Development of a Probabilistic Seismic Hazard Analysis for Offshore Facilities in the Santa Barbara Channel

by

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ABSTRACT

This paper summarizes initial efforts to develop a probabilistic seismic hazards analysis (PSHA) for the Santa Barbara Channel conducted by the Lawrence Livermore National Laboratory (LLNL) for the Minerals Management Service (MMS) of the U.S. Department of the Interior. The purpose of the PSHA is to provide a basis for development by MMS of regulations governing evaluation of applications to re-license existing oil platforms in Federal waters within the Channel with respect to seismic loading. The final product of the analysis will be hazard assessments of ground motion parameters at specified probability levels of excedence. This paper summarizes the characterization of local earthquake sources within the Channel and onshore areas of the Western Transverse Ranges, development of a ground motion attenuation model for the region, and presents preliminary hazard results at three selected offshore sites.

KEYWORDS: earthquake ground motions, earthquake source models, offshore platforms, probabilistic seismic hazard analysis, seismological uncertainties.

1. INTRODUCTION

The Minerals Management Service (MMS) of the U.S. Department of the Interior has considered several methodologies with which to re-evaluate the structural design and performance of existing oil-drilling platforms in the Santa Barbara Channel, offshore California. To provide the basis for the seismic loading aspects of these procedures, Lawrence Livermore National (LLNL), in collaboration with the Institute for Crustal Studies (ICS) at the University of California, Santa Barbara was requested to develop procedures to conduct a probabilistic seismic hazards analysis (PSHA) of the Channel.

The Santa Barbara Channel is located within the most seismically active region of the U.S. and can expect to experience moderate to large, and perhaps even great, earthquakes within the lifetimes of some of the existing platforms. Detailed seismic hazard analyses are being conducted onshore based upon an extensive and detailed characterization of earthquake sources by the Southern California Earthquake Center (SCEC). Current efforts are concentrated on the Los Angeles Basin, but the California Division of Mines and Geology (DMG) intends to expand the analyses to include the entire onshore area. An important goal of the MMS is to ensure that the seismic hazard analyses for the Santa Barbara Channel is fully integrated with the onshore analyses by adopting and refining the common SCEC data base and utilizing compatible ground motion attenuation and hazard analysis methodologies.

Phase I of the study concentrated on the eastern half of the Santa Barbara Channel where most of the existing platforms are located. Three levels of detail were used to describe potentially significant earthquake sources: (1) regional-scale faults within 300 km that can generate significant ground motions, including long-period (2 to 5 sec) ground motions, in the study area; (2) a general description of all potentially active faults between 10 and 50 km from the study area and detailed

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characterization of those capable of generating significant ground motions; (3) detailed characterization of all potentially active structures within 10 km of any platform. Characterizations of regional sources were taken from the SCEC data base and along with other data were used for the Phase II hazard analysis. For specific sites, however, a considerable number of fault sources in categories (2) and (3) above that are not presently characterized in the SCEC data base were considered. In particular, these include offshore faults within the Santa Barbara Channel.

This paper discusses some of the technical issues that may contribute to potential sources of significant uncertainty in the PSHA. These include issues concerning identification and characterization of earthquake sources, as well as issues relative to estimating ground motion offshore. Some of these issues are similar to those addressed in recent onshore studies conducted by the SCEC and DMG, but a number are particularly relevant to the study area and its offshore location. These issues are briefly summarized below.

2. EARTHQUAKE SOURCE CHARACTERIZATION

Major issues concerning identification and characterization of earthquake sources in the vicinity of the Santa Barbara Channel stem from the present poor understanding of the nature of large-scale tectonic deformation within the Western Transverse Ranges tectonic province of which the Channel occupies the southern half. Recent earthquakes, such as the 1994 Northridge event, show that some deformation takes place as moderate to large earthquakes on blind faults. These sources are particularly problematic in that, at present, they cannot be identified or evaluated in advance. Differing interpretations of the fundamental deformation style lead to significantly different characterizations of the blind faults in terms of the characteristic magnitudes they are capable of producing, their geometries relative to surface installations, and estimates of the rates of occurrence of earthquakes generated on them. A blind, shallow-dipping thrust fault, such as the Channel Islands thrust, has been hypothesized to underlie the entire area of the eastern Santa Barbara Channel at mid-crustal depth and has been estimated to be capable of generating earthquakes as large as magnitude 7.4. Several potentially long and active faults have been tentatively identified on the sea floor of the Santa Barbara Channel using seismic and oil well data. Some of these appear to be offshore continuations of major faults known to be active onshore. However, there are conflicting interprétations of certain prominent offshore features, especially features that are in the immediate vicinity of the platforms, which have significantly different implications for offshore seismic hazard analysis.

The SCEC methodology calculates earthquake recurrence intervals by integrating seismic moment rates estimated from geological data for specific faults, geodetic measurements of regional strain rates, and regional seismicity data. Each of these types of data is subject to potentially large uncertainties arising from limited temporal or spatial sampling of past events or long-term deformation and from the accuracy of the measurements. Estimating slip rates for the offshore faults is particularly problematic since, except where these cross the Channel Islands, detailed seismic data are not available. Segmenting long faults into individual rupture segments in an objective way remains a difficult problem even where major faults are mapped in detail. The problems of fault segmentation and slip rate estimation are particularly acute for blind faults and rely on indirect interpretation or modeling of surface observations.

3. STRONG GROUND MOTION

The lack of offshore strong ground motion recordings precludes determination of attenuation relations for offshore areas and investigation of site effects. The few existing offshore recordings for the Santa Barbara Channel are presently being studied, but results to date are not conclusive.[2]

Natural periods of offshore platforms are different from those of typical onshore structures. Steel template-type platforms commonly have natural periods in the range of 1 to 5 seconds. For comparison, residential and commercial structures have natural periods less than 2 seconds. Also, the first vertical modal period of platforms is often in the range of 0.3 to 0.5 seconds. Vertical motion can be important because of cantilevered structures on decks.

The roles of water-saturated sediments and the water itself are not well documented. Unusual characteristics and the generation of different phases and relationships are expected to occur and should be accounted for if onshore attenuation relations are used. There are indications that offshore vertical motions are significantly attenuated relative to similar onshore vertical records. The MMS initiated the Seafloor Earthquake Measurement System (SEMS) some 10 years ago to collect and analyze seismic data measured on the seafloor.

The geometry of the faults in the Santa Barbara Channel and their spatial relationships to the platforms present challenging questions in estimating ground motions. First, platforms may be on the hanging wall of the faults and, therefore, may be subject to large accelerations. Second, platforms may be located near the up-dip extensions of steeply- or moderately-dipping reverse fault planes. This type of geometry maximizes the directivity effect and, therefore, enhances the amplitude of the ground motion, particularly at longer periods. Also, because reverse or thrust faults predominate in the area, the vertical component could be as large as the horizontal.

4. SUMMARY OF PHASE I WORK

In order to properly achieve the intended regulatory basis, the PSHA must account for the uncertainties in characterizing earthquake sources and in ground motion attenuation in the Southern California region and propagate those uncertainties through the analysis to provide estimates of the uncertainty in the hazard in the form of mean estimates and other statistical parameters.[3] These uncertainties include both random uncertainties and uncertainties that arise from our inability, through lack of knowledge, to model the Earth or describe its behavior. Therefore, the primary objective of Phase 1 of the project was to define and evaluate issues that introduce significant uncertainties into seismic hazard estimation in Southern California in general and to assess in detail the impact of these issues on seismic hazards in the Channel.

As is generally the case in PSHA, the evaluation focused largely on sources of uncertainty. Due to our lack of knowledge, the major issues affecting earthquake source characterization in this region stem from the fundamentally different models of tectonic deformation, "thin-skinned" or "thick-skinned," that have been proposed based upon alternative interpretations of the available data. These issues are currently the focus of intense debate. The main issues affecting ground motion attenuation under the Channel are the absence of a strong motion data base for offshore environments, the effects of sedimentary basins and wedges, and the effects of the water column and saturated soils. Based upon the preliminary characterization of earthquake sources, two preliminary alternative earthquake source maps for the Western Transverse Ranges were developed, which incorporated the geometries and slip rate estimates of the potentially significant faults that form part of each of the proposed alternative tectonic models.

Phase I culminated in a workshop at Stanford University on August 16-17, 1995, in which scientists currently working on key aspects of the tectonics of the Western Transverse Ranges and on ground motion estimation offshore participated. The workshop served as a forum both for dissemination of current data and interpretations and to elicit expert opinion in finalizing earthquake source and ground motion models. Specific objectives were: (1) to ensure that all available data and current tectonic interpretations in forming the major issues were considered and in identifying significant earthquake sources, (2) to make a comparative evaluation of the evidence supporting the competing tectonic models and specific sources as a basis for weighting the alternatives, (3) using preliminary source maps as "straw men" to develop the basis for a set of maps that fully captures the alternative tectonic hypotheses and accurately represents significant potential sources, and (4) to refine a preliminary ground motion attenuation model and ensure that it is the most suitable form for use offshore. These objectives were successfully achieved during the workshop.

5. SUMMARY OF PHASE II WORK

The results of the workshop, together with comments on the Phase I report received from several reviewers, indicated that the major tectonic interpretations and their variations can be represented by two basic, or "core," earthquake source models corresponding to the thick- (Model 1) and thin-skinned (Model 2) interpretations. Within each of these a considerable number of alternative fault geometries are permitted by the data and need to be included to capture adequately the epistemic uncertainty in source characterization.

Having identified the sources comprising each of the core models, detailed characterization of the models involved: (1) defining the alternative geometries. These alternatives can include ranges of fault dips, possible fault segmentation schemes, and multi-segment rupture scenarios. One source of complexity is the inter-dependence of the down-dip geometries of several of the non-vertical faults, such that alternative geometries for one fault also require alternatives for neighboring faults. Combinations of all the possible fault geometries lead to a large number of alternative source maps for both Models 1 and 2, (2) estimating probability distributions for fault slip rates from the available data, (3) estimating probability distributions for characteristic moment magnitudes (M_W) for each of the fault segments and segment combinations based upon their fault areas. For this, the areas-moment magnitude (M_W) relationship of Wells and Coppersmith[4] were used, and (4) the slip rates and maximum magnitudes were combined to estimate earthquake recurrence rate distributions for a range of magnitudes for each source employing the characteristic earthquake recurrence model of Youngs and Coppersmith[5]. The regional Gutenberg-Richter "b" value of 0.75 ± 0.5 used to construct the recurrence relationships was estimated from the Caltech Western Transverse Ranges earthquake data.

6. SOURCE MODEL 1

Figure 1 is a map of the faults comprising Model 1. Depth sections through the model are shown in Figure 2. Model 1 is based upon the "thick-skinned" tectonic hypothesis proposed primarily by Yeats[6] and Huftile and Yeats[7]. According to this hypothesis, which is based largely upon surface or near-surface observations of fault slip and upon geodetic data, active faults extend into the middle and lower crust at relatively steep dips observed at shallow crustal depths. The model largely comprises surface faults but also includes three blind reverse faults (Figure 1)--a blind extension of the Oak Ridge fault under the Santa Barbara Channel, a major blind thrust fault under the Ojai Valley and Topatopa Mountains and the Northridge fault--the source of the 1994 Northridge earthquake. The Oak Ridge and Ojai blind thrusts have not been observed directly but are inferred from modeling of surface faulting and folding data. For this model, the blind Oak Ridge thrust in particular makes a large contribution to the hazard in the Channel. The Model 1 faults are described in the Phase I report.[1] Fault parameters are given in Table 1 in which data references are identified.

Each possible combination of the alternative characterizations (geometry, including segmentation, and slip rate) of the individual sources forms one source map from which the hazard can be estimated. Alternative characterizations are represented by branches of an event tree, and a source map is compiled by working along a limb formed by connected branches. A subjective weight was assigned to each branch that expresses degree of confidence both in the existence of that source and that this particular alternative characterization represents the process that generates earthquakes on the source. The weights are based upon assessment of all of the data supporting each interpretation. Weights assigned to multi-segment faults ("cascades") are based upon the subjective estimate of the likelihood that the fault will rupture in that combination of segments relative to other possible combinations and also express qualitatively the estimates of relative frequencies of occurrence of the different segment combinations. The final weight for each map is obtained as the product of the weights of the individual branches that comprise the corresponding limb of the tree. The maps were ranked according to their weights relative to the highest weighted, best estimate, map.

7. SOURCE MODEL 2

Model 2 is shown in Figure 3, with the cross section shown in Figure 4, and is based chiefly upon "thin-skinned" tectonic interpretations by Shaw and Suppe *et al.*[8] Many of the important sources in this model are major blind thrust ramps on regional-scale detachments that are inferred by balanced cross-section modeling. Therefore, the geometries, particularly depths and slip rates of these thrusts, are model-dependent and highly non-unique. This and the possible alternative interpretations of the relationships of surface faults to the detachments (Figure 4) mean that the epistemic uncertainties inherent in this model are large compared with Model 1. The slip rates for Model 2, given in Table 2, are preliminary only.

8. GROUND MOTION ATTENUATION MODEL

Given the state of knowledge about ground motions, the approach to deriving ground motion information for this project was to use Western US ground motion descriptions developed by several experts.

The assumptions underlying this project are:

The ground motion parameter; e.g., peak ground acceleration (PGA), is a lognormal stochastic variable (median = a50, variability = σln*).*

The median of the ground motion parameter is a function of earthquake magnitude and distance and other source parameters included in ground motion models.

The variability of the ground motion is quantified by the standard deviation of the natural logarithm of the ground motion parameter.

Given these assumptions, the data, data analyses, and the methodologies used to develop the ground motion models were reviewed to assess their adequacy for estimating median ground motion and variability as a function of magnitude and distance.

9. MODEL 1 HAZARD CALCULATIONS

The hazard curves for PGA shown in Figures 5-7 were calculated using the method described in Reference 9 and the Model 1 source characterization. The calculations were performed for three sites: Platforms Houchin, Dos Quadras A, and Pescado A-1, shown in Figures 1 and 3. Five hundred Monte Carlo simulations were performed for each site, one of the Model 1 source maps being selected for each simulation. Rather than sampling the entire source maps, only the 100 highest weighted maps were used to represent the overall map distribution. This procedure was felt justified by the fact that the relative weights of the ranked maps drop rapidly once low weighted alternatives (branches) begin to be included. Therefore, the hazard estimates stabilize at the values that result from a relatively small subset containing the highest weighted maps.

Each simulation sampled one value of the earthquake rate distribution at each magnitude in the range $m \le m \le m_u$ and one value of the distribution of m_u to construct the magnitude frequency distribution for each source in the map. The earthquake-site distance distributions were constructed as described in Reference 10. Each simulation sampled one value of the ground motion distribution for each magnitude and distance for each source.

Figures 5-7 show that the mean PGA hazard curves obtained using Model 1 alone are comparable with the results of previous analyses, which fall within the uncertainty bounds of the hazard curves. This is largely because the source models used for those analyses include many of the same local (Western Transverse Ranges) faults as Model 1, although the geometries and rate parameterizations of these faults differ from Model 1 to varying degrees; and significant sources, such as the Oak Ridge blind thrust, are absent from the previous models. It is anticipated that including source Model 2 in the PSHA will widen the uncertainty bounds shown in Figures 5-7. This is first because Models 1 and 2 are based upon fundamentally different tectonic hypotheses, so that including Model 2 in itself introduces significant uncertainty into the source characterization. Second, many of the Model 2 sources that have the potential for making the greatest contribution to the hazard in the Channel are blind thrust faults, which, as discussed earlier, have associated uncertainties that are significantly greater than those associated with most of the Model 1 sources. However, the large epistemic uncertainties associated with Model 2 also mean that this model receives an overall lower weight relative to Model 1, which should significantly mitigate the effect that the Model 2 uncertainties have on the hazard uncertainty. Incorporation of Model 2 into the analyses has not been complete to date due to lack of funding.[1]

10. CONCLUSION

Probabilistic seismic hazard methodologies have been in use for the past 30 years. Such analyses are based on three basic inputs. First, the seismic sources in the study region are identified, and earthquake rates are defined for each fault. Ground motion attenuation relations, which are generally expressed as ground accelerations vs. velocities as a function of magnitude and distance, are then used to model the seismic energy propagation from the source to give the ground motions at the site. An uncertainty analysis is then carried out to incorporate the range of interpretation for each parameter involved in the determination of earthquake recurrences, maximum magnitude, and ground motion attenuation.

The study has demonstrated that these same procedures employed to develop PSHA's for onshore sites can be used for offshore sites. The development of PSHA's can be of great benefit in assessing the structural integrity of offshore facilities with respect to future earthquakes. However, the great uncertainties associated with source models and the lack of historical seafloor seismic data will always lead to discussion on the relative reliability of the data produced.

11. REFERENCES

1. Foxall, W., A. Boisonnade, and L. Hutchings, *Technical Issues Relevant to Seismic Hazard Analysis of the Eastern Santa Barbara Channel*, prepared by Lawrence Livermore National Laboratory for the Minerals Management Service, April 1995.

2. Boore, D.M. and C. E. Smith, *Analysis of Earthquake Recordings Obtained from the Seafloor Earthquake Measurement System (SEMS) Instruments Deployed off the Coast of Southern California*, Bulletin of the Seismological Society of America, Vol. 89, No. 1, pp. 260-274, February 1999.

3. Senior Seismic Hazards Committee (SSHAC), *Recommendations for probabilistic seismic hazard analysis: Guidance on uncertainty and use of experts*, UCRL-ID-122160, Lawrence Livermore National Laboratory, 170 p, 1995.

4. Wells, D.L. and K. J. Coppersmith, *New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement*, Bulletin of the Seismological Society of America, No. 84, pp. 974-1002, 1994.

5. Youngs, R. R. and K. J. Coppersmith, *Implications of fault slip rates and earthquake recurrence models to probabilistic seismic hazard estimates*, Bulletin of the Seismological Society of America, No. 75, pp. 939-964, 1985.

6. Yeats, R. S., *Converging more slowly*, Nature, 366, pp. 299-301, 1993.

7. Huftile, G. J. and R. S. Yeats, *Convergency rates across a displacement transfer zone in the Western Transverse Ranges, Ventura Basin, California*, J. Geophys. Res., 100, pp. 2043-2067, 1995.

8. Shaw, J. H. and J. Suppe, *Active faulting and growth folding in the eastern Santa Barbara Channel, California*, Geological Society of America Bulletin, Vol. 106, pp. 607-626, 1994.

9. Bernreuter, D. L., J. B. Savy, R.W. Mensing, and J. C. Chen, *Seismic hazard characterization of 69 nuclear plant sites east of the Rocky Mountains*, Report NUREG/CR-1582, Vols. 1-5, prepared by Lawrence Livermore National Laboratory for the U.S. Nuclear Regulatory Commission, 1989.

10. Savy, J. B., UCRL ID 111115, Lawrence Livermore National Laboratory, 1993.

TABLE 1
SANTA BARBARA CHANNEL MODEL 1 SLIP RATES

FAULT	SEGMENT	DIP Deg	SLIP SENSE	V_{min}[a] mm/yr	V_{max}[a] mm/yr	V_{be}[a] mm/yr	Interval[b] Ma	$M_W(A)_u$[c]
Santa Ynez	South Branch	70S	LL-R	0.05[1,2,4]	0.4[1,2,4]	0.1	0.08-.105[1]	6.2
	Lake Cachuma	70S	LL(-R)	0.05	1	1		6.6
	Central	70S	LL-R	0.05[3,4]	6.7[3,4]	1.0	0.01-0.7[3,4]	6.9
	East	70S	LL(-R)	0.05	1	1		6.5
Arroyo Parida-Santa Ana		70S	R(-LL?)	0.3[3,4]	0.4[5]	0.4[5]	0.03-0.04[5,6,7]	6.7
San Cayetano	West	50N	R	0.9[8]	5.8[9]	4.0[8,9]	0.008-0.02[8]	6.6
	East	50N	R	4.4[10]	10.4[10,8]	7.4[10]	0.5[10]	6.5
Northridge		45S	R	1.0[10]	2.5[10]	1.7[10,11]	2.3[10]	6.8
Santa Susana		55/30N	R	2.1[10]	9.8[10]	6.0	0.6-2.3[10,12]	6.75
Santa Rosa Is.		85N	LL(-R)	0.1[13]	1.5[14]	0.75[15,16]		6.9
Santa Cruz Is.	East	85N	LL(-R)	0.1	1.25[16]	0.75[16]		6.9
	West	85N	LL(-R)	0.1	1	0.5[17]		6.9
Malibu Coast		85N	LL(-R)	<0.1[3,4]	1	0.3		6.9
Santa Monica		85N	LL-R	0.3[18]	1	0.6[19]		6.5
Dume		85N	R(-LL?)	0.5	3.5	2		6.9
North Channel Slope		65/35N	R	0.1[20,1]	1.1[21,22]	0.5	0.08-1.8[21]	7.0
Red Mountain	Central	65/35N	R	0.4[7,9]	7.0[9]	1.0[7]	0.045[7]; 0.5[9]	6.6
	East	65/35N	R	0.4[7,9]	7.0[9]	3.5	0.045[7]; 0.5[9]	6.2
	West 1	65/35N	R	0.1	1.1	0.5		
	West 2	65/35N	R	0.1	1.1	0.5		
Ojai Blind T	West	30N	R	6.0[9,23]	6.2[9,23]	6.1	0.5[9]	6.6
	East	30N	R	2.6[9,23]		2.6	0.5[9]	6.6
Blind Oak Ridge	Central	30S	R	4.0[9]	7.5[9]	5.0[9]	0.5[9]	6.9
	East	30S	R	4.0[9]	7.5[9]	5.0[9]	0.5[9]	6.8
	West	30S	R	4.0	7.5	5.0	0.5	
Oak Ridge	West	85/50S	R-LL	4.8[24,25,9]	5.6[24,25]	5.1[24,25]	0.975±.075[9]	6.4
	East	70/50S	R	3.4[10]	5.0[9,26]	4.5	0.5[9,10]	6.6

TABLE 2
SANTA BARBARA CHANNEL MODEL 2 PRELIMINARY SLIP RATES

FAULT	SEGMENT	DIP Deg	SLIP SENSE	V_{min}[a] mm/yr	V_{max}[a] mm/yr	V_{be}[a] mm/yr	Interval[b] Ma
Santa Lucia T.		25NE	R	1.1	2.2	1.6	6-3
Pt. San Luis T.	Tepesquet	23NE	R	1.1	2.1	1.6	6-3
	Figuora	27NE	R	0.6	2.3	1.7	6-3
Black Mtn. T.	NW	15NE	R	1.3	3.1	2.1	6-3
	SE	23NE	R	1.1	3.1	2.3	6-3
Little Pine F.		55NE	R	0.7	1.4	1.0	6-3
Big Pine F.	W	70NNE	R			(1.5)	
	E	70NNE	LL	2	7	4	6-1.8
San Cayetano T.	Pt Conception	20N	R	1.6	5.9	4.4	6-3
	Santa Barbara	20N	R	2.0	7.0	4.5	6-3
	Ojai	30N	R	3.2	7.0	5.1	6-3
	SCT1	20N	R	1.3	5.9	3.6	6-3
	Fillmore	20N	R	5.0	10.0	7.5	6-3
(San Cayetano F.)	SCT2	55NNE	R	0.55	3.7	2.1	6-3
Pico T		40S	R	1.4	1.7	1.6	2.3-2
Channel Is. T.		15N	R			1.3	3
Elysian Park T.	Sa. Monica Mtns.	20N	R	3.0	5.4	4.2	4-2.2
	Sepulveda	20N	R	3.0	5.4	4.2	4-2.2
	Los Angeles	20NE	R	2.5	4.6	3.5	4-2.2
Santa Rosa Is. F.		85N	LL(-R)	0.1	1.5	0.75	
Santa Cruz Is. F.	East	85N	LL(-R)	0.1	1.25	0.75	
	West	85N	LL(-R)	0.1	1	0.5	
Malibu Coast F.		85N	LL(-R?)	<0.1	1	0.3	
Dume F.		70N	R(-LL?)	0.5	3.5	2	
Santa Monica F.		65N	LL-R	0.3	1	0.6	
Sata Ynez F.	South Branch	70S	R	0.05	0.4	0.1	0.08-0.105
	Lake Cachuma	70S	R	0.6	1.2	1.0	6-3

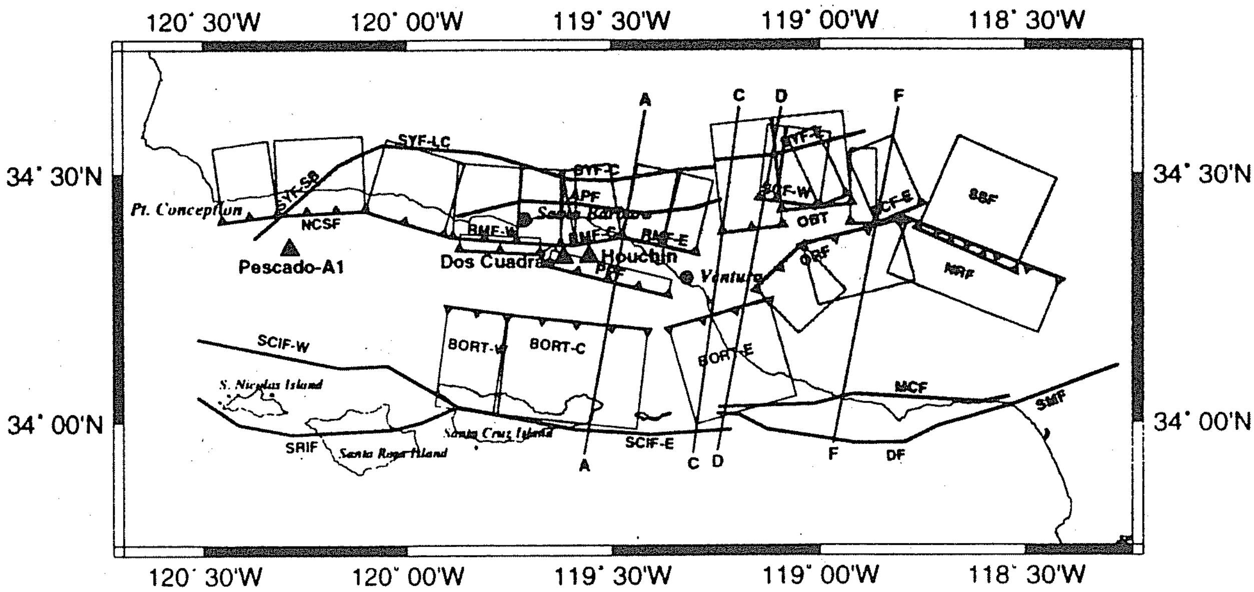

Figure 1: Source Model 1.

Map showing Model 1 fault sources. Surface traces of model faults having dips greater than and less than 65° are shown in red and blue, respectively. Upper edges of blind faults are shown in green. Green and blue rectangles are surface projections of the fault planes of blind faults and shallow-dipping (≤65°) surface faults, respectively. Fault name abbreviations: **SYF-SB, -LC, -C, -E**, Santa Ynez fault, south branch, Lake Cachuma, central, and eastern segments; **NCSF**, North Channel Slope fault; **RMF-E, -C, -W**, Red Mountain fault, eastern, central, west1+west2 segments; **APF**, Arroyo Parida-Santa Ana fault; **PPF**, Pitas Point fault; **SCF-E, -W**, San Cayetano fault, east, west segments; **OBT**, Ojai blind thrust, west+east segments, **SSF**, Santa Susana fault; **NRF**, Northridge blind fault; **ORF**, Oak Ridge fault, west+east segments; **BORT-E, -C, -W**, Oak Ridge blind thrust, east, central, west segments; **SMF**, Santa Monica fault; **MCF**, Malibu Coast fault; **DF**, Dume fault; **SCIF-E, -W**, Santa Cruz Island fault, east, west segments; **SRIF**, Santa Rosa Island fault. Magenta triangles are offshore platform sites

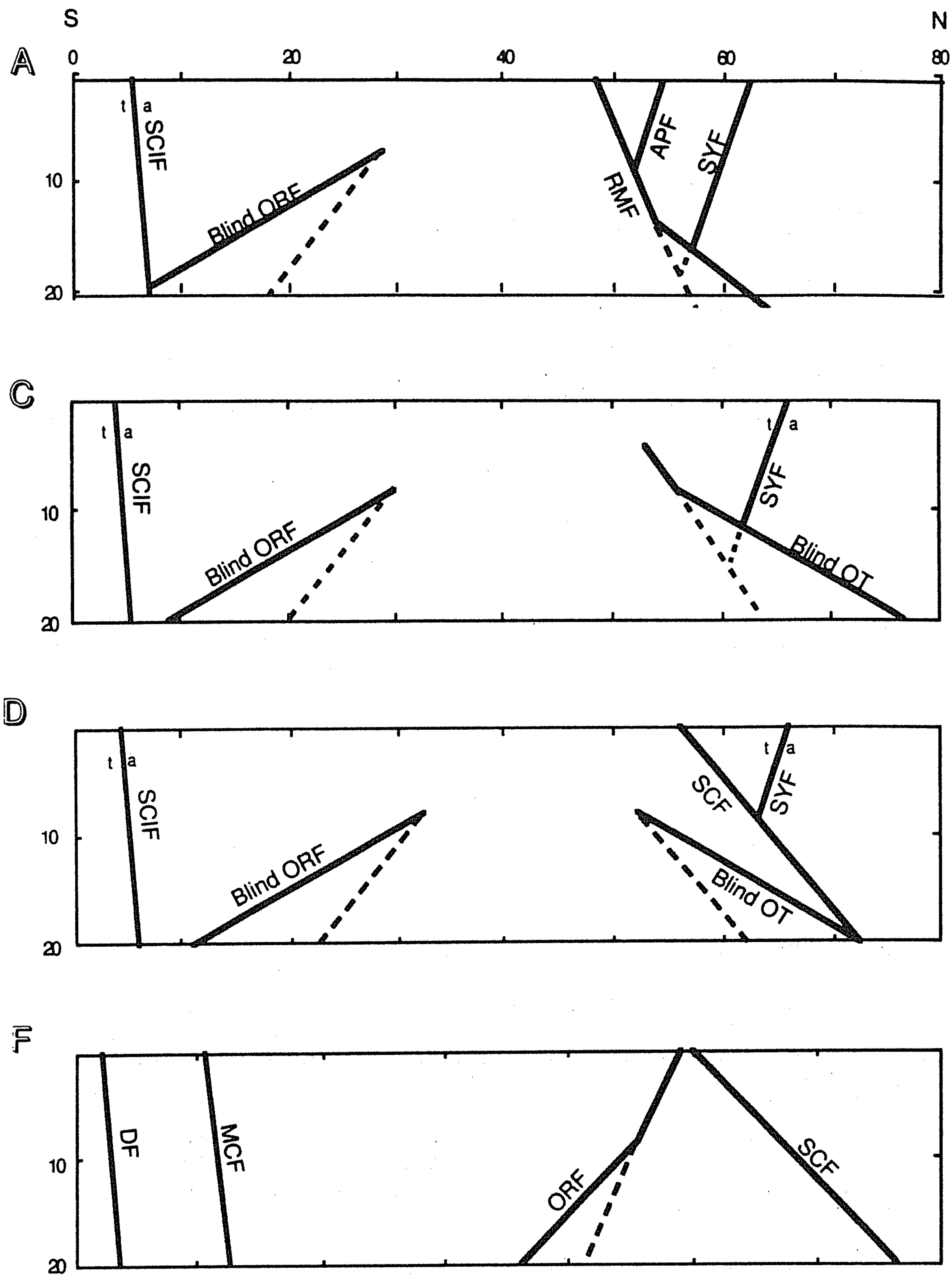

Figure 2: Source Model 1 Cross Sections.

Cross-sections AA, CC, DD, FF (see Figure 1) through source Model 1. Major alternative subsurface geometries shown dashed.

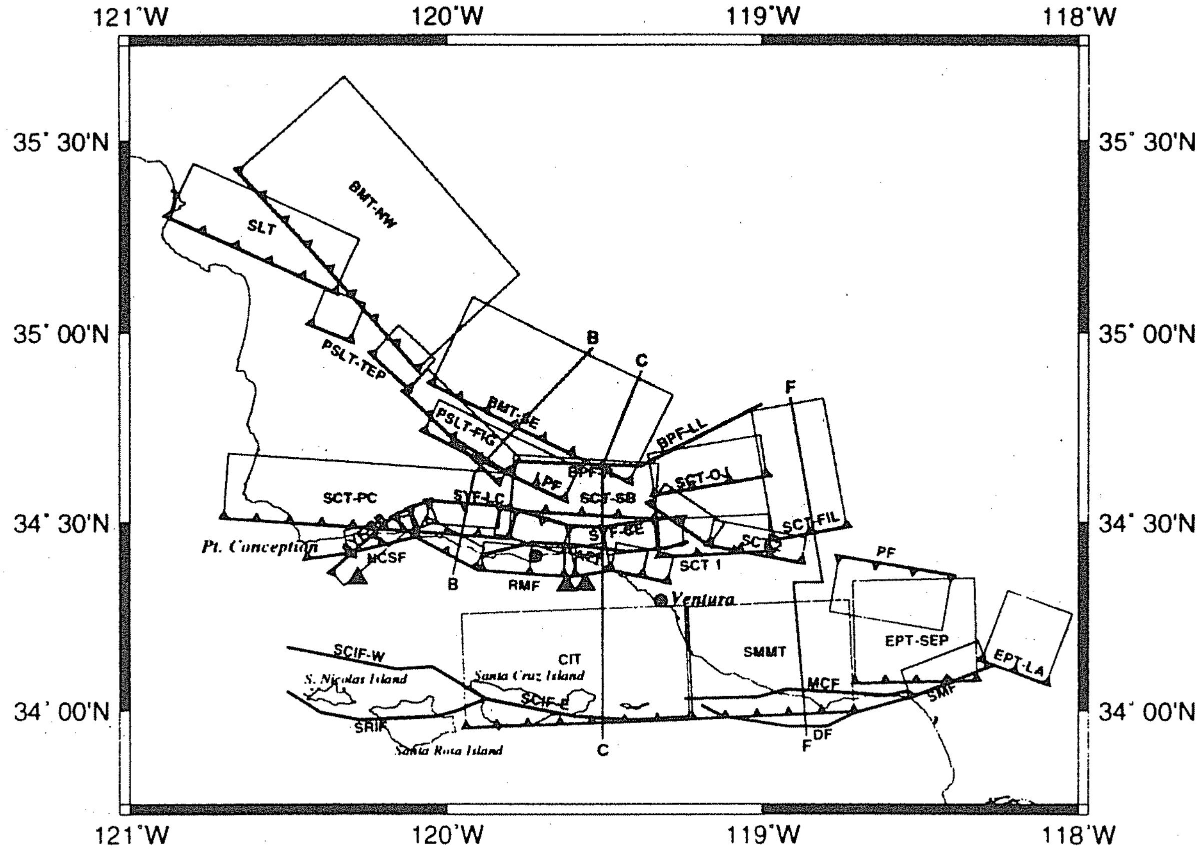

Figure 3: Source Model 2

Map showing Model 2 fault sources. Color coding and symbols the same as Figure 1. Fault abbreviations: **SLT**, Santa Lucia thrust; **BMT-NW**, **-SE**, Black Mountain thrust, northwest, southeast segments; **PSLT-TEP**, **-FIG**, Point San Luis thrust, Tepesquet, Figuora segments; **BPF-LL**, **-R**, Big Pine fault, left-lateral, reverse segments; **LPF**, Little Pine fault; **SCT-PC**,**-SB**, **-OJ**, **-SCT1**, **-SCT2**, **-FIL**, San Cayetano thrust, Point Conception, Santa Barbara, Ojai,, SCT1; SCT2 (surface San Cayetano fault), Fillmore segments; **SYF-SB**,**-LC**, **-C**, Santa Ynez fault, south branch, Lake Cachuma, central segments; **NCSF**, North Channel Slope fault, **RMF**, Red Mountain fault, [east, central, west1, west2 segments (see Figure 1)]; **APF**, Arroyo Parida-Santa Ana fault; **PF**, Pico fault; **EPT-LA**, **-SEP**, Elysian Park thrust, Los Angeles, Sepulveda segments; **SMMT**, Santa Monica Mountains thrust; **CIT**, Channel Islands thrust; **SMF**, Santa Monica fault; **MCF**, Malibu Coast fault; **DF**, Dume fault; **SCIF-E**, **-W**, Santa Cruz Island fault, east, west segments; **SRIF**, Santa Rosa Island fault.

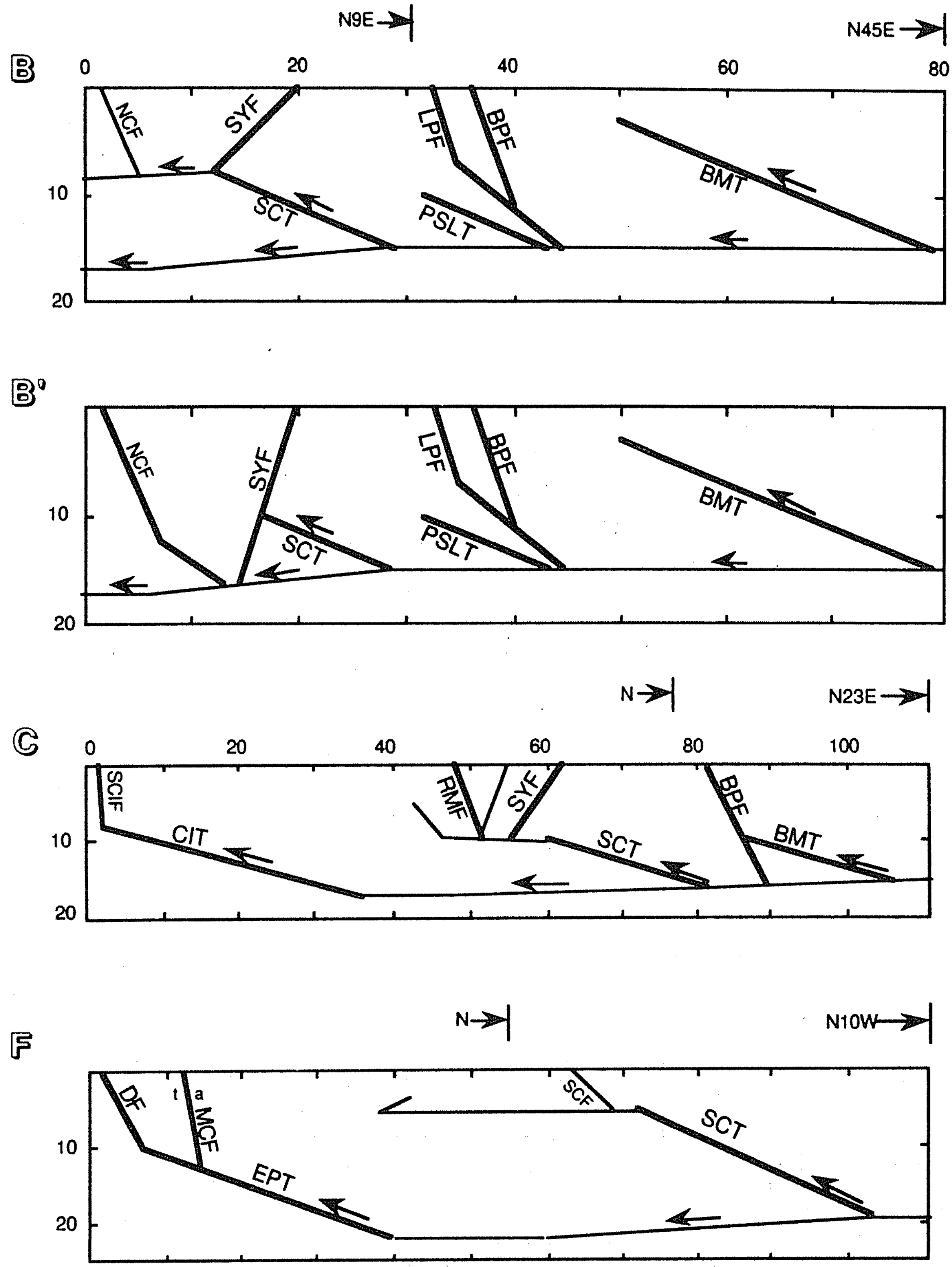

Figure 4: Model 2 Cross Sections

Cross-sections BB, B'B', CC, FF (see Figure 3) through source Model 2. Section B'B' shows a major alternative interpretation to the geometry shown in BB, in which the shallow San Cayetano detachment does not exist.

Figure 5

PLATFORM HOUCHIN HAZARD CURVE

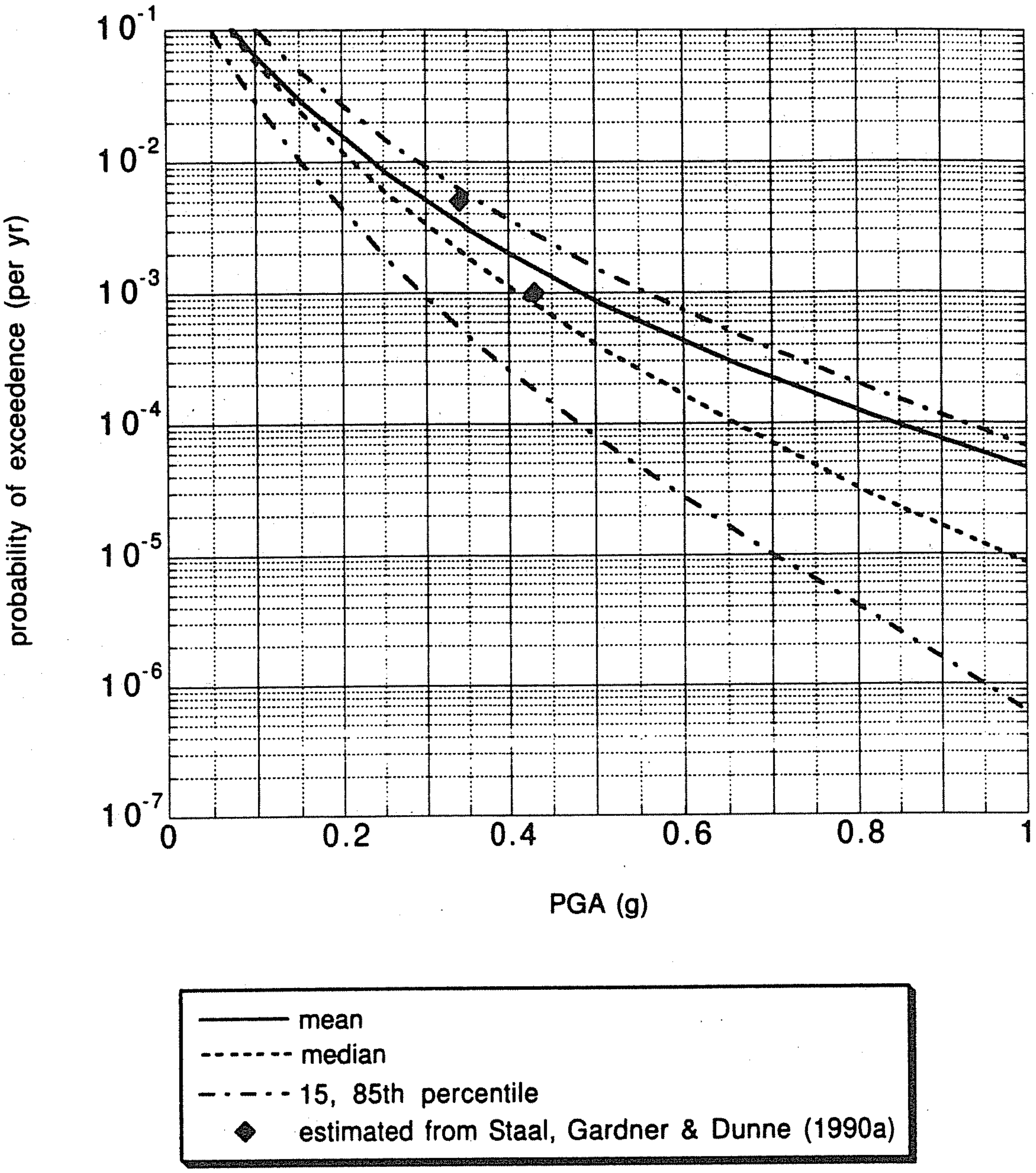

Figure 7

PLATFORM PESCADO-A1 HAZARD CURVE

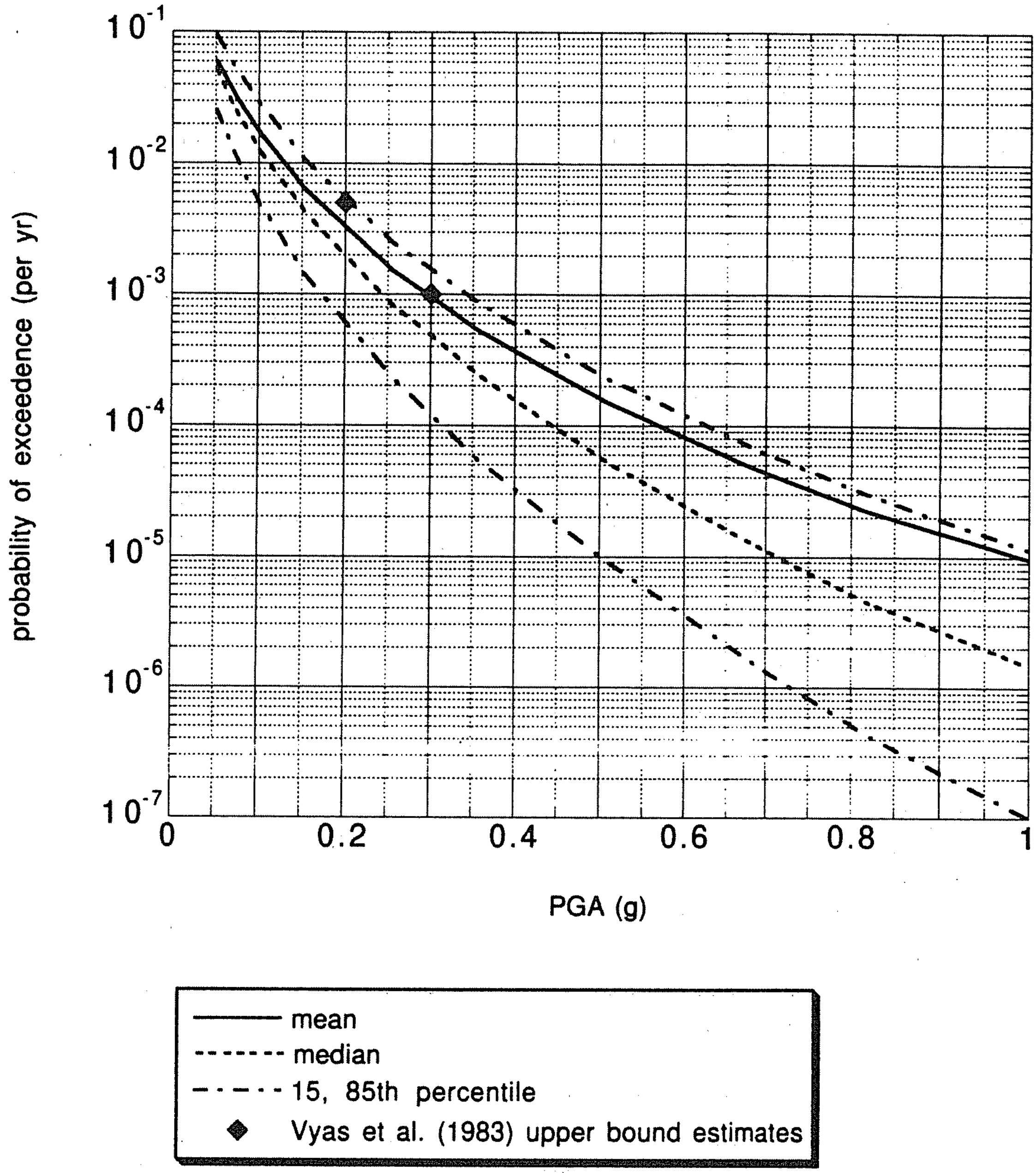

Figure 6

PLATFORM DOS QUADRAS HAZARD CURVE