NOTICE

**CERTAIN DATA
CONTAINED IN THIS
DOCUMENT MAY BE
DIFFICULT TO READ
IN MICROFICHE
PRODUCTS.**

EVALUATION OF THE GEOLOGIC RELATIONS AND SEISMOTECTONIC STABILITY OF THE YUCCA MOUNTAIN AREA, NEVADA NUCLEAR WASTE SITE INVESTIGATION (NNWSI)

FINAL REPORT

July 26, 1988

revised October 1988

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

CENTER FOR NEOTECTONIC STUDIES

MACKAY SCHOOL OF MINES

UNIVERSITY OF NEVADA-RENO

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

VOL II

fp?

FINAL REPORT, TASK 4, 01 JULY 1987 - 30 JUNE 1988

William A. Peppin

This document describes activities for the year ending 30 June 1988 by staff members of the Seismological Laboratory in support of the Yucca Mountain site assessment program. Participants include James N. Brune, Director, John Anderson, William Peppin, Keith Priestley, Martha Savage, and Ute Vetter. Activities during the year centered largely around acquisition of equipment to be used for site assessment and around a review of the draft site characterization plan for Yucca Mountain. Due to modifications in the scheduling and level of funding, this work has not progressed as originally anticipated. The report describes progress in seven areas, listed in approximate order of significance to the Yucca Mountain project. These are: (1) equipment acquisition, (2) review of the draft site characterization plan, (3) studies of earthquake sequence related to the tectonic problems at Yucca Mountain, (4) a review of the work of Szymanski in relation to Task 4 concerns, (5) coordination meetings with USGS, DOE, and NRC personnel, (6) studies related to Yucca Mountain, and (7) other studies.

1. Equipment Acquisition.

About \$100,000 was spent on various components of a seismic data logging system at UNR. The purpose of this expenditure was to permit the recording of up to 50 channels of seismic data, both analog and digital, from southern Nevada. This plan was put forward before the USGS announced their proposed major network enhancement, but allows the State of Nevada to record seismic data of our choosing independently. The data logging system involved the purchase of three major components: a Microvax II computer with VAX/VMS Version 4.6 and supporting software, a Systems Industries tapedrive, and a Tustin Industries analog/digital data acquisition module. Delivery has been taken on this hardware and software, and the system is operational apart from the software (to be placed online by USGS expert personnel Robert Dollar and Peter Johnson). In June 1988 they came to UNR and placed the CUSP software on the disc. However, initiation of data logging was not possible because the Tustin data logging system was not communicating with the Microvax. As a result, the Tustin system was taken to Menlo Park where Bob Dollar proposes to test it in a system where all of the other components are operational. Once the Tustin box operates, initiation of data logging should be immediate.

Another aspect of equipment acquisition which is not complete is the materials for data communication from southern Nevada. Some, but not all, of the microwave equipment is now either on hand or deployed in the field, but other expenditures will have to be made if digital data is to be brought up from southern Nevada. In view of the drastically revised state of funding, future additions and enhancements to this system are uncertain.

In addition to the above, \$55,000 was spent on portable seismic digital event recorders and seismometers. These instruments were to be used in field experiments in and near Yucca Mountain during the upcoming fiscal year. However, because of funding uncertainties, these systems are not complete either, and their future use on this project is uncertain.

2. Review of the Draft SCP.

All of the Task 4 personnel participated in a review of the draft site characterization plan for Yucca Mountain prepared by DOE. The review consisted of an overview by John Anderson and individual, independent comments from the various personnel. We believe that we have come up with a number of very significant and useful comments which will improve the final version of the site characterization plan. These comments range over topics including Task 4 concerns, but also extending to matters beyond the scope of Task 4. Some of these comments are bound to be naive, but because they are from fresh viewpoints they may be quite helpful.

3. Studies of Earthquake Sequences.

Manuscripts have been prepared covering the Edgecombe earthquake in New Zealand (a normal-faulting event with magnitude about 6.5) and for the Mina Nevada sequence. These manuscripts are appended to this report. The significance of these Edgecombe studies for Yucca Mountain are that very few close-in recordings of normal-faulting earthquakes are available. The importance of such recordings was highlighted by the Tennent Creek earthquakes in central Australia, which indicated that a recently-suggested hypothesis by McGarr-that normal-faulting earthquakes have smaller peak accelerations near the source than reverse-faulting events may not be true. The significance of the Mina swarm is that it is a sequence in the Walker Belt structure that also contains Yucca Mountain. It provides more information about the problem of strike slip versus normal faulting in this belt.

4. Review of Szymanski's work.

John Anderson set up a symposium for Jerry Szymanski. Szymanski's idea is that, because of a strain buildup preceding an impending earthquake, there could be significant changes in the water conducting properties near the repository, suggesting the possibility of a hitherto unforeseen mechanism for reducing the ability of the tuff members to isolate the nuclear waste. The upshot of this could be that previously used models of water movement are inadequate, in that they model the coupling of the equations (non-linearity) incorrectly. Professor Anderson concludes that this coupling, while believed to be unimportant, should be examined more closely in the site characterization plan.

5. Coordination Meetings.

Several important coordination meetings, plus a major symposium, were attended during this time period. The fall symposium at UNR brought together many scientists working on problems directly or indirectly related to tectonics at Yucca Mountain, and was attended by Task 4 personnel. In March a meeting at Golden was attended by J. Brune, W. Peppin, and W. Nicks on quality assurance. The USGS facilities where southern Nevada data is recorded was examined, and issues involving quality assurance were discussed with personnel from UNR, the USGS, DOE, and NRC. In April J. Anderson attended a meeting in Las Vegas to discuss alternate conceptual models for the groundwater system at Yucca Mountain, as this is one of the major site characterization issues. This conference was attended by many UNR co-workers on other tasks, and led to the Szymanski colloquium described above. In May J. Brune, W. Peppin, M. Savage and W. Nicks met with DOE and USGS personnel to discuss the USGS seismic instrumentation upgrade in southern Nevada. We agreed to coordinate any instrumentation efforts to complement the various research objectives.

6. Studies Related to Yucca Mountain

Work is underway with two graduate students to implement studies relevant to Task 4 work. A new graduate student, Zhang Jianjun, has put a major computer program PROSE on the new UNR computers. This program is to be used in a wide range of modelling experiments for wave propagation in and near Yucca Mountain in connection with source characterization, regional propagation effects, and the prediction of local strong ground motion at key repository sites. Verification of the program for quality assurance documentation is now underway. Another graduate student, Steve Horton, is working with Professor Anderson on the design of a site-characterization experiment this summer in connection with the joint US-Soviet CORTEX nuclear explosion. Permitting, instrumentation, and site selection are now being developed.

Another graduate student, Raul Castro, is working on the problem of short-period attenuation in the Great Basin. At issue is the question of how to estimate earthquake size, an important parameter for site characterization at Yucca Mountain. Recently published works disagree considerably on the attenuation of regional earthquake spectra. Along a path extending NW-SE he finds an intrinsic attenuation Q value of 725. However, along a path extending SW-NE, he finds a higher attenuation, and concludes that much of this is due to frequency-dependent attenuation. This matter must be resolved if accurate estimates of seismic moment are to be obtained.

Martha Savage participated in a cooperative project with the University of Wisconsin and the Carnegie Institute of Washington, in which 12 portable seismic stations were deployed in Nevada, 3 of which were set up in southern Nevada. The station recorded three chemical explosions, a nuclear explosion at the NTS and a number of teleseismic earthquakes. The data is being reduced with the intent to study anisotropy of the crust and upper mantle, to learn more about the state of stress and the structure of the region surrounding Yucca Mountain.

7. Other Activity

W. Peppin completed a writeup of technical procedures for quality assurance control of Task 4 work. These procedures have been reviewed by the Nevada Waste Project Office for compliance with the adopted quality-assurance guidelines.

Appendix 1

EARTHQUAKE CLUSTERING NEAR MINA NEVADA, JULY AND AUGUST 1987

Kenneth Smith, William R. Walter, Raul R. Castro,
Keith Priestley, Abdol R. Anooshepoor

Seismological Laboratory, Mackay School of Mines

University of Nevada Reno

INTRODUCTION

Several M_L 3.5+ including two M_L 4 earthquakes occurred within a shallow localized cluster of activity during July and August 1987 near the small town of Mina, Nevada. The larger earthquakes were strongly felt by residents of Mina. This area is of particular interest in terms of earthquake potential because it is within the proposed White Mountains 'seismic gap' defined to the south by the northern extent of the 1872 M_L 8 Owens Valley earthquake and to the north by the 1932 M_L 7.1 Cedar Mountains earthquake. The cluster occurred in the northern part of the 'gap' where it crosses the Walker Lane, a structurally complex northwest trending zone of significant right lateral offsets (130 to 190 km of lateral displacement during the late Cenozoic, Stewart 1978; Stewart et al, 1968; Nielsen, 1965; Shawe, 1965). The activity was just to the west (~7km) of the Pilot Mountains Range front fault which does show holocene off-sets and was initially thought to be causative fault. Ryall and Priestley (1974), in a study of the Excelsior Mountains region east of Mina, noted the high levels of seismicity in this region, and the lack of moderate to large earthquakes and suggested that the bulk of the stress release was being accommodated by smaller events. The Mesozoic tectonics of the Pilot Mountains-Mina, Nevada region has been discussed in detail by Oldow (1981, 1983).

Shallow clustering of small earthquakes has preceded several of the M_L - 6 events of the Bishop-Mammoth Lakes, California earthquake sequence (1978-present), 150 km to the southwest of Mina along the eastern front of the Sierra Nevada (Ryall and Ryall, 1981; Smith and Priestley, 1988). In particular, the two most recent earthquakes in this region, the 1984 M_L 5.8 Round Valley and 1986 M_L 6.4 Chalfant, California earthquakes, occurred in close association with significant range front faults, and were preceded by some degree of earthquake clustering. The active seismotectonics of the Bishop, California area is somewhat similar to major range bounding faults. Also, periods of localized clustering are a characteristic of the seismicity of both areas.

We shall define clustering in a qualitative sense. In the region, clustering, as opposed to aftershock sequences, tends to include a significant number events at the M_L 3-4 level with no particular event being dominant, no clearly identified main shock, and there is not the characteristic exponential decay with time of earthquake activity that is usually observed in classic mainshock-aftershock sequences. Also, these phenomena usually occur at shallow depth, are confined to a small volume of the crust and usually represent a significant amount of energy release for the restricted volume.

In this study we analyze the 1987 Mina activity, attempt to isolate the causative faults and discuss recent regional seismicity patterns with respect to localized clustering and active faulting.

DATA

The University of Nevada Seismological Laboratory (UNSL), in cooperation with the U.S. Geological Survey (USGS), monitors earthquake activity along the Sierra Nevada-Great Basin boundary of Nevada and California and with USGS funding extends coverage to the west central Great Basin boundary of Nevada. Data from the UNSL short period seismic network are telemetered to the Reno Lab where it is digitized and recorded. Seismograms are analyzed by Lab personnel and earthquakes of M_L ~ 1.5 and greater are routinely located. The trace data is archived and earthquake locations are published in a yearly catalogue.

Between July 28 and August 31, 1987, 140 events were located by UNSL in the Mina area. Of these, 13 were M_L 3 or greater, 2 were M_L 4 or greater (Table 1), and 45 were in the M_L 2.5-3.0 range (duration magnitudes in all cases). The activity occurred to the east of the network (gaps in locations greater than 180) significant affecting earthquake location quality. Three component digital seismographs were deployed from July 29 through August 4, to supplement the permanent network. These stations provided coverage to the east, near source S-wave arrival times, near source P-wave first motions to constrain focal mechanisms and digital waveform data for source parameter studies. Timing control was maintained in the field for the portable instruments, clock drifts were measured and P and S wave phase arrivals were time corrected prior to merging with network phase data. One instrument was placed several hundred feet within a mine tunnel, 12 km epicentral distance, to obtain digital waveform data not contaminated by surface effects.

A master event was chosen (1119 UTC July 31; ML 2.7; depth 6.0 km) which included several P and S arrival times from the portable instruments assuring a good location. All events for the July to August time period were then relocated using P wave residual times from this event as stations corrections. A simple layered velocity model was used (Table 2), in the University of Washington SPONG hypocentral location program to relocate all events. The reliability of such a technique depends on the accuracy of the location of the master event which in turn is dependant on the velocity model and P and S wave velocities used in the model. This relocation process significantly decreased the scatter, both in the lateral and depth distribution, in the early locations and moved the epicentral distribution approximately 2 km to the east.

HYPOCENTRAL DISTRIBUTION, FOCAL MECHANISMS AND RELATION TO MAPPED FAULTS

July and August 1987 Mina earthquake activity was confined to a small shallow volume of the crust. Map views and cross sections of the relocated hypocentral distribution are shown in Figures 1 and 2. The mean depth of the hypocentral distribution is approximately 5 km. The vertical extent of activity is seen to be greater than the lateral extent of activity is seen to be greater than the lateral extent and this is not totally due to the trade off between origin time and focal depth that can occur in the location process when there is poor station coverage, since even those events with highest quality locations (recorded on the portable instruments) show a similar distribution. Focal mechanisms show little variation and indicate nearly pure strike slip motion (Figure 3); right lateral on a NNE striking fault of left lateral on a WNW striking plane. This is precisely the location where left lateral striking faults of the Excelsior Mountains region meet the right lateral offsets of the Walker Lane, so a combination of both left lateral strike slip motion cannot be ruled out. Recent earthquake sequences in the Bishop, California area include both right lateral and left lateral strike slip mechanisms in near conjugate fault planes (Smith and Priestley, 1988; Priestley et al, 1988). The slight northeasterly trend in the epicentral distribution (Figure 1) would favor right lateral strike slip on the NNE striking plane.

For the Soda Springs Valley range front fault, 7 km to the east of the earthquake activity along the base of the Pilot Mountains, to by the causative fault would require it to dip less than 45 degrees (Figure 2). Considering that the displacement is predominantly strike slip on a northwest striking structure.

The projection of the northwest striking right-lateral slip plane, seen in all focal mechanisms looked at to date, is consistent with a series of northeast trending faults approximately 2 km east and southeast of the town of Sodaville. These structures are oblique to the range front. The slight northeasterly trend in the epicentral distribution (Figure 1) also supports the interpretation that these are the operative faults. The auxiliary plane from the focal mechanisms, or what is the east-west striking left lateral slip plane, in all cases projects to the surface north of the town of Sodaville and north of the activity. It would therefore be difficult to place this activity on faults seen in aerial photographs that occur south of the epicentral area (Figure 4). Also, these earthquakes may be associated with ground water activity in the Sodaville springs, the most dominant feature in the aerial photographs (Figure 4). The vertical extent of the hypocentral distribution may indicate that ground water activity is playing some role.

A check of seismicity of the past several years (Figures 5) indicates that small tight clusters of activity are not unusual in the Mina region. Several of these clustering points are active for short periods of times and others remain active for years.

CLUSTERING AND MODERATE EARTHQUAKES IN THE REGION

The two most recent moderate size earthquakes in the region, the 1984 M_L 5.7 Round Valley and 1986 M_L 6.4 Chalfant, California events, occurred on faults with a similar geometry with respect to local range fronts as those apparently responsible for the 1987 Mina activity (Figure 6). Aftershock distributions consistent with focal mechanisms define conjugate sets of fault planes for both the Round Valley and Chalfant events that are oblique to the range fronts.

The Chalfant earthquake was preceded for three weeks by a localized shallow cluster of activity very similar in character to that seen at Mina (Figure 7) and was one of the motivations for deploying portable instruments in the Mina area. At Chalfant this cluster was within 4 km hypocentral distance of the nucleation point of the mainshock and was at the hypocenter of the M_L 5.7 event that preceded the Chalfant main shock by 24 hours. Similarly, a cluster of activity, again in the epicentral region, preceded the Round Valley event (Figure 8), but this was 1 year prior to the earthquake (Smith and Priestley, 1988). At the time of Round Valley precursory activity the UNSL-USGS network did not extend to the east and location qualities are poor and these events have not been relocated.

SUMMARY AND CONCLUSIONS

Earthquake clustering in the Mina, Nevada region during late summer 1987 has been interpreted to be occurring on a series of NNE striking secondary faults evident on aerial photographs south and east of town of Sodaville. These faults are oblique to the main range bounding fault, the Soda Springs Valley fault which borders the Pilot Mountains and shows significant holocene right lateral displacement. The relocated hypocenters plot above the 45° down dip projection of the range front fault, and a similar focal mechanism for all events also rules out the range front fault as the causative structure. Faults with similar geometry with respect to local range fronts were involved in the two most recent moderate earthquakes in the Bishop-Mammoth Lakes area, the 1984 M_L 5.8 and 1986 M_L 6.4 Chalfant events. These two events were also preceded by precursory clustering very similar in character to that seen at Mina. This is particularly true in the case of the Chalfant event, whereas Round Valley precursory clustering is less well defined.

Secondary structures, oblique to large scale holocene structural trends, which have been responsible for much of the recent seismicity in the region are accounting for strike slip deformation in close association with range front normal fault systems. This may be indicative of the process of stress accumulation within the major fault zones and not regional stress release. In that case, we may be only seeing the secondary effects of stress build up which may make it even more difficult to recognize the potential nucleation zones of future Basin and Range earthquakes.

Acknowledgements

This research was funded by U.S. Geological Survey research grant 14-007-G1326.

References

References

- Nielson, R.L. (1965). Right-lateral strike-slip faulting in the Walker Lane, west central Nevada, *Geol. Soc. Am. Bull.* 76, 1301-1308.
- Oldow, J.S. (1983). Tectonic implications of a late Mesozoic fold and thrust belt in northwestern Nevada, *Geology* 11, 542-546.
- Oldow, J.S. (1981). Kinematics of late Mesozoic thrusting, Pilot mountains, west central Nevada, U. S. A., *J. Struc. Geol.* 3, 39-49.
- Priestley, K.F., K.D. Smith, and R.S. Cockerham (1988). The 1984 Round Valley California earthquake sequence, submitted to *Geophys. J. R. Astro. Soc.*
- Ryall, A. and K.F. Priestley (1975). Seismicity, secular strain and maximum magnitude in the Excelsior Mountains area, western Nevada and eastern California, *Bull. Geol. Soc. Am.* 86, 1585-1592.
- Ryall, A.S. and F. Ryall (1981). Spatial-temporal variations in seismicity preceding the May 1980, Mammoth Lakes, California, *Bull. Seism. Soc. Am.* 71, 747-760.
- Shawe, D.R. (1965). Strikes-slip control of Basin-Range structure indicated by historical faults in western Nevada, *Geol. Soc. Am.* 76, 1361-1378.
- Smith, K.D. and K.F. Priestley (1988). The foreshock sequence of the 1986 M_L 6.4 Chalfant, California earthquake, *Bull. Seism. Soc. Am.* 78.
- Stewart, J.H. (1978). Basin and range structure in western North America, in Smith, R.B. and G.P. Eaton, eds., *Cenozoic tectonic and regional geophysics of the western Cordillera: Geological Society of America Memoir* 152, 1-31.
- Stewart, J.H., J.P. Albers and F.G. Poole (1968). Summary of regional evidence for right-lateral displacement in the western Great Basin, *Geol. Soc. Am.* 79, 1407-1413.

Figure Captions

Figure (1). Epicentral distribution of July and August clustering in the Mina area. The Soda Springs Valley range front fault is represented by the solid line bordering the Pilot Mountains. The extent of the cross section for Figure 2 is labeled A-A'. The town of Sodaville would be less than 1 km north of the activity.

Figure (2). Cross section as labeled in Figure 1. The diagonal line is the 45° dip projection of the Pilot Mountains range front as discussed in the text.

Figure (3). Lower hemisphere projection of the focal mechanism for the largest event; 0309 GMT August 8. This mechanism includes several first motions from the portable instruments. The preferred plane as discussed in the text and which conforms to a series of faults seen on the ariel photographs (Figure 4) is the NNE striking right lateral near vertical plane. All mechanisms of M_L 3 events are nearly identical. The ESW striking left lateral slip plane projects to the surface north of the activity and therefore would rule against considering faults seen south of the activity on ariel photos (Figure 4) as the causative structures.

Figure (4). Ariel photographs covering the Sodaville area south of Mina. The is the center of the epicentral distribution and the suggested causative faults are seen striking NE and to the right of the Sodaville springs (dominant feature in center of photo). The Pilot Mountains range front fault is to the east of the picture and these secondary faults interpreted to be responsible for the 1987 activity are oblique to the range front.

Figure (5). Mina area activity from the UNR catalog for 1974-1987. The box is the area covered in Figure 1.

Figure (6). Faults planes active during the 1984 Round Valley and 1986 Chalfant sequences that also indicated nearly pure strike slip motion and were oblique to there corresponding range bounding fault, the Round Valley fault zone and the White Mountains fault zone respectively.

Figure (7). Precursory clustering in the Chalfant main shock source region. The large (+)'s are the epicenters of the M_L 5.7 foreshock, to the north, and the M_L 6.4 main shock to the south. The small (+) is the epicenter 1984 Round Valley main shock.

Figure (8). Precursory clustering in the Round Valley main shock source region. This clustering is less well defined than for the Chalfant event and mostly occurred 1 year before the earthquake.

Table 1

Origin Time	Latitude	Longitude	Depth (km)	M _L
870728 0905 8.44	38-19.75	118- 6.67	3.48	3.7
870728 1855 11.91	38-19.63	118- 6.73	3.33	3.8
870729 0352 32.61	38-19.84	118- 6.85	4.33	3.8
870729 0357 33.40	38-20.02	118- 6.81	4.67	3.5
870730 1213 59.62	38-19.96	118- 6.31	6.12	3.3
870803 0948 4.79	38-20.03	118- 7.22	10.13	4.0
870803 1008 56.19	38-19.68	118- 7.06	6.95	3.1
870804 0557 13.14	38-19.50	118- 6.88	8.62	3.4
870807 1147 49.15	38-19.59	118- 6.55	1.79	3.5
870807 1938 3.12	38-19.89	118- 6.20	4.91	3.0

Table 2

Depth	P-wave velocity
0.0	0.0
2.0	5.85
22.0	6.70
28.0	7.85

Mina Area
1987

(1)

0 3 Km

(2)

A 8030947 64.79 38N2003 118H 722 10.13 4.0 10/010 S 0.13 1.8GB KS

Velocity model, vel.M2

Reversed stations:

strike	dip	rake
plane1 198	85	-170
plane2 107	80	-5

P-axis	T-axis	slip1	slip2
trend 63	332	17	108
plunge 11	3	10	5

Lower hemisphere equal area projection

8-12-67

2349-19

(5)

0 15 Km

Fault Planes

(6)

Pre Round Valley 03-04

(7)

Pre Chalfant 06

(8)

Appendix 2

SOURCE PARAMETERS OF THE 1987 EDGE CUMBE, NEW ZEALAND EARTHQUAKE

Keith F. Priestley

Seismological Laboratory, Mackay School of Mines
University of Nevada - Reno, Reno, Nevada 89557

Abstract. Moment tensor inversion of low frequency normal mode and teleseismic body-wave data for the March 2, 1987 Edgecumbe, New Zealand earthquake give an average seismic moment of 7.0×10^{18} N-m. Measurements of seismic moment at low frequencies are converted to spectral levels and combined with the acceleration spectrum from a strong-motion seismogram recorded at about 15 km epicentral distance to give a composite source spectrum for the main shock. The source spectrum is simple, that is, it shows a constant low frequency level, a corner frequency of 0.22 Hz, and a high frequency slope of approximately ω^{-2} . The corner frequency implies a fault radius of 6 km giving an average fault displacement of 2 m and a stress drop of 5 MPa. Integration of the velocity-squared spectrum indicates an energy release of 1.1×10^{15} J resulting in an apparent stress of 5.5 MPa.

A suite of 255 three component, digital seismograph recordings of 57 aftershocks of the Edgecumbe earthquake have been analysed to obtain estimates of seismic moment, source radius, and stress drop. Seismic moments were calculated from the asymptotic long-period spectral levels which were corrected for the radiation pattern of a double-couple point source. They range from 10^{11} N-m to 10^{14} N-m. Corner frequencies were estimated both by fitting the spectra by hand and by integrating the velocity squared spectra. The source radii inferred from the corner frequencies ranged from 200 to 300 m. Because of the nearly constant source radii over three orders of magnitude in seismic moment, stress drop is strongly correlated with seismic moment. Stress drops from the Brune formulation were low and ranged from 0.01 to 3.0 MPa. Similar low values for stress drop have been reported for other normal faulting environments.

Introduction

The March 2, 1987 Edgecumbe, New Zealand earthquake (M_L 6.3, m_b 5.9, M_s 6.6) was a moderate, shallow, normal faulting event similar to the type of event anticipated in the Yucca Mountain region. This event had a maximum intensity of IX on the Modified Mercalli scale and caused extensive damage in the surrounding region. The 1987 earthquake occurred in a rifting environment behind the convergent Pacific - Indian plate boundary. In this region, the Pacific plate is presently being subducted westward beneath the Indian plate at approximately 50 mm/yr (Walcott,

1978). Typically, earthquakes along the Benioff Zone extend to 250 km depth (Reyners, 1980) however, some events as deep as 600 km have been observed (Adams and Ware, 1977). The 1987 earthquake occurred within the Central Volcanic Region (CVR), a zone of rifting within the continental crust of the North Island. The CVR is characterized by large volumes (approx 12,000 km³) of Quaternary rhyolitic volcanic rocks (Cole, 1979), an average heat flow of 700-800 mW/m² (Studt and Thompson, 1969; Thompson, 1977; Allis, 1979), historical extension (Walcott, 1978), thin crust (approx 15 km) and low Pn velocity (7.4 k/s) (Stern and Davey, 1986). Stern (1985) has used various lines of reasoning to show that the CVR is a direct continuation of a young oceanic back-arc basin into the continental structure of New Zealand.

The 1987 earthquake occurred at the southeastern margin of the CVR beneath the Rangitaiki Plain, a low lying alluvial basin consisting of volcanic and graywacke-derived sands and gravels with interbedded ignimbrites, silts, and peats, all Pleistocene to Holocene Age (DSIR staff, 1987). The basin is fault-bounded on the east by the Jurassic graywacke of the Raungaehe Range, and on the west by Quaternary volcanics. Several active faults were previously recognized in the region, however none had been recognized on the Rangitaiki Plain. The normal faulting surface rupture accompanying the 1987 main shock occurred along a number of strands over a approx 10 km broad and approx 15 km long region. In detail, the main rupture is quite irregular, but the downthrown side is always to the northwest. The deformation comprises a monoclinial flexure along the main fault, with fissures generally near the crest of the flexure. The fissures appear to be deeper than the total vertical offset of the terrace surface, an observation which indicates that they represent tectonic extension rather than near surface tension cracking at the crest of the flexure. The maximum vertical offset is 2 m, however Grapes et al (1987) suggest that the more than 1 km of unconsolidated sediment underlying the plain may have taken up part of the faulting. Measurements made on fissures, cracks, etc. crossing the rupture indicate a total extension of up to 1.6 m. The overall strike of the faulting is 51°, and the strike of the most easterly striking section is 77°± 6° (Grapes et al, 1987).

ANALYSIS OF THE MAIN SHOCK

Teleseismic Source Mechanism

Normal Mode Analysis: Low frequency digital seismograms from the International Deployment of Accelerometers (IDA) and the Seismic Research Observatory (SRO) networks were used in this analysis. The distribution of these stations relative to the epicenter is shown in Figure 1. Analysis of low frequency waves constrains the overall faulting process and the low frequency portion of the

source spectrum. Six hour long time series from vertical seismograms of the IDA and vertical and horizontal seismograms of the SRO networks were used in a linear inversion procedure to recover the elements of the seismic moment tensor (Buland and Gilbert, 1976). These time series are shorter than we have previously used in such inversion procedures (e.g. Priestley and Masters, 1986) but this was necessitated by the occurrences of a M_s 6.2 event in the Indian Ocean at 05:58 GMT. However for moderate events such as the Edgumbe earthquake, the instruments remain linear for the direct Love and Rayleigh wave arrivals, and these phases dominate the normal mode signal. Details of the inversion procedure are given in Masters et al (in preparation). Results from the normal mode inversion are given in Table 1. The largest uncertainty in determining the moment results from the indeterminacy of the dip. A 10% error in the assumed dip will result in a 10% error in the determined moment. The fault finiteness and the finite rise time introduce a source process time τ_s , which is 7.5 sec for the Edgumbe earthquake. Figure 1 compares the observed and synthetic low frequency waveforms. The phase of the event is well fit, however, amplitude anomalies exist for several azimuths. Such effects can arise due to the finite source size, or to aspherical earth structure. For moderate earthquakes such as the Edgumbe event, aspherical earth structure is likely to be the dominant effect.

Body wave analysis: Analysis of teleseismic body waves can constrain the depth of the initial rupture, provide details of the source time history of the event, and provide an estimate of seismic moment at a higher frequency than the normal mode analysis. Waveform inversion techniques for recovery of the seismic moment tensor have been discussed in a number of recent papers (e.g. Doornbos, 1982, 1985; Ward, 1980, 1983), and the Harvard Seismic group routinely reports moment tensor solutions for events larger than about m_b 5.5. Time series for the phases P, PP, PKP, S, and SKS were extracted from the SRO and ASRO digital seismograms. Greens functions used in the inversion procedure were calculated for the windowed phases, plus their near-source reflections (i.e., pP, sP, etc.) for specific source depths using the WKBJ approximation (Chapman, 1978) for earth model 1066B (Gilbert and Dziewonski, 1975). Only phases at a distance greater than 30° were used in the inversion procedure to avoid complications introduced by upper mantle structure. Individual arrivals may be early or late with respect to the arrival time predicted by the model 1066b, due to local deviations of the structure. The fitting procedure is performed interactively, permitting the theoretical waveform to be time aligned with the observed waveforms. If this alignment is not done, the solution is badly biased. The quality of the solution is assessed by calculating the average variance reduction (VR) which is a quantitative measure of the misfit between the synthetic waveform calculated for the moment tensor solution, and the observed waveform. The fitting procedure is repeated over a reasonable depth range until a maximum variance reduction is

achieved. Results from the body-wave inversion are given in Table 1.

Main Shock Source Spectrum

Band limitation of existing seismic instrumentation makes estimation of the source spectrum for moderate and large earthquakes difficult. Acceleration data collected in the epicentral region are hampered by the poor low frequency response of typical strong-motion instrumentation. High frequency data does not normally exist from teleseismic recordings because of the high attenuation for teleseismic propagation paths and low level response of most teleseismic seismographs. To overcome this problem, we have constructed a composite source spectrum for the Edgecumbe earthquake.

The Edgecumbe earthquake triggered five strong-motion accelerographs sited on and near the Matahina dam at about 15 km epicentral distance. Four of the instruments are sited on the dam, and the fifth is located a few meters in front of the dam (McVerry, written communication, 1987). Figure 2 shows the N83°E horizontal component of acceleration and the Fourier acceleration spectra from the instrument at the dam base. This component is nearly in the transverse direction with respect to the epicenter at 15 km epicentral distance. However the surface trace of the fault passes within about 7 km of the instrument, consequently, considering the fault dimension, the instrument is in the near field. The peak horizontal ground acceleration is 0.33 g (Anderson et al, 1987). The duration of the strong ground shaking is relatively short, and the integrated displacement pulse is simple in character, indicating a relatively smooth rupture. The low frequency energy observed in the displacement record for times greater than 10 seconds may be the result of surface wave energy trapped in the low velocity material comprising the Rangitaiki Plain, or the result of numeric noise. It is difficult at this point to take into account the proximity of the dam and for the present any possible coupling of energy back into the ground by this structure is ignored. Only data from this instrument is considered in constructing the source spectrum.

Estimates of seismic moment from the normal mode and body wave inversion, and from the surface wave magnitude were converted to full-space spectral amplitudes at their observed frequencies for comparison with the spectral amplitude determined from the near-source acceleration data. Using a shear wave speed (β) of 3.6 k/s, a density (ρ) of 2.8 Kg/m³ (Robinson, written communications, 1987), and a radiation factor ($R_{\theta\phi}$) of 0.6 (Thatcher and Hanks, 1973), the seismic moment M_0 related to the spectral amplitude normalized to 10 km is

$$\text{OMEGA (full space) sub (10 km)} = \frac{R_{\theta\phi} M_0}{4 \pi \rho \beta^3 (10 \text{ km})} = 3.65 \times 10^{-25} M_0$$

This gives values of $\Omega(f)$ at lower frequencies for comparison with values of $\Omega(f)$ obtained from the body wave accelerograms. The transverse component of the strong-motion accelerogram was normalized to a hypocentral distance of 10 km, corrected for the average radiation pattern, and converted to a full-space spectrum by accounting for the free surface amplification effects. Since the instrument was in the near field, as a first approximation to normalizing to 10 km hypocentral distance, we have assumed the energy radiated per unit area of the fault is constant. Therefore we multiplied the spectral amplitude by the ratio of twice the area of the fault (to account for the radiation from both sides of the fault) to the area of a patch of the fault of 7km radius. This value was assumed to be the actual amount of energy radiated from a point source. The r^2 scaling was then applied to normalize the spectrum to 10 km distance. The acceleration spectrum was corrected for a range of attenuation values which seemed reasonable for graywacke. Since these produced negligible effects on the spectrum in the frequency band of interest, an arbitrary whole path Q of 300 was assumed. Contamination of the spectrum by local recording site effects (near surface structure) may also be important. Archuleta (1986) has analyzed data recorded near Mammoth Lakes, California and found that the spectra from surface recording could be predicted by the spectra from borehole recordings by accounting for the acoustic impedance. Of relevance to the present study, spectral ratios between the surface and borehole recordings of his data show that the near surface amplification is uniform across the 2 to 50 Hz band. No such measurements exist in the vicinity of the Edgcumbe earthquake but we can use the Archuleta results as a guide. The acceleration spectrum was finally divided by ω^{-2} to convert to a displacement spectrum.

The composite displacement spectrum for the Edgcumbe earthquake is shown in Figure 3. The spectrum is simple, that is, it shows a constant low frequency amplitude, a corner frequency at 0.22 Hz, and high frequency falloff of ω^{-2} . The source spectrum shown in Figure 3 implies that the Edgcumbe earthquake had a relatively simple rupture, compatible with the time series shown in Figure 2.

Source Parameters of the Main Shock

Source parameters for the Edgcumbe earthquake can be estimated by combining results obtained from the analysis of the main shock data and the rupture dimensions from patterns in the aftershock distribution. The estimate of the seismic moment from the teleseismic analysis is 7.0×10^{18} N-m. During the first days of the aftershock sequence, events were distributed over a zone 20 km long. Surface faulting extended over a zone about 15 km long. This presumably represented the upper limit for the

surface which slipped during the main shock. In several cases where dense seismograph networks were in place at the time of the main shock allowing accurate aftershock locations immediately following the main shock, it has been observed that the aftershock zone grew in size by 10 to 20 % in the first few hours (e.g., Priestley et al, 1988; Smith and Priestley, 1988). This is to be expected since aftershocks should be most frequent at the boundaries of the slip zone where the main shock has increased the stress.

The source spectrum can be interrupted in terms of spectral source parameters. The source radius r (Brune, 1970; 1971) is

$$r = \frac{2.34 \cdot \beta}{2 \pi \cdot f_c} \approx 5.8 \text{ km}$$

giving a fault area of 105 km^2 . For comparison, early aftershocks (Robinson, Personal Communications, 1987) extend over a 12-15 km zone reaching to about 10 km depth. This gives a fault area of approximately 140 km^2 . Using these values as the extremes in the fault area, the average slip $\langle u \rangle$ is

$$2.2 \cdot 10^{-3} \text{ m} < \langle u \rangle = \frac{M_0}{\mu A} < 1.7 \cdot 10^{-3} \text{ m}$$

and the average stress drop $\Delta \sigma$ (Kanamori and Anderson, 1975)

$$5.6 \text{ MPa} < \Delta \sigma = \frac{8}{3 \pi} \cdot \mu \cdot \langle u \rangle \text{ over } W < 4.2 \text{ MPa}$$

where W is the shortest dimension of the fault. Errors enter into these values through errors in M_0 and A . M_0 have been estimated both from low frequency normal mode data and teleseismic body wave data and these values are within 4% of each other.

To determine the radiated seismic energy we have integrated the composite velocity squared spectrum, scaled it for the S-wave radiation pattern according to Wu (1966), and included 5% of the S-wave energy as the P-wave contribution. The seismic energy is

$$E_s = \frac{24}{15 \pi \rho \beta R^2} \int_{-\infty}^{\infty} |\Omega(f)|^2 df$$

where $\Omega(f)$ is the composite velocity spectrum. The

calculated radiated seismic energy of the composite spectral shape from the main shock is 1.1×10^{15} J. The apparent stress for the main shock is

$$\sigma_{app} = \left(\mu E_s \right) / M_0^{2/3} < 5.5 \text{ MPa}$$

The shape of the spectrum beyond the corner frequency is important to the calculation of the total radiated energy; if the amplitude spectrum falls off as ω^{-2} , the velocity spectrum falls off as ω^{-1} and the velocity squared spectrum which is proportional to energy, falls off as ω^{-2} , and thus there is relatively little contribution to the total energy for frequencies beyond the corner frequency. On the other hand, if the amplitude spectrum falls off as ω^{-1} beyond the corner, the velocity spectrum and the velocity squared spectrum are constant and the contribution to the total radiated energy is proportional to the band width of that portion of the spectrum (Smith et al, 1988). The additional high frequency energy causing the spectrum to drop off with a slope less than ω^{-2} past the corner frequency can arise due to fault roughness (Gusev, 1983). Such effects have been observed for earthquakes over a wide magnitude range (Anderson et al, 1986; Brune et al, 1986; Smith et al, 1988). The lack of this roughness energy in the spectrum of the Edgecumbe earthquake indicates a relatively uniform rupture process.

Analysis of the Aftershocks

Data

Following the March 2, 1987 Edgecumbe, New Zealand earthquake (M_L 6.3, m_b 5.9, M_s 6.6) Geophysics Division of D.S.I.R. and the Seismological Laboratory of the University of Nevada installed six portable, three component digital seismographs in the epicentral region. This augmented an array of ten smoke paper recorders installed by Geophysics Division of D.S.I.R. for aftershock locations, and provided digital recordings of aftershocks for spectral studies. This report presents source parameters results from spectral analysis of a subset of the aftershock data recorded. These data provide an important comparison of source parameters and scaling relationships for small earthquakes in New Zealand, with other regions, and an excellent opportunity to consider the suggestion of McGarr (1984) that earthquakes occurring in different states of stress and tectonic setting have different source properties.

Figure 4 shows the locations of the digital and smoked paper seismographs. Four of the digital seismograph stations had 1 Hz free period velocity sensors (BRA, COW, EDG, FAN), and two had

0.2 Hz free period velocity sensors (ASQ, DAM). The recording system was a Sprengnether DR-100 with a 12-bit (66 dB) analogue-to-digital converter. The three components are digitized at 100 samples per second and a 50 Hz, 30 dB per octave rolloff anti-aliasing filter was applied to the data prior to digitizing. Four of the seismographs (ASQ, DAM, EDG, FAN) were sited directly on competent rock; COW was located on soil covered hills of welded tuff forming the northern margin of the Rangitaiki Plain; and BRA was located near the northern edge of the graben on an unknown thickness of valley fill.

Approximately 900 earthquakes triggered at one or more stations during the three week deployment. Of these, 57 representative aftershocks that were recorded on three or more seismographs during the period March 14 to 19 were chosen for analysis in this report. The aftershocks studied were located using arrival times from both the smoke paper and digital seismographs. Robinson (1988) discusses the location of aftershocks in more detail. The location of the main shock, and the locations of the aftershocks analyzed here are shown in Figure 4. The hypocentral parameters of the aftershocks analysed in this study are summarized in Table 2. All records used are less than 20 km epicentral distance and many are less than 10 km. At these small epicentral distances wave propagation effects are minimized.

Analysis and Results

Determination of the Spectra: The displacement amplitude spectrum of the vertical component P-wave and horizontal component S-waves were computed by Fourier transforming a time window that started slightly before the phase arrival and ending 1 to 2 seconds later depending on the earthquake magnitude and/or the amplitude behavior of the time series. The time window was chosen to be long enough to include the entire phase arrival but short enough to minimize the inclusion of energy from secondary phases. This procedure will include some surface wave energy in the case of the S-wave analysis, however we found that increasing the time window length by 1/2 second or more did not affect the choice of the corner frequency and generally did not affect the choice of the low frequency level. In cases where we thought there was some ambiguity about the low frequency level, we tried several different window lengths. The instrument corrected velocity spectra were then converted to displacement spectra by multiplying by ω^{-1} and normalized to a distance of 10 km. We have not rotated the data into transverse and radial components but have computed the spectra for both horizontal components and computed the vector sum of these two values. The spectral analysis procedure is illustrated in Figure 5.

Almost all spectra have a constant low frequency level extending from some low frequency in the 0.2 to 0.5 Hz range to a corner in the 2 to 10 Hz range. Above this the spectral

amplitudes fall off in the range ω^{-1} to ω^{-3} . There is usually a second corner in the frequency range 16 to 23 Hz above which the spectral amplitudes fall off in the range ω^{-4} to ω^{-5} . At very low frequencies the spectra typically start to rise again because the low frequency noise is being amplified by the multiplication by ω^{-1} . Similarly, at very high frequencies, digitization noise may cause the spectral amplitudes to increase. Effect of Attenuation on the Spectra: Recent studies of attenuation of high-frequencies offer conflicting results. Archuleta (1986) found that surface recordings showed an amplification of approximately a factor of four compared to borehole recordings, but that this amplification was uniform across the 0.5 to 50 Hz band and was partially the result of the free surface amplification effect which we have taken into account, and partially the effect of the impedance contrast between the higher velocity bedrock and the low velocity near surface material. Data from downhole recordings at Parkfield (Malin, personal communications) suggest that measurements made near the surface may have some high-frequency energy preferentially attenuated by the low velocity surface material thus distorting the shape of the spectra. The apparent conflicting results may be explained by differences in the near surface geology at these sites. Two recent theoretical studies have shown that scattering causes a reduction of the high frequency content of body waves by transferring much of the high frequency energy to the coda. This mechanism helps explain the common observations that body wave records frequently begin with a lower frequency arrival but contain higher frequencies in the coda. Most body-wave spectra include enough coda that if high frequencies are significantly shifted in time (phases) the amplitude spectra should still resemble that of the original pulse. Scattering mechanisms however, are very difficult to evaluate due to lack of description of the size and location of scatterers in real earth.

The spectra of the earthquakes analysed in this report have not been corrected for whole path attenuation. All recording stations except BRA were located at hard rock sites which are presumably higher Q. We found that varying the whole path Q over a reasonable range of $250 < Q < 500$ had negligible effect on σ_0 and σ_{fc} . Near surface effects are impossible to estimate as no comparisons of surface and borehole recordings are available in this region. However the near surface geology is similar to that of the Mammoth Lakes area (volcanic tuff) where Archuleta (1986) found that surface recordings were amplified compared to borehole recordings, but the overall shape of the spectra were unaffected. The near surface effect may be even less at the graywacke sites (ASQ, DAM). However spectral amplitudes for frequencies greater than 16 to 23 Hz decay as ω^{-4} to ω^{-5} . This rapid decay is the rule and not the exception and indicates that some other mechanism besides whole path Q is affecting the data. This presumably reflects the f_{max} effect of Hanks (1982). The corner frequency for all the events

studied appears to be well below the observed $f_{\max}$. Other site effects such as those arising from reverberations in the low velocity surface layers have not been considered in this report. Some of the spectra, especially those from BRA show peaking which may be indicative of reverberations in the near-surface layers.

Interpretation of the Spectra: The log-log displacement spectra were parameterized in terms of a constant low frequency asymptote $\$00\$, a high frequency falloff proportional to ω^{-n} , and the corner frequency f_c at which the two trends intersect. The far-field spectral parameters were then related to the source parameter using the relation given by Brune (1970, 1971). The seismic moment is determined from the long period level, $\$00 (p,s)\$ according to$$

$$M_0 = \frac{4 \pi \rho (\alpha^3, \beta^3) R^3 (p,s)}{k R \text{ sub } (\text{THETA PHI})}$$

where ρ is the density, α and β are the P and S wave velocities respectively, R is the hypocentral distance, k is the free surface correction and $R \text{ sub } (\text{THETA PHI})$ is the average radiation pattern. An average radiation pattern correction was made rather than a specific radiation correction based on a fault plane solution because the radiation factor is highly sensitive to changes in the location of the nodal planes of the fault plane solution so that small errors in the fault plane solutions might lead to significant errors in the corrected spectra, and because there is some suggestion that the radiation pattern is not uniform for the entire rupture process. Stress drops were estimated from the corner frequency f_c , the spectral equivalent of the duration of the displacement pulse, using the relation

$$\Delta \sigma = \frac{7 M_0}{16 r^3} \quad (1)$$

where r is the source radius of the Brune circular model and is related to the corner frequency, $f_c (p,s)$ by

$$r = \frac{2.34 (\alpha, \beta)}{2 \pi f_c (p,s)} \quad (2)$$

The Brune model was developed for S-waves, we have made the additional assumption that the corner frequency shift for P-waves relative to S-waves is given by the ratio α/β (e.g. Molnar et al, 1973).

We have also used the Snoke (1987) method of determining Brune stress drops. Equations 1 and 2 show that the stress drop is proportional to the cube of the hand fit observable corner frequency, f_c^3 . Small uncertainties in f_c can have a much larger effect upon the stress drop. Using the Brune (1970, 1971) model, Snoke (1987) derives a relationship between J , the integrated squared velocity spectrum given by

$$J = \int_0^\infty \omega^2 |v(\omega)|^2 d\omega \quad (2)$$

and the corner frequency

$$f_c = \left[\frac{J}{2\pi^3} \right]^{1/3}$$

This new corner frequency is then used with equations 1 and 2 to determine the Brune stress drop. The Snoke method has the advantages of an objectively determined observable J that is linearly proportional to stress drop.

The radiated seismic energy, E_s , was determined from the integration of the P and S wave velocity squared spectra in the frequency band 1 to 20 Hz according to Wu (1968),

$$E_s(p,s) = I \rho (\alpha, \beta) R^2 \int_{-\infty}^{\infty} \omega^2 |v(\omega)|^2 d\omega$$

Where I is a constant equal to $(4\pi)/15$ for P-waves and $(24\pi)/15$ for S-waves. In this case ω is the velocity spectrum. It was further assumed that the P-wave energy is 5% of the S-wave energy. The total radiated seismic energy for each component is then given by the sum of the P and S wave energy.

The results of the spectral analysis are summarized in Table 3. The event number in column one of Table 3 correspond to the event number in column seven of Table 2. Seismic moments of the Edgacumbe aftershocks range from 10^{11} to 10^{14} N-m, radiated energies range from 10^{12} to 10^{16} J, and Brune stress drops range from 0.01 to 3.0 MPa. For the Edgacumbe aftershocks, $f_c^{\text{sup}}(p)$ is greater than $f_c^{\text{sup}}(s)$, a frequent (i.e., Molnar et al, 1973) but by no means universal feature of such data sets (Bakun et al, 1976). Infact not all source models predict that $f_c^{\text{sup}}(p)$ to $f_c^{\text{sup}}(s)$ ratio is approx 1.7 or even greater than 1.

Discussion

Scaling of the Edgecombe after shock source spectra is shown in Figure 6 where the logarithm of the low frequency spectral level or seismic movement is plotted as a function of the logarithm of the fault radius or spectral corner frequency. Diagonal lines across the plot are contours of constant stress drops. Source radii for the Edgecombe aftershocks are almost constant over nearly three orders of magnitude in moment. This apparent consistency leads to a strong dependence of stress drop on moment. The largest events (10^{14} N-m) have a stress drop of approx 15 MPa whereas the smallest events of (10^{11} N-m) have a stress drop of 0.01 MPa or less. The dependence of stress drop on movement over this range has been noted in a number of studies (Tucker and Brune, 1973; Choute et al 1978; Rautian et al 1978; Fletcher 1980; Archuleta et al 1982; Fletcher et al 1987). Such a cutoff in corner frequency could result from the effect of f_{max} (Hanks, 1982), a site related cutoff of the high frequency spectrum. However, spectra of the Edgecombe aftershocks typically show a second corner in the frequency range 16 to 23 Hz (Fig. 2) which more closely correspond to the f_{max} seen for spectra of California microearthquakes (Hanks, 1982). This is significantly above the corner frequencies picked from the Edgecombe aftershock spectra, hence the near constant source radii (corner frequency) with increasing moment in the range 10^{11} to 10^{14} N-m is a f_{max} effect.

Stress drop for events of the Edgecombe sequence range from 5 MPa for the main shock (Preistley, 1988), to about 0.01 MPa for the smallest events reported here. Low stress drops have been found for other small $M_0 < 10^{20}$ events in the Basin and Range of Nevada (e.g. Douglas and Ryall, 1972; Smith et al, 1988) and at Anza in California (Fletcher et al., 1987) in the western United States. These low observed stress drops do not necessarily imply low tectonic stress accumulation in the region. The tectonic significance of any measure of stress drop is in doubt because stress drop may be only a small fraction of the driving stress, in which case small-scale inhomogeneities could be a significant fraction in measures of the stress drop.

In recent experiments of stick-slip sliding in foam rubber Brune (personal communications, 1988) has found that the stress drop accompanying a stick-slip event is only 2 to 5% of the total accumulated stress. Tucker and Brune (1973) pointed out a correlation between the estimated stress drop and the high frequency spectral fall off and suggested that this might be a result of the smaller stress drop events corresponding to partial stress drops while the larger events might correspond to total stress drop events. Brune et al (1986) found that the average slope of the high frequency fall off for events with stress drop greater than 10 MPa was 2.9 whereas the average slope for events with stress drop was less than 0.2 MPa was 2.0 supporting the partial stress drop model of Brune (1970). The spectra of the Edgecombe aftershocks do not show the same relationship between the rate of high frequency spectral fall off and stress drop.

The high frequency fall off for most events are approximately 3.

McGarr (1984) has suggested that the ground motion parameters are controlled by the crustal environment of the hypocenter. For example, for comparable hypocentral depths, peak acceleration in a compressional tectonic regime is about 3 greater than in an extensional regime. Figure 6 indicates the relationship of fault radius (corner frequency) to seismic moment reported in several other microearthquake studies. The Edgecombe aftershocks and the data of Douglas and Ryall (1972) from the Basin and Range of Nevada, both from extensional crustal environments, have the largest source radius for a given seismic moment, and hence the smallest stress drop. This is in qualitative agreement with suggestion of McGarr (1984) at stress drop is related to the tectonic environment of the crust.

Summary and Conclusions

We have examined normal mode, teleseismic body wave, and local acceleration data to estimate source parameters of the 1987 Edgecumbe, New Zealand earthquake. The seismic moment from the inversion of low frequency data is 7.0×10^{18} N-m. Inversion of teleseismic body wave data gives a strike of 211° , a dip of 4° , and a slip of 73° . This is in excellent agreement with the fault plane solution from first motion data which gives a strike of 225° , dip of 45° , and a slip of 70° (Anderson and Webb, 1988). Inversion of the normal mode data gives a strike of 239° , a dip of 71° , and a slip of 59° . The strike of the faulting inferred from the normal mode data is closer to the overall trend of the surface faulting (Grapes et al, 1987). The differences in the mechanism inferred from the normal mode/surface faulting data and the teleseismic body wave/first motion data may arise from complications introduced by the second source suggested by Anderson and Webb (1988). Seismic moments have been used to constrain the low frequency far field acceleration spectrum, and near source acceleration data have been used to define the high frequency part of the spectrum. These indicate a relatively simple source spectrum in keeping with the nature of the acceleration records. Using the extremes of source size indicated by the corner frequency and the aftershock zone, the displacement is between 1.52 and 2.03 m, compatible with surface measurements, and the stress drop is between 3.2 and 4.5 MPa. From integration of the velocity squares source spectrum 1.1×10^{15} J of energy were radiated during the faulting process.

Acknowledgements. This research was supported by a grant from the Nevada Nuclear Waste Site Investigation office.

References

- Adams, R.D., and Ware, D.E., Subcrustal earthquakes beneath New Zealand: locations determined with a laterally inhomogeneous velocity model, *N.Z.J. Geol. Geophys.*, 20, 59-83, 1977.
- Allis, R.G., Heat flow, in: M.P. Hochstein and T.M. Hunt (Editors), *Scientific Excursion AS, Volcanic and Geothermal Areas of the North Island, New Zealand*, R. Soc. N. Z., Wellington, 49, 1979.
- Anderson, J.G., P. Bodin, J.N. Brune, J. Prince, S.K. Singh, R. Quaas, and M. Onate, Strong ground motion from the Michoacan, Mexico, earthquake, *Science*, 233, 1043-1049, 1986.
- Anderson, H., and others, The March 2, 1987, Earthquake near Edgecumbe, North Island, New Zealand, *EOS*, 68, 1162-1171, 1987.
- Anderson, H., and T. Webb, The rupture process of the Edgecumbe earthquake, March 2, 1987, New Zealand, preprint, 1988.
- Archuleta, R., Downhole recordings of seismic radiation, in *Earthquake source mechanics*, ed. S. Das, J. Boatwright, and C. Scholz, *Amer. Geophysic. Mono.*, 37, 319-329, 1986.
- Brune, J.N., Tectonic stress and the spectra of seismic shear waves from earthquakes, *J. Geophys. Res.*, 75, 4997-5009, 1970.
- Brune, J.N., Correction, *J. Geophys. Res.*, 76, 5002, 1971.
- Brune, J.N., J. Fletcher, F.L. Vernon, L. Harr, T. Hanks, and J. Berger, Low stress-drop earthquakes in light of new data from the Anza, California telemetered digital array, *Earthquake Source Mechanics, Geophys. Monogr. 37, Maurice Ewing Vol. 6, Am. Geophys. Un.*, 269-274, 1986.
- Buland, R., and F. Gilbert, Matched filtering for seismic moment tensor, *Geophys. Res. Lett.*, 3, 205-206, 1976.
- Chapman, C.H., A new method for computing synthetic seismograms, *Geophys. J.R. Astr. Soc.*, 54, 481-518, 1978.
- Cole, J.W., Structure, petrology and genesis of Cenozoic volcanism, Taupo Volcanic Zone, New Zealand - a review, *N.Z.J. Geol. Geophys.*, 22, 631-657, 1979.
- Doombos, D.J., Source solutions and station residuals from long- period waveform inversion of deep events, *J. Geophys. Res.*, 90, 5466-5478, 1985.
- Doombos, D.J., Seismic source spectra and moment tensors, *Phys. Earth Planet. Inter.*, 30, 214-227, 1982.
- Gilbert, F. and A.M. Dziewonski, An application of normal mode theory to the retrieval of structural parameters and source mechanisms from seismic spectra, *Philos. Trans. R. Soc. London Ser. A*, 278, 187-269, 1975.
- Grapes, R.H., B.A. Sissons, and H.W. Wellman, Widening of the Taupo volcanic zone, New Zealand, and the Edgecumbe earthquake of March 1987, *Geology*, 15, 1123-1125, 1987.
- Gusev, A. A., Descriptive statistical model of earthquake source radiation and its application to an estimation of short-period strong motion, *Geophys. J. Roy. Astron. Soc.*, 74, 787-808, 1983.
- Kanamori, H., and D.L. Anderson, Theoretical basis of some empirical relations in seismology, *Bull. Seis. Soc. Am.*, 65, 1073-1095, 1975.
- Priestley, K.F., and T.G. Masters, Source mechanism of the September 19, 1985 Michoacan earthquake and its implications, *Geophys. Res. Lett.*, 13, 601-604, 1986.
- Priestley, K.F., K.D. Smith, and R.S. Cockerham, The Round Valley, California earthquake sequence, *Geophys. J. R. Astron. Soc.*, in press.
- Reyners, M.E., A microearthquake study of the plate boundary, North Island, New Zealand, *Geophys. J. R. Astron. Soc.*, 63, 1-22, 1980.
- Smith, K.D., and K.F. Priestley, The Foreshock Sequence of the 1986 Chalfant, California Earthquake,

Bull. Geol. Soc. Am., in press.

- Smith, K.D., J.N. Brune and K.F. Priestley, Seismic Energy, Spectrum, and the Savage and Wood Inequality for Complex Earthquakes, *Proceedings of the Hundredth Anniversary of the Berkeley Seismograph Station*, in press.
- Stern, T.A., A back-arc basin formed within continental lithosphere: The Central Volcanic region of New Zealand, *Tectonophysics*, 112, 385-409, 1985.
- Stern, T.A., F.J. Davey, and E.G.C. Smith, Crustal structure studies in New Zealand, in *Reflection Seismology: A global perspective*, ed. M. Barazangi and L. Brown, *Amer. Geophysic. Geodyn. Ser.*, 13, 121-132, 1986.
- Studt, F.E., and G.E.K. Thompson, Geothermal heat flow in the North Island of New Zealand, *N.Z.J. Geol. Geophys.*, 12, 673-683, 1969.
- Thatcher, W., and T.C. Hanks, Source parameters of southern California earthquakes, *J. Geophys. Res.*, 78, 8547-8576, 1973.
- Thompson, G.E.K., Temperature gradients within and adjacent to the North Island volcanic belt, *N.Z.J. Geol. Geophys.*, 20, 85-97, 1977.
- Walcott, R.I., Tectonic and late Cenozoic evolution of New Zealand, *Geophys. J. R. Astron. Soc.*, 52, 137-164, 1978.
- Ward, S.N., A technique for the recovery of the seismic moment tensor applied to the Oaxaca, Mexico, earthquake of November 1978, *Bull. Seis. Soc. Am.*, 70, 717-734, 1980.
- Ward, S.N., Body wave inversion: Moment tensors and depths of oceanic intraplate bending earthquakes, *J. Geophys. Res.*, 88, 9315-9330, 1983.
- Wu, F.T., Lower limit of the total energy of earthquakes and partitioning of energy among seismic waves, Ph.D. Thesis, California Institute of Technology, Pasadena, 1966.

- Archuleta, R.J., E. Cranswick, C. Mueller, and P. Spudich, Source parameters of the 1980 Mammoth Lakes, California, earthquake sequence, *J. Geophys. Res.*, 87, 4595-4607, 1982.
- Bakun, W.H., C.G. Bufe, and R.M. Stewart (1976). Body-wave spectra of central California earthquakes, *Bull. Seis. Soc. Am.*, 66, 363-384.
- Brune, J.N., J. Fletcher, F. Vernon, L. Haar, T. Hanks, and J. Berger (1986). Low stress-drop earthquakes in the light of new data from the Anza, California telemetered digital array, *AGU Mono.* 37, 237-245.
- Chouet, B., K. Aki, and M. Tsujiura (1978). Regional variation of the scaling law of earthquake source spectrum, *Bull. Seis. Soc. Am.*, 68, 49-80.
- Douglas, B. M. and A. Ryall, (1972). Spectral Characteristics and stress drop for microearthquakes near Fairview Peak, Nevada, *J. Geophys. Res.* 77, 351-359.
- Fletcher, J.B. (1980). Spectra from high-dynamic range digital recordings of Orville, California aftershocks and their source parameters, *Bull. Seis. Soc. Am.*, 70, 735-756.
- Fletcher, J., L. Harr, T. Hanks, L. Baker, F. Vernon, J. Berger and J.N. Brune (1987). The digital array at Anza, California: processing and initial interpretation of source parameters, *J. Geophys. Res.* 92, 369-382.
- Hanks, T.C. (1982). f_{max} , *Bull. Seis. Soc. Am.*, 72, 1867-1879.
- Haar, L.C., J.B. Fletcher, and C.S. Mueller (1984). The 1982 Enola, Arkansas, swarm and scaling of ground motion in the eastern United States, *Bull. Seis. Soc. Am.*, 74, 2463-2482.
- McGarr, A. (1984). Scaling of ground motion parameters, state of stress, and focal depth, *J. Geophys. Res.*, 6969-6979.
- McGarr, A., R.W.E. Green, and S.M. Spottiswoode (1981). Strong ground motion of mine tremors: Some implications for near-source ground motion parameters, *Bull. Seis. Soc. Am.*, 71, 295-320.
- Molnar, P., B.E. Tucker, and J.N. Brune (1973). Corner frequencies of P and S waves and models of earthquakes sources, *Bull. Seis. Soc. Am.*, 63, 2091-2104.
- Mueller, C.S., and E. Cranswick (1985). Source parameters from locally recorded aftershocks of the 9 January 1982 Miramichi, New Brunswick, earthquake, *Bull. Seis. Soc. Am.*, 75, 337-360.
- Priestley 1988
- Rautian, T.G., V.I. Khalturin, V.G. Martynov, and P. Molnar (1978). Preliminary analysis of the spectral content of P and S waves from local earthquakes in the Garm, Tadjikistan region, *Bull. Seis. Soc. Am.*, 68, 949-971.
- Robinson 1988
- Smith, K.D., W.R. Walter, and K.F. Priestley (1988). The 1987 Mina, Nevada, earthquake sequence, in preparation.
- Snoke, J.A. (1987). Stable determination of (Brune) stress drops, *Bull. Seism. Soc. Am.*, 77, 530-538.
- Wu, F.T. (1966). Lower limit of the total energy of earthquakes and partitioning of energy among seismic waves, *Ph.D. Thesis, California Institute of Technology, Pasadena, 1966.*

Figure Captions

Fig. 1. Comparison of the low frequency (2 - 6 mHz) observed waveforms (solid lines) with synthetic waveforms (dashed lines) computed for the normal mode model of Table 1.

Fig. 2. Acceleration, velocity and displacement records, and Fourier acceleration spectra from the horizontal strong - motion records collected near the base of the Matahina dam. The acceleration record is of relatively short duration, and the displacement pulse is simple in character indicating a simple source - time function.

Fig. 3. Composite displacement source spectrum and source parameters for the Edgecumbe main shock.

Figure 4. Map showing the location of the digital and smoked paper seismographs, and the locations of the aftershocks analyzed in this report. The hatched area denotes the exposed rock on the hills surrounding the R plane. Stations ASQ and DAM are sited on graywacke outcrops, stations COW, EDG, and FAN are sited on outcrops of welded tuff, and station BRA is sited on and shallow thickness of valley alluvium.

Figure 5. Example of the spectral analysis procedure. The noise spectrum and the signal spectrum with the low frequency level, high frequency falloff, and the corner frequency fits are shown in the lower part of the figure; the time windows of the noise and signal are shown in the upper part of the figure. Almost all spectra show a second corner in the data in the frequency range 16 to 23 Hz.

Figure 6. Seismic moment versus source radius for the 57 Edgecombe aftershocks (---) compared with seismic moment versus source radius from Douglas and Ryall (1972) (---) , Munguia et al (1978) (---) , Fletcher (1980) (---) , Archuleta et al (1982) (---) , Haar et al (1984) (---) , and Mueller and Cranswick (1985) (---) . Lines of constant stress drop are indicated.

TABLE 1

	strike	dip	slip	M_0 (N-m)	τ (sec)	vr	records used
normal mode	239°	71°	59°	6.1×10^{18}	7.5	74%	20
body wave	211°	64°	73°	7.9×10^{18}	1.0	76%	17

Table 2. Event Hypocentral Parameters

Date	Time	Latitude	Longitude	Depth (km)	M _L
March 14	0520 33.87	37.982	176.777	0.3	1
	0648 16.83	37.911	176.847	8.5	2
	0838 14.42	37.917	176.840	8.7	3
	0843 32.91	37.921	176.846	7.8	4
	1108 25.69	38.132	176.666	8.3	5
	1149 04.35	38.114	176.676	7.7	6
	1227 19.25	37.942	176.794	7.6	7
	2112 45.74	38.034	176.764	3.9	8
March 15	0001 42.87	38.008	176.773	0.5	9
	0029 05.59	37.912	176.840	8.9	10
	0031 50.85	38.042	176.757	6.1	11
	0047 32.64	38.134	176.666	5.2	12
	0109 46.07	37.918	176.861	5.0	13
	0931 09.02	37.975	176.778	3.0	14
	1117 45.19	38.040	176.751	5.4	15
	1340 30.36	38.037	176.750	8.3	16
	1350 52.86	38.114	176.649	7.7	17
	1442 36.82	38.012	176.804	5.3	18
	1519 09.68	38.034	176.733	4.6	19
	155 06.80	38.036	176.747	0.3	20
	161 51.73	37.982	176.739	5.9	21
	0216 51.77	38.048	176.734	5.0	22
	0236 24.34	38.005	176.749	4.8	23
	0557 51.13	38.095	176.689	7.0	24
	0601 01.96	38.087	176.694	4.4	25
March 16	0613 20.35	38.093	176.683	7.6	26
	0843 45.53	37.959	176.845	3.6	27
	0953 13.29	37.978	176.808	7.1	28
	1238 37.70	38.180	176.640	6.3	29
	1656 12.32	38.024	176.770	5.3	30
	1813 23.70	37.906	176.806	8.5	31
	1813 59.95	38.161	176.597	7.6	32
	1816 58.85	37.910	176.807	7.9	33
	1824 07.95	38.171	176.597	9.2	34
	1852 14.61	37.910	176.810	6.1	35
	1918 12.42	38.117	176.652	3.5	36
	2057 03.65	37.985	176.821	9.2	37
	2110 25.98	38.047	176.764	5.9	38
	1115 23.99	37.927	176.861	5.4	39
March 17	0301 12.61	37.936	176.850	7.7	40
March 18	0957 24.78	38.019	176.772	5.0	41
	1258 32.21	38.108	176.655	9.1	42
	1432 28.54	38.037	176.713	5.1	43
	1949 53.52	38.113	176.688	8.9	44
March 19	2132 31.41	37.907	176.817	7.1	45
	2222 35.56	37.905	176.814	7.2	46
	0452 16.80	37.905	176.817	6.6	47
	0546 39.67	37.984	176.817	9.3	48
	0608 32.64	38.046	176.742	8.1	49
	0634 27.32	38.117	176.680	8.4	50
	0819 34.59	37.913	176.797	5.1	51
	0839 31.50	37.918	176.797	5.3	52
	0907 06.50	38.046	176.741	7.8	53
	1130 28.99	38.042	176.755	6.0	54
	1456 36.92	38.001	176.765	5.9	55
	1656 35.11	38.040	176.767	8.5	56
	2206 49.22	38.125	176.669	7.6	57

† Event number referred to in Table 3

Table 3. Spectral and Source Parameters

No.	$\langle M_0 \rangle$	E_s	Spectral Fit		$\langle \Delta \sigma \rangle$	$\langle r \rangle$	$\langle f_c(p) \rangle$	$\langle f_c(s) \rangle$	$\langle \Delta \sigma \rangle$
			$\langle f_c(p) \rangle$	$\langle f_c(s) \rangle$					
1	18.68	11.93	8.23	5.91	1.6	261	11.81	6.50	02.0
2	19.04	12.52	10.24	5.22	3.5	247	12.56	5.19	04.9
3	20.38	14.68	7.56	4.20	18.1	323	7.78	3.77	36.4
4	18.89	12.27	9.79	5.58	2.7	243	12.07	5.85	03.9
5	19.25	12.77	10.50	4.59	12.4	282	10.42	4.91	07.1
6	19.36	12.89	8.78	4.74	5.7	307	8.70	5.10	06.8
7	20.10	14.31	8.79	4.37	16.9	289	8.20	4.54	24.0
8	19.10	12.81	10.28	4.37	9.3	251	12.67	4.54	20.3
9	18.73	12.09	11.41	5.54	3.0	280	16.58	6.80	06.6
10	18.84	11.91	9.27	4.58	2.7	289	10.72	4.63	03.4
11	18.99	12.04	7.61	3.55	4.4	408	8.78	4.30	03.8
12	18.95	12.23	8.12	5.78	4.7	253	7.84	5.88	05.0
13	18.80	11.96	8.71	5.68	3.5	265	9.02	5.75	02.8
14	18.58	11.72	9.47	4.71	1.7	285	12.85	5.88	02.5
15	18.88	12.23	8.53	5.56	4.0	249	10.25	6.05	04.9
16	18.87	12.14	9.35	5.22	4.4	270	11.61	5.60	08.0
17	19.03	12.54	12.43	5.17	2.7	237	11.98	5.79	02.8
18	19.87	13.63	6.84	3.79	8.0	383	7.35	3.84	08.5
19	19.24	12.85	9.87	5.27	26.6	260	10.80	5.15	28.7
20	18.97	12.44	8.96	5.84	11.6	254	11.38	5.66	18.7
21	18.63	11.88	9.87	6.72	3.8	240	11.60	6.93	04.3
22	19.01	12.23	8.99	6.20	7.4	267	7.99	6.01	05.3
23	19.25	12.80	8.88	4.91	7.0	282	8.61	5.56	06.8
24	19.21	12.86	7.75	5.98	6.9	277	8.53	7.14	15.5
25	19.37	12.77	6.62	4.72	5.5	321	5.62	4.76	05.8
26	19.72	13.51	7.13	4.36	9.8	345	7.45	4.91	21.3
27	19.41	13.10	6.20	5.70	7.5	283	7.49	5.78	08.0
28	19.56	13.65	8.70	5.11	8.1	272	9.59	7.15	27.9
29	19.18	12.59	7.52	5.56	3.8	284	8.32	5.47	03.6
30	19.30	12.76	7.44	4.93	7.7	304	7.43	5.23	05.8
31	18.96	12.31	8.30	5.11	3.4	281	9.38	6.21	06.6
32	19.33	13.02	8.02	5.72	14.1	276	8.58	6.60	27.1
33	19.68	13.22	6.43	3.77	4.3	369	6.17	3.91	03.4
34	18.94	12.47	9.54	7.36	5.4	220	9.71	8.50	10.4
35	19.27	12.72	4.06	4.88	3.9	377	6.38	5.48	05.4
36	19.12	12.66	9.78	4.96	2.8	250	10.88	5.44	03.7
37	19.37	13.06	7.14	4.80	6.2	298	8.73	5.27	09.6
38	19.17	13.09	6.95	6.65	4.8	259	9.99	9.39	14.5
39	20.16	14.26	6.31	3.08	36.6	397	7.34	3.65	58.3
40	19.98	13.99	6.71	4.74	41.7	326	7.65	4.46	30.7
41	19.41	13.11	6.78	4.65	8.4	323	10.32	5.70	17.0
42	18.59	11.68	12.19	4.81	2.0	253	13.87	5.62	03.7
43	20.88	15.84	9.33		313.6	241	7.66		173.6
44	18.47	11.35	7.28	5.79	1.7	293	8.50	7.16	05.6
45	19.10	12.61	7.55	4.59	8.6	394	11.82	6.64	34.5
46	19.74	13.22	7.57	3.38	14.1	448	6.68	3.68	12.8
47	19.04	12.41	10.55	4.77	4.8	279	11.14	5.55	09.8
48	19.26	12.60	12.00	2.59	.66	315	10.91	2.58	.52
49	19.50	13.22	4.12	5.78	1.38	346	4.03	6.78	1.94
50	18.72	11.69	9.97	4.63	.17	303	10.59	5.11	.24
51	18.57	11.75	10.59	4.69	.22	298	11.72	6.90	.88
52	18.85	12.31	9.66	5.84	.24	284	12.35	6.55	.25
53	19.40	12.91	6.41	5.37	.95	320	7.39	5.59	.83
54	18.90	11.95	6.14	4.66	.32	327	7.12	5.05	.48
55	18.84	11.47	5.83	4.23	.23	377	4.84	4.42	.15
56	19.08	12.86	11.72	6.57	1.13	213	13.64	7.24	1.94
57	18.60	11.70	12.40	6.74	.54	257	12.29	7.12	.49
58	18.87	11.83	8.11	4.27	.22	308	8.48	4.27	.21

No. is the event number from Table 2, $\langle M_0 \rangle$ is $\log_{10}$ of the average seismic moment in N-m, E_s is $\log_{10}$ of the radiated seismic energy in joules, $\langle f_c(p) \rangle$ is the average p-wave corner frequency in Hz, $\langle f_c(s) \rangle$ is the average s-wave corner frequency in Hz, $\langle r \rangle$ is the average source radius, and $\langle \Delta \sigma \rangle$ is the average stress drop.

Tectonic and Neotectonic Framework of the Yucca Mountain Region

**Final Report: Yucca Mountain Project: Task 5
January 1, 1987 - June 30, 1988**

Personnel: Dr. R. A. Schweickert (Principal Investigator), M. A. Ellis (Postdoctoral Fellow); P. Buchanan, J. Caskey, D. Donovan, R. Elwood, J. Hoffard, T. Reynolds, T. Sawyer (Graduate Research Assistants).

Organization of this report

The text of this report consists of three parts. Part 1 consists of a brief summary of major accomplishments of Task 5 personnel during the report period. Part 2 is a brief report of technical studies or research projects conducted by members of Task 5. Part 3 is chronologically ordered summary of monitoring, research, and review activities, details of which may be obtained from the Quarterly Reports submitted to NWSO by R. A. Schweickert. Several appendices of reviews, manuscripts, and abstracts follow the body of the text.

Part 1

Highlights of major accomplishments of Task 5

1. Research

a. Recognition from Scott and Bonk's (1984) map and sections of at least two phases of late Cenozoic faulting at Yucca Mountain, extensional faults post-Paintbrush and pre-Timber Mountain tuff, and probable strike-slip faults post-Timber Mountain tuff (and currently active). In addition to this, recognition that Scott and Bonk's (1984) sections are not viable.

b. Recognition of west-vergent, rather than east-vergent, thrust faults from existing mapping at NTS east of Yucca Mountain means that an entirely new structural synthesis of the NTS region is needed.

c. Circumstantial evidence from existing mapping that Paintbrush Canyon fault may be an active fault extending northwest across Beatty Wash and into Timber Mountain caldera.

d. Recognition of at least three discrete paleoseismic events and surface ruptures along the northern Death Valley-Furnace Creek fault zone, suggesting that this is one of the most active faults in the Great Basin.

e. Recognition of evidence of late Quaternary or Holocene activity along the Maynard Lake strand of the Pahrangat shear zone, and evidence that it continues farther southwest toward NTS. In addition, recognition that a major component of shortening, expressed by tilting and folding of Tertiary ashflow tuffs, has occurred across the fault. This raises the possibility of similar types of deformation occurring along northeast-striking faults at NTS near Yucca Mountain.

f. Recognition of evidence for active faulting along the Stateline-Stewart Valley fault zone, which trends toward Amargosa Valley and Yucca Mountain. Preliminary results suggest that the character of the active faulting has changed during the

past few (?) million years from predominantly dip-slip normal to strike-slip.

g. Recognition through review of recent (1987/8) work on the relation between fault displacements and fault geometry that the geometry of dip-slip faults may not be predicted through the application of simple geometrical rules. For example, hanging wall rollover does not necessarily support a listric fault geometry.

2. Reviewing and monitoring of DOE work

a. Comprehensive review of Consultation draft, Site Characterization Plan.

b. Review of Szymanski report.

c. Attended DOE meetings in Las Vegas and Reno and pointed out flaws in DOE conceptual models pertaining to Yucca Mountain.

d. Attended all pertinent GSA fieldtrips and scientific sessions on current and ongoing research on Tertiary and Mesozoic tectonics in the southern Great Basin region.

e. Acquired and reviewed pertinent literature which has been published in past 18 months on Yucca Mountain and vicinity.

Part 2

Research Projects

This section presents an overview of the research projects conducted by

Task 5 personnel. For reasons of both time and convenience, this section does not represent an exhaustive or complete review of Task 5 research. For further details the reader is referred to the appendices attached to this report and to the various publications listed in the references.

The research projects underway during the period covered by this report, and the personnel responsible for their investigation, include the following:

1: *Tectonics and Neotectonics of the Pahranaagat shear zone; Lincoln County, Nevada; R. Elwood, and T. Reynolds.*

The rationale for this study is that the Pahranaagat shear zone lies on trend with the Spotted Range-Mine Mountain structural zone, comprised of seismically active, ENE-striking, sinistral strike-slip faults. This zone lies immediately south of Yucca Mountain. Studies of the Pahranaagat shear zone have been undertaken to determine whether the two zones are related parts of a single tectonic and neotectonic feature, and thus may have had similar deformational histories, and whether they reflect neotectonic activity along a deeply buried, ancient crustal flaw.

2: *Structure and geometry of the Mine Mountain and CP Hills thrust complex, NTS, Nye County, Nevada; J. Caskey.*

The rationale for this study is to develop an understanding of kinematics and geometry of Mesozoic thrusts east of Yucca Mountain to enable more confident modelling of deep structural geometry of pre-Tertiary units beneath Yucca Mountain. A by-product of this study will be a

better understanding of pre, syn, and post-volcanic normal faulting in the region east of Yucca Mountain.

3: *Analysis of fault and fracture patterns in the vicinity of the Timber Mountain caldera*; P. Buchanan.

The purpose of this study is to determine the geometry, sense of slip, and timing of faults (and especially the Paintbrush Canyon fault) that extend north from Yucca Mountain into the Timber Mountain caldera. In the vicinity of Beatty Wash, these faults involve Pliocene or younger gravels which may offer an opportunity for estimating the age of the movements along some of the faults.

4: *Active tectonics of the Pahrump and Stewart Valleys, Nevada and California*; J. Hoffard and M. Ellis.

Pahrump and Stewart Valleys are host to the strike-slip Stateline fault, considered to represent the youngest tectonic activity in the area, as well as a series of range-front faults whose character has yet to be determined. In addition, modern deformation has produced a series of uplifted ridges and hills in the central part of Pahrump Valley. The determination of the active tectonics of this area is essential in understanding the character of the modern seismic activity in the Yucca Mountain region.

5: *Active tectonics of the eastern half of the Death Valley 2-degree sheet, with emphasis on the southern half of Amargosa Valley*; D. Donovan.

This work involves a detailed analysis of low-sun-angle photography and other imagery to develop a compilation of all Quaternary and active faults.

6: *Active tectonics of northern Fish Lake valley*; T. Sawyer.

The rationale of this study is to develop information about slip rates, rupture lengths, and recurrence intervals for large earthquakes that will apply to the northern part of this important fault. Knowledge of the paleoseismology of this fault zone will contribute to the data base of paleoseismology of the Yucca Mountain region, enabling a more realistic characterization of the present deformation, and consequently a more reliable characterization of future seismicity than is presently realized.

7: *Structure and geometry of Mesozoic thrust faults and folds in the area around Yucca Mountain*; R. A. Schweickert. The rationale of this study is that a detailed understanding of Mesozoic contractional structures of regions around Yucca Mountain is necessary for modelling the geometry of carbonate aquifers and clastic aquitards beneath Yucca Mountain.

8: *Regional seismic deformation patterns, with special emphasis on regional seismic strain*; M. Ellis. Determination of such regional deformation patterns may reveal the following characteristics of the tectonics and seismic potential of the region: a) temporal and spatial seismic cycles which may not be revealed by traditional seismic hazard analyses; b) the validity and significance of the seismic gap at 3.5 km reported by the USGS; and c) evaluation of the regional seismic strain with the purpose of comparing the modern strain field to that which characterizes the Neogene deformation in the southern Great Basin.

9: *Evaluation of the geometry of normal faults at depth*; M. Ellis. Recent work shows that the geometry of off-fault deformation may not be used to reconstruct the geometry of faults at depth. This project involves the characterization of off-fault deformation through strain inversion of earthquake swarms, and review of the current modeling of off-fault deformation.

10: *Evaluation of the Bare Mountain-Bullfrog Hills detachment system and various methods of paleostress determination*; P. Buchanan. The rationale for this study was to develop an understanding of the geometry, kinematics, and timing of the detachment system to enable an evaluation of its possible role in the development of shallow and deep crustal structure at Yucca Mountain. This project has been terminated in light of the extensive recent work by the USGS on this problem. In addition, it has become apparent that methods of paleostress analysis of Angelier cannot be applied with confidence to the complexly faulted upper plate rocks in the vicinity of Bare Mountain and the Bullfrog Hills.

1) *Tectonics and Neotectonics of the Pahranaagat shear zone: Lincoln County, Nevada*

Report from R. Elwood and R. A. Schweickert: A full bibliographic search was made to locate and read pertinent published material on shear zones, particularly northeast trending shears in Nevada. Information collected includes: theoretical con-

siderations of shear zone development, appropriate research methods, necessary equipment and research materials, and research studies similar to the that proposed here, such as the northeast trending Rock Valley fault zone.

Reconnaissance mapping, rock sampling, and studies of photography were conducted to define, limit and analyze the research project. This included measuring a section in Tertiary ashflow tuffs located in the nose of a northeast-plunging, open syncline. Attitudes were taken in the vicinity of folded volcanic units, principally in the Hiko and Kane Wash tuffs, where folding is possibly related to the left-lateral (?) displacement along the Pahranaagat shear zone. Representative rock samples were collected.

A magnetometer survey was conducted across a segment of the shear zone, along a clear northeast-trending regional lineament. Prominently folded ashflow tuffs were the focus of detailed mapping. Field evidence indicates a major component of shortening is represented by tight folds in tuffs along the Maynard Lake strand. Various types of imagery were further examined in anticipation of future field work. Evidence for extension of the shear zone southwesterly through the Desert Range has been observed. Geomorphic evidence of late Quaternary or Holocene activity was discovered from field studies and examination of imagery.

Report from T. Reynolds: Preliminary reconnaissance was conducted in Spring, 1987. September to December, 1987--Conducted air photo studies and reviewed maps. Looked for evidence of major north-

east-trending faults that might be continuations of Pahrnagat shear zone into the Delamar Mountains. Also collected and reviewed literature on tectonics of the southern Great Basin and surrounding areas.

January, 1988--Conducted field studies in southeastern Delamar Mountains, Lincoln County, Nevada. Found no conclusive evidence for through-going northeast-trending faults.

May 22-June 3, 1988--Conducted field studies in central Delamar Mountains. Identified possible evidence for through-going northeast-trending faults in Tertiary ashflow tuffs east of Delamar mining district.

Conducted field studies in southwestern Delamar Mountains, southern Hiko Range, and South Pahroc Range. Identified possible evidence for oblique slip on Maynard Lake fault. Identified possible evidence substantiating north-trending faults as earthquake faults in the Hiko Range segment of the Pahrnagat shear zone. Also identified key areas for regional study of Pahrnagat shear zone.

2) Structure and geometry of the Mine Mountain and CP Hills thrust complex. NTS, Nye County, Nevada

Report from J. Caskey and R. A. Schweickert: Preliminary field observations with Peter Guth in the CP Hills confirmed evidence for west-vergent overturned folds in hanging-wall and footwall of the CP thrust, strongly suggesting it is a west-vergent structure. As of 6/30/88 access to NTS for this mapping project has yet to be obtained. Permission to

enter NTS and begin detailed field work is anticipated in August, 1988.

Further details of the project plan are presented in appendix 8.

3) Analysis of fault and fracture patterns in the vicinity of the Timber Mountain caldera

Report from R. A. Schweickert and P. Buchanan: Preliminary evaluation of published geologic maps has revealed circumstantial evidence that the Paintbrush Canyon fault may extend northwest across Beatty Wash as one of the northwest-trending faults in Timber Mountain caldera. Locally the fault is shown displacing Tertiary gravels. As of 6/30/88 access to the Nellis Bombing Range has yet to be obtained.

Further details of the project plan are presented in appendix 9.

4) Active tectonics of the Pahrump and Stewart Valleys, Nevada and California

Report from J. Hoffard and M. Ellis: Reconnaissance field work in Pahrump and Stewart Valleys during June, 1988, was conducted to confirm the existence of, and characterize, the various lineaments and scarps recognized on 1:80,000 aerial photograph images.

The lineaments recognized along the alluvial fans on the west side of Stewart Valley are thought to be paleoshorelines; these lineaments are only moderately well developed on the imagery, and were not found in the field. However, from the east side of Stewart Valley these lineaments appear to coincide with a color, and possibly a vegetation,

change, and this change can be seen to follow modern contours. The color change is related to the existence of sandy (beach ?) deposits on the lower side of the lineament. Walking in the field confirmed the sandy deposits.

Two prominent tree and vegetation lineaments form the northeastern and southwestern boundaries of the modern playa, although the former becomes less well developed toward the southeast, and the latter becomes less well developed toward the northwest. No scarps are visible along either of these lineaments, with the exception of the southeastern extension of the northeastern lineament.

A series of apparent left-stepping lineaments and low (~ 1 m high) scarps, up to the east, continue the trend of the tree lineament forming the northeastern boundary of the Stewart Valley playa. These scarps tend to follow the State line, and are in places marked by the abrupt ending of Mesquite tree growth along scarp-transverse drainages. These scarps and lineaments are not evident in the field or imagery more than a few kilometers to the southeast, where they are replaced by a series of low hills and, in one place, a distinct vegetation lineament devoid of a scarp. It is possible that the scarps represent paleoshorelines from either the Pahrump Valley or Stewart Valley playa, or perhaps reflect an older fluvial system. The hills are in places ridge-like, and comprise lake beds (?) with calcareous cement to the north, and silica cemented lake beds (?) to the south. These hills may represent paleospring mounds.

The range-front scarps along the eastern side of the Nopah range were found to be facing toward the Nopah Range. Reconnaissance field work suggests that the recent movements on this system may be strike-slip and right-lateral; further detailed work is planned for the late fall and winter.

Work is to be continued in July, and again in the late fall (when the weather is more suitable). Plans are to continue the reconnaissance work in July, and in addition to sample Mesquite trees with the purpose of analyzing tree ring growth.

5) Active tectonics of the eastern half of the Death Valley 2-degree sheet, with emphasis on the southern half of Amargosa Valley

Report from D. Donovan: To date, research has been limited to reconnaissance examination of available aerial photography, the compilation of fault maps, and field confirmation of imagery analysis.

6) Active tectonics of northern Fish Lake Valley

Report from T. Sawyer: This research project has identified a sequence of at least three discrete paleoseismic events that resulted in surface ruptures along the northern Death Valley-Furnace Creek fault zone. Radiocarbon dates, tephrochronology, and a calibrated soil development index support a late Holocene chronology of the paleoseismic sequence, suggesting that the Death Valley-Furnace Creek fault zone is one of the most active faults in the Basin and Range Province. (See also appendix 10.)

7) Structure and geometry of Mesozoic thrusts in the area around Yucca Mountain

Report from R. A. Schweickert: Our work on drawing cross-sections on the Last Chance thrust system west of the Death Valley-Furnace Creek fault zone reveals that it is a major east-vergent thrust system, with 30 to 75 km of translation. Its footwall may extend as far west as Mt. Goddard pendant in the eastern Sierra. Work by Kevin Corbett of UCLA indicates that it may consist of two allochthons. Its presumed correlative at Bare Mountain, mapped by Mike Carr, USGS, is southeast vergent, and has a modest amount of displacement. Correlation with the Last Chance thrust is uncertain. In contrast to these structures, mapped thrusts on NTS east of Yucca Mountain show convincing evidence of west-vergent geometry, and seem unlikely to correlate with Last Chance system. The importance of Tertiary low-angle normal faults is uncertain, and will be studied by John Caskey. It seems plausible that these west-vergent structures could correlate with the Panama thrust, mapped by Mike Carr, in the southern part of Bare Mountain. If so, the east-vergent thrusts, if they are present, probably lie beneath Buckboard Mesa and Timber Mountain caldera.

8) Regional seismic deformation patterns, with special emphasis on regional seismic strain

Report from M. Ellis: Digital data collected by the Southern Great Basin (SGB) USGS network was requested, and is now arriving in batches of 100 tapes. To date, only local events

(within the SGB network) have arrived.

9) Off-fault deformation, and evaluation of the geometry of normal faults at depth

Report from M. Ellis: Work to date has been restricted to reviewing recent work by the Liverpool Fault Group (including reviewing a paper submitted by this group to the Journal of Structural Geology), and in collecting software from Geoff King (USGS) with the purpose of modeling off-fault deformation. In addition, work is planned for the summer of 1988 involving strain inversion of earthquake swarms within the southern Great Basin.

Part 3

Monitoring, Research and Review Activities

January - March, 1987

February 22-27, R. Schweickert and several staff members attended a field trip led by Charlotte Abrams and other NRC staff to Yucca Mountain to review evidence for Quaternary and Holocene activity on faults in the area. Faults visited included Bow Ridge (trench 14 and 14A), Rock Valley, Busted Butte, Windy Wash, Solitario Canyon, Stagecoach Road, Bare Mountain, and the Beatty scarp. In addition, several mines were examined near Beatty and Rhyolite, and in Goldfield and Tonopah to review the expression of hydrothermal mineralization.

T. Sawyer conducted field work in northern Fish Lake valley, Nevada. A total of more than 90 days of field work has been conducted by Sawyer through June 30, 1988.

Meetings on the Quality Assurance program were held.

April - June, 1987

Work continued on quality assurance and technical procedures. The draft of the state of Nevada's quality assurance manual was reviewed and returned to NWPO by R. Schweickert. Procedures for sampling and geologic mapping were written and reviewed. In addition, a description of the general responsibilities of Task 5 was written.

T. Sawyer presented a thesis seminar on his proposed work along the northern section of the Death Valley - Furnace Creek fault zone, in Fish Lake valley, Nevada.

Angela Jayko and Mike Carr (both of the USGS) were contacted about their past and planned work in the southern Nevada region. Jayko visited UNR and discussed her project with R. Schweickert.

R. Schweickert gave a guest lecture at Humboldt State University in Arcata, California, on "Tertiary extensional faulting in the southern Klamath Mountains, a new hypothesis."

R. Schweickert, J. Trexler, and P. Cashman examined Mississippian clastic rocks in eastern Nevada for comparison with equivalent rocks at NTS.

B. Cernoch completed a colored version of Scott and Bonk's (1984) cross sections of Yucca Mountain, coded to conform with the colored map completed during the previous quarter.

In May, several members attended the G.S.A. Annual Meeting of the Cordilleran Section in Hilo, Hawaii, and participated in sessions on tectonics, neotectonics and quaternary geology.

T. Reynolds began his field work in the Delamar Mountains; R. Elwood began her field work in the Desert Mountains, Nevada. Both areas expose part of the Pahranaagat shear zone, which may be related to the Mine Mountain - Spotted Range zone of northeast-trending left-lateral faults that passes through the Nevada Test Site.

Paul Buchanan began preliminary literature review of the Bare Mountain - Bullfrog Hills region in anticipation of beginning fieldwork on the detachment system in the summer or fall of 1987; however, the decision was later made to suspend fieldwork on this project.

A search was conducted for the postdoctoral fellow position, funded jointly by Task 5 and the General Task. The position was awarded to Dr. Michael A. Ellis, recently a member of the Graduate Faculty of the University of Minnesota, and member of the Department of Geology, University of Minnesota, Duluth.

July - September, 1987

T. Sawyer attended the Friends of the Pleistocene, Pacific Cell, field trip. The trip included an introduc-

tion to the Pleistocene geology of northwestern Lake Lahontan, Nevada.

M. A. Ellis reviewed literature pertinent to the geology of the Yucca Mountain region, with particular emphasis on the state of stress, including the various methods of determining present-day stress fields. In this connection, a seminar was organized on the then-recent findings by Van Mount, Zoback, and others, on the anomalous state of stress along the San Andreas fault zone, and on the consequences for stress studies at Yucca Mountain.

On August 31, R. Schweickert and D. B. Slemmons met at UNR with Bob Castle, Chief of the Branch of Western Regional Geology, USGS, Menlo Park, to discuss plans for the UNR Southern Great Basin Workshop.

M. A. Ellis accompanied R. Elwood to her thesis area, the Pahranaagat shear zone. It was decided then that detailed mapping of the tilted blocks at the southeastern end of the shear zone, at 6 inches to the mile, would be an appropriate start to the project.

M. Ellis completed the final stages of the paper, "Displacement variation along thrust faults: Implications for the development of large faults" by MAE and W.J. Dunlap. The paper was accepted for publication to the Journal of Structural Geology and eventually came out in Vol. 10, no. 2, 1988; see appendix 1.

M. Ellis accompanied various personnel from the Yucca Mountain project at UNR on a field trip, taken with a group from the University of Arizona (P. Pearthree, and T. Wallace), to examine some of Pearthree's

work along Walker Lake, and some of the work of dePolo, Ramelli, and Bell along the 1932 Cedar Mountain earthquake fault in Monte Cristo Valley.

The main effort from M. Ellis during this period went into the organization of the workshop, Late Cenozoic Evolution of the Southern Great Basin, held at UNR in mid-November. The workshop convenors are: D. B. Slemmons, R. A. Schweickert, and J. Bell. A copy of the schedule is included as appendix 2.

R. A. Schweickert and M. A. Ellis attended the DOE meeting in Las Vegas, September 22-23, " . . . to summarize the seismo/tectonic strategies presented in the consultation draft of the Nevada nuclear waste storage investigations (NNWSI) project site characterization plan (SCP)".

M. Ellis organized and designed the Geology 900 course as a series of informal seminars on new topics of interest, particularly as they relate to the southern Great Basin.

T. Reynolds conducted air photo studies and reviewed field maps from earlier field work.

October - December, 1987:

On October 20, R. Schweickert and M. Ellis attended a meeting at NWPO, Carson City, to discuss the state's review of the Szymanski report: Conceptual considerations of the Death Valley groundwater system with special emphasis on the adequacy of this system to accommodate the high level nuclear waste repository.

M. Ellis and J. Caskey accompanied B. Troxel (U. C. Davis) on a field trip to Pahrump Valley and the nearby region, with the purpose of evaluating the potential for active deformation in Pahrump Valley. As a result of this field trip, and the examination of aerial photography and Landsat thematic mapper images of the region, several well defined lineaments and scarps were considered worthy of careful study; one M.S. student (presently Joanne Hoffard) and M. Ellis are responsible for the characterization of the Valley.

M. Ellis initiated the transfer of digital seismic data from the USGS, and the DOE office in Las Vegas. All digital data between the start date for the USGS system to the present day was requested. Tapes began to arrive at the State NWSO in May, 1988.

The following personnel from Task 5 attended the Geological Society of America National Annual Meeting in Phoenix, Arizona, October 26-29: R. A. Schweickert, M. Ellis, J. Caskey, J. Hoffard, T. Sawyer, T. Reynolds, R. Elwood, P. Buchanan. R. A. Schweickert attended the pre-meeting shortcourse on Kinematics and Strain Analysis, offered by Declan dePaor for the Structure and Tectonics Division of GSA. M. Ellis and R. Elwood attended the pre-meeting field trip to examine Mesozoic thrust faults and Tertiary extensional faults in the southeastern Basin and Range. R. Schweickert also attended the post-meeting field trip led by Calvin Miller, Keith Howard, and Barbara John to examine a transect of Mesozoic contractional and Cenozoic extensional features in the Old Woman, Piute, and Chemehuevi Mountains of the eastern Mojave Desert.

The following personnel attended the post-meeting short course, Paleoseismology and Active Tectonics: M. Ellis, J. Caskey, and T. Sawyer.

The workshop, organized by M. Ellis, Late Cenozoic Evolution of the Southern Great Basin, was held at UNR November 9-10. The workshop drew over a hundred participants, and involved two full days of lectures. R. A. Schweickert and T. Sawyer presented lectures. A three-day field trip to Monte Cristo Valley (led by Task 1 personnel), southern Fish Lake Valley (led by Marith Reheis of the USGS), and northern Fish Lake Valley (led by Tom Sawyer of Task 5) followed the meeting.

R. A. Schweickert and M. Ellis wrote the Tectonics and Neotectonics part of the three-year Yucca Mountain proposal, Evaluation of the Geologic relations and seismotectonic stability of the Yucca mountain area, Nevada Nuclear Waste Site Investigation (NNWSI). Dr. P. Cashman was taken on as a Research Scientist in Task 5. M. Ellis also wrote the Introduction to the three-year proposal.

M. Ellis presented a paper at the Fall Meeting of the American Geophysical Union, December, 1987, entitled, The relation between stretching lineations and plate motions, and the origin of orogen-parallel extension. (See appendix 3.)

M. Ellis presented a paper at the Annual Meeting of the Tectonic Studies Group in the U.K., December, 1987, entitled, Displacement variation along thrust faults. He also attended a field trip with Juan Watterson and John Walsh (of the Liverpool Fault Group, University of Liverpool) to examine some well ex-

posed normal faults in quarries in the U.K. In addition, while attending this meeting, M. Ellis was contacted by Professor Paul Hancock, editor of the international newsletter, IGCP Project 206, Worldwide Comparison of Active Faults, and coordinated various press releases concerning activities by personnel in the Center for Neotectonic Studies.

R. Elwood continued reconnaissance field work in the Desert Mountains, Nevada. This included measuring a section in the Tertiary ash-flow tuffs located in the nose of a northeast plunging, open syncline. Representative samples were collected. Elwood also conducted an extensive literature review of the region.

T. Reynolds continued air photo studies and a literature review of his thesis area. Reynolds also met with L. McKague (LLNL) to discuss the Pahranaagat shear zone, and contacted R. Scott (USGS) to coordinate research activities in southeastern Lincoln County.

January - March, 1988:

R. A. Schweickert submitted to Tectonics a new manuscript entitled, "Extensional faulting in the southern Klamath Mountains, California," with W. P. Irwin of the USGS.

R. Elwood and T. Reynolds attended a planning meeting in Denver for the USGS National Mapping Program, involving the Caliente 2-degree sheet.

R. Elwood conducted field work in the Eleana Range at the NTS, and

in the Desert Range on the Pahranaagat shear zone.

T. Sawyer continued field studies in northern Fish Lake Valley. This included extensive soil analysis, and trenching work along part of the fault zone.

M. Ellis and P. Zhang spent 8 days in the field in Panamint Valley to examine evidence for Holocene tectonics.

D. Donovan spent two days in southern Amargosa Valley, conducting reconnaissance field examination of possible fault scarps.

R. Schweickert took a fieldtrip to the western Mojave Desert in late February to examine aspects of Paleozoic and Mesozoic stratigraphy, and Cenozoic extensional tectonics.

M. Ellis and D. B. Slemmons attended a DOE open-meeting in Reno concerned with DOE's Site Characterization Plan for the Yucca Mountain high-level nuclear waste repository site.

R. A. Schweickert and students began construction of restorable cross-sections of the Last Chance thrust in the Inyo Mountains and Last Chance Range to explore subsurface geometry of thrust faults similar to those believed to underlie the NTS. In addition, published 7.5-minute quadrangle maps of the NTS were reviewed, and evidence was discovered that the CP and Mine Mountain thrusts are west-vergent, rather than east-vergent, as has been assumed in most recent literature. This will have important implications for modelling subsurface structure at Yucca Mountain.

M. Ellis (with A. Ramelli, Task 1) took a field trip to Yucca Mountain and Pahrump Valley. The purpose was to evaluate that part of R. Scott's cross-section concerned with the near-vertical fracturing in the hanging wall of the Paintbrush Canyon fault. This preliminary trip did not reveal the extensive fracturing and faulting portrayed by Scott's cross section.

M. Ellis began preparatory work for two of the studies in Neotectonics, one concerned with strain inversion of fault and earthquake data, the second with fault geometry and off-fault deformation.

M. Ellis began to organize the collation of quality assurance documents, written by the Task leaders and assigned personnel. Final draft technical procedures and quality assurance documents were complete and collated by March 22, 1988, with the exception of Task 6 material. These procedures and documents were finally submitted on April 1, 1988.

R. A. Schweickert and M. Ellis reviewed the Szymanski report; M. Ellis summarized the reviews conducted by other Yucca Mountain project personnel. This review was forwarded to the State of Nevada, NWSO, in late March, 1988.

M. Ellis initiated contact with H. Dickensheets of the USAF and Nellis Bombing Range, and presented plans for a study of the Thirsty Canyon area.

R. A. Schweickert, M. Ellis, and students began initial review of the

DOE's Consultation Draft of the Site Characterization Plan.

M. Ellis obtained computer code from Geoff King (USGS) concerned with the deformation around a fault. This will be used (and possibly modified) to evaluate topography adjacent to faults within the Yucca Mountain region.

All Task 5 personnel (except T. Reynolds) attended the Annual Meeting of the Cordilleran Section of the G.S.A. in Las Vegas, March 28-31. The following pre-meeting field trips were attended:

- Cenozoic tectonics of a transect through eastern Nevada near 38-degrees N. latitude, led by John Bartley (Utah), Gary Axen (Harvard), Wanda Taylor (Utah), and Joan Fryxell (Harvard);

- Detachment surfaces in the southern Great Basin, led by Bennie Troxel (UC Davis), Michael Carr (USGS), and Brian Wernicke (Harvard);

- Mesozoic thrust faults and Cenozoic low-angle normal faults, eastern Spring Mountains, Nevada, and Clark Mountains thrust complex, California, led by Clark Burchfiel (MIT) and Greg Davis (USC).

The following post-meeting field trips were attended:

- Correlation of early Mesozoic thrusts in the southern Great Basin and their possible indication of 250 - 300 km of Neogene crustal extension, led by Brian Wernicke (Harvard), Doug Walker (U of Kansas), and Zeke Snow (Harvard); and

- Structure and tectonic history of the Last Chance thrust system, Inyo

Mountains and Last Chance range, California, led by Kevin Corbett.

T. Sawyer and D. B. Slemmons presented a paper at the meeting, entitled, Chronology of Late Holocene paleoseismicity of the northern Death Valley-Furnace Creek fault zone, Fish Lake Valley, California-Nevada.

M. Ellis began preparatory work on the UNR workshop open-file report, which will be published by the Nevada Bureau of Mines and Geology.

April - June, 1988:

D. B. Slemmons, R. A. Schweickert, and M. Ellis chartered a plane for an overflight to the Pahrnatag Range and Pahrnatag shear zone. Evidence for youthful scarps was observed in the north part of Pahrnatag Valley.

R. A. Schweickert accompanied R. Elwood to her field area, May 12-14, and spent two days with Angela Jayko of the USGS. They reviewed evidence of extensive folding and tilting of Neogene volcanic units along the Pahrnatag shear zone. New evidence was observed for late Quaternary activity along the Maynard Lake strand of the Pahrnatag shear zone.

R. A. Schweickert gave invited lectures at UCLA on May 19, and at the California Division of Mines and Geology in Sacramento on May 26, entitled, "New concepts on Sierra Nevada tectonic history."

R. A. Schweickert and M. Ellis completed the Task 5 review of the DOE's Consultation Draft of the Site Characterization Plan. M. Ellis summarized all reviews of the CDSCP and, with Steve Nitchman, collated the

complete review. The final draft was forwarded to Carl Johnson (NWSO) June 30, 1988. An important outgrowth of this review was the recognition that existing cross-sections of Yucca Mountain are not viable. Faults depicted on Scott and Bonk (1984) are actually contractional faults rather than extensional faults. In addition, these sections show (correctly) that a major episode of extension predates the Rainier Mesa Member of Timber Mountain Tuff, suggesting that there are two major groups of faults at Yucca Mountain rather than a single set as DOE currently assumes.

M. Ellis assisted D. B. Slemmons in the proposal for a UNR sanctioned Center for Neotectonic Studies.

M. Ellis assisted D. B. Slemmons in the graduate course, Active Faulting.

Jerry Szymanski of DOE visited UNR May 10-11, gave two lectures, and conducted discussions with Task 5 personnel and other Yucca Mountain personnel.

R. A. Schweickert attended a GSA Penrose Conference in Redding, California, June 5-10, and presented a keynote lecture on Sierra Nevada tectonic evolution and a poster session (with Mary Lahren) on recent research results in the eastern Sierra Nevada. He also attended a post-meeting fieldtrip in the northern Sierra Nevada.

Low sun angle photography of Pahrump Valley was flown in late June, 1988. Prints will not be ready until after July 1, 1988.

M. Ellis and J. Hoffard undertook preliminary field work in Pahrump

Valley in mid-June. Reconnaissance of mid-valley scarps was completed, and plans were made for future work in July.

M. Ellis submitted two abstracts to the Annual National Meeting of the G.S.A. in Denver, October 1988: Geological and geophysical constraints on the existence of low angle normal faults, by Ellis, P. Bodin, and J. Anderson; (appendix 4) and Plate convergence angles and ductile deformation fabrics: Results of numerical kinematic modeling, by Ellis, (appendix 5).

R. A. Schweickert, M. M. Lahren, and S. J. Caskey submitted an abstract to the Annual National Meeting of the G.S.A. in Denver, October 1988: Major Triassic thrust belt in eastern Sierra Nevada (ESN) and White-Inyo Mountains (WIM): A new hypothesis. (See appendix 6.)

T. Sawyer submitted an abstract to the G. S. A. Annual Meeting in Denver, October, 1988, entitled: Terrace forms of possible solifluction origin on piedmont slopes of the western Great Basin. (See appendix 7.)

T. Sawyer participated, following an invitation, in a NASA Overview flight, comprising a geological reconnaissance flight with NASA, JPL, USGS, and University of Washington personnel. The flight took place over the Death Valley - Owens Valley - Fish Lake Valley region.

J. Caskey spent five days in the NTS with Peter Guth and Jim Cole (USGS) conducting reconnaissance field work and mapping in the Mine Mountain/CP Hills region.

J. Caskey accompanied R. Elwood to her thesis area for reconnaissance field work.

R. Elwood conducted a magnetometer survey across a segment of the Pahrangat shear zone where a prominent northeast lineation occurs on aerial photography. Elwood also conducted detailed mapping of volcanic units, and sampled representative lithologies.

P. Buchanan began negotiations with USAF (Harley Dickensheets) to obtain access to Beatty Wash on the Nellis Bombing Range.

T. Reynolds continued field work in the Delamar Mountains and the Hiko Range, Lincoln Co., Nevada.

R. A. Schweickert, M. Ellis, and students began preparation of the final report for the period January 1, 1987 to June 30, 1988.

Appendix 2:

Program for the workshop.

Late Cenozoic Evolution of the Southern Great Basin

held at UNR, November 10 - 13, 1987.

**Late Cenozoic Evolution of the southern Basin and Range:
A workshop**

Convenors: D. Burton Slemmons, John W. Bell, and Richard A. Schweickert
Coordinator: Michael Ellis

Lauren Wright	Wrench faulting and normal faulting in the Cenozoic structural framework of the Death Valley region.
Brian Wernicke	Neogene extensional tectonism in the Basin and Range province at the latitude of Las Vegas, Nevada.
Bennie Troxel	Evidence for right slip along the south Death Valley fault zone.
Gary Axen	Magnitude and style of Miocene upper crustal extension in the southern Nevada area.
Wanda Taylor and John Bartley	Style and timing of Cenozoic extension in the Dry Lake Valley area, southeast Nevada.
Bob Scott	Regional tectonic interpretation of the evolution of Cenozoic extensional detachment terranes between the Funeral Mountains and the Calico Hills based on structural and paleomagnetic evidence.
T. M. Brocher, J. McCarthy, W. D. Mooney, R. D. Catchings, E. L. Geist, C. Jarchow, and W. S. Holbrook.	Seismic refraction lines in the Great Basin: A review of USGS efforts.
Laura Serpa	Doming of lower crust beneath an extensional orogen?
Jack Stewart	Tectonics of the Walker Lane belt, western Great Basin.
Marith Reheis and Jay Noller	New perspectives on Quaternary faulting in the southern Walker Lane, Nevada.
Thomas Sawyer	Late Holocene surface faulting along the northern Death Valley - Furnace Creek fault zone, Fish Lake Valley, California - Nevada.
John Bell, Craig dePolo, Alan Ramelli	The 1932 Cedar Mountain earthquake, and its relation to Yucca Mountain.
Ron Bruhn	Deformation in the Dixie Valley area, west-central Nevada.
Bob Smith	Paradox and paradigm of normal faulting earthquakes: deep vs. shallow, listric vs. planar, big vs. really big.
Virgil Frizzell and Mary Lou Zoback	Application of a refined method for determining principal stress orientations in southern Nevada.
Larry Anderson	USBR seismotectonic studies in the Lake Mead area, Nevada - Arizona.
John Geissman, Mark Hudson, Jim Foults, Jim Callian, and Steve Harland	General paleomagnetic applications to late Cenozoic tectonics in the Basin and Range.
Al Rogers and Steve Harmsen	Characteristics of seismicity in the southern Great Basin of Nevada - California.

*Appendix 1 -
Reprint.
Removed + cycled
separately.*

Keith Priestly	The 1987 Edgecombe, New Zealand, earthquake: A moderate normal faulting event.
Kenneth Smith, William Walter, Raul Castro, Rassol Anooshehpour, and Keith Priestly	Earthquake clustering in the Mina, Nevada, region, July and August, 1987.
Richard Blakely	Estimation and tectonic implications of the curie-temperature isotherm of Nevada.
Terry Wallace, Clem Chase, Karen Demsey, and Philip Pearthree	The role of preconditioned crust and flexural isostasy in the development of Basin and Range terrain.
John Dohrenwend	Rates and patterns of piedmont evolution in the southwest Basin and Range.
Emily Taylor	Late Quaternary paleoclimate studies - geologic problems and questions.
Eugene Smith	Evolution of calc-alkaline igneous rocks during mid-Miocene extension in the Lake Mead area, Nevada and Arizona.
Mac Roy Jackson, Don Noble, Steve Weiss, and Larry Larson.	Timber Mountain magmato-thermal event: An intense widespread culmination of magmatic and hydrothermal activity at the SW Nevada volcanic field.
Ken Fox and Fran Singer	Current U. S. Geological Survey research in the southern Great Basin: Location, scope, and potential contribution to understanding of late Cenozoic tectonics of the region.
D. Burton Slemmons and Richard A. Schweickert	Present and proposed research at UNR in tectonics and neotectonics in the southern Great Basin.
Michael Ellis	Closing remarks.

Appendix 3:

Reprint of the abstract appearing in EOS, v. 68, 1987:

The relation between stretching lineations and relative plate motions, and the origin of orogen-parallel extension.

MICHAEL ELLIS (Center for Neotectonic Studies,
University of Nevada-Reno, Reno, NV 89557)
A. J. WATKINSON (Dept. Geology, Washington State
University, Pullman, WA 99164)

Many continental collisional orogens exhibit two distinct deformation phases. The older suite of structures and associated stretching lineations develop within the downgoing continent (footwall) and reflect the relative plate motion. This early phase of deformation occurs during progressive metamorphism, and is characterized by high-strain (up to 300%) cylindrical and sheath folds whose axes parallel the associated stretching lineation (finite X direction). Younger structures and stretching lineations are syn- to post-metamorphic peak and reflect emergence of the crustal hanging wall along normal-directed thrusts; maximum extension is at a high angle to the orogen length, and is independent of relative plate motion.

The early phase of deformation is preserved within thrust sheets while younger structures are found along and close to thrust surfaces. Across imbricated thrust slices within an oblique subduction boundary this results in the early and late stretching lineations alternating between subparallel and perpendicular to the orogen respectively. The kinematics of oblique subduction used here resolve the potential space problem implied by significant orogen-parallel extension by invoking deformation partitioning between the footwall and hanging wall; footwall deformation reflects relative plate motion, hanging wall deformation reflects isostatically-driven emergence perpendicular to the orogen length.

Kinematic modeling of oblique subduction and geological examples from the Canadian Cordillera, French Alps, Irish and French Hercynides, and Himalayas illustrate these relations.

Appendix 4:

Abstract submitted to the G.S.A. National Annual Meeting in Denver, 1988.

GEOLOGICAL AND GEOPHYSICAL CONSTRAINTS ON THE EXISTENCE OF LOW ANGLE NORMAL FAULTS

ELLIS, Michael A., Center for Neotectonic Studies, UNR, Reno, NV 89557;

BODIN, Paul, CIRES, CU Boulder, Boulder, CO 80302; ANDERSON, J., Seismological Laboratory, UNR, Reno, NV 89557.

We assess the current state of the controversy surrounding the seismic potential and geological significance of normal faults with low dip angles. In the southwest U.S., these features were originally identified as accommodating Neogene extensional deformation. Several recent models of the Basin and Range feature low-angle normal faults at upper crustal (seismogenic) depths playing a primary role in current deformation. Yet, in what is becoming a classic geoscience standoff, there are many who feel that such shallow-dipping faults are not, or even could not possibly be, active at seismogenic depths. Classical faulting theory is not able to predict low-angle normal faults without resorting to *ad hoc* boundary conditions or special material properties. Moreover, the historic record of seismicity does not support the hypothesis of their existence as active structures. We review the geological and geophysical observations leading to hypotheses of active low-angle normal faults and the various interpretations and models that the observations support.

In addition, simple energy calculations suggest that low angle normal faults (20°) require the average shear stress to be 2.5 to 6.4 lower than that on high angle normal faults (60°) to energetically favor their formation, given constant displacement and strain conditions respectively. Possible mechanisms for lowering the shear stress required to activate low angle faults involve the ability to more easily sustain high pore fluid pressures on these structures, or call on a lower frictional coefficient. An example of the latter may be an anisotropic fracture orientation. Alternatively, we suggest a physically reasonable motivation for horizontal shear stresses at seismogenic depths, thereby adjusting the solution to Airy's stress function, giving stress trajectories appropriate to low angle normal faults. Such a stress field may be derived from the deformed and reequilibrating thermal structure of previously shortened crust, and is compatible with the well documented observation that significant extension follows crustal shortening.

Appendix 5:

Abstract submitted to the G.S.A. National Annual Meeting in Denver, 1988.

PLATE CONVERGENCE ANGLES AND DUCTILE DEFORMATION FABRICS: RESULTS OF NUMERICAL KINEMATIC MODELING

ELLIS, Michael, A., Center for Neotectonic Studies, UNR, Reno, NV 89557

There is considerable geological evidence that even subtle changes in relative plate velocities may lead to tectonic regimes in which crustal deformation is achieved through differently oriented faults and folds, and associated ductile fabrics, than evident in an earlier plate tectonic setting. This paper addresses the relation between plate tectonics and the formation of ductile structures.

Numerical calculations are based on seven kinematic models of deformation within an obliquely deforming, subducting, and imbricating plate; deformation reflects the relatively early stages of tectonism in a compressional orogenic belt, and is pre- and syn-metamorphic peak conditions. The deformation is considered to occur within crustal scale shear zones, or adjacent to large faults where strain rates are appropriately low.

Results presented relate plate convergence angles to the character of ductile fabrics. The models predict the orientation and character of finite structures such as cleavage, folds, and stretching lineations, and, in addition, yield progressive deformation histories and finite strains. These results compare well with examples from various orogenic belts, such as the hinterland of the Canadian Rockies, parts of the Western Alps, the western Klamaths, and the Airtunga nappe in Australia.

Results include the prediction that linear fabrics may either under- or over-estimate the plate convergence angle, and that their declination may be either opposite or sympathetic with that of the convergence angle.

The number of currently reasonable kinematic models do not allow the discriminatory use of ductile fabrics in predicting the plate convergence. Thus, an ancillary part of the paper poses the problem, what is a good choice of kinematics? or how is the deformation partitioned in an obliquely deforming plate? The choice may be motivated by the partitioning of seismic deformation at obliquely convergent margins, or by the corroboration of the existence of low angle faults or shear zones predicted by the models. Alternatively, predicted deformation histories may be used as discriminators, although there is little such data currently available.

Appendix 6:

Abstract submitted to the G.S.A. National Annual Meeting in Denver, 1988.

Major Triassic thrust belt in eastern Sierra Nevada (ESN) and White - Inyo Mountains (WIM): A new hypothesis

by R. A. Schweickert, M. M. Lahren, and S. J. Caskey

MAJOR TRIASSIC THRUST BELT IN EASTERN SIERRA NEVADA (ESN) AND WHITE-INYO MOUNTAINS (WIM): A NEW HYPOTHESIS

SCHWEICKERT, Richard A., LAHREN, Mary M., and CASKEY, Stanley J., Department of Geological Sciences, University of Nevada-Reno, Reno, NV 89557

Ongoing and recently published studies in the ESN-WIM region suggest that Paleozoic metamorphic rocks occur in several regional thrust sheets that were emplaced above major east-vergent Triassic thrust faults. The highest known thrust, the Lundy Canyon thrust in Saddlebag Lake pendant, imbricates parts of the lower Paleozoic Roberts Mountains allochthon and its Mesozoic cover, and predates a 219 Ma pluton (Schweickert and Lahren, 1987). Within the WIM region, the Last Chance thrust is the highest of several major pre-Jurassic thrusts that imbricate Proterozoic to Permian miogeoclinal sections of Inyo and Death Valley facies. The Last Chance thrust may consist of two plates with an overall displacement of 50-75 km (Corbett and others (1988). Restored structure sections indicate that the footwall of the Last Chance thrust must extend westward beneath the WIM, Owens Valley, and ESN as far west as Mount Goddard pendant. Paleozoic metamorphic rocks in ESN roof pendants were highly deformed and metamorphosed prior to the intrusion of 215-180 Ma plutons, and their structural style resembles that of rocks of the WIM region. We propose that these pendants comprise two thrust sheets, each with a west-facing section of Inyo facies strata. The proposed Bishop thrust sheet is made up of Lower Cambrian rocks of the Benton Range and Big Pine Creek pendant, Ordovician rocks of Bishop Creek pendant, and probable Mississippian rocks of Pine Creek pendant. This thrust sheet lies structurally above rocks of the WIM that comprise the upper plate of the Last Chance thrust. A proposed higher thrust sheet, the Mt. Morrison thrust sheet, consists of possible Cambrian and known Ordovician strata overlain by Carboniferous and Permian strata of Mt. Morrison pendant. This sheet lies west of, and structurally upon, the Bishop thrust sheet, and may be footwall to the Lundy Canyon thrust. Implications of this interpretation include: 1) lower Paleozoic rocks of Inyo facies thicken westward and extend as far west as Mount Morrison pendant; 2) more complete reconstructions of the early Paleozoic miogeoclinal may eventually be possible with continued studies in ESN; 3) a major belt of east-vergent Triassic thrusting and folding extends continuously southeastward from Tioga Pass to the vicinity of Las Vegas.

Appendix 7:

Abstract submitted to the G.S.A. National Annual Meeting in Denver, 1988.

Terrace forms of possible solifluction origin on piedmont slopes of the western Great Basin,

by T. Sawyer.

TERRACE-FORMS OF POSSIBLE SOLIFLUCTION ORIGIN ON PIEDMONT SLOPES OF THE WESTERN GREAT BASIN

SAWYER, Thomas L., Center for Neotectonic Studies, LME #100, Univ. of Nevada Reno, Reno, NV 89557

Terrace-forms are ubiquitous on many mid Pleistocene piedmont slopes of the western Great Basin. The terrace-forms occur at elevations ranging from 1000 to 2000 m and are restricted to gently sloping surfaces that have a multitude of aspects. The morphology of the terrace-forms is strongly influenced by variations in surface slope. Nearly planar tread surfaces are characterized by well-developed stone pavements. Risers trend sub-parallel to surface contours, range from 0.2 to 1 m in height, and have slopes ranging from 3 to 18 degrees. Terrace-forms in loess are evidence of both current solifluction activity and relict landscape evolution. The terrace-forms differ from typical solifluction features in that the presence of an infiltration impeding layer is not dependent on climate or season, but rather on pedogenic processes. Less permeable, strongly developed argillic B horizons that directly underlie relative thick accumulations of loess are requisites critical to solifluction. Once these conditions have been satisfied, all that is required for solifluction is sufficient water to saturate and induce flow in the layer of loess. The overlying stone pavements are apparently rafted upon this flowing layer in a passive and semi-coherent manner. The Quaternary paleoclimatic significance of the terrace-forms is not well understood, but solifluction is favored under wetter and colder conditions than presently occur in the arid climate of the Great Basin. Therefore, formation of the terrace-forms may be favored during pluvial and periglacial climates of the Quaternary.

Appendix 8

Task 5 project plans for

Structure and geometry of the Mine Mountain and CP Hills thrust complex, NTS, Nye County, Nevada,

by S.J. Caskey

The area immediately surrounding Yucca Flat offers a rare and by far the most extensive window through Cenozoic volcanic rocks on NTS. In this area, exposures of structurally complex Precambrian through upper Paleozoic rocks may reveal important insights regarding the subsurface geology at the candidate Nuclear Waste Repository Site. Present studies involving ground water flow models beneath Yucca Mountain rely partially on minimal subsurface (drill) data (M.D. Carr and others, 1986) and probably portray an unrealistic view of underlying geologic structure. A better understanding of the structural geology in the Yucca Flat area (than that presently expressed in existing literature (Barnes and Poole, 1968; Hinrichs, 1968)) may aid hydrologic studies by placing more viable constraints on subsurface boundary conditions. In addition, this will greatly enhance ongoing research of southern Great Basin tectonics.

Of particular interest to regional and NTS geologic structure studies are the CP and Mine Mountain thrust faults exposed at the southwestern edge of Yucca Flat. Geologic mapping and cross-sections by McKeown and others (1976) delineate large-scale west-facing overturned folds in both the upper and lower plates of the CP Thrust near Yucca Pass that suggest west-directed thrusting. This contrasts sharply with the structural interpretations of Barnes and Poole (1968) who cite evidence for southeast-directed faulting on the CP Thrust. The suggestion of west-directed thrusting is one of great significance since thrusts in the southern Great Basin are overwhelmingly east-to southeast-directed structures. Based on limited field reconnaissance I tentatively concur with the work of McKeown and others (1976). However, a complex overprinting of Cenozoic extensional faulting (and possible reactivation along thrust surfaces) clouds a clear picture of the Mesozoic structure. Imbricately faulted, west-tilted blocks of 12.4-13.2 m.y. (Byers and others, 1976) Paintbrush Tuff (that exist throughout an east-west transect within the CP Hills) may serve as a useful tool to restore post mid-Miocene extension and reveal better the Mesozoic structure.

REFERENCES CITED

- Barnes, Harley and Poole, Forrest G. (1968), **Regional Thrust-Fault System in Nevada Test Site and Vicinity**, GSA Memoir 110; pp. 233-238.

- Byers, F.M., Jr., Carr, W.J., Orkild, Paul J., Quinlivan, W.D., and Sargent, K.A. (1976), **Volcanic Suites and Related Cauldrons of Timber Mountain-Oasis Valley Caldera Complex, Southern Nevada**, U.S. Geol. Survey Professional Paper 910.
- Carr, M.D., Waddell, S.J., Vick, G.S., Stock, J.M., Monsen, S.A., Harris, H.G., Cork, B.W., and Byers, F.M., Jr., 1986, **Geology of drill hole UE25 p#1: A test hole into pre-Tertiary rocks near Yucca Mountain, southern Nevada**: U.S. Geol. Survey Open-File Report 86-175, 87 p.
- Hinrichs, E. Neal (1968), **Geologic Structure of Yucca Flat Area, Nevada**, GSA Memoir 110; 239-246.
- McKeown, F.A., Healey, D.L., and Miller, C.H. (1976), **Geologic Map of the Yucca Lake Quadrangle, Nye County, Nevada**, U.S. Geol. Survey Geol. Quad. Map GQ 1327.

Appendix 9: Summary of Proposed Research, Paul K. Buchanan - Task 5

A conspicuous north trending fault system is present at both Yucca Mountain and Pahute Mesa. Between these two locations, the system is interrupted by the Timber Mountain Caldera and related faults. There is conjecture in the literature as to the extent to which these separated north trending systems are related and whether the fault system continues through the caldera, masked by the caldera faulting. The regional implications include a potential relationship to the Spotted Range - Mine Mountain - Pahrnagat left lateral shear system and the Death Valley right lateral shear system. If the Spotted Range - Mine Mountain - Pahrnagat shear system is operating as a single system, it's left lateral sense in conjunction with the right lateral sense of the Death Valley shear system would create a major room problem at their intersection in the Amargosa Desert south of Yucca Mountain. The north trending fault system could be operating as a pathway for excess material to exit the convergence zone.

Timber Mountain Caldera is surrounded on all sides by north trending strike-slip faults. It is possible that the stress causing this faulting outside the caldera is being taken up within the caldera by caldera faults. Performance of a Jacque Angelier type stress inversion on faults within and without the caldera should reveal whether the most recent movements were in response to the same regional stress, and whether that stress could be related to the intersection of the aforementioned shear systems.

Areas slated for study are as follows:

- (1) Paintbrush fault south of the caldera
- (2) Caldera faulting in the vicinity of Buttonhook Wash and West Cat Canyon
- (3) North trending faults immediately west of the caldera and north of Camp Transvaal
- (4) North trending faults north of the caldera
- (5) Possible continuation of the Paintbrush fault across Three Forks Wash into the caldera

Appendix 10:

Abstract presented at the G.S.A. Cordilleran Section Annual Meeting in Las Vegas, March, 1988,

Chronology of late Holocene Paleoseismicity of the northern Death Valley - Furnace Creek fault zone, Fish Lake Valley, California - Nevada,

by T. L. Sawyer

Nº 7392

CHRONOLOGY OF LATE HOLOCENE PALEOSEISMICITY OF THE NORTHERN DEATH VALLEY-FURNACE CREEK FAULT ZONE, FISH LAKE VALLEY, CALIFORNIA-NEVADA

SAWYER, Thomas L., SLEMMONS, David B., Center for Neotectonic Studies, University of Nevada Reno, Reno NV 89557

An ongoing paleoseismic study has identified at least three discrete slip events from stratigraphic relations in trenches across the northern Death Valley-Furnace Creek Fault Zone (DV-FCFZ). Facies and thickness changes of alluvial units across the fault suggest a dominant lateral component of faulting which is consistent with the regional kinematics of the fault. Geomorphic surface correlations, radiocarbon analyses, tephrochronology, and soil development studies support a late Holocene chronology for the sequence of three events. A Mono (?) tephra offset about 33 cm in a trench records the first slip event. The tephra is probably time-correlative to an alluvial unit that is stratigraphically above a buried log ^{14}C dated at 2170 ka B.P. (± 45). The date of 2170 is likely the limiting maximum date for the sequence. The second event in the same trench displaces an alluvial unit (about 18 cm) that contains a buried log dated at 1670 ^{14}C ka B.P. (± 40). A colluvial wedge formed by degradation of a scarp associated with the second event is fractured by a fault that passes within 4 to 6 cm of the surface and represents the most recent slip event. Intersismic intervals of about 600 to 800 years are estimated for this trench site. These preliminary data suggest that the DV-FCFZ is one of the most active tectonic elements in the Basin and Range.

TASK 6: REMOTE SENSING TECHNICAL ASSESSMENT

Dr. James V. Taranik Principal Investigator

William H. Aymard Research Associate

John J. Perry Research Associate

TABLE OF CONTENTS

	Page
1. INTRODUCTION	1
1.1 Glossary of Definitions, Acronyms and Abbreviations .	2
2. DIGITAL DATA PREPARATION	11
2.1 Geopotential Data as a Image	11
2.1.1 Data Conversion to a Grid	11
2.1.2 Transformation of the Data Range	11
2.2 Registration and Resampling	12
2.2.1 Ground Control Point Selection	12
2.2.2 Registration to UTM	12
2.2.3 Grid Resampling	12
3. IMAGE ANALYSIS TECHNIQUES IN IDIMS	13
3.1 Density Slicing	14
3.2 Shaded Relief Images	14
3.3 Principal Components Analysis	16
3.4 Color Enhancement of Multispectral Thematic Mapper Data	
3.4.1 Transformation	20
3.4.2 Contrast Enhancement	23
3.4.3 Inverse Transformation	23
4. IMAGE INTERPRETATION OF DIGITAL DATA	24
4.1 Interpretation of Aeromagnetic Data	24
4.2 Gravity Data	26
4.3 Interpretation of Satellite Data	27
5. CONCLUSION AND RECOMMENDATIONS	28
6. REFERENCE	30
APPENDIX 1 THEMATIC MAPPER CHARACTERISTICS	40
APPENDIX 2 SPOT IMAGE CHARACTERISTICS	46
APPENDIX 3 AEROMAGNETIC DATA REDUCTION	51
APPENDIX 4 GRAVITY DATA CHARACTERISTICS	53
APPENDIX 5 AVHRR DATA CHARACTERISTICS	57

LIST OF PLATES

- Plate 1 Density Sliced Image 12 color
- Plate 2 Density Sliced Image 64 color
- Plate 3 Shaded Relief Image Azimuth = 0
- Plate 4 Shaded Relief Image Azimuth = 45
- Plate 5 Shaded Relief Image Azimuth = 65
- Plate 6 Shaded Relief Image Azimuth = 90
- Plate 7 Shaded Relief Image Azimuth = 135
- Plate 8 Aeromagnetic Image of Southern Nevada
- Plate 9 Total field Timber Mtn.
- Plate 10 Gravity Stations
- Plate 11 Plot of Standard Deviation vs Resolution Size
- Plate 12 B/W AVHRR AV = 3 X 3
- Plate 13 Color AVHRR AV = 3 X 3
- Plate 14 B/W AVHRR AV = 2 X 2
- Plate 15 Color AVHRR AV = 2 X 2
- Plate 16 B/W AVHRR AV = 1 X 1
- Plate 17 Color AVHRR AV = 1 X 1
- Plate 18 Inverse PC
- Plate 19 SPOT IHS

1.0 INTRODUCTION

This report is one part of an on-going study to evaluate the seismo-tectonic setting of the proposed high-level nuclear waste repository at Yucca Mountain in Nye County, Nevada. Task 6, the Remote Sensing Technical Assessment, under the auspices of the Neo-tectonics Laboratory and the Nevada Nuclear Waste Project Office, slightly modified the scope of its project. The task modified its activities from a strict lineament analysis to include:

1. Acquisition of all pertinent digital data sets
2. Correction and registration of this data to UTM coordinates for the establishment of a spatially referenced geologic data base
3. Dissemination of satellite imagery to various task groups and other subcontractors to the State of Nevada
4. Delineate areas of lineament intersections mapped from processed imagery and zones of interest for more detailed study

Acquisition of satellite data, both large and small scale, was acquired. Available digital geo-potential data, both gravity and magnetic, was also acquired. Formalization of the digital processing steps, necessary for the correction, registration and integration into a spatially referenced geo data base was performed.

In addition to the preceding responsibilities, Quality Assurance Technical Procedures were written and rewritten. This essential responsibility was to guarantee compliance with the contractual obligations between the University and the Nevada Nuclear Waste Project Office. Since the vast majority of work undertaken by Task 6 is computer oriented, hardware and software performance evaluation was needed. This particular assignment was most time consuming due to the verification and documentation necessary.

Additionally, members attended conferences concerning Geographical Information Systems and presented papers at national meetings. This exposure, at a national level, was most important due to the very sensitive nature of high-level nuclear waste location.

1.1 GLOSSARY OF DEFINITIONS, ACRONYMS AND ABBREVIATIONS

This section comprises definitions from the areas of computer science, remote sensing, digital image processing and geophysics.

Altitude:

height above a given point, the point usually being mean sea level. It generally refers to points above the Earth's surface rather than those on it.

Ancillary:

in remote sensing, ancillary data are secondary data pertaining to the area of interest. These data may be digitized and used with the primary remote sensing data.

Angle of view:

the angle subtended by lines that pass through the center of the lens to diametrically opposite corners of the plate or film used.

Anomaly:

an area on an image that differs from the surrounding normal area. For example, a concentration of vegetation within a desert scene constitutes an anomaly.

Attitude:

the angular orientation of a spacecraft, determined by the relationship between its axes and some reference line or plane or some fixed system of axes. Usually, "y" is used for the axis that defines the direction of flight, "x" for the cross-track axis perpendicular to the direction of flight and "z" for the vertical axis.

Azimuth:

the geographical orientation of a line given as an angle measured clockwise from north.

Bandwidth:

- (1) the range of frequencies within which its performance, with respect to some characteristic, conforms to a specified standard.
- (2) in a wave, the least frequency intervalous side which the power spectrum of a time-varying quantity is everywhere less than some specified fraction of its value at a reference frequency.
- (3) the number of cycles per second between the limits of a frequency band.

Base-height ratio:

airbase (ground distance between centers of successive overlapping imagery) divided by aircraft height. This ratio determines vertical exaggeration on stereo models.

BSQ:

band sequential

bpi:

bits per inch

CCD:

charge-coupled device

CCT:

Computer-compatible tape

CCT-PT

full processed CCT

Change detection:

process by which two images are compared pixel by pixel, and an output is generated whenever corresponding pixels have sufficiently different gray values.

Color composite:

in multiband photography applications, a color photograph is produced by combining individual monochrome images (usually three) in which each band is reproduced in a given color.

Computer program:

a procedure that has been coded for a computer and designed for solving a problem, including such problems as collection and processing of data and presentation of results.

Contrast stretch:

an image contrast enhancement technique in which the original range of digital values representing the image gray levels has been increased. This application maximizes the use of the dynamic range offered by a display medium.

Control points:

recognizable geographic features or landmarks in an image that relate the image with the object.

CP:

control point

Density slicing:

the process of converting the continuous gray tone on an image into a series of density intervals, or slices, each corresponding to a specific digital range.

Digitization:

partitioning of an image into discrete resolution cells, then assignment of a representative gray value to each cell.

Documentation:

a written description of a software package, including mathematical models, associated computer programs and specific calculations which has received peer review and management approval.

EDC:

EROS Data Center.

Ephemeris:

any tabular statement of the assigned places of a celestial body, including man-made satellites, for regular intervals. Ephemeris data help to characterize the conditions under which remote sensing data are collected. They are used in Landsat to correct the sensor data before analysis.

EROS:

Earth Resource Observation System

Format:

the arrangement of descriptive data in descriptors, identifiers, or labels. The arrangement of data in bit, byte and word form in the CPU or on a digital tape.

Free-Air Anomaly:

to reduce gravity to sea level, the normal gradient of gravity or 'free-air' correction is used: $+ 0.3086h$ mgal, where h is in meters and positive down to the geoid.

The second-order terms of the elevation correction will be applied if they are magnitude 0.1 mgal or more. The free-air anomaly is derived from g_f (mgal) = $g + 0.3086h$ - this corresponds to the classical definition between gravity at the geoid and normal gravity at the reference ellipsoid.

Frequency spectrum:

function representing the image components for each spatial frequency. Formally the magnitude of the Fourier transform of an image.

GCP:
ground control point

Geocoded image data:
imagery in which the data elements are uniquely and systematically aligned along the axes of a coordinate reference system that has known position and scaling. The process of geocoding imagery is known as registration when the resulting pixels overlay a set from another image.

Geometrical transformation:
adjustments made in the image data to change its geometrical character, usually to improve its geometrical consistency or cartographic utility.

Gray scale:
range of gray values from black to white.

Gray value:
number that is assigned to a position (x, y) on an image and that is proportional to the integrated image value (reflectance, radiance, brightness, color coordinate, density etc.) of a small area, called a resolution cell, or a pixel, centered on the position (x, y).

Ground track:
the vertical projection of the actual flight path of an aerial or space vehicle onto the Earth's surface. If attitude or pointing varies, the ground track of the image varies accordingly.

GSFC:
Goddard Space Flight Center (Greenbelt, Maryland)

High-pass filter:
spatial filter that suppresses low spatial frequencies in an image and enhances fine detail.

Histogram:
a frequency-distribution plot; a graphical representation of a frequency by means of lines or other symbol that represent class intervals along the x-axis and corresponding class frequencies along the y-axis.

HRV:
high-resolution visible-range instruments on-board SPOT

IFOV:
Instantaneous field of view

Image:

spatial representation of an object, a scene or a map which may be abstractly represented by a continuous function of two variables defined on some bounded region of a plane.

Image enhancement:

the process of altering the appearance of an image so that more information can be extracted and/or making a given image more suitable for a specific application. Enhancement may be done by either digital or photographic means.

Image processing:

encompasses all the various operations that can be applied to photographic or image data. These include, but are not limited to image compression, restoration, enhancement, preprocessing, quantization, spatial filtering and other image pattern recognition techniques.

Instantaneous field of view:

- (1) the solid angle through which a detector is sensitive to radiation. In a scanning system, this refers to the solid angle subtended by the detector when the scanning motion is stopped; commonly expressed in milliradians.
- (2) the ground area covered by this solid angle (GIFOV)
- (3) that scene area contributing to a single digital measurement, as defined by the instrument aperture.

Low-pass filter:

spatial filter that suppresses high spatial frequency components in an image and suppresses fine detail.

Map:

a representation in a plane surface, at an established scale, of the physical features (natural, artificial or both) of a part of the Earth's surface, with the means of orientation indicated.

Mathematical model:

a mathematical representation of a process or system.

mgal:

unit of gravity data which is equivalent to 10 meters/sec

model:

a representation of a system or process

mosaic, controlled:

a mosaic or an assemblage of overlapping images whose edges have been matched to form a continuous pictorial representation of a portion of the Earth's surface, that is laid to ground control.

MSS:

multispectral scanner

NASA:

National Aeronautics and Space Administration

Numerical Method:

a procedure for solving a problem primarily by a sequence of arithmetic operations.

Numerical model:

a system or process that solves a problem by numerical methods.

Observed (or measured) Gravity (g):

the value of gravity at the site of the gravity instrument referenced to a recoverable base reference station.

Pixel:

(derived from "picture element") a data element having both spatial and spectral aspects. The spatial variable defines the apparent size of the resolution cell (i.e., the area on the ground represented by the data values) and the spectral variable defines the intensity of the spectral response for that cell in a particular channel.

Quality assurance of computer software:

those planned and systematic actions necessary to provide adequate confidence that the software will serve its intended purpose.

rad:

radian

Radiometric resolution:

the sensitivity of the sensor to the differences in signal strength, defining the number of discernible signal levels.

Registration:

the operation by which an image is mapped onto another image which may be an image or map representing the same segment of the Earth's surface. Because, in the digital world, pixels have definite locations and pixel spacing has a definite scale, digital registration also requires

pixel scaling in the two (or more) registered images to be the same and pixel corresponding to the same ground area to be precisely superposed. An image may be geocoded and yet not registered to another image if the pixel scales or the projection are different.

Resolution:

the ability of an entire remote sensor system, including lens, antennae, display, exposure, processing and other factors to render a sharply defined image. There are four types, including: spatial, spectral, radiometric and temporal.

Retrievability:

the capability to access all previous versions of software developed over a reasonable period of time even though they may not be executable due to hardware and/or system software changes.

rms:

root mean square

Sampling:

process of measuring the brightness or intensity of a continuous image of discrete points, producing an array of numbers.

Scale:

the ratio of a distance on a photograph, image or map to its corresponding distance on the ground. Scale may be expressed as a ratio, a representative fraction or as an equivalence.

SNR:

signal-to-noise ratio

Software:

written or printed data, such as programs, routines, symbolic languages and control languages essential to the operation of computers.

SOM:

Space Oblique Mercator

Spatial filter:

an image transformation, usually a one-to-one operator used to lessen noise or enhance certain characteristics of the image. For an particular (x, y) coordinate on the transformed image, the spatial filter assigns a gray shade on the basis of the gray shades of a particular spatial pattern near the coordinates (x, y).

Spatial resolution:

a description of how well a system or image can reproduce an isolated object or separate closely spaced objects or lines in terms of the smallest dimension of the object that can just be observed or discriminated.

SPOT:

Systeme Probatoire d'Observation de la Terre

Temporal resolution:

the time interval between measurements.

Terrain Correction:

a terrain database with point values of topographic height every 30 arc-seconds is used for this task. The effect of topographic variations on a point gravity value is computed to a distance of 0.5. These corrections are commonly in the 2 to 4 mgal range, but in mountainous areas they may be as much as 20 to 30 mgal range. The terrain corrections are computed only once and then are stored with the point gravity values. The corrections remove only the effect of terrain variations relative to the height of the point gravity observation. Bouguer reductions are then used to reference the gravity observations to any arbitrary height.

TIPS:

TM image Processing System

TM:

Thematic Mapper

Traceability:

the ability to identify the actual configuration of the software used in the calculations. This characteristic is closely related to retrievability, which is described in detail above.

UTM:

Universal Transverse Mercator

Validation:

assurance that a model as embodied in a computer code is a correct representation of the process or system for which it is intended. Validation is generally accomplished by using computer programs to simulate field or laboratory experiments. For cases where these experiments are well defined, validation is possible. However, parameters controlling experiments involving numerous variables which are poorly defined do not allow for the validation of

computer programs. The application of these programs to experiments, is still a valuable test but falls short of "validation"

Verification:

assurance that a computer code correctly performs the operations specified in a numerical model.

WRS:

Worldwide Reference System.

2.0 DIGITAL DATA PREPARATION

There are two main steps involved in the registration and image processing of satellite data (Landsat Thematic Mapper and Spot) and Geopotential data (gravity and magnetic). The first step deals with digital image generation of geopotential data. The second involves registration of all data sets to a UTM projection.

2.1 Geopotential data as a image

The generation of a digital image (a digital matrix of 8-bit bytes) from a geopotential data set requires two basic process. First, irregularly spaced data must be interpolated to form a regularly spaced grid and second, the data range must be transformed into a 8-bit data range.

2.1.1 Data Conversion to Grid

The data conversion to a regularly spaced grid was performed using the program MINC. Written in 1978 by Mike Webring at the U.S.G.S, Geophysics Branch in Denver, Colorado. This program was used to generate a 2-dimensional smooth surface grid from irregularly spaced data points. This surface has the property of minimum curvature, where curvature refers to the estimate of the second horizontal derivatives in x and y at each grid location. MINC requires two input files. The first file contains X, Y, Z data records in decimals of degree while the second contains the NAMELIST parameters. Specification of grid size, number of rows and columns, origin coordinates, number of iterations are some of the those mandatory parameters. The program takes about 3 minutes to generate a 181 x 245 grid from 6,650 original data points.

An irregularly spaced grid may be used however, gaps will appear in the image. For this reason is it recommended to convert any irregularly spaced data set to a regularly spaced grid.

2.1.2 Data range transformation

For purposes of display, the data values were rescaled into an 8-bit range. This was accomplished by setting the minimum and maximum values of the resampled data to 0 and 255 respectively.

2.2 IMAGE REGISTRATION AND RESAMPLING

Registration is the process of geometrically aligning data sets from which geological and geophysical information may be extracted. The registration procedure involves three main steps. First, ground control points must be selected second, the data set (image) is registered to a UTM type projection through an affine transformation and third, the grid produced is resampled by using an interpolation technique such as bilinear or cubic convolution.

2.2.1 Ground Control Points Selection

The Calcomp 9100 was utilized to digitize ground control points from topographic maps (1:24,000) over the study area. Twenty five uniformly spaced GCP's were located and digitized. These map points have known latitude and longitude coordinates as well as known UTM grid locations. The corresponding points (line and sample number) on the imagery were noted and listed for the production of a transformation matrix. In order to minimize errors the points were digitized twice and the results averaged. Accuracy tolerances were within 0.5 pixels in both x and y directions.

2.2.2 Registration to UTM

Once these control points were selected, regression analysis was used to determine the coefficients for the affine transformation. These transformation coefficients were used to warp the original image into a UTM projection. The following equations were used to calculate the affine transformation:

$$X' = a_1X + b_1Y + c_1$$

$$Y' = a_2X + b_2Y + c_2$$

X and Y are the input pixel coordinates and

X' and Y' are the output coordinates.

Higher order polynomials may be used when the study area is larger than 250 Kilometers, in order to obtain accurate registration. (M. Crawford 1980)

2.2.3 Grid Resampling

The grid scale produced by the affine transformation was determined by the original pixel size of each image. The grids were resampled using a cubic convolution algorithm.

3. IMAGE ANALYSIS TECHNIQUES IN IDIMS

A list of all the hardware components within the Remote Sensing and Spatial Analysis Laboratory is followed by a brief description of the software already on line.

Manuf.	Model	Description
DEC	780XA-AE	VAX 11/780 CPU with 8 MB memory
DEC	BA-DO-11	Expansion Box and expansion backplane
DEC	FP780-AA	Floating Point Accelerator
DEC	RUA81-CA	456 MB Fixed Disks (2 each)
DEC	RUA60	205 MB Removable Disks
SI	9700-53	800/1600/6250 bpi, 125 ips Tape Drives (2 each)
DEC	A100-BA	Decwriter Terminal
DEC	VT100-AA	2 Video Terminals
DEC	LP11-AA	300 lpm Printer
DEC	11/24-DC	LSI 11/24 Controller with 1 MB memory
DEANZA	IP8500	Gould-DeAnza Image Array Processor
DEANZA	IP85-M	8 Image Memory (512 X 512 X 8 bit) Planes
DEANZA	IP85-DVP	Digital Video Processor
CONRAC	7211	19" High Resolution Monitor
ESL	-----	IDIMS, GES, ERIS, Data Catalog Software License
DEC	QE100-VZ	Fortran License
DEC	QE126-VZ	Pascal License
	-----	C License
DUNN	634	Color Camera (35 mm and 8" X 10" formats)
CALCOMP	9160	Digitizing Station
	-----	Plotter
	-----	Memodyne Cassette to Disk Converter Computer

The Mackay School of Mines has a VAX-based Electromagnetic Systems Laboratories (ESL) Interactive Digital Image Manipulation System (IDIMS). The software package consists of the Geographic Entry System (GES), the Earth Resources Information System (ERIS) the Interactive Digital Image Manipulation System (IDIMS) and a Data Base Management System.

In this study several image analysis techniques were used to effectively extract the information content of the Thematic Mapper, AVHRR and geopotential images.

They were: Density slicing, shaded relief, principal components analysis and color enhancement of multispectral Thematic Mapper data.

3.1 Density Slicing

Density slicing is achieved by remapping the gray levels of an image into a series of discrete colors. The total information content of the image is reduced through quantization into several colors. The final density sliced image is less ambiguous than the original gray level image.

There are two ways of generating colors in IDIMS : First through the use of a 32 color table built into the system. In this table the red end of the spectrum is associated with the higher gravity and magnetic values and the blue end of the spectrum with the lower values. This coloring gives the interpreter a quick indication of the positive and negative anomalies present in the study area (plate 1). The second way to achieve color in IDIMS is by replacing the color table with one of your own. The maximum number of colors is limited to 64 with 10 gradations each (plate 2).

3.2 Shaded Relief

Shaded relief is a directional first-derivative filter, which enhances slope information by giving the data the appearance of an illuminated surface. The shading process is based on the assumption of a photometric function for the surface (Lambertian surface in our case). The value assigned to a given pixel element depends on the local slope magnitude and direction and its relation to an assumed solar azimuth and elevation (Batson, Edwards, and Elliason 1975).

One of the disadvantages of directional filters is the introduction of linear artifacts into the original data. The interpreter must be able to identify these artifacts and separate them from real lineaments. To accomplish this, shaded relief images in the major azimuths must be produced and compared.

Five different shaded relief images of magnetic data were produced. These images were generated using the following azimuth angles: 0, 45, 65, 90 and 135 (plates 3, 4, 5, 6, 7) with a constant solar elevation angle of 25 degrees.

The general trend of the original data proved to be of paramount importance for the selection of the best directional filter. Filters which are normal to the overall trend will maximize its display. Both gravity and magnetics data have

trends approximating north 20 to north 50 west. Comparison of the various filtered images indicate a directional filter of 65 degrees provided superior results.

Gravity shaded relief images were not useful, because of the lower quantization of the original data set.

3.3 PRINCIPAL COMPONENTS

Multispectral data has progressed from three-banded color photographs to imaging spectrometers having as many as 128 spectral bands. A problem arises in the selection of the most appropriate bands for consideration. Knowledge of spectral characteristics is mandatory or considerable time and effort will be consumed. There also exists a great deal of redundancy in multispectral data which is evident by the high degree of correlation between bands. The cause of such a high interband correlation is not only natural spectral correlation but also topography (Schowengerdt, 1986). A Principal Component transformation solves these two problems by creating new variables, which are linear combinations of the original variables. There are generally fewer new variables containing a majority of information content which reduces the dimensionality of the original data set. Furthermore, these new variables have zero correlation between them which eliminates the spectral redundancy.

Consider a distribution of bivariate data enclosed by a conic within a rectangular Cartesian coordinate system. This may be represented by the quadratic form

$$g(X) = ax^2 + 2bxy + cy^2$$

or, in matrix notation

$$g(X) = X'AX$$

where

$$X = [x \ y]$$

$$X' = \begin{bmatrix} x \\ y \end{bmatrix}$$

$$A = \begin{bmatrix} a & b \\ b & c \end{bmatrix}$$

The matrix X is called the transpose of X , while A is the matrix of the quadratic form of g .

The matrix A that is used in principal components analysis is the covariance-variance matrix. The variance of a variable is defined as the average of the sum of squared

deviations from the mean, while covariance is a measure of the joint variation of two variables about their common mean. The variance occupies a position along the main diagonal (upper left to lower right) while the off-diagonal positions are filled with the covariance values. For simplicity, only two variables are considered in the example covariance matrix; although, the matrix may be extended to include almost any number of variables.

Some special properties of the covariance matrix should be noted at this time. First, the matrix is square and symmetric. This symmetry is caused by the covariance; the covariance between variables a and c must be equal to the covariance between variables c and a. Secondly, the value of the covariance must be equal to or less than the square root of the product of the individual variances. For example,

$$-\sqrt{ac} \leq b \leq +\sqrt{ac}$$

A value of b equal to the square root of the product of the individual variances indicates perfect correlation. No correlation exists between variables when b is equal to zero. And lastly, the total non-random variance may be regarded as the total information present. Since we can not be certain of the amount of random variance (noise), all we can do is sum the total variance. This sum is called the trace of the matrix A and is denoted by $\text{tr } A$. The Principal Axis theorem states that any quadratic form (ie. $g(X) = X' A X$) is equivalent by means of an orthogonal matrix P to a quadratic form

$$h(Y) = Y' B Y,$$

where the new variables are related to the old variables by

$$X = P Y \quad (\text{Kolman, 1986}). \quad \text{Here,}$$

$$Y = \begin{bmatrix} x' & y' \end{bmatrix}$$

$$Y = \begin{bmatrix} x' \\ y' \end{bmatrix}$$

$$B = \begin{bmatrix} \lambda_1 & 0 \\ 0 & \lambda_2 \end{bmatrix}$$

The matrix Y is called the transpose of Y , while B is the diagonal matrix with the λ 's equal to the eigenvalues associated with matrix A . Since,

$$X = P Y$$

and

$$g(X) = X' A X$$

$$(P Y)' A (P Y)$$

$$Y' (P' A P) Y$$

then,

$$= Y' B Y$$

$$\text{if we let } B = (P' A P).$$

Thus,

$$g(X) = h(Y)$$

and

$$ax^2 + 2bxy + cy^2 = \lambda_1 x'^2 + \lambda_2 y'^2$$

which eliminates the need of an xy term. Matrix B is the new covariance matrix with eigenvalues along the main diagonal with zeros occupying the off-diagonal elements. This procedure of transforming our original matrix A into a diagonal matrix (values along the diagonal with zeros everywhere else) is called diagonalization. The basic idea is to determine the characteristic roots of the characteristic polynomial of matrix A . The eigenvectors (characteristic vectors) are determined by substituting the eigenvalues back into the matrix equation.

The following is a compilation of properties and generalizations concerning eigenvalues and their associated eigenvectors (Kolman, 1986; Davis, 1986; Joreskog et. al., 1976):

1. The sum of the eigenvalues equals the sum of the original variances. For example,

$$\text{tr } A = \text{tr } B$$

2. The eigenvalues are ordered in decreasing value.

$$\lambda_1 > \lambda_2 \dots > \lambda_n$$

3. A zero eigenvalue indicates that the original dimensionality has been reduced. Near zero eigenvalues may be discarded due to the lack of statistical information content; however, there appears to be no statistical tests to evaluate a level of significance.
4. There may be a zero eigenvalue but never a zero eigenvector.
5. The largest eigenvalue is directed by its associated eigenvector. The second largest eigenvalue is along its associated vector, which must be orthogonal to the first. The remaining vectors must all be orthogonal to the previous vectors.
6. The coefficients in the transformation matrix (eigenvectors) may be viewed as directional cosines. The greater the coefficient, the larger the cosine value, the smaller the angle between the old and new variable. Thus, the greater the influence of the original variable.
7. Each eigenvector is a linear combination of the original variables.
8. Since P is a matrix consisting of orthonormal vectors, then
- $$P^{-1} = P'$$
- the transpose is equal to its inverse.
9. If variables are correlated, then at least the first eigenvalue is greater than the maximum variance in the original variables.

3.4 COLOR ENHANCEMENT OF MULTISPECTRAL THEMATIC MAPPER DATA

Due to the highly correlated nature of the Thematic Mapper data, a color enhancement technique has been employed for the discrimination of various geologic and pedologic units in the study area. A systematic procedure has been established for the generation and display of this enhanced imagery. A description of this enhancement technique is listed below.

Three essential steps which include:

1. Transformation of the original correlated bands into new uncorrelated channels
2. Contrast enhancement of these new channels
3. Inverse transformation
are described below.

3.4.1 Step. Transformation

The selection of the best band combination has already been determined and described (Taranik and Perry, 1986). The choice of Thematic Mapper bands 5, 4 and 1 displayed as red, green and blue respectively may be additionally enhanced. The covariance matrix along with the means and standard deviations are listed below for these bands.

Covariance Matrix

Band	1	4	5
1	590		
4	387	322	
5	586	489	942
Mean	135	80	138
St. Dev.	24	18	31

Correlation Matrix

Band	1	4	5
1	1.00		
4	0.89	1.00	
5	0.79	0.89	1.00

The determination of the eigenvalues and eigenvectors of a symmetric matrix was by the Jacobi method. This method is based on relatively simple orthogonal transformations but is not competitive in terms of computer time with more efficient methods.

All methods require on the order of n basic arithmetic operations, but the Jacobi method generally requires about 10 times as many operations as the most efficient. However, this is a safe and sure method of producing the eigenvalues along with the eigenvectors. The results are listed below.

Eigenvalues		Eigenvectors		
1.	1667	0.5454	0.4206	0.7250
2.	156	0.7585	0.1204	-0.6404
3.	31	-0.3566	0.8998	-0.2534

The eigenvalues represent the values along the diagonalized matrix, such as:

```

1667
  0   156
  0   0   31
  
```

The eigenvectors represent the values which are multiplied by the original values, such as:

```

multiplying band 1 by 0.5454
multiplying band 4 by 0.4206
multiplying band 5 by 0.7250
  
```

and adding the results. This new variable, principal component 1 which has a variance of 1667 is a linear combination of the original variables and has a zero correlation with the other two components.

It should be noted here, that the trace (the addition of the diagonal elements) of the original covariance matrix is 1854 and that all three eigenvalues add to the same total variance. The best signal to noise ratio in the original band combination is defined as:

$$\text{SNR (x)} = \text{Band 5 variance} / \text{noise}$$

and in the best in the principal component images it is defined as:

$$\text{SNR (y)} = \text{Principal Component 1 variance} / \text{noise}$$

Thus, the change in the signal to noise ratio is

$$\begin{aligned} \sqrt{\text{SNR}} &= \frac{\text{Principal Component 1 variance}}{\text{Band 5 variance}} \\ &= 1667 / 942 \\ &= 1.77 \end{aligned}$$

And, only the first principal component image has an increase in the SNR. The second and third component images have a greater amount of noise than in any of the original bands. The percentage of variance represented by the first principal component is approximately 90%, while the second accounts for 8% and the third represents the remaining 2%. A physical interpretation may be related to the fact that most of the land cover materials have very little spectral variation. The greatest variation is due primarily to bright and dark areas corresponding to albedo. If a surface feature is bright in one band it is most likely to be bright in other bands as well.

Inspection of the eigenvectors indicates that the band contributing the greatest amount to this first principal component is band 5, the band with the greatest variance.

The second principal component is being dominated by a contribution from band 2 which has the second greatest variance. And the last component, containing the least amount of variance is controlled by band 4.

3.4.2 STEP 2. Contrast Enhancement

This process consists of some type of contrast enhancement, which is always scene dependent. The amount of contrast stretching is dependent on the derived eigenvalues or variances of the component images. It is generally preferred to scale the data into an 8-bit range and not to enhance the noise at the same time.

3.4.3 STEP 3. Inverse Transformation

In the description of Principal Components, it was stated that the transpose of a matrix consisting of orthonormal vectors was equal to its inverse. The original transformation matrix and its transpose are listed below.

Original Transformation Matrix			Transpose		
0.5454	0.4206	0.7250	0.5454	0.7585	-0.3566
0.7585	0.1204	-0.6404	0.4206	0.1204	0.8992
-0.3566	0.8992	-0.2534	0.7250	-0.6404	-0.2534

The transpose is now the transformation matrix and the contrast enhanced principal component images are the original images.

4.0 IMAGE INTERPRETATION OF THE DIGITAL DATA

Standard photo interpretation techniques were used to generated lineaments overlays of each one of the data set produced over the study area. These were analyzed individually and then in conjunction with each other. Several interesting correlations were detected between AVHRR, Thematic Mapper lineaments, and aeromagnetic gradients. These correlations suggest that several of the prominent AVHRR and Thematic Mapper lineaments identified in the study area are surface expressions of basement structures.

4.1 Interpretation of Aeromagnetic Data

Most magnetic interpretations are based on quantitative analysis of measured anomalies and their relationship to theoretical anomalies of known models. The final goal of these methods is to gather information (in this case) about the Tertiary volcanic rock that placed between older nonmagnetic sediments and Quaternary alluvium.

We did not follow this approach, because of the main goal of this study was a lineament analysis. Instead a qualitative analysis of the data was done on a computer controlled interactive display, by overlaying the various data sets in different colors.

Due to the contrast in elevation, (flight spacing between the Nevada State magnetic anomaly data and the Timber Mtn survey) two different images were produced for the interpretation.

First, a two by two degree image was generated using the Nevada State magnetic anomaly data. This survey was reduced to the pole and the grid was resampled by MINC to 750 meters pixels. In order to enhance the interpreter's perception, a combined image was produced by adding the red, green and blue renditions of the density sliced image with the shaded relief representation of the resampled magnetic image (plate 8).

The combined image was displayed on a color monitor . The flat magnetic response corresponds to Quaternary alluvium sediments. The magnetic rough terrain response corresponds to the Calc-Alkaline igneous rocks.

There is one predominant linear feature represented on the image. The expression of the N 50 W trending negative magnetic lineament (plate 8) corresponds with the Walker Lane zone. This close spatial association suggest that AVHRR

lineaments identified in the study area are surface expressions of basement structures.

Second, a 45 by 45 minute image was produced using the high resolution Timber Mountain survey. The survey was resampled by MINC to 71 meters pixels. Once again a combined image was produced by adding the red, green and blue renditions of the density sliced image with the shaded relief representation of the resampled magnetic image. (plate 9).

A fault overlay was digitized from the southern Nye County geologic map. This overlay was registered to the Total field Timber Mountain magnetic image (plate 9). The mapped faults appear to be surface expressions of the basement lineaments.

An east west curvilinear magnetic lineament, south of Timber Mountain caldera (plate 9, location A-A'), has not been previously mapped. North south trending mapped faults, south of Timber Mountain caldera, terminate abruptly at this location. This indicates the utility of merging multi-data sets.

4.2 Gravity Data

Gravity images were not generated for this study. Due to poor resolution of the gravity data that was available to us (plate 10). We recommend that a high resolution survey be acquired over the area for future detail studies.

4.3 Interpretation of Satellite Imagery

The inherent spatial structure of the Basin and Range Province is such that it is possible to use a spatial resolution cell of approximately 9.3 kilometers and still retain the basic information content. Thematic Mapper 28.5 meter resolution cells were used to demonstrate this characteristic of the southwestern United States. Pixels were averaged and the local variance of a 3 by 3 resolution cell was determined (see plate 11). This result determined the choice of utilizing AVHRR satellite data for a regional display of structural blocks. Black/white imagery of the thermal channel is followed by a color composite of the thermal and reflected near-infrared for average cell sizes of 9.3, 6.2 and 3.1 kilometers, respectively (see plates 12 through 17, inclusive). The peak of the local variance in plate 11 indicates that 6.2 should reveal the basic characteristics of the province without much loss in detail. The structural blocks of interest are indeed displayed in a unique regional setting. By mapping lineaments on this type of imagery, it is apparent that there are three particular areas of importance. The Pahrana-gut Shear Zone, the Las Vegas Valley Shear Zone and its intersection with structures southeast and northwest of the Timber Mountain Caldera.

Previous work by this task has demonstrated that best band combination of Thematic Mapper imagery. With the additional processing of enhancing the inverted principal components, lithologic discrimination is simplified (see plate 18). With the enhanced data set, not only are various tuff units easily separated, but also individual members as well.

As stated earlier, higher order principal components relate to the spectral characteristics of the lithology. By combining the spatial resolution of the SPOT Image data with the spectral resolution of Thematic Mapper data additional lithographic and structural discrimination is possible. Plate 19 is an example of this type of enhancement. The hue and saturation of the 2nd, 3rd and 4th components of TM data was combined with intensity of SPOT and inverted back into RGB color space.

These two types of enhanced imagery will be provided for the three specified areas of interest which require additional and detailed geologic mapping. Specifically, the mapped lineaments on our imagery which probably coincide with the intersections of the Las Vegas Valley Shear Zone with the northwest and southeast Timber Mt. caldera and the Pahrana-gut Shear Zone.

5.0 CONCLUSION AND RECOMMENDATIONS

Previously funded studies have already established a geologic, geohydrologic, geochemical and seismic data base Subcontractors to the Department of Energy, as well as the various task groups within the Mackay School of Mines, have acquired and will continue to amass voluminous amounts of pertinent data concerning the character of Yucca Mountain. This important data base must not only be maintained but also integrated for full realization of its potential.

An Integrated Geographic Information System (IGIS) involves the integration of spatially referenced data in a problem solving environment. The ultimate goal of an Integrated Geographical Information System is to provide assistance in the decision making process by analyzing how the spatially referenced data interact as factors or variables. The interactions may be extremely complex and will necessitate the development of models which will establish the operations, sequences and feedback effects. The establishment of the dominant variables within this dynamic system will require an integration of approaches and procedures developed in a variety of disciplines that are related to Geographic Information Systems. Several of these disciplines are computer vision, image processing and digital cartography.

The merging of digital remote sensing data in raster format with the vectorized representations of map features for spatial analysis have been developed by these disciplines and is referred to as an integrated GIS (IGIS).

There are a number of recommendations which should be formalized at the conclusion of this report. These recommendations may be related to specific tasks or encompass all of the task groups within the Mackay School of Mines. Several of these suggestions should include all of the subcontractors for the State of Nevada Nuclear Waste Office.

1. The establishment of a permanent geologic, geophysical, geochemical and hydrological spatial data base. This data base should be digital and be permanently archived at the Mackay School of Mines.
2. Implementation of Arc-Info (a GIS) package for TASK 6.
3. Dissemination of all data collected by the Department of Energy and all of its subcontractors

4. All of the subcontractors should glean information from the extensive data base and derive appropriate models for its introduction into a Integrated Geographical Information System.
5. Establishment of a continual monitoring system.
6. Acquisition of high resolution gravity data over the test site and environs.
7. Specific geographical areas designated for detailed geologic mapping includes:
 - a. Paharanagut Shear Zone intersection with north-west trending lineaments.
 - b. Intersection of northwest and northeast trending lineaments on the southeast side of the Timber Mt. caldera.
 - c. northwest and southeast sides of the Timber Mt. area

It has been demonstrated that remote sensing and magnetic data have proven usefull for the delineation of previously unmapped linear features. Further study into the cause and mechanism for these features appears warranted. Correlation between satellite remote sensing data and aeromagnetic data suggest several prominent lineaments identified in the study area are surface expressions of basement structures.

6.0 REFERENCE

- Abdel-Gawad, M., and Tubbesing, L., 1974, Transverse shear in southwestern North America: A tectonic analysis: in Proceedings, First International Conference on the New Basement Tectonics, Salt Lake City, Utah, Utah Geological Publication #5, p. 61-80.
- Abdel-Rahman, M. A., 1976, A statistical method for determining the orientation relationship between geological variables: in Proceedings, Second International Conference on Basement Tectonics, Newark, Delaware, p. 486-490.
- Abdel-Rahman, M. A., and Hay, A. M., 1978, Sampling and statistical analysis of multi-modal orientation data: in Proceedings, Third International Conference on Basement Tectonics, Durango, Colorado, p. 73-86.
- Abrams, M. J., Conel, J. E., and Lang, H.R., 1984, The Joint NASA/Geosat Test Case Report, Final Report: Tulsa, Oklahoma: American Association of Petroleum Geologists, v.1/v.2.
- ANSI, 1970, Flowchart symbols and their usage in information processing: American National Standards Institute, ANSI X3.5-1970.
- Bernstein, R., and Ferneyhough, D. G., Jr., 1975, Digital image processing: Photogrammetric Engineering and Remote Sensing, v. 41, no. 12, p. 1465-1476.
- Bernstein, R., Lotspiech, J. B., Myers, J. H., Kolsky, H. G., and Lees, R.D., 1984, Analysis and processing of Landsat-4 sensor data using advanced image processing techniques and technologies: IEEE Transactions on Geoscience and Remote Sensing, v.GE-22, no. 3, p. 192-221.
- Baranov, V., 1957, A New Method for Interpretation of Aeromagnetic Maps, Pseudo-gravimetric Anomalies: Geophysics, Vol. 22, pp. 359-383
- Baranov, V. and Naudy, H., 1964, Numerical Calculation of the Formula of Reduction to the Magnetic Pole: Geophysics, Vol. 29, pp. 67-79
- Bhattacharyya, B.K., 1965, Two-dimensional Harmonic Analysis as a Tool for Magnetic Interpretation: Geophysics, Vol. 30, pp. 829-857
- Bhattacharyya, B.K., 1969, Bicubic Spline Interpolation as a Treatment of Potential Field Data: Geophysics, Vol. 34, pp. 402-423

- Beyer, E. P., Brooks, J., and Salomonson, V.V., 1984, Geometric correction of Landsat 4 and 5 Thematic Mapper data: International Symposium on Remote Sensing of Environment, v. 18, p. 89-100.
- Boregeson, W. T., Batson, R. M., and Kieffer, H.H., 1985, Geometrical accuracy of Landsat-4 and Landsat-5 Thematic Mapper images: Photogrammetric Engineering and Remote Sensing, v. 51, no. 12, p. 1893-1898.
- Buchanan, M. D., 1979, Effective utilization of color in multidimensional data presentations: SPIE Advances in Display Technology, v. 199, p. 9-18.
- Cappellini, V., 1983, Digital comparison and correlation techniques for Remote Sensing images having different space resolution: International Symposium on Remote Sensing of Environment, v. 17, p. 1121-1124.
- Carr, W. J., 1984, Regional structural setting of Yucca Mountain southwestern Nevada, and Late Cenozoic rates of tectonic activity in part of the southwestern Great Basin, Nevada and California: U. S. Geological Survey Open-File Report 84-854, 109 p.
- Carr, W. J., Byers, F. M., Jr., and Orkild, P.P., 1986, Stratigraphic and Volcano-Tectonic Relations of Crater Flat Tuff and Some Older Volcanic Units, Nye County, Nevada: U. S. Geological Survey Professional Paper 1323, 28 p.
- Chavez, P. S., Jr, O'Connor, J. T., McMacken, D. K., and Eliason, E., 1979, Digital image processing techniques of integrated images and non-image data sets: International Symposium on Remote Sensing of Environment, v. 13, p. 439-449.
- Chavez, P. S., Jr., 1984, Digital processing techniques for image mapping with Landsat TM and SPOT simulation data: International Symposium on Remote Sensing of Environment, v. 18, p. 101-116.
- Chavez, P. S., Jr., 1986, Digital merging of Landsat TM and digitized NHAP data for 1:24,000 scale image mapping: Photogrammetric Engineering and Remote Sensing, v. 52, no. 10, p. 1637-1646.
- Chavez, P. S., Jr., and Bauer, B., 1982, An automatic optimum kernel-size selection technique for edge enhancement: Remote Sensing of Environment, v. 12, p. 23-38.

- Chavez, P. S., Jr., and Berlin, G. L., 1984, Digital processing of SPOT simulator and Landsat TM data for the SP Mountain Region, Arizona: SPOT Simulation Applications Handbook: Falls Church, VA, American Society of Photogrammetry, p. 56-66.
- Chavez, P. S., Jr., Guptill, S. C., and Bowell, J., 1984, Image processing techniques for Thematic Mapper data: 50th Annual ASP-ACSM Symposium, American Society of Photogrammetry Falls Church, VA, p. 728-743.
- Cliche, G., Bonn, F., and Teillet, P., 1985, Integration of the SPOT panchromatic channel into its multispectral mode for image sharpness enhancement: Photogrammetric Engineering and Remote Sensing, v. 51, no. 3, p. 311-316.
- Colvocoresses, A. P., 1986, Image mapping with the Thematic Mapper: Photogrammetric Engineering and Remote Sensing, v. 52, no. 9, p. 1499-1505.
- Colwell, R. N., (editor), 1983, Manual of Remote Sensing: Falls, Church, VA, American Society of Photogrammetry, 2nd ed. 2440 p.
- Condit, C. D., and Chavez, P. S., Jr., 1979, Basic concepts of computerized digital image processing for geologists: U. S. Geological Survey Professional Paper 1462, 16 p.
- Crippen, R. E., 1986, The Regression Intersection Method of adjusting image data for band rationing: Presented at the Fifth Thematic Conference: "Remote Sensing for Exploration Geology", Reno, Nevada, September 29-October 2, 1986, 10 p.
- Crist, E. P., and Cicone, R. C., 1984, A physically-based transformation of Thematic Mapper data -- The TM Tasseled Cap: IEEE Transactions on Geoscience and Remote Sensing, v. GE-22, no. 3, p. 256-263.
- Crist, E. P., and Cicone, R. C., 1984, Application of the Tasseled Cap concept to simulated Thematic Mapper: Photographic Engineering and Remote Sensing, v. 50, no. 3, p. 343-352.
- Crist, E. P., and Kauth, R. J., 1986, The Tasseled Cap demystified: Photogrammetric Engineering and Remote Sensing, v. 52, no. 1, p. 81-86.
- Daily, M., 1983, Hue-Saturation-Intensity split-spectrum processing of Seasat radar imagery: Photogrammetric Engineering and Remote Sensing, v. 49, no. 3, p. 349-355.
- Darch, J. P., and Barber, J., 1983, Multitemporal Remote Sensing of a geobotanical anomaly: Economic Geology, v. 78, no. 4, p. 770-782.

- Davidson, M., 1968, Perturbation approach to spatial brightness interaction in human vision: *Journal of the Optical Society of America*, v. 58, no. 9, p. 1300-1308.
- Davis, J. C., 1986, *Statistics and Data Analysis in Geology*: New York, John Wiley & Sons, 646 p.
- De Grandis, L., and Trans. by Gilbert, J., 1986, *Theory and Use of Color*: New York, Harry N. Abrams, Inc., 159 p.
- Drury, S. A., 1986, Remote Sensing of geological structure in temperate agricultural terranes: *Geological Magazine*, 123 (2), p. 113-121.
- Ekren, E. B., Bucknam, R. C., Carr, W. J., Dixon, G. L., and Quinlivan, W.D., 1976, East-trending structural lineaments in central Nevada: U. S. Geological Survey Professional Paper 986, 16 p.
- Ekstrom, M. P., 1984, *Digital Image Processing Techniques*: Orlando, Florida, Academic Press, Inc., 372 p.
- EOSAT, 1985, Earth Observation Satellite Company, *User's Guide for Landsat Thematic Mapper Computer Compatible Tapes*: EOSAT, Lanham, Maryland.
- Ervin, C.P., 1976, Reduction to the Magnetic Pole Using a Fast Fourier Series Algorithm: *Computers and Geoscience*, Vol. 2, pp. 211-217
- ESL, 1983, *VAX-IDIMS functional guide*: Sunnyvale, Ca., ESL Inc., 506 p.
- Ford, G. E., and Zanelli, C. I., 1985, Analysis and quantification of errors in the geometric correction of satellite images: *Photogrammetric Engineering and Remote Sensing*, v. 51, no. 11, p. 1725-1734.
- Freeman, H., 1981, Scenes and Shapes: Map and line-drawing processing: In J.C. Simon and R.M. Haralick (eds), *Digital Image Processing: Proceedings of the NATO Advanced Study Institute held at Bonas, France, June 23-July 4, 1980*. Dordrecht, Holland, D. Reidel Publishing Company, p. 363-382.
- Gay, S. P., Jr., 1974, Standardization of azimuthal presentations: in *Proceedings, First International Conference on the New Basement Tectonics*, Salt Lake City, Utah, Utah Geological Publication #5, p. 499-500.

- Grenn, A.A., 1980, Combined Display of LANDSAT and Geophysical Data for improved Interpretation: in Official Program for the Sixth Annual Pecora Symposium and Exposition, pp. 101-102
Vol. 4, pp. 189-198
- Gillespie, A. R., 1976, Directional fabrics introduced by digital filtering of images: in Proceedings, Second International Conference on Basement Tectonics, Newark, Delaware, p. 500-507.
- Gillespie, A. R., 1980, Digital techniques for image enhancement: In B.S. Siegal and A.R. Gillespie (eds), Remote Sensing in Geology. New York, John Wiley & Sons, p. 139-226.
- Goldberg, M., 1981, Applications: Digital image processing of remotely sensed imagery: In J.C. Simon and R.M. Haralick (eds), Digital Image Processing: Proceedings of the NATO Advanced Study Institute held at Bonas, France, June 23-July 4, 1980. Dordrecht, Holland, D. Reidel Publishing Company, p. 383-437.
- Gonzales, R. C., and Wintz, P., 1977, Digital Image Processing: Reading, MA, Addison-Wesley Publishing Company, 431 p.
- Green, R. O., and Roberts, D. A., 1985, Mapping structure and related geobotanical phenomena using several dates of Landsat imagery: Presented at the Fourth Thematic Conference: "Remote Sensing for Exploration Geology", San Francisco, California.
- Guinness, E. A., Arvidson, R. E., Leff, C. E., Edwards, M. H., and Bindschadler, D.L., 1983, Digital image processing applied to analysis of geophysical and geochemical data for southern Missouri: Economic Geology, v. 78, no. 4, p. 654-663.
- Hallada, W. A., and Cox, S., 1983, Image sharpening for mixed spatial and spectral resolution satellite systems: International Symposium on Remote Sensing of Environment, v. 17, p. 1023-1032.
- Haralick, R. M., 1984, Digital step edges from zero crossing of second directional derivatives: IEEE Transactions on Pattern Analysis and Machine Intelligence, v. 6, no. 1, p. 58-68.
- Haydn, R., Dalke, G. W., Henkel, J., and Bare, J.E., 1982, Applications of the IHS color transform to the processing of multisensor data and image enhancement: International Symposium on Remote Sensing of Arid and Semi-Arid Lands, Cairo, Egypt, p. 599-616.
- Hebert, P., and Rouge, B., 1984, Digital image mosaics: International Symposium on Remote Sensing of Environment, v.18, p. 1263-1270.

- Hodgson, R. A., 1977, Regional Linear Analysis as a Guide to Mineral Resource Exploration Using Landsat (ERTS) Data: U. S. Geological Survey Professional Paper 1015, p. 155-171.
- Holroyd, M.T., 1978, Changes of Source Coding to Produce a 43 Percent Increase in CPU Efficiency in the Program for "Reduction to the Magnetic Pole Using A Fast Fourier Series algorithm": Computers and Geoscience,
- Horii, S., Oshima, Y., and Hirao, K., 1984, Digital mosaic processing: International Symposium on Remote Sensing of Environment, v. 18, p. 1785-1794.
- Hotelling, H., 1933, Analysis of a complex of statistical variables into principal components: The Journal of Educational Psychology, v. 24, p. 417-441, p. 498-520.
- Jeansoulin, R., 1981, Applications: Automated image-to-image registration, a way to multi-temporal analysis of remotely sensed data: In J.C. Simon and R.M. Haralick (eds), Digital Image Processing: Proceedings of the NATO Advanced Study Institute held at Bonas, France, June 23-July 4, 1980. Dordrecht, Holland, D. Reidel Publishing Company, p. 561-577.
- Kaneko, T., 1976, Evaluation of LANDSAT Image Registration Accuracy: Photo. Eng. and Remote sensing, Vol. 42, pp. 1285-1299
- Kowalik, W.S., 1980, Atmospheric Correction to LANDSAT Data for Limonite Discrimination: Ph.D dissertation, Stanford University, 365 p.
- Kauth, R. J., and Thomas, G. S., 1976, The Tasseled Cap -- A graphic description of the spectral-temporal development of agricultural crops as seen by Landsat: in Proceedings, Machine Processing of Remotely Sensed Data, Purdue University, West Lafayette, Indiana, 4B-41/4B-50.
- Koch, G. S., Jr., and Link, R. F., 1970, Statistical Analysis of Geological Data: New York, Dover Publications, Inc., vol.1 375 p.: vol.2 438 p.
- Kodak, 1984, Kodak professional black-and-white films: Rochester, NY, Eastman Kodak Company, 88 p.
- Kodak, 1986, Kodak color films and papers for professionals: Rochester, NY, Eastman Kodak Company, 132 p.
- Levandowski, D. W., Jennings, T. V., and Lehman, W.T., 1974, Relations between ERTS lineaments, aeromagnetic anomalies and geological structures in north-central Nevada: in Proceedings,

- First International Conference on the New Basement Tectonics, Salt Lake City, Utah, Utah Geological Publication #5, p. 106-117.
- Liggett, M. A., and Childs, J. F., 1977, An Application of Satellite Imagery to Mineral Exploration: U. S. Geological Survey Professional Paper 1015, p. 253-270.
- Malila, W. M., Metzler, M. D., Rice, D. P., and Crist, E.P., 1984, Characterization of Landsat-4 MSS and TM digital image data: IEEE Transactions on Geoscience and Remote Sensing, v. GE-22, no.3, p. 177-191.
- McDonnell, M. J., 1981, Box-filtering techniques: Computer Graphics and Image Processing, v. 17, p. 65-70.
- Moik, J. G., 1980, Digital Processing of Remotely Sensed Images: NASA SP-431: Washington, D.C., 330 p.
- NASA, 1986, Landsat to Ground Station Interface Description, Document GSFC 435- D-400: Greenbelt, Maryland, Goddard Space Flight Institute, Revision 9.
- Nassau, K., 1980, The Causes of Color: Scientific American, v. 243, no. 4, p. 124-154.
- Niblack, W., 1986, An Introduction to Digital Image Processing: London, England (UK), Prentice-Hall International Ltd., 215 p.
- O'Leary, D. W., Friedman, J. D., and Pohn, H.A., 1976, Lineament, linear, lineation: Some proposed new standards for old terms: Geological Society of America Bulletin, v. 87, p. 1463-1469.
- Pitas, I., and Venetsanopoulos, A. N., 1986, Nonlinear mean filters in image processing: IEEE Transactions on Acoustics, Speech and Signal Processing, ASSP-34, no. 3, p. 573-584.
- Podwysocki, M. H., and Gold, D. P., 1976, Some Possible Surface Expressions of a Regular Grid Deformed by Subsurface Structures: in Proceedings, Second International Conference on Basement Tectonics, Newark, Delaware, p. 542-559.
- Podwysocki, M. H., Gunther, F. J., and Blodget, H.W., 1977, Discrimination of rock and soil types by digital analysis of Landsat data: Goddard Space Flight Center, Publication X-923-77-17, Greenbelt, Maryland, 37 p.
- Potter, J. F., and Mendlowitz, M. A., 1975, On the determination of haze levels from Landsat data: in Proceedings, Tenth International Symposium on Remote Sensing of Environment, v. 10, p. 695-703.

- Pratt, W. K., 1978, Digital Image Processing: New York, John Wiley & Sons, 750 p.
- Ready, P., and Wintz, P., 1973, Information extraction, SNR improvements and data compression in multispectral imagery: IEEE Transaction on Communications, COM-21, no. 10, p. 1123-1131.
- Richards, J. A., 1986, Remote Sensing Digital Image Analysis: Berlin, Germany, Springer-Verlag, 281 p.
- Rosas, U., 1986, Vertical exaggeration in stereo-vision: theories and facts: Photogrammetric Engineering and Remote Sensing, v. 52, no. 11, p. 1747-1751.
- Rowan, L. C., and Wetlaufer, P. H., 1979, Geologic evaluation of major Landsat lineaments in Nevada and their relationship to ore deposits: U. S. Geological Survey Open-File Report 79-544, 64 p.
- Rowan, L. C., and Wetlaufer, P. H., 1981, Relation between regional lineament systems and structural zones in Nevada: American Association of Petroleum Geologists, v. 65, no. 8, p. 1414-1432.
- Sabins, F. F., 1978, Remote Sensing: New York, W. H. Freeman and Company, 449 p.
- Schowengerdt, R. A., 1983, Techniques for Image Processing and Classification in Remote Sensing: Orlando, Florida, Academic Press, Inc., 249 p.
- Sheffield, C., 1985, Selecting band combinations from multispectral data: Photogrammetric Engineering and Remote Sensing, v. 51, no. 6, 681-687.
- Short, N. M., 1982, The LANDSAT Tutorial Workbook, NASA Reference Publication 1078: Washington, D.C., 553 p.
- Shlien, S., 1979, Geometric Correction, Registration and resampling of LANDSAT Imagery: Can. Jour. Remote Sensing, Vol. 5, pp.74-89
- Siegal, B. S., and Short, N. M., 1977, Significance of operator variation and the angle of illumination in lineament analysis on synoptic images: Modern Geology, v. 6, p. 75-85.
- Skaley, J. E., 1980, Photooptical techniques of image enhancement: In B.S. Siegal and A.R. Gillespie (eds), Remote Sensing in Geology. New York, John Wiley & Sons, p. 119-138.

- Soha, J. M., and Schwartz, A. A., 1978, Multispectral histogram normalization contrast enhancement: 5th Canadian Symposium on Remote Sensing, Victoria, Canada, p. 86-93.
- SPOT, 1986, SPOT Image Corp., Format for Computer Compatible Tapes (Preliminary Release): Reston, Virginia, CNES and SPOT Image Corporation, 21 p.
- Strahler, A. H., Woodcock, C. E., and Smith, J.A., 1986, On the nature of models in Remote Sensing: Remote Sensing of Environment, v. 20, p. 121-139.
- Switzer, P., and Kowalik, W. S., 1981, Estimation of atmospheric path-radiance by the covariance matrix method: Photogrammetric Engineering and Remote Sensing, v. 47, no. 10, p. 1469-1476.
- Snyder, J. P., 1981, Space Oblique Mercator projection: mathematical development: U. S. Geological Survey Bulletin 1518, 108 p.
- Taranik, J. V., 1978, Principles of computer processing of Landsat data for geologic applications: U. S. Geological Survey Open-File Report 78-117, 50 p.
- Taranik, J. V., 1978, Characteristics of the Landsat multispectral data system: U. S. Geological Survey Open-File Report 78-187, 76 p.
- Taranik, J. V., and Trautwein, C. M., 1976, Integration of geological Remote Sensing techniques in subsurface analysis: U. S. Geological Survey Open-File Report 76-402, 60 p.
- Taylor, M. M., 1974, Principal components colour display of ERTS imagery: in Proceedings, Third Earth Resources Technology Satellite Symposium, p. 1877-1897.
- Thurrell, R. F., Jr., 1953, Vertical exaggeration in stereoscopic models: Photogrammetric Engineering and Remote Sensing, v. 19, p. 579-588.
- Van Der Horst, G., De Weert, C., and Bouman, M., 1967, Transfer of spatial chromaticity-contrast at threshold in the human eye: Journal of the Optical Society of America, v. 57, no. 10, p. 1260-1266.
- Walker, N. D., 1986, Remote Sensing analysis of southern Walker Lane [M.S. thesis]: Reno, University of Nevada, 117 p.
- Webring, M., 1981, MINC: A gridding program based on minimum curvature: U. S. Geological Survey Open-File Report 81-1224, 61 p.

- Werner, E., 1976, Graphical display of orientation data for visual analysis: in Proceedings, Second International Conference on Basement Tectonics, Newark, Delaware, p. 521-527.
- Wrigley, R. C., Card, D. H., Hlavka, C. A., Hall, J. R., Mertz, F. C., Archwamety, C., and Schowengerdt, R.A., 1984, Thematic Mapper image quality: Registration, noise and resolution: IEEE Transactions on Geoscience and Remote Sensing, v.GE-22, no. 3, p. 263-271.
- Zobrist, A. L., Bryant, N. A., and McLeod, R.G., 1983, Technology for large digital mosaics of Landsat data: Photogrammetric Engineering and Remote Sensing, v. 49, p. 1325-1335.

APPENDIX 1
THEMATIC MAPPER CHARACTERISTICS

THEMATIC MAPPER DESCRIPTION

The Thematic Mapper sensor is on board the Landsat series of satellites. Landsat 5 was launched in March 1984 and is essentially the same as Landsat 4. This is the second generation of Landsat satellites (4 and 5) and marks a significant advance in remote sensing through the addition of the more sophisticated sensor, the Thematic Mapper.

Orbit And Coverage:

There is a 185 kilometer east-to-west swathing pattern, where successive swaths are designed to overlap for complete surface coverage. It is a Sun-synchronous, near polar orbit at an altitude of approximately 705 kilometers. The equatorial crossing time is 09:45 a.m. with a 16 day 233 orbit cycle. This altitude permits a 30 meter ground resolution and the crossing time optimize the scanning parameters. At the Equator, adjacent swaths overlap at the edges by approximately 7 percent. This overlap increases as the satellite moves from the equator toward either pole because the orbit paths converge with increasing latitude.

Orbital Parameter:	Landsat 4 and 5 (nominal)
1. Altitude (km)	705
2. Semimajor Axis (km)	7083.465
3. Inclination (deg)	98.22
4. Period (min)	98.9
5. Time of Descending Node Equatorial Crossing (local time)	09:45 a. m.
6. Coverage Cycle Duration	16 days (233 revs)
7. Distance Between Adjacent Ground Tracks at Equator (km)	172

Worldwide Reference System:

During ground processing, the continuous data stream from the sensors is divided into separate scenes or frames. Each

1 of 5 scene displays an area of 100 by 100 nautical miles in an approximately square format. There are 233 ground tracks of Landsat 4 and 5 which define the paths in the WRS. Each path contains 248 rows, a row being the center line of latitude through a framed scene along any given path.

Subsystems:

For the Landsat sensors to obtain usable data, the spacecraft must be properly oriented relative to the Earth. The Landsat attitude control subsystem achieves a three-axis pointing accuracy of 0.01 degree and a stability of 10 to the -6 degree per second.

The TM is a scanning optical sensor operating in the visible and near infrared wavelengths. It contains a scan mirror assembly that directly projects the reflected Earth radiation on to detectors arrayed in two focal planes. It relies on the forward motion of the spacecraft for the along-track scan and uses a moving mirror assembly to scan in the cross-track direction (perpendicular to the spacecraft). The instantaneous field of view (IFOV) for each detector for bands 1 through 5 and band 7 is equivalent to a 30 meter square when projected on the ground. Band 6 has an IFOV equivalent to a 120 meter square. These data are resampled during geometric processing to produce a 28.5 meter IFOV. Radiometric sensitivity is achieved through a digitizing scheme that encodes all radiometric data telemetry information into 8 bit "words". This permits the observation of fine changes in the radiometric response for each band and provides a greater sensitivity to changes in the relationship between bands. The characteristics are listed below.

Spectral Band	micrometers	radiometric sensitivity	IFOV	Quantization level
1	0.45 - 0.52	0.8%	30 m	256
2	0.52 - 0.60	0.5%		
3	0.63 - 0.69	0.5%		
4	0.76 - 0.90	0.5%		
5	1.55 - 1.75	1.0%		
7	2.08 - 2.35	2.4%		
* 6	10.40 - 12.50	0.5K (NE T)	120 m	

* Thermal Band with a noise equivalent change in temperature

Scan Mirror:

The elliptical scan mirror is located above the Sun shade opening which enables the telescope to operate at very small field angles. The object space angle, or swath angle, that the scan mirror travels during an active scan is approximately 15.39 degrees. The mirror sweeps the TM line-of-sight back and forth 7 times per second to collect data during both the forward (west-to-east) and the reverse (east-to-west) scans, with a scanning efficiency of 85 percent.

Scan Line Corrector:

If only the motion of the scan mirror were used to reflect the ground imagery into the TM, part of a sweep would contain redundant data and part would miss data completely. Oscillating at a rate twice that of the scan mirror, two mirrors, parallel to one another but rotating around a common axis, rotate the TM line of sight backward along the ground track to generate scan lines that are straight and perpendicular to the ground track for both scan directions.

Focal Plane Arrays:

The filtered detector systems for the seven spectral bands are placed directly on the focal planes. Sixteen silicon detectors are used for each of the four visible spectral bands (bands 1 through 4) and are on the uncooled prime focal plane. Bands 5, 6 and 7 require cooled detectors to achieve the necessary radiometric sensitivity. There are 16 indium antimonide detectors each for bands 5 and 7 and 4 mercury cadmium telluride detectors for band 6, the thermal band. During each sweep of the scan mirror, 16 scan lines of data are produced for each one of bands 1 through 5 and for band 7; 4 scan lines are produced for band 6. The ground distance covered by a scan line varies with changes in satellite altitude; this variation is usually within a 4 km range. The total output of 100 scan lines (or signal channels) is the data to be relayed to Earth. The detector arrays translate the radiant energy from a scene into low-level electrical signals that are amplified by the preamplifiers and frequency-boosting post-amplifiers, converted into 8 bit words and merged into the 84.9 mega bits per second data stream.

Internal Calibrator:

The internal calibrator is synchronized with the scan mirror.

During the turnaround period of the scan mirror, the 3 of 5 shutter introduces the calibration source energy and a black direct-current restoration surface into the 1000 detector fields of view. The calibration signals for bands 1 through 5 and band 7 are derived from three, regulated tungsten filament lamps. The calibration source for band 6 is a "blackbody" with three temperature selections.

Ground System:

The data processing facility at Goddard Space Flight Center (GSFC) processes the raw sensor data through the TM Image processing System (TIPS). The raw data are recorded on 28 track high-density tapes and are achieved. The major functions of TIPS are:

1. screening imagery for quality
2. applying radiometric corrections
3. computing sets of geometric corrections corresponding to different map projections
4. applying a set of geometric corrections
5. determining cloud cover
6. generating user products

The Space Oblique Mercator (SOM) is the standard map projection applied to TM scenes.

TM Image Processing:

Transmitted digital image data have some degree of distortion because of characteristics of the sensing and recording systems as well as of atmospheric and scene conditions. Radiometric distortions derive from blurring effects of the sensor system itself, transmission noise, atmospheric interference, variable surface illumination and changes in surface radiance due to changes in the viewing angle. Geometric distortion arises from spacecraft effects, such as attitude and altitude changes; Earth effects caused by its curvature, rotation, terrain relief and temporary aberrations in the scanning system. These distortions must be corrected during processing.

The image consists of sequential rows of digital data for each spectral band. Within each row are individual picture elements called pixels. These are the fundamental units of the data structure. Each raw pixel constitutes a mutually exclusive area of the Earth's surface and is digitized according to pixel brightness level. Digitization results in a single number from 0 to 255 being assigned to each pixel as it is acquired. During processing, these pixels are forced to overlap; this avoids data gaps. The existence of 256 gray levels, or digital counts,

allows the representation of fine detail and mitigates the contouring effect in which the human visual system sees discrete 4 of 5 rather than gradual brightness changes. The finer the sampling and the quantization, the better the approximation of the original data. The digital data are loaded onto CCT's in band sequential (BSQ) format. The digital images are produced in fully calibrated form; that is, both radiometric and geometric corrections have been applied. Two types of CCT's can be produced. CCT-AT's consist of image data that have been fully corrected radiometrically (geometric corrections are appended to the data but have not been applied). CCT-PT's have both corrections applied. The consequence of the geometric correction is that scan lines lose their one-to-one identification with a unique detector after the data are mathematically resampled.

Products:

The digital product that we have acquired consist of the following options:

1. 9 track CCT's
2. 6250 bpi
3. CCT-PT's (radiometric and geometric corrections)
4. cubic convolution resampling
5. Space Oblique Mercator projection

Computer Compatible Tape Format

See reference for the user guide.

All TM CCT's will have a print-out of the pertinent files which relate to ephemeris data, acquisition date, sun elevation angle, sun azimuth and all scene header record information.

APPENDIX 2
SPOT IMAGE CHARACTERISTICS

SPOT DESCRIPTION

The SPOT system comprises:

1. the SPOT satellite which has two parts:
 - a. the platform
 - b. the mission specific payload
2. the ground segment consisting of:
 - a. ground control
 - b. ground image reception segments

Choice of spectral bands:

Band limits at half maximum response are:

Band	micrometers	spatial resolution (meters)
XS1	0.50 - 0.59	20
XS2	0.61 - 0.68	20
XS3	0.79 - 0.89	20
*Pa	0.51 - 0.73	10

*Pa is the panchromatic band

Due to the greater number of spectral bands in the Thematic Mapper sensor, the multispectral SPOT data was not deemed appropriate in spite of its greater spatial resolution. However, the panchromatic band with its 10 meter spatial resolution was chosen.

Choice of Orbit:

To achieve a constant resolution and global coverage at reasonable sun angles throughout the year, a circular, sun-synchronous orbit was chosen. SPOT was chosen to have a midmorning (10: 30 a.m.) descending node. The orbital characteristics are summarized below.

Revolutions/day	14	+	5/26
Nodal period	101.46	min	
Mean altitude (45 deg N)	832	km	

Inclination (mean)	98.37 deg
Orbital (repeat) cycle	26 days
Number of tracks per orbital cycle	369
Intertrack distance (equatorial)	108.4 km
Mean local solar time at descending node	10:30 a.m.

SPOT 1 Payload:

This includes two identical high-resolution visible range instruments (HRV). The instruments are pointable in the across track direction in order to allow rapid access to any point on the globe and the acquisition of stereoscopic image pairs from different satellite passes. The HRV system performance specifications are summarized below only for the panchromatic band.

Radiometric Performance

Parameters	Panchromatic
Spectral band	0.51 - 0.73 micrometers
Detector IFOV	1.2 X 10 to the minus 5th Detect.
Detector, numbers per line	6000
Modulation transfer function:	
to CCD line	0.26
along CCD line	0.27
SNR at radiance, max	>233
On-orbit calibration (%)	
Relative	1
Absolute	10
Number of gains	8
Signal encoding, bit	6 or DPCM (8/5/5/8)

Geometric Characteristics

Ground swath width	60 km/HRV
Off-nadir viewing capability (field center)	117 km SPOT payload + or - 27 deg or 460 km on ground
Ground resolution	10 m

The off-nadir viewing mechanism will have an absolute pointing accuracy (without ground calibration) of 4×10^{-4} to the negative fourth power rad for any position within a range of + or - 27 degrees.

The HRV instrument includes a "push-broom" technique for image generation, thus eliminating the need for a mechanical scanner. A wide-angle optical assembly images the totality of 2 of 4 the line (perpendicular to the satellite ground track) over a linear array of solid-state detectors that are sampled at the appropriate frequency as the satellite moves along its orbit. The charge-coupled devices (CCD's) made this possible.

Calibration:

In order to maintain the radiometric accuracy of the instrument during its lifetime in orbit and to correct for changes in response that may occur, the HRV is equipped with a calibration system placed under ground control. This device provides a means for relative calibration by using a lamp of known radiance. Alternatively, a known quantity of solar flux is allowed to enter and be focused on the CCD's providing high precision absolute calibration.

Image Reception and Processing:

Data are transmitted to Toulouse, France for processing for the data takes in the United States (at the inception of the SPOT system) with other facilities coming on-line at later times. The processed data is then transferred to the United States to be distributed by SPOT Image, Corp. of the United States. Product output consist of various levels:

Level 1A

1. Radiometric corrections: detector gain and offset correction
2. Localization accuracy: 1500 meters rms for nadir viewing
3. Panchromatic scenes contain 6000 pixels along each of the 6000 scanlines

Level 1B

All corrections for level 1A, including

1. bulk geometric processing to remove earth rotation effects

2. scenes resampled in the across track direction to remove off nadir imaging effects.
3. resampling of image data to a 10 meter pixel

Level 2

These corrections were not available at the time of acquisition

SPOT imagery has been acquired with the following specifications:

1. CCT's at 6250 bpi
2. Level 1B processing
3. Vertical acquisition
4. Off nadir (approximately 27.5 deg) acquisition

APPENDIX 3
AEROMAGNETIC DATA REDUCTION

AEROMAGNETIC DATA REDUCTION

1. The total field airborne magnetometer data was corrected for diurnal variation and instrument drift.

2. **RESIDUAL TOTAL-FIELD-MAGNETIC.**

Was prepared by removing the International Geomagnetic Reference Field as described by IAGA Bulletin No. 38 "Grid values and charts by the IGRF 1987.0" from the final corrected total field data.

The values were computed by using the date and elevation of the observation at the locations where the IGRF values were determined. Since the IGRF field is nonlinear, the IGRF values was computed at intervals no larger than 15 minutes of latitude or longitude. Linear Interpolation was used between computed values. These correction were performed by Applied Geophysics, Inc.

3. **REDUCTION TO THE POLE.**

The mathematics and explanation of this technique have been described by Baranov (1957), Baranov and Naudy (1964), and Bhattacharyya (1965). Basically this operation transforms magnetic anomalies produced by an inclined magnetic field to anomalies which would have been produced by a vertical field. This transformation produces the anomaly that would be observed if the geological source was physically moved to the magnetic pole. THE OPERATION ASSUMES THAT ALL OF THE MAGNETIZATION MEASURED IS DUE TO INDUCED MAGNETIZATION, NOT REMNANT MAGNETIZATION. After the transformation, the peaks of the anomalies should directly overlie the magnetic sources. The computer program FFTFIL by Thomas Hildenbrand was used for the conversion to the pole.

4. **SURVEYS CHARACTERISTICS**

Name Project	Year Flown	Elevation (ft)	Flight-line Spacing(mi)	Flight-line Direction	Report
1.) Timber Mtn.	1977	400'	.25	E-W	of 79-587
2.) Nevada State Magnetic	1987	1000'	.7	N-S	D 87-0270
3.) Lathrop Wells (3137)	1978	400'	.25-.5	N-S	OF 78-1103

APPENDIX 4
GRAVITY DATA CHARACTERISTICS

GRAVITY DATA

DATA TYPE = Gravity data state of Nevada

DATA SOURCE = National Geodetic Survey

DATA DESCRIPTION = The NGS file contains about 40,000 gravity stations with terrain corrections for the state of Nevada.

Gravimetric parameters include:

	Precision	Reference
Observed gravity	0.001 mgal	IGSN-71
Free-air anomaly	0.1 mgal	IAG-67
Bouguer anomaly	0.1 mgal	=1.67 g/cm
Terrain correction (if available)	0.1 mgal	

Supplemental data include latitude and longitude (precision, 0.00001); elevation (precision, 0.1 m); standard deviation for the free-air and Bouguer anomalies; and codes for quality, contributing agency, and source.

FORMULAS USED IN COMPUTING FREE-AIR AND BOUGUER ANOMALIES IN THE NGS FILE

1. Symbology

Symbol	Definition	Units
gf	free-air anomaly	miligals
gb	Bouguer anomaly	miligals
	Latitude of observation	degrees, minutes
	Theoretical gravity	miligals
g	Observed gravity	miligals
h	Elevation (col. 23-29) of surface of land, ice, or water; depth of ocean (positive downward), elevation types 3, 4, and 5. + = above sea level; - = bellow sea level.	meters
d	Supplemental elevation (col. 31-35) = depth of ocean, lake, ice, or instrument (positive downward).	meters

2. Anomaly Computations (see table)

b = Bouguer Correction Factor = 2 = 0.04191

= Density Used in computations

Substance		b = 2
Fresh water	1.0	0.04191
Salt water	1.027	0.04304
Ice	0.917	0.03843
Land	2.67	0.1119

Land; fresh water	1.67	0.06999
Land; salt water	1.643	0.06886
Land and ice	1.753	0.07347

APPENDIX 5
AVHRR DATA CHARACTERISTICS

Advanced Very High Resolution Radiometer

NOAA-G was launched in September of 1986 and was renamed NOAA-10. The satellite was designed to operate in a near-polar, sun-synchronous orbit. The orbital period is about 102 minutes which produces approximately 14 orbits per day. The descending node (southbound Equator crossing in Local Solar Time (LST) is 0730. The AVHRR instrument has 4 channels. Only two channels were utilized. Channel 2, which is sensitive to near-infrared wavelengths and channel 4, responding to broadband thermal infrared energy. Redwood City, California maintains a 90-day rotating file of only 8-bit data. The loss of 2-bits in precision is inconsequential, since only relative values are of any import. Local Area Coverage (LAC) normally has a 1.1 kilometer resolution cell on the ground. This occurs only directly underneath the satellite. A scanning sensor with a rotating mirror sweeps through equal angles in equal time intervals. And, it generally scans in a direction normal to the flight path. Thus, each sample represents a view at a given angle along the sweep. They are spaced evenly in angular increments but not in ground distance. Samples are closer together at the nadir than at the extremes. Distortion is described by the equation:

$$X = H \tan O$$

where,

X = total ground distance from nadir

H = sensor altitude

O = total angular spacing from nadir

Correction for the uniform angular sample was performed to convert into a nonuniform ground spacing and then resampled to achieve a uniform ground spacing.

A correction to a UTM projection was not performed however, which accounts for most of the distortion in the imagery. It was reasoned that the satellite data was to only contribute information concerning large structural blocks.

PLATE 1

PLATE 2

TOTAL FIELD
SUN AZIMUTH = 0
SUN ELEVATION = 25

PLATE 3

TOTAL FIELD
SUN AZIMUTH = 45
SUN ELEVATION = 25

PLATE 4

TOTAL FIELD
SUN AZIMUTH = 65
SUN ELEVATION = 25

PLATE 5

TOTAL FIELD
SUN AZIMUTH = 90
SUN ELEVATION = 25

PLATE 6

TOTAL FIELD .
SUN AZIMUTH = 135
SUN ELEVATION = 25

PLATE 7

PLATE 8

PLATE 9

GRAVITY STATIONS

PLATE 10

PLATE 11

NDAA-10 AVHRR CH 4 LAC AVNL = 3 AVNS = 3

PLATE 12

NDAA-10 AVHRR 4 2 2 = R 6 B LAC AVNL = 3 AVNS = 3

PLATE 13

NDAA-10 AMBER CH 4 LAC AYRL = 2 AMRS = 2

PLATE 14

NDAA-10 AMRR 4 2 2 = R 6 B LAC AMEL = 2 AMYS = 2

PLATE 15

NDAA-10 AMRR CH 4 LAC AVTL = 1 AVNS = 1

PLATE 16

NDA-10 AMER 422-R6B LAC AMIL = 1 AMIS = 1

PLATE 17

THIS INV PC 541 - R E B AWL - 2 AMB - 2

PLATE 18

NUCCA MT, NU PC 2 3 4 -- I S H --> SPOT S H --> R G B

PLATE 19

FINAL REPORT - TASK 7
GEOTECHNICAL AND ROCK MASS ASSESSMENT

Period covered : January 1, 1987 - June 30, 1988

Principal Investigators : Robert J. Watters and James R. Carr

This report covers two subtasks within the main task :

- a) Rock properties and acoustic emissions.
- b) Fractals and fractal dimension.

Task 7a - Rock Properties and acoustic emissions.

Experiments were performed to investigate two major areas.

1. The material properties and mechanical behavior of the welded to partially welded tuff.
2. The acoustic emission response of the welded to partially welded tuff.

1. MATERIAL PROPERTIES

Six different rock types were tested for their material properties. The properties tested were unconfined compressive strength, Young's modulus, density, unit weight, and porosity. The rocks varied from partly-welded to densely-welded tuffs of the Topopah Spring Member of the Paintbrush Tuff. Descriptions of the samples used are listed in Table 1. Photographs of cored samples and sample location are shown in Figures 1 through 5, and demonstrate both the dense and lithophysae nature of the tuffs. The samples were all collected from the Yucca Mountain region.

Strength testing :

Unconfined compressive strengths were determined by taking cores from the various samples and tested using an MTS model 315.02A-02 test frame and model 458 MicroController. The load frame has a capacity of 600,000 lb (2669 kN) and a spring rate of 6.00×10^7 lb/in. (10.5×10^9 N/m). Average strength values ranged from 4698.6 psi for the moderately-welded tuff (sample type SMF05) to 39,042.3 psi for the densely-welded tuffs (sample types SMH06 and SMH11). Young's Modulus values were determined for two of the units, SMF05 had an average modulus of 3.126×10^6 psi and SMH06 a modulus of 11.71×10^6 psi. A summary of the strength values for all of the samples is shown in Table 2.

Density and porosity testing :

Density and porosity values were obtained for the six rock types using the pulverizing method. In this method, a sample of known volume is dried in an oven for 24 hrs at 110°C. The sample is weighed to determine the density. It is then pulverized in order to determine the porosity of the rock. The resulting densities, porosities, and unit weights of the samples are listed in Table 3. It should be noted that this method does give quite a variation in results. Also, the samples themselves vary greatly due to the location of lithophysae and where the cores were taken from the original sample.

2. ACOUSTIC EMISSION STUDIES

One of the goals of the study was to compare the acoustic emission signatures of the samples and determine if there were any differences due to porosity and density of the rocks.

Equipment :

The acoustic emission studies were performed using an Acoustic Emission Technology 5000A system. The system includes piezoelectric sensors, preamplifiers, the main processing computer, and a computer terminal and printer to display the results. The sensors used were AET type AC175L sensors with a nominal resonant frequency of 175kHz. Sensor serial no.7394 was used for channel 1 and no.7414 used for channel 2. Calibration charts for these two sensors are shown in Figures 6 and 7. The signals from the sensors were fed into AET model 160B preamplifiers which provide a 60 dB gain.

Signals for channel 1 were filtered for a range of 125kHz to 250kHz. Channel two was filtered with a wideband filter of 1kHz to 50kHz. The signals were then passed to the AET 5000A where an additional 8 dB of amplification was provided for a total system gain of 68 dB. The AET 5000A then processed the signals and provided the resulting graphs. The detection threshold used was a floating 1.00v to help eliminate background noise. The acoustic emissions were produced by stressing the rock samples in the MTS load frame described above. The samples were studied for the following information: acoustic emissions versus time and distributions of the parameters peak amplitude, event duration, ringdown counts, rise time, and slope. A good discussion of these parameters can be found in Beattie, 1983. Representative resulting displays are shown in Figures 8 through 55.

Results :

The typical events versus time display consists of high activity at the beginning of loading. This is the result of pore and fracture closing. Activity then quiets down until failure is imminent or has occurred. The differences between samples are seen for channel 1 data (125kHz - 250 kHz) in the beginning of loading and the quiet period before failure. The densely-welded sample SMH11-03 (Fig.8) shows the initial noise peak at the onset of loading and then activity disappears during the elastic stage. Activity does not increase again until failure occurs. Sample SMF02-04 (Fig.9) is also a densely-welded tuff but contains numerous lithophysae thus providing more activity throughout the test than does SMH11-03. For sample SMF05-01 (Fig.10), which is less dense and more porous, there is more activity involved at the onset of loading and acoustic emission activity remains high for the duration of the loading. Sample SMH14-02 (Fig.11) also

shows this trend. The wideband data (1kHz to 50kHz) from channel 2 (Fig.12-15) does not appear to show much difference between the four samples. This may indicate some frequency dependence among changes in acoustic emissions due to porosity and density.

The biggest differences in acoustic emission characteristics among the samples can be seen in the distributions of events according to peak amplitude. From the sensor one data for the densely-welded sample, SMH11-03 (Fig.16), the peak amplitudes of the signal range in a narrow band from about 59dB to 68 dB with the majority of the events having a peak amplitude of 63dB. At the other end of the spectrum we have a much wider range of peak amplitudes for the less dense, partially-welded samples of SMF05-01 and SMH14-02 (Fig.18 & 19). For SMF05-02 the range of peak amplitudes is from about 49dB to 78dB with the majority of the events ranging from 53dB to 59dB. For SMH14-02 (Fig.17) the range is about the same with the majority range from 53dB to 57dB. Sample SMF02-04 which is densely welded but contains several lythophysae there is a narrower range of peak amplitudes for the majority of the events but it is still a wider range than that of SMH11-03 which does not contain any lythophysae.

Differences can be seen in the peak amplitude distributions for sensor two. For the densely-welded tuff, the majority of events have a peak amplitude of about 73dB with a much smaller number of events existing at about 62dB. For SMF02-04 (Fig.21), which is the densely-welded tuff with lythophysae, there is still a greater number of events above 70 dB than below, but we see an increase in the number of events with peak amplitudes at about 56dB. Continuing on to the less dense, partly-welded tuffs we see that the majority of the events now have peak amplitudes of about 58dB and very few events have peak amplitudes of greater than 70 dB. The distributions based on peak amplitudes may also give clues as to the main processes involved in the failure of the rock. In the densely-welded materials, the main cause of failure is fracture. In the more porous material, there is the addition of pore closure and void collapse adding to the overall failure of the rock.

The acoustic emission parameters, ringdown counts, event duration, rise time, and slope, did not appear to show any significant variations among the tests. See figures 24 to 35.

Kaiser effect :

The property known as the Kaiser effect was studied. The Kaiser effect is a way of determining any prior stress history of a material. Two samples, SMF05-01 and SMF05-02, were each preloaded to a load of about half of their ultimate compressive strength. Sample SMF05-01 was held at that load for 1 week and SMF05-02 was loaded for 24 hours. Each sample was then unloaded and tested in the MTS frame. The Kaiser effect was not detectable for either sample. The Kaiser effect was detected, though, during the

testing series for sample SMH06-04 (see Figures 56&57). During test 5 of the series, the sample had been loaded to 39.7 kips (1kip = 1000lb). During test 6, the load was carried out to a much higher level. Looking at Figure 56 which displays total events versus time, it can be seen that there is at first a gradual increase in the number of events followed by a change to a higher rate of events. The point at which this change in rate occurs corresponds to a load of 38.82 kips as seen on Figure 57 which displays analog parameter 1 versus time. The voltage displayed corresponds to the load being applied by the MTS load frame. In this case the full scale reading is 10 volts = 120 kips. It is interesting to note that the Kaiser effect was seen in the densely-welded tuff but not seen in the partly-welded tuffs. Future work should involve seeing how long the Kaiser effect can be retained by samples.

CONCLUSIONS

The unconfined compressive strength, Young's modulus, porosity and density values concur with previously obtained data from DOE contractors.

It appears to be possible to discriminate between porous and less porous tuff using Acoustic emission techniques. This is especially true when one studies events versus time and peak amplitude differences for tuffs with different porosities. The signature also show changes with changes in density of the material. Further research into discriminating between porosity due to pores and porosity due to fractures utilizing acoustic emission techniques should be pursued. This research could yield a workable relationship for establishing the percentage porosity due to pores verses fractures and its applicability to rockmass permeability.

The Kaiser effect was observed in the tuffs, but this appears to be true for the denser tuffs than for the less dense.

REFERENCE

Beatty, A.G., 1983, Acoustic emission, principles and instrumentation, Journal of Acoustic Emission, vol. 2, no. 1/2, pp.95 - 128

TABLE 1
Sample Descriptions

SAMPLE TYPE	DESCRIPTION
SMF01	- densely welded, pale red color, convolute and oblate lithophysae present
SMF02	- same as above
SMF05	- moderately welded, very light grey with flattened pumice fragments
SMH06	- densely welded, nonlithophysal, moderately dark grey
SMH11	- same as SMH06 .
SMH14	- moderately welded, pinkish grey, pumice fragments and some lithophysae
SMH15	- partly welded light brown pumiceous tuff, probably caprock

TABLE 2
Average Strength Values

<u>SAMPLE</u>	<u>UNCONFINED COMPRESSIVE STRENGTH</u> (σ_c)		<u>YOUNG'S MODULUS</u> ($\times 10^6$ PSI)	
SMF01	10,918.35 psi	75.28 MPa		
SMF02	17,408.50 psi	120.03 MPa		
SMF05	5,222.52 psi	36.01 MPa	3.13	21.58 GPa
SMH06	36,887.35 psi	254.33 MPa	11.71	80.74 GPa
SMH11	31,774.65 psi	219.08 MPa		
SMH14	6,507.05 psi	44.86 MPa		
SMH15	8,729.55 psi	60.19 MPa		

STATISTICS

<u>SAMPLE</u>	<u>n</u>	<u>ave.</u>	<u>σ</u>	<u>Σx</u>	<u>Σx^2</u>
SMF01	2	10,918.35	4326.3	21,836.7	2.57×10^8
SMF02	1	17,408.50			
SMF05	5	5,222.52	397.8	26,112.6	1.37×10^8
SMH06	2	36,887.35	179.2	73,774.7	2.72×10^9
SMH11	2	31,774.65	10,278.0	63,549.3	2.12×10^9
SMH14	2	6,507.05	2151.2	13,014.1	89,311.19
SMH15	2	8,729.55	1995.8	17,459.1	1.56×10^8

TABLE 3
Average Material Properties

SAMPLE	DENSITY (g/cm ³)	UNIT WEIGHT (lb/ft ³)	POROSITY
SMF01	2.24	139.5	13.5%
SMF02	2.29	143.0	12.4%
SMF05	1.99	124.3	22.3%
SMH06	2.26	140.7	9.9%
SMH11	2.23	139.2	9.5%
SMH14	2.03	126.7	21.8%
SMH15	2.16	134.8	17.4%

STATISTICS

DENSITY:

Sample	n	ave.	σ	var.	Σx	Σx^2
SMF01	3	2.24	.03055	.00093	6.71	15.01
SMF02	4	2.29	.05123	.00262	9.17	21.03
SMF05	4	1.99	.02672	.00082	7.97	15.88
SMH06	4	2.26	.02644	.00070	9.02	20.34
SMH11	4	2.23	.01154	.00013	8.92	19.89
SMH14	4	2.03	.03741	.00140	8.12	16.49
SMH15	4	2.16	.01825	.00033	8.64	18.66

POROSITY

Sample	n	ave.	σ	var.	Σx	Σx^2
SMF01	3	13.5	4.0796	16.643	40.4	577.34
SMF02	3	12.4	1.8502	3.423	37.3	470.61
SMF05	4	22.3	1.9619	3.849	89.3	2005.17
SMH06	4	9.9	6.3903	40.836	39.5	512.57
SMH11	4	9.5	2.5013	6.257	37.8	375.98
SMH14	4	21.8	2.1282	4.529	87.1	1910.19
SMH15	4	17.4	3.2042	10.267	69.6	1241.84

UNIT WEIGHT

Sample	n	ave.	σ	Σx	Σx^2
SMF01	3	139.5	1.8877	418.6	58,415.78
SMF02	4	143.0	3.1669	572.1	81,854.69
SMF05	4	124.3	1.7758	497.2	61,811.42
SMH06	4	140.7	1.6194	562.9	79,221.97
SMH11	4	139.2	0.7506	556.6	77,452.58
SMH14	4	126.7	2.3252	506.8	64,227.78
SMH15	4	134.8	1.1325	539.1	72,661.05

Figure 1
Photograph showing the distribution of lithophysae
in the Tiva Canyon Member on Busted Butte

Figure 2
Photograph showing a close-up of a lithophysa
in the Tiva Canyon Member, Busted Butte

Figure 3
Photograph of the Topopah Spring Member near Yucca
Mountain. Profilometer shows depth of lithophysae
at this particular location.

Figure 4 (top) shows a core from sample SMF02, a densely welded tuff with lithophysae. Figure 5 (bottom) shows a core of densely welded tuff without lithophysae.

SENSOR CALIBRATION RECORD

Figure 6

AET Corp. • 1824 J Tribute Road
 Sacramento, California 95818 • USA
 Phone: (916) 927-3881 Telex: 171-368

DONE BY 1824J
 DATE 7/24/87

MODEL AC175L
 SERIAL NO. 7394

SENSOR CALIBRATION RECORD

Figure 7

AET Corp. • 1824J Tribute Road
 Sacramento, California 95816 • USA
 Phone: (916) 927-3861 Telex: 171-358

DONE BY Barry
 DATE 10/16/87

MODEL AE75L
 SERIAL NO. 7414

ELAPSED TIME = 00:23:50

SNH11-03 TEST 3

Figure 8

SAMPLE SMF02-04 TEST 1
ELAPSED TIME = 00:07:48

Figure 9

SMF05-01 TEST 1 ELAPSED TIME = 00:12:30

Figure 10

SMH14-02 TEST 1
ELAPSED TIME = 00:13:18

Figure 11

ELAPSED TIME = 00:23:45

SMH11-03 TEST 3

Figure 12

ELAPSED TIME = 00:07:39

SMF02-04 TEST 1

Figure 13

Figure 14

SAMPLE SMH14-02 TEST 1 ELAPSED TIME = 00:13:26

Figure 15

SAMPLE SMH11-03 ELAPSED TIME = 00:07:11
TEST 1

Figure 16

ELAPSED TIME = 00:07:39

SMF02-04 TEST 1

Figure 17

SNF05-01 TEST 1 ELAPSED TIME = 00:12:30

Figure 18

SMH14-02 TEST 1 ELAPSED TIME = 00:13:18

Figure 19

SMH11-03 TEST 3 ELAPSED TIME = 00:23:45

Figure 20

ELAPSED TIME = 00:07:39

SMF02-04 TEST 1

Figure 21

SMF05-01 TEST 1 ELAPSED TIME = 00:12:30

Figure 22

SMH14-02 TEST 1 ELAPSED TIME = 00:13:18

Figure 23

ELAPSED TIME = 00:23:50

SMH11-03 TEST 3

Figure 24

ELAPSED TIME = 00:07:39

SMF02-04 TEST 1

Figure 25

SNF05-01 TEST 1 ELAPSED TIME = 00:12:30

Figure 26

ELAPSED TIME = 00:13:18

SMH14-02 TEST 1

Figure 27

ELAPSED TIME = 00:23:50

SMH11-03 TEST 3

Figure 28

ELAPSED TIME = 00:07:39

SMF02-04 TEST 1

Figure 29

SMF05-01 TEST 1 ELAPSED TIME = 00:12:30

Figure 30

SNH14-02 TEST 1 ELAPSED TIME = 00:13:18

Figure 31

SMH11-03 TEST 3 ELAPSED TIME = 00:23:50

Figure 32

ELAPSED TIME = 00:07:39

SMF02-04 TEST 1

Figure 33

ELAPSED TIME = 00:12:30

SMF05-01 TEST 1

Figure 34

SMH14-02 1001 1 ELAPSED TIME = 00:13:18

Figure 35

ELAPSED TIME = 00:23:50

SMH11-03 TEST 3

Figure 36

SLOPE = -1.000539
FILENAME = DEADYRD2
OK

Figure 13. Compass method fractal dimension results for the Dead Yucca Ridge #2 joint surface. The fractal dimension is 1.000539 in this case.

SLOPE = -1.014517
FILENAME = DEADYRD3

OK

Figure 14. Compass method fractal dimension results for the Dead Yucca Ridge #3 joint surface. The fractal dimension is 1.014517 in this case.

SLOPE = -1.000002
FILENAME = DEADYRD4

OK

Figure 15. Compass method fractal dimension results for the Dead Yucca Ridge #4 joint surface. The fractal dimension is 1.000002 (approx. 1) in this case.

SLOPE = -1.002685
FILENAME = TSWT1
OK

Figure 16. Compass method fractal dimension results for the Topopah Springs #1 weathered joint surface. The fractal dimension is 1.002685 in this case.

SLOPE = -1.006759
FILENAME = TSWT2
OK

Figure 17. Compass method fractal dimension results for the Topopah Springs #2 weathered joint surface. The fractal dimension is 1.006759 in this case.

SLOPE = -1.00328
FILENAME = BBUTTE1
OK

Figure 18. Compass method fractal dimension results for the Busted Butte #1 joint surface. The fractal dimension is 1.00328.

SLOPE = - .9999533
FILENAME = BBUTTPL1
Ok

Figure 19. Compass method fractal dimension results for the Busted Butte, polygon #1 joint surface. The fractal dimension is 0.9999533 (approx. 1) in this case.

SLOPE = -1.002203
FILENAME = BBUTTPL2
Ok

Figure 20. Compass method fractal dimension results for the Busted Butte, polygon #2 joint surface. The fractal dimension is 1.002203 in this case.

SLOPE = -1.001901
FILENAME = BBUTTPL3
Ok

Figure 21. Compass method fractal dimension results for the Busted Butte, polygon #3 joint surface. The fractal dimension is 1.001901.

SLOPE = -1.031518
FILENAME = TRENCH14
OK

Figure 22. Compass method fractal dimension results for the Trench 14 fault surface. The fractal dimension is 1.031518 in this case.

APPENDIX 1:7B

A COMMENT ON THE DESCRIPTION OF SURFACE ROUGHNESS USING
FRACTAL DIMENSION

James R. Carr

Department of Geological Sciences, University of Nevada-Reno

ABSTRACT. Brown (1987) provides a succinct overview of the description of surface roughness using fractal dimension. Application was demonstrated for rock surfaces. An argument was presented favoring the use of a power spectrum technique for such application. An alternate technique, the divider - or compass - method, was not favored because this technique was found to yield estimates of fractal dimension quite close to the topological dimension for rock surfaces. In application to ten rock surfaces, a correlation is found between the divider and power spectrum methods for fractal dimension calculation. Correlation coefficients are 0.73 (unfiltered) and 0.96 (filtered). This suggests either technique is useful for the description of rock surface roughness using fractal dimension, albeit the divider method does yield fractal dimension values that differ from unity only by thousandths, whereas power spectrum estimates differ from unity by tenths. The divider fractal dimension is better correlated with the joint roughness parameter estimated using the technique of Tse and Cruden (1979).

Introduction

This discussion is based on the notion of fractal geometry [e.g., Mandelbrot, 1983] applied for the study of surface roughness. It begs the notion of self-similar versus self-affine fractals, thereby acknowledging surface roughness to be a self-affine phenomenon [e.g., Mandelbrot, 1985]. Surface roughness is often analyzed using the power spectrum of the surface, a practice motivated by Sayles and Thomas (1978). Therefore, studies applying a technique for fractal dimension calculation known as the divider method (or compass method) for the study of surface roughness [e.g., Carr and Warriner, 1987] are questioned.

An hypothesis is proposed: the divider method for fractal dimension calculation is useful for the analysis of rock surface roughness. This hypothesis is tested in the ensuing sections.

Proposed Hypothesis Test

A test of the proposed hypothesis is designed consisting of three steps: 1) the fractal dimension of rock surface profiles is calculated using the power spectra of the profiles; 2) the fractal dimension of rock surface profiles is calculated using the divider method; 3) a scatter diagram of the results is plotted and the correlation coefficient is computed. If the scatter diagram (and associated correlation coefficient) reveal a poor or lack of correlation between the results from the two fractal dimension calculation methods, the proposed hypothesis shall be rejected. If, on the other hand, a correlation is found, no basis will be found to reject the hypothesis (note:

this will not necessarily confirm the hypothesis, but will establish the foundation for further research). The proposed hypothesis is tested for ten (10) different rock surfaces.

Results

Ten rock surfaces are listed by letter code in Table 1. Power spectra were calculated using the subprogram, SPCTRM (Press, et. al., 1986, p. 428 - 429). Examples of two spectra are shown in Figures 1 and 2. Determination of the fractal dimension using the power spectrum involves two steps: 1) plot the log of the power spectrum versus the log of frequency (Figures 1 and 2); then, 2) using the slope of this plot, calculate the fractal dimension, D as [e.g., Brown and Scholz, 1985]:

$$D = 0.5(5 - \text{ABS}(\text{SLOPE})) \quad (1)$$

If the absolute value of slope is 2, as it is for brown noise, D is 1.5.

Calculation results are shown in Table 1. Divider method results were obtained using the procedure outlined in Carr and Warriner [1987]; these are also listed in Table 1. A scatter diagram of these results is presented as Figure 3. The correlation coefficient for power spectrum D with divider method D is 0.73, a positive correlation. If rock surfaces, D and P, are filtered, the correlation coefficient based on the remaining eight sections is 0.96. The selection of the two locations for filtering was based on a visual inspection of Figure 3.

At this point, no evidence is available to reject the proposed hypothesis. The fractal dimension results from the two

calculation techniques are well correlated for these ten surfaces.

It is not possible or valid, based on the rather limited data of Table 1, to suggest an empirical relationship between the divider method fractal dimension and that yielded using the power spectrum. The scatter plot of Figure 3 might encourage a variety of expressions, of first or higher order. If surfaces D and F are excluded, as is done above to obtain the better correlation, a first order (linear) expression seems adequate. If the fractal dimension results are averaged for sub-groups of the ten surfaces, Figure 4 is produced. This figure suggests a non-linear expression is necessary if such an empirical relationship is developed. Further research to include more self-affine fractals than the ten used here is required before this uncertainty is overcome.

Discussion

Consideration should be given to the motivation behind the objective to characterize rock surface roughness. One motivation is to relate fractal dimension to joint roughness coefficient, JRC [see Barton and Choubey, 1977, for the development of the notion of JRC; see Carr and Warriner, 1987, for an empirical relationship between fractal dimension and JRC].

Several relationships are available for calculating JRC using surface elevations, y , along a surface. One such method is presented by Tse and Cruden [1979]:

$$JRC = 32.2 + 32.7(\log(ZZ)) \quad (2)$$

where:

$$Z2 = \sum (y(i+1) - y(i))^2 / [M(dx)^2] \quad (2a)$$

where M is the number of intervals, $y(i+1)-y(i)$, and dx is the regular increment in x along which samples of elevation are measured.

A relationship between the divider method fractal dimension, D, and JRC is presented by Carr and Warriner [1987]:

$$JRC = -1022.55 + 1023.92D \quad (3)$$

Further research has suggested this relationship should be non-linear [Lee, 1988]:

$$JRC = -0.878 + 37.7844((D-1)/0.015) - 16.9304((D-1)/0.015)^2 \quad (4)$$

Thus, methods are available to estimate JRC directly from surface elevations, y [Tse and Cruden, 1979], or indirectly from surface elevations by first calculating a fractal dimension using x and y information, then estimating JRC from the fractal dimension.

A comparison of equation (2) with fractal dimension is presented in Table 2. Also shown in this table are correlation coefficients between JRC from equation (2) and the fractal dimensions from both calculation methods. Scatter diagrams are shown in Figures 5 and 6. The poor initial correlation between equation (2) and fractal dimension, for either fractal dimension calculation technique, is noted. Simply removing three surfaces (E, F, and J) from the data shown in Table 2 results in a correlation coefficient of 0.98 between the divider fractal dimension and Tse and Cruden's JRC value. Removal of five surfaces (C, D, E, G, and J) results in a correlation coefficient of 0.96 between the power spectrum fractal dimension and Tse and Cruden's JRC value. It is also seen from Table 2 that removing only surface J from the data substantially affects the

correlation of either fractal dimension calculation technique and Tse and Cruden's JRC value. It is concluded, based on these ten rock surfaces, that the divider method fractal dimension is better correlated with Tse and Cruden's JRC value than is the power spectrum fractal dimension.

Conclusion

One misunderstanding of Brown [1987] is that it invalidates the divider method for the study of rock surface roughness; this is not a correct impression. The article does demonstrate the divider method to yield resolution between different self-affine fractal surfaces when $r \gg b$, albeit the resolution is extremely small [Brown, 1987, Figure 4, p. 1096]. Moreover, although not presented in this paper, Figure 5 of Brown [1987, p. 1097] was verified. Through verification of this figure, it was observed that the slope of the log-log plot of the power spectrum remains unchanged through vertical exaggeration, whereas the divider method results are markedly affected.

Related to this idea is the resolution at which rock profile elevations are collected. Elevations were sampled at 15 cm spacings for the ten rock surfaces used in this study. It is concluded from Brown [1987] that $r \gg b$ for these surfaces. As the resolution at which elevation values are measured is improved (i.e., the sampling interval, dx , is reduced), the correlation between the divider method and power spectrum method is likely to change. Taken to the extreme, if resolution results in $r < b$, the correlation between the power spectrum and divider methods should equal unity.

Relative to joint roughness coefficient (JRC), the poor initial correlation between either fractal dimension calculation technique and the technique of Tse and Cruden [1979] requires further investigation. Filtering was required to improve the correlation between fractal dimension and Tse and Cruden's JRC value. More rock surface profiles must be studied to evaluate the usefulness of the correlation coefficients presented earlier. Nevertheless, the filtering experiments are interesting and encouraging.

Finally, Mandelbrot [1986] has presented extensive information regarding self-affine fractals. He has said the divider method applied to a self-affine fractal yields an indirect measure of the local box-mass dimension (Mandelbrot, 1987). The preceding sections of this paper demonstrate a correlation between the divider and power spectrum methods when applied to self-affine fractals (at least for the ten self-affine fractals studied). Regardless of the measure obtained by the divider method, no evidence is yet found to reject the foregoing hypothesis: the divider method is useful for the study of rock surface roughness.

Acknowledgment

I thank Drs. Charles E. Glass and Stephen R. Brown for help in answering questions concerning this research. This research was supported by the State of Nevada, Agency for Nuclear Projects, Nuclear Waste Project Office.

References

- Barton, N. and V. Choubey, The shear strength of rock joints in theory and practice, *Rock Mech.*, 10, 1-54, 1977.
- Brown, S. R., A note on the description of surface roughness using fractal dimension, *Geophys. Res. Lett.*, 14, 1095-1098, 1987.
- Brown, S. R. and C. H. Scholz, Broad bandwidth study of the topography of natural rock surfaces, *J. Geophys. Res.*, 90, 12,575 - 12,582, 1985.
- Carr, J. R. and J. B. Warriner, Rock mass classification using fractal dimension, in *Proc. 28th U.S. Symp. Rock Mech.*, edited by I. Farmer, J. Daemen, C. Desai, C. Glass, and S. Neuman, pp. 73 - 80, A. A. Balkema, Boston, Mass., 1987.
- Lee, Y. H., The fractal dimension as a measure of the roughness of rock discontinuity profiles, unpublished doctoral dissertation, University of Missouri-Rolla, 189 p., 1988.
- Mandelbrot, B. B., *The Fractal Geometry of Nature*, 468 pp., W. H. Freeman, San Francisco, Calif., 1983.
- Mandelbrot, B. B., Self-affine fractals and fractal dimension, *Physica Scripta*, 32, 257 - 260, 1985.
- Mandelbrot, B. B., Self-affine fractal sets, Parts I - III, in *Fractals in Physics*, edited by L. Pietronero and E. Tosatti, pp. 3 - 28, 1986.
- Mandelbrot, B. B., Personal communication, 1987.

- Press, W. H., B. P. Flannery, S. A. Teukolsky and W. T. Vetterling, Numerical Recipes, Cambridge University Press, New York, 818 p., 1986.
- Sayles, R. S. and T. R. Thomas, Surface topography as a non-stationary random process, Nature, 271, 431-434, 1978.
- Tse, R. and D. M. Cruden, Estimating joint roughness coefficients, Int. J. Rock Mech. Min. Sci. and Geomech. Abstr., 16, 303 - 307, 1979.
-

J. R. Carr, Department of Geological Sciences, University of Nevada-Reno, Reno, Nevada 89557.

Table 1
Fractal dimension results for ten rock surfaces

Surface	X	Y
	Power Spectrum	Divider
	Fractal Dimension	Fractal Dimension
A	1.410	1.00085
B	1.496	1.00194
C	1.204	1.00049
D	1.478	1.00534
E	1.764	1.00465
F	1.537	1.00368
G	1.448	1.00195
H	1.374	1.00059
I	1.663	1.00230
J	1.123	1.00000

Correlation coefficient, R, X:Y = 0.73 (all ten surfaces);

= 0.96 (less surfaces D and F)

Table 2

Comparison of fractal dimension to Tse and Cruden's JRC value

Surface	X	Y	Z
	Tse and Cruden JRC	Power Spectrum Fractal Dimension	Divider Fractal Dim.
A	1.5	1.410	1.00085
B	4.2	1.496	1.00194
C	4.3	1.204	1.00049
D	19.2	1.478	1.00534
E	7.1	1.764	1.00465
F	7.7	1.537	1.00368
G	9.3	1.448	1.00195
H	0.0	1.374	1.00059
I	9.2	1.663	1.00230
J	21.3	1.123	1.00000

Correlation coefficients, R:

- 1) X:Y = -0.21 (all)
 = 0.30 (less J)
 = 0.96 (less C,D,E,G,J)
- 2) X:Z = 0.28 (all)
 = 0.77 (less J)
 = 0.98 (less E,F,J)

Figure 1. Plot of power spectral density for surface, A (Table 1). A least squares fit is also shown. The slope of this line gives a fractal dimension of 1.41.

Figure 2. Plot of power spectral density for surface, F (Table 1). A least squares fit is also shown. The slope of this line gives a fractal dimension of 1.537.

Figure 3. Scatter plot of power spectrum fractal dimension versus divider fractal dimension. Surfaces are described by letter relative to Table 1.

Figure 4. The ten surfaces (Table 1) are shown here averaged in four groups. The groups are: 1 (C,J); 2(A,H); 3(B,G,I); 4 (D,E,F).

Figure 5. Scatter plot of JRC (Tse and Cruden, 1979) versus power spectrum fractal dimension. Surfaces are shown by letter relative to Table 2.

Figure 6. Scatter plot of JRC (Tse and Cruden, 1979) versus divider fractal dimension. Surfaces are described by letter relative to Table 2.

SMF02-94 TEST 1
ELAPSED TIME = 00:07:39

Figure 37

ELAPSED TIME = 00:12:30

SMF05-01 TEST 1

Figure 38

ELAPSED TIME = 00:13:18

SMH14-02 TEST 1

Figure 39

ELAPSED TIME = 00:07:11

SAMPLE SNH11-03

Figure 40

ELAPSED TIME = 00:07:39

SNP03-04 TEST 1

Figure 41

ELAPSED TIME = 00:12:30

SMF05-01 TEST 1

Figure 42

ELAPSED TIME = 00:13:18

SNH14-02 TEST 1

Figure 43

ELAPSED TIME = 00:23:50

SMH11-03 TEST 3

Figure 44

ELAPSED TIME = 00:07:39

SNF02-04 TEST 1

Figure 45

SMF05-01 TEST 1 ELAPSED TIME = 00:12:30

Figure 46

ELAPSED TIME = 00:13:18

SMH14-02 TEST 1

Figure 47

ELAPSED TIME = 00:23:50

SMH11-03 TEST 3

Figure 48

ELAPSED TIME = 00:07:39

SMF02-04 TEST 1

Figure 49

SMF05-01 TEST 1 ELAPSED TIME = 00:12:30

Figure 50

SMH14-02 TEST 1
 ELAPSED TIME = 00:13:18

Figure 51

ELAPSED TIME = 00:23:50

SMH11-03 TEST 3

Figure 52

ELAPSED TIME = 00:07:39

SMF02-04 TEST 1

Figure 53

SMF05-01 TEST 1 ELAPSED TIME = 00:12:30

Figure 54

ELAPSED TIME = 00:13:18

SNH14-02 TEST 1

Figure 55

ELAPSED TIME = 00:11:22

SMH06-04 TEST 6

Figure 56

SMH06-04 TEST 6

ELAPSED TIME = 00:11:22

Figure 57

FINAL REPORT

Task 7b Geotechnical and Rock Mass Assessment: Rock Mass Characterization using Fractals and Fractal Dimension

James R. Carr, Principal Investigator

During the period, January 1, 1987 through June 30, 1988, the following results were obtained for Yucca Mountain, Nevada:

Two methods for computing fractal dimension were applied to profiles of 11 fracture surfaces at or adjacent to Yucca Mountain, Nevada. In addition, a method for estimating joint roughness coefficient given by Tse and Cruden (1979) was applied for comparison to the fractal dimension techniques.

One fractal dimension calculation technique involves the computation of the power spectrum of the surface. This is an accepted procedure (Brown, 1987). The second fractal dimension technique relies on a divider, or compass, method; this technique is newly recognized for rock surfaces (Carr and Warriner, 1989). As will be shown, the compass method is better applied to fracture surfaces at or adjacent to Yucca Mountain.

Fracture surfaces were measured on Friday and Saturday, May 5 and 6, 1988. These fractures were found in fresh to moderately weathered welded tuff. Measurements consisted of taut string line profiles, measured every 1 inch; distance from string to rock surface was measured in hundredths of a foot. These distance values represent the profile for each rock surface. All fractures that were measured were vertical, hence profile measurements were taken as a horizontal distance from string to the fracture exposure.

Power spectra were calculated first for the Yucca Mountain profiles. Fractal dimension is estimated from the slope of the power spectrum as:

$$\text{fractal dimension} = 0.5(5 - \text{ABS}(\text{slope}))$$

These spectra are included as Figures 1 through 11. These spectra are summarized in Table 1. The Topopah Springs #1 joint (moderately weathered) and the Trench 14 fault surfaces are found to be the roughest with the power spectrum approach.

Subsequent to the spectral analysis, compass method fractal dimensions were determined for the eleven surfaces. These results showed the Dead Yucca Ridge #3 joint and the Trench 14 fault surfaces are the roughest. The Topopah Springs #1 and #2 surfaces, both moderately weathered, and the Busted Butte #1 joint surface are the three roughest surfaces after the Dead Yucca Ridge #3 and Trench 14 surfaces. These results are summarized in Table 2 and shown graphically in Figures 12 through 22.

A comparison of the two fractal dimension calculation methods for the Yucca Mountain surfaces is provided by Table 3. A correlation coefficient of 0.325 is found between these calculation techniques. This is a relatively poor correlation. Therefore, Tse and Cruden's joint roughness coefficient (JRC) calculation method was applied to the eleven Yucca Mountain rock surfaces for comparison to the fractal dimension values. This comparison is shown in Table 4. The compass, or divider, fractal dimension has a correlation coefficient of 0.91 (good) with the Tse and Cruden JRC value, whereas the power spectrum fractal dimension has a poor correlation with JRC (correlation coefficient of 0.05).

These results are similar to results found for rock surfaces adjacent to Libby Dam, Montana. These rock surfaces were analyzed originally using the compass method fractal dimension (Carr and Warriner, 1989) and analyzed again to study the similarity between the power spectrum fractal dimension and the compass method fractal dimension (Carr, 1988; attached as Appendix 1:7b). Unlike the Libby Dam surfaces, there was practically no correlation between Tse and Cruden's JRC value and the power spectrum fractal dimension for the Yucca Mountain surfaces.

For rock surfaces at or adjacent to Yucca Mountain, the compass method fractal dimension calculation technique is preferred based on Table 4. A regression relating compass fractal dimension to Tse and Cruden's JRC value is proposed as:

$$\text{JRC} = -702 + 706(\text{fractal dimension})$$

This equation is somewhat conservative when estimating JRC. An expression found useful for Libby Dam, Montana surfaces (Carr and Warriner, 1989) is appropriate as well for Yucca Mountain:

$$\text{JRC} = 1000(\text{fractal dimension} - 1)$$

Either expression is useful for Yucca Mountain.

REFERENCES

- Brown, S. R., 1987, A note on the description of surface roughness using fractal dimension, Geophysical Research Letters, Vol. 14, No. 11, pp. 1095 - 1098.
- Carr, J. R. and J. B. Warriner, 1989, Relationship between the fractal dimension and joint roughness coefficient, Bulletin of the Association of Engineering Geologists, Accepted for Publication, May, 1988; to appear.
- Tse, R. and D. M. Cruden, 1979, Estimating joint roughness coefficients, International Journal of Rock Mechanics and Mining Science with Geomechanics Abstracts, Vol. 16, pp. 303 - 307.

Table 1
Power Spectrum Fractal Dimensions

Profile	Slope of Spectrum	Fractal Dimension
1. Dead Yucca Ridge #1	-2.206	1.397
2. Dead Yucca Ridge #2	-2.539	1.231
3. Dead Yucca Ridge #3	-2.245	1.378
4. Dead Yucca Ridge #4	-2.514	1.243
5. Top. Springs #1	-2.066	1.467
6. Top. Springs #2	-2.482	1.259
7. Busted Butte #1	-3.241	0.880
8. Busted Butte, Poly #1	-2.332	1.334
9. Busted Butte, Poly #2	-3.171	0.915
10. Busted Butte, Poly #3	-3.118	0.941
11. Trench 14, Fault surface	-2.186	1.407

Notes: Topopah Springs #1 and #2 represent weathered surfaces. The Dead Yucca Ridge sections represent vertical joints associated with numerous lithophyse. The Busted Butte sections represent vertical joints in tuff capping Busted Butte. The Trench 14 fault profile was taken for experimentation with fractal dimension calculations.

Table 2
Fractal Dimensions from the Divider Method

Profile	Slope Log N versus Log y	Fractal Dimension
1. Dead Yucca Ridge #1	-0.9999609	1.0000
2. Dead Yucca Ridge #2	-1.0005390	1.0005
3. Dead Yucca Ridge #3	-1.0145170	1.0145
4. Dead Yucca Ridge #4	-1.0000020	1.0000
5. Top. Springs #1	-1.0026850	1.0027
6. Top. Springs #2	-1.0067590	1.0068
7. Busted Butte #1	-1.0032800	1.0033
8. Busted Butte, Poly #1	-0.9999533	1.0000
9. Busted Butte, Poly #2	-1.0022030	1.0022
10. Busted Butte, Poly #3	-1.0019010	1.0019
11. Trench 14, fault sur.	-1.0315180	1.0315

Table 3
Comparison of Power Spectrum and Divider Fractal Dimensions

	Profile	Fractal Dimensions	
		Spectrum	Divider
1.	Dead Yucca Ridge #1	1.397	1.0000
2.	Dead Yucca Ridge #2	1.231	1.0005
3.	Dead Yucca Ridge #3	1.378	1.0145
4.	Dead Yucca Ridge #4	1.243	1.0000
5.	Top. Springs #1	1.467	1.0027
6.	Top. Springs #2	1.259	1.0068
7.	Busted Butte, #1	0.880	1.0033
8.	Busted Butte, Poly #1	1.334	1.0000
9.	Busted Butte, Poly #2	0.915	1.0022
10.	Busted Butte, Poly #3	0.941	1.0019
11.	Trench 14, Fault surface	1.407	1.0315

Correlation coefficient, R, spectrum/divider is 0.325.

Table 4
Comparison of Fractal Dimensions with Tse and Cruden (1979) JRC

	Profile	Fractal Dimensions		Tse and Cruden JRC
		Spectrum	Divider	
1.	Dead Yucca Ridge #1	1.397	1.0000	0.0
2.	Dead Yucca Ridge #2	1.231	1.0005	4.1
3.	Dead Yucca Ridge #3	1.378	1.0145	16.2
4.	Dead Yucca Ridge #4	1.243	1.0000	0.0
5.	Top. Springs #1	1.467	1.0027	5.5
6.	Top. Springs #2	1.259	1.0068	12.3
7.	Busted Butte, #1	0.880	1.0033	11.5
8.	Busted Butte, Poly #1	1.334	1.0000	1.0
9.	Busted Butte, Poly #2	0.915	1.0022	8.1
10.	Busted Butte, Poly #3	0.941	1.0019	5.9
11.	Trench 14, Fault sur.	1.407	1.0315	23.8

Correlation coefficient, Divider with JRC = 0.91;
 Correlation coefficient, Spectrum with JRC = 0.05.

SLOPE = -2.205851
FILENAME = B:DEADYRD1.LOG
OK

Figure 1. Power spectrum for the Dead Yucca Ridge #1 joint surface.

SLOPE = -2.539113
FILENAME = B:DEADYRD2.LOG
OK

Figure 2. Power spectrum for the Dead Yucca Ridge #2 joint surface.

SLOPE = -2.244972
FILENAME = B:DEADYRD3.LOG
Ok

Figure 3. Power spectrum for the Dead Yucca Ridge #3 joint surface.

SLOPE = -2.513801
FILENAME = B:DEADYRD4.LOG
Ok

Figure 4. Power spectrum for the Dead Yucca Ridge #4 joint surface.

SLOPE = -2.06615
FILENAME = B:TSWT1.LOG

OK

Figure 5. Power spectrum for the Topopah Springs #1 weathered joint surface.

SLOPE = -2.482296
FILENAME = B:TSWT2.LOG

OK

Figure 6. Power spectrum for the Topopah Springs #2 weathered joint surface.

SLOPE = -3.241024
FILENAME = B:BBUTTE1.LOG
Ok

Figure 7. Power spectrum for the Busted Butte #1 joint surface.

SLOPE = -2.332305
FILENAME = B:BBUTTPL1.LOG
OK

Figure 8. Power spectrum for the Busted Butte, polygon #1 joint surface.

SLOPE = -3.171233
FILENAME = B:BBUTTPL2.LOG
OK

Figure 9. Power spectrum for the Busted Butte, polygon #2 joint surface.

SLOPE = -3.117968
FILENAME = B:BBUTTPL3.LOG
OK

Figure 10. Power spectrum for the Busted Butte, polygon #3 joint surface.

SLOPE = -2.185535
FILENAME = B:TRENCH14.LOG
OK

Figure 11. Power spectrum for the Trench 14 fault surface.

SLOPE = - .9999609
FILENAME = DEADYRD1
OK

Figure 12. Compass method fractal dimension results for the Dead Yucca Ridge #1 joint surface. The fractal dimension is equal to the absolute value of the slope, 0.9999609 (approx. 1) in this case.

END

**DATE
FILMED**

9 / 3 / 92