CENTER FOR NUCLEAR WASTE REGULATORY ANALYSES

TRIP REPORT

SUBJECT: Joint International Association of Geomagnetism and Aeronomy (IAGA) and International Association of Seismology and Physics of the Earth's Interior (IASPEI) Meeting.

DATE/PLACE: August 21–26, 2001, at Hanoi, Vietnam

AUTHOR: John Stamatakos

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PERSONS PRESENT: About 1,000 Scientists from around the world

BACKGROUND AND PURPOSE OF TRIP:

On August 21–29, 2001, Dr. John Stamatakos participated in the joint International Association of Geomagnetism and Aeronomy (IAGA) and International Association of Seismology and Physics of the Earth's Interior (IASPEI) meeting in Hanoi, Vietnam. IAGA and IASPEI are two of the seven Associations in the International Union of Geodesy and Geophysics (IUGG). IAGA and IASPEI meet every four years (although not always jointly) to allow the international scientific community to discuss current and emerging methods in geomagnetism, paleomagnetism, space and atmospheric physics, and seismicity. The full IUGG meets in the intervening two years. This joint IAGA-IASPEI meeting was hosted by the Hanoi Institute of Geophysics, National Center for Natural Sciences and Technologies of Vietnam.

Dr. Stamatakos' participation in the IAGA-IASPEI meeting directly supports NRC goals for nuclear waste safety. Dr. Stamatakos presented a paper entitled Application of 3DStress™ to Probabilistic Seismic Hazard Assessments. The presentation introduced a new methodology for seismic hazard assessment that incorporates slip tendency results from the 3DStress™ computer program into a PSHA logic tree analysis. This methodology offers a new way to evaluate uncertainties in seismic source parameters for probabilistic seismic hazard assessments, and offers the potential for reducing uncertainties. The presentation demonstrated how technical activities conducted at the CNWRA in support of the NRC high-level waste program are at the leading edge of quantitative hazard assessment techniques. Positive and constructive comments were received about the methods or analyses presented at the meeting. Interactions at this meeting re-enforce confidence that methods used to evaluate the DOE PSHA for the proposed Yucca Mountain repository site are accepted by the international seismological community and represent state of the art science.

SUMMARY OF PERTINENT POINTS

3DStress™ Presentation

Many probabilistic seismic hazard assessments (PSHA) rely on expert judgement to develop input parameters for seismic sources and a logic tree approach to incorporate uncertainty of those parameters. Seismic source input parameters include the likelihood of fault activity, location of an earthquake rupture along a mapped fault trace or fault surface, and maximum magnitude ($\mathbf{M}_{max}$) of the characteristic earthquake that the fault is deemed capable of generating. The expert judgement and the logic tree approach has been used for recently completed PSHA studies at several existing and proposed nuclear waste facilities in the United States, including the Paducah Gaseous Diffusion Plant (PGDP) in Kentucky (Risk Engineering, Inc., 1999), the potential high-level nuclear waste repository at Yucca Mountain Nevada (CRWMS M&O, 1998; Stepp et al., 2000), and the candidate interim high-level nuclear waste facility at Skull Valley, Utah (Geomatrix Consultants Inc., 1999). Because PSHA studies rely on the subjectivity of expert judgement to appraise many of the seismic source parameters, uncertainties can be large. The goal of my presentation was to show that several important seismic source input parameters could be more objectively determined by considering the influence of crustal stress on the generation of earthquakes.

Most geoscientists conclude that crustal stress controls when and where earthquakes occur. Tectonic forces are thought to create crustal stresses and thereby drive deformation of the crust. The result is an accumulation of strain in the crust especially along crustal discontinuities (i.e., faults). When the accumulated strains overwhelm the frictional resistance on the fault surface, the fault ruptures, and an earthquake results. The earthquake releases elastic energy into the surrounding region that causes the violent ground vibrations that cause damage. My presentation at the IAGA-IASPEI meeting showed how knowledge of the crustal stress conditions, specifically the slip tendency of a fault trace or fault, can be used to develop or refine estimates of seismic source input parameters used in PSHA studies.

Slip tendency is defined as the ratio of the shear stress divided by the normal stress acting on a fault surface (Morris et al., 1996; Ferrill et al., 1999). Calculation of slip tendency is simple for planar surfaces, but complicated for more intricate complex geometries. The 3DStress™ computer program provides an integrated analysis of the relationship between in-situ ambient crustal stress and the complicated two- and three-dimensional geometries of faults. In essence, the program treats each fault trace or fault surface as a composite of a large number of individual fault elements (lines or planes). For each fault element, 3DStress™ calculates the slip tendency and visually displays the results. Each fault element (line or plane) is color coded to its slip tendency value. Along side the color-coded slip tendency maps or three-dimensional volumes is a display of the associated stress conditions (orientation and magnitudes of the three principal stresses). Users can interactively change the ambient stress conditions and view how those changes are manifest in the slip tendency maps or three-dimensional volumes.

For seismic hazards analyses, slip tendency values can be used to develop or modify probability distribution functions used in the PSHA logic trees. The application assumes knowledge of stress conditions in the crust and geometries of seismogenic faults. I presented two examples: (1) a probability weighted model for determining the location of earthquake ruptures along fault traces and fault surfaces and how this model for earthquake rupture influences site-to-source distance distributions used in ground motion attenuation equations;

and (2) development of fault segment models and fault segmentation in the determination of $\mathbf{M}_{max}$.

1. Location of earthquakes and site-to-source distance distributions.

Ground motion attenuation equations describe changes in earthquake energy as seismic waves travel from the earthquake focus to the site. The degree of attenuation depends, among other factors, on the distance between the site and earthquake source. In many attenuation relationships (e.g., Campbell, 1997) the site-to-source distance distribution is determined from plan-view distances between seismogenic faults and the site, usually determined from geologic maps that document surface traces of faults (Figure 1). For many other attenuation equations (e.g., Abramson and Silva, 1997), the distance distribution is determined based on a simplified three-dimensional projection of the fault surfaces.

A simplifying assumption in many estimates of the site-to-source distance distributions is that they are uniform. Earthquakes are considered equally likely to occur anywhere on the fault trace (2D) or fault surface (3D). Slip tendency values, however, suggest that some segments of the fault trace (2D) or patches of the fault surface (3D) are more favorably oriented for fault slip, and thus more apt to rupture, than others. Based on this observation, I proposed that slip tendency values be used to weight the site-to-source distance distributions as a way to more accurately depict the likely location of future earthquake ruptures.

As an example, 3DStress™ results were used to adjust the site-to-source distance distributions for the Bare Mountain, Paintbrush Canyon-Stagecoach Road, and Solitario Canyon faults near Yucca Mountain, Nevada. In the 2D example a site near the center of Crater Flat basin, near Red Cone was arbitrarily selected as the reference site (Figure 1). The normalized slip tendency values for each fault trace were then calculated (Figure 2) and those values used to weight the distribution of site-to-source distances, giving proportionally greater weight in the frequency plots to those nodes along the fault traces with higher slip tendencies. Figure 3 compares the site-to-source distance PDFs assuming uniform distribution of fault nodes with those that incorporate the slip tendency weighting. The results indicate that weighting the site-to-source distances by slip tendency significantly changes the resulting frequency distributions. In this case, the PDFs tend to be skewed to nearer site-to-source distances because many of the fault segments closest to the Red Cone site have the highest normalized slip tendency values.

A similar example was developed for the 3D fault surface of the Bare Mountain fault. Figure 4 shows the slip tendency values for the Bare Mountain fault. Site-to-source distances were calculated from several hundred nodes on the fault surface. As in the 2D example, the distribution of site-to-source distances with unit weight given to each node were compared to site-to-source distances in which the distance measures were weighted by the normalized slip-tendency values (Figure 5). In this case the difference between the two frequency distributions is substantial. The distribution of site-to-source distances weighted by slip tendency is highly skewed toward distances nearest the site compared to the uniform model. This large change in the distribution results because patches of the Bare Mountain fault surface with the highest slip tendency values are quite close to the site in Crater Flat compared to those patches of the fault surface with lower slip tendency values.

2. Fault segmentation and estimation of $\mathbf{M}_{max}$.

The plots of slip tendency along strike of the fault traces and of fault area can also be used to determine the length or area of potential fault rupture. Knowledge of rupture length or rupture area is important because these values are often to estimate $\mathbf{M}_{max}$ (e.g., Wells and Coppersmith, 1994). For surface rupture length, Wells and Coppersmith (1994) found that regression of 77 historical earthquakes yielded a scaling relationship of :

$$\mathbf{M} = 5.08 + 1.16 * \log(SRL) \tag{1}$$

where **M** is the Moment magnitude of the earthquake and SRL is the surface rupture length (in km).

Slip tendency values along the Bare Mountain fault for both fault trace length (Figure 2) and fault area (Figure 4) indicate that at least two segments or patches of relatively high slip tendency values are separated by regions of lower slip tendency. This pattern reflects the corrugated geometry of the Bare Mountain fault surface and indicates that the fault may be segmented. If correct, earthquakes on the Bare Mountain fault may more often be restricted to one or the other fault segments rather than a rupture of the entire fault. This observation is consistent with slip rate estimates that show much larger slip rates for the southern Bare Mountain fault (Ferrill et al., 1996; Stamatakos et al., 1997). The observation may also explain differences in the age and magnitude of paleoseismic events on the northern and southern segments (cf., Reheis, 1988; Anderson and Klinger, 1994).

To develop a distribution function for $\mathbf{M}_{max}$, the Wells and Coppersmith empirical equation (1) was used to derive moment magnitudes for various fault lengths indicated by the slip tendency results. The full fault length is 20 km has a normalized slip tendency value of 0.2 or less. Fault segments with higher slip tendency values are much shorter; 4 to 7 km long segments as defined by relatively larger slip tendency values shown in Figure 2. These $\mathbf{M}_{max}$ values were then weighted by the normalized slip tendency values producing the resulting PDF for $\mathbf{M}_{max}$ (Figure 6). We compared this distribution of $\mathbf{M}_{max}$ to a normal distribution centered around $\mathbf{M} = 6.6$, which is the $\mathbf{M}_{max}$ assuming a 20 km fault length.

In summary, these preliminary calculations show that incorporation of slip tendency values from 3DStress™ may provide an improved and more objective basis for the development of seismic source parameters used in PSHA logic trees. More work needs to be done to test the validity and applicability of the proposed technique. In particular, future work will examine the concepts of the probability-weighted earthquake locations along fault traces and on fault planes based on slip tendency, and the associated effects on the site-to-source distance distributions against recent historical earthquake data. Sensitivity studies of the effects of the techniques on ground motions could also be developed to show the impact the slip tendency technique may have on the Yucca Mountain PSHA.

Other Interesting Talks at the Meeting

There were a number of interesting talks at the meeting, both in earthquake seismiology and in general geophysics. In particular I was impressed by a sequence of talks given by Dr. David Rhoades (Institute of Geological and Nuclear Sciences of New Zealand) and his coauthors on their analyses of precursor earthquake swarms. Dr. Rhoades shows how large earthquakes are

often preceded by long-term earthquake swarms and how this information can be used to develop earthquake recurrence models that include a time-dependent parameter.

Traditionally, seismic hazard studies have assumed that earthquakes can occur at a given frequency along a fault source but independent of the time since the last earthquake (Poisson model) . The new methods assume that stress cycling is important in generating earthquakes and that a time-since-last-earthquake parameter can be incorporated into the hazard assessments. In addition, Dr. Rhoades gave several talks on probability forecasting and on precursory scale increases in seismicity before large earthquakes. Dr. Rhoades showed a relationship between the size and duration of pre-shock earthquake swarms for large magnitude earthquakes. His methods may offer promise for real time forecasting based on past earthquake information. Examples of application of Dr. Rhoades' swarm model are published in a number of recent papers (Evison and Rhoades, 1999a, 1999b, 2000, 2001).

Dr. David Gubbins from the University of Leeds, England, gave a general lecture on the thermal core-mantle interactions. Theories of the thermal structure of the outer core and its relationship to the lowermost mantle are very important to core dynamics and ultimately to the generation and perturbations of the earth's magnetic field. Dr. Gubbins was able to incorporate a number of theoretical constraints with the existing data of polar wander and secular variation of the earth's magnetic field during field reversals into a unified model of core dynamics.

CONCLUSIONS:

The joint International Association of geomagnetism and Aeronomy (IAGA) and International Association of Seismology and Physics of the Earth's Interior (IASPEI) meeting was of great benefit to both myself and to the development of CNWRA technical expertise in seismic hazard analyses. The meeting provided an opportunity to present our new methods of incorporating the 3DStress™ computer code into evaluations of probabilistic seismic hazard assessments. I received positive and constructive feedback from scientists attending the sessions, and plan to update the models for a presentation at next year's Seismological Society of America meeting. My presentation also gave the international seismic community an opportunity to see how the Nuclear regulatory Commission is developing the technical capabilities to adequately review license applications for nuclear waste facilities such as a geologic repository.

PROBLEMS ENCOUNTERED:

None.

PENDING ACTIONS:

None.

RECOMMENDATIONS:

None.

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Date

JAS/rae

Attachments

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FIGURES

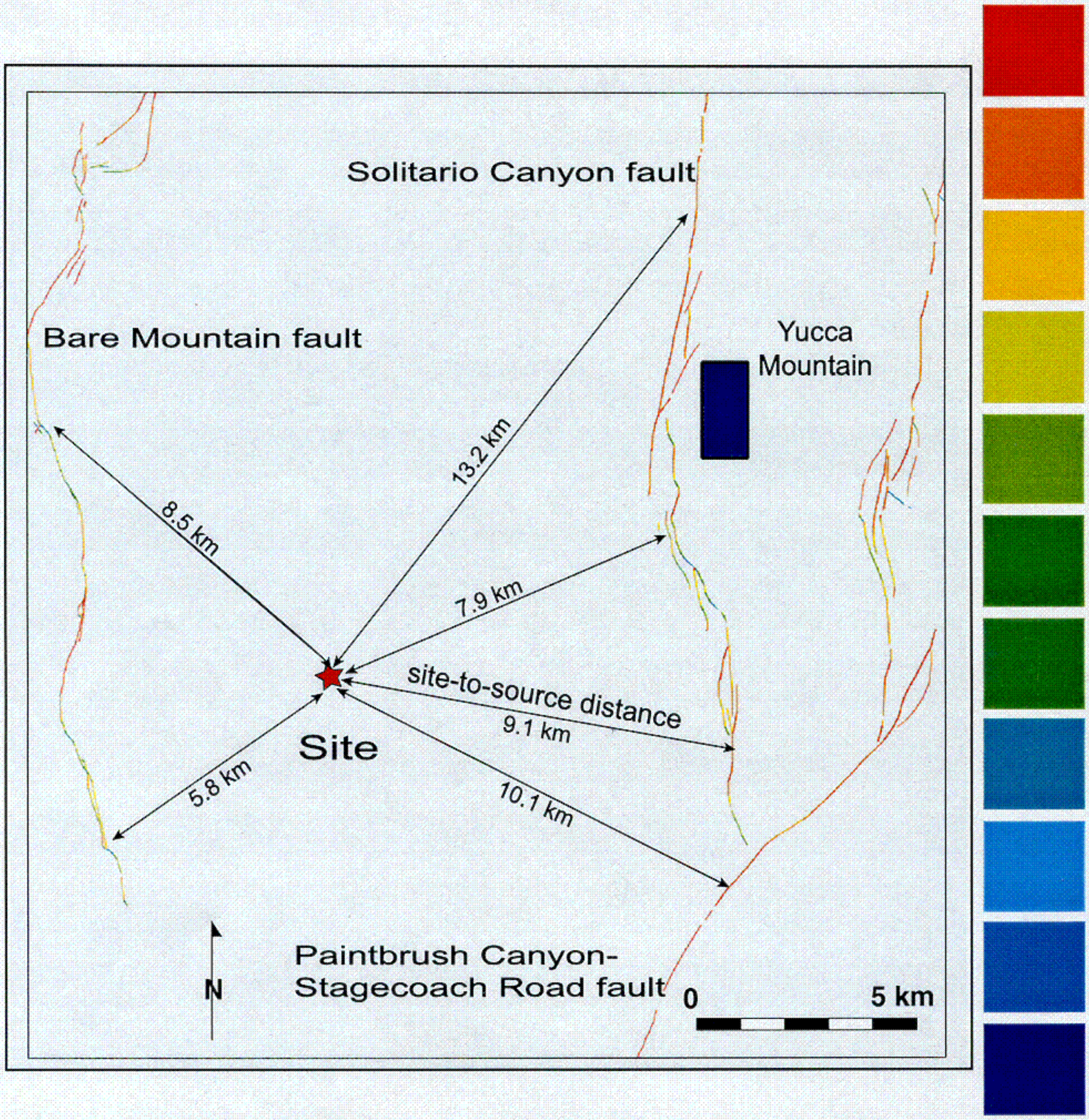

Figure 1. Map showing the slip tendency along fault traces of the Bare Mountain, Solitario Canyon, and Paintbrush-Stagecoach Road faults. The site (star) is an arbitrarily selected site in the center of Crater Flat basin used to demonstrate the proposed 3DStress^{TM} technique. The double arrows illustrate a few example site-to-source measurements. Hundreds of such measurements are used to derive the probability distribution functions shown in figure 3. The blue rectangle shows the approximate location of the proposed Yucca Mountain repository (primary block).

C01

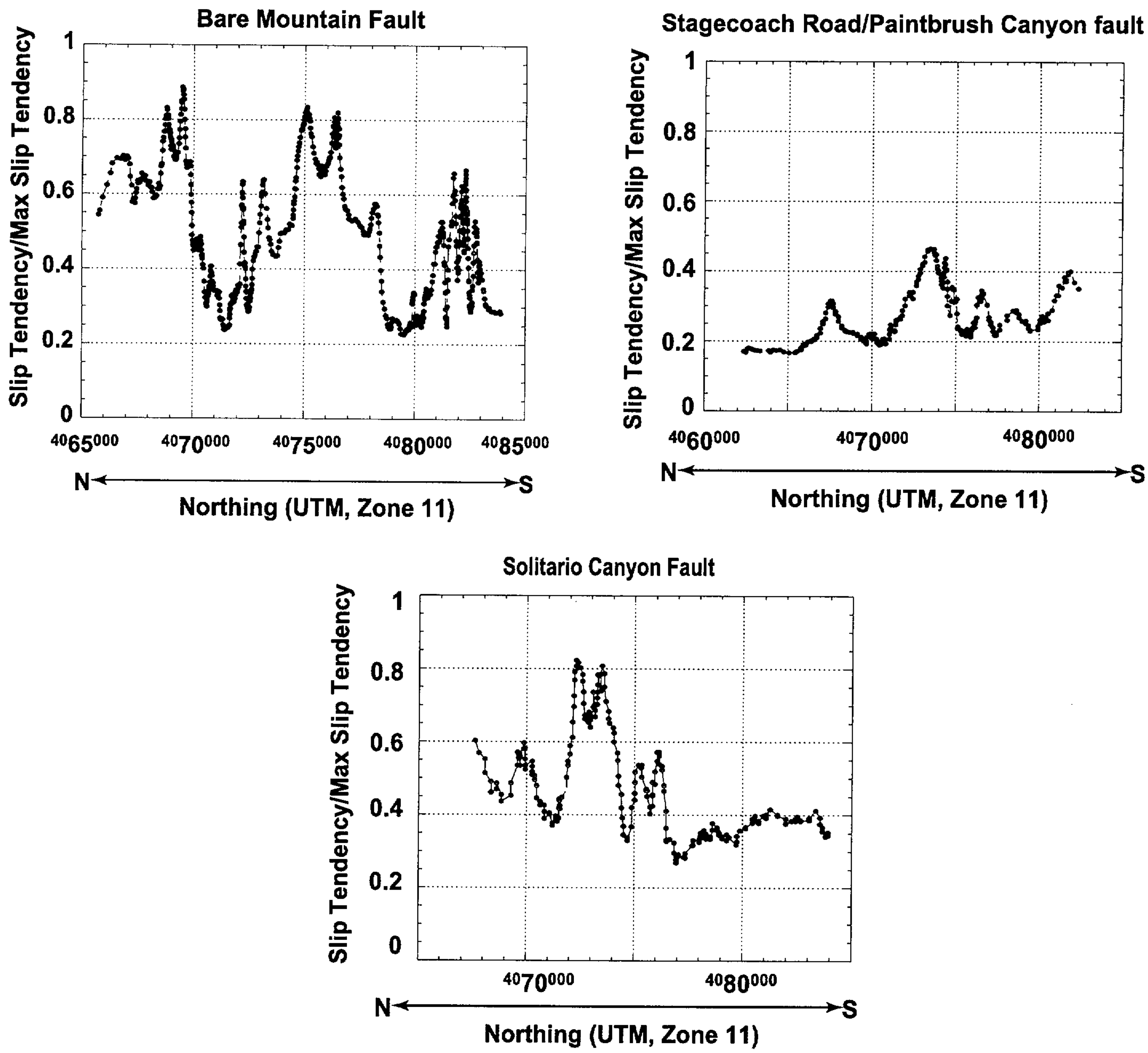

Figure 2. Variation of normalized slip tendency plotted as a function of distance along the trends of the Bare Mountain, Solitario Canyon, and Stagecoach Road-Paintbrush Canyon faults. Maximum slip tendency is determined from input stress conditions (Morris et al., 1996).

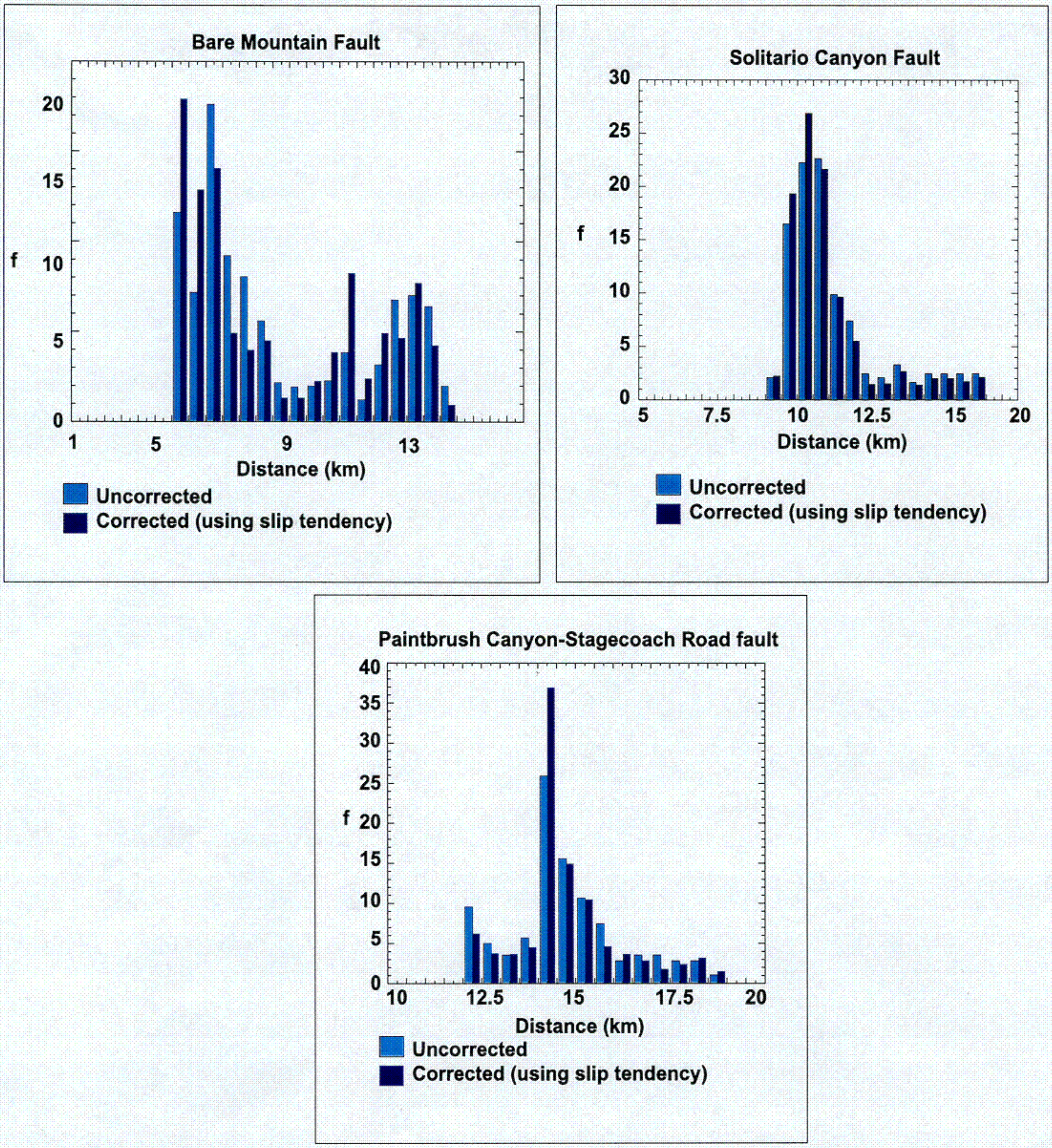

Figure 3. Histograms of site-to-source distances assuming uniform distribution of nodes along each fault trace compared to one in which the 0.5 km distance bins are weighted by the normalized slip tendency values.

C02

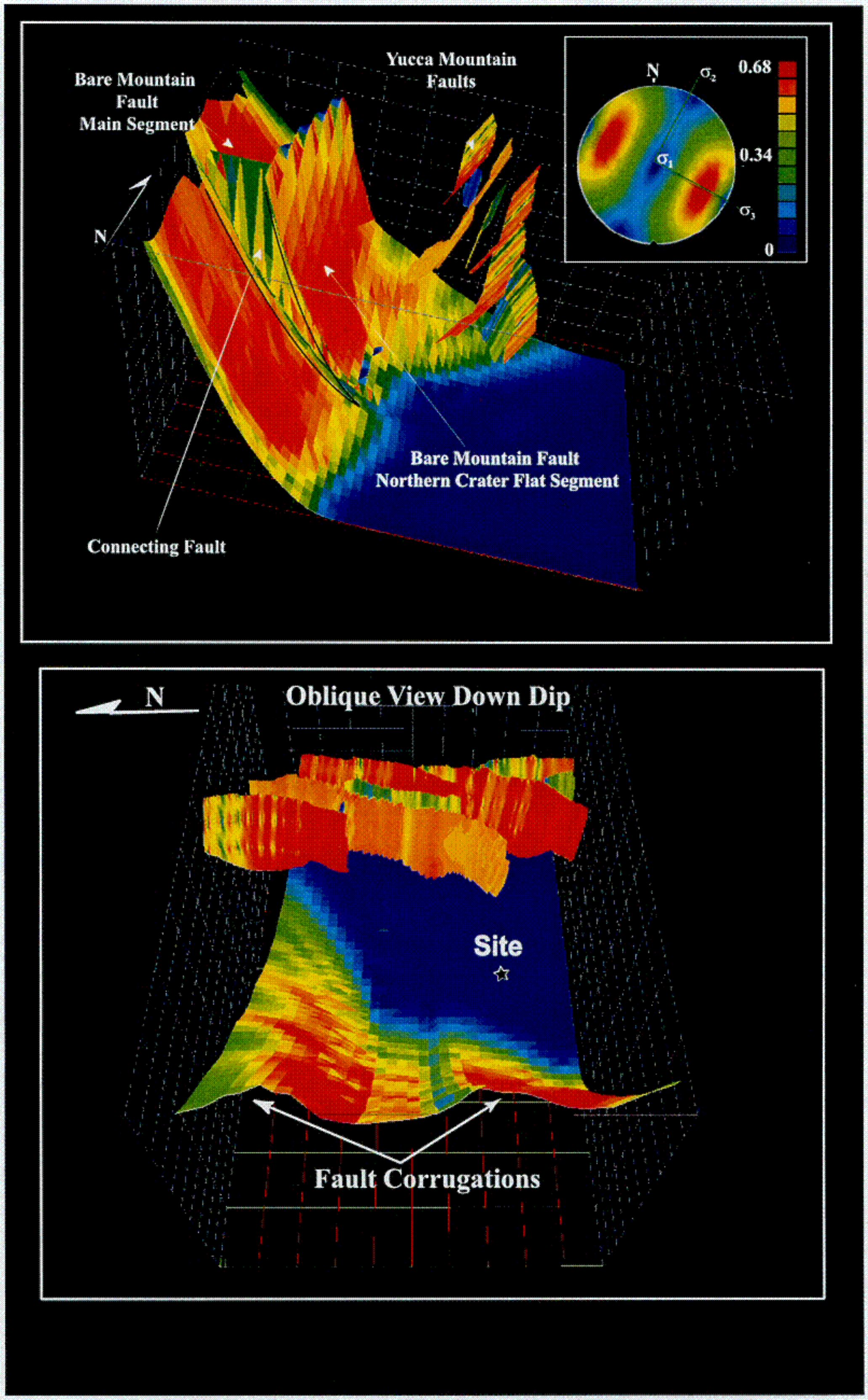

Figure 4. Slip tendency of the Bare Mountain Fault surface. For clarity, the down-dip extensions of the Yucca Mountain faults, including the Solitario Canyon and Paintbrush Canyon-Stagecoach Road faults have been omitted. Also for clarity, the northern Crater Flat segment of Bare Mountain fault was removed from the lower diagram. Hot colors (reds and yellows) indicate parts of the fault with relatively high slip tendency values. Cooler colors (blue and green) are areas of the fault with relatively low slip tendency values.

C03

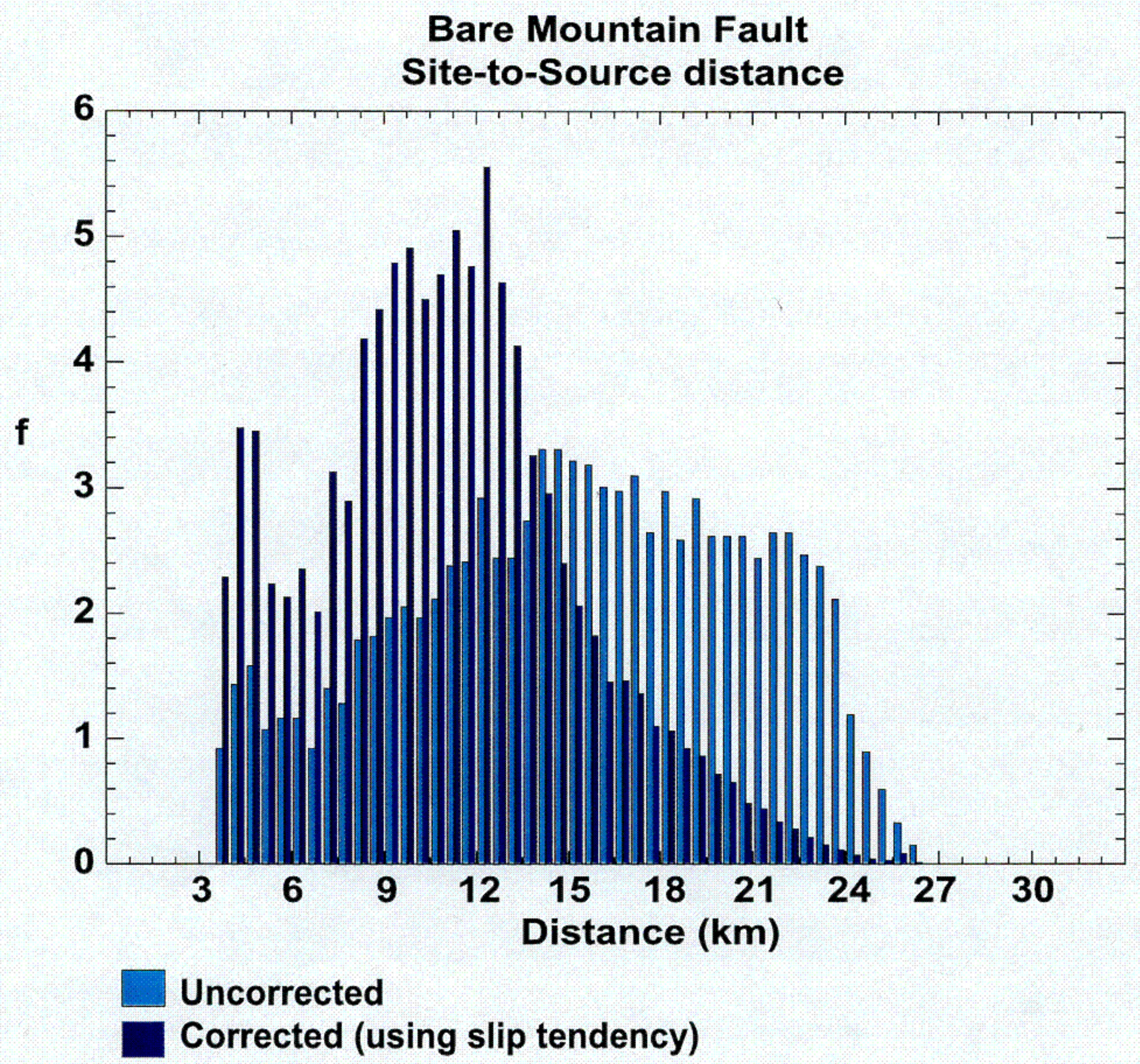

Figure 5. Histograms of site-to-source distances assuming uniform distribution of nodes along each fault node compared to one in which the distance bins are weighted by the normalized slip tendency values.

C04

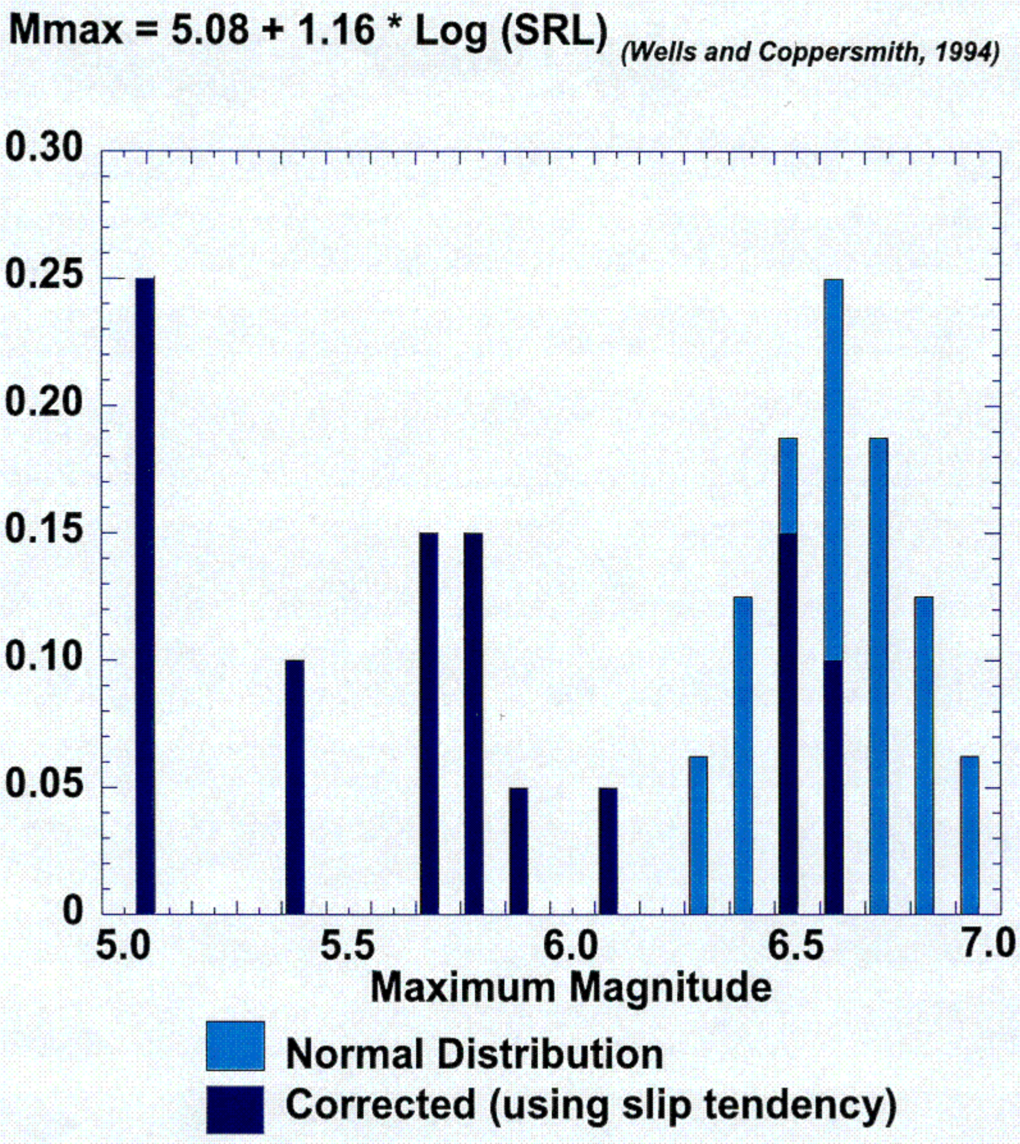

Figure 6. Histogram of maximum magnitude (Mmax) for the Bare Mountain fault assuming a normal distribution of Mmax compared to one that was generated using fault segment lengths and probability of rupture based on slip tendency.

C05