Report of the Workshop on Extreme Ground Motions at Yucca Mountain, August 23-25, 2004

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The Workshop on Extreme Ground Motions at Yucca Mountain

August 23, 24 and 25, 2004
U.S. Geological Survey, Menlo Park, CA 94025

The Workshop Committee:
T.C. Hanks, Chair, N.A. Abrahamson, M. Board, D.M. Boore, J.N. Brune, and C.A. Cornell

INTRODUCTION

This Workshop has its origins in the probabilistic seismic hazard analysis (PSHA) for Yucca Mountain, the designated site of the underground repository for the nation's high-level radioactive waste. In 1998 the Nuclear Regulatory Commission's Senior Seismic Hazard Analysis Committee (SSHAC) developed guidelines for PSHA which were published as *NUREG/CR-6372*, "Recommendations for probabilistic seismic hazard analysis: guidance on uncertainty and the use of experts," (SSHAC, 1997). This Level-4 study was the most complicated and complex PSHA ever undertaken at the time. The procedures, methods, and results of this PSHA are described in Stepp *et al.* (2001), mostly in the context of a probability of exceedance (hazard) of 10^{-4}/yr for ground motion at Site A, a hypothetical, reference rock outcrop site at the elevation of the proposed emplacement drifts within the mountain. Analysis and inclusion of both aleatory and epistemic uncertainty were significant and time-consuming aspects of the study, which took place over three years and involved several dozen scientists, engineers, and analysts.

Because of these uncertainties, the 1998 Yucca Mountain PSHA provides for progressively higher ground motions as it is extended to progressively lower hazard levels: at mean-value hazard levels of 10^{-6}/yr, 10^{-7}/yr, and 10^{-8}/yr, the resulting peak ground accelerations (PGA) and peak ground velocities (PGV) are 3 g, 6 g, and 11 g and 3.5 m/sec, 7 m/sec, and 13 m/sec, respectively. We refer to these as *extreme ground motions*, the extremely large-amplitude ground motions that will arise in any PSHA at extremely low probabilities-of-exceedance, given untruncated ground-motion distribution functions. These large-amplitude ground motions have generated considerable consternation in the scientific, engineering, and regulatory communities, for such PGV's and PGA's have never been recorded for earthquakes, present exceptional challenges to the design and construction of the underground facilities, and are regarded by at least some qualified seismologists as "physically unrealizable."

The most direct way of addressing these extreme ground motions is to re-visit and re-calculate the 1998 Yucca Mountain PSHA, but the Workshop Committee (or "Committee") concurs with the consensus view that the 1998 Yucca Mountain PSHA should not be re-opened unless and until there is a solid scientific and/or technical basis for doing so. The Workshop Committee also believes that the demonstration of physical limits to earthquake ground motion that can be meaningfully applied to the 1998 Yucca Mountain PSHA would provide such a basis.

There is more to this problem than just physical limits to ground motion, however. When Jim Brune speaks to ground accelerations associated with untoppled, precarious rocks, for example, he speaks to ground motions that have not been exceeded at specific sites populated by these precarious rocks for specific periods of time. These "unexceeded" ground motions are far less than likely physical limits for these sites, if only because they are considerably smaller than many instrumentally recorded ground accelerations.

It is also important to distinguish what **can** happen at Yucca Mountain (or any other place), which involves long, essentially open intervals of time that might involve hundreds of millions of years, and what **has** (or **has not**) happened at Yucca Mountain over the closed, much smaller interval of 12.8 Ma since the volcanic section in which the mountain exists was laid down. The Committee, for example, is convinced, for reasons discussed below, that the 10^{-6}/yr hazard PGV = 3.5 m/sec has not passed through the lithophysal units of the Topapah Springs tuff since these lithophysae were formed more than 10^{7} years ago. Whether or not such ground motions **can** pass through these units, which must be considered in the context of hazard levels of 10^{-7}/yr to 10^{-8}/yr, will be decided on other grounds, however.

Unexceeded ground motions, then, are ground motions that have not happened at a specific site for a specific time interval, at the locations of precarious rocks for the past tens of thousands of years, for example, or in the lithophysal units since 12.8 Ma. Physical limits to earthquake ground motions specify amplitudes of ground motion that cannot happen, ever. PSHA calculations can employ both unexceeded ground motions and physical limits to ground motion. To a limited extent, unexceeded ground motions (for precarious rocks) were considered in the 1998 Yucca Mountain PSHA. The many participants in this exercise did not, however, consider physical limits to earthquake ground motions in their deliberations, for it was never anticipated that they might make a difference. We now know better. The primary purpose of the Workshop was to explore the state of knowledge pertaining to a wide range of geologic structures that speak to unexceeded ground-motion levels and define real or potential physical limits to earthquake ground motion, as they might apply to either the excitation or propagation of the radiated field of crustal earthquakes.

Finally, it is worth noting explicitly that physical limits to earthquake ground motion do not exist in the realm of linear elasticity, in which earthquake scientists have lived so successfully for more than a century: they arise from non-linear, dissipative deformation mechanisms that are fundamentally due to the finite strength of crustal rocks and their erosional detritus.

WORKSHOP ORGANIZATION AND OVERVIEW

Broadly speaking, the Workshop on Extreme Ground Motions at Yucca Mountain was organized around the two themes of unexceeded ground motions and physical limits to ground motion. Most of the first day, however, was devoted to presenting and exploring the results of the 1998 Yucca Mountain PSHA (Stepp *et al.*,2001), as well as the more recent PEGASOS PSHA conducted for nuclear power plants in Switzerland (Abrahamson *et al.*, 2002).

The purpose of these talks was to get everyone into the same bandwidth as to how and why extreme ground motions arise in the first place and how and why unexceeded ground motions and/or physical limits might make a difference in dealing with them. Most earth scientists are not well attuned to even the basics of probabilistic hazard analysis, let alone the additional and subtler problems that arise at very low hazard levels. Nor do they know of the substantial body of relevant science and innovative methodology in seismic hazard analysis that the Yucca Mountain Project has contributed. At the same time, the scientists and engineers of the Yucca Mountain Project are constrained by existing PSHA methodology related to extremely rare events to accept unrealistically large ground motions. Thus the Committee, through this workshop, was looking for research that will help advance the state of the science and enable reductions in uncertainty in extreme ground motion predictions.

Physical limits to ground motion might arise from the strength of crustal materials as they exist at or near the site of interest, in the source region at 10-15 km depth, or anywhere along the path in between. Quite generally, the strength of crustal material increases with confining pressure, so we may expect that rock properties at or near the site will apply more stringent limits on ground motions than will rock properties at mid-crustal depths, where the earthquakes occur. Moreover, rocks at shallow depth are easily accessible, allowing for both *in situ* observation of their structure and fabric as well as sampling for laboratory testing. Such analyses, however, are inevitably site specific, at least to some degree. More general physical limits on earthquake ground motion exist, we believe, in the form of limiting conditions on the source excitation of crustal earthquakes. These more general conditions, however, are more difficult to discern with confidence, given the inaccessibility of what goes on at mid-crustal depths and the short record of instrumental recordings of earthquakes.

Physical limits to ground motion at Yucca Mountain were discussed mainly in the context of the lithophysal units. Much of this discussion, in fact, pertained to upper-bound ground motions, ground motions that have not traversed the lithophysal units since they were formed. Quasistatic failure analysis of the lithophysal units indicates that observable damage should ensue at shear strains of ~0.1%, which would correspond to maximum particle velocities of ~2 m/sec. Preliminary numerical calculations of waveforms passing through the lithophysal units, however, suggest that velocity amplitudes in excess of ~3 m/sec could not emanate from the lithophysal units, no matter what the incoming amplitudes were beneath them, due to the dissipation of energy attending the damage to the lithophysal units.

Physical limits to the excitation of ground motion in the source region were discussed in a number of presentations, but here again we are hampered by the inability to clearly define the limits to what can happen, even if we know what has happened for tens of thousands of crustal earthquakes. Crustal earthquake stress drops are surprisingly constant (several tens of bars, although the variance is large) for the thousands of earthquakes for which they have been determined. m_b-M_S data for tens of thousands of crustal earthquakes worldwide point to a similar result, although much further work needs to be performed on this huge data set. Evidence for the kilobar-type stress drops of the sort required to produce the extreme ground motions at Yucca Mountain exists, but it is rare (~parts per thousand).

Unexceeded ground motions in the vicinity of Yucca Mountain were presented and discussed with respect to several different types of geologic structures that involve very different lifetimes. These include: (1) The undamaged lithophysal units (12.8 Ma), (2) The undamaged blades and filaments precipitated in the lithophysal cavities (~10 Ma), (3) Absence of seismically fractured rock and absence of slip on existing cooling fractures (~10 Ma), (4) Absence of large single-event slip on the Yucca Mountain faults (~1 Ma), (5) Precipitous slopes (~0.01-0.1 Ma) and (6) Precarious rocks (~0.01-0.1 Ma). Like-minded presentations were made by Brune on unfractured sandstone units adjacent to the San Andreas fault (~5 Ma) and by Stuckless on the use of fragile speleothems as paleoseismoscopes.

Unexceeded ground motions associated with one or more of these geologic structures provide important constraints on the seismic hazard at Yucca Mountain and can be used to down-weight or reject branches of the logic tree that lead to hazard curves inconsistent with these observations.

The remainder of this report consists of brief summaries of the 28 presentations delivered at the Workshop. More extensive, written summaries of these presentations have been prepared by the presenters and may be found Appendix C. The text below relies heavily on this supplementary material, which includes greater explanation and extensive reference lists, so not to be much longer than it otherwise would have been. The Workshop Program is attached as Appendix A, and workshop participant contact information is provided in Appendix B.

WORKSHOP PRESENTATIONS

The conference began Monday morning, August 23, with a short presentation by Tom Hanks of the problem of extreme ground motions at Yucca Mountain, illustrated with the PGA and PGV seismic hazard curves down to hazard levels of 10^{-8}/yr, and how this problem might be addressed in terms of either physical limits to ground motions and/or unexceeded ground motions. These introductory remarks were followed by three presentations (Ivan Wong, Norm Abrahamson, and Gabriel Toro) that discussed in detail the 1998 Yucca Mountain PSHA.

Wong presented the broad outlines of the 1998 Yucca Mountain PSHA (Stepp *et al.*,2001) to determine both ground-motion and fault-displacement hazard, the uncertainties that attended these hazard estimates, and the process by which all of this was achieved according to the SSHAC (1997) Level-4 procedures. The primary ingredients of any PSHA are characterization of potential earthquakes in terms of locations, magnitudes, and rates of occurrence and the estimation of the earthquake ground motion that can result from any of them. Six teams of three experts each were assembled for the "source characterization" work, and they dealt with both historical seismicity data and paleoseismic investigations of the faults local to Yucca Mountain as well as with the important regional faults. These six teams were also responsible for characterizing the rate and amount of slip per event for the Yucca Mountain faults to calculate the fault-displacement hazard. Seven ground-motion experts were chosen to estimate earthquake ground motion at Yucca Mountain.

Because uncertainties in the ground-motion estimation for the Yucca Mountain PSHA are widely agreed to be more important than uncertainties in source characterization, especially at the low hazard levels of interest to the Workshop, Abrahamson followed Wong with a detailed description of the ground-motion uncertainties.

The Yucca Mountain ground-motion experts relied primarily on empirical ground-motion prediction equations (often called attenuation relations) in the development of their ground-motion models (median and standard deviation for a given magnitude, distance, style-of-faulting and site condition). The ground-motion experts used these empirical ground-motion models (with adjustment factors applicable to Yucca Mountain), together with numerical simulations specific to Yucca Mountain, to develop estimates of the median ground motion and the probability distribution reflecting the aleatory (event-to-event) variability of the ground motion for a suite of earthquake magnitudes and distances. This distribution function was assumed to be log-normal, with median μ and standard deviation σ. Epistemic uncertainty was specified by distributions assigned to the median values of these two parameters, epistemic uncertainty in the median being measured by σ_μ, and epistemic uncertainty in σ by σ_σ. Although the experts were given the option of using asymmetric functions for the two epistemic distributions, they all used symmetric distributions. The intent of having the experts provide ground motions for scenario earthquakes was to focus their attention on the resulting ground motions and not just on weights assigned to models; as things turned out, the experts primarily focused on the model weights.

A key issue in the ground-motion results is the specification of epistemic uncertainty. Near the end of the 1998 PSHA project, one of the ground motion experts (Anderson) made significant increases to his epistemic uncertainty for small distances. Anderson wished to allow for the possibility that *all* of the ground-motion models could be wrong. Secondly, Anderson was concerned with the large discrepancy between the model predictions and the precarious rock constraints. The first concern could lead to ground motions either larger or smaller, but the second concern would lead only to lower ground motions, which should have been specified by an asymmetric distribution of the median μ. The large epistemic uncertainty in Anderson's ground-motion estimates leads to a large increase in the mean hazard at low probability levels, but it is by no means the only cause of the extreme ground motions at low probability levels.

Finally, none of the experts considered truncation of the ground-motion distribution in the development of their models, principally because the 1998 Yucca Mountain PSHA was focused on the 10^{-4}/yr hazard level. Accordingly, the experts did not know of the extreme ground motions that resulted from their models when ground-motion exceedances were computed at much smaller hazard levels.

De-aggregation of seismic hazard is the determination of the fractional contribution to the hazard associated with a given ground motion level arising from a chosen range of magnitudes, distances, and "epsilons", which measure the random deviation of a future ground-motion amplitude from its median value; basically, de-aggregation is simply differentiating the integration over magnitudes, distances, and epsilons that provides the seismic hazard estimate in the first place. As part of the Workshop organization, the Committee asked Gabriel Toro to de-aggregate the 1998 Yucca Mountain PSHA with much finer resolution than had been done before.

Toro demonstrated that at hazard levels of 10^{-6}/yr and smaller, the PGA and PGV hazard is dominated by close distances ($R < 5$ km), the magnitude range 6 to 7, and epsilons of 1 to 3.5 standard deviations, revealing the Solitario Canyon fault to be the principal/only player at small hazard levels. Toro examined the sensitivity of the ground-motion hazard through expert-by-expert contributions to it; Anderson was consistently higher than the other six experts for both PGA and PGV at all hazard levels. At 10^{-6}/yr, Anderson contributed about 50% and 30% of the total weighted hazard for PGA and PGV, respectively. Toro did not explain why Anderson's estimates were higher, but simple equations ("tools") provided by Toro in an appendix should help to identify the cause(s).

Toro also showed that epistemic uncertainty becomes a greater contributor to the mean hazard as hazard levels becomes smaller and smaller. His results confirm that at 10^{-4}/yr aleatory uncertainty predominates over epistemic uncertainty, but at 10^{-8}/yr both contribute significantly. Toro also concluded that truncating the aleatory uncertainty distributions at +3 σ will not have a significant effect on the hazard at 10^{-8}/yr. Finally, Toro provided very simple analytical representations of the hazard integral that will facilitate presentation and investigation of the impacts of various sources of uncertainty and their relative roles.

The U.S. Nuclear Waste Technical Review Board (NWTRB) held a meeting on February 24, 2003, to discuss the extreme ground motions at Yucca Mountain, and these deliberations were summarized at the Workshop by Leon Reiter of NWTRB and Art McGarr, who served as an expert consultant to NWTRB on this matter. Reiter emphasized the necessity of dealing with the extreme ground motions at Yucca Mountain in terms of physical limitations in the source, path or site and/or in terms of the treatment of uncertainty in the ground-motion estimates. NWTRB recommended to DOE that it needs to bound the extreme ground motions on the basis of sound physical principles, although NWTRB recognized the difficulty in doing so. No particular guidance was given beyond the desirability of maintaining external peer review and consideration of precarious rocks. Reiter addressed at some length objections to an early defense adopted by some with the Yucca Mountain Project that so long as the extreme ground motions could be tolerated in the Total System Performance Assessment (which is to say that they did not lead to exceeding the 10,000 year expected dose criterion) it was unnecessary to determine why the extreme ground motions arose in the first place and if they violate physical limits. Reiter dismissed this logic quickly: unrealistic/overly conservative ground motions could skew the understanding of the system behavior, lead to processes beyond our understanding, lead to unreasonable costs, undermine scientific confidence, and make subsequent reductions more difficult should that prove necessary later.

McGarr was one of four experts retained by NWTRB to attend the 2003 meeting, each of whom wrote a report to NWTRB based on what they heard at the meeting and on their own experience and expertise. McGarr recapitulated a small number of the largest recorded PGV's for earthquakes spanning ten orders of magnitude in seismic moment (M_0) to conclude that near-fault slip velocities did not exceed ~2 m/sec, although the TCU068 station recorded 2.6 m/sec for the Chi-Chi, Taiwan (Sept. 20, 1999; **M** = 7.6) earthquake, a thrust-faulting event. McGarr also assembled a large number of apparent stress observations spanning more than 16 orders of magnitude of M_0 to conclude that apparent stress does not depend on M_0 and has an upper-bound value of ~1 Mpa for crustal earthquake and laboratory analogues alike. Because near-fault PGV is controlled by apparent stress and because neither apparent stress nor near-fault PGV depends on **M** or M_0, McGarr concluded that the "worst-case scenario at Point A" in terms of PGV is ~2 m/sec.

The Monday afternoon session began with presentations by Abrahamson and Julian Bommer on the PEGASOS project, just the second SSHAC Level-4 PSHA ever conducted, in this case for nuclear reactors in Switzerland (Abrahamson et al, 2002). Notably, with the Yucca Mountain experience in hand, the PEGASOS project required the ground-motion experts "to specify bounding values on the ground motions" (Bommer *et al.*, 2004).

Abrahamson began by noting that PEGASOS was structured in a manner similar to the 1998 Yucca Mountain PSHA but with some important differences. First, site response was included as part of the problem. Thus, three groups of experts were convened for PEGASOS: one each for source characterization, hard rock ground motion, and site response.

Second, the ground motion experts developed sets of weights for models rather than distributions for the epistemic uncertainty (σ_μ and σ_σ). This approach forced the experts to consider asymmetric distributions of the epistemic uncertainties. It also avoided creating epistemic distributions that included models without a technical basis (unintended models). The experts were not restricted to the available ground-motion models and were allowed to modify the existing models to develop new models as long as they had an explicit basis for the modifications.

Abrahamson and Bommer both discussed the important matter of "bounding values on ground motion" for the PEGASOS project, and it was explored in several different ways. (In the PEGASOS project, the terms "maximum" or "bounding" ground motion refer to the physical limits to ground motion, not unexceeded ground motions as defined in this report.) Maximum rock ground motions reflected perceived limits of the seismic source with the effects of geometrical spreading and attenuation considered. In contrast, the site-response experts developed physical limits to ground motions based on site-specific soil properties.

Two statistical approaches were considered for defining maximum ground motions on rock: truncation of ground motion amplitudes for a given magnitude and distance and departures from the log-normal distribution. (Distributions different from lognormal change the probability of getting very large ground motions but does not require an absolute maximum). The experts were provided with distributions of residuals from existing ground-motion prediction equations involving ~1,000 recordings and summaries of the largest empirically observed ground motions as a function of magnitude and distance.

The distributions of the residuals from a number of strong-motion data sets show that the largest observed residuals are, consistent with the total number of observations, three standard deviations (or more) removed from the median value and show no tendency to deviate from an untruncated log-normal distribution. As such, there is no statistical basis for truncating the distribution of the aleatory variability of ground motion at some maximum number of standard deviations or to depart from the log-normal distribution at all shaking levels.

Numerical simulations based on kinematic models of crustal-earthquake rupture were also provided to the ground-motion experts. As described by Paul Somerville in a Workshop presentation summarized below, these numerical simulations were calculated for a range of magnitudes, distance, and site locations around the rupture zone (at a given distance), employing a range of source-parameter combinations (e.g., fault dimensions, slip rise-time, rupture velocity, asperity size and stress drop). "Worst-case" combinations of these parameters (for, example large rupture velocity coupled with short rise times) and unfavorable propagation directions lead to very large ground motions, again to PGA's and PGV's that have never been recorded.

While these simulations provided a basis for the ground motion expert's choice of maximum rock ground motion, this choice apparently involved little more than replacing an arbitrary selection of the maximum ground motion in the first place with an arbitrary selection of the worst-case source parameters that would cause it. This approach appears to lead to "reasonable" estimates of very rare, rock ground motions, but it does not fundamentally address the issue of physically limited ground motions since there was not a clear technical basis for the selection of the combinations of the source parameters.

That experts must defend and document the technical basis for their assessments is an essential feature of the SSHAC Level-4 process. As the PEGASOS project developed, it became clear that while the experts felt that some very large ground motions were very unlikely, it was difficult to provide a clear technical basis for selecting a true maximum ground motion. An important consequence of all of this was the rock ground-motion experts tended to increase their estimates of the maximum ground motion as the project went on. This is an important finding, and this experience should be kept in mind for future PSHA's that may or must have to deal with maximum possible ground motions.

Jerry King summarized recent developments in the Ground Motion Saturation Evaluation project, which has as its principal focus constraints on PGV provided by the undamaged lithophysal units that underlie Yucca Mountain. Lithophysae are cavities in the volcanic tuffs, caused by gases exsolved from them following their airfall deposition at 12.8 Ma, and the lithophysae weaken these tuffs considerably. Strains at which these rocks fail can be related to PGV's which would have caused such failure had they occurred since 12.8 Ma; the absence of any observable, seismically induced damage to these units indicate that such strains and PGV's have not occurred. King provided ranges of these strains (0.10 to 0.35) and related PGV's (1.5 to 5.0 m/sec) and several distribution functions for both.

Branko Damjanac presented Mark Board's review of the mechanical properties of the rocks at the repository level in Yucca Mountain. The welded tuff units at and near the repository horizon are subdivided into two basic mechanical groupings: lithophysal and nonlithophysal rocks. The primary difference in these rock units, from a mechanical perspective, is the fabric of the lithophysae. The matrix of both lithophysal and nonlithophysal rocks is mineralogically and mechanically the same. The lithophysal rocks contain up to about 30% porosity in lithophysal (gas) cavities, as well as a ubiquitous fracture fabric, both formed during the cooling process. The nonlithophysal rocks are generally devoid of these cavities, but do show three regular cooling fracture sets: one subhorizontal, long trace-length set of vapor phase partings and two shorter trace-length subvertical sets that tend to terminate against other fractures or within the rock mass.

Extensive testing of the material properties of the rock matrix, rock mass, and fractures of these units has been conducted over the past twenty years. In general, the rock matrix is a strong, elastic, and brittle material, characterized by compressive strength of about 150 MPa for 51 mm diameter samples and a brittle post-peak response. Tensile strength of the rock matrix has been determined through indirect (Brazilian) and direct pull tensile testing. The compression to tensile strength ratio is approximately 9 to 10.

Lithophysal rock-mass properties are size dependent due to the presence of the cavities. Testing of small cores are not representative of rock-mass properties, as they are primarily composed of the matrix and do not include lithophysae. Therefore, large (290 mm) cores have been tested in uniaxial compression to define the strength and deformability of the lithophysal units. These tests show that the mechanical properties are primarily a function of lithophysal porosity. Fracture properties have been determined in direct shear, showing that the vertical cooling joints are smooth, with essentially no cohesion and low friction angle. The vapor phase partings are rough and healed with secondary silicate minerals; they are cohesive and have higher friction angle. A large data base is currently available to describe the mechanical response of the lithophysal and nonlithophysal tuffs.

Ground-motion models typically are concerned only with shear strains induced in the rock mass. Shear waves from extreme ground motions can result in significant tensile strain as well. Since rock has a significantly lower strain limit in tension than in shear, physical bounds to extreme ground motions may be more sensitive to tensile limits. Unfortunately, tensile strength and strain limits of fractured rock masses are not well understood. Currently, empirical estimates of the ratio of compressive to tensile strength, based on laboratory testing of rock and concrete are used as a guide for selecting tensile strength of a jointed rock mass.

Charles Fairhurst reviewed the current theoretical basis for the strength of rock in compression (shear) and tension. He began with the basic physics of tensile rock fracture in a compressive stress field. Fairhurst used the Griffith rupture criteria and the fracture mechanics of tensile fracturing in rock to show that tensile fractures may form from the ends of pre-existing flaws in a compressive stress field, propagating in a direction perpendicular to the minimum compression. Increasing confining pressures suppress this crack growth, resulting in strengthening of the rock mass. The effect of sample size on rock strength was described as the basis for development of yield criteria for fractured rock masses. Failure criteria, such as the Hoek-Brown criteria have been developed to account for the effect of natural fracturing, primarily on failure in compression. A series of discontinuum model simulations of rock in uniaxial compression were presented to illustrate the effect of the presence of natural fracturing on rock-mass tensile strength. This modeling technique is capable of allowing tensile and shear fractures to propagate within the rock mass as the stresses dictate. An initial intact rock sample was modeled in which the ratio of compression to tensile strength was fixed at approximately 10. Pre-existing fractures with length much less than the sample dimension were introduced into the sample, first as isolated fractures, then as sets of fractures with intervening intact "bridges". Compression and tension experiments were then simulated and the compression and tensile strength of the rock mass determined. Tensile failure of the rock mass occurs as tensile fractures propagate from the ends of existing fractures through the solid rock bridges. Fairhurst showed that compression and tensile strengths of the rock mass are controlled by the percentage of solid rock bridges, as compared to the interconnected fracture surface area. The ratio of compression to tensile strength of the rock mass falls within the range of about 9 to 14, indicating that the ratio of the compressive to tensile strength of the *rock mass* is reasonably represented by the ratio of compressive strength to tensile strength for intact rock of the same material.

Joe Andrews began the second day of the Workshop with a presentation of how one might use non-linear phenomena, both at the source and along the path, to investigate physical limits to earthquake ground motion. The use of similar non-linear methods, developed in the 1960's, to simulate the response of geologic materials to underground nuclear explosions was also discussed.

Andrews considered a two-dimensional, plane-strain, dynamic model of slip on the Solitario Canyon fault, the bounding fault on the west side of the Yucca Mountain block. Consistent with the borehole data presented later by Mark Zoback, shear stress along the fault was initialized under *in situ* stress conditions to be 0.6 times normal compressive stress and was near the failure condition represented by a static coefficient of friction of 0.7 used in the calculation. Stress drop and dynamic slip on the fault were induced by reducing the friction coefficient along the fault to 0.1. This resulted in a maximum stress drop of 40 MPa and a maximum slip of approximately 15 m at and near the free surface. For a 10-km fault length, the magnitude of this event is 7.2. Results for linear elastic wave propagation and wave propagation allowing for Mohr-Coulomb (nonlinear) failure were presented, and these calculations showed a significant decrease in shear-wave amplitudes, whether in the time or spectral domain, of the non-linear relative to the linear cases.

Andrew's principal conclusions were that modeling methods that take into account the nonlinear response of the geologic materials are required to investigate strength bounds and that these strength bounds will provide physical limits to ground motions, whether excited by earthquakes or nuclear explosions. Andrews also noted that non-linear modeling methods for geologic materials, while generally unknown to the community of earthquake seismologists, are nevertheless in use in closely related fields.

Peter Cundall described the use of fully nonlinear numerical methods for modeling of wave transmission through rock and compared the fully nonlinear approach to the well known and often used equivalent linear methods (ELM). Cundall described a simple example problem to compare results from SHAKE, an ELM code, and FLAC, a fully non-linear code, showing reasonable agreement of the acceleration amplification factor for ground motions to 1 g. A site-specific example for Yucca Mountain applying a 10^{-6}/yr ground-motion time history to a free-field lithophysal rock mass reveals that these large motions produce both shear and tensile fracturing, even though only horizontal shear components were supplied as input ground motion.

Cundall recommended that fully nonlinear methods that account for details of rock mass constitutive behavior be used in addition to ELM in cases where ground motions are extreme and produce strains in rock beyond the typical range of application of the ELM. The nonlinear methods can be used as a means for validating ELM. Current post-closure ground motions developed from PSHA results and ELM methods at Yucca Mountain produce shear and tensile strains that are in excess of rock-mass fracture strains in repository host horizons. Consequently, extensive shear and tensile fracturing is predicted in the free field in repository tuff units at Yucca Mountain.

Chris Scholz presented fault-tip taper data, derived from faulting-displacement/ fault-length measurements, for both earthquakes (ETT) and faults (FTT) in extensional regimes. Both ETT and FTT tend to have linear displacements tapers, in agreement with the critical fault-tip taper

(CFTT) model, an elastic-plastic model for faulting displacements. FTT are larger than ETT by one to two orders of magnitude, the unsurprising consequence of faulting displacements along any one fault being the aggregate of many earthquakes along it. ETT data are consistent with individual earthquake stress drops in the range of 10 to 100 bars, and Scholz interpreted the FTT data as pointing to crustal strengths as high as 10 kbar. Scholz also suggested that earthquake stress drops can locally be as high as a kilobar at interior fault jogs, where rupture encounters the end of the fault, and/or when the rupture tip enters the stress shadow of an earlier earthquake. Scholz then briefly summarized seismological evidence for high (~kilobar), sub-event stress drops for the 1968 Tokachi-oki (M = 7.9), 1980 Victoria, Mexico (M = 6.1 and 1992 Petrolia (M = 7) earthquakes. Scholz concluded that because the faults at Yucca Mountain are intraplate faults they would be expected to have average earthquake stress drops of ~100 bars, with sub-event stress drops of ~ 1 kbar.

Considerable discussion centered around whether the strain associated with FTT's in fact supported (elastic) stresses of up to 10 kbar. High stress-drop sub-events and the ground motions they excite were addressed in later Workshop presentations by Somerville, Beroza, and Anderson. The frequency of occurrence of these events, however, remains an outstanding issue.

Paul Somerville discussed a number of topics that relate to variations in earthquake ground motion, including: 1) simulations of ground motion using distributions of parameters describing the seismic source; 2) empirical evidence suggesting a difference in ground motions for shallow and buried faulting; 3) comparison of dynamic rupture parameters of shallow and buried faulting earthquakes; 4) magnitude scaling of the near-fault rupture directivity pulse; 5) physical factors limiting ground motions at Yucca Mountain.

Somerville described ground motion calculations performed for the PEGASOS project which include all of the following source parameters and ranges for them: faulting mechanism (strike-slip, normal, or reverse), amounts of surface and subsurface faulting, rupture area, slip distribution, slip functions, rise time, rupture velocity, and hypocenter(s). Somerville noted that the two source parameters having the strongest influence on large-amplitude ground motions, rupture area and rise time, have an inverse correlation and that combinations of small rupture area and short rise time give rise to very large ground motions that were considered unphysical. Little was presented regarding the specific variations and correlations in the source parameters. As Abrahamson previously noted for these calculations, the specific values used in the simulations seemed to be chosen subjectively, and thus the results are of limited help in defining physical limits to ground motions. One may anticipate that such information will be crucial for any PSHA that utilizes these kinematic models of the source.

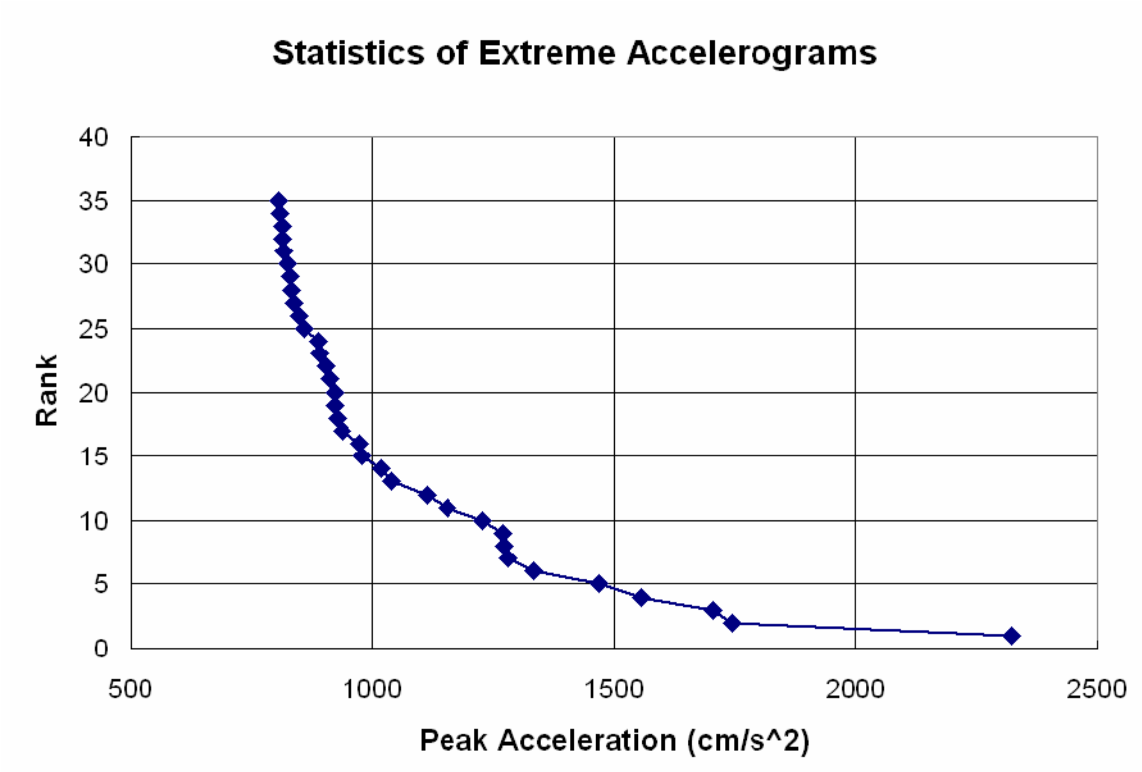
Somerville also noted that ground motions from shallow-faulting earthquakes are weaker than from buried earthquakes and that there is magnitude saturation of the rupture-directivity pulse, both of which may be important to physical limits to ground motion in specific cases.

Greg Beroza complemented and extended Somerville's presentation with his stochastic approach to estimating source effects on earthquake ground motions utilizing dynamic models. The essential feature of this approach, which Beroza developed with Martin Mai, is characterizing and scaling the spatial variability of faulting displacements that attend crustal earthquakes (heterogeneous faulting). The power spectra of slip distributions computed from seismological inversions of seismograms to source are considered in terms of various random field models. These stochastic slip distributions are used to develop the temporal behavior of slip using physically consistent, stochastic dynamic earthquake source models or pseudo-dynamic approximations to such models. Extreme ground motions can then be judged within the context of the known source-slip behavior of past earthquakes. Unfortunately, this library consists of just 18 earthquakes, only one of which is a normal-faulting event such as might occur at Yucca Mountain.

Beroza presented two slip-distribution models for the Solitario Canyon fault, capable of producing extreme ground motions at Yucca Mountain. Both involved large, but localized slips (as high as 10 m) and stress drops (several kbar), and both these slips and stress drops exceed, by a considerable margin, corresponding values within the current library of 18 earthquakes.

John Anderson presented an observational study of PGV and PGA, concentrating mostly on the PGA data set. He looked specifically at all available recordings with PGV > 50 cm/s and PGA > 800 cm/s^2. For PGV his preliminary finding is that they all are for M > 6 earthquakes and are influenced by rupture propagation toward the recording site (forward directivity). Anderson expressed concern that the different processing procedures used by different institutions precluded meaningful, detailed analysis and recommended that all of these velocity records be processed in the same way.

The PGA data set comes from 36 accelerograms (see distribution below) of 22 earthquakes occurring between 1971 and 2003. PGA's are less clearly related to magnitude than PGV's. Twelve of these records came from just two earthquakes, six each for the earthquake offshore of Miyagi Prefecture, Japan (May 26, 2003; **M** = 7.0) and for the Northridge, California earthquake (Jan. 17, 1994; **M** = 6.7); remarkably for the ground motion it generated, the Japanese earthquake occurred at a depth of 75 km. Fourteen accelerograms of 12 earthquakes yielded PGA in excess of 1g, and 78% of these PGA's came from a horizontal component. [The Parkfield earthquake (Sep. 28, 2004; **M** = 6.0), occurring a month after the Workshop, will alter this data set and significantly change the statistics given above and below.]



Anderson also examined the waveforms from which these PGA's came, the relation of the recording station to the fault, and a parameter characterizing the diminution of high frequencies for each recording. From this analysis, he developed the following statistics for the largest known PGA's: 69% of these values result from thrust faulting with 47% on the hanging wall of the thrust fault. Forward directivity is associated with 33% of the data. Dam abutments (topographic amplification) accounts for 20% of the data, and site condition plays an important role (soil site condition accounts for 33% and a strong resonance accounts for 6%). Deep sources, perhaps involving very high stress drops, account for 20% of the data. Notably, every one of these records is associated with one or more of this limited set of conditions. Unfortunately, there are no normal-faulting earthquakes in this data set.

Anderson also investigated data from the Kik-Net in Japan, which features stations possessing both uphole and downhole sensors. He found that there are large amplifications of the surface ground motions relative to those at the downhole levels.

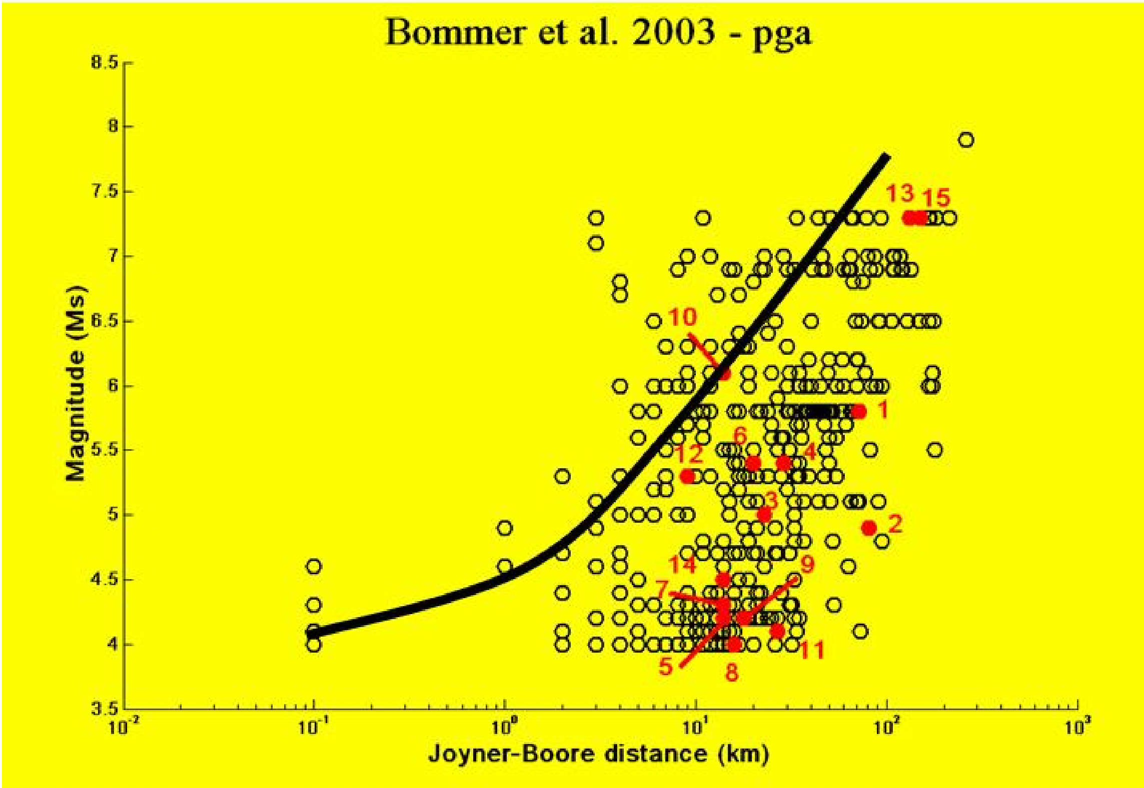
At the request of the Committee, Jim Dewey initiated a preliminary investigation of the very large m_b (body-wave magnitude)–M_S (surface-wave magnitude) data set, available for $\mathbf{M} \geq 5$ crustal earthquake worldwide since the installation of the World Wide Standardized Seismographic Network in the 1960's. Just as underground nuclear explosions have higher m_b for a given M_S than do most crustal earthquakes, higher stress-drop earthquakes should have higher m_b for the same M_S than do average stress-drop earthquakes because of the enhanced excitation of high-frequency radiation.

In a presentation given by Tom Hanks, Dewey compiled m_b–$\mathbf{M}$ (moment magnitude, which for all but the very largest earthquakes, $\mathbf{M} > 8.5$, is very close to M_S) data for more than 13,000 worldwide crustal earthquakes for the interval 1977–2002. A small percentage of these earthquakes indicated stress drops > 500 bars, but this is mostly due to the western U.S. attenuation rules applied to the entire data set. No more than 3 of these > 13,000 events indicated a stress drop > 500 bars when eastern U.S. attenuation equations were used. For earthquakes actually occurring in the western U.S., mostly in California, three of 103 events indicated stress drops > 500 bars.

Dewey cautioned that reasons other than earthquake stress drops exist that can result in large m_b for a given M_S. Thus, this analysis identifies events that should be examined individually for their source characteristics. Nevertheless, the m_b–M_S data sets are huge and should allow us to reckon the frequency of occurrence of high stress-drop at fairly low probabilities.

Of great interest to the matter of extreme ground motions are those ground motions far removed from the median values, as they are known from model calculations or empirical analyses, the so-called "outliers", and Julian Bommer addressed this matter in his presentation "Outliers in Strong-Motion Datasets". He noted that aleatory variability in ground-motion data sets has not decreased over the past several decades, despite the addition of large amounts of data or the many recent studies including more complicated prediction equations. Moreover, he showed that for large sets of PGA data, probability distributions conform to the log-normal distribution out to two and even three standard deviations.

In a detailed study of data with logarithmic residuals at > $+2\sigma$, Bommer pointed out several interesting observations. Even though the higher residuals are reasonably well correlated with ground-motion amplitudes, the highest residuals are mostly associated with ground motion of small enough amplitude to be of little engineering significance, as indicated in the plot below:



The red numbers and arrows identify the 15 largest residuals in magnitude and distance space. The heavy curve is an approximate boundary dividing regions where damage might be expected (above the curve) from magnitudes and distances with little expected damage. All of the residuals fall in the little-to-no-expected damage region (small magnitudes, or larger magnitudes at greater distances). There is no tendency for the largest outliers to be from a particular type of site or from a particular earthquake as would be expected if the outliers were caused by a strong systematic site effect or by an overall source effect (e.g. stress-drop). Factors that may be responsible for these large, positive residuals include forward directivity, seismic-ray focussing, site effects, and, possibly, processing noise.

Extensional tectonic regimes, such as the Basin and Range province in which the Yucca Mountain region is set, are typified by thinned crust and high heat flow, and the extension of the Basin and Range province has been considerable over the past 20 Ma. Extensional tectonic regimes are generally thought of as low-stress environments, and earthquake stress drops in extensional tectonic regimes are somewhat lower than for compressional regimes. Mark Zoback reviewed the *in situ* stress measurements to depths of ~1.3 km depth in the Yucca Mountain block. They indicate, although the extrapolation to seismogenic depths is considerable, that the Solitario Canyon fault, and other faults in the vicinity of Yucca Mountain, exists within a high shear-stress field, only marginally stable with respect to normal faulting due to frictional shear failure. Indeed, such *in situ* stress measurements indicate that the upper (seismogenic) continental crust everywhere, with the notable exception of the San Andreas fault, is affected by high absolute deviatoric stresses corresponding to Byerlee's Law and hydrostatic fluid pressures.

An outstanding issue is whether earthquake source parameters and the ground motion they control should be greater in high-stress regimes than in low-stress regimes. In successive talks, Mark Zoback spoke to these matters with respect to Yucca Mountain, and Art McGarr described the situation in deep-level gold mines in South Africa, in which the mining operations themselves induce high shear stresses.

Zoback noted that rotations of hydrofracture orientations along the borehole suggested that, at least in some circumstances, the associated stress drops could be near total, a result of near frictionless faulting. The rotations were modeled by dislocations near or crossing the borehole. Dimensions of these faulting events varied from a few meters to a few tens of meters. Some of the inferred stress drops were much larger than those observed for most crustal earthquakes, tens to hundreds of bars. Zoback suggested that near total stress drop with near frictionless faulting might be a common phenomenon. Unfortunately, no instrumental records of this faulting process are known to exist. Neither are much instrumental data available for the few earthquakes in and around Yucca Mountain, apart from the Little Skull Mountain sequence in 1992. Jim Brune noted that data collected by the University of Nevada, Reno, indicate that the stress drops near Yucca Mountain are not noticeably different than those at Anza along the San Jacinto fault, part of the San Andreas system.

McGarr noted that the deep-level gold mines in South Africa also exist in a marginally stable, regional extensional stress regime. The mining operations depress the water table in the vicinity of the mines, stabilizing the rock mass locally with respect to frictional failure, but also induce large deviatoric stress fields about the advancing stopes, in which most of the rockbursts occur. Like their California cousins, these rockbursts have quadripole radiation patterns indicative of shear failure and stress drops of several tens of bars making them indistinguishable from crustal earthquakes anywhere of comparable magnitudes. McGarr noted, however, that these events occur in shear stress fields that he estimates to be 300 to 600 bars. Using an intact rock strength of 164 MPa, McGarr estimated a maximum near-source particle velocity of 4.1 m/sec. He also noted that even higher ground motions might result from failure of intact-rock asperities. McGarr concluded by noting that ground motion results from mining-induced earthquakes could be applied to Yucca Mountain if the differences in rock strength were taken into account.

As we learned from Jerry King on the first day of the Workshop, the Yucca Mountain Project is currently pursuing the development of an upper-bound PGV for ground motions based on the absence of seismically induced damage to the lithophysal units in the 12.8 Ma welded tuffs exposed in underground excavations at the site. David Buesch began the Wednesday presentations with observations of the structural features in the lithophysal and nonlithophysal subunits of the Topopah Spring tuff, which include the lithophysae themselves (voids created by gases exsolved during cooling) and cooling-related fractures. These observations are captured in 1m x 3 m “panel maps” of the walls in the ECRB (Enhanced Characterization of the Repository Block) Cross Drift, detailed line surveys of fractures in all of the underground excavations at the site, and in sectioned slabs of rock derived from the various repository host horizons.

In the lithophysal units, Buesch found that the lithophysal cavities show no evidence of post-formation damage. Moreover, the inter-lithophysal fracturing isconsistent with a cooling origin indicated by the orientation, short trace length, lack of offset of the fractures and the occurrence of vapor-phase alteration minerals within them. In the nonlithophysal rock units, Buesch found that ~70% of the fractures can be traced directly to a cooling origin, with the remainder classified as of indeterminate origin, although they could be a result of cooling as well. There is minimal evidence of post-formation shear dislocation on these features. Buesch concluded from his enormous number of observations that strains due to earthquake ground motions since 12.8 Ma have not been sufficient to cause obvious structural disturbance to the ubiquitous lithophysae in the lower lithophysal unit of the Topopah Spring tuff or to form new fractures or cause shear offset on existing fractures in the lithophysal and nonlithophysal units of the Topopah Spring tuff.

Joe Whelan took the Workshop into the small world of the lithophysal cavities and the even smaller world (millimeters) of the delicate calcite/silica blades and filaments within them, precipitated from meteoric water percolating slowly through the mountain over millions of years. These secondary mineral assemblages have been forming for at least 8 Ma, and suggest that the repository horizon has been an unsaturated zone at least since then. Potentially, these undamaged fragile blades and filaments also speak to unexceeded ground motions since 8 Ma.

Dave McCallen analyzed the dynamic response of these structures to earthquake ground motion in terms of a Bernoulli-Euler beam. Typically, given their dimensions and material properties, these blades and filaments would have natural frequencies of vibrations of a kilohertz or so, and would respond to typical earthquake ground motion as undeformed, rigid bodies requiring very large accelerations (25-130 g) to overcome their tensile strength.

Branko Damjanac followed this summary of observational evidence with a presentation of the shear strains at failure of the lithophysal rock as well as shear strains in nonlithophysal rock that would result in 1 mm (about the observable limit) of offset on preexisting cooling fractures. The analyses, conducted using discontinuum numerical models, also provide a physical interpretation of the type of fracturing one would expect to observe in underground exposures in these units. Shear strain levels of about 0.1% are required to fail these rock units, and would result in observable inter-lithophysal fracturing. The 0.1% shear strain limit corresponds to a PGV of approximately 2 m/sec. Amplitudes larger than this level would also result in significant shear displacement on induced fractures, with observable offset in lithophysae. Because *no* damage of either type has been observed, PGV of 2 m/sec is a likely upper bound for particle velocities traversing the Topopah Spring tuff in the past ~ 10 million years.

Bill Foxall reported on a preliminary investigation of the availability and accessibility of ground-motion recordings of underground nuclear explosions on the nearby Nevada Test Site, many of them detonated in the same or very similar volcanic tuffs that underlie Yucca Mountain. At close distances, these explosions generate large-amplitude ground motions, although with a source mechanism (radial compression) much different from earthquakes (shear failure) and with a far greater energy density. These data provide insights into material response and stress propagation and attenuation in the high-strain (nonlinear) regime and thus should provide information and constraints on these properties for the Yucca Mountain tuffs. Typically, ground motions generated by these nuclear explosions attenuate rapidly due to highly nonlinear damage mechanisms and yielding within a few hundred meters of the shotpoint.

Jim Brune presented numerous examples of precarious rocks and precipitous slopes from California and Nevada, as well as unfractured, Miocene-age sandstones adjacent to the San Andreas fault. These observations speak to unexceeded ground motions on time scales of ~10 ka to ~10 Ma or more. Brune also showed examples of precarious rocks and precipitous slopes that were toppled/activated by the 1992 Little Skull Mountain earthquake (**M** = 5.6) and underground nuclear explosions on the Nevada test Site, observations that validate, at least qualitatively, laboratory and field determinations of toppling accelerations. Brune has estimated that precarious rocks on Yucca Mountain, with ages of ~30 ka to ~250 ka, would have been toppled by peak accelerations of 0.15–0.35 g, significantly less than the 10^{-4}/yr Site A value of 0.53 g. Brune also noted that Miocene sandstones adjacent to the San Andreas fault in southern California, with a tensile strength of ~10 bars have been unfractured by the 20,000 or so **M** ~8 earthquakes that have occurred along the fault since ~5 Ma. Both the diversity in type and in age of these indicators of unexceeded ground motions provide numerous opportunities to constrain seismic hazard.

As yet another example of fragile geologic structures serving as potential paleoseismoscopes, John Stuckless summarized the use of speleothems in caves to develop pre-historic earthquake chronologies. Considerable work has been done with this approach in Italy and Israel, much less so in the United States. Stuckless reviewed several candidate caves in the American Southwest that might be amenable to this analysis, but none of them are close to Yucca Mountain. Stuckless did not indicate whether caves suitable for this analysis exist near Yucca Mountain. Stuckless also presented a number of examples of natural and anthropogenic caves, tunnels, and excavations in seismically active areas that have never been damaged by earthquake shaking, over time spans of thousands to millions of years.

The Committee asked John Whitney and David Schwartz to speak on the largest faulting displacements observed for normal faults, the faults local to Yucca Mountain in the case of Whitney and faults elsewhere in the Basin and Range Province in the case of Schwartz. For the Yucca Mountain area, available erosion-rate data indicate that ~15 m surface-faulting displacements (or even 5 to 10 m fault scarps) would last for a million years or more in this terrain of erosionally resistant, bedrock scarps. Whitney presented an overview of the paleoseismic history of the Yucca Mountain faults, by far the most complete paleoseismic history for any place on the planet. It is complete for all the Yucca Mountain faults to 100 ka and extends back to 700 ka for individual faults. Average co-seismic displacements range from 20 to 127 cm; maximum co-seismic displacements are 32 to 205 cm for the Yucca Mountain faults and are 300 cm for the Bare Mountain fault. Perhaps the most interesting event in this history is the distributed surface ruptures along three of the Yucca Mountain faults that are related to a volcanic eruption of the Lathrop Wells cone at 77 ka. Thus, there is nothing in this long history that points to unusually large faulting displacements, and large faulting displacements (> 5 m) of even greater antiquity (~1 Ma) would still be observable.

Schwartz followed Whitney with a similar discussion of normal-faulting behavior throughout the Basin and Range province. Unlike the Yucca Mountain area, large normal-faulting earthquakes do provide, at least occasionally, for faulting displacements in excess of 5 m. Such vertical offsets were observed at a few places along the fault traces for the 1915 Pleasant Valley, Nevada (**M** =7.3) and 1959 Hebgen Lake, Montana (**M** = 7.4) earthquakes, with fault lengths of 61 and 26 km, respectively. Both of these earthquakes have magnitudes in excess of those believed possible for the faults local Yucca Mountain, and the Pleasant Valley earthquake has a fault length much greater than those of the Yucca Mountain faults. As a matter of fault length alone, the Hebgen Lake earthquake could fit on the Yucca Mountain faults. Had this been the case in the last ~0.5 Ma, however, its large displacements, typically 3 m or more, would have been readily observable.

FINDINGS

The findings listed below are given primarily to inform the research recommendations which follow. They do not constitute an all-inclusive summary of the many things that come to mind as a result of the Workshop presentations.

As an overall and quite general finding–and also as a brief summary of the findings that follow–the Committee finds that there are many lines of evidence and argument that can be drawn from a wide range of geological, geophysical, seismological, and material-properties studies that all point to the same general conclusion: at probabilities of exceedance of 10^{-4}/yr and smaller the seismic hazard at Yucca Mountain as calculated from the 1998 PSHA is too high.

For the purposes of clearly explaining matters of interest in this Report, the Committee has found it necessary to define "unexceeded ground motions" as ground motions that have not occurred at a specific site during a specific period of time and "physical limits to ground motion" as amplitudes of ground motion that cannot happen, ever.

The Yucca Mountain site is composed of laterally extensive and relatively flat-lying welded and bedded tuff units. The proposed repository footprint is approximately 6 km by 2.5 km in plan dimension. The footprint is completely underlain by the laterally extensive, relatively weak and unfractured Calico Hills formation, a ~50-m thick bedded tuff unit that underlies the entire repository. The repository itself is located largely within (about 85%) the lower lithophysal unit of the Topopah Spring formation. As described by numerous speakers during this workshop, the lower lithophysal unit has relatively high porosity and is significantly weaker than the overlying and underlying welded, nonlithophysal units. Both of these geologic formations–the Calico Hills tuff and the lower lithophysal unit–provide constraints on unexceeded ground motions at Yucca Mountain.

The Committee endorses the current efforts at the Yucca Mountain Project in which the lithophysal rock strain limits are being used as a means for determining unexceeded PGV's experienced at the site in the past 12.8 Ma; however, the Committee believes that the distribution function of bounding horizontal PGV's presented by Jerry King may be too broad, insofar as *no* seismically induced damage to the lithophysae has been observed. Presumably, there is considerable variation in the local strength of the lithophysal units due to variable density/void fractions of the lithophysae. Given the negative observations, then, the lower ranges of King's distribution are more likely upper ranges to PGV's that have not passed through Yucca Mountain in the past 12.8 Ma. That these units could have/should have failed at even lower strengths associated with tensile failure would reduce these values even more. The Committee believes that similar analyses should be conducted for the Calico Hills formation.

The shear and tensile strains induced by the earthquake source are limited by the strength of the rock mass. At source depths of 10 to 15 km, the lithostatic (overburden) pressure results in high rock strength and strain limits. As the seismic wave propagates to shallower depths, the confining pressure and strength are reduced, with subsequently lower strain limits. The amplitude of extreme ground motions are thus most stringently limited by the nonlinear constitutive behavior of rock at relatively shallow depths.

The ground motions corresponding to shear strain limits are derived from an equivalent-linear site response model which accounts, in only a general way, for rock-mass yield in shear which includes slip on existing fractures, the creation of new ones, and potential tensile failure mechanisms. Uncertainty in the nonlinear material properties of the rock units is accounted for through bounding material-properties assumptions. These assumptions yield a conservative estimate of the physical limit of the ground motions. Defining physical limits to ground motion that arise from the finite strength of rocks, specifically the Calico Hills formation and the lower lithophysal unit, requires calculation of stress propagation through these units that fully accounts for their nonlinear, dissipative response.

The data sets available to seismologists to study the excitation and propagation of strong ground motion are large and diverse, and it was not surprising that the seismological presentations, including those of McGarr, Somerville, Beroza, Anderson, Dewey, and Bommer were drawn mainly from existing data sets. The Committee believes, however, that the essential matter here is whether or not the metric of what *can* happen, at very low probabilities of occurrence/exceedance, is determined by what *has* happened, and this was a recurring theme in these presentations, whether the particulars involved earthquake stress drops, PGA and PGV data, or rise time and asperity sizes. While seismologists indeed have large data sets with which to work, they are not so large and so definitive as to rule out the occurrence of high-stress-drop events at the rate of a few events per thousand or more, for example. Unfortunately, existing rheological rules and constraints provide considerable latitude as to what can happen in the source region, as indicated by Andrews' presentation.

Unexceeded ground motions in the vicinity of Yucca Mountain were presented and discussed with respect to several different types of geologic structures that involve very different lifetimes. These include: (1) The undamaged lithophysal units (12.8 Ma), (2) The undamaged blades and filaments precipitated in the lithophysal cavities (~10 Ma), (3) Absence of seismically fractured rock and absence of slip on existing cooling fractures (~10 Ma), (4) Absence of large single-event slip on the Yucca Mountain faults (~1 Ma), (5) Precipitous slopes (~0.01-0.1 Ma) and (6) Precarious rocks (~0.01-0.1 Ma). Additional presentations were made by Brune on unfractured sandstone units adjacent to the San Andreas fault (~5 Ma) and by Stuckless on the use of fragile speleothems as paleoseismoscopes. Because of the higher rate of occurrence of large earthquakes on the San Andreas fault compared to Yucca Mountain, the sandstones along the San Andreas fault have the potential of constraining inferred ground motions at Yucca Mountain at 10^{-8}/yr annual probability.

Unexceeded ground motions associated with one or more of these geologic structures provide important constraints on the seismic hazard at Yucca Mountain and can be used to down-weight or reject branches of the logic tree that lead to hazard curves inconsistent with these observations. Some question yet remains just how to put these constraints into play in the PSHA format, and further work is necessary, in some cases, to document and quantify the amplitudes of ground motion from the various indicators and the time intervals over which that ground motion has not occurred.

The undamaged lithophysal units, (1) above, are the subject of continuing study. The cavity blades and filaments (2) described by Whelan and analyzed for their dynamic behavior by McCallen have resonance frequencies much higher than those of interest to repository design and safety issues at Yucca Mountain. The possible use of speleothems for Yucca Mountain ground-motion constraints depends on the location and accessibility of limestone caves in the area, to which the Committee cannot speak. The Committee notes, however, that DOE, for reasons entirely separate from the ones that motivate this Workshop, could apply this approach to limestone caves in Kentucky and Tennessee to extend the history of large earthquakes in the New Madrid seismic zone back thousands and perhaps tens of thousands of years.

The absence of earthquake faulting with surface displacements greater than 2 m in the case of the Yucca Mountain faults (Whitney) over the past 700 ka or surface displacements greater than 6 m for earthquake faulting anywhere in the Basin and Range province (Schwartz) suggests that Andrews' model earthquake, with its 15 m of surface displacement, is an unlikely if not impossible event in this geologic setting. Andrews, Beroza, and Somerville generally confirmed the view that large displacements/stress drops are required somewhere in the source region if the source itself is the causative agent of extreme ground motions, although other possibilities exist in the way of forward directivity, seismic-ray focusing, and site amplification.

No consistent use of unexceeded ground motions or physical limits to ground motion was employed in the 1998 Yucca Mountain PSHA. No formal feedback was provided to the experts about extending the 1998 results to hazard levels of 10^{-6}/yr and smaller.

The Committee finds the Point A PGV = 3.5 m/sec at a hazard level of 10^{-6}/yr as determined from the 1998 Yucca Mountain PSHA is contradicted by the undamaged lithophysal units and the existing corpus of PGV data. First, such a PGV would have caused observable damage to the lithophysal units, which has not occurred in 10^7 yrs. Second, assuming such a large PGV would have been the result of a large event ($6.5 \leq \mathbf{M} \leq 7$) on the Solitario Canyon fault, with a recurrence interval of ~50,000 years, a PGV occurring in one of 20 events suffices to reach 10^{-6}/yr. In the PEER strong motion data set, there are 73 recordings from 20 earthquakes with $6.3 \leq \mathbf{M} \leq 7.3$ at distance from 0 to 10 km. The largest PGV for the average horizontal component from this subset is 1.1 m/s. (This record is from a soil site; the largest average horizontal PGV in this subset from a rock site is 0.9 m/sec.) This subset includes distances greater than the distance from Point A to the Solitario Canyon fault, but it also includes sites with near-surface shear – wave velocity (V_s) values of 200-2000 m/sec, which are on average lower than the V_s for Point A. These data indicate that the 1 in 20 PGV for Point A is much smaller than 3.5 m/sec. Furthermore, the largest PGV ever recorded of 3.0 m/s from the 1999 Chi-Chi earthquake (**M** = 7.6) is associated with 9 m of fault slip near the recording site, fault displacements larger by a factor of ~5 than those on faults near Yucca Mountain.

RECOMMENDATIONS FOR RESEARCH

The research recommendations that follow below are placed in three categories: physical limits, unexceeded values, and frequency of occurrence. Physical limits to and unexceeded values of earthquake ground motion have been discussed at length in this report, but things like frequency of occurrence of high-stress-drop earthquakes or the frequency of occurrence of PGA's > 1 g and PGV's > 1 m/sec do not fit easily into either of these categories; hence the third.

A. PHYSICAL LIMITS

The Committee recommends that research be conducted into the physical limits on ground motion in two specific areas: 1) nonlinear effects due to rock-mass degradation, including slip on pre-existing fractures and creation of new fractures, along the travel path of the seismic wave as it transits from the source to the ground surface at the Yucca Mountain site, and, 2) nonlinear effects at the source resulting from slip on the fault and rock-mass damage in the source region.

A.1. Nonlinear Modeling of the Seismic Travel Path

The shear and tensile strain limits of the rock mass provide physical limits to seismic wave propagation through the rock units at the Yucca Mountain site. Using nonlinear wave propagation models, these physical limits can be used to provide an estimate of the largest possible ground motions.

The Committee recommends a nonlinear numerical analysis of the response of the site-specific rock units at Yucca Mountain to the seismic waves. Joe Andrews (USGS), Peter Cundall and Branko Damjanac (Itasca) described preliminary results from nonlinear one and two-dimensional site response calculations during the workshop. This analysis would account for wave propagation from a seismic source in the linear elastic regime at depth that subsequently travels through the rock units underlying the repository, the repository horizon and the overlying tuff units to the ground surface. Numerical models capable of accounting for the nonlinear effects and energy dissipation mechanisms of shear and tensile strain limits of welded, fractured rock tuff as well as the nonwelded, bedded rocks are required.

Energy is naturally dissipated as a rock mass undergoes shear and tensile failure in the intact rock matrix as well as along natural fractures such as joints and bedding surfaces. Dissipation of energy during yield is taken into account in nonlinear numerical models through enforcement of inelastic material stress-strain laws for the rock matrix as well as fractures. For example, yield and energy dissipation within the rock matrix may be represented by a continuum-based constitutive law (e.g., Mohr-Coulomb with a brittle post-peak softening using a finite element or finite difference numerical formulation) or by models that explicitly account for rock fracture and creation of new surface area (e.g., discontinuum or particle models). An example of the continuum-based method was presented by Joe Andrews, and examples of the use of discontinuum approaches to model rock shear and tensile fracturing were presented by Branko Damjanac and Peter Cundall. Nonlinear response and energy dissipation due to shear or tensile failure along fractures or bedding surfaces along the travel path are typically accounted for through the use of explicit fracture representations or continuum-based in the rock mass. Slip and/or separation, and the associated energy dissipation mechanisms, on fractures or bedding surfaces is often modeled explicitly using discontinuities within the rock mass upon which a constitutive law for slip (e.g., Mohr-Coulomb) is enforced. Alternatively, the general effect of fracture sets may be represented using equivalent rock mass shear strength in which the presence of fracturing has been accounted for in a reduction of strength and moduli. A potentially important mechanism of energy dissipation at the Yucca Mountain site is separation of subhorizontal bedding surfaces or creation of subhorizontal fractures due to vertically-propagating shear and compression waves near the ground surface (e.g., a spalling-type phenomena).

For the Yucca Mountain site, in particular, the input seismic waves would begin in the limestone units at depth and travel through the Bullfrog, Prow Pass and Tram welded and Calico Hills nonwelded units below the repository horizon. Representation of the proposed repository host horizon should include the weaker lithophysal units. Rock mass properties estimates and mechanical constitutive laws developed for the Yucca Mountain project can be used as input to these studies. The analyses would provide the input and output seismograms from each of the site geologic units as the wave transits to the ground surface. The results will be used to provide a detailed understanding of the mechanism and extent to which the site response is altered due to nonlinear effects, and to provide a more realistic, mechanistic-based assessment of physical limits to the ground motions.

The Committee notes that these calculations will require a considerable amount of material-properties input data, together with associated uncertainties. The Committee is not informed as to what scope of effort may be needed to assemble this information.

A.2. Nonlinear Modeling of the Source

Limits on the ground motions generated by the source provide a mechanism for physical limits to the ground motions that are input into the rock units at the Yucca Mountain site.

The Committee recommends that research be conducted into nonlinear modeling of the seismic source to gain a better understanding of the effect of the physical strength limits of rock on the source mechanisms and energy generation resulting from fault slip. The ultimate purpose of this work is to examine whether the geometry, properties and constitutive behavior of the fault, the *in situ* state of stress, and the rheology of the surrounding rock mass result in a bound to the magnitude of energy release from slip events. Such nonlinear source modeling, which dates back to the 1960's to simulate nuclear weapons effects, should extend the Workshop presentations of Andrews and Cundall to other material rheologies, stress states, and faulting geometries, including the roughness geometry of faults

Nonlinear response and energy dissipation due to shear or tensile failure along faults, and in the near field of the faults is an area in which research may be performed using existing numerical modeling methods. For example, the slip and/or separation on the fault surface and the yield and fracturing in the fault near field may be modeled using interfaces within the rock mass upon which a constitutive law for slip is enforced. The representation of the fault surface could include roughness (e.g., asperities), and thus an inhomogeneous representation of strength.

Other factors, such as time-dependency could be included. Energy dissipation via yield in the fault near field may be represented through continuum-based plasticity models or via explicit fracturing as described by Cundall.

This task will lead to source models and computational tools that can be used to compute the ground motions in the near-fault region, before they are propagated into the shallow rock (task A.1.).

A.3. Nevada Test Site (NTS) Nuclear Explosion Data

The Committee believes that instrumental recordings of the downhole response of rock to the extreme strain pulses from NTS nuclear explosions at close distances would be valuable in assessing extreme ground motions at nearby Yucca Mountain. Such data could, in principle, be used to validate the nonlinear models discussed above and also to assess the validity of various estimates of the levels of ground motion that fracture rock. Such data could also be valuable in assessing the nonlinear response of the alluvium beneath and adjacent to the surface waste-handling facilities. Questions remain, however, as to the availability, accessibility, and the quality of these data. The Committee recommends funding further analysis of these matters, building on Foxall's findings as reported in his Workshop presentation.

A.4 Implementation of Source Models

The Committee recommends that initial application of the source constraints from task A.2 be used to develop more computationally efficient, representative kinematic source models. These kinematic representations of the source should then be used to compute broadband seismic motions that can be used as inputs to the nonlinear wave propagation models. By using representative kinematic models, initial simulation results can be derived in a relatively short time, whereas some broadband non-linear source models may not be readily available for engineering application. This also has the advantage that the source is parameterized in a simplified manner that is familiar to ground motion experts.

Working Groups

The nonlinear modeling of the wave propagation and source involve a range of expertise. The Committee recommends that working groups of rock-mechanics modeling specialists and seismologists be assembled to conduct these research tasks. Seismologists will provide expertise in source mechanics and ground motion characterization; the rock mechanics specialists will bring a detailed understanding of the rheological behavior of rocks and state-of-the art experience in development and use of dynamic, nonlinear modeling. Recent research by Andrews and by Cundall and Scholz in dynamic modeling of rough faults provides examples of the modeling approaches that can be applied to this problem.

For the new models developed by the working groups to be accepted for use, some calibration/validation of the source models and non-linear wave propagation using empirical observations will be needed to show that the models are working properly. The compilation of the empirical data for the source model calibration is discussed in tasks A3 and C1. The compilation of the data for the non-linear wave propagation model is discussed in task A.3.

B. UNEXCEEDED VALUES

B.1. The Committee supports continuation of the ongoing study and analysis of the lithophysal units within the Yucca Mountain Project to determine unexceeded ground motions for the repository level since 12.8 Ma. The Committee recommends extending such studies to the underlying Calico Hills tuff.

B.2. The Committee recommends that the present status of unexceeded ground-motion amplitudes associated with precarious rocks, precipitous slopes, and unfractured rock, together with available age determinations for these structures, be synthesized for the Yucca Mountain Project. This synthesis should also serve as plan for supplemental age determinations as necessary. Likewise, the Committee recommends that similar information be developed for the unfractured sandstones adjacent to the San Andreas fault.

B.3. The Committee also recommends that syntheses of the Whitney and Schwartz presentations with respect to single-event faulting displacements for the Yucca Mountain and the entire Basin and Range, respectively, be written for the Yucca Mountain Project.

B.4. The Committee also recommends that research be conducted as to the ways in which unexceeded ground motions can be formally employed in PSHA, for example through Bayesian updating.

C. EVENT FREQUENCIES OF OCCURRENCE

Earthquake source parameters and ground-motion peak parameters in the existing literature and catalogues can be used to establish empirical constraints on the distributions of source/ground-motion properties. Such studies should emphasize the upper tail of the distributions. With tens of thousands of earthquakes and ground-motion records now available, the upper tail of these distributions can be reliably determined. These distributions can be used directly in simple ground-motion models (e.g. point-source stochastic models) or they can be used to test the non-linear source models developed in task A.2.

C.1. Earthquake Stress Drops

Despite three decades of study of crustal earthquake stress drops involving hundreds of seismologists around the world, the frequency-of-occurrence of high-stress-drop earthquakes is still poorly known. The most comprehensive way to explore this, the Committee believes, is through the m_b-M_S pairs that exist for tens of thousands of crustal earthquakes, as described by Dewey. This will also be the most time-consuming approach, as those earthquakes that do suggest high stress drop will need to be studied individually to verify that this the case. A less time-consuming alternative would be to conduct a literature search for all $\mathbf{M} > 5$ earthquakes for which a Brune stress drop has been determined, which still involves perhaps a thousand (or more) earthquakes. In both cases, it would be desirable that the tectonic regime be specified, for the particular interest at Yucca Mountain is the extensional faulting regime.

C.2. The Larger PGA's and PGV's

In a like manner, the Committee recommends documentation and analysis of the 100 largest PGA's and PGV's, in a manner building on Anderson's presentation. Further, the Committee recommends a synthesis of the analysis of ground-motion outliers as parameterized by their normalized residuals, after Bommer's presentation. Of particular importance is the association of the largest known absolute values (PGA's and PGV's) and relative values (normalized residuals) with forward directivity, faulting mechanism, and earthquake magnitude. These empirical results can then be compared to the numerical calculations of the non-linear modeling of the source and wave propagation.

C.3. Simplified Representation of Nonlinear Source Models

To provide a method for calibrating the non-linear source models from Task A.2, the Committee recommends that equivalent (representative) simplified source parameters from task C.1 and C.2 be computed for a suite of source model realizations. The shape of the distribution of these simplified parameters should be compared to that from the catalog data (task C.1) as a check of the non-linear source models. For example, the distribution of the equivalent Brune stress drop from the non-linear source models can be compared to the empirical distribution determined in Task C.1.

IMPLEMENTATION OF RESEARCH RESULTS IN PSHA

This Committee was constituted by Bob Budnitz, with the Science and Technology Program of the Office of Civilian Radioactive Waste Management, to review the guidelines and procedures for PSHA in the context of the extreme ground motions resulting from the 1998 Yucca Mountain PSHA. As a prelude to that task (Task A), the Committee undertook the present one (Task B) on the basis that the application of either physical limits to ground motion or unexceeded ground-motion amplitudes within the PSHA formalism would require new and different guidelines, procedures, and rules.

Given the very large PGA's and PGV's arising from the 1998 PSHA at hazard levels of 10^{-6}/yr and smaller, the Committee has little doubt that the application of both physical limits and unexceeeded values for specific time intervals will reduce these ground-motion amplitudes at hazard levels of at least 10^{-6}/yr and smaller and perhaps at larger hazard levels as well. While the Committee makes no recommendation about re-visiting the 1998 Yucca Mountain PSHA or conducting a new one, it nevertheless believes that work should be conducted in a manner that keeps implementation into PSHA in mind.

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