

# **CNWRA** *A center of excellence in earth sciences and engineering*

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(210) 522-5160 • Fax (210) 522-5155

January 28, 2002

U.S. Nuclear Regulatory Commission  
ATTN: Dr. Mahendra Shah  
NMSS/SFPO  
OWFN, Mail Stop 13 D13  
Washington, DC 20555

Dear Dr. Shah:

Enclosed are the document requested by the State of Utah in "The State of Utah's Seventeenth Set of Discovery Requests Directed to the NRC Staff." The enclosures include:


1. Copy of Scientific Notebook 353 entries regarding the additional analyses carried out in support of the Supplemental Safety Analysis Report (SSER). These analyses are provided in the scientific notebook because they were not documented in any other paper or report (e.g., Stamatakis et al., 1999-*Seismic Ground Motion at the Private Fuel Storage Facility Site in the Skull Valley Indian Reservation*. San Antonio, TX: Center for Nuclear Waste Regulatory Analyses). I have also added a set of color figures for clarity and a disk with the figures in pdf format.
  - a. Comparative analysis of probabilistic hazards results for sites in the western United States used to support SSER conclusions that the Private Fuel Storage (PFS) probabilistic seismic hazard assessment (PSHA) is conservative.
  - b. 3DStress™ Analysis performed on the Skull Valley and central Utah fault systems also used to support SSER conclusions that the PFS PSHA is conservative.
2. Copy of the User's Manual for 3DStress™ (version 1.3.3), printed from the HTML files.

For all other document requests, we have determined that all information requested by the state (i) has been provided in previous document requests; (ii) can be obtained from public literature (e.g., scientific journals); (iii) is in the existing PFS docket; or (iv) is in our reports (e.g., Stamatakis et al., 1999, SER, SSER). In particular, the sensitivity calculations referred to by the State in Document Request No. 9 was carried out in support of the original SER and is not new nor has it been updated for the revised SSER. The calculation is documented in Stamatakis et al., (1999).

If you have any additional questions regarding this information, please contact me at (210) 522-5247.

Sincerely,

Dr. John Stamatakis



JS/cap  
Attachments



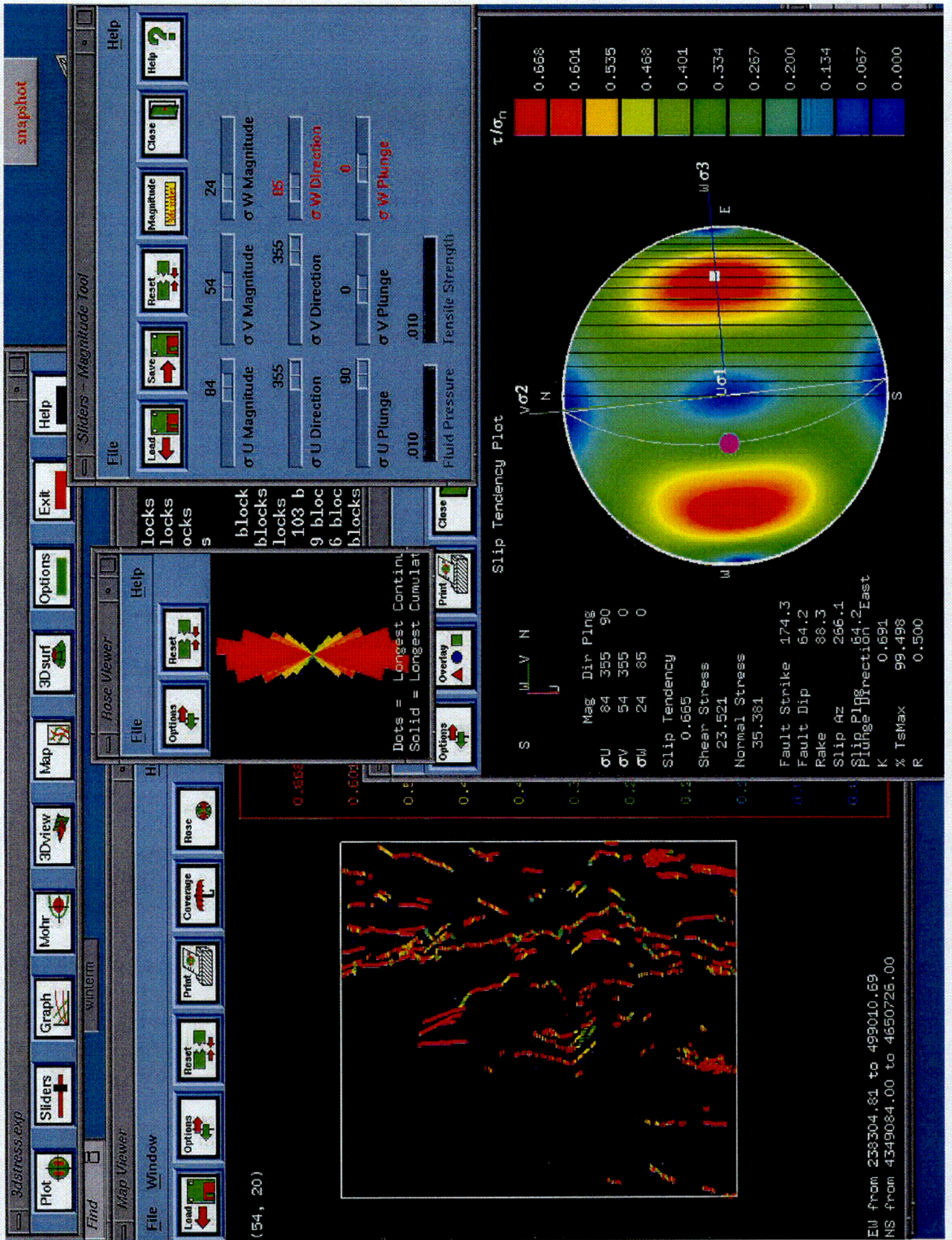
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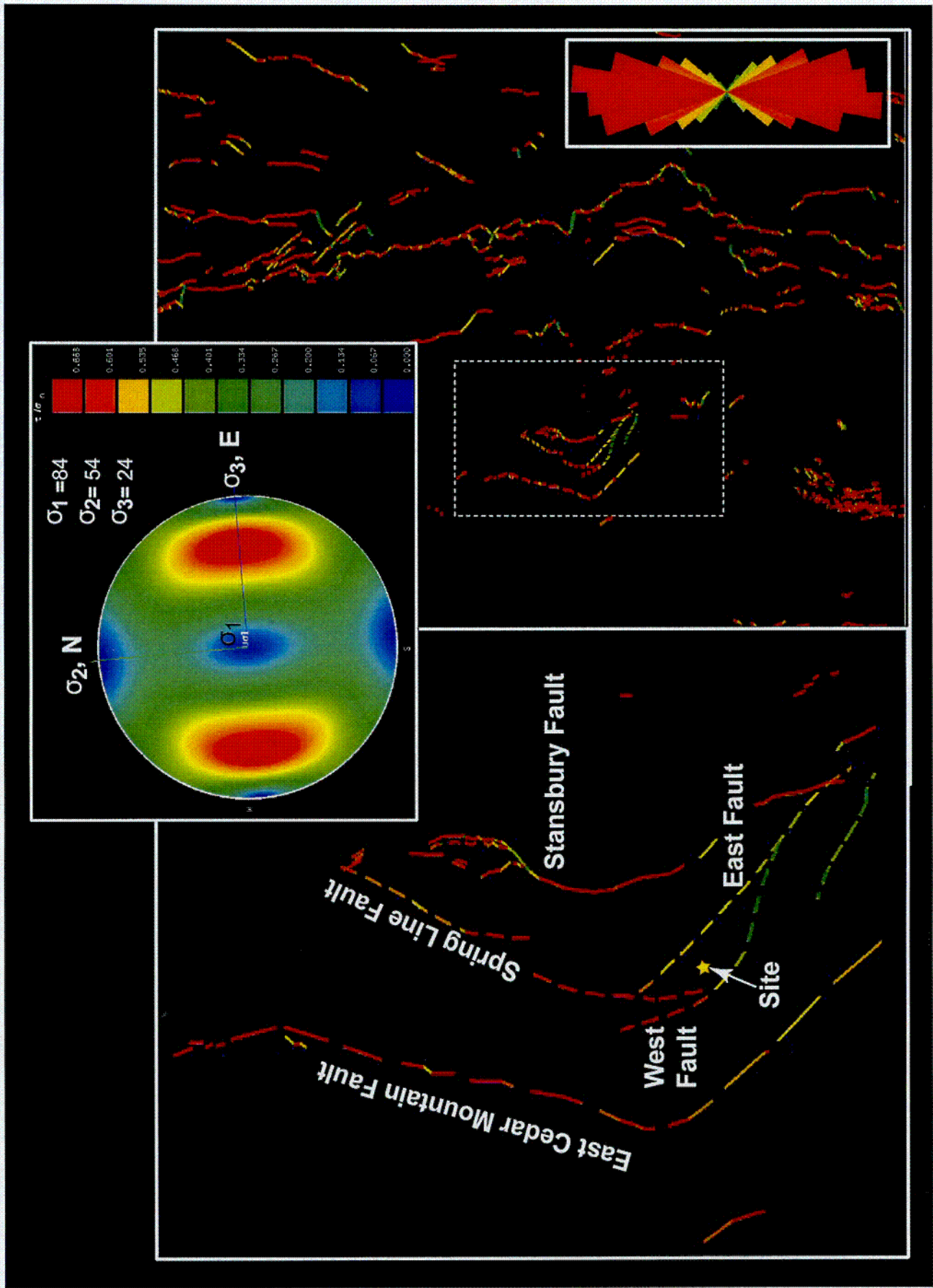
Dr. Mahendra Shah  
January 28, 2002  
Page 2

M. Delligatti  
S. Turk  
M. Waters  
C. Marco  
A. Chowdhury  
A. Ghosh



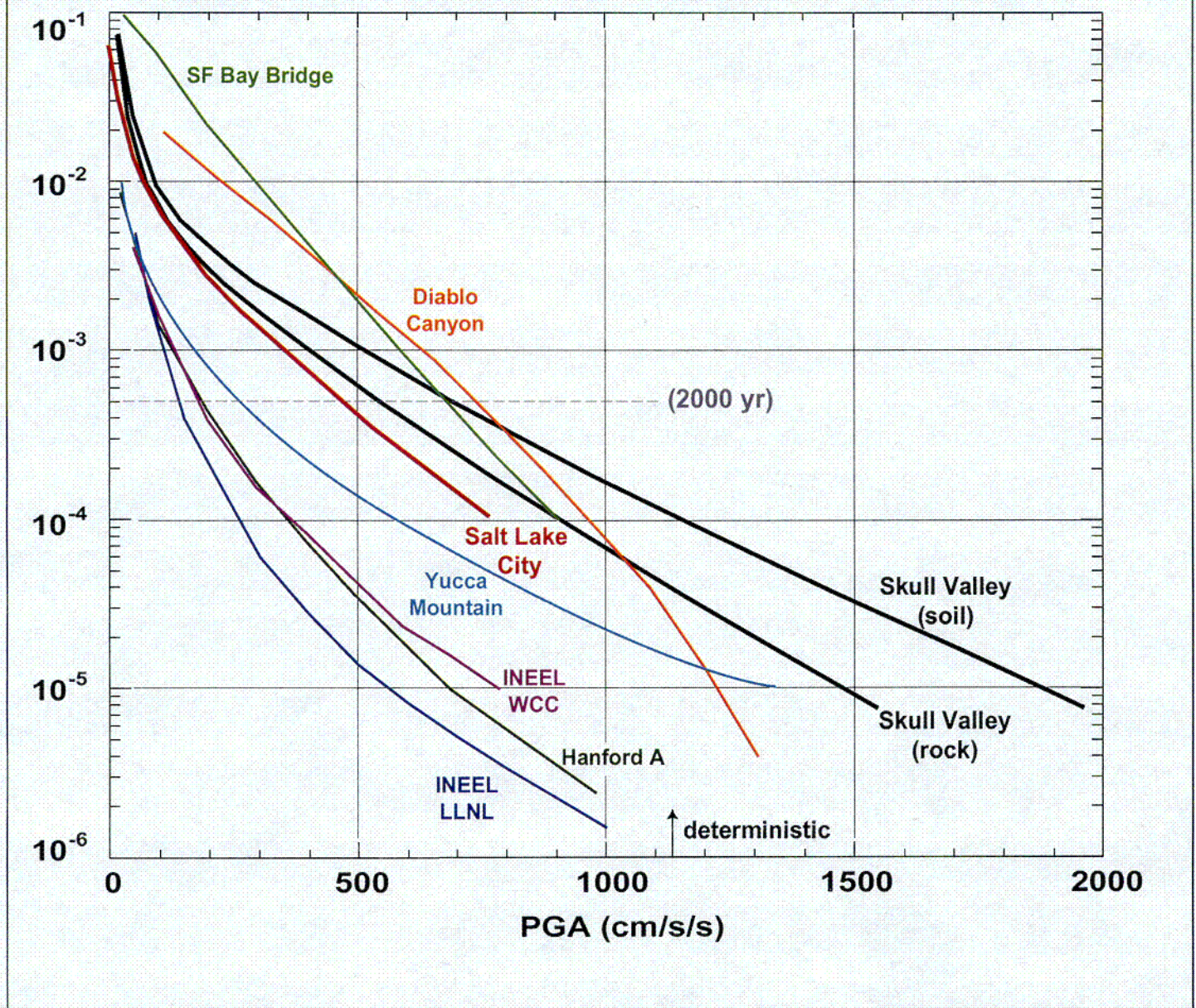








### Comparison of Western US Hazard Curves



JOHN STAMATAKOS

353

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INDIAN ENTRY

01

DISCUSSION OF WESTERN U.S. FISH CURVES

02-06

3D STRESS ANALYSIS OF SKULL VALLEY

07-12

Scientific Notebook 353

August 1, 2000

Initial Entry: John Stamatakos

Project: 20-01405-041 Private Fuel Storage Facility

**Title:** Evaluation of PFS Earthquake Analyses for SER on PFSF License Application (SAR)

The entries in this notebook document work done in support of the staff evaluation of the PFS seismic hazard studies for the NRC Safety Evaluation Report (SER) on the Utah PFSF License Application (SAR) and supporting document titled "*Seismic Motion and faulting hazard at Private Fuel Storage Facility in the Skull Valley Indian Reservation, Toelle County, Utah.*"

*S 21/2000*

Dr. John Stamatakos, Ph.D. - CNWRA Senior Research Scientist

Dr. Rui Chen - CNWRA Senior Research Scientist

Mr. Peter La Femina - CNWRA Research Scientist

Dr. Martin McCann, Ph.D. - Consultant, Jack R Benjamin and Associates, Menlo Park, California

December 18, 2001

*[Handwritten signature]*

**Note:** All data and reviews pertaining to this project to date are documenting in CNWRA reports (Draft and Final SER, and Stamatakos et al., 1999). No additional calculations or analyses were permed in support of these documents that required entry into this Scientific Notebook. In support of the review of the Supplemental SER, we carried out two additional analyses. These additional analyses will be added to the revision of the Stamatakos et al (1999) report if a revision is published. Current schedule for hearings on the seismic issues may preclude revision of that report. Thus, the additional analysis were added to this notebook for proper QA documentation.

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**Scientific Notebook 353**

**December, 18, 2001**

**Entry By: John A. Stamatakos**

**Purpose:** To document comparison of Private Fuel Storage Facility (PFS) probabilistic seismic hazard results (PSHA) to other PSHA results for the western United States.

**Investigator:** John A. Stamatakos

**Background Information**

In the revisions to the SAR by the applicant completed in the Spring of 2001, the seismic hazard increased by a large amount. The large increase in the hazard appears to be primarily from a revision to the site response models. For example the peak ground acceleration for the 2000 yr return period rose 35% from 0.528 g to 0.711 g. The following Table summarizes some of the changes in spectral acceleration.

**Comparison of PSHA for 2,000-yr Return Period Spectral Acceleration (with 5% Damping)**

Period (sec)	Horizontal Ground Motion (g)		Vertical Ground Motion (g)	
	SAR Revision 22	SAR Revision 18 (former design)	SAR Revision 22	SAR Revision 18 (former design)
PGA	0.711	0.528	0.695	0.533
0.1	1.541	1.045	1.752	1.369
0.5	1.045	1.166	0.509	0.476
2.0	0.164	0.272	0.088	0.088

**Data and Procedure:**

1. To assess these ground motion results, I plotted the hazard curves for the Skull Valley site against PSHA hazard curves for other sites in the western United States. The skull valley data were provided to me on disk within the responses to RAI package following the March, 2001 meeting in San Antonio.

A set of seven hazard curves were provided to me from Dr. M. McCann n September, 30, 2001. Dr. McCann indicated that the data were from 1993.

The following table is a printout of the Excell work sheet of the data provided to me by Dr. McCann.

# Peak ground Accelerations for Seven Western United States Sites

No	Site	Ground Motion Curve Type												
1	SF Bay Bridge	PGA (cm/s/s)	3434	981	1962	3924	5886	7848	9123					
		Mean	1.00E-01	6.00E-02	2.22E-02	4.81E-03	1.00E-03	2.36E-04	1.00E-04					
2	Diablo Canyon	PGA (cm/s/s)	103	218	327	435	545	654	763	872	981	1090	1199	1308
		80th Fractile	2.00E-02	1.08E-02	6.00E-03	3.18E-03	1.63E-03	9.00E-04	4.33E-04	2.00E-04	9.00E-05	3.94E-05	1.33E-05	4.00E-06
3	Los Alamos Site 1	PGA (cm/s/s)	559	775	981	1962	2943	3924	4905	5886	6867	7848	8829	9810
		Mean	8.51E-03	5.44E-03	3.30E-03	8.95E-04	2.80E-04	1.86E-04	1.04E-04	1.00E-05				
4	Hanford Site A	PGA (cm/s/s)	1962	981	1962	2943	3924	4905	5886	6867	7848	8829	9810	10791
		Mean	8.55E-03	1.44E-03	4.41E-04	1.70E-04	7.55E-05	3.66E-05	1.00E-05	2.42E-06				
5	INEL 1 (LLNL)	PGA (cm/s/s)	50	50	150	250	300	400	500	600	700	800	1000	
		Mean	5.00E-03	2.00E-03	4.00E-04	1.18E-04	6.00E-05	2.85E-05	1.37E-05	8.41E-06	5.32E-06	3.14E-06	1.53E-06	
6	INEL 1 (WCC)	PGA (cm/s/s)	4905	981	1962	2943	3924	4905	5886	6867	7848	8829	9810	10791
		Mean	4.18E-03	1.55E-03	4.00E-04	1.55E-04	8.46E-05	4.48E-05	2.42E-05	1.55E-05	1.00E-05			
7	PALO VERDE	PGA (cm/s/s)	10	20	50	70	100	150	200	300	500	1000		
		Mean	3.50E-02	7.20E-03	1.00E-03	5.40E-04	2.80E-04	1.30E-04	6.90E-05	2.10E-05	3.10E-05	2.10E-05		

SF Bay Bridge - Geomatrix Consultants, Inc., PSHA for the San Francisco Bay Bridge, prepared for the California Department of Transportation.

Diablo Canyon - Pacific Gas and Electric Company, "Final Report of the Diablo Canyon Long Term Seismic Program," Docket Nos. 50-275 and 50-323, San Francisco, CA, July 1988.

Los Alamos Site 1 - Woodward Clyde Consultants, Inc., PSHA for the Los Alamos Site, New Mexico, date unknown.

Hanford Site A - Geomatrix Consultants, Inc., "Seismic Hazards Assessment for WNP-3, SATSOP Washington," prepared for Washington Public Power Supply System, Richland, WA, date unknown.

INEL 1 (LLNL) - Lawrence Livermore National Laboratory, date unknown.

INEL 1 (WCC) - Woodward Clyde Consultants, Inc., PSHA for the INEL Site, Idaho, date unknown.

Palo Verde - Risk Engineering, Inc., PSHA for the Palo Verde Nuclear Power Plant Site, Arizona, date unknown.

2. In addition to the data provided to me by Dr. McCann, I gather one additional seismic hazard curve from a publication I found on the web published by the United States geological Survey

Frankel, A., S. Harmsen, C. Mueller, T. Barnhard, E.V. Leyendecker, D. Perkins, S. Hanson, N. Dickman, M. Hopper, 1997. *USGS National Seismic Hazard Maps: Uniform Hazard Spectra, De-aggregation, and Uncertainty*, Proceedings of FHWA/NCEER Workshop on the National Representation of Seismic Ground Motion for New and Existing Highway Facilities, NCEER Technology Report 97-0010, pp. 39-73, <http://geohazards.cr.usgs.gov/eq/uncertainties/nceer.html>.

The following figure (figure 3) is from that paper. From the figure I digitized values for the Salt Lake City Hazard curve, and converted them to cm/s/s  $1 g = 9.8 m/s/s = 980 cm/s/s$ .



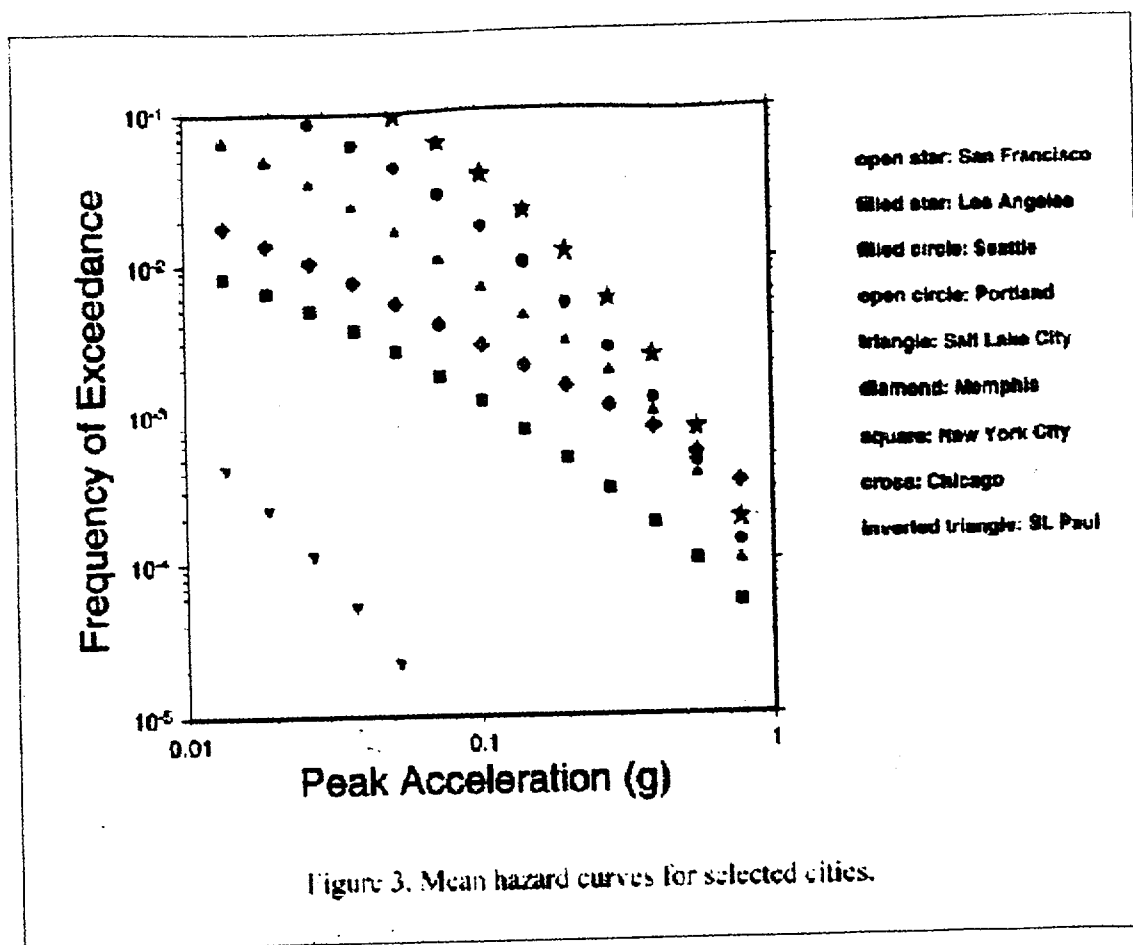
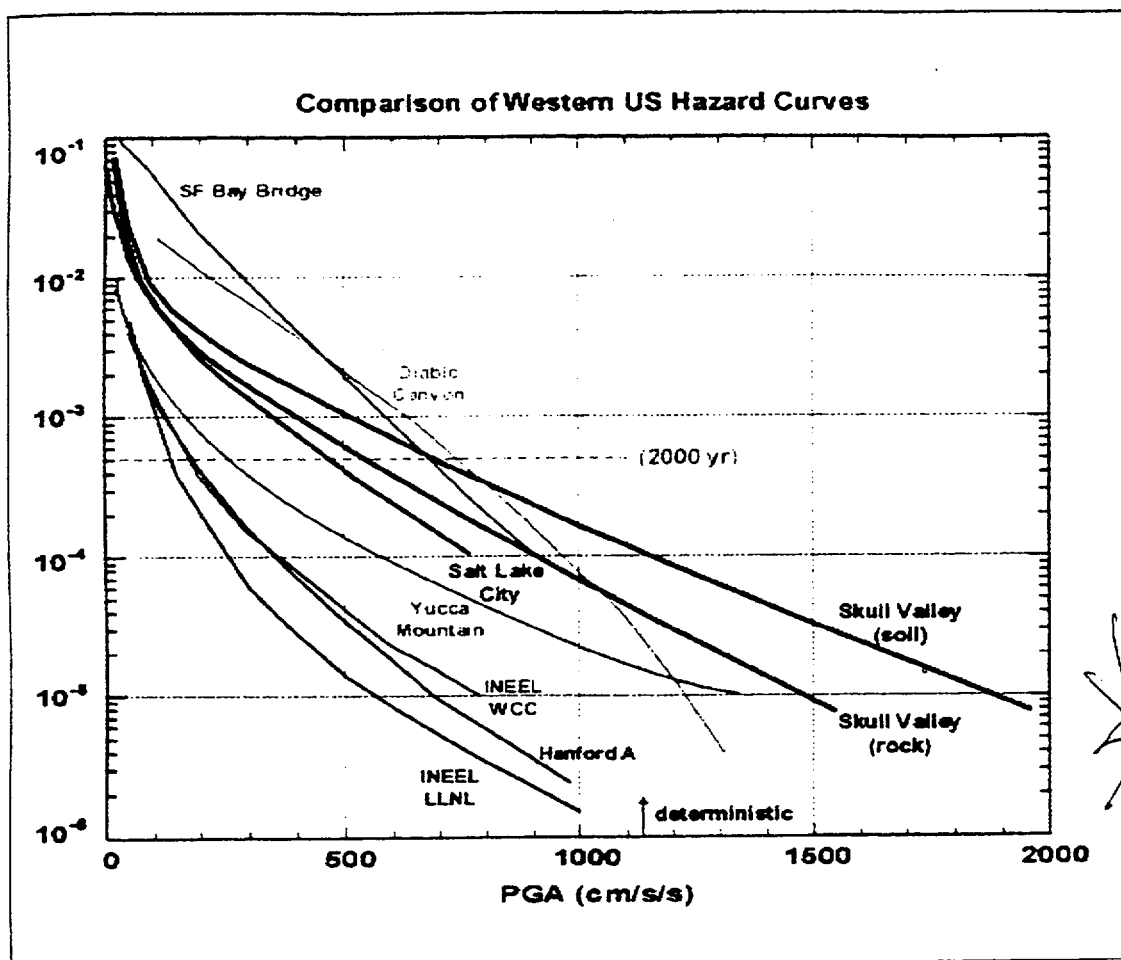


Table of PGA values derived from Frankel et al (1997) curve.

PGA (cm/s/s)	Probability
0	0.064
18.62	0.052
23.52	0.0325
36.26	0.0225
49.98	0.014
73.5	0.01
107.8	0.0064
127.4	0.0042
205.8	0.0028
264.6	0.00175
392	0.00095
529.2	0.00035
764.4	1.00E-04

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3. I then plotted all the data (using Kaleida Graph, version 3.09) to produce the following graph.



4. Based on deposition testimony by the State during October, 2001, I learned of a seismic hazard study completed by Dames and Moore in 1996 as part of the I-15 Corridor construction project.

Dames & Moore, Inc. 1996. *Final Report Seismic Hazard Analysis of the I-15 Corridor 10600 South to 500 North Salt Lake County, Utah*. UT-47026. Report submitted to Parsons Brinckerhoff. Salt Lake City, UT: Dames & Moore.

In that report, table 4.3 on p. 4-9 provides a summary of PGA values for 9 sites along the I-15 interstate highway corridor for probabilities of exceedence values at approximately 500, 1000, and 2500 yrs. Those values (mean) are:

Site	PGA (mean)
	2500 yr
PB-1	0.654
PG17DhR-15A	0.686
PG17DH-7A	0.674
PB-2	0.65
PB-3	0.602
PB-4	0.575
PB-5	0.566
PG17DH-16A	0.562
PG17DH-17A	0.561



### Discussion

The results show the conservative nature of the applicant's source characterization and PSHA results presented in the SAR. This conservatism is evident when the results are compared to PSHA results for other sites in Utah, especially those in and around Salt Lake City. This a comparison shows that the seismic hazard in Skull Valley was calculated by the applicant to be higher than seismic hazard estimates that have been performed for sites at, or near, Salt Lake City, despite the fact that fault sources near Salt Lake City are larger and more active than fault sources near the PFS site. For example, the results of the applicant's PSHA for Skull Valley (Geomatrix Consultants, Inc., 2001a) suggest that it is 1.5 times more likely that a ground motion of 0.5g horizontal peak ground acceleration or greater will be exceeded at the PFS site (assuming hard rock site conditions), than at Salt Lake City, based on the USGS National Earthquake Hazard Reduction Program (Frankel et al., 1997).

Similarly, the 2000-yr horizontal peak ground acceleration for Skull Valley (soil hazard) as estimated by the applicant, is higher than the 2500-yr ground motions for the nine sites along the Wasatch Front that were evaluated as part of the Utah Department of Transportation I-15 Reconstruction Project (Dames & Moore, Inc., 1996). The ground motions estimated by the applicant in Skull Valley are higher than those for the I-15 corridor, despite the close proximity of Salt Lake City to the Wasatch fault, which has a slip rate nearly ten times larger than the Stansbury or East Faults (cf., Martinez et al., 1998; Geomatrix Consultants, Inc., 1999a ) and is capable of producing significantly larger magnitude earthquakes than the faults near the PFS Facility site in Skull Valley (cf., Machette et al., 1991; Geomatrix Consultants, Inc., 1999a).

Geomatrix Consultants, Inc. 1999a. *Fault Evaluation Study and Seismic Hazard Assessment Private Fuel Storage Facility, Skull Valley, Utah*. San Francisco, CA: Geomatrix Consultants, Inc.

Machette, M.N., S.F. Personius, A.R. Nelson, D.P. Schwartz, and W.R. Lund. 1991. *The Wasatch fault zone, Utah-segmentation and history of Holocene earthquakes*. Journal of Structural Geology 13: 137-149.

Martinez, L., C. M. Meertens, and R. B. Smith. 1998. *Anomalous intraplate deformation of the Basin and Range-Rocky Mountain transition from initial GPS measurements*, Geophysical Research. Letters 24: 2741-2744.

*SGM*  
12/15/01

**Scientific Notebook 353**  
**December, 18, 2001**  
**Entry By: John Stamatakos**

**Purpose:** Document Slip Tendency Analysis for Supplemental Safety Evaluation Report, Private Fuel Storage, Skull Valley, Utah.

**Investigator:** John A Stamatakos

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12/18/01

### **Background Information**

The previous entry shows concludes that the ground motion hazard for Skull Valley, as estimated by the applicant, is conservative. To assess potential conservatism in the applicant's calculations I performed a slip tendency analysis of the Skull Valley Site using the computer program 3DStress™ (version 1.3.3). The aim of the analysis was to determine if the faults in Skull Valley are in optimal orientations for future slip, given what is known about the current stress conditions in this part of the earth's crust in Utah. Specifically, I wanted to determining if assumptions made by the applicant about rupture initiation and fault length or fault segmentation led to overestimation of the ground motion hazard.

### **Procedures**

The faults from Skull Valley and Central Utah (including the Wasatch fault) were digitized from maps provided in the SAR and rectified in Arcview (version 3.1). The digital files were then exported to 3dStress™. I then asked Dr. David Ferrill and Dr. Alan Morris to run the program for me to assess slip tendency values. The analysis was performed on October 11, 2001.

The slip tendency analysis (Morris et al., 1996) was completed using an interactive stress analysis program (3DStress™) that assesses potential fault activity relative to crustal stress. For Skull Valley, the stress tensor is defined with a vertical maximum principal stress ( $\sigma_1$ ), a horizontal intermediate principal stress ( $\sigma_2$ ) with azimuth of  $355^\circ$ , and a horizontal minimum principal stress ( $\sigma_3$ ) with an azimuth of  $085^\circ$ . The stress magnitude ratios are  $\sigma_1/\sigma_3 = 3.50$  and  $\sigma_1/\sigma_2 = 1.56$ . This orientation for the principal stresses was based on recent global positioning satellite information (Martinez, et al., 1998a). The slip tendency analysis assumed a normal-faulting regime, with rock density equal to 2.7 g/cc, fault dip equal to  $60^\circ$ , water table at a depth of 40 m, and a hydrostatic fluid pressure gradient.

### **Software:**

3DStress v.1.3.3

### **Stress Tensor Assumptions:**

- (i) Rock density = 2.7 g/cc
- (ii) Water table depth = 40 m
- (iii) Stress tensor calculated for depth of 5 km.
- (iv) Fluid pressure gradient is hydrostatic
- (v) Maximum slip tendency must be sufficient to produce slip on ideally oriented faults (Ts max

greater than or equal to 0.67)

(vi) Normal faulting stress regime -  $\sigma_1$  vertical, lithostatic

(vii) Faults dip  $60^\circ$

(viii) Magnitude of intermediate principal stress is centered between max and min principal stresses

**Effective Stress Tensor (corrected for fluid pressure):**

Effective  $\sigma_1$  = vertical, 84 Mpa

Effective  $\sigma_2$  = azimuth 355, 54 Mpa

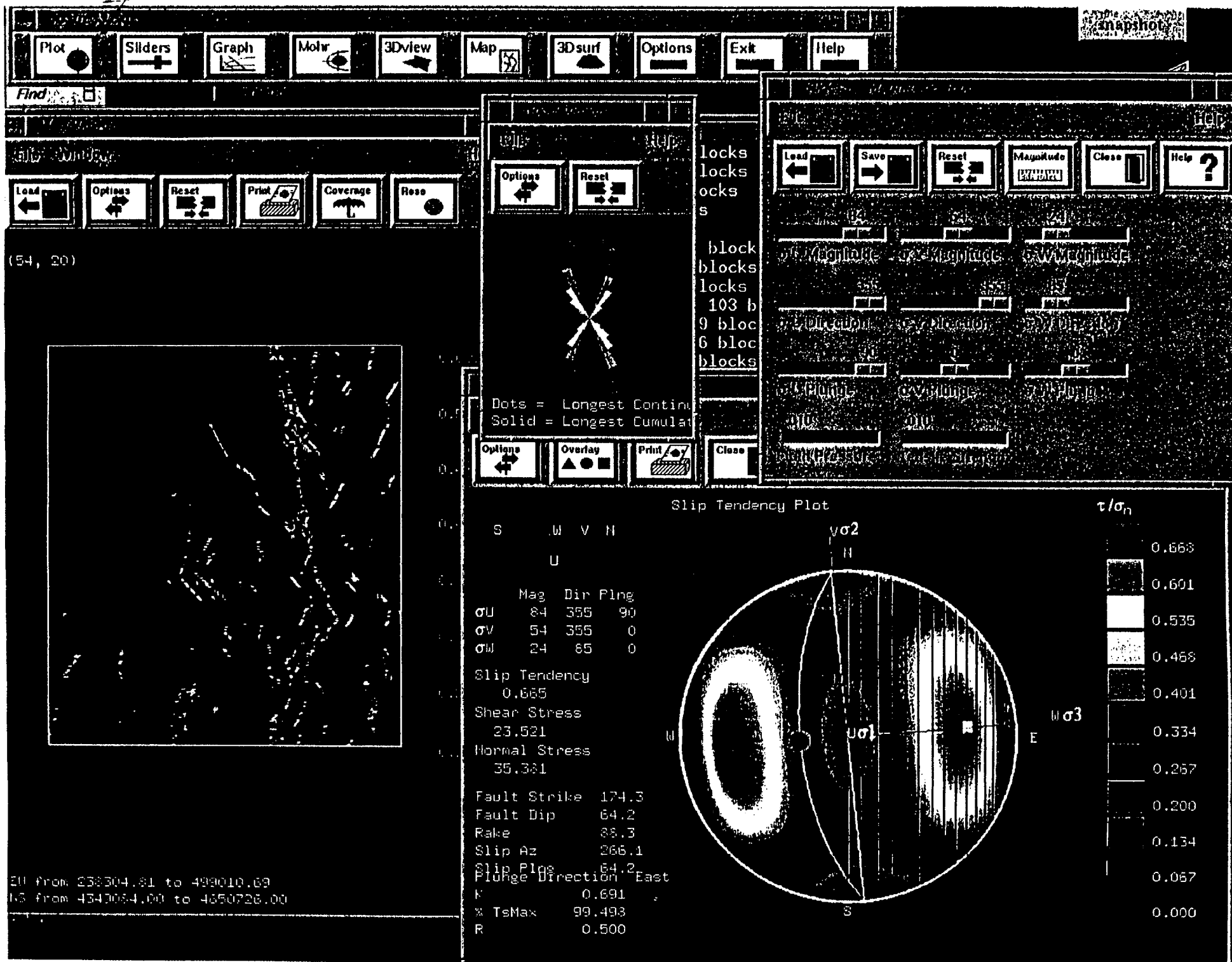
Effective  $\sigma_3$  = azimuth 085, 24 MPa

Martinez, L., C. M. Meertens, and R. B. Smith. 1998. *Anomalous intraplate deformation of the Basin and Range-Rocky Mountain transition from initial GPS measurements*, Geophysical Research. Letters 24: 2741-2744.

Morris, A., D.A. Ferrill, and D.B. Henderson. 1996. *Slip-tendency analysis and fault reactivation*. Geology 24, 275-278.

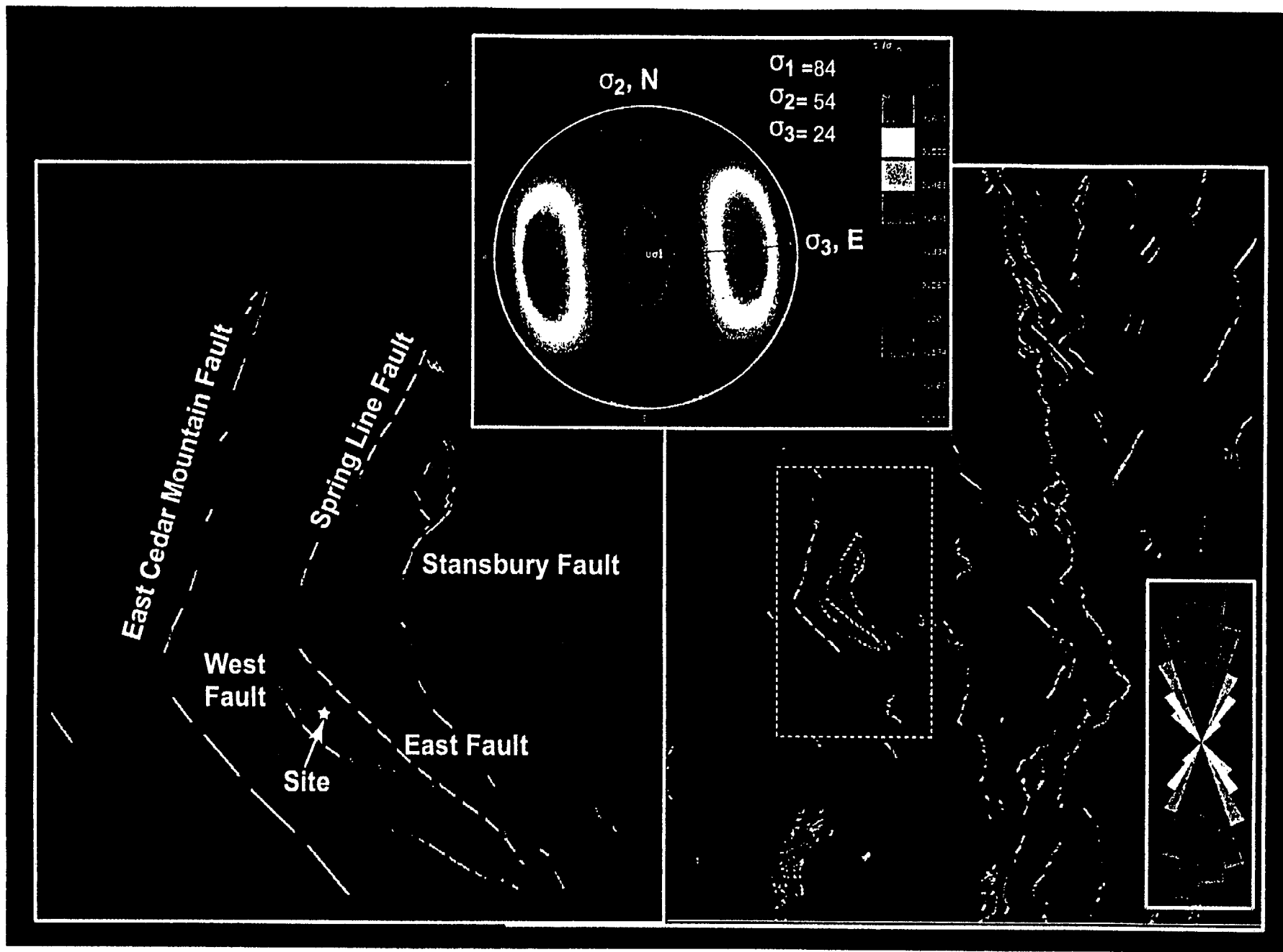
The following two pages are figures from 3DStress™ that summarize the slip tendency results. The first figure is an electronic snapshot of the screen showing the results of the analysis. The second figure is a summary shot showing a close-up of Skull Valley along site the central Utah regional map.

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## Discussion

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In slip tendency analysis, the underlying assumption is that the regional stress state controls slip tendency and that there are no significant deviations due to local perturbations of the stress conditions. This assumption is supported by a similar slip tendency analysis of the Wasatch fault, which shows highest slip tendency values for the segments of the fault considered to be most active (Machette et al., 1991).

The slip tendency analysis shows that segments of the East fault and the East Cedar Mountain fault nearest the PFS site have relatively low slip tendency values compared to segments farther north in Skull Valley. As discussed in the following sections on site-to-source distances and maximum magnitudes, these results indicate that the seismic source characterization of the PSHA study conducted by Geomatrix Consultants, Inc. (1999a, and 2001a) is conservative. Three areas of conservatism are the distribution of site-to-source distance, maximum magnitude earthquakes, and potential of the West fault as a seismogenic source (discussed in Stamatakis et al., 1999).

### Distributions of Site-to-Source Distances

Results of the slip tendency analysis indicate that fault segments with approximately North-South strikes (azimuth =  $175^\circ$ ) are optimally oriented for future fault slip. Faults with north northeast-south southwest strikes have high slip tendency values. In contrast, fault segments with northwest-southeast strikes, such as the East fault near the PFS Facility site and the southern segments of the East Cedar Mountain fault also near the PFS Facility site, have relatively low slip tendency values. Therefore, these fault segments are less likely to slip in the future than fault segments further from the site. Fault rupture close to the site greatly influence the seismic hazard. The closer the earthquake is to the site, the larger the resulting ground motions compared to an equal magnitude earthquake on a fault segment farther away from the site.

In the site-to-source distributions used in the ground motion attenuation equations, Geomatrix Consultants, Inc. (1999a) assumed uniform distributions of earthquake ruptures along active fault segments. Given the slip tendency analysis described above, this assumption by Geomatrix Consultants, Inc. (1999a) is conservative. The staff concludes that seismic source models that incorporate slip tendency would result in a lower ground motion hazard than the one developed by the applicant.

### Maximum Magnitude

The slip tendency results suggest that Geomatrix Consultants, Inc. (1999a) may have overestimated the maximum magnitude of the East and East Cedar Mountain faults near the PSFS site. In the SAR, the applicant first developed conceptual models of the physical dimensions of fault rupture—either rupture area or trace length of surface fault rupture—based on the geologic record (Geomatrix Consultants, Inc., 1999a). Second, the applicant developed distributions of maximum magnitudes for each active fault using empirical scaling relationships developed from the magnitudes and associated rupture dimensions of historical earthquakes (e.g., Wells and Coppersmith, 1994). In developing the fault segment models, the applicant conservatively assumed that the entire mapped length of the surface trace length represents active fault segments. Thus, these maximum fault dimensions produce conservative estimates of maximum magnitude.

The slip tendency analysis indicates that parts of the East and East Cedar Mountain faults near the

PFS Facility site have relatively low slip tendency values. Thus, these faults may be smaller than in the fault models used by the applicant to estimate maximum magnitude. Fault rupture models developed using slip tendency analysis would therefore lead to fault segment models with smaller rupture dimensions (length or area) than those used by Geomatrix Consultants, Inc. (1999a). Because distributions of maximum magnitude for each active fault are derived from empirical scaling relationships of rupture area or rupture length (e.g., Wells and Coppersmith, 1994) application of the slip tendency analysis would thereby result in smaller predicted maximum magnitudes than those developed by the applicant. Smaller maximum magnitudes would reduce the overall ground motion hazard.

In summary, the staff found that the applicant's considerations of seismic source characteristics and associated uncertainties provide reasonable assurance that all significant sources of future seismic activity have been identified and their characteristics and associated uncertainties are adequately or conservatively described and appropriately included in the evaluation of the seismic ground motion hazard. Stamatakos et al. (1999) provides more details of PFS's seismic source characterization and the staff's independent sensitivity analyses.

Geomatrix Consultants, Inc. 1999a. *Fault Evaluation Study and Seismic Hazard Assessment Private Fuel Storage Facility, Skull Valley, Utah*. San Francisco, CA: Geomatrix Consultants, Inc.

Machette, M.N., S.F. Personius, A.R. Nelson, D.P. Schwartz, and W.R. Lund. 1991. *The Wasatch fault zone, Utah: segmentation and history of Holocene earthquakes*. *Journal of Structural Geology* 13: 137-149.

Stamatakos, J., R. Chen, M. McCann, and A.H. Chowdhury. 1999. *Seismic Ground Motion at the Private Fuel Storage Facility Site in the Skull Valley Indian Reservation*. San Antonio, TX: Center for Nuclear Waste Regulatory Analyses.

Wells, D.W., and K.J. Coppersmith. 1994. New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement. *Bulletin of the Seismological Society of America* 84: 974-1,002

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## **User's Guide for Version 1.3.3**

3DStress was prepared as an account of work performed by the Center for Nuclear Waste Regulatory Analyses (CNWRA) for the Division of Waste Management of the Nuclear Regulatory Commission (NRC), an independent agency of the United States Government. Neither the developer(s) of 3DStress nor any of their sponsors make any warranty, expressed or implied, or assume any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product or process disclosed, or represent that its use would not fringe on privately-owned rights.

### **Technical Support**

For technical support for 3DStress contact:

Dr. David A. Ferrill, CNWRA, Southwest Research Institute, 6220 Culebra Road, San Antonio Texas 78238 USA, 210-522-6082 (voice), 210-522-5155 (fax), E-mail: [dferrill@swri.edu](mailto:dferrill@swri.edu)

### **Hardware Requirements**

Sun Ultra Workstation Running Solaris 2.7 Operating System

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# Overview

**3DStress** is a tool for computing the propensity for a fault to slip or dilate based on three-dimensional (3D) stress conditions. **Slip** tendency is a ratio of the shear stress  $\tau$  divided by the normal stress ( $\sigma_n$ ) on a fault surface, as shown in the equation below:

$$\text{Slip tendency} = \tau / \sigma_n$$

The stress axis with the **greatest** magnitude is called  $\sigma_1$ . The stress axis with the **smallest** magnitude is called  $\sigma_3$ . The **intermediate** stress axis is called  $\sigma_2$ . Any of the stress axes ( $\sigma_u$ ,  $\sigma_v$ , or  $\sigma_w$ ) can be  $\sigma_1$ ,  $\sigma_2$ , or  $\sigma_3$  depending on the user selection.

**Dilation** tendency is the relative propensity for a fault to dilate based on the 3D stress conditions and is computed as shown in the equation below:

$$\text{Dilation tendency} = (\sigma_1 - \sigma_n) / (\sigma_1 - \sigma_3)$$

**Leakage** factor is a quantitative estimate of the propensity for a fault or fracture to dilate, for situations where fluid pressure and fault or fracture tensile strength are known or can be inferred. Leakage factor is computed as a function of pore fluid pressure ( $P_f$ ),  $\sigma_n$ , and tensile strength (T) by the equation below:

$$\text{Leakage factor} = P_f / (\sigma_n - T)$$

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**Helpful Hint:** 3DStress is memory intensive, especially with large data files; it will perform more smoothly in short sessions. Try to exit 3DStress and restart before moving from one project to the next to give it the chance to start with the maximum amount of memory and swap space available.

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For additional background and details on slip tendency see the following references:

Morris, A., D. A. Ferrill, and D. B. Henderson, 1996, "Slip-tendency analysis and fault reactivation," *Geology*, March 1996, 24(3): 275-278.

Morris, A. P., D. A. Ferrill, and D. B. Henderson, 1994, "Slip tendency analysis and fault reactivation," *EOS, Transactions of the American Geophysical Union*, 75(44): 591.

Ferrill, D. A., S. R. Young, A. P. Morris, D. B. Henderson, and R. H. Martin, 1994, "3-Dimensional stress domains interpreted from fault slip patterns in southern Society of America Abstracts with Programs, 26(7): A185.

Ferrill, D. A., A. P. Morris, D. B. Henderson, and R. H. Martin, 1994, "Tectonic processes in the Central Basin and Range region," NRC High-Level Radioactive Waste Research at

CNWRA, July-December, 1994. CNWRA 94-02S. 121-139.

Ferrill, D. A., A. P. Morris, S. M. Jones, and J. A. Stamatakis, 1998, "Extensional Layer-Parallel Shear and Normal Faulting," *Journal of Structural Geology*, 20(4): 355-362.

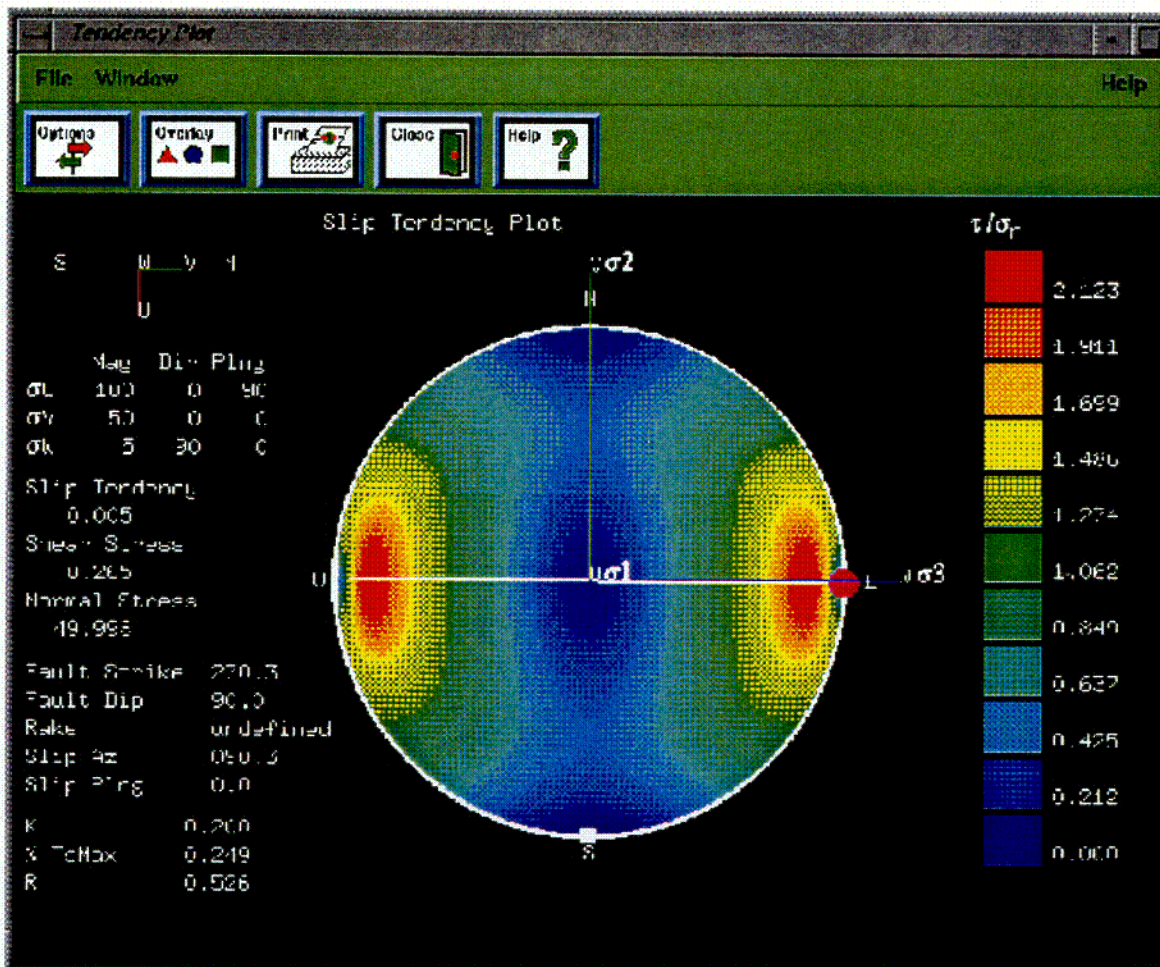
Ferrill, D. A., James, Winterle, Gordon Wittmeyer, Darrell Sims, Shannon Colton, Amit Armstrong, and Alan P. Morris, 1999, "Stressed Rock Strains Groundwater at Yucca Mountain, Nevada," *GSA Today*, 9(5): 1-8

## Starting 3DStress

To start 3DStress from a shell window, change directories to the directory with the executable for 3DStress and enter:

```
% 3dstress
```

Two windows similar to the ones below will appear on the display.



C04


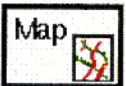


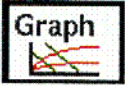
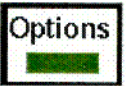
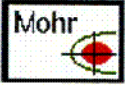
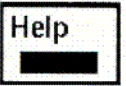

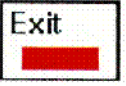
10/30/00 10:24 AM



## The Controller

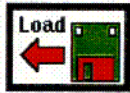
The 3DStress controller is used to access each of the main windows by clicking the left mouse button over the desired button.



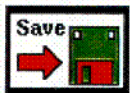
	Tendency Plot		Map Viewer
	Magnitude Tool		Surface Viewer
	Stress Ratio Graph		Options
	Mohr Graph		Help
	3D Fault Viewer		Exit 3DStress

## Common Buttons

Each of the different main windows accessed from the Controller has buttons located near the top of the window that serve a common purpose.



Load a file



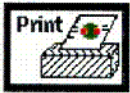
Save loaded file(s)



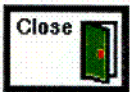
Options applying to that particular window



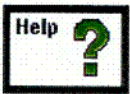
Centers the viewer and any loaded file(s)



Saves the window to a screen raster file (bitmapped xwd format)



Closes the window



Help file for the window

# Tendency Plot



3DStress computes slip tendency based on a user-selected stress state. The stress state is defined by the magnitudes and orientations of the orthogonal stress axes called  $\sigma_u$ ,  $\sigma_v$ , and  $\sigma_w$ . The magnitude values in 3DStress are **normalized** to range from 1 to 100. These represent principal compressive stresses.

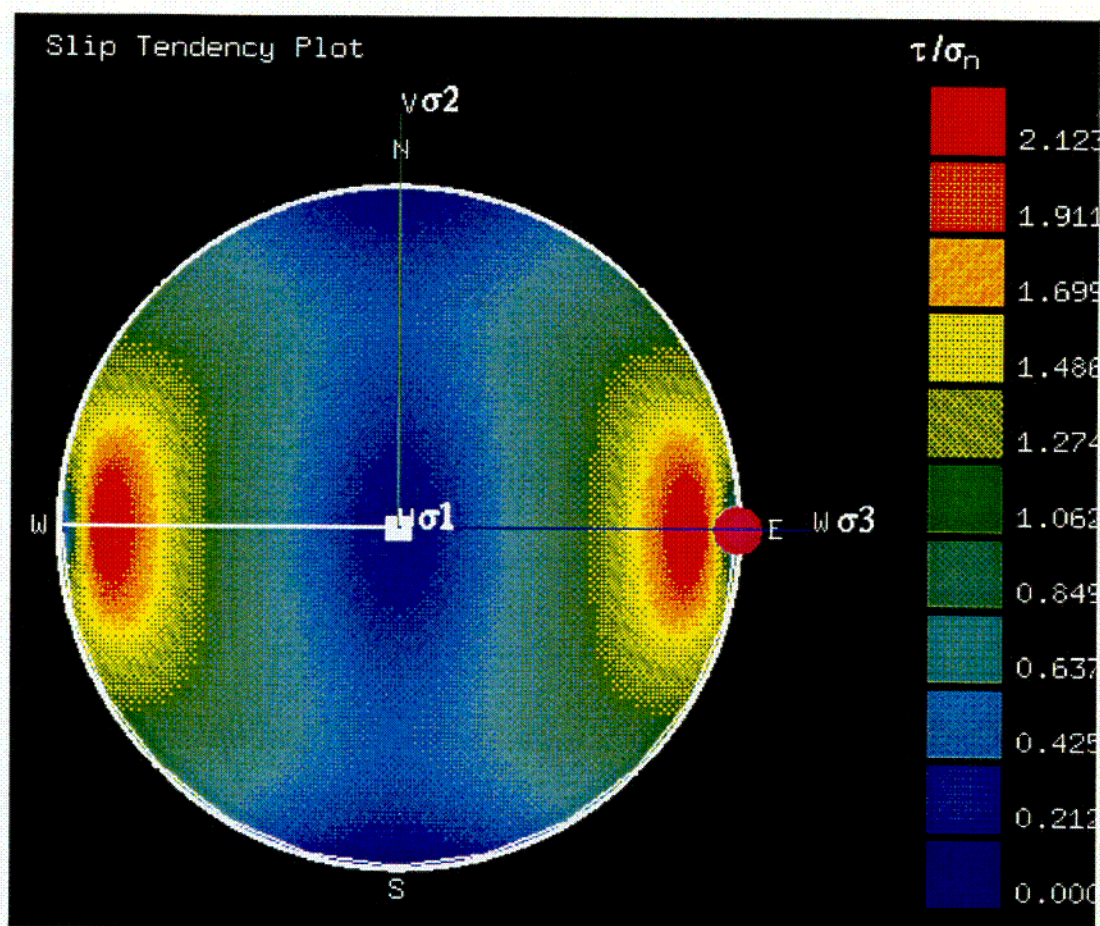
The stress axis with the **greatest** magnitude is called  $\sigma_1$ . The stress axis with the **smallest** magnitude is called  $\sigma_3$ . The **intermediate** stress axis is called  $\sigma_2$ . Any of the stress axes ( $\sigma_u$ ,  $\sigma_v$ , or  $\sigma_w$ ) can be  $\sigma_1$ ,  $\sigma_2$ , or  $\sigma_3$  depending on the user selection.

A **stress state** is defined in terms of principal stress components  $\sigma_1$ ,  $\sigma_2$ , and  $\sigma_3$  ( $\sigma_3 \leq \sigma_2 \leq \sigma_1$ ), which are oriented along orthogonal directions u, v, and w. The user may set the relative magnitudes of the principal stress components and may choose any two of the three orthogonal axes for  $\sigma_1$  and  $\sigma_3$ . Initially, u points vertically down, but the user may rotate the stress axes to other orientations (see the **Magnitude Tool** section). Only mutually orthogonal stress-axis orientations are allowed by 3DStress.



## Reading Slip Tendency and Direction Values

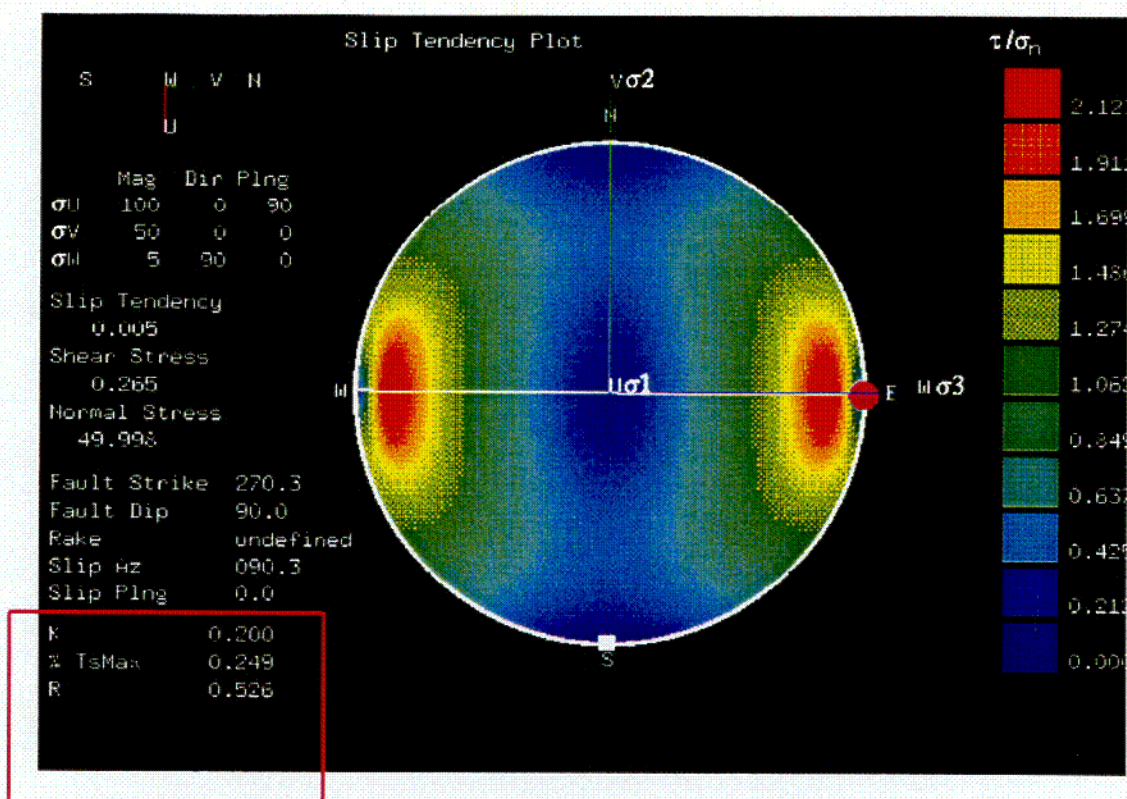
**Slip tendency** is displayed on a lower hemisphere equal-angle stereographic projection as shown below. Lower hemisphere plot correspond to fault surface poles. The slip tendency for a given fault pole is indicated on a color scale. **Red** indicates relatively high slip tendency and **blue** indicates relatively low slip tendency.



Slip is likely to occur on a surface when the resolved shear stress equals or exceeds the frictional resistance. For more information see the references listed in the [overview](#) section.

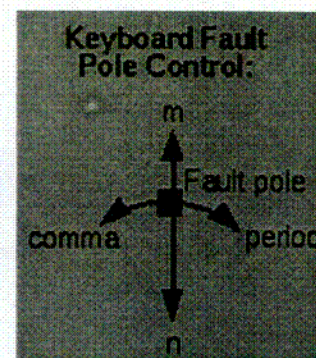
Slip direction is shown as a purple dot on the lower hemisphere plot. Slip direction is always in the plane of the fault pole, indicated by the white square. The user may select the fault pole by holding down the left mouse button and moving the mouse over the lower hemisphere plot or by keyboard control. For keyboard control the **comma** key selects the fault pole strike while the **n** and **m** keys control dip (for additional key controls see the [appendix](#) or the help on the tendency plot window).





For further explanation of K, TsMax, and R see the [Stress Ratio Graph](#) section.

$$\%TsMax = \frac{\text{Slip Tendency for a select fault orientation}}{\text{Max Slip Tendency for all fault orientations in the current stress state}}$$



C08

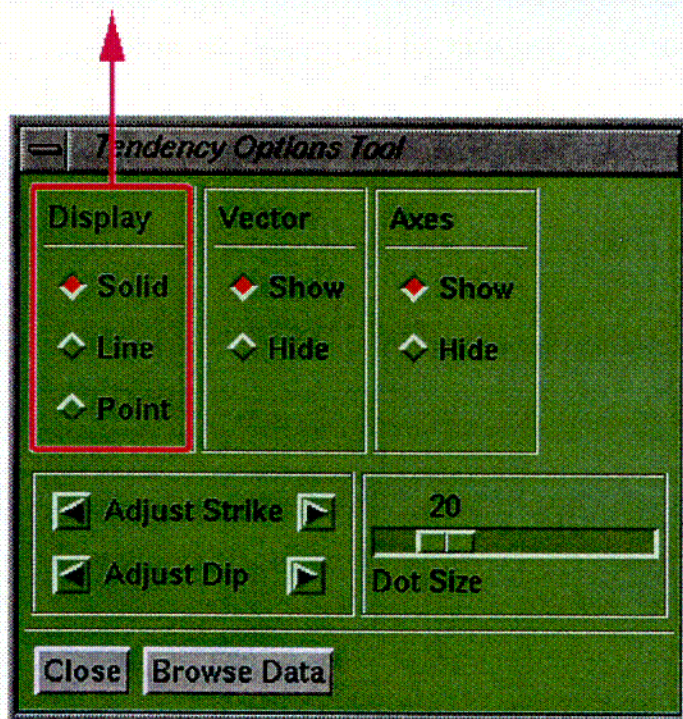
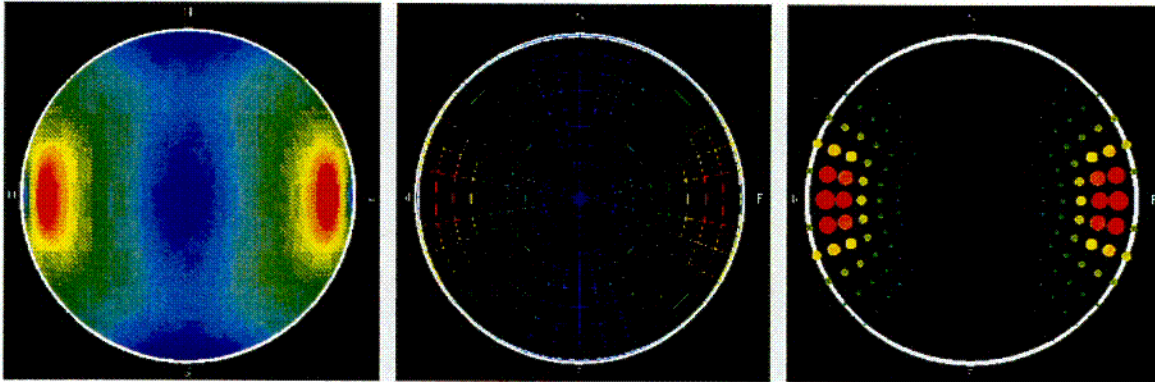
10/30/00 10:26 AM



## Tendency Plot Options

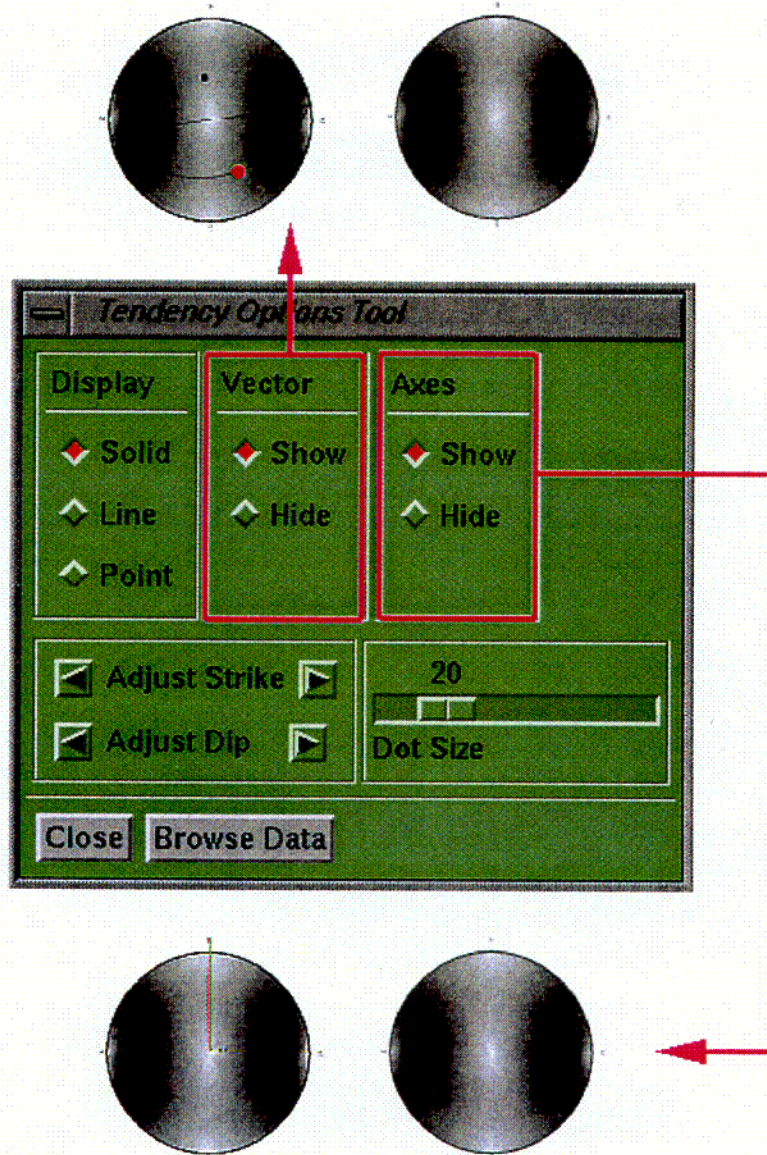


The **display** option allows rendering of the plot using either a **solid** shading, colored **lines**, or colored **points** as shown below.





The vector show and hide button controls the slip vector data display as shown below.

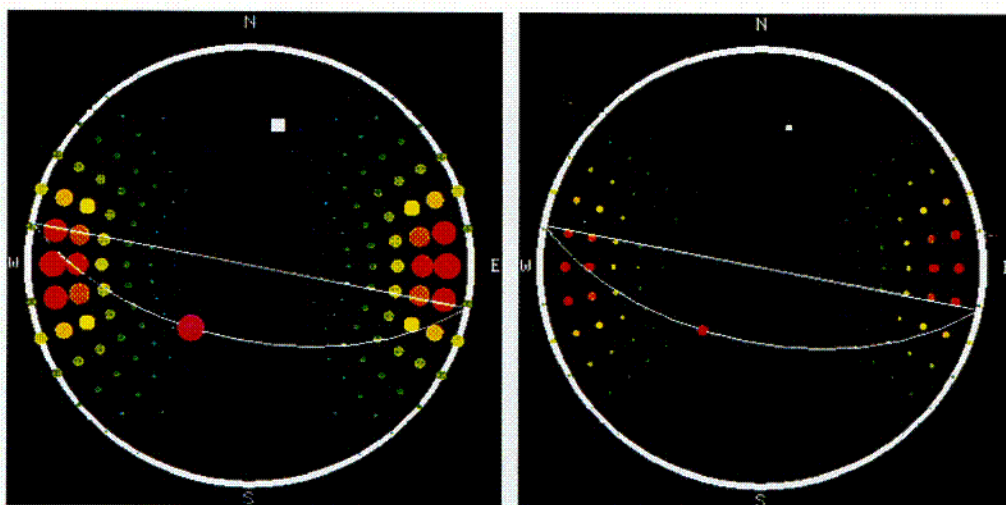
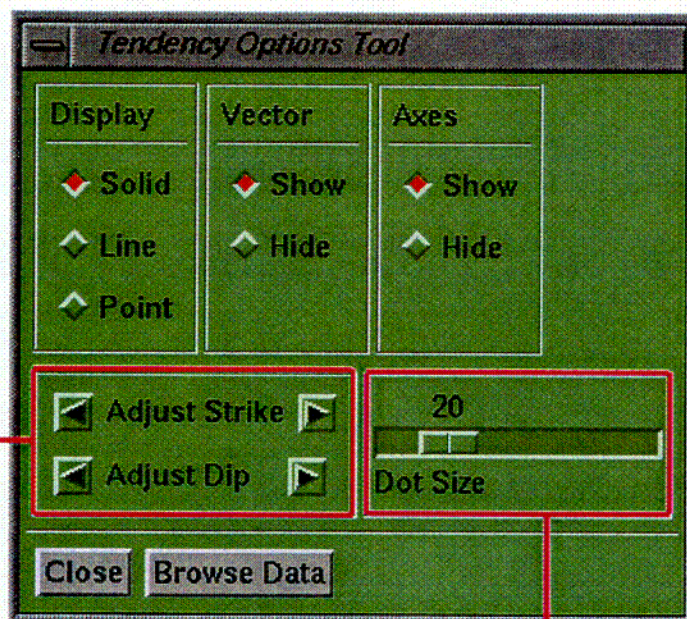


The axes show and hide button controls the plot axes display as shown above.

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Controls the positioning of the pole by adjusting the strike or dip.



The **dot size** slider is only used with the display point mode as shown above.

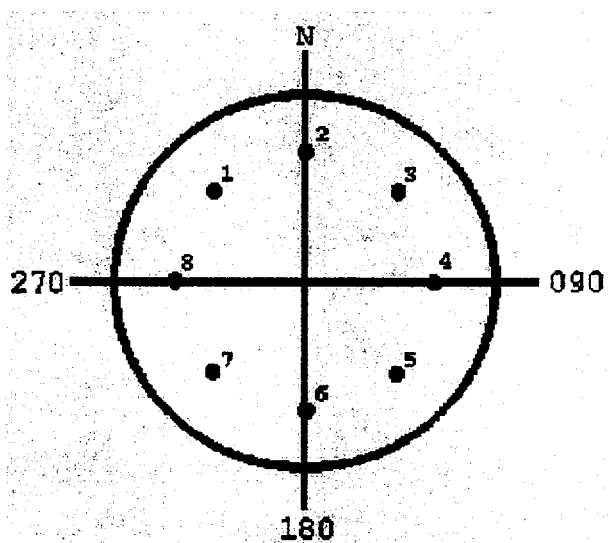
[page 2](#)

## Overlaying Points on the Slip Tendency Plot

Measured or pre-computed fault pole and slip vector data points may be displayed over the lower hemisphere plot. This enables comparison of measure or pre-computed data with the user selected stress conditions. Measured or pre-computed data sorted in an ASCII data file with the following format may be displayed with 3DStress.

```
# Comment lines begin with a "#" symbol
# Strike / dip
45 65
90 65
135 65
180 65
225 65
270 65
315 65
0 65
```

Numbered in the order they appear above, data is plotted according to the right hand rule.

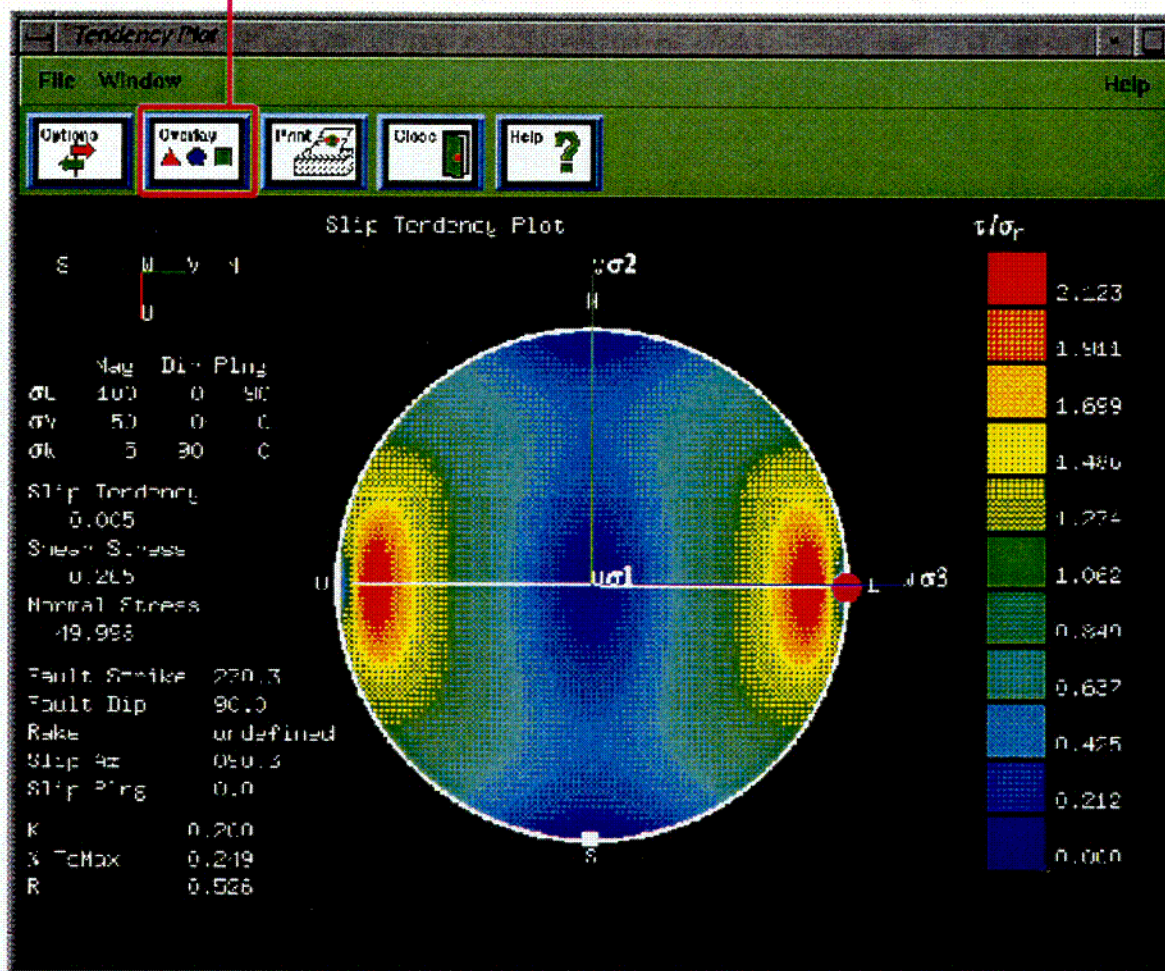


page 2



Overlay files are expected to have a file name extension of ".ovr". Each overlay file may contain 1 or more data points. Multiple overlay files may be displayed simultaneously with 3DStress.

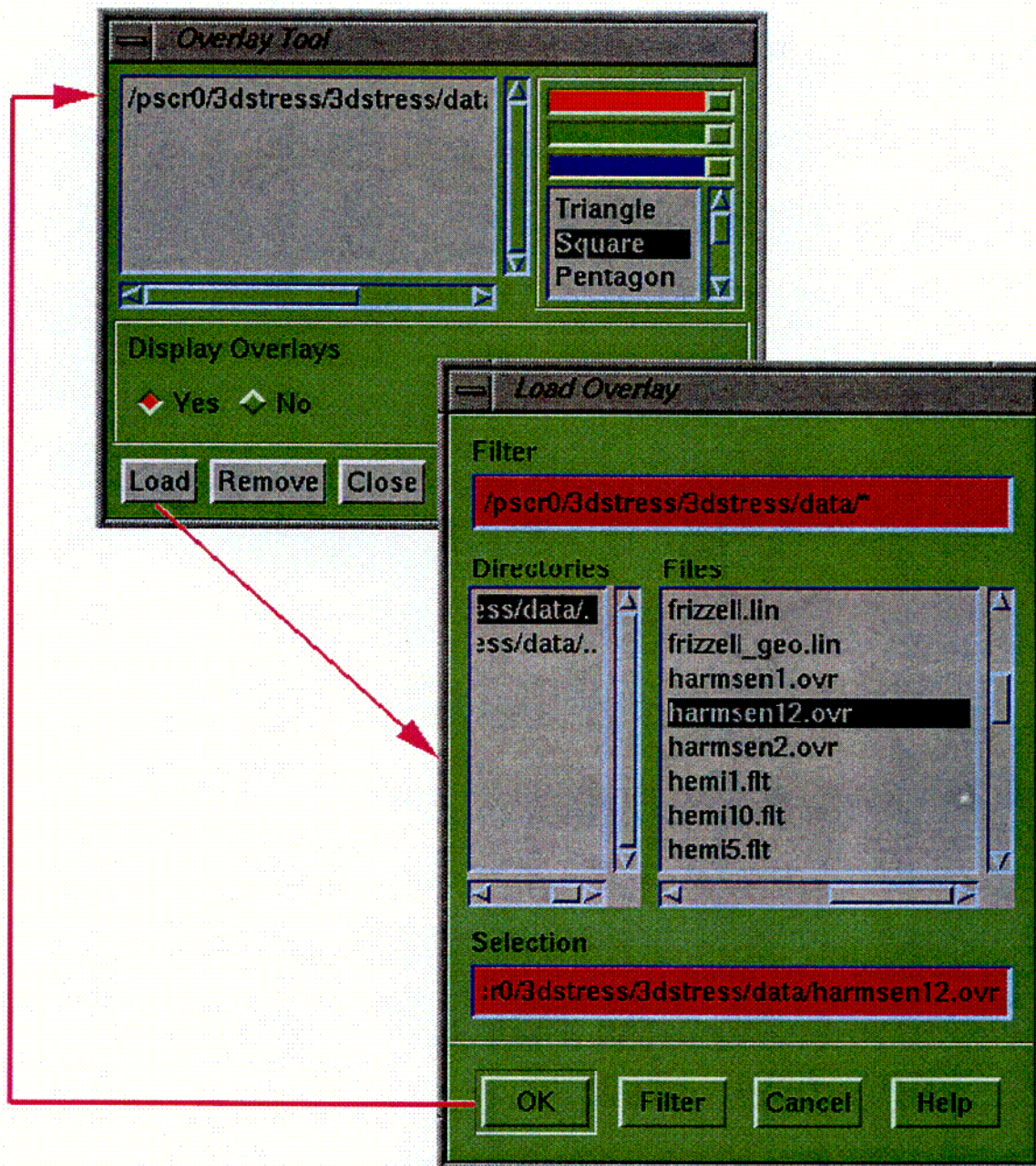
Overlays are handled by the Overlay Tool, which is displayed by pressing the overlay button on the Tendency Plot.



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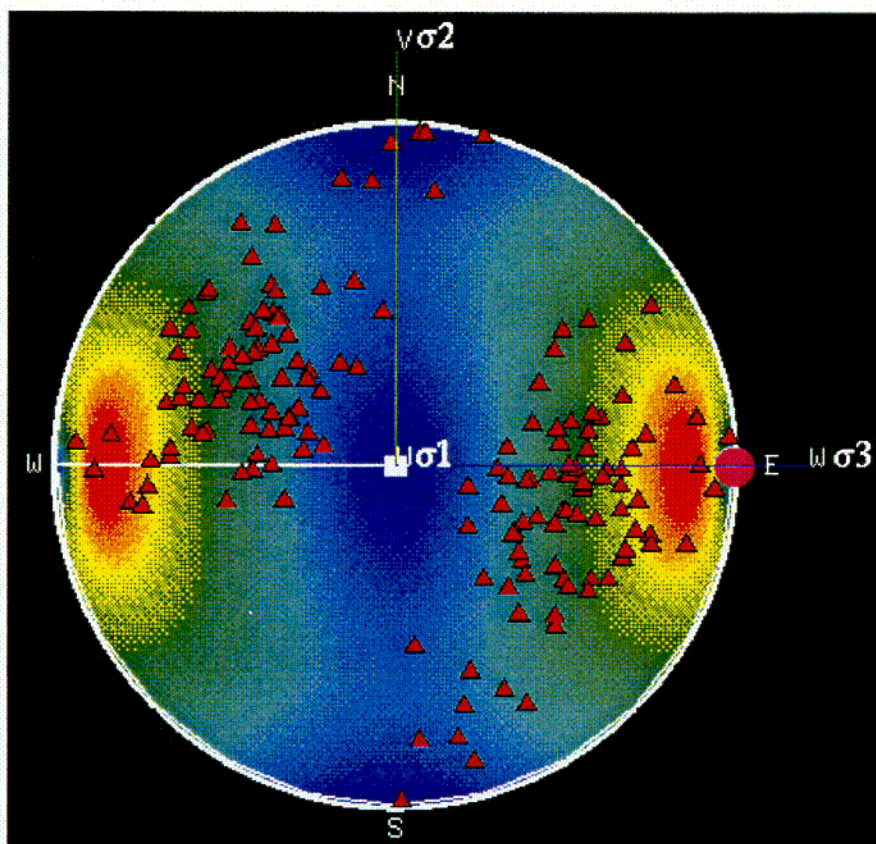
To load an overlay file, press the **Load** button and a file selector will appear. After selecting an overlay file, the name of the file is displayed in the Overlay Tool. Each loaded overlay may be manipulated by clicking on the overlay name, then adjusting the color sliders or clicking on one of the various shapes. Removal is done in a similar fashion by selecting an overlay and pressing the **Remove** button.



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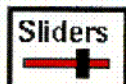
Overlay data will appear as colored polygons on the lower hemisphere plot. All the points from a given overlay file will have the same color. Overlay data may represent fault poles or slip vectors. For example, one of the overlay datapoints (red triangle) below is located near the current slip vector (purple circle). Clicking on an overlay with the right mouse button displays the overlay file name.



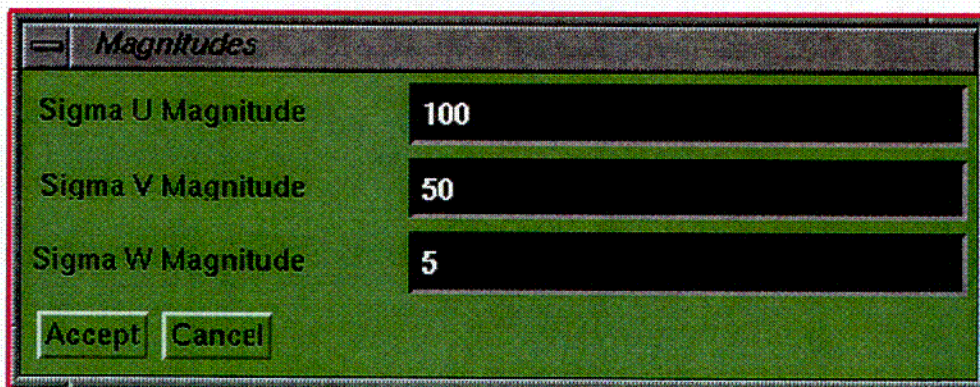
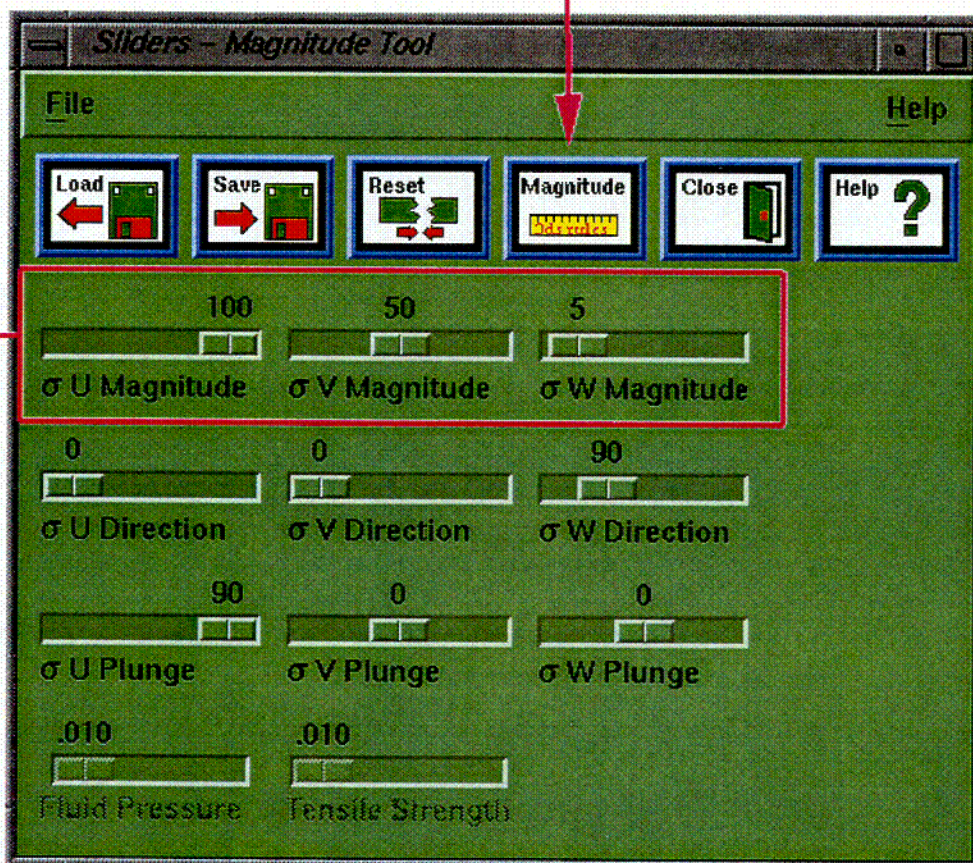
[page 3](#)



# Magnitude Tool



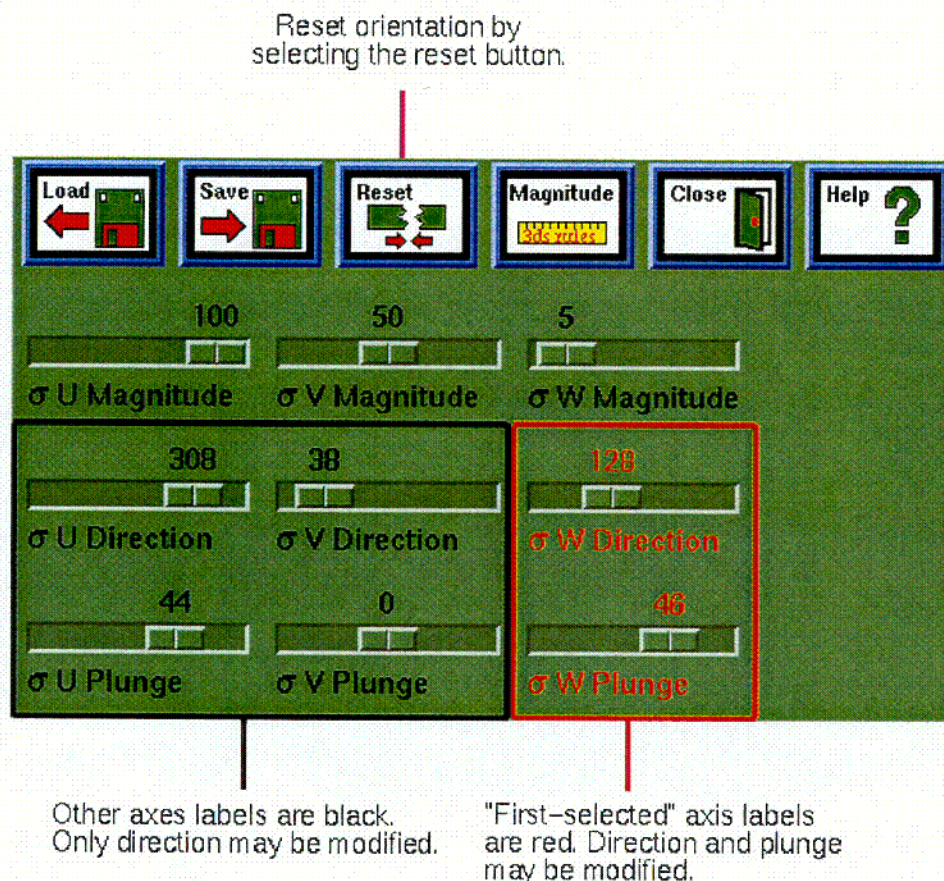
Stress magnitudes can be modified by using either the left or middle mouse button to select the desired normalized magnitude on the stress magnitude sliders. Input magnitudes range from 1 to 100 on each slider.



Use the magnitudes entry window to enter true magnitudes from the keyboard. The program will automatically normalize the input values to range from 1 to 100 while maintaining the correct magnitude ratios.



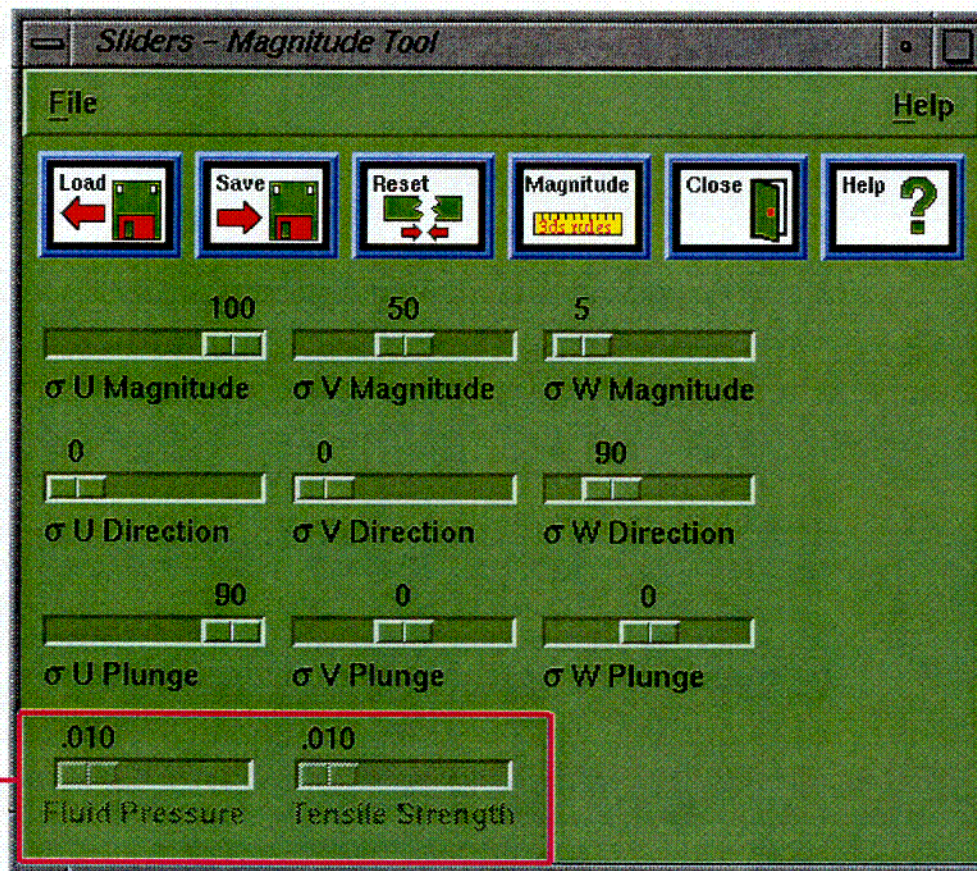
Stress orientations are shown in degrees and are selected by using the left and middle **mouse buttons** with the orientation control **sliders**. The labels of the first axis selected will turn **red**. The **direction** and **plunge** of the **first-selected axis** may be entered. Only **direction** changes are allowed for the **other two axes**. Pressing the reset button will **reset** the orientations and allow selection of a new first-selected axis. Directions range from 0 to 360 and plunges range from 0 to 90 in order to enable any measured or simulated 3D stress orientation.



Fluid pressure and tensile strength may be used when computing leakage factor (see [options](#)).

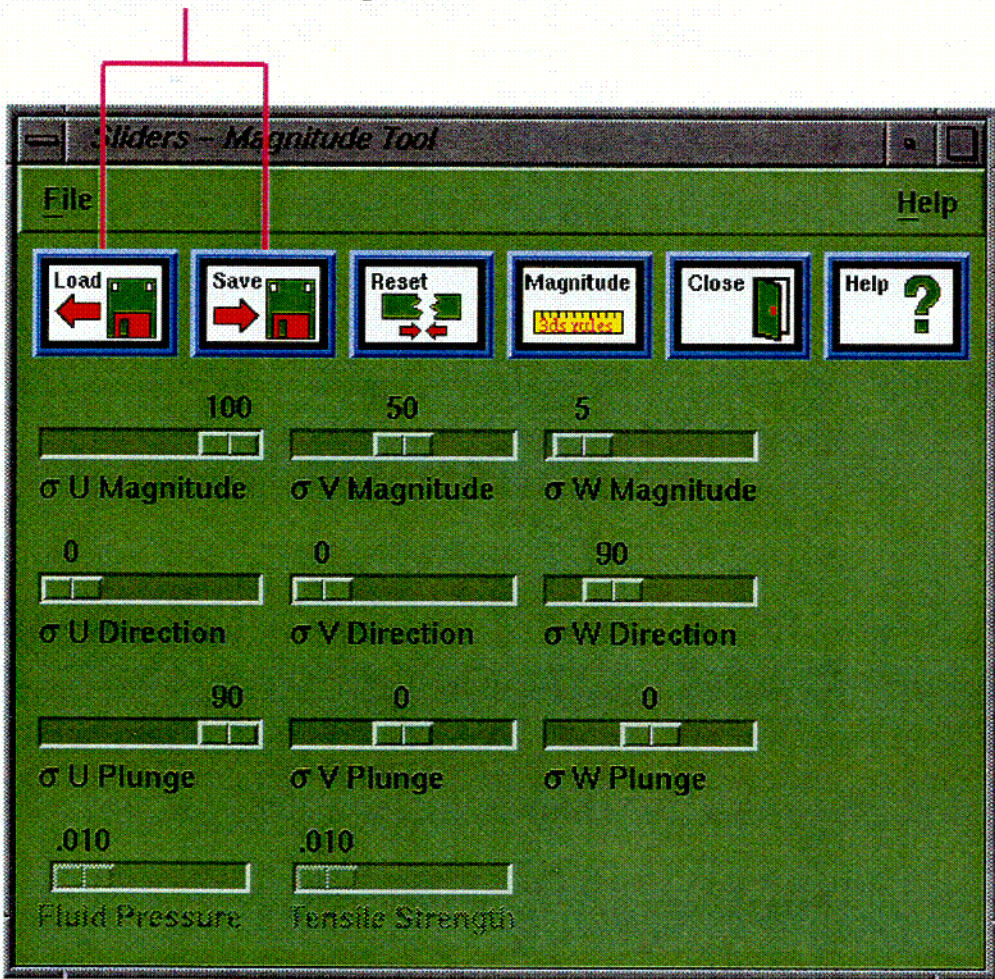


Values are changed by using the left and right mouse buttons.





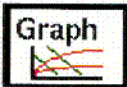
Stress magnitudes and orientations may be saved by pressing the save button and specifying a file name. These values may then later be reapplied by using the load button and choosing a file.



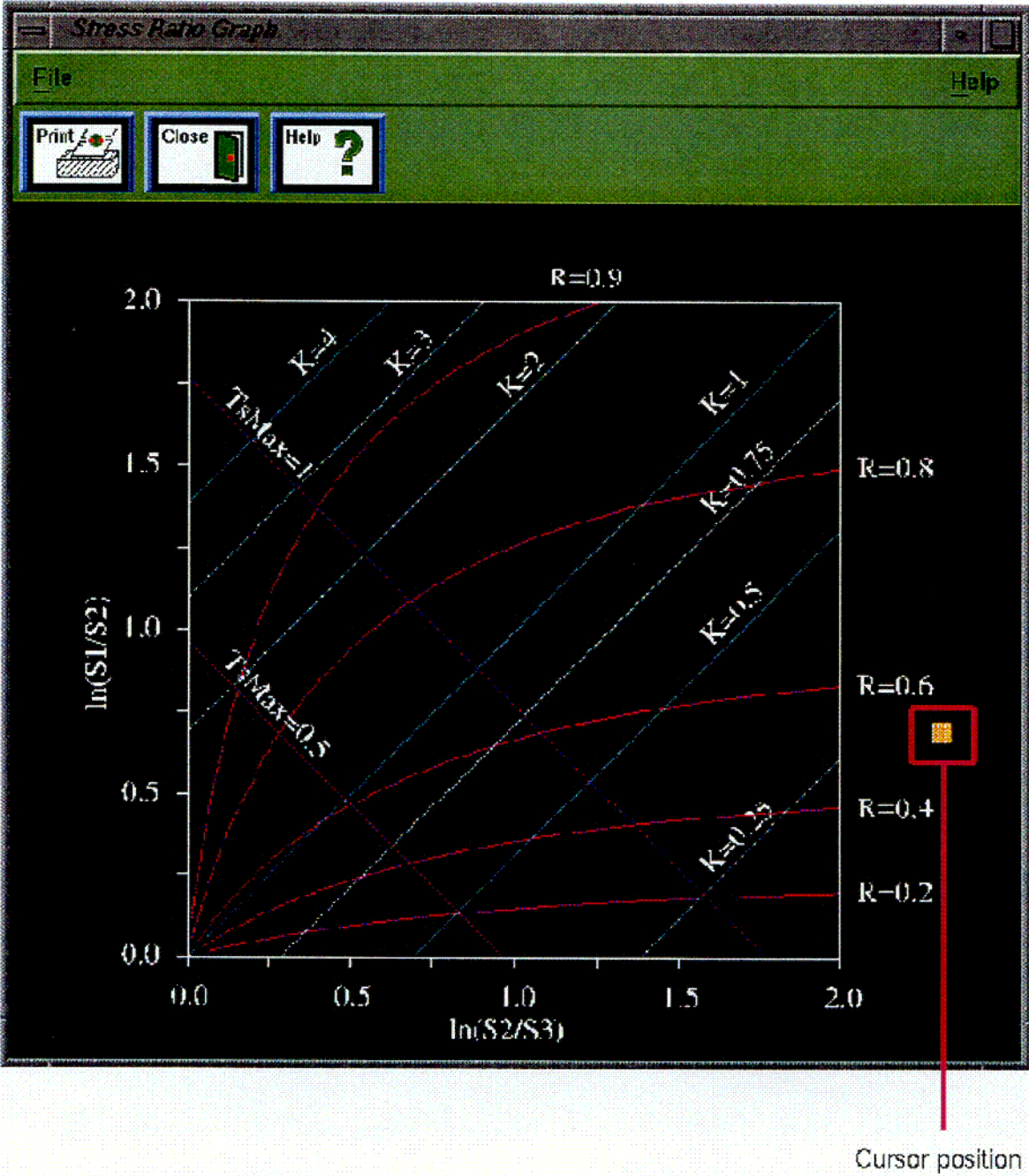
C18



# Stress Ratio Graph



Use the stress ratio graph window to select the desired stress magnitude ratios by holding down the **left mouse button** and moving the cursor to the desired stress state and releasing the mouse button. The **right mouse button** toggles between a logarithm base 10 (log-log) and natural logarithm (ln-ln) scale.



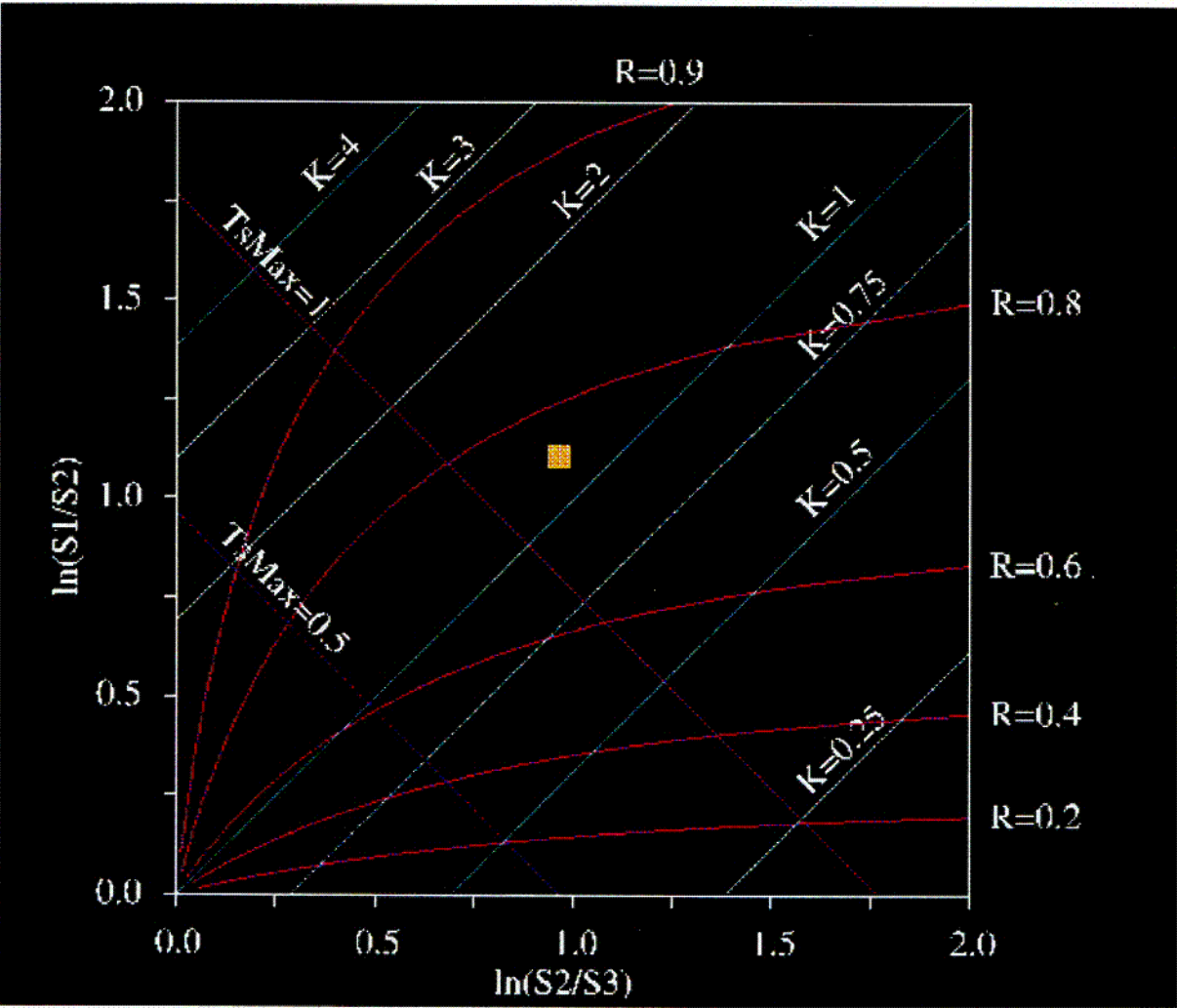
page 2



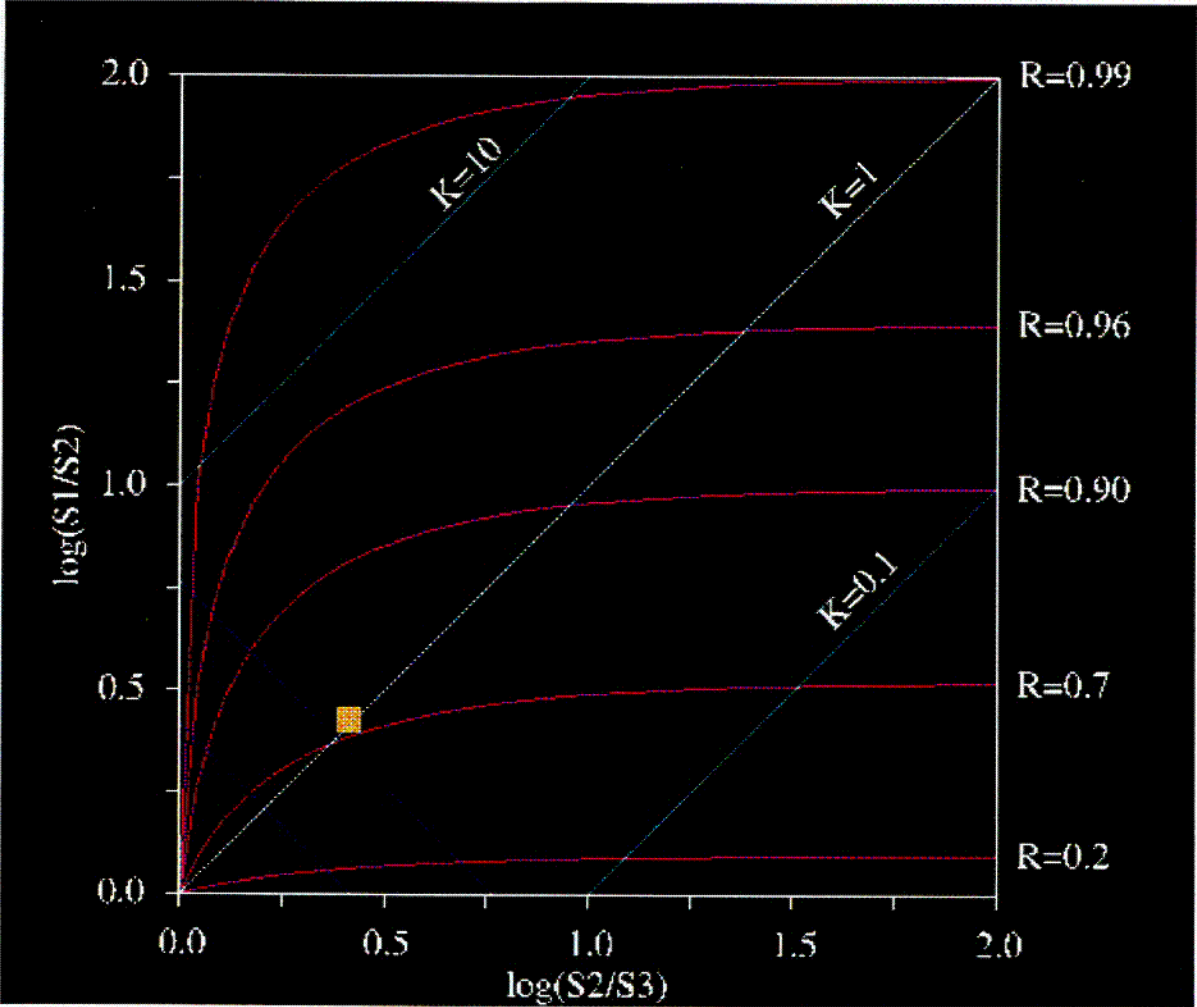
The stress ratio graph displays a **yellow square** whose location is based on the stress ratios of  $\sigma_1$  to  $\sigma_2$  along the y-axis and  $\sigma_2$  to  $\sigma_3$  along the x-axis of the plot.  $\sigma_1$  is the magnitude of the maximum principal stress,  $\sigma_2$  is the intermediate principal stress, and  $\sigma_3$  is the minimum principal stress. In addition to showing the location of the current stress state on a logarithmic scale, the graph also shows where the current stress state lies relative to plots of the following parameters:

$$K = (\sigma_1 / \sigma_2) / (\sigma_2 / \sigma_3)$$
$$R = (\sigma_1 - \sigma_2) / (\sigma_1 - \sigma_3)$$

TsMax = maximum slip tendency of all fault orientations for a given stress state.



Natural logarithm scale



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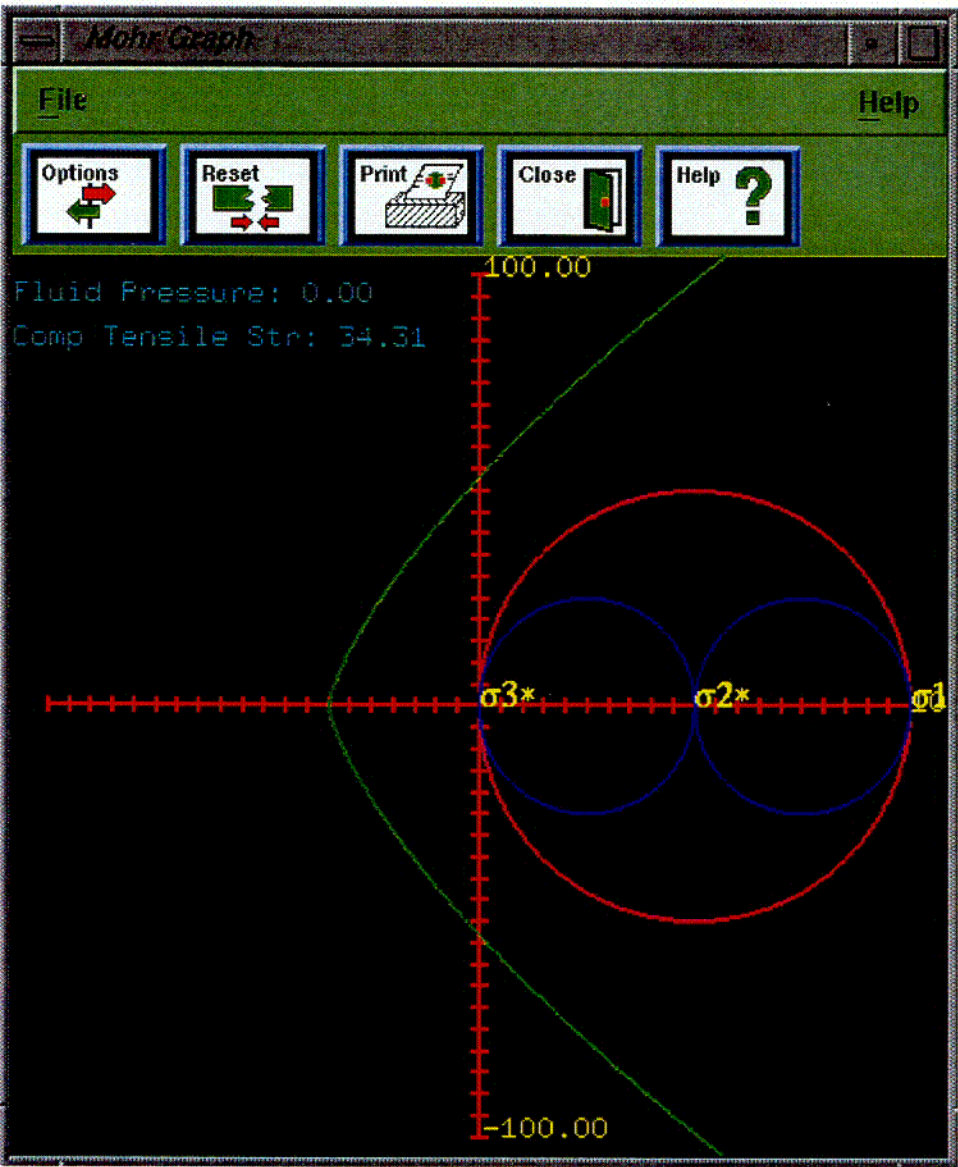
C21



# Mohr Graph



The Mohr Graph allows the user to apply stress and fluid pressure to a specified type of rock and visualize the result. The result of the stresses and fluid pressure on the rock is displayed in a traditional Mohr Graph. Effective stresses are indicated in the visual display by an asterisk.





The rock attributes may be altered in the Hoek-Brown Strength portion of the Options window.

Mohr Options Tool

Stress Mode

☒ Dependent Stresses

☒ Independent Stresses

.0

Fluid Pressure

Reset

.00

$\sigma$  U Magnitude

50.00

$\sigma$  V Magnitude

100.00

$\sigma$  W Magnitude

100

$\sigma$  Max Value

-100

$\sigma$  Min Value

100

Fluid Pressure Max

Effective Stresses ( $\sigma$  - Fluid Pressure)

$\sigma$ U' 0.00

$\sigma$ 3' to  $\sigma$ 1' Ratio 0.000

$\sigma$ V' 50.00

$\sigma$ 2' to  $\sigma$ 1' Ratio 0.500

$\sigma$ W' 100.00

Hoek-Brown Strength

Rock Intact

Rock Type Carbonate

m 7.00000 s 1.00000

Uniaxial Compressive Strength Solenhofen limestone

c 245.0

References

☒ Show Axis

☒ Show Inner Circles

2

Line Width

Render Mode

☒ Solid

☒ Line

Update

Update magnitudes in sliders window with effective stresses

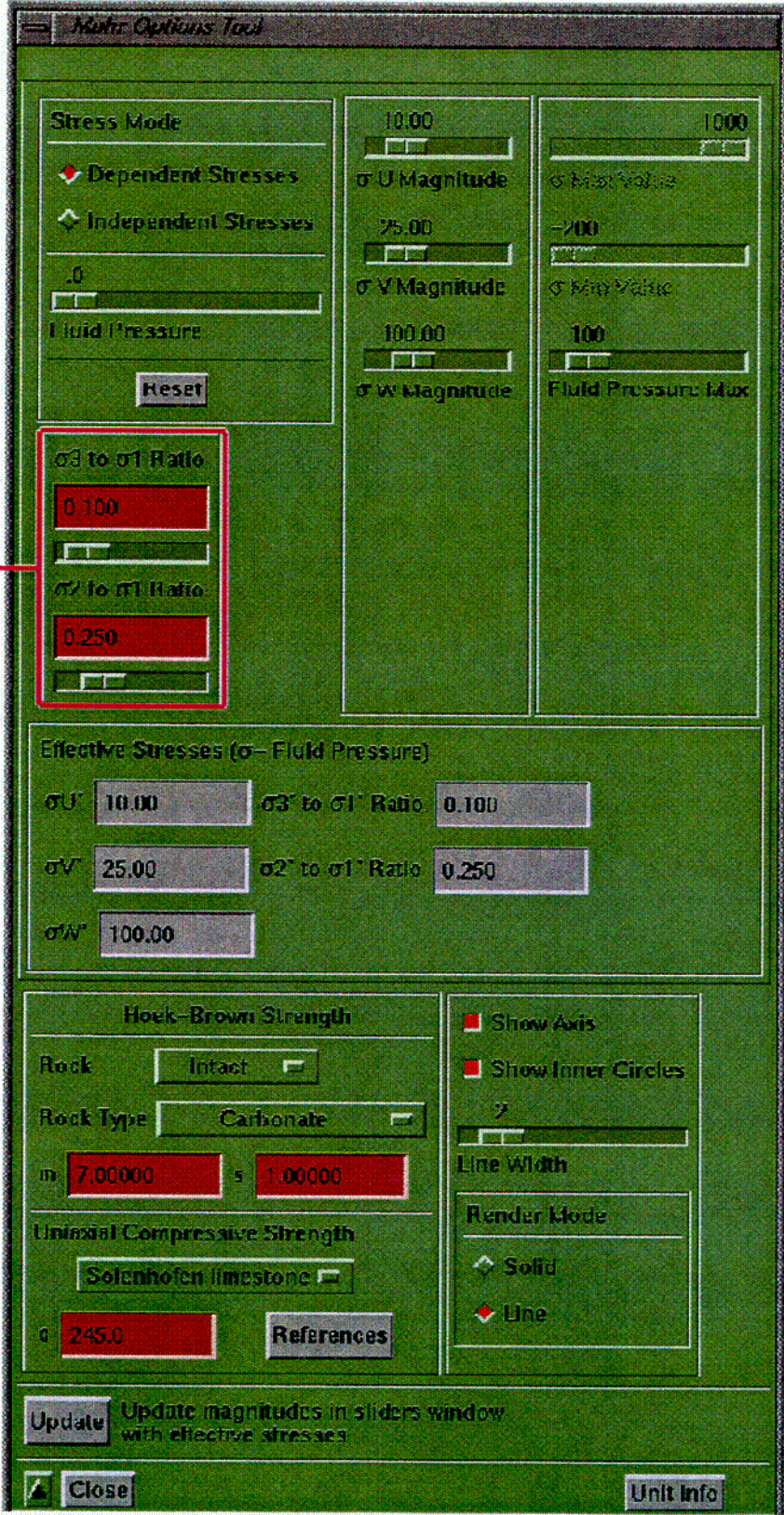
Close

Unit Info



In particular, the user may enter the quality, material type, and specific rock test results to work with pull down menus. The variables m, s, and c may be entered via text fields.

Another interesting feature of the 3D Stress Mohr Graph is the ability to switch between dependent and independent stress modes. When Dependent Stress Mode is selected, sliders and text boxes for the specification of the stress ratios appear.



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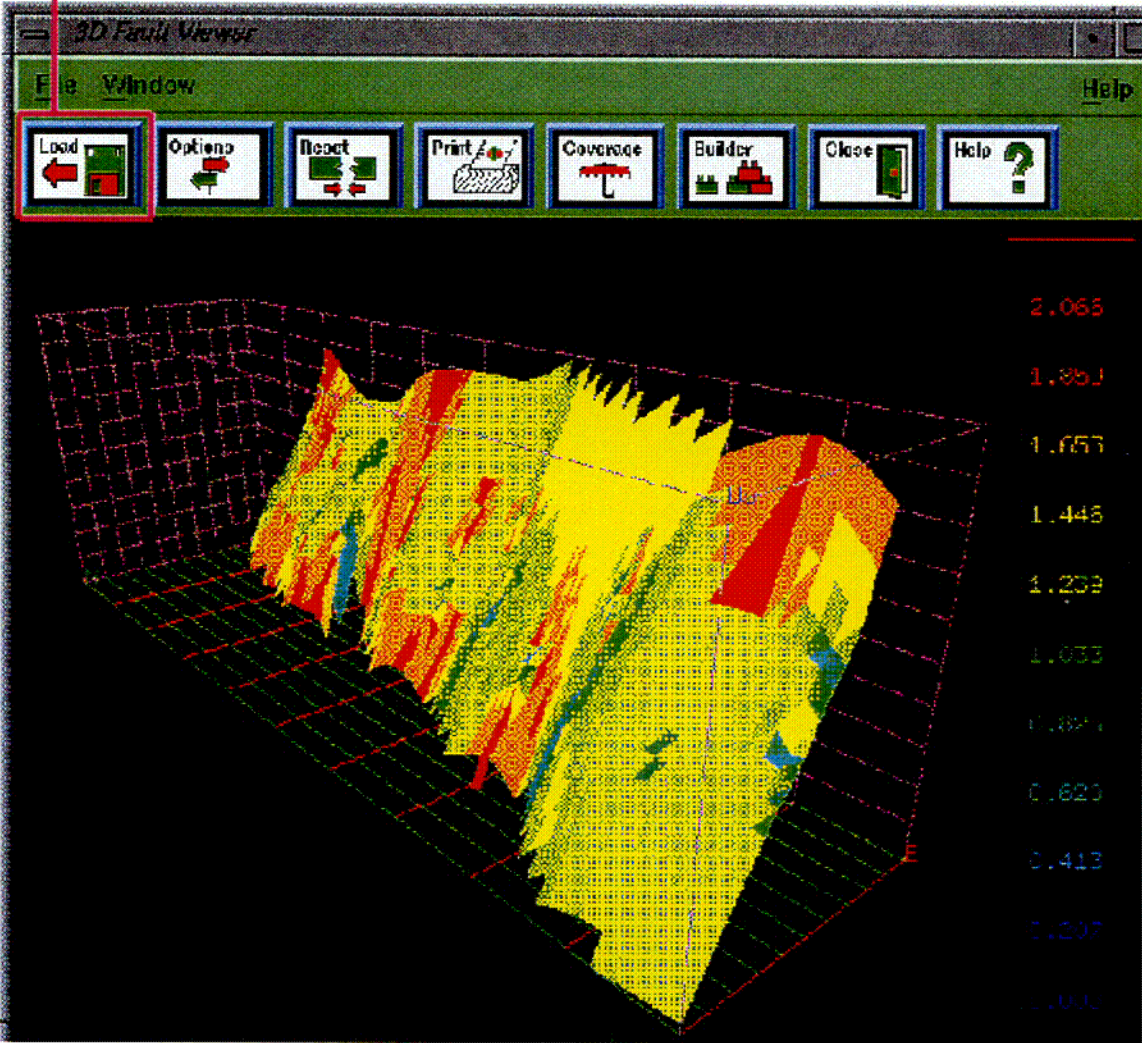


# 3D Fault Viewer



The 3D Fault Viewer enables the user to view and interact with faults defined in 3-space as polygons. The following formats for input files are currently supported: flt, vbl, and 3ds. The 3ds file format is the 3DStress application's own specific format not to be confused with the popular three-dimension modeling mesh format.

To load a file, the user must click on the Load Button located at the top of the 3D Fault Viewer.



Upon clicking load, the user will be prompted with a file browser dialog window with which the file may be selected.