The San Francisco Bay Area –

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Association of Bay Area Governments
Earthquake and Hazards Program

Credits for 1995 Report –

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Background

During the last 35 years, ABAG, with funding from both the U.S. Geological Survey and the National Science Foundation, has developed a number of earthquake ground shaking hazard maps for the nine-county San Francisco Bay Area. Those maps resulted in the publication in 1987 of the first ***On Shaky Ground*** report. The Loma Prieta earthquake in 1989 and the Northridge earthquake in 1994 were devastating in their effects on northern and southern California. However, they have also provided us with valuable information to test the hypotheses forming a basis for those earlier maps and to develop a better understanding of the physical processes that occur in earthquakes. The maps described and shown on ABAG's Earthquake and Hazards internet site are the result of this research and better understanding. They are an updated version of the maps documented in the 1987, 1995, 1998 ***On Shaky Ground*** report (as "hard" copy), as well as the more recent web-based 1999, 2001, and 2003 revisions. The 2010 maps remain essentially unchanged from the 2003 version A separate document on ABAG's Earthquake and Hazard Program website at http://quake.abag.ca.gov/shaking describes some of the research that has been conducted since 2003 that have promise to create more realistic maps in the future.

This *On Shaky Ground* report documents ABAG's ground shaking hazard maps to encourage appropriate planning for and mitigation of earthquake hazards.

Many people have used the maps of ground shaking. During these past years, however, questions have been raised about how ABAG produces these maps, as well as appropriate and inappropriate uses of the maps. This documentation is intended to encourage more use, and more appropriate use, of ABAG's ground shaking hazard information for the San Francisco Bay Area.

The discussion in this documentation focuses on the earthquake hazard of ground shaking, and its secondary impacts on buildings and ground failure. Ground shaking is the cause of the vast majority of earthquake-related damage, deaths and injuries.

Some Words of Caution

The following maps and tables answer several common questions. However, as with any general assessment of what might happen in the future, the information is imperfect and incomplete. Because large earthquakes are not an everyday common occurrence, our understanding of their impacts is limited. We generally know what types of damage will occur and what types of ground will have problems, but we cannot predict the specific damage to specific buildings. This lack should not serve as an excuse to not act. There are many things that each of us can do as individuals, and working with our neighbors, offices and agencies, to reduce the risk of damage and other earthquake effects. Thus, it is very important that you read the materials explaining:

- What question each map and table is trying to answer;
- When you might want to use the map or table, and when you should not use it;
- How each type of map or chart was prepared; and
- What assumptions we needed to make to prepare the maps and charts, including what information is unknown.

Table of Contents

The San Francisco Bay Area Is Earthquake Country

The fact that a devastating earthquake occurred in 1906 -- the San Francisco earthquake -- is common knowledge. Larger earthquakes generally affect larger areas; the San Francisco earthquake caused extensive damage in Oakland, San Jose and Santa Rosa. More recently, the 1989 Loma Prieta earthquake caused extensive damage in the Santa Cruz Mountains, as well as in Oakland and San Francisco tens of miles away. But many moderate to great earthquakes (over magnitude 6.0) have affected the Bay Area; 22 such events have occurred in the last 160 years -- for an average of one every seven years.

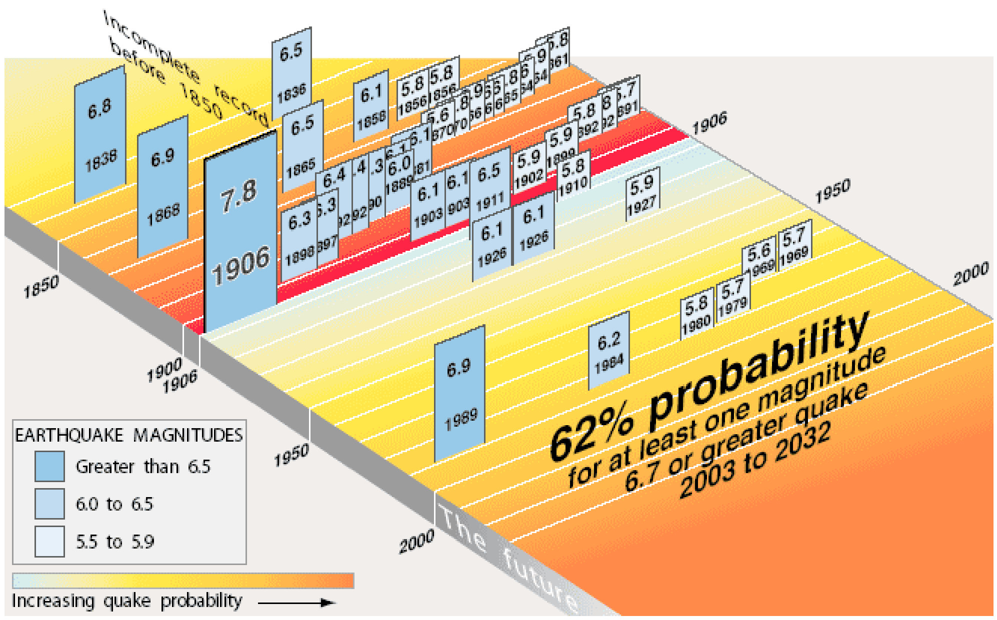
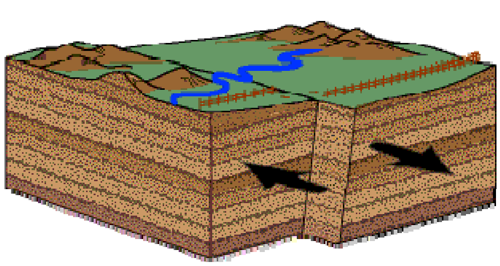


Figure 1 - Estimated magnitude and year of occurrence of major Bay Area earthquakes. Note that the 1911 to 1979 period, when most of the Bay Area developed, is exceptional quiet. Source: USGS

Just like the top layer of an orange is the peel, the earth has a top layer and it is called the crust. Faults slice through the earth's crust and allow pieces of the crust, called plates, to slide past each other. We feel the ground shake when forces underground cause the faults near us to snap and move past each other. Because faults are weaknesses in the rock, earthquakes tend to occur over and over on these same faults. Most Bay Area faults are called strike-slip faults and slip sideways, grinding up the ground and making our valleys. Some faults slip up and down and make our mountains. The blind thrust fault beneath Mt. Diablo is one of these.



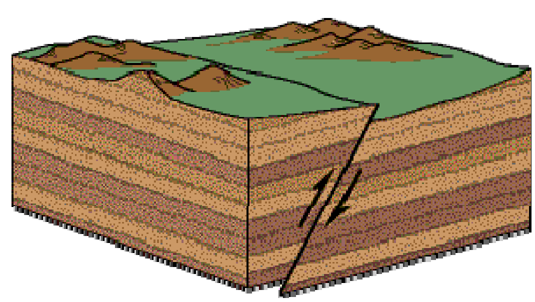


Figure 2 – Strike-Sip and Reverse Faults [Thrust faults are low angle reverse faults.] Source: USGS

Why Shaking Hazard Maps Are Important

In ***some*** earthquakes, the surface of the ground can rupture along a fault -- or a landslide can be triggered -- or underground sand layers may flow (liquefy) -- or a tsunami ("tidal" wave) may be generated in water**. *But in ALL earthquakes, the ground shakes***. In large magnitude earthquakes, more ground shakes, and it shakes longer, than in small magnitude earthquakes. Ground shaking causes damage tens of miles away from the fault source.

When the ground shakes, damage occurs to buildings, facilities and their contents. People can be injured or killed. People find that they may no longer be able to sleep in their homes, or even have access to their belongings. Businesses can't function and segments of the economy suffer. Hazardous materials are released which can be damaging to people and the environment.

Various options are available to avoid, reduce or otherwise mitigate these results. What YOU do to prepare for shaking can minimize or eliminate these effects.

Most earthquake damage is caused by the shaking of the ground itself. Yet, at the same time, many existing local and State government hazard reduction programs and regulations focus on other earthquake hazards. Our purposes in providing shaking hazard information are to expose ground shaking as a significant hazard, to show (using maps) the areas with the strongest expected shaking, and to suggest ways to mitigate shaking damage.

A Call to Action

Better maps can only be truly better if they lead to actions that save lives, reduce suffering and economic hardship, and help protect our environment. What ***you*** do to prepare for shaking can minimize or completely eliminate these effects. We believe that it is imperative that these revised maps be used for earthquake hazard mitigation and disaster response planning ***now.***

ABAG personnel are already working to ensure that these maps are used fully by the city and county governments in the Bay Area, by those planning for a better more earthquake-resistant transportation system, and by relief agencies such as the American Red Cross. To see more about the mitigation efforts of the local governments in the San Francisco Bay Area, see http://quake.abag.ca.gov/mitigation. But more is needed. It is in this spirit of a call for more ***mitigation*** that the following maps showing the extent of our ***hazard*** are provided to you, the local governments, business owners, homeowners and residents of the San Francisco Bay Area.

We all need to take responsibility for making our own homes and workplaces safer so that we can better prepare for the ride of our lives.

How Big Is BIG – Measuring Earthquake SIZE

Magnitude is a measure of overall earthquake size.

Larger magnitude earthquakes generally cause a larger area of ground to shake hard, and to shake longer. This relationship is generally well understood. Thus, one principal factor in determining shaking hazard is the magnitude of the earthquake.

Seismologists now have several measures of earthquake magnitude in addition to the familiar Richter (or "local") magnitude. The Richter magnitude has difficulty differentiating the size of large and great (7-1/2+) magnitude earthquakes. To overcome this difficulty, modern seismologists use ***moment magnitude*** because it best reflects the energy released by the earthquake. The moment magnitude is proportional to the area of the fault surface that has slipped. Thus, it is directly related to the fault length. Because the models used to generate ABAG's shaking hazard maps are based on fault length, they, in effect, bypass magnitude. (See 1995 "On Shaky Ground" report Appendix A for more technical documentation.)

How Strong Is STRONG – Measuring Earthquake INTENSITY

Intensity is a measure of the effect of the earthquake at a specific location.

An earthquake has one moment magnitude, but a range of intensities. The most commonly used intensity scale is the modified Mercalli intensity scale (MMI scale). The intensity of ground shaking at a site varies for any particular earthquake based on several factors:

- the size (magnitude) of the earthquake (which is related to the length of the fault that ruptures);
- the distance from the site to the fault source for the earthquake;
- the directivity (focusing of earthquake energy along the fault axis rather than perpendicular to the fault); and
- the type of geologic material underlying the site, with stronger shaking occurring on softer soils

Just as a light bulb above my desk is 100 watts regardless of where I'm sitting, and the intensity of the light varies with where I am in my office, an earthquake has a single moment magnitude and a variety of intensities distributed throughout the region. *Jeanne Perkins*

ABAG uses the modified Mercalli Intensity Scale to depict shaking severity. For additional information on the percentages of residential units that have statistically been made uninhabitable in past California earthquakes by construction type and MMI level, see http://quake.abag.ca.gov/housing. For information on how to make your home safer, see http://quake.abag.ca.gov/residents.

Figure 3 - Modified Mercalli Intensity Scale of Shaking Intensity

MMI Value	Description of Shaking Severity	Summary Damage Description Used on 1995 Maps	Full Description
I.			Not felt. Marginal and long period effects of large earthquakes.
II.			Felt by persons at rest, on upper floors, or favorably placed.
III.			Felt indoors. Hanging objects swing. Vibration like passing of light trucks. Duration estimated. May not be recognized as an earthquake.
IV.			Hanging objects swing. Vibration like passing of heavy trucks; or sensation of a jolt like a heavy ball striking the walls. Standing motor cars rock. Windows, dishes, doors rattle. Glasses clink. Crockery clashes. In the upper range of IV, wooden walls and frame creak.
V.	Light	Pictures Move	Felt outdoors; direction estimated. Sleepers wakened. Liquids disturbed, some spilled. Small unstable objects displaced or upset. Doors swing, close, open. Shutters, pictures move. Pendulum clocks stop, start, change rate.
VI.	Moderate	Objects Fall	Felt by all. Many frightened and run outdoors. Persons walk unsteadily. Windows, dishes, glassware broken. Knickknacks, books, etc., off shelves. Pictures off walls. Furniture moved or overturned. Weak plaster and masonry D cracked. Small bells ring (church, school). Trees, bushes shaken (visibly, or heard to rustle).
VII.	Strong	Nonstructural Damage	Difficult to stand. Noticed by drivers of motor cars. Hanging objects quiver. Furniture broken. Damage to masonry D, including cracks. Weak chimneys broken at roof line. Fall of plaster, loose bricks, stones, tiles, cornices (also unbraced parapets and architectural ornaments). Some cracks in masonry C. Waves on ponds; water turbid with mud. Small slides and caving in along sand or gravel banks. Large bells ring. Concrete irrigation ditches damaged.

Figure 3 - Modified Mercalli Intensity Scale of Shaking Intensity (continued)

VIII.	**Very Strong**	**Moderate Damage**	Steering of motor cars affected. Damage to masonry C; partial collapse. Some damage to masonry B; none to masonry A. Fall of stucco and some masonry walls. Twisting, fall of chimneys, factory stacks, monuments, towers, elevated tanks. Frame houses moved on foundations if not bolted down; loose panel walls thrown out. Decayed piling broken off. Branches broken from trees. Changes in flow or temperature of springs and wells. Cracks in wet ground and on steep slopes.
IX.	**Violent**	**Heavy Damage**	General panic. Masonry D destroyed; masonry C heavily damaged, sometimes with complete collapse; masonry B seriously damaged. (General damage to foundations.) Frame structures, if not bolted, shifted off foundations. Frames racked. Serious damage to reservoirs. Underground pipes broken. Conspicuous cracks in ground. In alluvial areas sand and mud ejected, earthquake fountains, sand craters.
X.	**Very Violent**	**Extreme Damage**	Most masonry and frame structures destroyed with their foundations. Some well-built wooden structures and bridges destroyed. Serious damage to dams, dikes, embankments. Large landslides. Water thrown on banks of canals, rivers, lakes, etc. Sand and mud shifted horizontally on beaches and flat land. Rails bent slightly.
XI.			Rails bent greatly. Underground pipelines completely out of service.
XII.			Damage nearly total. Large rock masses displaced. Lines of sight and level distorted. Objects thrown into the air.

Masonry A: Good workmanship, mortar, and design; reinforced, especially laterally, and bound together by using steel, concrete, etc.; designed to resist lateral forces.
Masonry B: Good workmanship and mortar; reinforced, but not designed in detail to resist lateral forces.
Masonry C: Ordinary workmanship and mortar; no extreme weaknesses like failing to tie in at corners, but neither reinforced nor designed against horizontal forces.
Masonry D: Weak materials, such as adobe; poor mortar; low standards of workmanship; weak horizontally.

Full descriptions are from: Richter, C.F., 1958. ***Elementary Seismology.*** W.H. Freeman andCompany, San Francisco, pp. 135-149; 650-653.

Graphics courtesy of the **Campagna Mulitmediale di Informazione** of the **Osservatorio Geofisico Sperimentale** in Italy ("Italia"). *Molte grazie.*

What Does Ground Shaking Intensity REALLY Mean?

INTRODUCTION

"Official" Modified Mercalli Intensity Descriptions Can Be Confusing

The ABAG Earthquake and Hazards Program web site provides maps showing modeled shaking intensity for expected future earthquakes using the modified Mercalli intensity (MMI) scale. The full description of each intensity level is provided in the description of the MMI scale. However, the "official" descriptions of MMI level (1995-Ref. 2) were written approximately 40 years ago and are often difficult to interpret, vague and archaic.

Current Research Provides Examples of MMI Impacts

We can now provide more "quantitative" descriptions of the impacts of shaking on buildings, probabilities of ground failure (including liquefaction and landsliding), and conversions among intensity scales and to other measures of shaking strength than were provided by the "official" descriptions. These data are based on research by ABAG and others in the past few years, and are provided below.

SHAKING INTENSITY AND BUILDING DAMAGE

The Question How does ground shaking intensity relate to damage to various types of building construction?

What We Know The likelihood of building damage is radically different for different types of buildings. After the Northridge earthquake, the Superior Apartments (shown below) were heavily damaged. However, a group of single family homes behind the apartments experienced little damage. These apartments were constructed to comply with modern building codes.

The damage to buildings can be depicted using two separate measures of damage:

1. The percentage of buildings of a particular construction type (defined by use, construction materials, height and age) "red-tagged" by the local government building inspector as "unsafe for human occupancy," that is, uninhabitable, or
2. The average dollar loss (expressed as a percentage of the replacement value) for each construction type.

Based on information compiled by ABAG for residential construction (Ref. 3) and by EQE and OES for commercial construction (Ref. 4), it is relatively easy to generate a table of percent of housing units and commercial buildings typically "red tagged" for several construction types, as shown in the following table.

What We Don't Know

Although a table of average dollar loss by construction type might, arguably, be more useful than the habitability information provided here, it is our judgment that information is insufficient to create such a table at this time. Data on the value of buildings "at risk" in past earthquakes and reliable damage data are scarce. In addition, there is no reliable data on the habitability of tilt-up concrete buildings (separate from other types of concrete buildings), or on wood-frame commercial buildings (separate from residential buildings). Information on these two types of buildings is therefore not included in this table.

Figure 4 – Building Damage in Earthquakes Varies by Type of Construction

Example of Damage to Post-1940s Multifamily Residential (Superior Apartments, Northridge)
Source: Jeanne Perkins, ABAG

Example of Damage to Mobile Home
Source: Karl Steinbrugge

Example of Damage to Unreinforced Masonry Cafe with Residential Units Above
Source: Henry Degenkolb

Example of Damage to Concrete Building
Source: Northridge Earthquake Collection, Earthquake Engineering Research Center, University of California, Berkeley

Table 1: Percent of Dwelling Units (for Residential) and Buildings (for Commercial) Red Tagged as Uninhabitable by Construction Type and MMI Intensity						
	INTENSITY					
RESIDENTIAL TYPE [1]	**V**	**VI**	**VII**	**VIII**	**IX**	**X**
Mobile Homes	almost 0	0	0.87	40	90	100
Unreinforced Masonry	almost 0	0.05	2.9	45	70	80
Non-Wood, 4-7 Stories, <1940	almost 0	0.30	8.0	45	70	80
Wood-Frame, 4-7 Stories, <1940, Multi-family	almost 0	1.4	2.5	45	70	80
Wood-Frame, 1-3 Stories, <1940, Multi-family	almost 0	0.05	0.53	11	44	64
Wood-Frame, 1-3 Stories, >1939, Multi-family [2]	almost 0	0.01	0.04	6.5	15	25
Wood-Frame, 1-3 Stories, <1940, Single Family [3]	almost 0	0.04	0.12	1.8	8.4	12
Wood-Frame, 1-3 Stories, >1939, Single Family	almost 0	0	0.02	0.18	0.69	1.8
COMMERCIAL OR INDUSTRIAL						
Unreinforced Masonry [4]	almost 0	1.0	8.0	45	70	80
Miscellaneous Concrete [5]	almost 0	0	1.0	20	33	40

Note 1. The relationship between intensity and construction type for residential buildings are taken from Ref. 3, pg. 68.

Note 2**.** *These percentages include a mixture of buildings with anf without full or partial parking underneath the structure. Data for buildings with and without parkingare not directly available. However, the values for multi-family buildings without parking are probably closer to those for >1939 wood-frame single family homes, and those for buildings with parking could easily be double the percentages listed here.*

Note 3**.** Homes built prior to 1940 were not bolted to their foundations. However, these percentages include an unknown mixture of homes that have, and have not, been retrofitted by adding thesse bolts and installing plywood sheathing on the inside of the crawl space.

Note 4**.** Note that the percentages of commercial unreinforced masonry buildings red tagged are higher than those for the residential unreinforced masonry because these buildings typically have fewer room partitions.

Note 5. Taken from Ref. (Table 4-3), except for MMI VII (which was revised downward from 8% to 1% based on lack of damage in the Loma Prieta earthquake). These percentages apply to "general" concrete buildings.

SHAKING INTENSITY AND LANDSLIDING

The Question

Can ground shaking intensity be correlated to earthquake-triggered landsliding?

What Is the Hazard?

Landslides are often triggered by the shaking of earthquakes. These ground failures are of two principal types (Ref. 5): ¨ disrupted slides, falls and flows - landslides with highly jumbled materials that start on steep slopes and move at relatively high speeds, such as soil or rock slides, rock falls and avalanches, and debris flows; and ¨ coherent slides - blocks of unjumbled materials that move on a discrete slide surface, such as slumps, block slides and earth flows.

What We Know

The California Division of Mines and Geology (CDMG) has a program to map earthquake-induced landslide hazard areas throughout California. Currently, this type of Seismic Hazard Zone Map is only available for portions of the Bay Area and several areas in Los Angeles, Ventura and Orange counties in southern California. Additional mapping is subject to the availability of state and federal funding. The program is mandated by the Seismic Hazards Mapping Act (Public Resources Code, Ch. 7.8)

Much effort was made to document the location, shape, and severity of the landslides triggered by the October 1989 Loma Prieta earthquake and the January 1994 Northridge earthquake. Approximately 1,500 earthquake-triggered landslides were mapped, and up to 4,000 slides may have moved, in the Loma Prieta earthquake (Ref. 6). Over 11,000 landslides occurred in the Northridge earthquake (Ref. 7). Significantly, both earthquakes occurred when the ground was exceptionally dry. Extensive research on the distribution and causes of these slides shows that failure rates can be correlated with (1) shaking severity; (2) slope steepness; (3) strength and engineering properties of geologic materials; (4) water saturation (which varies with precipitation and by season); (5) existing landslide areas; and (6) vegetative cover.

Researchers have correlated areas of known earthquake-induced landslides to Arias intensity, a measure of shaking severity defined on page 11. Areas subjected to Arias intensities of greater than about 0.54 m/sec commonly have earthquake-triggered landslides. Table 7 on page 11 shows this intensity is roughly equivalent to a modified Mercalli intensity of VII or greater. Small numbers of landslides can occur at MMI VI. Slope length and slope aspect (that is, orientation facing north, south or somewhere in between) contribute to earthquake-induced landslide susceptibility. However, slope steepness (as expressed in percent slope) is the most critical slope factor.

The mapped geologic units in the Bay Area can be grouped according to an approximate material shear strength classification of A, B, or C, with A being those units least susceptible to sliding and C being those units most susceptible to sliding. A table correlating these geologic material units with their shear strength classifications is included in Riding Out Future Quakes (Ref. 8, Appendix C). The final factor included in this analysis is degree of water saturation. This variable depends in large part on length of time since the last major storm and rainfall to date. Because these data cannot be known ahead of time, two tables correlating landslide susceptibility with saturation have been generated - one for dry (summer) conditions and a second for wet (winter) conditions. The intensities required for landslides tend to be lowered by approximately one intensity unit under wet conditions.

What We Don't Know

Two important factors contributing to earthquake-induced landslide susceptibility have not been incorporated into these tables.

First, **existing landslides** are not included because any compilation of data on their location is presently sporadic; no regional depository exists for the wealth of data collected for individual development projects.

Second, **vegetative cover** is not incorporated into the following tables because very little research has been conducted quantifying its effect.

Table 2: Earthquake-Induced Landslide Susceptibility – Dry (Summer) Conditions – Based on Modified Mercalli Intensity (MMI), Percent Slope, and Material Type (A, B, or C). [Values in this table are the percentage of the land units being analyzed expected to have at least one landslide. The land units analyzed are one hectare squares, or units 100 meters on each side.]

Percent Slope	0-5% Slope			6-15% Slope			16-30% Slope			30+% Slope		
Material Type	A	B	C	A	B	C	A	B	C	A	B	C
MMI IX and X	0	1	2	1	2	12	5	8	18	8	18	30
MMI VIII	0	0	0	0	0	5	0	5	12	5	8	18
MMI VII	0	0	0	0	0	3	0	3	4	3	5	12
MMI VI	0	0	0	0	0	0	0	0	0	0	0	0

Table 3: Earthquake-Induced Landslide Susceptibility – Wet (Winter) Conditions – Based on Modified Mercalli Intensity (MMI), Percent Slope, and Material Type (A, B, or C). [Values in this table are the percentage of the land units being analyzed expected to have at least one landslide. The land units analyzed are one hectare squares, or units 100 meters on each side.]

Percent Slope	0-5% Slope			6-15% Slope			16-30% Slope			30+% Slope		
Material Type	A	B	C	A	B	C	A	B	C	A	B	C
MMI IX and X	1	2	12	5	8	18	8	18	30	12	24	50
MMI VIII	0	1	2	1	2	12	5	8	18	8	18	30
MMI VII	0	0	0	0	0	5	0	5	12	5	8	18
MMI VI	0	0	0	0	0	3	0	3	4	3	5	12

*Note 1. A table correlating these geologic material units with their shear strength classifications is included in **Riding Out Future Quakes** (Ref. 1999-8, Appendix C).*

SHAKING INTENSTIY AND LIQUEFACTION

The Question

Can shaking intensity be correlated to areas of liquefaction?

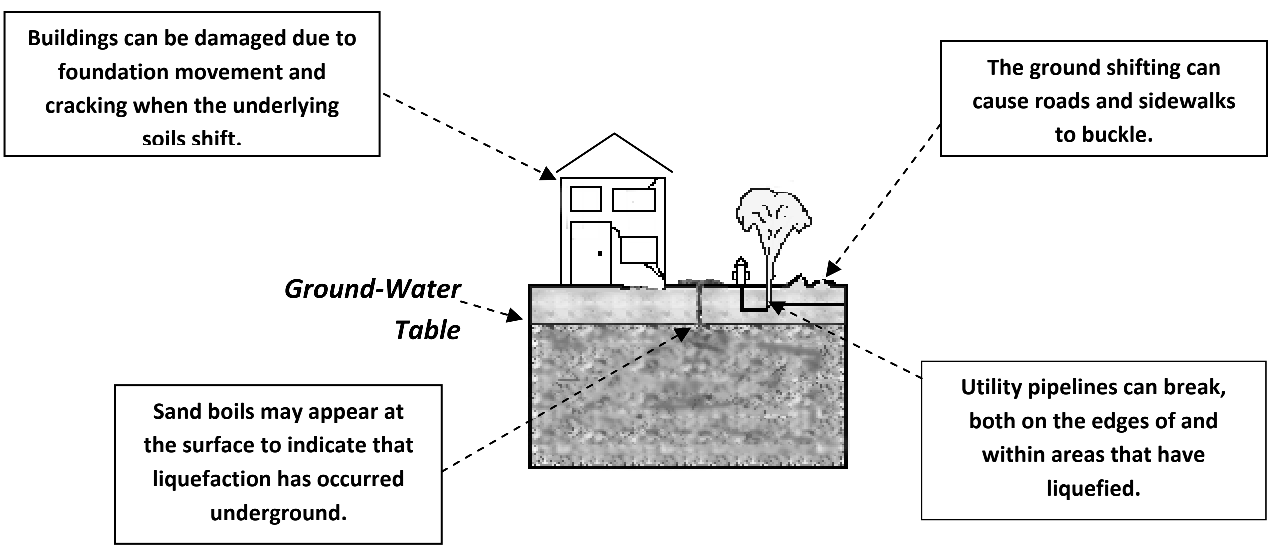
When the ground liquefies, sandy materials which are saturated with water can behave like a liquid, instead of like solid ground. In essence, the sand grains momentarily behave like a liquid.

What Is the Hazard?

Liquefaction is defined as "the transformation of a granular material from a solid state into a liquefied state as a consequence of increased pore-water pressure" (Ref. 9, p. 1). Engineers call this "loss of shear strength." The ground needs to be shaken strongly for liquefaction to occur, and this shaking can occur as a result of an earthquake.

Liquefaction can cause ground displacement and ground failure. In addition, it can cause lateral spreads and flows (essentially landslides on flat ground next to rivers, harbors, and drainage channels).

Figure 5 – Potential Effects of Liquefaction



What We Know

ADD PHOTO

The "recipe" includes three ingredients necessary for damaging liquefaction to occur:

- INGREDIENT 1 - The ground at the site must be "loose" - uncompacted or unconsolidated sand and silt without much clay or stuck together.
- INGREDIENT 2 - The sand and silt must be "soggy" (water saturated) due to a high water table.
- INGREDIENT 3 - The site must be shaken long and hard enough by the earthquake to "trigger" liquefaction.

In areas farther from the earthquake fault source, a material that has high liquefaction susceptibility may liquefy, but an adjacent material of moderate susceptibility may not. Only some materials with very high liquefaction susceptibility will liquefy when exposed to strong shaking (modified Mercalli intensity (MMI) VII), with less susceptible materials being triggered with very strong shaking (MMI VIII). (Intensity is a measure of shaking severity at a particular location.) Liquefaction in areas shaken less than MMI VII, or in areas mapped as having a low to very low liquefaction susceptibility, is a statistical possibility, but it is not likely. The following maps show liquefaction hazard in various earthquake scenarios in three simplified categories, graphically shown below.

Table 4: Potential Likelihood for Liquefaction Based on a Combination of Shaking Intensity and Liquefaction Susceptibility

Modified Mercalli Intensity	Liquefaction Susceptibility	Liquefaction Hazard
IX and X	Very High	High
	High	High
	Moderate	High
VIII	Very High	Moderate
	High	Moderate
	Moderate	Moderate
VII	Very High	Moderate
	High	Moderately Low
	Moderate	Moderately Low
VI	Very High	Very Low
	High	Very Low

Where We're Going

ABAG, William Lettis & Associates (WLA), and the U.S. Geological Survey last produced revised liquefaction susceptibility and liquefaction hazard maps for the San Francisco Bay Area in 2006. As part of that effort, additional data on the shaking required for liquefaction to take place was collected. Other researchers have conducted studies of the relationship between liquefaction and Arias intensity (see 1998-Refs. 10 and 11).

The California Division of Mines and Geology (CDMG) has a program to map liquefaction hazard areas throughout California. Currently, this type of Seismic Hazard Zone Map is only available for parts of the Bay Area and several areas in Los Angeles, Ventura and Orange counties in southern California. Additional mapping is subject to the availability of state and federal funding. The program is mandated by the Seismic Hazards Mapping Act (Public Resources Code, Ch. 7.8)

Correlation of Shaking Intensity with Other Measures of Shaking Severity

The Question The modified Mercalli intensity scale seems so subjective. Can ABAG's intensity maps be converted to other, more quantitative, measures of shaking severity? What peak velocities or undamped velocity response spectra are roughly comparable to the shaking intensities shown on ABAG's maps?

What We Know The ABAG ground shaking intensity maps were produced using a model that predicts the decrease (attenuation) of shaking away from the fault source developed by J. Boatwright (Ref. 1). The model predicts the undamped velocity response spectra, in units of cm/sec (typical of a velocity measurement), not cm/sec2 (units of acceleration). This model therefore predicts a parameter more closely related to velocity than acceleration, and does not model intensity directly.

To predict intensity, we correlated the resulting model maps using both modified Mercalli intensity information and rarer San Francisco intensity information (from, largely, the 1906 San Francisco earthquake) in order to calibrate the model. We use units of intensity in the map legend because they are much easier for most people to understand. Typical intensity maps made by others use damage information and what people felt to map intensities of earthquakes which have already occurred. We have attempted to model these general effects in future earthquakes based on shaking severity information.

If, however, you want or need a quantitative measure of shaking strength, you can correlate the map legend to these other measurements using Table 5, below. This table was generated using more information than was available for On Shaky Ground in 1995 (Ref. 1, pg. A46). It is consistent with Riding Out Future Quakes published in 1997 (Ref. 8, pg. 29) and the shaking maps on ABAG's web site in 2010.

What We Don't Know

Overall, however, there is a shortage of actual data from seismographs near the source faults of major earthquakes to test this theoretical model. The values need to be checked, and may need to be modified, following future major earthquakes.

The maps are intended to depict the relative severity of shaking in one area relative to other areas in the earthquakes modeled. They do not, nor can any general map created prior to an earthquake, be a substitute for evaluation of the level of shaking at a specific site made by qualified seismologists or geotechnical engineers, or assessment of the performance of a specific structure at that site by a licensed structural engineer.

Where to Go for Maps Showing Probability of Exceedance Information

Because the shaking severity maps for individual earthquakes are based on a shaking measurement called the undamped velocity response spectra, the maps could be combined to create a map based on the probability of exceeding this level. This scheme was used to create the probabilistic shaking hazard maps developed by the U.S. Geological Survey and the California Division of Mines and Geology (see Refs. 1998-12 and 13) for peak horizontal ground acceleration, not undamped velocity response spectra used for ABAG's maps. The correlation between undamped velocity response spectra and peak acceleration is too weak to warrant inclusion in the table below.

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Table 5: Approximate Relationships Among Intensity Scales, Particle Velocity and Undamped Velocity Response Spectra

NOTE - These correlations apply to the ABAG maps because of the way they were generated. ***They do not work with other MMI maps.*** Therefore, this table should not be used to convert MMI or San Francisco Intensity maps generated by others to Aria intensity, undamped velocity response spectra, or peak velocity.

Undamped Velocity Reponse Spectra [1] (cm/sec)	Peak Velocity (cm/sec)	Arias Intensity [2](m/sec)	San Francisco Intensity	Modified Mercalli Intensity (as shown on ABAG maps)		
				Summary of Damage Used in 1995	Shaking Severity [3]	Roman Numeral
(more than shaking) (more than shaking)			A - Very Violent			XII XI
450 300 204 141 96 66 45 30 21 15 9	286 191 130 90 61 42 30 19 13 10 6	48.7 21.6 10.0 4.8 2.2 1.1 0.5 0.2 0.1 0.05 0.02	B -Violent C -Very Strong D - Strong E - Weak <E - Very	Extreme Heavy Moderate Nonstructural Objects Fall Pictures Move	Very Violent Violent Very Strong Strong Moderate	X IX VIII VII VI V

Note 1. *Undamped velocity response spectra is equivalent, but not identical, to average acceleration spectral level.* The relationship between these quantities and the intensity values has been modified due to additional data gathers after the Loma Prieta and Northridge earthquakes (oral communication, J. Boatwright, U.S. Geological Survey). *All of the quantitative measurements of shaking strength used in this table have units of velocity, not acceleration.*

Note 2. Arias intensity is an estimate of the energy delivered to structures on the earth's surface. The actual formula is provided in Ref. 10:

$$I_\alpha = \frac{\pi}{2g}\int_0^\infty [a(t)]^2\,dt$$

where I_α is Arias intensity, g is the acceleration of gravity, and the remaining term is the integral of the square of acceleration over time.

Note 3. As can be seen from this table, the terms for shaking intensity now being used on the ABAG maps are similar, but not identical, to those used to describe San Francisco intensity (an intensity scale used following the 1906 San Francisco earthquake). These quantitative terms do not refer to the same quantitative shaking levels, however.

How Faults Were Chosen as Sources of Shaking

Fault segments generate "characteristic" earthquakes. Some faults are weak and tend to generate earthquakes with moment magnitudes of 5 and 6. However, several fault segments in the Bay Area are relatively strong and can store up enough energy to generate earthquakes of magnitude 7 or so. These stronger faults will generate these large earthquakes, not magnitude 5 and 6 events. The concept of "characteristic" earthquakes means that we can anticipate, with reasonable certainty, the actual damaging earthquakes that will occur on these fault segments. These anticipated events are the scenario earthquakes depicted in the ABAG ground shaking hazard maps.

Various researchers have produced lists of faults capable of generating major earthquakes affecting the San Francisco Bay Area. The most recent list, and the one most widely accepted at the present time, was prepared by the Working Group on Northern California Earthquake Probabilities and released in 2003. This report provides information on a number of faults or fault segments which might impact the Bay Area.

This Working Group did not compile information on some additional faults in the Bay Area that are felt to be unlikely to generate a large (greater than magnitude 6) earthquake in the next 30 years or so. These faults are responsible for background seismicity and are often poorly understood. An earthquake can occur on one or more of these other faults. While they could produce a large earthquake, they are less likely to generate a significant earthquake than the major faults included in their report and in the following table. These faults include the Maacama in northern Sonoma County, the Monte Vista on the western side of the Santa Clara Valley, and the West Napa fault in southern Napa County. ABAG has mapped shaking intensity for these three faults because the earthquakes they may generate are useful for emergency planning and stimulating mitigation efforts.

Note that the Santa Cruz Mts.-San Andreas is similar, but not identical, to the fault causing the Loma Prieta earthquake, which occurred deeper and at an angle to the principal trace of the San Andreas fault. On the other hand, the Southern Calaveras, the Southern San Gregorio, and the northern North Coast-San Andreas faults are outside of the Bay Area. The Bay Area impacts of earthquakes on these fault segments are dwarfed by their Bay Area segments so they are not included.

The length of fault that generates an earthquake can sometimes have a disproportionate impact on damage. For example, USGS has changed the fault segment "end point" for the Peninsula segment of the San Andreas fault from south of San Francisco to off the Golden Gate Bridge. This change increased the magnitude of that earthquake from 7.1 to 7.3. However, the expected number of road closures increased from over 400 to over 800, and the expected number of uninhabitable housing units increased from over 45,000 to over 107,000, largely due to increased shaking in San Francisco. Thus, "minor" changes in assumptions can make MAJOR changes in scenarios used in emergency planning.

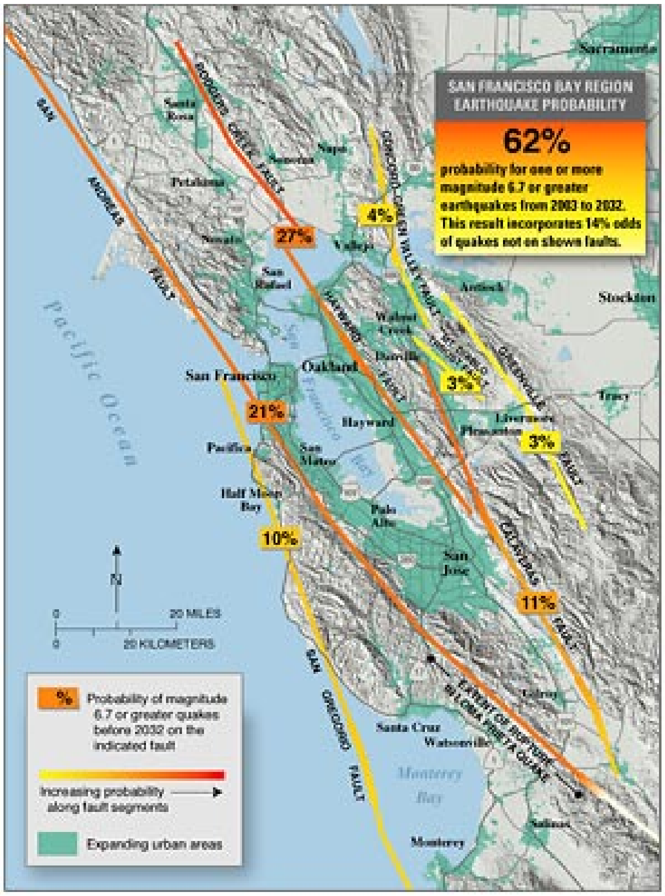

Figure 5 – Strike-Sip and Reverse Faults
Source: U.S. Geological Survey

On the basis of research conducted since the 1989 Loma Prieta earthquake, the U.S. Geological Survey (USGS) Working Group on Northern California Earthquake Probabilities published a report in 2003 concluding that there is a 62% probability of at least one magnitude 6.7 or greater quake, capable of causing widespread damage, striking the San Francisco Bay region before 2032. **Thus, a major quake is about twice as likely to happen as not to happen in the next 30 years.**

This overall regional probability is broken down by fault system on the adjacent map, with probabilities for individual fault systems shown in the smaller boxes. As is shown, many earthquake faults realistically generate these large earthquakes and the faults are located throughout the Bay Area.

Probabilities for individual fault scenarios are available from USGS as part of a larger report on earthquake probabilities.

The California Geological Survey and USGS have also produced a **probabilistic shaking hazard map of California** that shows the probability of a variety of shaking accelerations being exceeded over the next 50 years throughout California. This map may be viewed on ABAG's Earthquake and Hazard Program website at http://quake.abag.ca.gov/shaking.

All of these scenario earthquakes result in areas of modified Mercalli intensities of V to X.

Insert map of bay area faults here

Table 6: Probabilities of Selected Earthquake Scenarios Occurring in the Next 30 Years and Slip Rates on Associated Fault Segments [*based on USGS Working Group on Earthquake Probabilities, 2003 and 2008**], [*Scenario maps on ABAG web site are shaded.*]

Fault	Segment (s)	Average Long-Term Slip Rate (mm / year)	% Probability of Characteristic Quake 2002-2031	% Probability of Quake ≥ 6.7 2007-2036
N. San Andreas	Santa Cruz Mountains (SAS)	17	2.6	4.0*
	Peninsula (SAP)	17	4.4	0.6*
	North Bay (SAN)	24	0.9	0.04*
	Ocean (north of Bay Area – SAO)	24	0.9	1.9*
	South Bay Segments (SAS + SAP)	17	3.5	4.4*
	Central Bay Segments (SAP + SAN)	17 – 24	0.0	0.0*
	Northern Segments (SAN + SAO)	24	3.4	4.1*
	Bay Area Segments (SAS+SAP+SAN)	17 – 24	0.1	0.05*
	Central + North (SAP + SAN + SAO)	17 – 24	0.2	0.2*
	Entire – Repeat of 1906 (SAS + SAP + SAN + SAO)	17 – 24	4.7	3.8*
	Floating M6.9	17 – 24	7.1	6.8
Hayward/Rogers Creek	Southern (HS)	9	11.3	4.8*
	Northern (HN)	9	12.3	1.2*
	Entire (HS + HN)	9	8.5	8.8*
	Rogers Creek (RC)	9	15.2	16.3*
	HN + RC	9	1.8	2.1*
	HS + HN + RC	9	1.0	1.2*
	Floating M6.9	9	0.7	0.7
Calaveras	Southern (Outside Bay Area - CS)	15	21.3	0.0*
	Central (CC)	15	13.8	0.0*
	CS + CC	15	5.0	0.1*
	Northern (CN)	6	12.4	2.4*
	CC + CN	6 – 15	0.3	0.3*
	CS + CC + CN	6 – 15	2.0	3.6*
	Floating M6.2	6 – 15	7.4	0.0
	Floating M6.2 on CS + CC	15	7.4	0.0
Concord/Green Valley	Concord (CON)	4	5.0	0.1
	Southern Green Valley (GVS)	5	2.3	0.0
	CON + GVS	4 – 5	1.6	0.3
	Northern Green Valley (GVN)	5	6.1	0.0
	Entire Green Valley (GVS + GVN)	5	3.2	0.4
	Entire (CON + GVS + GVN)	4 – 5	6.0	2.7
	Floating M6.2	4 – 5	6.2	0.0
San Gregorio	Southern (Outside Bay Area - SGS)	3	2.3	2.1
	Northern (SGN)	7	3.9	3.9
	SGS + SGN	3 – 7	2.6	2.6
	Floating M6.9	3 – 7	2.1	2.0
Greenville	Southern (GS)	2	3.1	0.7
	Northern (GN)	2	2.9	1.0
	Entire (GS + GN)	2	1.5	1.4
	Floating M6.2	2	0.4	0.0
Mt. Diablo Thrust	Mt. Diablo Thrust (MTD)	2	7.5	0.7*
Maacama - Garberville	Southern (only part in Bay Area)	9*	*Not available*	*12.6**
Monte Vista - Shannon	Monte Vista Segment	0.4*	*Not available*	*0.02**
West Napa	Entire Segment	1*	*Not available*	*0.3**

How Distance and Directivity Affect Shaking Intensity

The epicenter is the point on the surface above the location where the fault begins the slip which generates the earthquake. There is a common myth that most damage will occur near the epicenter of the earthquake, or that the epicenter is synonymous with "ground zero." However, the earthquake epicenter is typically ***not*** the point at which most damage occurs. The fault rupture can be tens of miles long and waves are generated along the entire length of the fault.

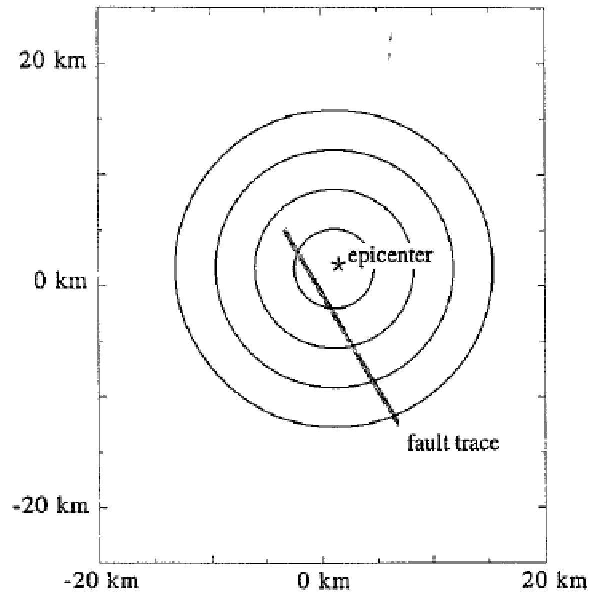

Figure 6a - There is a myth of the epicenter. This "donut" pattern is NOT the intensity pattern one should use.

Thus, predictions of ground shaking intensities are not based on distances from possible epicenters, but on distances from known faults, or segments of faults, on which large earthquakes are anticipated.

Intensity decreases ("attenuates") with distance from the fault. (See Ref. 28.) But the critical distance is not simply the nearest distance to the fault. Seismologists have come to realize that earthquake sources radiate energy at depth; thus, the distance used to attenuate expected shaking must be measured between the site and this underground source. (See Refs. 1995-25, 33, 34, 35, and 38.) However, rupture propagates both upward from this underground source and along the fault axis. (This "directivity" effect is described in the next paragraph.) Thus, there is significant amplification of shaking within a mile of these major fault zones.

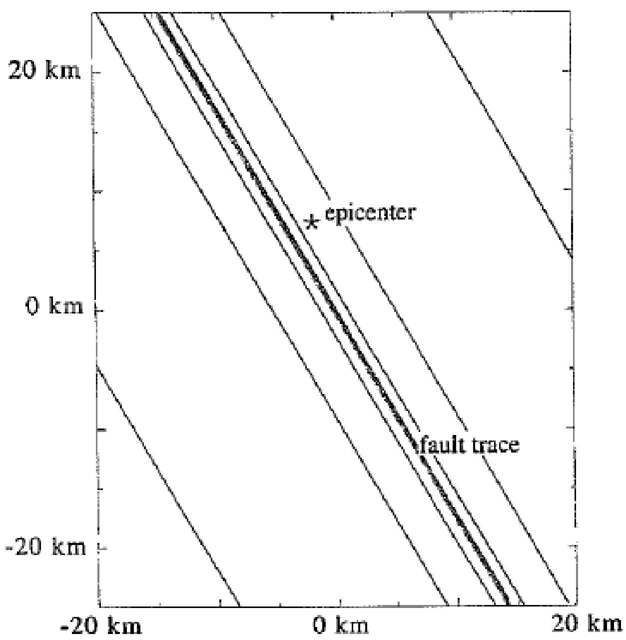

Figure 6b - In general, areas closer to the source fault will be shaken more than areas further away.

Directivity, or focusing of energy along the fault in the direction of rupture, is a significant factor for most large earthquakes in the Bay Area, including the Loma Prieta earthquake. Shaking intensity decreases ("attenuates") much more rapidly perpendicular to the fault rupture plane (or surface fault trace) than along the fault axis. Thus, San Francisco and Oakland, in line with the fault axis, felt stronger shaking than expected in the Loma Prieta earthquake, while San Jose, perpendicular to the fault, felt weaker shaking. The directivity varies with the location of the epicenter. The maps show an "average" directivity since we do not know the location of the epicenter prior to an earthquake. (See "On Shaky Ground" Appendix A and Note below for more technical information.)

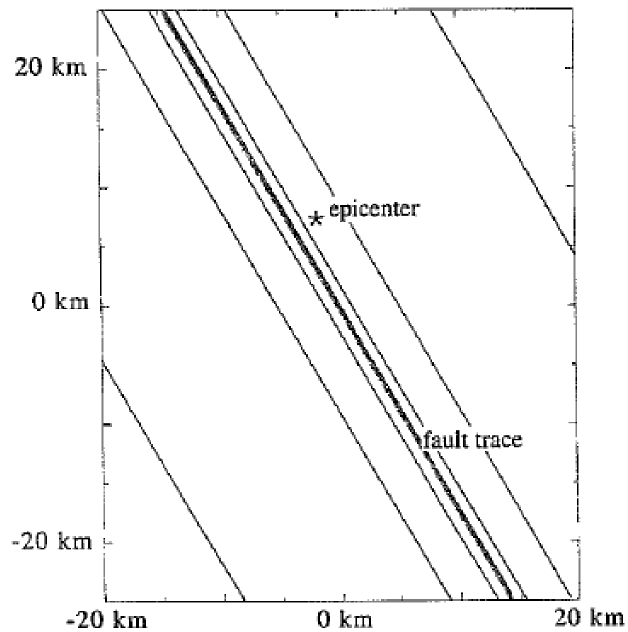

Figure 6c - Elongated pattern shows intensity decreasing much more rapidly perpendicular to the fault source than along the fault axis.

The final factor affecting the change of intensity with distance from the fault is the magnitude of the earthquake. The intensity boundaries extend further from the fault source for larger magnitude earthquakes. Thus, a site 20 miles from the fault source will experience stronger and longer shaking from an earthquake with a moment magnitude of 7 than from an earthquake with a moment magnitude of 6. Even though the energy released in an earthquake is over thirty times as great in a magnitude 7 earthquake than a magnitude 6 quake, the shaking is not 30 times as intense. Rather, a larger area is exposed to strong shaking.

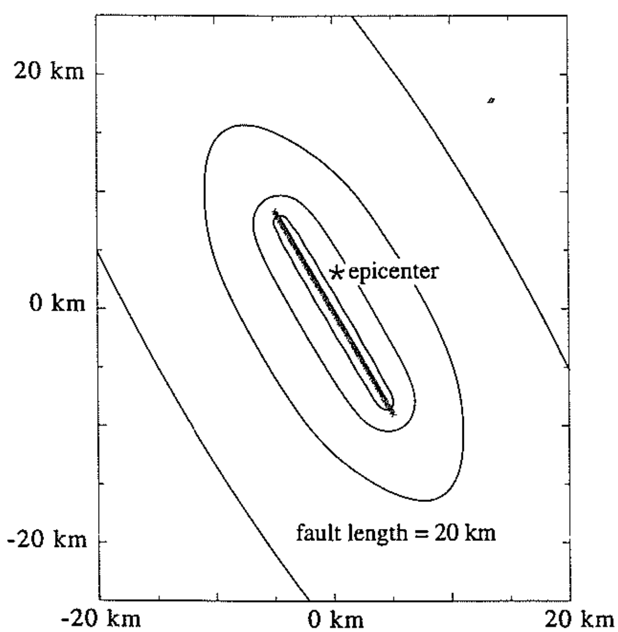

Figure 6d - Elongated bands of intensity shrink for earthquakes of smaller moment magnitudes. For the earthquakes of concern to us, modified Mercalli intensities are assumed to range from V to X, regardless of the moment magnitude of the earthquake.

Note: *One additional factor in the recent Loma Prieta earthquake was the reflection of the seismic waves from the Moho. (The "Moho" is short for the Mohorovicic discontinuity, the boundary between the earth's crust and mantle, and is named for the Croatian scientist who discovered it.) This "bounce" resulted in stronger shaking which ranged from 45 to 60 miles from the fault trace and amounted to somewhere between one-half and one intensity increment level increase over what might have been expected. (See, for example, Ref. 45.) Both Oakland and San Francisco were within this distance band. However, there are insufficient data to reliably calculate such increases for future earthquakes. Because the Loma Prieta earthquake began deeper than is typical for Bay Area earthquakes, this Moho-related increase was probably closer to the fault source than would be expected in future Bay Area earthquakes. Thus, the increase, if it occurs, will be in areas with lower baseline shaking levels and should result in small or insignificant increases in damage.*

How Geologic Materials Affect Shaking Intensity

All ground in the Bay Area was ***not*** created equal. A critical factor affecting intensity at a site is the geologic material underneath that site. Deep, loose soils tend to amplify and prolong the shaking. The worst such soils in the Bay Area are the loose clays bordering the Bay – the Bay mud –and the filled areas. The type of rock that least amplifies the shaking is granite. The remaining materials fall between these two extremes, with the deeper soils in the valleys shaking more than the rocks in the hills. Most development is in the valleys. The map below groups the geologic materials in the region into eight categories, each with similar amplification in earthquakes.

If you compare two houses, both of which are the same distance and orientation to the earthquake source, the one on Bay mud will experience stronger and longer shaking than the one on rock.

The role of geologic materials in affecting the intensity of shaking has been known for almost 30 years. Several researchers at the U.S. Geological Survey clearly demonstrated this relationship when they examined data from the 1906 San Francisco earthquake in 1975. (See Ref. 1995-28.) Other researchers have expanded this effort by examining the relationship between intensity and geologic materials. (See Ref. 1995-36.) Although the categories of geologic materials are the same as used in earlier ABAG maps (Refs. 1995-41, 42, 43, and 44), the extent to which these materials modify the shaking intensity has been changed slightly. These susceptibility categories are quite similar, but not identical, to the categories recently developed for use in site-dependent building code provisions. (See Ref. 1995-26.)

The distance-based intensities mapped for each scenario earthquake are increased or decreased based on the shaking amplification potential of each geologic material to produce the final intensity map for each scenario. The extent of these changes ("intensity increments" or fractional changes in intensity units) is listed in Appendix B.

MAP NEEDED HERE

The Role of Thrust Faulting in Contributing to the Bay Area Earthquake Hazard

Most of the major faults in the Bay Area are strike-slip faults, where the rupture plane extends almost vertically into the ground and the ground on one side slips horizontally past the ground on the other side of the fault. There are, however, several thrust or reverse faults in the Bay Area, where ground moves upward and over adjacent ground. (These faults are more common in southern California than the Bay Area because the San Andreas fault makes a large bend to the west there before heading northwest. Many thrust faults in southern California are caused by this bending.)

In the Bay Area, thrust faults are less well understood than strike-slip faults. However, the U.S. Geological Survey is actively conducting studies of several of these faults or is funding studies by other researchers.

One of the most dangerous Bay Area thrust faults, because of its location near an urban area, is the Monte Vista fault on the western side of the Santa Clara Valley. However, this fault has a long recurrence interval for large earthquakes - on the order of several thousand years. As with other thrust faults, we know generally where the fault is located, but it is difficult to identify the actual surface trace.

We estimate that an earthquake on the Monte Vista fault might generate 15,000 uninhabitable housing units, almost as many as the Loma Prieta earthquake. Notably, 13,500 would be in Santa Clara County, making it as damaging in the county as a magnitude 7.3 on the entire Hayward fault.

The most active thrust fault in the Bay Area is the Mt. Diablo thrust fault. This fault has made Mt. Diablo the fastest growing mountain in the Bay Area.

Each of the seven Great Valley faults identified along the western side of the Central Valley are also thrust faults. The location and size of earthquakes generated by the Great Valley faults are less well understood than for the Monte Vista. The recurrence intervals for earthquakes on segments of this fault system may be as short as approximately 500-600 years, but this estimate is uncertain.

Because the Northridge earthquake was caused by a reverse fault and there was a small thrust component in the Loma Prieta earthquake, it is possible to test various ways to model shaking caused by movement of thrust faults. ABAG is testing such a model in cooperation with researchers at USGS. Interim maps using that model are used to create shaking intensity maps for the Mt. Diablo and Monte Vista thrust faults, as shown below.

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Map Plates for 18 Scenario Earthquakes