Appendix A

Implications of the Depth of Seismicity for the Rupture Extent of Future Earthquakes in the San Francisco Bay Area

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Introduction

This appendix addresses some issues related to the depth extent of seismicity in the San Francisco Bay Area and the potential implications for the rupture extent of future major earthquakes. The connection between the depth extent of seismicity and the size of major earthquakes lies in the seismic moment, M_0, for an earthquake, which is defined as $M_)$ = μDA, where μ is the shear modulus, D is the average coseismic displacement across the fault, and A is the area of the ruptured fault surface. The resulting moment magnitude, **M**, is then calculated from the relation **M** = 2/3*log M_0 – 10.7 (Hanks and Kanamori, 1979). The rupture area A is the product of the rupture length, L, and the downdip rupture width, W. Consequently, it is important to place constraints on the value of W in order to accurately estimate the seismic moment release from future major earthquakes.

Because almost all of the historical major earthquakes in the San Francisco Bay region predate the deployment of Northern California Seismic Network (NCSN), there are few direct observations on the depth extent of coseismic rupture. However, the available evidence from the major continental earthquakes in California and elsewhere suggests that the maximum depth extent of “background” seismicity is essentially equal to the maximum coseismic rupture extent of a major earthquake on the same fault segment, provided there is enough seismicity to illuminate the entire seismogenic portion of the fault segment (e.g., Strehlau and Williams, 1998). The first section of this appendix summarizes observations on the depth extent of seismicity in the San Francisco Bay region based on well-recorded seismicity. The third section discusses some of the uncertainties inherent in using various sorts of seismic events (i.e., background microseismicity, aftershocks, mainshocks) to quantify the likely depth extent of rupture.

An additional constraint on the width of the seismogenic zone is found in the thermal state of the crust, as temperature controls both the mode of crustal deformation (brittle versus plastic) and the frictional behavior (seismic versus aseismic) of faults within the brittle field. The second section of this appendix addresses the significance of the seismicity observations in light of what is known about the thermal field in the region, with estimates of temperatures at seismogenic depth derived from near-surface heat flow measurement. The appendix refers to fault segments established by OF96-705 (the Working Group on Northern California Earthquake Potential) and those established by Working Group 02 for the current study.

Observations Based on Seismicity

Bay Area faults show substantial variations in the frequency and distribution of “background” seismicity (Figure 1). The portion of the San Andreas fault passing through the Peninsula and the

North Bay is relatively aseismic and presumably has been locked since the 1906 earthquake. Historical seismicity for the Santa Cruz Mountains segment is dominated by aftershocks of the Loma Prieta earthquake but was somewhat more active than other segments even before 1989. Similarly, the San Gregorio Fault is relatively aseismic along its northern section but active over a fairly broad zone adjoining the Santa Cruz Mountains and entering Monterey Bay. The Hayward, Calaveras, and Rodgers Creek faults are characterized by abundant microseismicity, although there are aseismic segments along each fault. Northeast of these faults the seismicity becomes more diffuse and the individual fault segments more difficult to trace.

The seismicity data presented in the figures and analyzed in this report consist of NCSN events of $M \geq 1.5$ with an rms <0.15 seconds and at least 6 stations recording each event in the years from 1980 to the end of 1998. The analysis summarized in this appendix includes the Maacama fault, which is the northwestward extension of the Rodgers Creek fault, and the NCSN catalogue from the period before 1980 is too uneven in its geographic coverage of the region encompassing the Maacama fault to be used for the study. In order to verify the statistical consistency of the results the same analysis has been repeated with the lower magnitude cut-off varied in the range from 1.2 to 1.8 and adjustments to the $M \geq 1.5$ dataset related to the rms of the event solution, the number of stations recording the event, and the covered time period. The quantitative results did not vary significantly with any of these changes. For a few segments reducing the sample population by increasing the lower magnitude threshold to 1.8 introduced greater uncertainties even though the mean values remained essentially the same.

The basic results are consistent with those found in earlier studies (e.g., Hill et al., 1990; Walter et al., 1998), although the lower cut-off magnitude relative to Walter et al. (1998) and the longer time interval relative to Hill et al. (1990) fill in gaps in some of the fault segments. The average depth extent of seismicity on Bay Area faults is approximately 14 km. On the Loma Prieta (Santa Cruz Mountains) segment of the San Andrea fault, the deep (>14 km) seismicity that characterized both the 1989 mainshock and its aftershocks is absent from the catalogue during the time from 1980 to 1989. Seismicity from the period of 1969 through 1980 does reveal deeper seismicity along the Loma Prieta segment. It is possible that other segments discussed below are similarly undersampled with respect to the maximum depth extent of seismicity.

In all cases the “95% Cut-off” column in the table refers to the 95% cut-off depth (i.e., 95% of the hypocenters are equal to or shallower than that depth). As discussed below, the available evidence suggests that a 95% cut-off provides a reasonable estimate of the likely depth extent of coseismic rupture in a major earthquake, provided there is enough seismicity to reduce statistical uncertainties. In general a 90% cut-off tends to underestimate the depth extent of rupture, and a 98% or 99% cut-off tends to overestimate the depth extent of rupture and to suffer from greater scatter due to anomalously deep events unrelated to the overall depth extent of coseismic moment release in major earthquakes.

The results are best summarized with a segment-by-segment comparison of the 95% cut-off depths with the segment widths reported in OF96-705 and selected for WG02. The segment boundaries used for determining the 95% cut-off are those updated for the WG02 study. Fault segments are abbreviated as follows: SAO, San Andreas fault offshore; SAN, San Andreas fault north; SAP, San Andreas fault peninsula; SAS, San Andreas fault south; SGN, San Gregorio fault north; SGS, San Gregorio fault south; HN, Hayward fault north; HS, Hayward fault south; RC, Rodgers Creek fault; MF, Maacama fault; CN, Calaveras fault north; CC, Calaveras fault central; CS, Calaveras fault south; CON, Concord fault; GVN, Green Valley fault north; GVS, Green Valley fault south; GN, Greenville fault north: GS, Greenville fault south.

Segment	**OF96-705**	**95% Cutoff**	**WG02**
SAN[1]	13 km	Too few eqs	11±2
SAO[1]	13 km	Too few eqs	11±2
SAP[1]	14	14	13±2
SAS[2]	18	18	15±2
SGN[3]	15	Too few eqs	13±2
SGS[4]	12	16	12±2
RC[5]	10	10	12±2
HN	12	13	12±2
HS	12	13	12±2
MF Central	12	8	N/A
MF South	12	<8	N/A
CN	13	15	13±2
CC	10	10	11±2
CS	10	10	11±2
CON	12	16	16±2
GVN	12	16	14±2
GVS	12	14	14±2
GN	11	21[6]	15±3
GS	11	15	15±3

Notes:

1. The change in width from OF96-705 to WG02 for these two segments is due to a slightly more conservative estimate of the maximum depth of seismicity from earthquakes larger than magnitude 1.5.
2. The OF96-705 and the 95% cut-off values reflect the abundant deep seismicity associated with the Loma Prieta earthquake. These events form a local maximum in depth for the entire segment, so the WG02 value of 15 reflects an average width for the segment. In addition, standard catalogue depths are probably affected by lateral velocity contrasts (see Section on Uncertainties).
3. Research by Stephanie Ross (Ross et al., 1998) suggests that the OF96-705 width is too large. This is supported by heat flow measurements along the San Mateo County and Santa Cruz County coast, which would be consistent with widths less than 14 km.
4. Seismicity along the southern SGF is relatively sparse, leaving some question as to the statistical significance of the 95% cut-off. In addition, location of events along the SGF in this vicinity is probably affected by the same effects biasing hypocenters for the Loma Prieta earthquake (see Section on Uncertainties).
5. The WG02 width for the RCF has been deepened by 2 km in order to allow for the possibility that the relatively sparse seismicity on the RCF undersamples the true segment width. However, the limited heat flow constraints suggest the 10 km figure may be correct (see below).
6. There is a substantial deepening of seismicity along the northern portion of the Greenville Fault trend (see Figures 2-4). The WG02 value reflects an average.

These variations among fault segments are easily seen in the accompanying plots (Figures 1 through 6) which show selected SW-NE cross-sections of seismicity through the San Francisco Bay Area. In the tabulated results there are five segments/areas for which the 95% cut-off depth differs significantly from the 1996 report. These are the central and southern Maacama fault (which includes the Healdsburg fault), the Concord and Green Valley faults, and the northern portion of the Greenville fault trend. Seismicity is shallower by about 4 km on the Maacama than the rupture depth postulated by the 1996 report and deeper by 3 to 10 km on the East Bay segments. Although the resulting change in moment is large (25 to 100%), the effect on moment magnitude (using the Wells and Coppersmith [1994] magnitude-area formulas) is generally less than 0.3. The primary effect on regional forecasts would be to reduce the hazard in the North Bay and increase the hazard in the East Bay beyond the Calaveras fault. The shallower depths along the Hayward-Rodgers Creek-Maacama fault trend is best seen in Figure 7, which shows a steady shallowing in seismicity from the nothern Hayward up to The Geysers steam field. (Note – The northwestern edge of Box A starts at 160 km on this section.)

Observations Based on Heat Flow

Temperature is an important factor in determining whether a fault zone slips seismically or aseismically. Sibson (1982) was the first to highlight the general inverse correlation between heat flow in the maximum depth of seismicity along the San Andreas fault. Recent efforts to quantify this relationship indicate that the base of seismicity corresponds with a temperature of 350 to 400 ^{o}C in the California Coast Ranges (Williams, 1995) but may vary over a wider temperature range in southern California (Williams, 1996; Strehlau and Williams, 1998). This section extends these earlier studies to a detailed segment-by-segment comparison of subsurface temperatures estimated from shallow heat-flow measurements with the observed base of seismicity.

Figure 8 shows the locations of heat flow measurements in the San Francisco Bay Area along with contours that are both consistent with the data and thought to be representative of the conductive thermal regime at mid-crustal depths. The figure also includes events from Figure 1 with depths greater than 15 km. These data highlight the general correlation of deeper events with lower heat flow. Although data are sparse in the North Bay along the Rodgers Creek fault, the broad heat flow anomaly associated with The Geysers geothermal field and the Clear Lake volcanics coincides with the shallow seismic-aseismic transition on the central and southern Maacama fault segments. The deep seismicity in the Suisun Bay/Mt. Diablo region (COF, GVF, GF) is related to low heat flow mostly on the basis of contouring rather than on local measurments. New heat flow data have been collected from this area, and the preliminary results are consistent with the existing contours. Figure 9 summarizes the quantitative results for selected areas with estimated temperatures at the depths recorded in the first table. Overall the results are consistent with a seismic-aseismic transition in the temperature range of 350 to 400 ^{o}C. This agrees with results from elsewhere in the Coast Ranges and in portions of southern California (Strehlau and Williams, 1998). The bottom line is that the heat flow data would predict a shallow seismic-aseismic transition along the Rodgers Creek/Maacama fault trend as it nears The Geysers, a deep seismic-aseismic transition in the Santa Cruz Mts and a deep seismic-aseismic transition to the east of the Calaveras fault and continuing on into the Great Valley. The observed pattern of seismicity is consistent with these predictions, both qualitatively and quantitatively.

Uncertainties

Uncertainties enter into this analysis on a number of levels. First, what is the absolute accuracy of the hypocentral depths reported in the catalogue? The question of absolute accuracy is difficult, if not impossible, to resolve, but it seems clear that even with the best quality locations ±1 km is the minimum uncertainty. In the Loma Prieta area, where lateral velocity discontinuities and the location of the fault at the western edge of the network combine to reduce the absolute accuracy, Dietz and Ellsworth (1993) report six different hypocentral depth estimates for the 1989 earthquake. These vary from 15.6 to 17.85 km for a range of 2.25 km, although many of the techniques applied for locating the mainshock are not applicable to locating the background microseismicity (and vice versa), and relative differences might mask some absolute error inherent in all techniques. However, the various models that relocated aftershocks also yield a similar range of differences in result, suggesting that the high quality catalogue depth determinations for the San Francisco Bay Area are within ±2 km of the true depth.

With the exception of the Loma Prieta area (which is already accounted for in the widths chosen for the SAF), it is most likely that any significant error in the hypocentral depths would be consistent throughout the region (i.e., either too depth or too shallow). For this reason the uncertainties in width for the WG02 report are applied to all segments simultaneously. A recent analysis of earthquake depths in the San Francisco Bay region by Hole et al. (2000) suggests that the shallower hypocenters for the Loma Prieta earthquake are more consistent with the true nucleation depth and confirms the overall accuracy of the hypocentral depths reported by the NCSN elsewhere in the region.

Second, given reasonable accuracy in the hypocentral depths of individual events, how many events are necessary to illuminate the entire depth extent of the seismogenic layer? This is not the question of how microseismicity relates to mainshock rupture extent (see below) but simply how many earthquakes it takes to obtain a statistically robust estimate. With the use of 95% as the cut-off value there typically have to be at least 100 earthquakes (and often many more) in a fault segment to get a stable value. In this case “stable” means an estimate that varies by less than two hundred meters when the population is increased or decreased by 10% (either by changing the length of fault segment studied or by adjusting the time frame of the catalogue search). The “too few eqs” entries in Table1 identify segments for which this stability criterion could not be met over the segment length defined by WG02. As a practical matter this dependence on a minimum number of earthquakes places a lower limit on the length of a fault segment for which the maximum depth can be determined. For the post-1980 seismicity this length is on the order of 20 km for the average active segment of Bay Area faults. In some areas it is possible to reduce this to 10 km, but there are others where there is not enough seismicity to determine a result at the 20 km scale. As a rule of thumb, looking at segments much longer than 20 km tends to average out some apparently real spatial variations in the depth of seismicity, while looking at segments much shorter than 20 km yields spatial variations reflecting inadequate sampling of the seismic record rather than real changes.

Third, how do these results vary by type of event (e.g., background seismicity, aftershocks, mainshocks)? This appendix incorporates all of the “small” events, including aftershocks. There is a reasonable chance that aftershocks, as events located for the most part “outside” of the ruptured fault patch, will extend to depths much greater than the seismogenic crust as defined by the mainshock hypocenter or the depth extent of the seismic source as defined by coseismic rupture. For the two recent significant earthquakes in the Bay Area (Morgan Hill and Loma Prieta), the 95% cut-off is less than 2 km deeper than the mainshock hypocenter (Schaff et al., 2002). This observation is confirmed by most other recent events in California, including Northridge, San Fernando, Whittier Narrows, Coalinga, and Joshua Tree (Williams, 1996; Strehlau and Williams, 1998). One prominent exception to this is the Landers earthquake, which had a very shallow hypocenter (the deepest of all the various relocations places it around 7 km), but this appears to be the exception rather than the rule (Williams, 1996). Most waveform inversions for coseismic slip do not provide independent estimates of the depth extent of rupture because the vertical extent of the model space is typically preset to the depth of the mainshock or the deepest aftershocks. Finding an adequate fit to the waveform data could constitute a test or simply the discovery of a local minimum.

Fourth, what uncertainty should be attached to the numbers tabulated above? The consensus view is that ±2 km is a generally a reasonable value as it covers all of the uncertainties in absolute depth for the earthquakes themselves and allows for some offset between a future mainshock rupture and the background seismicity. The uncertainty for the Greenville fault has been set to ±3 km in order to reflect the unusual variability in the depth of seismicity along the segment.

References

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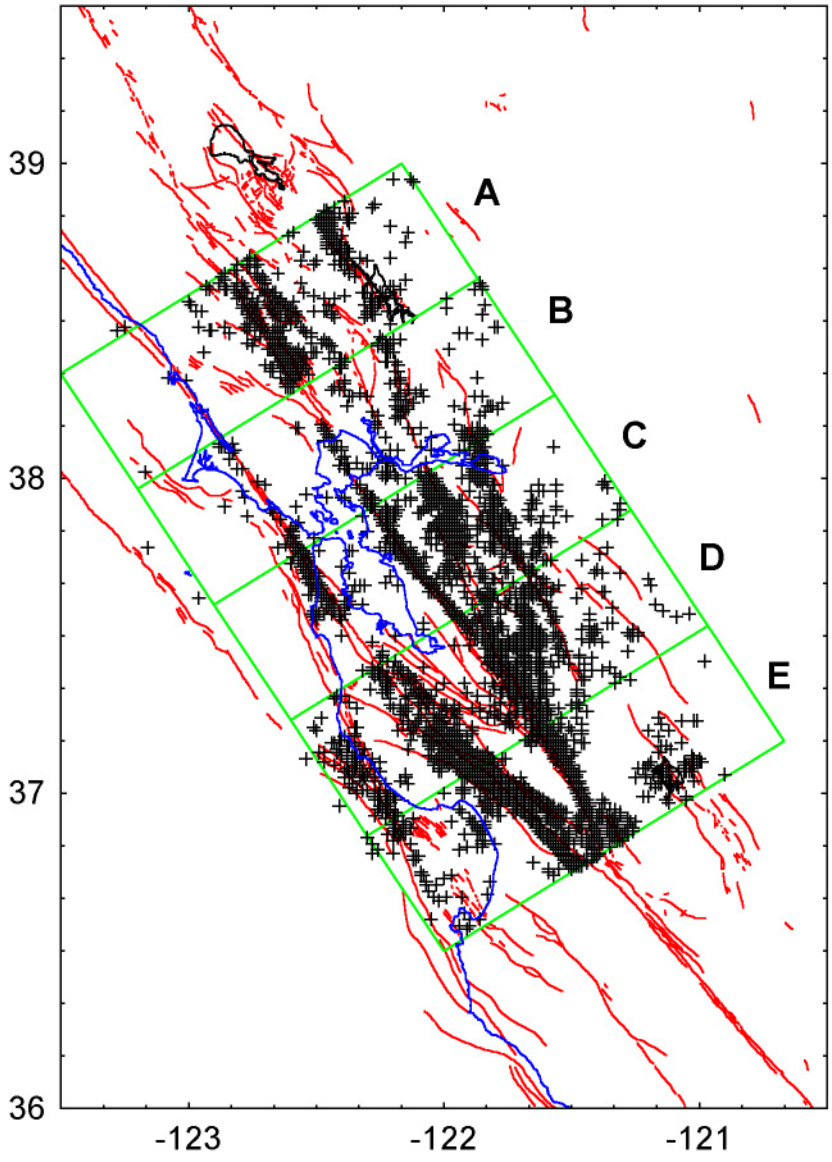

Figure 1. NCSN events of M •1.5 with an rms <0.15 seconds and at least 6 stations recording each event in the years from 1980 to the end of 1998. Lettered boxes define subregions depicted in following figures.

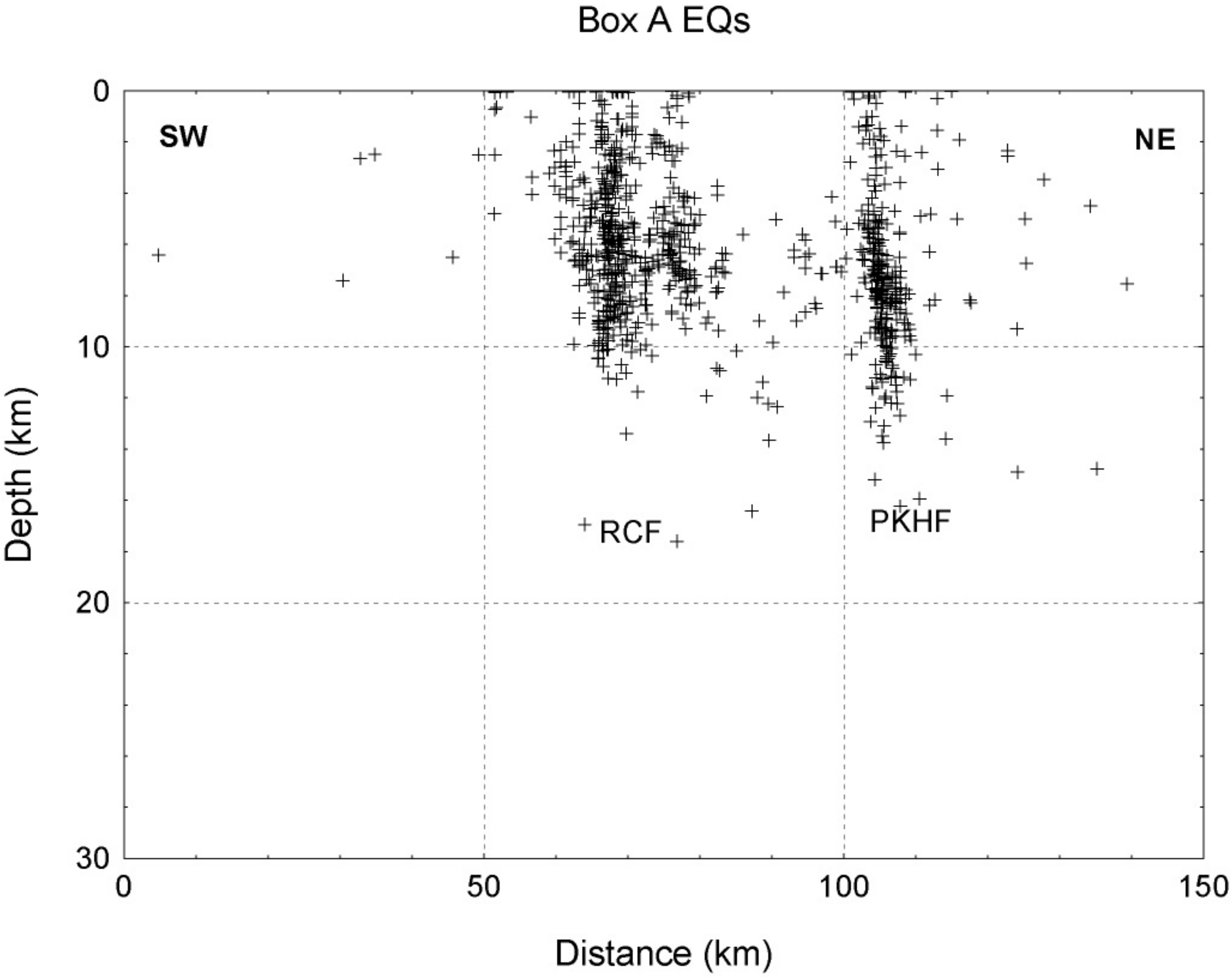

Figure 2. Cross-section of seismicity from Box A of Figure 1.

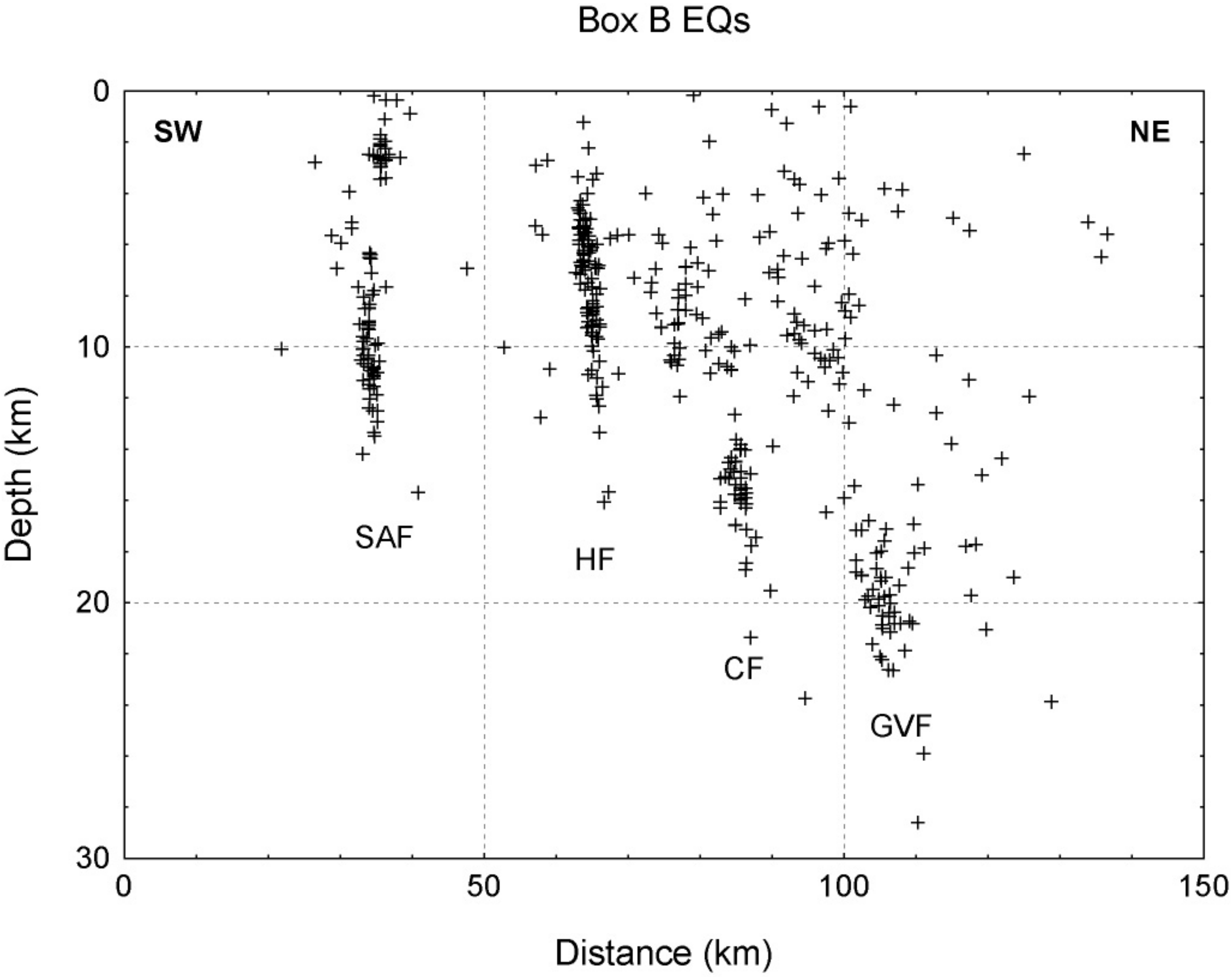

Figure 3. Cross-section of seismicity from Box B of Figure 1.

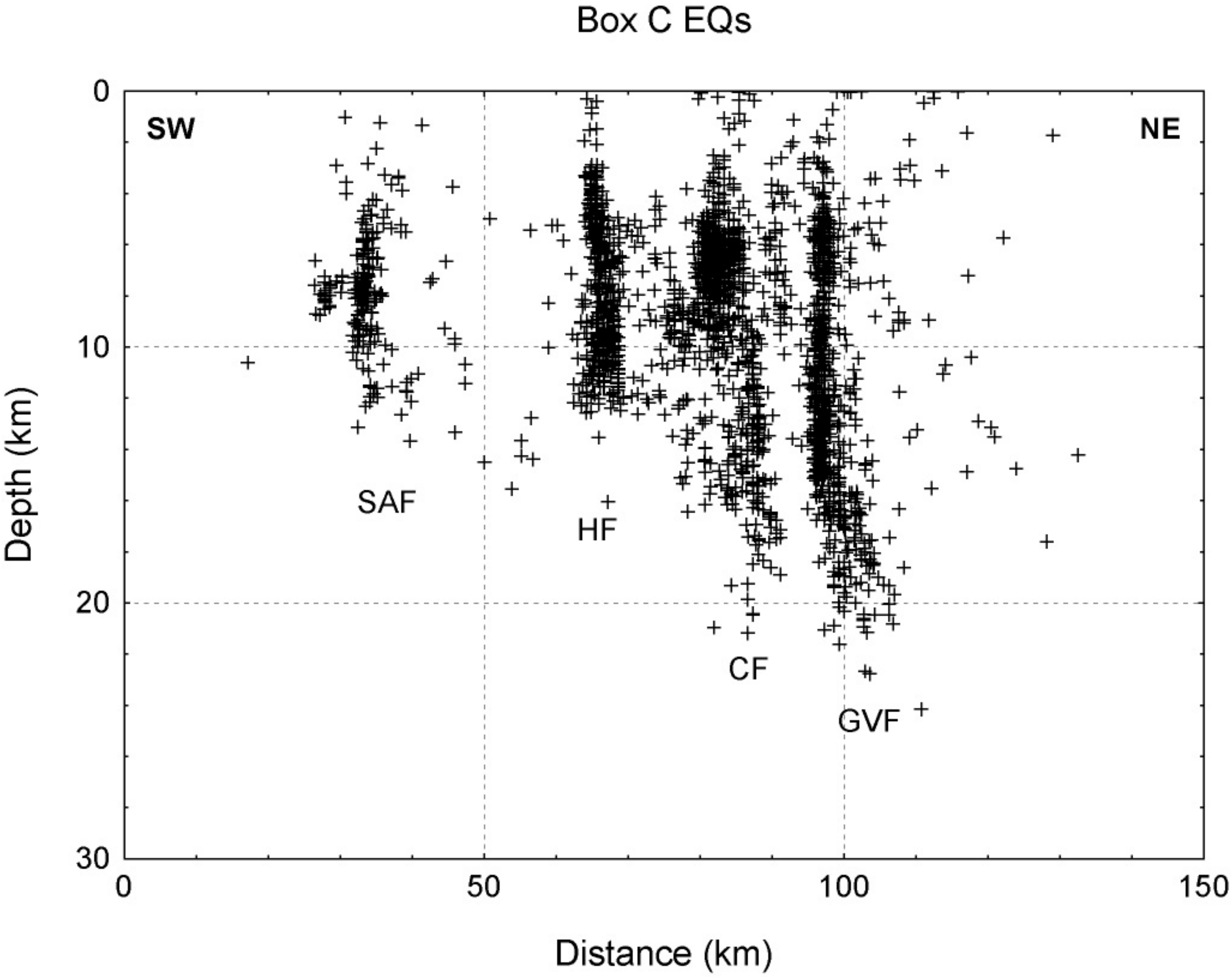

Figure 4. Cross-section of seismicity from Box C of Figure 1.

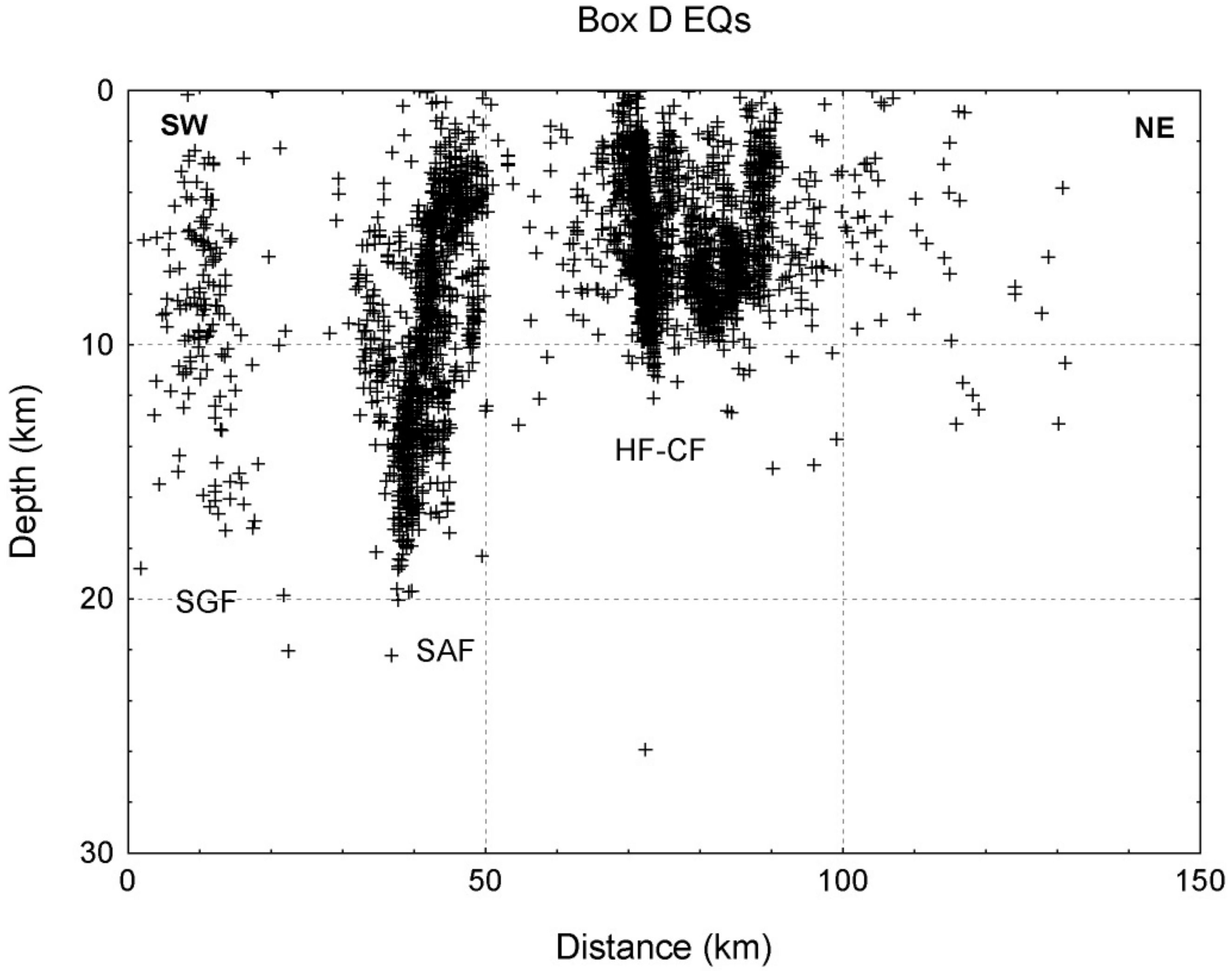

Figure 5. Cross-section of seismicity from Box D of Figure 1.

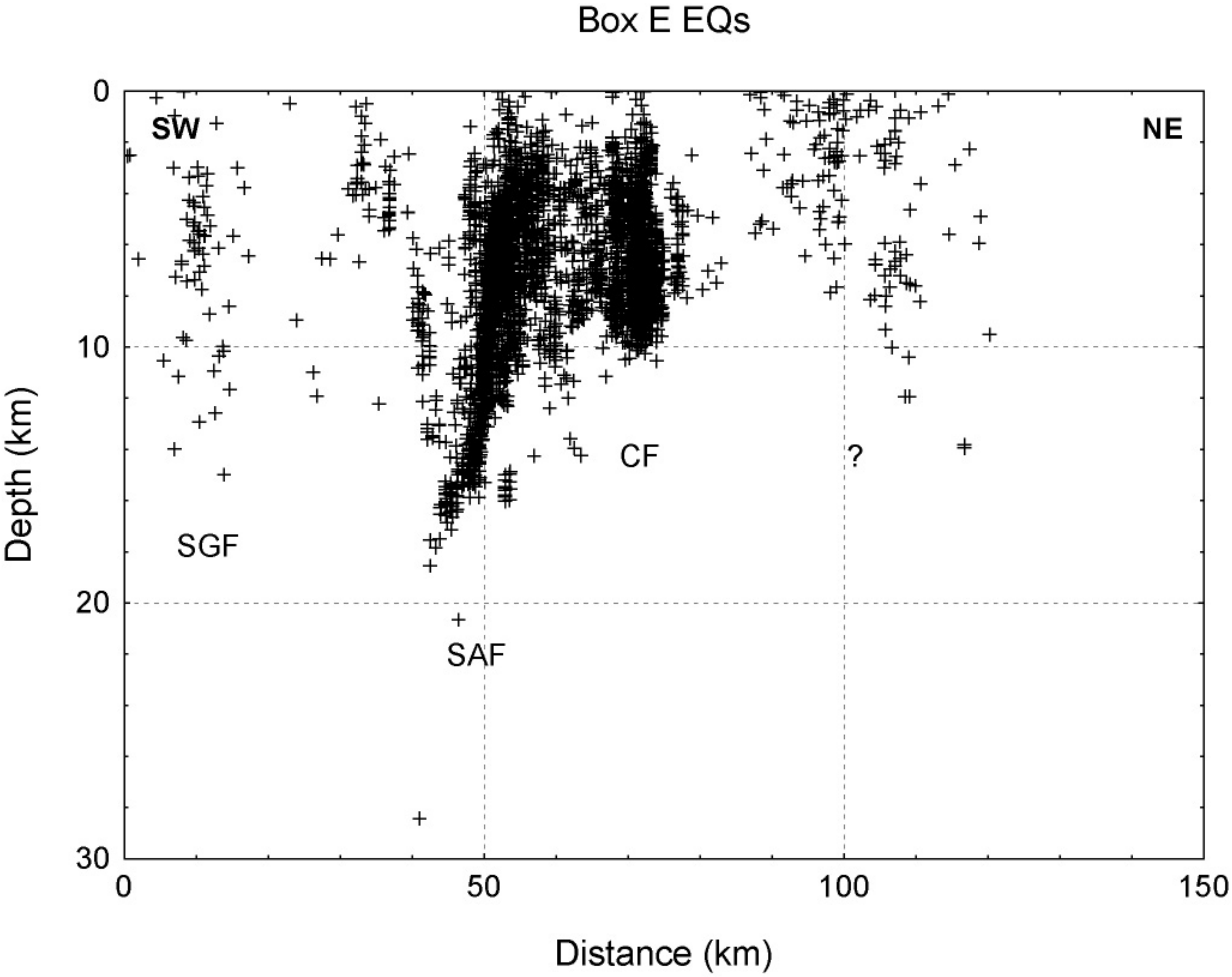

Figure 6. Cross-section of seismicity from Box E of Figure 1.

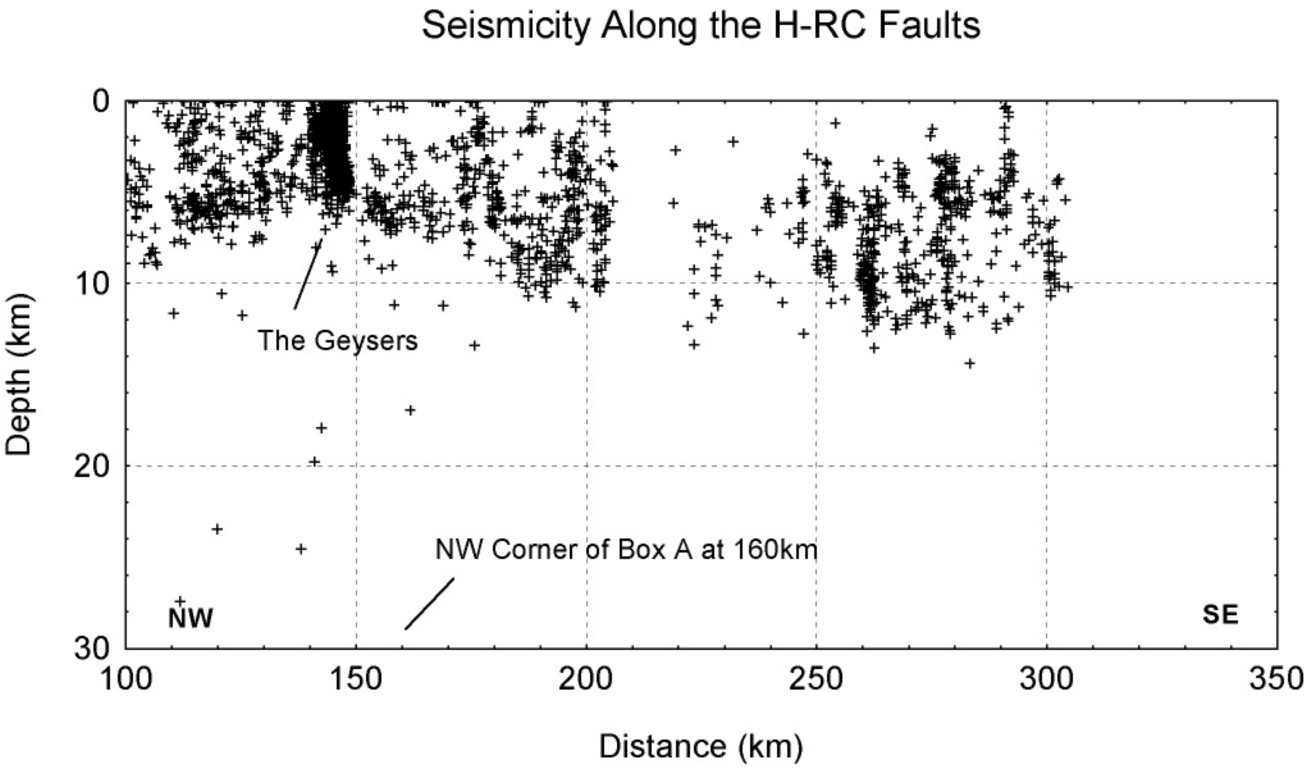

Figure 7. Seismicity cross-section along the Hayward-Rodgers Creek-Maacama fault trend.

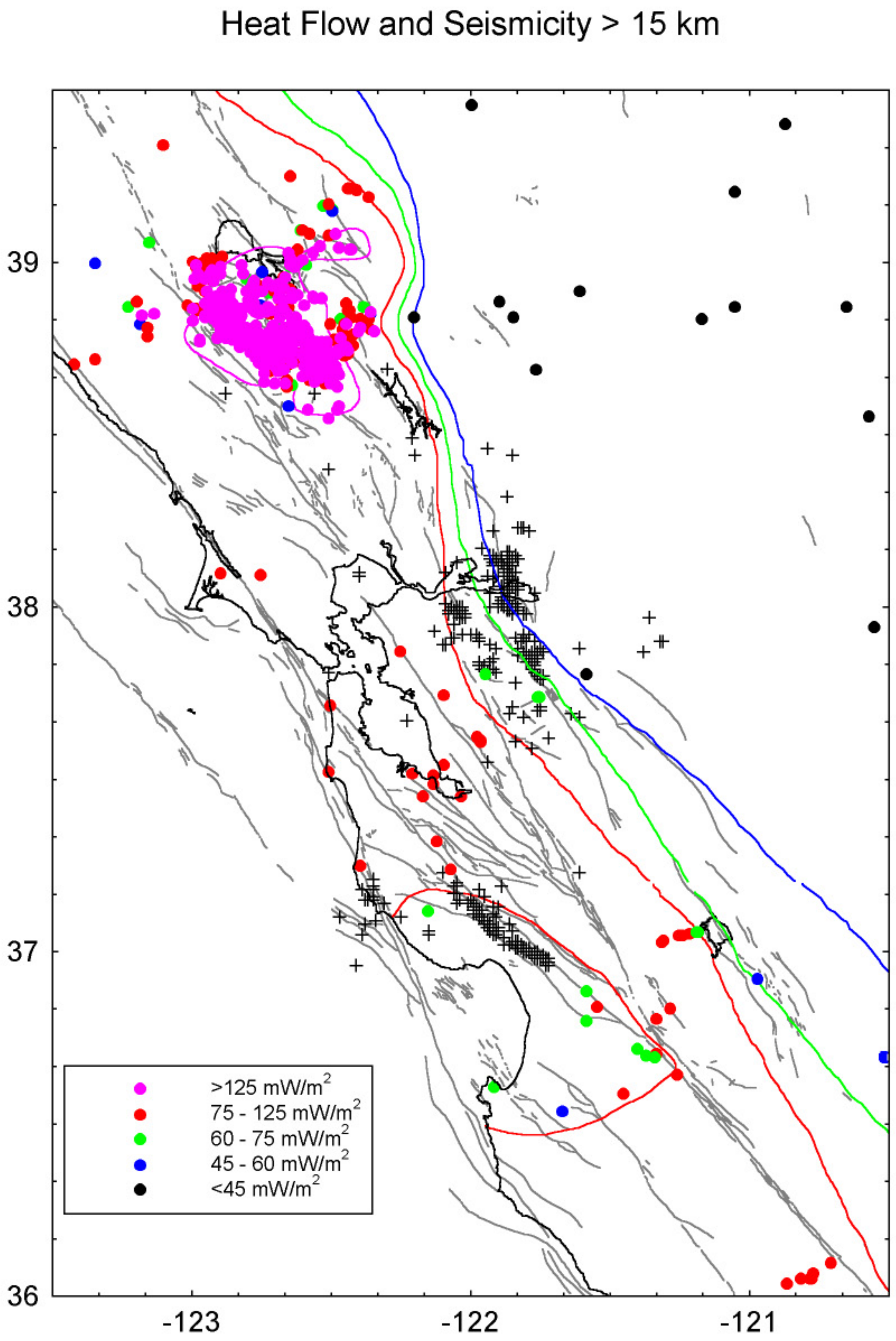

Figure 8. Locations of heat flow measurements in the San Francisco Bay Region. Colored contour lines provide an adequate grouping of the data and a depiction of the thermal regime at seismogenic depths. Black + symbols are epicenters of earthquakes from Figure 1 with depths greater than 15 km.

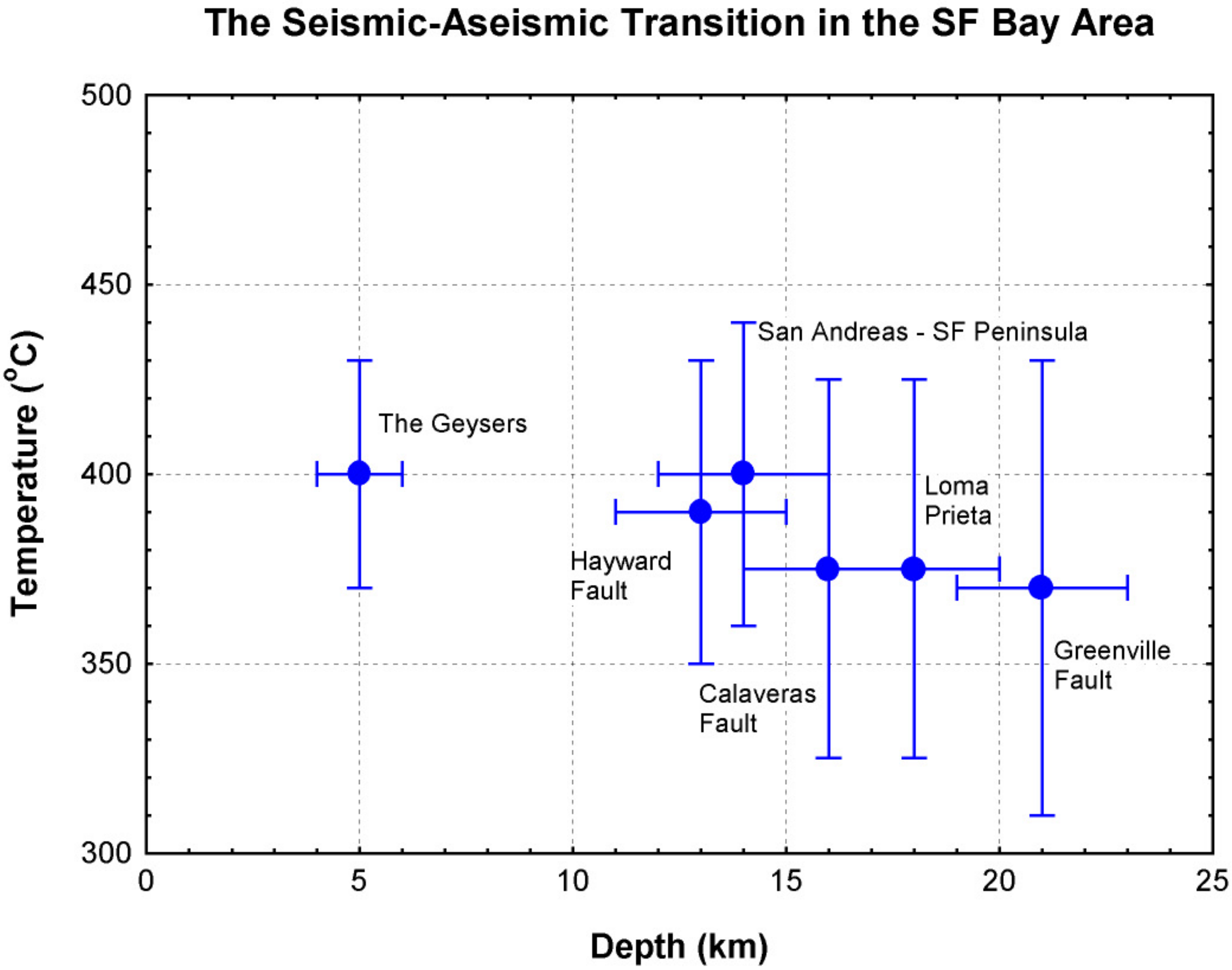

Figure 9. Estimated temperatures at the depths recorded in the table on page 3.