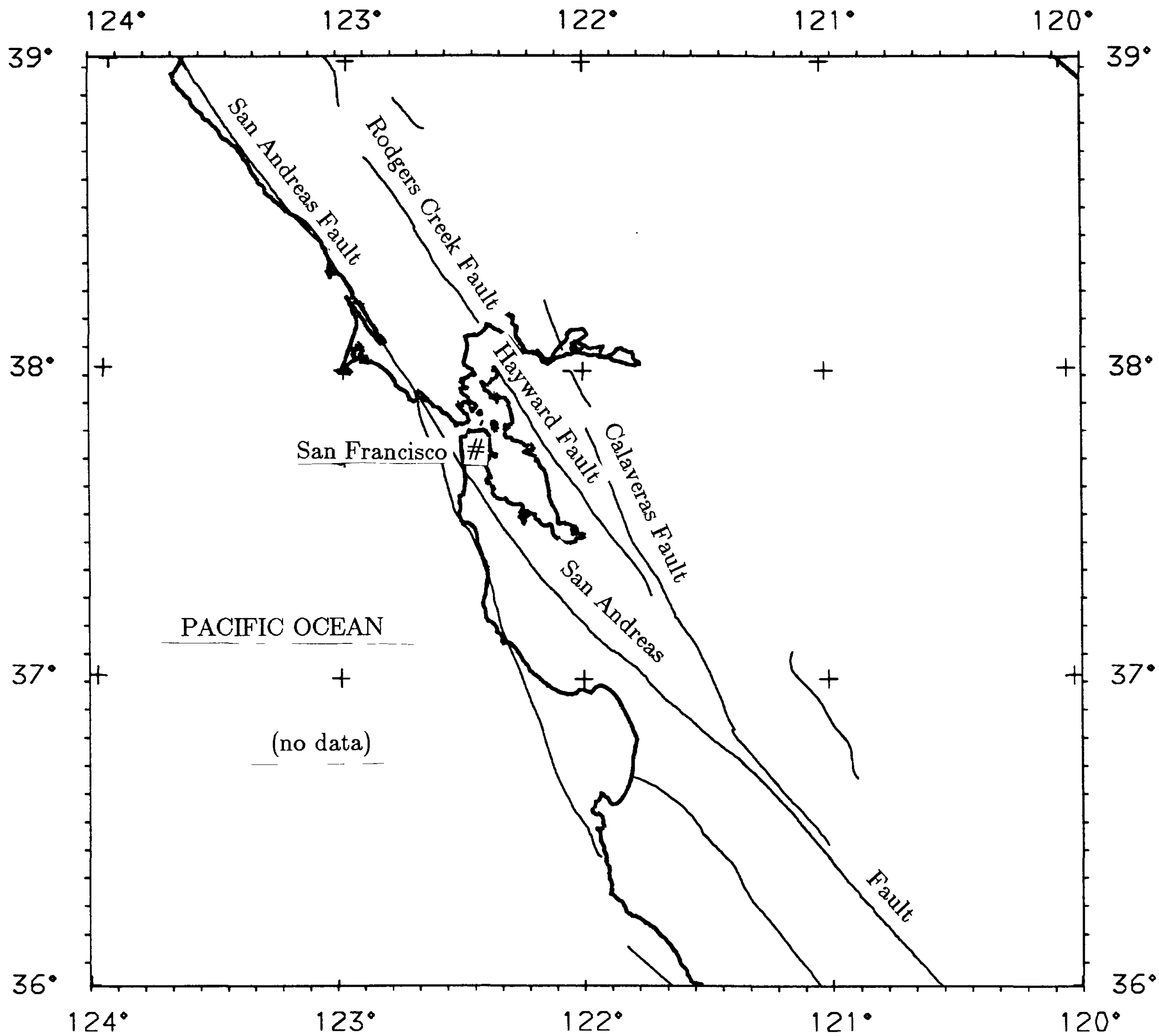

Figure 2. San Francisco Bay study area in northern California, showing coastline and selected faults. Tic marks along the edges are 10 km apart. Lambert conformal conic projection with standard parallels at 33°N and 45°N.

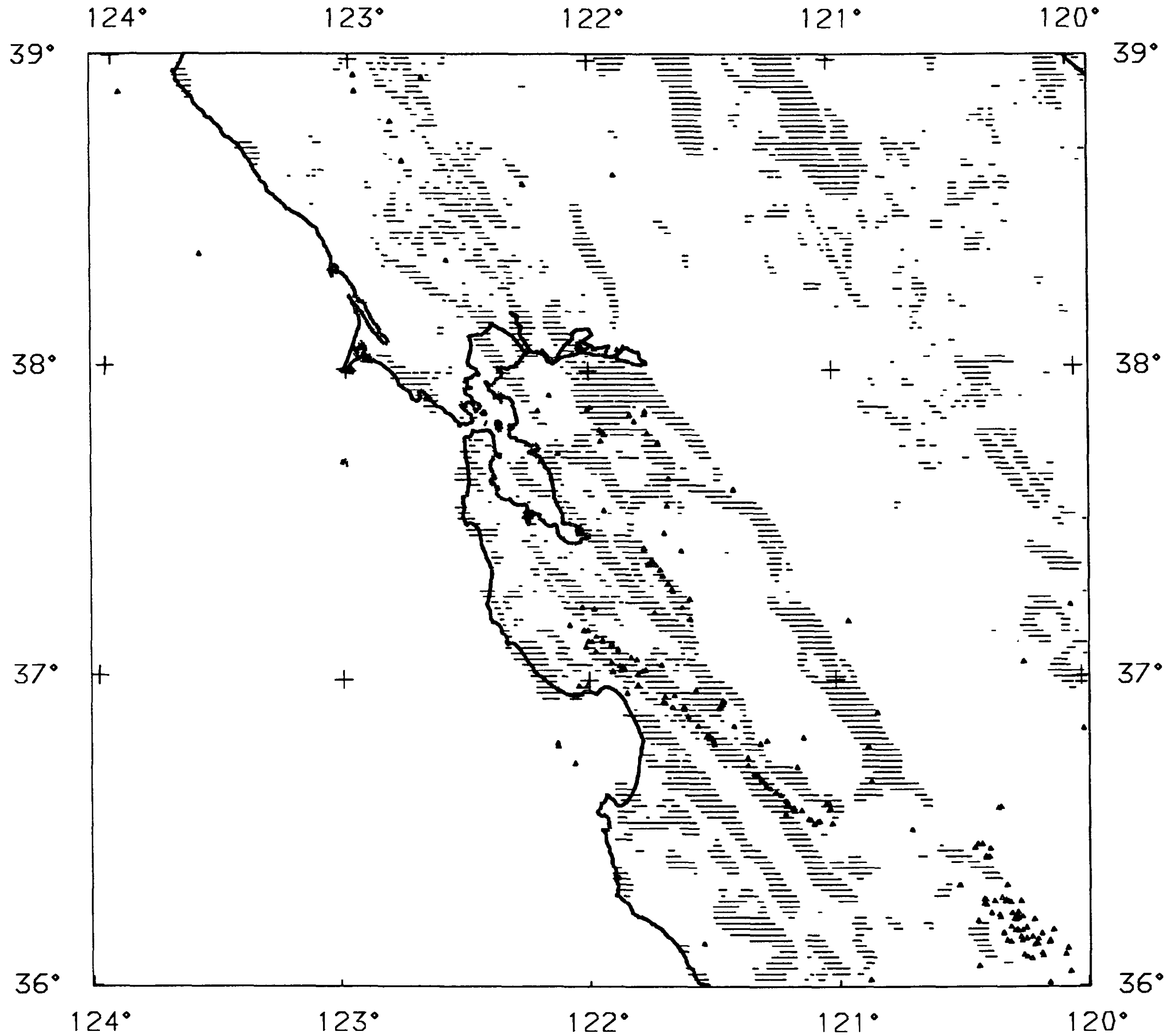

Figure 3. Horizontal gradient of isostatic residual gravity in San Francisco Bay study area. Shading indicates regions in which the horizontal gradient is greater than 2.5 mGal/km. Gravity data used continued only about 20 km offshore. Earthquakes with magnitude ≥ 4 from 1969 to 1990 are shown as small triangles. The cluster of earthquakes in the lower right corner of the map consists of Coalinga aftershocks. See Table 1 for statistics of earthquake distribution.

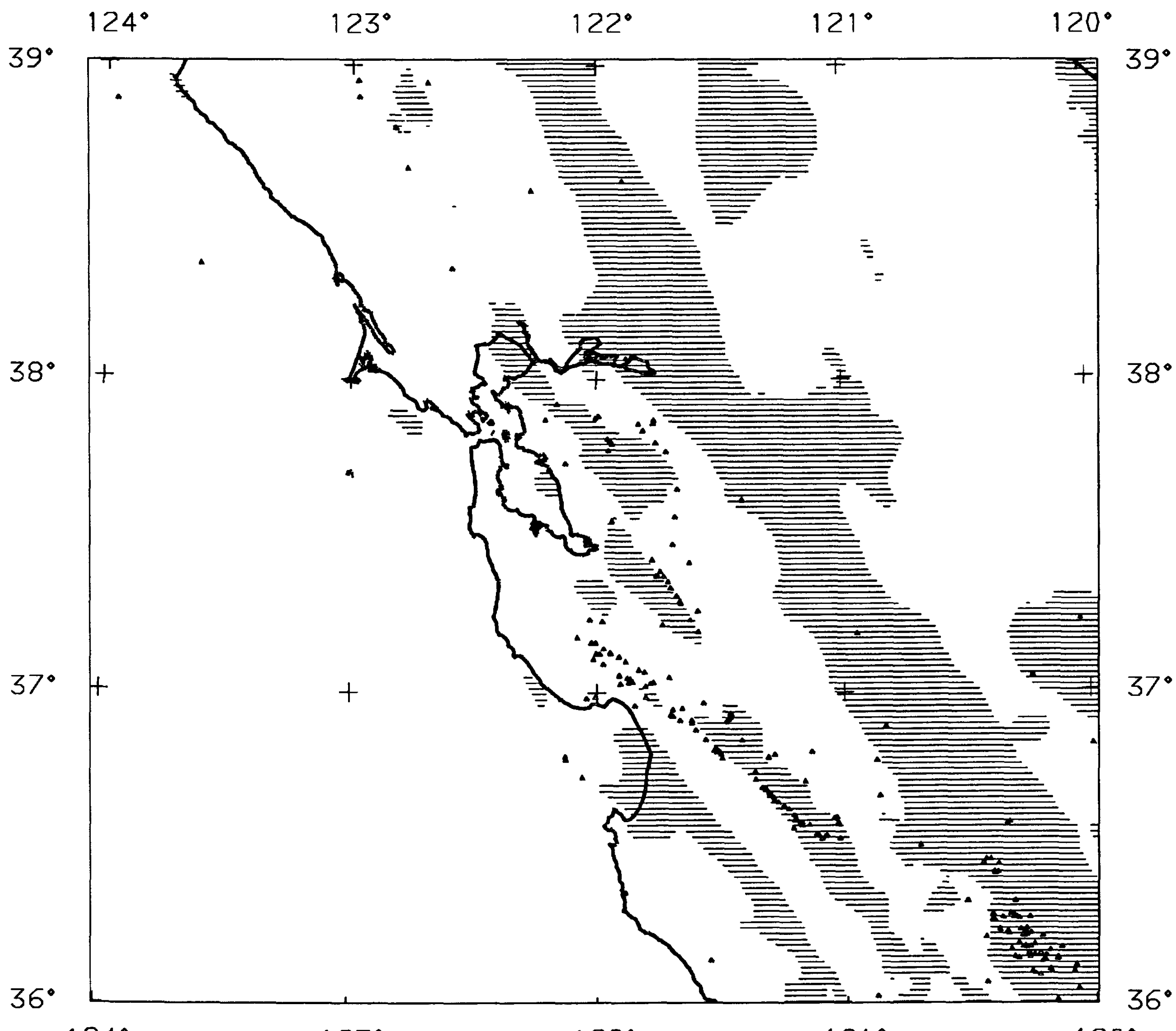

Figure 4. Isostatic residual gravity in San Francisco Bay study area. Shading indicates regions in which the isostatic residual gravity has values less than -20 mGal. Gravity data used only continued about 20 km offshore. Earthquakes with magnitude ≥ 4 from 1969 to 1990 are shown as small triangles. See Table 2 for statistics of earthquake distribution.

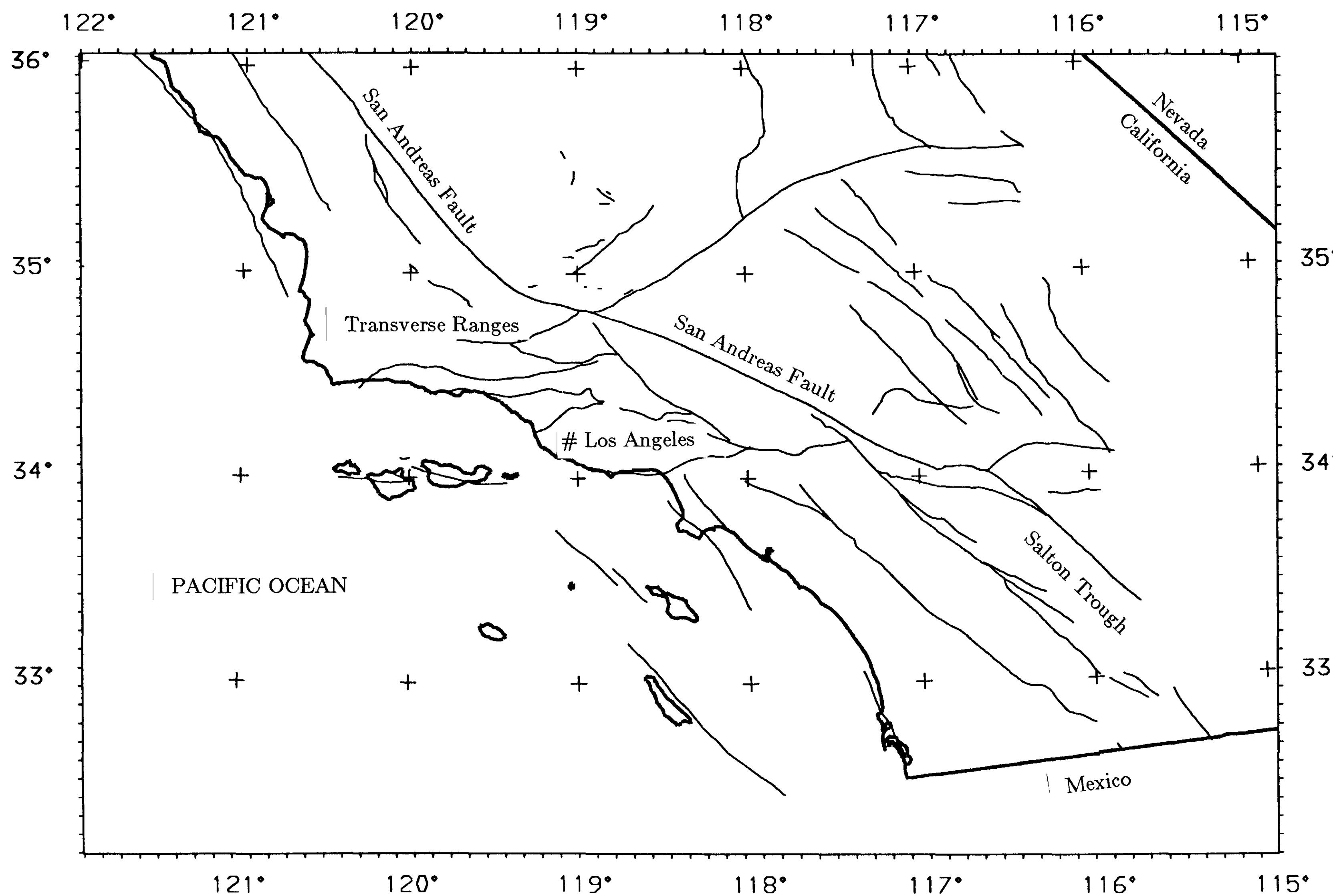

Figure 5. Southern California study area, showing coastline and selected faults. Tic marks along the edges are 10 km apart. Lambert conformal conic projection with standard parallels at 33°N and 45°N.

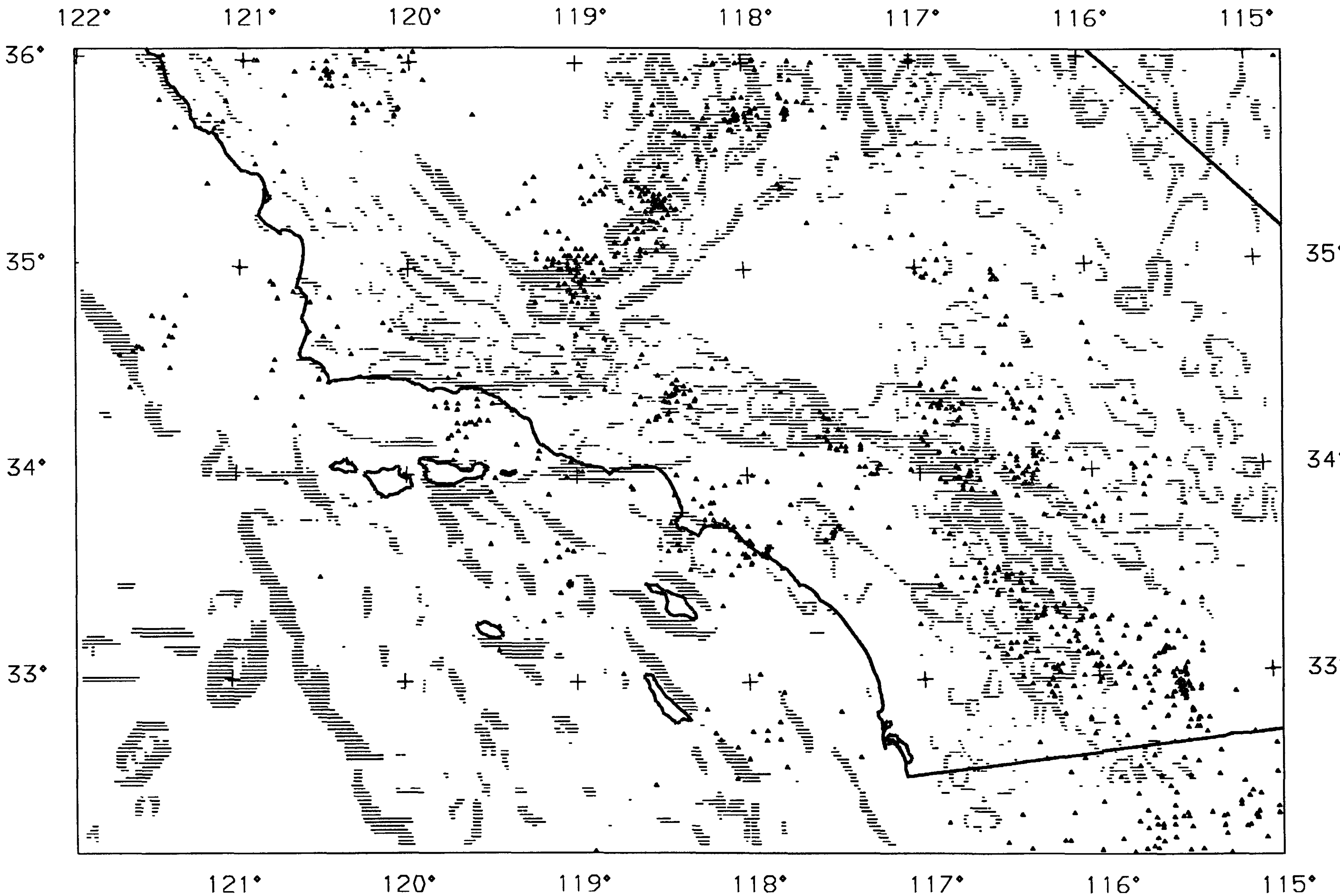

Figure 6. Horizontal gradient of S-parameter in southern California study area. Shading indicates regions in which the gradient is greater than 10 mGal/km. Earthquakes with magnitude ≥ 4 from 1932 to 1985 are shown as small triangles. See Table 3 for statistics of earthquake distribution.

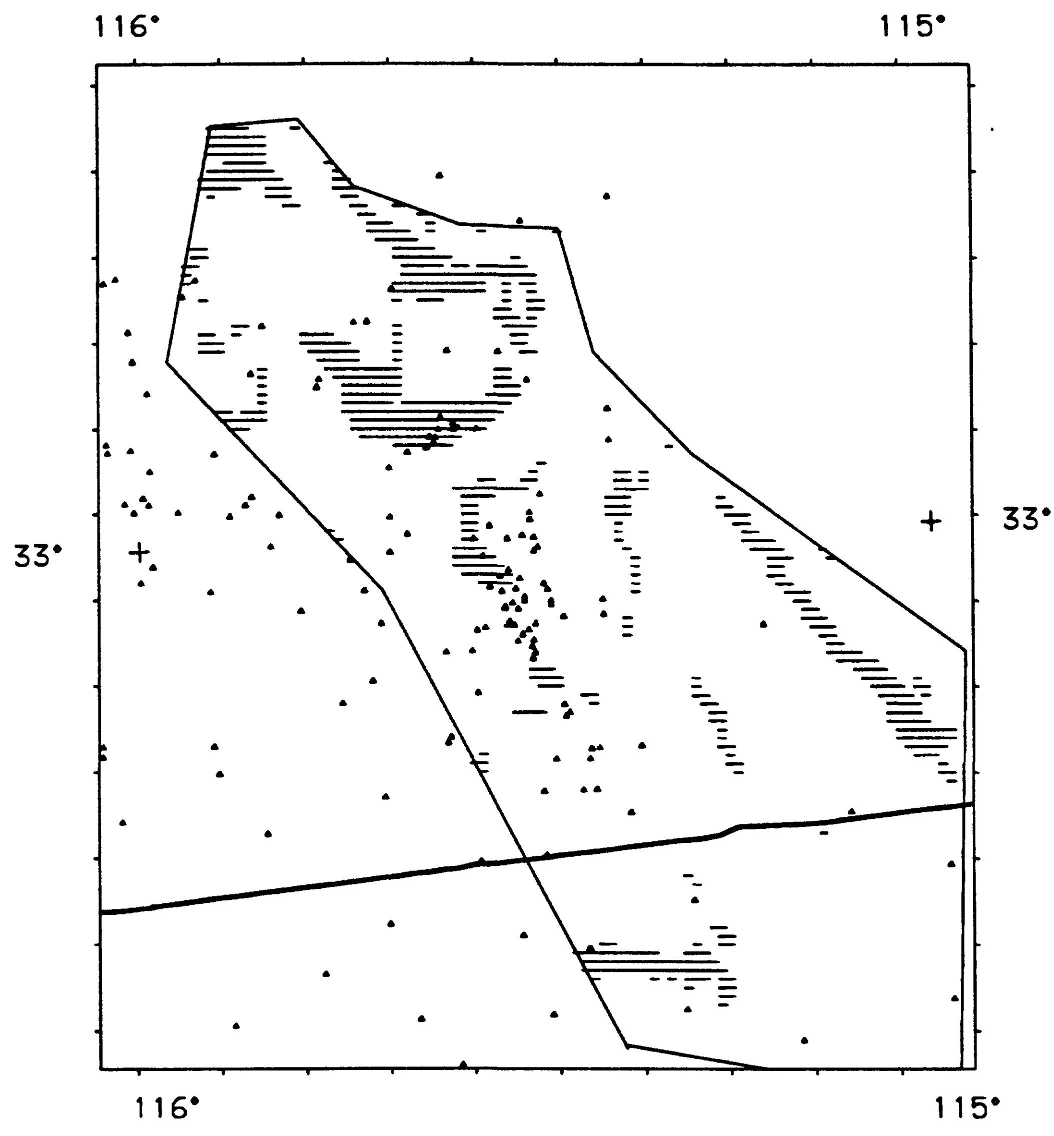

Figure 7. Horizontal gradient of S-parameter for Salton Trough region in southern California study area. Shading indicates regions in which the gradient is greater than 1.5 mGal/km. Earthquakes with magnitude ≥ 4 from 1932 to 1985 are shown as small triangles. Tics around outside edges of plot are 10 km apart. See Table 4 for statistics of earthquake distribution.

```
Program = g+eqs2hist.f

Grid = isos.grad
   |ID  = Gradient of Isostatic Residual Gravity                    PGM=gradient
   |ntot= 119520        nz=  1
   |ncol=    360        xo= -179.58730     dx=  1.0004897     xmax=  179.58852
   |nrow=    332        yo=  1.9760742     dy=  1.0006609     ymax=  333.19482
   |    projection= 4        cm=    -122.0000    bl=      36.0000
          ncol*nrow =             119520
          ngood   in grid =        76494
          nblanks in grid =        43026

Eq file = ncal_m4.eq
          neqs read =              234
          neqs used =              229
          neqs at blanks =           5
```

INTERVAL	Grid Pts	EQ No.	Grid%	Eq%	GridCum%	EqCum%	GridCum%	EqCum%
-infinity -> 0.00	0	0	0.00	0.00	0.00	0.00	100.00	100.00
0.00 -> 0.50	9460	10	12.37	4.37	12.37	4.37	100.00	100.00
0.50 -> 1.00	17848	45	23.33	19.65	35.70	24.02	87.63	95.63
1.00 -> 1.50	16283	34	21.29	14.85	56.99	38.86	64.30	75.98
1.50 -> 2.00	11898	34	15.55	14.85	72.54	53.71	43.01	61.14
2.00 -> 2.50	7665	20	10.02	8.73	82.56	62.45	27.46	46.29
2.50 -> 3.00	4558	14	5.96	6.11	88.52	68.56	17.44	37.55
3.00 -> 3.50	3088	16	4.04	6.99	92.56	75.55	11.48	31.44
3.50 -> 4.00	1978	12	2.59	5.24	95.14	80.79	7.44	24.45
4.00 -> 4.50	1245	6	1.63	2.62	96.77	83.41	4.86	19.21
4.50 -> 5.00	824	5	1.08	2.18	97.85	85.59	3.23	16.59
5.00 -> 5.50	535	5	0.70	2.18	98.55	87.77	2.15	14.41
5.50 -> 6.00	370	12	0.48	5.24	99.03	93.01	1.45	12.23
6.00 -> 6.50	236	4	0.31	1.75	99.34	94.76	0.97	6.99
6.50 -> 7.00	144	3	0.19	1.31	99.53	96.07	0.66	5.24
7.00 -> 7.50	106	1	0.14	0.44	99.67	96.51	0.47	3.93
7.50 -> 8.00	93	1	0.12	0.44	99.79	96.94	0.33	3.49
8.00 -> 8.50	40	3	0.05	1.31	99.84	98.25	0.21	3.06
8.50 -> 9.00	35	2	0.05	0.87	99.88	99.13	0.16	1.75
9.00 -> 9.50	24	0	0.03	0.00	99.92	99.13	0.12	0.87
9.50 -> 10.00	19	1	0.02	0.44	99.94	99.56	0.08	0.87
10.00 -> 10.50	14	0	0.02	0.00	99.96	99.56	0.06	0.44
10.50 -> 11.00	7	0	0.01	0.00	99.97	99.56	0.04	0.44
11.00 -> 11.50	6	0	0.01	0.00	99.98	99.56	0.03	0.44
11.50 -> 12.00	8	0	0.01	0.00	99.99	99.56	0.02	0.44
12.00 -> 12.50	3	0	0.00	0.00	99.99	99.56	0.01	0.44
12.50 ->infinity	7	1	0.01	0.44	100.00	100.00	0.01	0.44

```
      INTERVAL                Grid%                        Eq%         (5 percent steps)
-infinity ->    0.00          |                            |
    0.00 ->    0.50           |GG                          |Q
    0.50 ->    1.00           |GGGGG                       |QQQQ
    1.00 ->    1.50           |GGGG                        |QQQ
    1.50 ->    2.00           |GGG                         |QQQ
    2.00 ->    2.50           |GG                          |QQ
    2.50 ->    3.00           |G                           |Q
    3.00 ->    3.50           |G                           |Q
    3.50 ->    4.00           |G                           |Q
    4.00 ->    4.50           |                            |Q
    4.50 ->    5.00           |                            |
    5.00 ->    5.50           |                            |
    5.50 ->    6.00           |                            |Q
    6.00 ->    6.50           |                            |
    6.50 ->    7.00           |                            |
    7.00 ->    7.50           |                            |
    7.50 ->    8.00           |                            |
    8.00 ->    8.50           |                            |
    8.50 ->    9.00           |                            |
    9.00 ->    9.50           |                            |
    9.50 ->   10.00           |                            |
   10.00 ->   10.50           |                            |
   10.50 ->   11.00           |                            |
   11.00 ->   11.50           |                            |
   11.50 ->   12.00           |                            |
   12.00 ->   12.50           |                            |
   12.50 ->infinity           |                            |
```

Table 1. Statistics of earthquake distribution (m$\geq$4 from 1969-1990) relative to the distribution of values of the horizontal gradient of isostatic residual gravity for the San Francisco Bay study area. See Figure 3 for locations of earthquakes. See Appendix A for explanation of terms in table.

```
Program = g+eqs2hist.f

Grid = isos.sg
   |ID   = Isostatic Residual Gravity                                    PGM=gblot
   |ntot= 119520        ns=  1
   |ncol=    360        xo= -179.58730      dx=  1.0004897      xmax=  179.58852
   |nrow=    332        yo=  1.9760742      dy=  1.0006609      ymax=  333.19482
   |     projection= 4          cm=    -122.0000     bl=       36.0000
          ncol*nrow =               119520
          ngood   in grid =          77664
          nblanks in grid =          41856

Eq file = ncol_m4.eq
          neqs read =                  234
          neqs used =                  229
          neqs at blanks =               5
```

INTERVAL	Grid Pts	EQ No.	Grid%	Eq%	GridCum%	EqCum%	GridCum%	EqCum%
-infinity -> -100.00	0	0	0.00	0.00	0.00	0.00	100.00	100.00
-100.00 -> -90.00	0	0	0.00	0.00	0.00	0.00	100.00	100.00
-90.00 -> -80.00	0	0	0.00	0.00	0.00	0.00	100.00	100.00
-80.00 -> -70.00	0	0	0.00	0.00	0.00	0.00	100.00	100.00
-70.00 -> -60.00	0	0	0.00	0.00	0.00	0.00	100.00	100.00
-60.00 -> -50.00	673	0	0.87	0.00	0.87	0.00	100.00	100.00
-50.00 -> -40.00	4791	19	6.17	8.30	7.04	8.30	99.13	100.00
-40.00 -> -30.00	7043	60	9.07	26.20	16.10	34.50	92.96	91.70
-30.00 -> -20.00	11613	50	14.95	21.83	31.06	56.33	83.90	65.50
-20.00 -> -10.00	16949	50	21.82	21.83	52.88	78.17	68.94	43.67
-10.00 -> 0.00	19257	32	24.80	13.97	77.68	92.14	47.12	21.83
0.00 -> 10.00	10987	12	14.15	5.24	91.82	97.38	22.32	7.86
10.00 -> 20.00	5130	5	6.61	2.18	98.43	99.56	8.18	2.62
20.00 -> 30.00	1122	1	1.44	0.44	99.87	100.00	1.57	0.44
30.00 -> 40.00	99	0	0.13	0.00	100.00	100.00	0.13	0.00
40.00 -> 50.00	0	0	0.00	0.00	100.00	100.00	0.00	0.00
50.00 -> 60.00	0	0	0.00	0.00	100.00	100.00	0.00	0.00
60.00 -> 70.00	0	0	0.00	0.00	100.00	100.00	0.00	0.00
70.00 -> 80.00	0	0	0.00	0.00	100.00	100.00	0.00	0.00
80.00 -> 90.00	0	0	0.00	0.00	100.00	100.00	0.00	0.00
90.00 -> 100.00	0	0	0.00	0.00	100.00	100.00	0.00	0.00
100.00 ->infinity	0	0	0.00	0.00	100.00	100.00	0.00	0.00

```
      INTERVAL               Grid%                    Eq%            (5 percent steps)
-infinity -> -100.00          |                        |
  -100.00 ->  -90.00          |                        |
   -90.00 ->  -80.00          |                        |
   -80.00 ->  -70.00          |                        |
   -70.00 ->  -60.00          |                        |
   -60.00 ->  -50.00          |                        |
   -50.00 ->  -40.00          |G                       |QQ
   -40.00 ->  -30.00          |GG                      |QQQQQ
   -30.00 ->  -20.00          |GGG                     |QQQQ
   -20.00 ->  -10.00          |GGGG                    |QQQQ
   -10.00 ->    0.00          |GGGGG                   |QQQ
     0.00 ->   10.00          |GGG                     |Q
    10.00 ->   20.00          |G                       |
    20.00 ->   30.00          |                        |
    30.00 ->   40.00          |                        |
    40.00 ->   50.00          |                        |
    50.00 ->   60.00          |                        |
    60.00 ->   70.00          |                        |
    70.00 ->   80.00          |                        |
    80.00 ->   90.00          |                        |
    90.00 ->  100.00          |                        |
   100.00 ->infinity          |                        |
```

Table 2. Statistics of earthquake distribution ($m \geq 4$ from 1969-1990) relative to the distribution of values isostatic residual gravity for the San Francisco Bay study area. See Figure 4 for locations of earthquakes. See Appendix A for explanation of terms in table.

```
Program = g+eqs2hist.f

Grid = sparam.grad
   |ID  = Gradient of Boug(max)+0.1*Topo(max), Window=   5.        PGM=gradient
   |ntot= 280800        ns=  1
   |ncol=    650        xo= -270.00000     dx=  1.0000000     xmax=  379.00000
   |nrow=    432        yo=  20.000000     dy=  1.0000000     ymax=  451.00000
   |    projection= 4        cm=    -119.0000     bl=     32.0000
          ncol*nrow =           280800
          ngood   in grid =     269514
          nblanks in grid =      11286

Eq file = CIT_m4.eq
          neqs read =           1597
          neqs used =           1468
          neqs at blanks =       129
```

INTERVAL		Grid Pts	EQ No.	Grid%	Eq%	GridCum%	EqCum%	GridCum%	EqCum%
-infinity ->	0.00	0	0	0.00	0.00	0.00	0.00	100.00	100.00
0.00 ->	1.00	31794	182	11.80	12.40	11.80	12.40	100.00	100.00
1.00 ->	2.00	46557	244	17.27	16.62	29.07	29.02	88.20	87.60
2.00 ->	3.00	37732	133	14.00	9.06	43.07	38.08	70.93	70.98
3.00 ->	4.00	29343	130	10.89	8.86	53.96	46.93	56.93	61.92
4.00 ->	5.00	24040	216	8.92	14.71	62.88	61.65	46.04	53.07
5.00 ->	6.00	19167	59	7.11	4.02	69.99	65.67	37.12	38.35
6.00 ->	7.00	15525	49	5.76	3.34	75.75	69.01	30.01	34.33
7.00 ->	8.00	12606	55	4.68	3.75	80.43	72.75	24.25	30.99
8.00 ->	9.00	10222	31	3.79	2.11	84.22	74.86	19.57	27.25
9.00 ->	10.00	8263	39	3.07	2.66	87.29	77.52	15.78	25.14
10.00 ->	11.00	6919	37	2.57	2.52	89.85	80.04	12.71	22.48
11.00 ->	12.00	5687	32	2.11	2.18	91.96	82.22	10.15	19.96
12.00 ->	13.00	4321	54	1.60	3.68	93.57	85.90	8.04	17.78
13.00 ->	14.00	3583	93	1.33	6.34	94.90	92.23	6.43	14.10
14.00 ->	15.00	2829	21	1.05	1.43	95.95	93.66	5.10	7.77
15.00 ->	16.00	2209	17	0.82	1.16	96.77	94.82	4.05	6.34
16.00 ->	17.00	1854	25	0.69	1.70	97.45	96.53	3.23	5.18
17.00 ->	18.00	1434	10	0.53	0.68	97.99	97.21	2.55	3.47
18.00 ->	19.00	1078	10	0.40	0.68	98.39	97.89	2.01	2.79
19.00 ->	20.00	939	7	0.35	0.48	98.73	98.37	1.61	2.11
20.00 ->	21.00	715	5	0.27	0.34	99.00	98.71	1.27	1.63
21.00 ->	22.00	557	4	0.21	0.27	99.21	98.98	1.00	1.29
22.00 ->	23.00	431	2	0.16	0.14	99.37	99.11	0.79	1.02
23.00 ->	24.00	363	4	0.13	0.27	99.50	99.39	0.63	0.89
24.00 ->	25.00	303	2	0.11	0.14	99.61	99.52	0.50	0.61
25.00 ->	infinity	1043	7	0.39	0.48	100.00	100.00	0.39	0.48

```
       INTERVAL                Grid%                        Eq%            (5 percent steps)
-infinity ->    0.00           |                            |
     0.00 ->    1.00           |GG                          |QQ
     1.00 ->    2.00           |GGG                         |QQQ
     2.00 ->    3.00           |GGG                         |QQ
     3.00 ->    4.00           |GG                          |QQ
     4.00 ->    5.00           |GG                          |QQQ
     5.00 ->    6.00           |G                           |Q
     6.00 ->    7.00           |G                           |Q
     7.00 ->    8.00           |G                           |Q
     8.00 ->    9.00           |G                           |
     9.00 ->   10.00           |G                           |Q
    10.00 ->   11.00           |G                           |Q
    11.00 ->   12.00           |                            |
    12.00 ->   13.00           |                            |Q
    13.00 ->   14.00           |                            |Q
    14.00 ->   15.00           |                            |
    15.00 ->   16.00           |                            |
    16.00 ->   17.00           |                            |
    17.00 ->   18.00           |                            |
    18.00 ->   19.00           |                            |
    19.00 ->   20.00           |                            |
    20.00 ->   21.00           |                            |
    21.00 ->   22.00           |                            |
    22.00 ->   23.00           |                            |
    23.00 ->   24.00           |                            |
    24.00 ->   25.00           |                            |
    25.00 ->infinity           |                            |
```

Table 3. Statistics of earthquake distribution (m$\geq$4 from 1932 to 1985) relative to the distribution of values of horizontal gradient of S-parameter for the southern California study area. See Figure 6 for locations of earthquakes. See Appendix A for explanation of terms in table.

```
Program = g+eqs2hist.f

Grid = ss_sparam.grad
   |ID  = Gradient of Boug(max)+0.1*Topo(max), Window=   5.         PGM=gclr
   |ntot=  12051        ns=  1
   |ncol=    103        xo=  276.00000     dx=  1.0000000     xmax=  378.00000
   |nrow=    117        yo=  56.000000     dy=  1.0000000     ymax=  172.00000
   |     projection= 4        cm=    -119.0000     bl=      32.0000
          ncol*nrow =              12051
          ngood   in grid =         5027
          nblanks in grid =         7024

Eq file = CIT_m4.eq
          neqs read =               271
          neqs used =               167
          neqs at blanks =          104
```

INTERVAL	Grid Pts	EQ No.	Grid%	Eq%	GridCum%	EqCum%	GridCum%	EqCum%
-infinity -> 0.00	0	0	0.00	0.00	0.00	0.00	100.00	100.00
0.00 -> 0.25	525	25	10.44	14.97	10.44	14.97	100.00	100.00
0.25 -> 0.50	842	14	16.75	8.38	27.19	23.35	89.56	85.03
0.50 -> 0.75	961	46	19.12	27.54	46.31	50.90	72.81	76.65
0.75 -> 1.00	865	13	17.21	7.78	63.52	58.68	53.69	49.10
1.00 -> 1.25	659	16	13.11	9.58	76.63	68.26	36.48	41.32
1.25 -> 1.50	474	12	9.43	7.19	86.06	75.45	23.37	31.74
1.50 -> 1.75	296	30	5.89	17.96	91.94	93.41	13.94	24.55
1.75 -> 2.00	209	5	4.16	2.99	96.10	96.41	8.06	6.59
2.00 -> 2.25	104	5	2.07	2.99	98.17	99.40	3.90	3.59
2.25 -> 2.50	41	1	0.82	0.60	98.99	100.00	1.83	0.60
2.50 -> 2.75	24	0	0.48	0.00	99.46	100.00	1.01	0.00
2.75 -> 3.00	14	0	0.28	0.00	99.74	100.00	0.54	0.00
3.00 -> 3.25	5	0	0.10	0.00	99.84	100.00	0.26	0.00
3.25 -> 3.50	5	0	0.10	0.00	99.94	100.00	0.16	0.00
3.50 -> 3.75	1	0	0.02	0.00	99.96	100.00	0.06	0.00
3.75 -> 4.00	1	0	0.02	0.00	99.98	100.00	0.04	0.00
4.00 -> 4.25	1	0	0.02	0.00	100.00	100.00	0.02	0.00
4.25 -> 4.50	0	0	0.00	0.00	100.00	100.00	0.00	0.00
4.50 -> 4.75	0	0	0.00	0.00	100.00	100.00	0.00	0.00
4.75 -> 5.00	0	0	0.00	0.00	100.00	100.00	0.00	0.00
5.00 -> 5.25	0	0	0.00	0.00	100.00	100.00	0.00	0.00
5.25 -> 5.50	0	0	0.00	0.00	100.00	100.00	0.00	0.00
5.50 -> 5.75	0	0	0.00	0.00	100.00	100.00	0.00	0.00
5.75 -> 6.00	0	0	0.00	0.00	100.00	100.00	0.00	0.00
6.00 -> 6.25	0	0	0.00	0.00	100.00	100.00	0.00	0.00
6.25 ->infinity	0	0	0.00	0.00	100.00	100.00	0.00	0.00

```
     INTERVAL                 Grid%                       Eq%            (5 percent steps)
-infinity ->     0.00         |                           |
     0.00 ->     0.25         |GG                         |QQQ
     0.25 ->     0.50         |GGG                        |QQ
     0.50 ->     0.75         |GGGG                       |QQQQQQ
     0.75 ->     1.00         |GGG                        |QQ
     1.00 ->     1.25         |GGG                        |QQ
     1.25 ->     1.50         |GG                         |Q
     1.50 ->     1.75         |G                          |QQQQ
     1.75 ->     2.00         |G                          |Q
     2.00 ->     2.25         |                           |Q
     2.25 ->     2.50         |                           |
     2.50 ->     2.75         |                           |
     2.75 ->     3.00         |                           |
     3.00 ->     3.25         |                           |
     3.25 ->     3.50         |                           |
     3.50 ->     3.75         |                           |
     3.75 ->     4.00         |                           |
     4.00 ->     4.25         |                           |
     4.25 ->     4.50         |                           |
     4.50 ->     4.75         |                           |
     4.75 ->     5.00         |                           |
     5.00 ->     5.25         |                           |
     5.25 ->     5.50         |                           |
     5.50 ->     5.75         |                           |
     5.75 ->     6.00         |                           |
     6.00 ->     6.25         |                           |
     6.25 ->infinity          |                           |
```

Table 4. Statistics of earthquake distribution ($m \geq 4$ from 1932 to 1985) relative to the distribution of values of horizontal gradient of S-parameter for Salton Trough region of the southern California study area. See Figure 7 for locations of earthquakes. (Note that earthquakes falling outside the Salton Trough region were not used in the statistics.) See Appendix A for explanation of terms in table.