Geologic Constraints on the Seismic Hazard of the White Wolf Fault Earthquake Zone

Nathan Earl Robison, September 1999

Abstract

Field methods established by Brune and others are used in surveying precarious and semi-precarious rocks within 10-15km of the White Wolf Fault, which ruptured in 1952 in the Kern County or Arvin/Tehachapi earthquake, one of the three most significant in California history. Twenty-five (25) rocks were identified and catalogued. A method of estimating the toppling accelerations is developed using graphical and geometrical calculations in drafting software. The rocks range in estimated horizontal toppling acceleration from 0.12g to 0.61g, with a mean of 0.33g. A permanent database of precarious rock data is suggested as a model for comparison with traditional seismic hazard analysis.

Introduction

Probabilistic seismic hazard analysis is based on two distinct analyses. First, a fault model must be generated, in which knowledge of the geology, structural characteristics (potential rupture length, sense of rupture, e.g. thrust, strike-slip) and in some studies topography and potential amplifying or dampening structures. In addition, rates of slip and thus potential activity of a fault must be estimated. Second, a means for calculating the attenuation of strong ground motion must be developed which adequately predicts the effect of a seismic event of a given magnitude and location, as developed in the faulting model.

Almost two centuries of geologic and public observation have refined the first analysis to give a reasonably accurate picture of earthquake sources. However, the omissions, in the form of faults which have no surface expression;

blind thrusts or long return period faults, may in some cases be more significant than the knowledge which we possess.

A thought experiment proposed by J. Anderson is as follows: imagine a strong-motion seismometer at an arbitrary location that recorded continuously for 2500 years. If the collected data were organized by determining number of events in which each of several discrete values of acceleration were exceeded, and dividing the recording interval by these number of events, the result may look as follows:

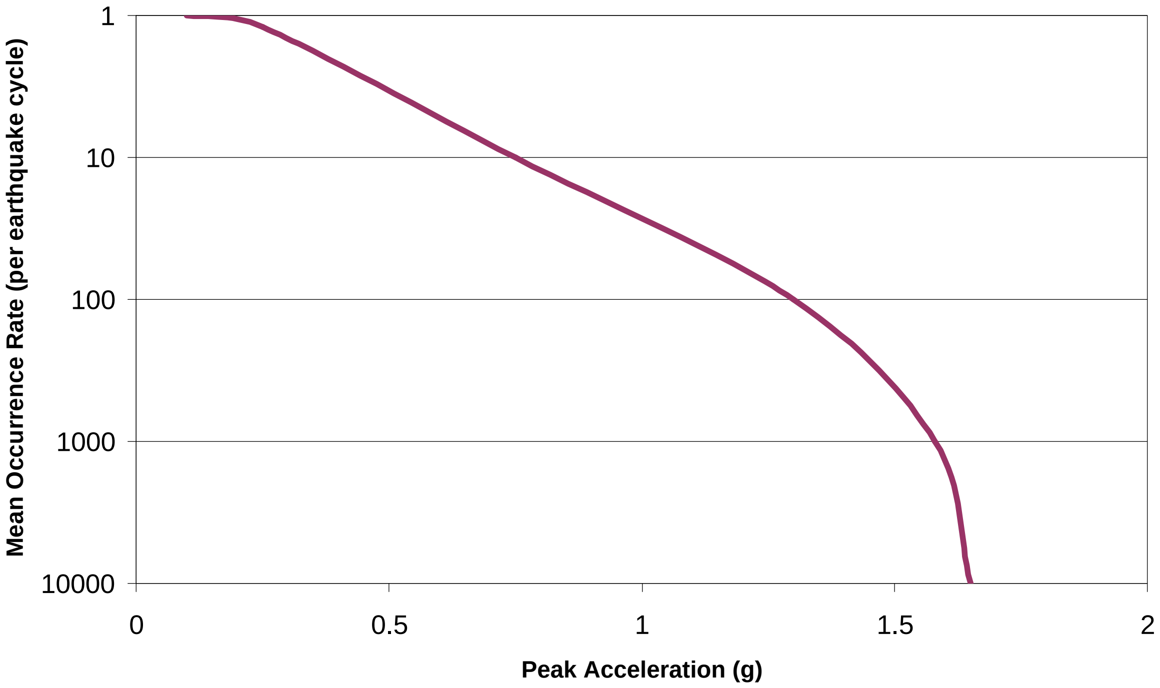


Figure 1.1 Characteristic Seismic Hazard Model

Chart adapted from Anderson, J. and Brune, J., 1999

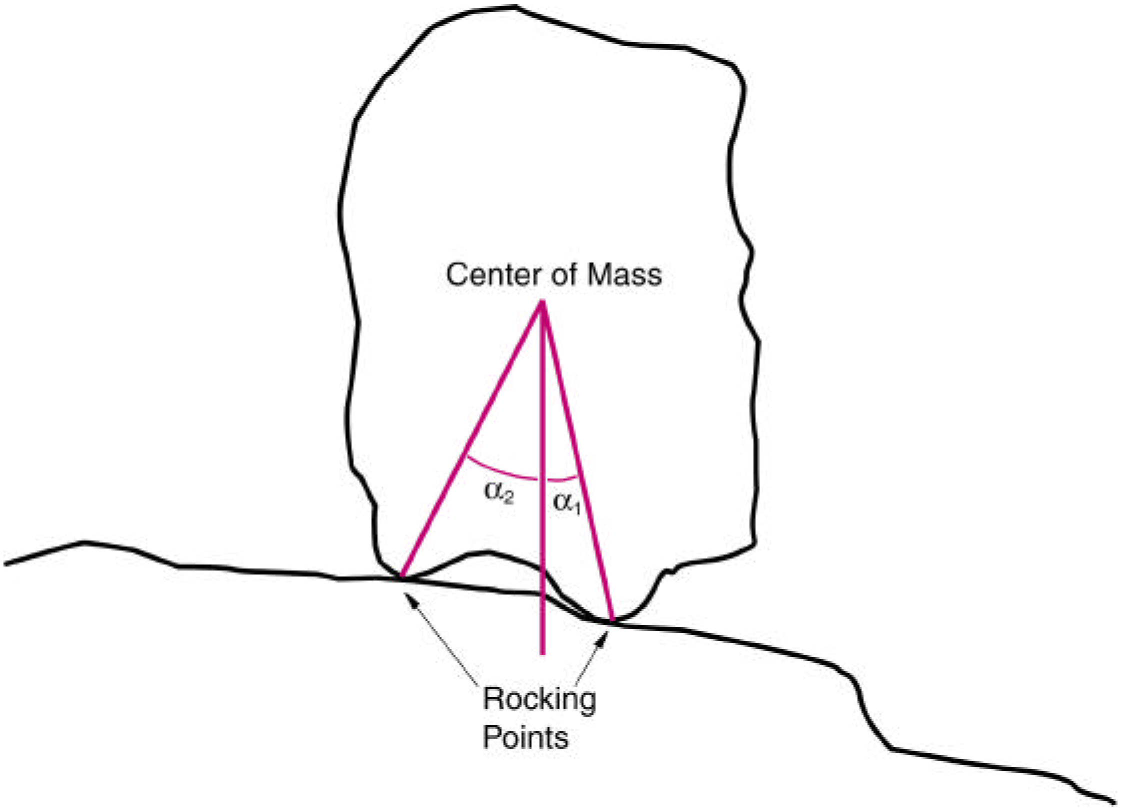
Simply put, our historical sample of some 200 years is quite insufficient to characterize the longer-return section of this hypothetical model. Though physical models and observance suggest that there are practical limits to the energy that a particular fault source may release, there remains considerable debate over the true nature of the 500-year and later shape of such a graph.

Thus, much of the challenge of modern seismology is to answer the simple question "how bad can it get." Paleoseismology in the practices of fault trenching and reconstruction from historical accounts are limited in application, the former because the physical connection of an earthquake source and the hazard it presents for near- and far-field sites is not entirely clear, and is severely complicated by site effects and incomplete data, and the latter because accepted intensity correlations remain elusive, and at best (in the US), historical records only extend our view 100 or so years; not the order of magnitude necessary to answer the question posed above.

At this point we search for alternatives. Jim Brune has proposed that balanced rocks, if the acceleration necessary to topple them could be found, may be a means to understanding paleoseismicity. (Brune, J., 1999) As early as 1963, Housner and others (Housner, G., 1963) examined the analytical response of precarious objects and structures to strong ground motion. This was done in response to the observation that some structures, such as water tanks and weak masonry buildings, sometimes survived earthquakes unexpectedly. More rigorous analyses by Shi et al. (Shi et al., 1996) support Housner's general conclusions about the horizontal acceleration necessary to topple precarious objects, but show that, for cyclical motion, the necessary peak acceleration may be lower than that concluded by Housner.   Shi et al. show that the horizontal acceleration necessary to topple a rigid object may be determined from the mass, geometry, and natural frequency of the object as well as characteristics of the input motion.

In a simpler and somewhat conservative pseudo-static analysis, the acceleration necessary to topple a rigid object may be shown to be simply the tangent of the interior angle connecting the center of mass and the angle to a rocking point of contact, as diagrammed below:

Figure 1.2: Diagram of a balanced rock and angle α



This angle, α, may easily be estimated in the field by lining up an assumed center of mass with the rocking point and measuring the vertical angle with a Brunton compass. More exacting analysis requires independent determination of the mass of the rock and the force required to tip it on this rocking point – a considerable use of time complicated by difficulties in determining volume or mass directly. The current field study includes a method for refining field observations using computational drafting techniques.

The use of balanced rocks in seismic hazard analysis has been extensively documented by Brune and others. The intrinsic value of these common geologic features is their probable longevity. Age determination by several means has been used to quantify the geologist's intuition that very little changes in 2-3 thousand years; rocks which appear to have faces weathered by exposure, or which display desert varnish, lichen growth, photodegradation, or other testable features. In addition, the history of exposure of the rocking base must be determined to demonstrate that such a rock was free to move during the time span of interest. Using paleoclimatic knowledge and analysis of soil erosion rates, rocks with bases exposed   0.3m may comfortably be assumed to have been exposed over the past 3 thousand years, except in areas of rapid geomorphologic change.

The 1952 Arvin/Tehachapi Earthquake and White Wolf Fault

The series of earthquakes in the study area during 1952 were generated by NE-striking left-lateral reverse ruptures along a fault dipping approximately 60^{O} to the SE, with most of the movement reverse. This earthquake source, the White Wolf Fault, had been recognized by geologists, but its modern potential to generate so severe an earthquake (M_W 7.5 on July 21, 1952) had not been presumed.

Probably no earthquake in history has been so completely studied; the happenstance placement of strong motion instruments, geologic data from petroleum exploration, rapid and massive response from seismological institutions, and the social significance of this earthquake made it one of the best sources of data for modern seismology. The destruction caused by the earthquake in the nearby towns of Tehachapi (about 23km SE of the fault trace, on the hanging wall) and Arvin (about 5km NW of the fault trace, on the footwall) accounted for much of the $60 million in losses due to the earthquake. Structural, highway, and utilities damages were in some cases catastrophic. (Oakeschott, G., 1954)

The 1952 earthquake was one of the three greatest in California history. Still the question remains; how much worse can it get? Shattered bedrock, a steep upthrust mountain range, and possible landslide blocks on the order of $5km^3$ attest to a long history of events on this fault. But is that earthquake history one of similar, characteristic events, or of a random range of larger and smaller earthquakes with no clear upper boundary?

Several characteristics of the White Wolf fault region point to a history of intense energy release. In particular, the region of shattered rock near the scarp on the hanging wall of the fault is evinced by geomorphologic and physical features. Most noticeably, the stream channel formation more closely resembles erosion of a soil than rock. Gently sloping dendritic, intermittent watersheds terminate in weakly developed alluvial fans and the footwall basin of Arvin and Bakersfield. The formation of the fans is probably interrupted by rock avalanches, the scarp itself, and other dominating features of the active mountain front. Massive landslide blocks, on the order of several cubic kilometers of material, may have been released from the tectonically over-steepened and strain weakened shattered granitic slopes of Bear Mountain and the disconnected section of the Tehachapi Mts. to the southwest.

Methods

Selection of sites for precarious rock surveys is at present controlled by the significance of the region, known seismicity, and geologic suitability.

The significance of the White Wolf fault zone is related to its proximity to the major city of Bakersfield and Los Angeles, the significant agricultural and petroleum economic value of the region, and the value of information it provides on major thrust fault events in general.

The seismic setting is a complex result of compressive strain generated by a left-bend in the San Andreas fault and relations in the strain regime to the Garlock, Pleito, and Kern Canyon faults.

Granitic corestones developed by subsurface weathering and exposed by erosion are the most likely candidates for balanced rocks. Volcanic formations such as tuffs, andesites, and basalts may also be of value, but the means of exposure and outcrop degradation may make these rock types less determinate, and in any case rarer, than the granitic exposures. In this area, Mesozoic granodiorite and granite outcrops with strongly developed joint sets are prominent and very common.

The field activity of surveying for precarious rocks consists of several steps. Regions fitting the description above are identified, and an initial reconnaissance using aerial photographs or binocular/telescope review of visible slopes. If data, that is, balanced rocks appear likely, closer inspection is undertaken by driving along ridge crests and opposing valley slopes, if possible, for likely candidate rocks. It is important to establish several viewpoints, in that a rock that appears balanced from one angle may prove to be attached to outcrop, leaning against a slope or vegetation, or otherwise not free to rock and topple. Thus the process is initially an application of geologic and physical instinct - identification of rocks at some distance with 10x binoculars is very much a learned application of the mechanics of the earth.

After likely individual rocks were identified, they were approached on foot, and if an initial overview suggested a precarious state, the following procedure was undertaken to catalogue the rocks:

Field Documentation

A. Careful notes describing the rock are taken, including but not limited to;
    1. Height of pedestal or other potential measure of base exposure
    2. Existence of lichen, desert varnish, photodegradation, evidence of release of rock material (fresh surfaces or surrounding debris)
    3. Evidence of freedom to rock – including attempting to move by hand or complete separation from base.
    4. Estimate of mass
    5. Description of geology, degree of weathering, presence of regolith, and general observations of the condition, not obviously related to the determination of precariousness.
    6. Available means of testing; may be trees or well-set rocks nearby to which a cable could be attached, or closer rocks against which a jack might be placed.

B. Location of the rock is estimated on a map using standard triangulation and measuring techniques. This location is verified, if available, by a GPS receiver, calibrated to the base map geodesy and allowed to iteratively decrease error while other measurement are being taken. In addition, the estimated GPS position error and elevation are recorded, if available.

C. A plumb bob is attached by a nail or by hanging from a protrusion. Ideally, a Gammon reel is used for more accurate determination of the vertical direction. The distance from the center of the cross on the Gammon reel and the tip of the plumb bob is taken.

D. A Brunton compass or other device is used to estimate the α angle by sighting down an horizontal line perpendicular to the most precarious cross section and including the estimated center of mass, holding one end of a line in the instrument visually on this line, and crossing with the instrumental line the rocking point. Using a bubble level, the vertical angle is measured and recorded as α. Ideally, this estimation may be done several times during cataloguing of the rock or by several investigators.

E. The rock is photographed along this horizontal line. In particular, any protrusions or oddities of shape which are obscured by the rock body in the photograph are noted.

F. A sketch of the rock is made for correlation with photographs later and for identification of significant features. This exercise may refine the quality of observation significantly, and provides a record should photographs be lost.

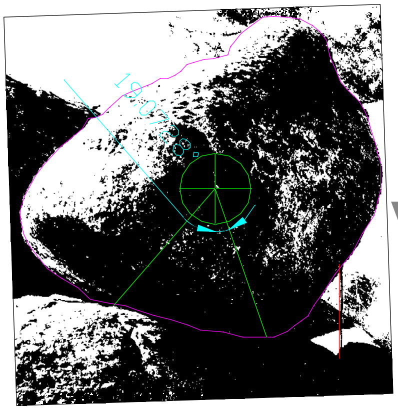
The process described above is at once good observational field geology and a means of refining judgment and insight into the physics of the rocks. As can be observed in the field records presented below, this researcher's estimates of α in the field improved significantly even in the course of this field time. As this cataloguing is being done, an overall picture of the regional seismicity and geology should be kept in mind. A rock 6km from a fault, which has a toppling acceleration of 0.3g may be more important than one 12km from the fault which could be overturned by 0.15g. As well, observations of areas with many potential balanced rocks or that appears dramatically "shaken down" may indicate that site effects or unrecognized earthquake sources may be influencing the region.

Included in the process of documentation is a description of the means available to test the rock. Testing, as mentioned in the introduction, is time-consuming and may be subject to considerable error in the estimation of mass and volume of a rock. However, direct testing is probably the surest means to establish a defensible value for toppling acceleration. Following is a description of a method of refining the visual method of field estimation which, if shown to correlate well with testing results, could offer a satisfactory alternative to direct testing,

Center of Area Method

In this procedure, which we describe as the "center of area method," a developed photograph of the rock is scanned into a raster graphic computer file, in this case the GIF compression format, which offers better resolution than the JPEG. This image is imported into graphics software. The plumb bob is used to (1) scale and (2) rotate the image to exact vertical.

Figure 2.1: Example of calculation of α by center of area method



WW-10

View to 346°

α=19.1°

Autodesk software (AutoCAD R14) includes a method of calculating the centroid of an area (or a volume, for that matter, if more involved surveying techniques were used to fully characterize the rock's shape) In this method, a line is drawn connecting the center of the Gammon reel and the end of the plumb bob, and the length of this line is determined within the software. Then the image and line are scaled using the <scale> command to their actual dimensions for communication of the size of the rock and clear comparison with others. Next, a polyline is manually drawn around the perimeter of the rock, the command<region> is entered and the software prompts the selection of objects. The closed polyline is selected and the command <massprop> is entered. The defined region is selected and such properties as the x-y location of the centroid and moment of inertia are displayed. Lines are drawn vertically from the centroid and from the centroid to the furthest contact point of the rock with the pedestal. The Dimension tool is then used to measure this angle.

This method has several advantages and disadvantages. It is intended to mimic the psychology of the field estimation technique, without the considerable sources of error in the cruder angles determinable, unsteadiness of hands, and the difficulty in estimating the location of the center of area or mass, particularly in the vertical direction. It is simple and readily reproducible, and requires no additional field work except added care in photography. The sources of error are in the photograph itself- if it is not taken along a hypothetical line through the center of mass, and in the possibility of irregular shape. Strictly, the method assumes that the largest cross section is representative of all arbitrary cross sections parallel to the photograph, in that the distribution of mass in these cross sections would be identical. This is, of course, not generally true, however if the axis of the photograph is generally the same as that of some regular geometric shape, such as a sphere, rounded rectangle, or ellipsoid that the rock approximates, the error introduced should be negligible. In addition, judgment or notation in the field may correct for gross irregularity in the shape of the rock.

A total of 25 rocks were catalogued in the Tehachapi Mountains/Bear Mountain area. A summary of the results of field and analytical work is presented below.

Table 2.1: Summary of White Wolf Fault Zone Precarious Rock Survey

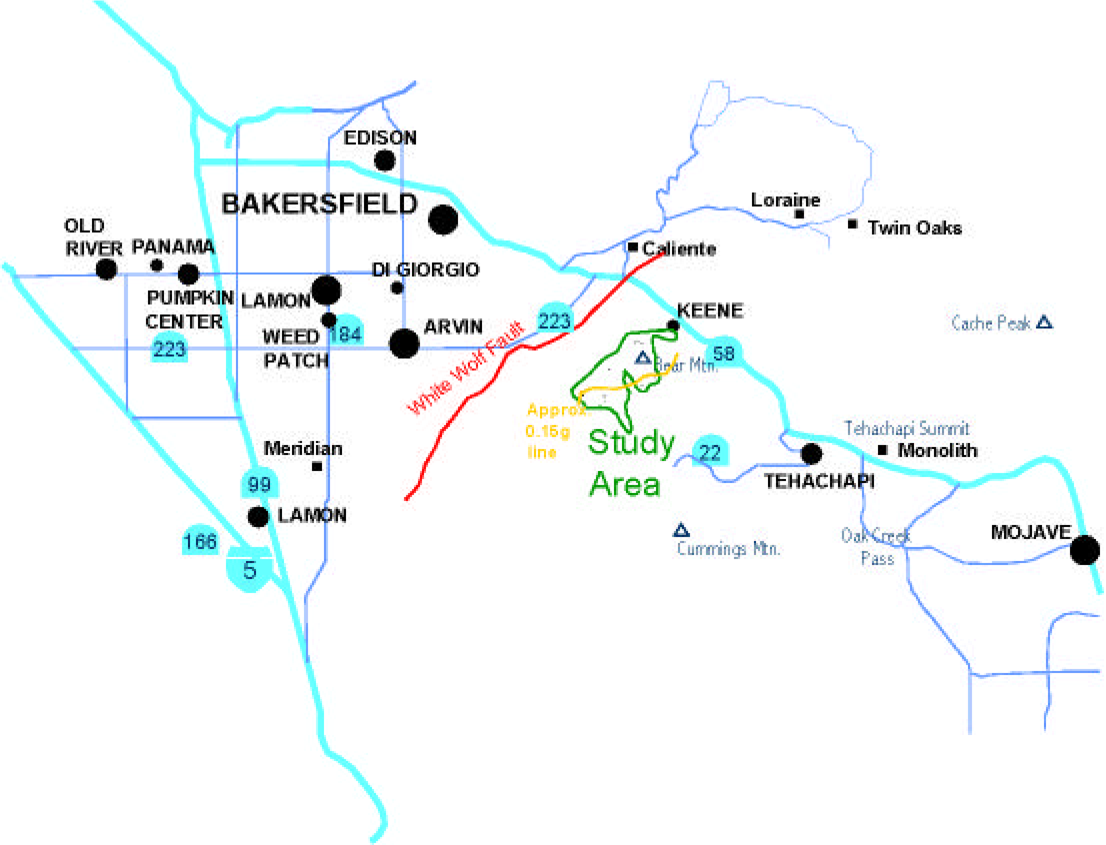
		Position		estimated	$\alpha_{\text{field estimate}}$		$\alpha_{\text{center of area}}$		Min. Tipping
Rock	Description	latitude	longitude	error (m)	deg.	g	deg.	g	Axis (deg.)
WW-01	massive, perched on 3m pedestal	35.091	-118.650	13.7	26	0.49	18.280	0.33	182
WW-02	midsize, 3 tipping directions, overhanging, squat, 0.5m pedestal	35.118	-118.680	13.1	21	0.38	19.824	0.36	186
WW-03	small/midsize, 2 tipping directions, squat, easily moved by hand	35.114	-118.680	11.9	15	0.27	19.484	0.35	266
WW-04	Massive, old, 1.5m pedestal, several semi-precarious in area	35.115	-118.680	10.5	15	0.27	23.838	0.44	170
WW-05	large, 0.7m pedestal, old	35.113	-118.683	10.1	18	0.32	26.686	0.50	351
WW-06	large, <0.1m base	35.117	-118.682	8.3	18	0.32	17.280	0.31	003
WW-07	small, well-developed pack-rat midden, 1.1m pedestal, moved by hand	35.117	-118.684	9.3	14	0.25	13.043	0.23	340
WW-08	large, base in 1cm of soil, for 1952 only?	35.117	-118.683	8.3	8	0.14	24.401	0.45	177
WW-09	midsize, 2 tipping directions, close to soil level on one side	35.121	-118.681	12.3	20	0.36	31.321	0.61	332
WW-10	large, 0.9m pedestal, old (lichen)	35.111	-118.681	10.0	12	0.21	19.073	0.35	346
WW-11	small, 0.1m pedestal, moved by hand	35.111	-118.689	10.2	20	0.36	14.497	0.26	321
WW-12	midsize, 0.5m pedestal, old (lichen)	35.115	-118.692	10.1	17	0.31	14.239	0.25	008
WW-13	massive, 0.6m pedestal, old (lichen)	35.121	-118.718	13.1	13	0.23	10.075	0.18	122
WW-14	midsize, 0.5m pedestal, old (lichen)	35.153	-118.604	13.7	17	0.31	21.675	0.40	175
WW-15	large, 1 tipping direction, 0.4m pedestal, old (lichen)	35.155	-118.603	13.2	14	0.25	15.742	0.28	332
WW-16	massive, (24 tons+), 1.2m pedestal, v. old breakage made precarious	35.150	-118.594	10.8	18	0.32	20.646	0.38	350
WW-17	midsize, 0.2m pedestal, moderate age (lichen)	35.149	-118.593	9.9	16	0.29	26.346	0.50	021
WW-18	large, 1.4m pedestal, clear separation from base	35.138	-118.615	15.4	14	0.25	7.104	0.12	012
WW-19	large, easily reached by car, sliding has made precarious, 0.3m pedestal	35.160	-118.673	13.9	15	0.27	14.124	0.25	151
WW-20	large, free to rock, v. old (lichen, wx), 0.5m pedestal	35.184	-118.636	11.0	14	0.25	14.265	0.25	206
WW-21	small, squat, near to road, 2.5m pedestal	35.187	-118.601	12.1	14	0.25	19.282	0.35	185
WW-22	large, several semi-prec. adjacent, near to road, 0.8m pedestal	35.198	-118.616	14.8	15	0.27	16.641	0.30	108
WW-23	v.massive, 40 tons+, near to ground	35.199	-118.627	14.5	15	0.27	16.145	0.29	100
WW-24	massive, 18 tons+, near historic cabin ruins, road, 1.3m pedestal	35.201	-118.623	14.6	15	0.27	14.764	0.26	160
WW-25	midsize/large, 0.1m pedestal, old (lichen)	35.220	-118.559	8.9	14	0.25	13.725	0.24	304

The standard deviation of field estimates of α and tanα with respect to the center of area method are 1.232 and 0.024, respectively. Several of these rocks impose significant constraints on the history of strong ground motion in the region. Testing verification of the lowest-α rocks should be conducted in conjunction with dating of the exposures. Note that published maps showing 2% probability of exceedance in 50 years (roughly analogous to a 2500-year return event) suggest peak accelerations of 0.6g to 0.8g throughout the study area.

Mapping

The locations of rocks are projected on to an electronic or paper base map by standard mapping methods. In this study the UTM projection was used for correlation with USGS 7½-minute quadrangles. A schematic of the study area is presented below.

Figure 2.3: Regional map of study area and approximate limit to ground motion (approx. scale 1:1,000,000)



The locations of the rocks themselves are located exactly according to the UTM grid projection. A method was developed to read a "script" of commands into drafting software, which plots their physical locations with the z-component equal to estimated toppling acceleration as circles, the radius of which are determined by the estimated position error of GPS readings. This technique, with a suitable base such as a compiled digital model of 1:100,000-scale maps being prepared by the USGS, may serve as the basis for a permanent catalogue of precarious rocks in California and Nevada. Such a map may be contoured with respect to the estimated toppling accelerations of these rocks, or could be used as a comparative model in probabilistic seismic hazard analysis.

Discussion

Southern California is among the most seismically active regions in the world. Great earthquakes within human memory have fostered an atmosphere of research and regulation that has saved much in human life, property, and public works. However, the cost of earthquake-resistant design and construction is considerable. Among the goals of seismologists and regulators should be the clarification of realistic hazard; toward answering the question "how bad can it get?" we are economically and socially bound to use all the information at our disposal. The possibility of several thousand low-resolution seismometers that have "recorded," or rather survived a seismic history which we otherwise have almost no access to is exciting. Even with the limits of anisotropy and potential for error in estimation of the ground motion required to topple them, balanced rocks are a resource which potential should not be overlooked.

The techniques developed in this study and geographic extent of the survey are intended to contribute to the developing basis of paleoseismic evidence in the balanced rock record. Potentially, as suitable and well-correlated data is gathered, significant constraints may be placed on long return period seismic hazard analysis for all of the western United States. In a sense, these discrete data points are a means of minimizing the epistemic component of uncertainty that is factored in to analysis, bringing our understanding of regional seismicity closer to the truth.

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