The most active regions within the southern Great Basin are the north and southeast sections of the NTS, the area west of the Bare Mountain fault, the region at the north end of the Death Valley-Furnace Creek fault system, and the Pahranagat Shear Zone (Rogers *et al.*, 1987a). The level of seismic activity may reflect tectonic release following explosions in the region surrounding the NTS. Mining-related explosions have occurred in the Bullfrog Hills west of the Bare Mountain fault and various other mining sites around the region (Vortman, 1991).

Underground Nuclear Explosions

Extensive aftershock sequences followed several UNEs in the Pahute Mesa area from 1968 through 1970 (Hamilton *et al.*, 1971). These sequences were not confined to the test locations, but were distributed along several mapped faults as far as 15 km from the shot points. Portable instruments deployed in the late 1960s following the Benham shot recorded about 2500 earthquakes greater than M 2.0 from December 1968 through December 1970. This period included several explosions. Hamilton *et al.* (1971) reported that 94 percent of the events with well-constrained focal mechanisms were shallower than 5 km; some of the events were as deep as 8 km. Focal mechanisms show dominantly normal slip on northeast- to north-northeast-striking fault planes, and fault planes generally align with the fabric of mapped normal faults in the Tertiary tuffs. This correlation would imply a predominantly down-to-the-west/northwest sense of motion for most of the earthquakes.

Aftershocks of UNEs also appear in the Yucca Flat and Raineer Mesa areas in the eastern NTS, although they are not as prolific or as distributed as the triggered seismicity in the Pahute Mesa area. The earthquake locations and depth distributions of these earthquakes have not been studied in the detail Hamilton *et al.* (1971) applied to the Pahute Mesa area. There are also complications in resolving the relationship of UNEs to triggered earthquakes in the southeastern NTS south and east of Yucca Flat, wherein a notable increase in seismicity occurred in the 1970s following the initiation of underground testing in that area. All UNEs in Yucca Flat were reported at or below 150 kilotons, whereas some explosions at Pahute Mesa had reported yields as great as 1 megaton (Mt).

Large UNEs (~1 Mt) have been known to trigger release of natural tectonic strain (Wallace *et al.*, 1983, 1985). Thus, the potential exists that future testing may induce displacements on faults in the Yucca Mountain site vicinity and adjacent region; although coseismic tectonic release has not been observed far from the UNEs. The relations between UNEs and natural seismic activity near the NTS have been discussed by Aki *et al.* (1969); Bucknam (1969); Dickey (1968, 1969, 1971); Dickey *et al.* (1972); McKeown and Dickey (1969); Hamilton and Healy (1969); Hamilton *et al.* (1969, 1972); Smith *et al.* (1972); Rogers *et al.* (1987a); and Vortman (1991). These studies observed that strain release and related effects become difficult to find beyond 5 to 10 km from surface ground zero of even the largest events (1 Mt). The Buckboard area is the nearest historical or proposed UNE testing area to Yucca Mountain, and is approximately 25 km northeast.

The relationship between UNEs and seismicity has been discussed by Rogers *et al.* (1987a), Vortman (1991), and Hamilton *et al.* (1971). Vortman's (1991) analysis of the seismicity of the NTS and vicinity deleted those events interpreted as human-made, but considered the number and location of earthquakes triggered by UNEs. Vortman (1991) proposed that considerable numbers of small-magnitude earthquakes apparently are induced by dynamic stresses of the seismic energy generated during the explosion, whereas other small events seem to occur in response to the altered static-stress field resulting from the explosion. Some events are triggered by the arrival of the UNE phase; others appear to be in response to changes in an altered stress field caused by the explosion. A UNE may cause a stress change on the order of several bars, a fraction of the lithostatic stress in the hypocentral region. Some areas of the southern Great Basin may be in a state of critical stress, in which a small perturbation in the load on a fault, such as UNE-induced stress changes, can cause the release of accumulated tectonic strain.

Triggered Earthquakes

The triggering of aftershocks by UNEs at the Nevada Test Site near Yucca Mountain (Hamilton and Healy, 1969; Hamilton *et al.*, 1972, Rogers *et al.*, 1983) and the continued occurrence of induced seismicity following the impoundment of Lake Mead (Carder, 1945; Rogers and Lee, 1976) are evidence that a number of fault segments in the southern Great Basin may be near failure. There is strong evidence that the June 29, 1992, Little Skull Mountain earthquake was triggered by the June 28, 1992, Landers, California, earthquake (Ms 7.6, Mw 7.3). The Landers earthquake also apparently triggered smaller earthquakes at locations throughout a large region of the western United States, extending as far as the

Yellowstone Caldera at a distance of 1250 km (Hill *et al.*, 1993). The Little Skull Mountain earthquake occurred about 225 km north of the Landers rupture. An increase in microseismic activity in the vicinity of Little Skull Mountain was observed beginning in the coda of the Landers event (Anderson *et al.*, 1994). This was recorded by the Yucca Mountain microearthquake array (instrumentation described in Brune *et al.*, 1992). The activity accelerated over the next 23 hours, culminating in the M 5.6 Little Skull Mountain main shock. This pattern may indicate that the Little Skull Mountain region was near failure prior to the Landers earthquake, which in turn may have advanced the time of rupture.

The specific mechanism of triggering of the Little Skull Mountain earthquake is uncertain, but a consensus appears to be that the dynamic strains associated with the propagation of long-period surface waves from the Landers earthquake (Anderson *et al.*, 1994; Gomberg and Bodin, 1994) initiated a failure process possibly involving fluids (Hill *et al.*, 1993) or sympathetic slip or creep (Bodin and Gomberg, 1994). Following the Landers main shock, Johnston *et al.* (1995) observed a transient strain change associated with an increase in seismicity at the Long Valley Caldera. The Landers earthquake produced an unprecedented increase in seismicity in the eastern California shear zone (Roquemore and Simila, 1994) and in the Sierra Nevada-Great Basin boundary zone (Anderson *et al.*, 1994).

Historical Seismicity near Yucca Mountain

Throughout the southern Great Basin and including the site area, seismicity generally is distributed in a broad belt that trends east-west from the Utah border to California. Earthquakes generally have strike-slip and normal faulting mechanisms and focal depths ranging from near-surface to 12 to 15 km deep. The number of resolved focal mechanisms indicates that approximately half of the solutions are strike-slip and half are dip-slip (Rogers *et al.*, 1992). In this region, as elsewhere in the Great Basin, there is a general lack of correlation between the distribution of epicenters and Quaternary faults.

The focal mechanisms of earthquakes closer to Yucca Mountain are strike slip to normal oblique slip along moderately to steeply dipping fault planes. The nodal planes are consistent with right-lateral faulting on north- to north-northwest-striking planes or normal-left oblique slip on northeast- to east-striking faults. These directions of inferred faulting are consistent with the style of Quaternary faulting and the orientations of principal stresses in the region.

Rogers *et al.* (1987a, 1991) and Bellier and Zoback (1995) analyze the modern stress field in regions of Nevada near Yucca Mountain.

A zone of quiescence centered on Yucca Mountain is apparent in all studies that describe seismicity in the southern Great Basin. Brune *et al.* (1992) and Gomberg (1991a, b) have shown that this zone is a real feature of the seismicity and not an artifact of network design. The largest earthquake to occur under Yucca Mountain from the inception of the SGBSN in 1978 was an ML 2.1 event that occurred on November 18, 1988, located 12 km north-northwest of the proposed repository at a depth of 11 km (Harmsen and Bufe, 1992). The inferred tension axis for this event is rotated about 25 degrees counterclockwise from the average tension axis observed in the region. The observed relatively aseismic character of the site area may result because the principal faults in the Yucca Mountain block are unfavorably oriented with respect to the present stress field. In other words, in the present regional stress field, north-striking faults would be expected to accommodate a portion of right-lateral motion and not pure normal slip.

RECENT SEISMICITY

The 1992 M 5.6 Little Skull Mountain Earthquake

The largest and most significant earthquake recorded in the vicinity of Yucca Mountain since the regional seismic network was established in 1979 was the June 29, 1992, M 5.6 Little Skull Mountain (LSM) earthquake (Lum and Honda, 1992; Harmsen, 1994; Walter, 1993; Meremonte *et al.*, 1995; Smith *et al.*, 1997). Origin Time: June 29, 1992; 1014 22.47 UTC; Latitude: 36 N 43.1'; Longitude: 116 W 17.16'; depth 11.8 km; ML 5.8 UNRSL; ML 5.6 NEIC. The event occurred approximately 20 km southeast of the proposed repository. The highest ground acceleration was 0.206 g recorded at a strong-motion station a Lathrop Wells, Nevada, at about 11 km epicentral distance (Blume and Honda, 1992). The earthquake caused some minor damage to the Yucca Mountain Field Operations Center in Jackass Flat, which was almost directly on the surface projection of the buried fault plane. The event was widely felt throughout the region.

The LSM earthquake initiated at a depth of 11.7 km, and nearly the entire sequence, main shock rupture surface and aftershock sequence, was confined to between 5 and 12 km depth.

Fault rupture propagated unilaterally from southwest to northeast for about 6 km; the epicenter of the main shock plots near the southwest end of the aftershock zone. There was no evidence of primary or secondary surface faulting. Rockfalls along the south-facing cliffs of Little Skull Mountain were observed shortly after the earthquake. The distribution of rockfalls, which was found to be consistent with the ground shaking predicted from the source model, provided a means of calibrating the distribution of ground shaking in the epicentral region (Brune and Smith, 1996). The earthquake occurred on a northeast-striking fault plane dipping steeply to the southeast (Harmsen, 1993; Meremonte *et al.*, 1995; Smith *et al.*, 1997) and involved nearly pure normal slip with a small left-slip component. The following table is a compilation of short-period and waveform-based focal mechanisms and reported seismic moments for the LSM earthquake.

THE 1992 LITTLE SKULL MOUNTAIN MAIN SHOCK SOURCE PARAMETERS *

Information Source	Strike	Dip	Rake	Mo x10^24 dyne-cm
Smith *et al.* (1997)	60±15	70±13	-70±10	-
Meremonte *et al.* (1995)	55	56	-72	-
Romanowicz *et al.* (1993)	43	66	-73	3.5
Romanowicz *et al.* (1993)	34	44	-70	2.6
Zhao and Helmberger (1994)	45	55	-60	3.0
Walter (1993)	35	54	-87	4.1
Harmsen (1994)	55	56	-72	-

There were three aftershocks of M > 4; none occurred on the main shock fault plane, but rather on adjacent "off-fault" structures that most likely accommodated the stress change from main shock rupture. These larger aftershocks also triggered near-source stations of the Blume strong motion network (Lum and Honda, 1992). The first M 4 aftershock occurred in the coda of the main shock; its location could be constrained only as being east of the main shock epicenter. Focal mechanisms and quality locations could be determined for the following two M 4+ events: M 4.4 July 5th, 0654 13.27 UT; Latitude: 36 N 43.55'; Longitude: 116 W 16.46'; depth 9.39 km; (Fault Plane Parameters: Strike: N75°E, Dip: 70°SE, Rake: -20°); M 4.5 September 13th, 1146 20.87 UT; Latitude: 36 N 43.41'; Longitude: 116 W 18.28'; depth 8.93 km (Fault Plane Parameters: Strike: N20°E, Dip: 45°SE, Rake: -80°).

* Source parameters strike, dip, and rake are in degrees using the convention of Aki and Richards (1980); seismic moment, Mo, is in units of 10^24 dyne-cm. Modified from Schneider *et al.* (1996).

The LSM earthquake could not be correlated with any mapped faults, although Harmsen (1993) and Meremonte *et al.* (1993) suggested that it may have taken place on a southern extension of the Mine Mountain fault zone. Smith *et al.* (1997) point out that the LSM sequence is situated where the Wahmonie, Caine Springs, as well as the Mine Mountain fault systems project into the Rock Valley fault zone. Some earthquakes within the LSM aftershock zone that occurred off the main shock fault plane align along a southern projection of the Wahmonie fault zone as well.

The LSM earthquake occurred in an area of persistent recent seismicity throughout the recording period of the network. This may be a zone of stress concentration, accommodating strain throughout the fault systems in the southcentral NTS area. The Rock Valley fault zone is the primary Quaternary system in this group and shows the most associated seismicity. The LSM main shock epicenter plots directly along the crest of LSM, which would place it, at hypocentral depth, at the base of the seismogenic zone, potentially near an intersection with the Rock Valley fault system. Whether the Mine Mountain fault was the causative structure for the LSM earthquake, it is clear that there is a direct relationship with the Rock Valley system.

Earthquakes in the Rock Valley Region in the Post-LSM Period

Following the Little Skull Mountain earthquake, there has been a notable increase in earthquake activity in the southern Rock Valley fault zone (Smith and Brune, 1997; Shields *et al.*, 1995; O'Leary, 1996). Only two M 3+ earthquakes adjacent to the Rock Valley fault zone in the southern NTS region are included in the SGBSN earthquake catalog from 1979 to prior to the LSM sequence. Since LSM, three M 3.5+ earthquakes, and an unusual sequence of very shallow earthquakes in mid-1993 (Smith *et al.*, 1997, written communication; Shields *et al.*, 1995), have taken place in Rock Valley; these M 3.5+ earthquakes occurred at various locations in southern Rock Valley near the LSM sequence. This activity appears to be diminishing (at the time of this report - October 1997), suggesting that indeed the LSM event may have had a role in triggering the increased activity along the Rock Valley fault.

The shallow sequence of earthquakes in 1993 (main event M 3.8) was recorded on a near-source portable digital instrument. This station recorded more than 500 earthquakes, of which only 140 triggered the regional seismic network and could be located. S minus P times for the events averaged about 0.5 sec at this station; relocations of the earthquakes place them about 2 km from the surface. The largest event of the sequence, M 3.8, was also reported at a 2-km depth. Stress drops determined from modeling the S-wave spectra and using an empirical Green's function were on the order of 10 bars for all the larger events. A cluster of earthquake activity also occurred southeast of the Rock Valley fault zone in the Spotted Range in late 1993. This was the most active cluster of seismicity in the region east of the NTS since the 1973 Ranger Mountain sequence. In contrast to the Ranger Mountain and 1971 Massachusetts Mountain sequences, the 1992 cluster was confined to a small volume and included only one earthquake greater than M 3.

Micro-Earthquakes at Yucca Mountain: 1995 and 1996

From May 1995 through September 1996, 15 micro-earthquakes were located in and around the Yucca Mountain block (Smith *et al.*, 1996; Brune and Anooshepoor, 1996). Depths ranged from 5 to 10 km; magnitudes ranged from M -0.76 to M 0.72 (Brune and Anooshepoor, 1997). Short-period focal mechanisms were determined for four of the events, and although there was not enough information from the focal mechanism data to unequivocally correlate the earthquake with mapped faults, one event may have occurred on or near the Stage Coach Road Fault, and another three events may have taken place on or near the Paintbrush Canyon Fault. Gross and Jaume (1995) reviewed the archived waveform data to analyze a number of small events that were in the catalog and reported to be in the Yucca Mountain block after 1978 and before 1992. Their report lists some events that were incorrectly identified as earthquakes.

TABLE: SMALL-MAGNITUDE EARTHQUAKES AT YUCCA MOUNTAIN

#	Date		Origin Time		Lat	Lon	Depth	M
1.	*95	5 5	1321	33.12	36N50.66	116W24.08	6.15	0.58
2.	95	7 1	1526	56.69	36N40.84	116W30.88	8.65	
3.	95	7 7	759	-0.33	36N49.67	116W24.85	6.02	-0.27
4.	95	728	618	51.42	36N54.10	116W30.52	4.80	-0.48
5.	*95	9 4	1239	47.11	36N44.43	116W30.02	4.45	0.72
6.	95	1119	2215	84.91	36N50.80	116W23.59	6.46	-0.25
7.	95	1120	226	57.44	36N50.81	116W23.67	5.95	-0.43
8.	95	12 6	2327	15.90	36N43.74	116W29.06	7.80	0.29
9.	96	129	1020	32.32	36N44.23	116W29.44	9.90	
10.	96	330	1957	28.63	36N48.60	116W27.98	7.24	-0.59
11.	96	4 8	714	49.64	36N49.96	116W25.21	8.23	-0.58
12.	96	6 2	1645	75.18	36N49.11	116W29.44	9.61	-0.69
13.	*96	6 2	1015	33.29	36N49.23	116W29.55	9.87	0.01
14.	96	731	357	37.30	36N45.91	116W34.54	8.55	-0.76
15.	96	812	422	50.68	36N48.48	116W23.09	5.02	-0.62

- referenced on figure of Smith, SSC Workshop 3.
Origin Time: Year-Month-Day-Hour-Minute-Second (UTC). Depth: event depth referenced to surface elevation. M - ML
* - triggered; the older analog seismic network.

REFERENCES

See reference list that follows main SBK text.

APPENDIX SBK-3
POTENTIAL ANALOGS TO FUTURE SITE AREA ACTIVITY

This appendix includes a discussion of earthquakes related to volcanic activity in the Mammoth Lakes, California, area as an analog to potential volcanic earthquakes in Crater Flat and a discussion of the 1986 M 6.3 Chalfant Valley, California, earthquake and aftershock sequence, which we believe represents the most likely analog to the maximum background earthquake for the southern Great Basin.

Analog to Yucca Mountain Volcanic Earthquakes

The Mammoth Lakes, California, volcanic area, within and adjacent to the Long Valley caldera, has been the location of a recent series of moderate-sized (M 5 to 6) earthquakes, aftershock sequences, and volcanic-related earthquake swarms (1940 to the present) (Hill *et al.*, 1985). We believe that this area may represent an analog to potential earthquake activity associated with the emplacement of volcanic materials in Crater Flat and to activity that contributed to the structural features present in the northern Nevada Test Site (NTS), which formed during emplacement of the Timber Mountain Caldera. Several late Pleistocene and younger eruptions (> 750 ka) of the Long Valley caldera have shaped the physiography of the Mammoth Lakes-Chalfant Valley-Bishop area of California (Bailey *et al.*, 1976). Deformation in the caldera (1980 to the present) has been directly associated with most of the foreshock-mainshock-aftershock sequences (main shocks M > 6) and volcanic earthquake swarms (Hill *et al.*, 1990). These sequences have been prolific, producing tens of thousands of earthquakes in and adjacent to the caldera.

Before the recent increase in seismicity, activity in the area had been at a low level since the 1940s (Gumper and Scholz, 1971; Pitt and Steeples, 1975; VanWormer and Ryall, 1980). But in the 1940s, two M 5 earthquakes coincided with the filling of Crowley Lake in the western part of the caldera. The recent series of moderate-sized earthquakes that began in October 1978 culminated with four M 6+ earthquakes during a 48-hour period from May 25 to May 27, 1980 (Cramer and Toppazada, 1980; Lide and Ryall, 1985). The sequence continued with the 1984 M 5.8 Round Valley earthquake (Priestley *et al.*, 1988) and 1986 M 6.4 Chalfant Valley earthquake. Swarm-like earthquake activity (Savage and Cockerham, 1984; Cockerham and Pitt, 1984; Hill *et al.*, 1990) and occasional tremors (Ryall and Ryall, 1983; Aki, 1984) within and adjacent to the caldera were accompanied by inflation of the caldera's resurgent dome (Savage and Clark, 1982; Rundle and Whitcomb, 1984; Denlinger and Bailey, 1984).

An energetic earthquake swarm under Mammoth Mountain near the town of Mammoth Lakes in 1989 included a number of deep, long-period earthquakes that may be associated with deep magma movement (Pitt and Hill, 1994; Langbein *et al.*, 1993). There is some controversy regarding the possibility of non-double-couple source mechanisms, possibly associated with dike injection, determined for some of the earthquakes in and around the caldera (Julian, 1983; Julian and Sipken, 1985; Wallace, 1984). Although none of the moderate earthquakes have shown a significant component of dip-slip motion, Holocene faulting with predominantly normal offsets bound the Sierra Nevada and White Mountains (Bryant, 1984). The recent series of moderate-sized earthquakes have shown predominantly strike-slip motion.

The 1986 M 6+ Chalfant Valley Earthquake Sequence

The Chalfant Valley sequence occurred adjacent to the White Mountains beneath the volcanic Tableland, 15 km east of the Long Valley caldera (Smith and Priestly, 1988; dePolo and Ramelli, 1987; Lienkaemper *et al.*, 1987). We believe that this sequence of earthquakes represents the best analog to the maximum background earthquake for the southern Great Basin. The sequence is a composite of three distinct faulting events (M 6.3, M 5.8, and M 5.5) that occurred over a period of 11 days (Smith and Priestly, 1988). All three earthquakes showed predominantly strike slip-motion, with the main shock occurring within the hanging wall block of the White Mountains fault zone. The main shock, M 6.3, was the largest event in the western Nevada seismic region since the 1954 Fairview Peak-Dixie Valley earthquakes.

The Chalfant sequence produced surface ruptures along the White Mountains fault zone and within the Tableland fault system west of the White Mountains (dePolo and Ramelli, 1987; Lienkaemper *et al.*, 1987). Surface ruptures along the White Mountains fault zone stretched for a distance of 12 ± 2 km, with scattered cracks within the volcanic Tableland. The M 6.3 Chalfant earthquake may be the model event for the maximum background earthquake (MBE) in the western Basin and Range (dePolo, 1994; Pezzopane and Dawson, 1996). The

MBE is defined as the largest magnitude earthquake that does not produce primary displacement on faults at the surface. Although extensive fracturing occurred at the surface along mapped Holocene faults in the volcanic Tableland area, it is arguable whether any of that is primary rupture (Lienkaemper *et al.*, 1987).

Smith and Priestly (1997) have performed a detailed relocation of the earthquakes of the first three months of the sequence and determined the source parameters of the primary events. Static stress drops determined from the teleseismic moment and rupture areas estimated from the extent of the aftershock activity for the three primary events (M 5.8, M 6.3, and M 5.5) are 87, 26, and 23 bars, respectively. Uncertainties in these estimates are shown in that report. The primary characteristic of the sequence is the conjugate fault geometry resulting from the first two moderate-sized events: left-lateral strike-slip motion for the initial M 5.8 event, followed 24 hours later by right-lateral slip during the M 6.3 main shock (Smith and Priestley, 1997; Savage and Gross, 1995). Main shock rupture extended 12 to 15 km on a northwest-striking, southwest-dipping (55 degrees) fault plane. Surface fracturing in the volcanic Tableland area was confined to the hanging wall of the main shock fault plane (Smith and Priestley, 1997). A peak acceleration of 0.46 g was recorded on an accelerometer record of horizontal component at a sediment site on an alluvial fan about 12 km northeast of the main shock epicenter.

REFERENCES

See reference list that follows main SBK text.

ELICITATION SUMMARY

ROBERT SMITH, CRAIG DEPOLO, AND DENNIS O'LEARY

TABLE OF CONTENTS

TABLE OF CONTENTS

TABLES

FIGURES

TABLE OF CONTENTS

TABLE OF CONTENTS

APPENDICES

ELICITATION SUMMARY
ROBERT SMITH, CRAIG DEPOLO, AND DENNIS O'LEARY

1.0
INTRODUCTION

To properly represent expert epistemic uncertainty, the Yucca Mountain Probabilistic Seismic Hazard Analysis (PSHA) input evaluations were carried out by six expert teams free to choose their own methodologies, but also free to share or combine approaches. The team Smith, DePolo, O'Leary followed the evaluation structure provided to all of the teams at the PSHA workshops. We attempted to be impartial and objective in our evaluations, taking into account our different levels and areas of expertise. We amassed the data that were freely available to all participants, we attended the Yucca Mountain field trip to observe local faults and the Bare Mountain fault, and we obtained guidance from the expert presentations. We then developed our own interpretations based on the evidence, and developed our own scenarios and evaluations, then put the information and the models into a PSHA context. Team Smith, DePolo, and O'Leary shared a number of hypotheses and premises with other teams, but we adopted a fundamentally reductionist and epistemic approach to the analysis. We realized that the issue of earthquake hazard has a historical component inherent in the paleoseismic data that could not be accounted for by numerical or theory-based techniques. Accordingly, we relied as much as possible on data for Pleistocene events. Our first step was to evaluate tectonic models on the basis of field evidence or tectonic history, especially Quaternary history. The tectonic model we consider best supported by the data (a planar fault model) and its variants guided our evaluations of fundamental fault behavior, and set bounds on the key seismic parameters of magnitude and displacement. Field data from trench studies guided our estimates of recurrence and slip rates for local faults.

2.0
TECTONIC MODELS

A useful tectonic model provides an explanation for the origin, mechanical behavior, and resulting structure (deformation) of some volume of the Earth's crust. A tectonic model integrates: (1) geometry and spatial relations among structures; (2) mechanisms by which structures interact and respond to regional stress; and (3) the succession, duration, and evolution of deformation events (i.e., the history of strain). We look to tectonic models to help (1) guide understanding of present (and future) seismotectonics; (2) relate observable structure to inferences concerning fault parameters (e.g., width, distribution, extent, linkage); (3) provide bounding estimates or boundary conditions for fault behavior; and (4) identify hidden structure and behavior at seismogenic depths. Because our model must account for fault displacement hazard, it is specifically a model for Yucca Mountain. Therefore, the model incorporates Quaternary fault activity, basaltic volcanism, and other tectonic phenomena that provide evidence for seismogenic behavior at Yucca Mountain during late Pleistocene.

The model we use is conceptual and primarily kinematic. Three fundamental concepts constrain our evaluation of a model, the first of which is the domain concept. This concept holds that the crust of the southern Great Basin is an assemblage of structurally bounded slabs or blocks in various states of destruction and activity. Observed at sufficiently small scale, the domains evince regional strain patterns; taken individually they reveal local histories of deformation that complicate a regional pattern. We term the second concept "inheritance". In evaluating a tectonic model, a certain degree of idealization is necessary. However, our model does not assume pristine, ideal components; we consider that Yucca Mountain formed in a hybrid tectonic environment having a complex stress history, that the structural components reflect the processes that have varied with time and place, and that some processes are more tectonic than others. To a greater or lesser degree, present-day deformation follows ancient strain patterns. Our third concept focuses on history. The pattern and amplitude of deformation were set millions of years ago; although the style of deformation may be inherited, ancient deformation may have nothing to do with present rates and distributions of strain. Therefore, our analyses and probabilities rely on evidence of Quaternary, not Miocene, events.

An important aspect of the tectonic setting of Yucca Mountain (that is, the structural and stratigraphic assemblage of rocks within a radius of about 100 km of the mountain) is the current strain rate. Strain rate is assessed based on the moment rate of observed seismicity, geodetic data, and paleoseismology. All indications are that the current strain rate is very low--on the order of 10^{-16}/yr to 10^{-17}/yr (Eddington *et al.*, 1987; data from Chapter 6 of the Seismotectonic Framework report [USGS, written communication, 1996]). This is an order of magnitude lower than strain rates in the more active areas of the nearby Basin and Range province. This low rate constrains the loading rate of active faults and hence our deductions about the potential for activity and seismogenic depths.

Our preferred model for Yucca Mountain is that of an asymmetric graben, or a half graben, partly filled by a collapsed volcanic carapace. There are two fundamental components to this model. First is the half graben itself, represented by Crater Flat basin. The USGS seismic reflection profile (Brocher *et al.*, 1996) shows clearly the structural asymmetry of the half graben, of which Bare Mountain represents the relatively uplifted footwall. Second is the volcanic carapace. Yucca Mountain is the emergent part of a faulted, extended slab of volcanic rock about 2.5 to 3 km thick that has subsided into the half graben. We call this the carapace because it forms a resistant shield that completely covers the Paleozoic bedrock beneath Yucca Mountain. Most block-bounding faults at Yucca Mountain dip westward toward Bare Mountain and show a history of extension antithetic to the Bare Mountain fault.

The half graben model requires that the Bare Mountain fault be the master fault and that the strata to the east (the hanging wall) subside against it, as a group of antithetic fault blocks. This mechanical model has two limitations which affect uncertainty in our analysis: (1) the cumulative Pleistocene dip slip on the Bare Mountain fault is less than that measured across Yucca Mountain; and (2) some faults at Yucca Mountain and in Crater Flat have a down-to-the east offset. The latter observations can be explained by local keystone faulting in the volcanic carapace, but the former observation is less readily explained. Nevertheless, the asymmetry of Crater Flat basin, the structural relief of Bare Mountain (several kilometers), the overall sense of slip on the main block-bounding faults of Yucca Mountain, the profound (about 30 mgal) gravity gradient along the Bare Mountain fault, and the evidence that the Bare Mountain front was the source of large slab slides into Crater Flat in late Miocene time indicate that the early history of the Bare Mountain fault was that of a master, range-front fault.

The pre-Pleistocene slip history of the Bare Mountain fault lies buried beneath the pediment cover in Crater Flat. The steep part of the gravity gradient, which lies a kilometer or more east of the present range front, indicates that the fault generally dips east at less than 50 degrees. Our model, and the seismic reflection profile (Brocher *et al.*, 1996), permit the interpretation that the Bare Mountain fault consists of an imbricate zone of several more steeply dipping fault planes, variously banked at depth by colluvial wedges or mass movement deposits. The Pleistocene fault trace sampled for this study may be the most recently active of several synthetic fault planes, and may have the least cummulative displacement (see, for example, Hancock and Barka, 1987, Figure 10).

The half graben model works well only near the central latitudinal axis of Crater Flat basin. Viewed longitudinally, the basin is plugged at its north end by the emergent caldera complex from which a population of radial faults extends through generally south-dipping strata into Crater Flat (S. Minor, USGS, written communication, 1995). The Bare Mountain fault loses throw near the caldera rim area and transitions northward into a minor normal fault, the Tram Ridge fault, which dies out within the Rainier Mesa caldera rim zone (C.J. Fridrich, USGS, written communication, 1995). To the south, the Crater Flat basin abruptly narrows and shallows. The Bare Mountain fault has not been traced south of Steve's Pass (Figure SDO-1), and the faults of Yucca Mountain are abruptly terminated, or at least are not traceable south of a dissected escarpment along Highway 95 at the southern margin of the basin. The strata of the escarpment are the same volcanic units that form Yucca Mountain, but dip northward into the basin. The eastern margin of Crater Flat basin is well defined by an arcuate gravity gradient concave to the west, which closely parallels the trace of the combined Paintbrush Canyon-Stagecoach Road fault. On this basis, we infer that the Paintbrush Canyon-Stagecoach Road fault is a major bounding fault for Yucca Mountain, the fault that defines the basin rim and most likely descends to the base of the seismogenic crust.

The form of Crater Flat basin and its association with the caldera complex led Carr (1990) to interpret it as a sector graben, an area of subsidence caused by evacuation of an apophysis of magma from the base of the crust during or shortly following eruption of the Topopah Spring

Tuff. This interpretation accords well with the timing and magnitude of initial faulting of Yucca Mountain as well as with the shape and position of the basin. Brun *et al.* (1994) effectively simulated the structure, in cross section, with a sandbox model that utilized deformation of a low-density viscous mass at the base of the crust.

If the location and longitudinal axis of Crater Flat basin indicate that it originated as a sector graben, they also imply that it is a flaw within the larger rift-like Amargosa trough (i.e., the Kawich-Greenwater rift of Carr [1988, 1990] or the Amargosa Desert rift zone of Wright [1989]); that is, it is a rift within a rift. As such, crustal extension within Crater Flat basin reflects the structural orientation of the trough and perhaps is linked to basement faulting of greater extent. Carr (1990) noted the similarity between the faults at Yucca Mountain and a fault population in Pahute Mesa north of the caldera complex and on strike with Yucca Mountain (Minor *et al.*, 1993), and surmised that both fault sets reflect extension fundamentally tied to the evolution of the Amargosa trough. Accordingly, Crater Flat basin can be understood as the southern part of a deeper, narrower flanking rift along the western flank of the Amargosa trough; or perhaps even a basin that projects from the Basin and Range terrane southward into the Walker Lane. This rift-like aspect of the model downplays the notion of the Bare Mountain fault as a conventional range-front fault. It implies that Pleistocene extensional faulting at Yucca Mountain is not a function of antithetic slip controlled by the Bare Mountain fault, but is instead controlled by axial fractures within the deepest part of the Amargosa trough.

But casting Crater Flat basin and Yucca Mountain in the context of a trough controlled (at least during its Middle Miocene phase) by dominantly east-west extension raises two questions relevant to faulting at Yucca Mountain: (1) what becomes of Bare Mountain fault at and beyond the south end of Yucca Mountain, and (2) what is the nature of the fault that bounds the east side of the Amargosa trough near Yucca Mountain?

The southward projection of the Bare Mountain fault is problematic. We infer that the fault is not traceable south of Steve's Pass (Figure SDO-1) because there it loses its identity, including its expression as a pronounced gravity gradient (Snyder and Carr, 1984), among a distributed set of small right-lateral fault segments within a shear zone that steps to the southeast for about 4 km across the dissected escarpment that marks the southern end of

Crater Flat (C.J. Fridrich, USGS, written communication, 1995). The fault then regains its identity as a unified structure, gains dip displacement, and strikes south as the boundary between the Funeral Mountains and the Amargosa trough. Although the fault is a major domain-bounding feature south of Bare Mountain, its projection along a relatively subdued gravity gradient and its weak expression as a physiographic feature indicates that the fault has played little part in the late Neogene and Quaternary history of the Amargosa trough.

The eastern margin of the Amargosa trough is bounded by faults of seismogenic significance. Especially significant for model evaluation is the so-called gravity fault (Figure SDO-1). The gravity fault was defined by Winograd and Thordarson (1975) on the basis of a gravity gradient (hence their term "gravity fault") that extends along the spring line in Ash Meadows north to Highway 95 (Figure SDO-1) and the west end of the Skeleton Hills. Down-to-the-west displacement of Paleozoic bedrock is estimated to range from about 150 m at the north end to several hundred meters at the south end. Brocher *et al.* (1993), on the basis of seismic profile data, confirmed that the gravity fault forms the structural boundary of the east side of the trough at about 36°35'N. Brocher *et al.* (1993) interpreted the gravity fault as being listric to a reflector (K) at about 2 s. (5.5 km) depth. Although Brocher *et al.* (1993) did not offer a preferred interpretation of reflector K, they emphasized the role of ductile flow in the lower crust at a depth of about 6 s. below the Amargosa trough. Reflector K may represent an abandoned, pre-late Oligocene detachment that controlled extension of the Specter Range.

A concident gravity and aeromagnetic gradient aligned with the gravity fault implies that the fault can be carried northward past the west end of Little Skull Mountain (Chapter 8, Seismotectonic Framework report [USGS, written communication, 1996])). The fault trace passes through the magnetic anomaly that marks the position of the 4.4-Ma buried volcano south of Highway 95. North of this point, a high magnetic anomaly along the gradient suggests that the hanging wall of the gravity fault contains considerable basalt or volcaniclastic sediment. There are sparse surface expressions of the gravity fault. At the west end of the Striped Hills, bedrock exposures indicate strike-slip displacement, but the western flank of Little Skull Mountain is marked by toreva blocks that indicate down-to-the-west collapse. Reheis and Noller (1991) mapped a 2.5-km-long Pleistocene scarp along the fault trace between the Striped Hills and the Skeleton Hills. The scarp is clear in large-scale aerial photos, which show that the most recent drainage courses have been influenced by the fault. The scarp probably represents displacement within the last 10 ka.

The gravity fault is an important domain boundary; it separates dominantly east-striking structures associated with the Rock Valley fault system to the east from the north-striking structures of the Amargosa trough-Crater Flat domain to the west. North of Little Skull Mountain, the trace of the gravity fault and the eastern margin of the trough are obscure. We infer that the eastern border of the trough trends roughly due north, as expressed by a set of down-to-the west, post-12.7 Ma faults along the west side of the Calico Hills dome (F.W. Simonds and R.B. Scott, USGS, written communication, 1996).

If formation of the Bare Mountain fault and one or more crustal faults at Yucca Mountain were driven by a deep master fracture zone in the axis of Crater Flat basin, they may be largely independent of each other in terms of slip budget. This modification of our basic model is based on a mechanism proposed by Okaya and Thompson (1985) and demonstrated by boundary element modeling done for Crater Flat basin by King and Janssen (Chapter 8, Seismotectonic Framework report [USGS, written communication, 1996]). The interpretation is consistent with the localization of basaltic volcanism near the axis of the basin: extensional stress is focused along one or more axial fractures or fault intersections at the base of the seismogenic crust. Such intersections can focus dilational strain, even at depths of 15 to 20 km, and thereby facilitate the ascent of basaltic magma to higher crustal levels. The Bare Mountain fault and the Paintbrush Canyon-Stagecoach Road fault likely would be the primary intersecting faults at the deepest crustal level; interaction of these faults at a sufficient stress threshold could be accompanied by basaltic intrusion. We consider such events would cause most faults at Yucca Mountain to slip, including those that might be antithetic to Bare Mountain fault, and that some fault crevasses might receive basaltic ash fill. G.A. Thompson (Stanford University., written communication, 1994) proposed that basaltic dike intrusion would compensate for local extensional stress and significantly reduce deviatoric stress. This would cause the stress threshold for post-intrusive faulting at Yucca Mountain to be reset to some higher level. However, as regional extensional stress continues to be applied to the mountain, small stress thresholds are exceeded and weaker faults slip from time to time. Ultimately, the maximum basinal stress threshold is exceeded, at which point the basin may experience widespread faulting associated with basaltic intrusion. This aspect of the model holds that not all faulting at Yucca Mountain is accompanied by volcanism, but that volcanism is always associated with faulting.

2.1 DEXTRAL SHEARING AND BURIED STRIKE-SLIP FAULTS

The alignment of basaltic cones and vents in Crater Flat follows a northeast trend, oblique to the axis of the basin. Volcanism is clustered in the southwest quadrant of the basin, the area of most recent subsidence and deposition. These facts indicate a distinct tectonic asymmetry linked to processes active within the past 4 m.y. Tectonic asymmetry is also indicated by paleomagnetic evidence for clockwise vertical axis rotation of fault-bounded blocks across the south end of the mountain. The rotation, which is about 30 percent, is considered to have occurred following deposition of the Tiva Canyon Tuff at about 12.7 Ma (S. Minor, written communication, 1995). These data led C.J. Fridrich (USGS, written communication, 1995) to infer that Crater Flat basin has evolved as a sphenochasm, opening at its southern end but fixed at its northern end.

This motion is compatible with a northwest-oriented zone of dextral shear at the southern end of the basin, and with a general N50°W-oriented transtensional stress throughout the Walker Lane. In terms of our model, the question is whether oblique dextral shear is confined to Crater Flat basin (i.e., the basin itself is becoming distorted because of distributed, regional shear), or whether shear is imposed by a buried regional right-lateral fault that passes through Crater Flat basin. The latter case has been argued by Schweickert and Lahren (1997) and modeled as a pull-apart basin in sandbox experiments by the Center for Nuclear Waste Regulatory Analyses (presentation by D. Ferrill at Workshop 4). The question is important because a hidden throughgoing fault could generate an earthquake comparable in magnitude and mechanism to the 1932 Cedar Mountain earthquake.

Nonsystematic distributions of vertical axis rotations in time and space within the southwest Nevada volcanic field, as reported by Hudson *et al.* (1994), imply that individual basins have responded uniquely to distributed northwest-oriented dextral shear typical of the Walker Lane setting. This observation, plus the lack of evidence for transcurrent dextral fault offset of Pleistocene age though Crater Flat basin, supports the interpretation that dextral shear is restricted to the basin itself. The only hint of a discrete dextral shear feature within the basin is a N25°W-striking alignment known informally as the hingeline (C.J. Fridrich, written communication, 1995). The hingeline separates paleomagnetic rotations of 10 degrees or less to its north from rotations of 20 degrees or more to its south. The boundary is more strongly indicated by the divergence of aeromagnetic gradient alignments across the mountain, and by landform terminations along the trace of the hingeline. The hingeline is considered to define a structural boundary that concentrates dextral shear between it and the southern end of the mountain. A possible second indication of a buried strike-slip fault are the scarps and lineaments along the Black Cone fault, shown on Faulds *et al.* (1994).

Despite painstaking investigation, researchers have identified no expression of any feature comparable to the hingeline along its strike northwest of Crater Flat. However, a strong structural alignment does exist to the southeast of Crater Flat. The structural alignment extends along Stewart Valley and along the trace of the Pahrump-Stewart Valley fault zone for a distance of about 120 km. At least 4 km of dextral offset is shown along the alignment between the Resting Spring Range and the Montgomery Mountains.

The alignment is expressed by isostatic gravity anomalies that include the gradients that form the western flank of Pahrump Valley basin and (farther north) the eastern flank of Ash Meadows basin. In general, the alignment defines the eastern margin of a large crustal block that is expressed by the Amargosa Range on the west, and by Bare Mountain, the Resting Spring Range, and the Nopah Range on the east. Structurally, the alignment is comparable to the subparallel Death Valley and Panamint faults farther west. The alignment is less well expressed by aeormagnetic anomalies except for the local gradients along the hingeline through Yucca Mountain.

We consider the structural alignment, which includes the Yucca Mountain hingeline, to be a projection of the Pahrump-Stewart Valley fault zone into, but not through, Crater Flat basin thus accounting for clockwise vertical axis rotation at Yucca Mountain, northeast alignment of basaltic volcanic centers in Crater Flat, dextral shear at the south end of Crater Flat basin, and a dextral slip component toward the southern end of Bare Mountain fault. Additionally, shear stress concentrated at the edge of the basin is considered have contributed to uplift of Bare Mountain and Calico Hills within the past 9 m.y. In light of these features, we include a buried fault source among our regional seismic fault sources and assign a 40% probability to a model that contains a strike-slip earthquake within or proximal to Crater Flat basin along the hingeline-Pahrump-Stewart Valley fault zone alignment (Figure SDO- 1). Such an earthquake could have a magnitude as great as the 1932 Cedar Mountain earthquake. Basaltic volcanism could be associated with such an event.

2.2 DETACHMENT FAULTS

Detachment fault models of varied geometries and crustal depths have been applied to Yucca Mountain solely on the basis of the succession of rotated, west-facing normal faults that form the mountain. Each detachment mechanism invariably is referred to a single latitudinal cross section that emphasizes the rotated normal fault blocks but ignores the structural complications at the northern and southern ends of Crater Flat basin. A detachment fault model has important implications. Because all rotated normal faults of the upper plate are rooted in a common slip plane (the detachment), all faulting necessarily is distributed, and (if the detachment is deep enough) all rooted normal faults are equally seismogenic. Because the subhorizontal detachment plane is of wide lateral extent and separates structures of radically different ages and attitudes, a major seismogenic feature such as a strike-slip fault could be hidden beneath the detachment.

The most recent attempts to fit a detachment model to Yucca Mountain are provided by D.A. Ferrill *et al.* (CNWRA, written communication,1995), who describe two model variants based on syntheses of previous proposals. Model 1 of D.A. Ferrill *et al.* (CNWRA, written communication, 1995) assumes that the faults of Yucca Mountain developed from the headwall of the Bullfrog Hills detachment system, which is thought to accommodate as much as 275 percent of local extension (D.A. Ferrill *et al.*, CNWRA, written communication, 1995). According to this model, Yucca Mountain faults were isolated from the Bullfrog Hills system by rise of the Bare Mountain block along the Bare Mountain fault, which truncated the Yucca-Bullfrog detachment. Continued motion of the Bare Mountain fault formed a deeper, east-directed detachment plane. According to this model, the older, shallower, west-directed detachment accounts for the imbricate faulting at Yucca Mountain; the younger, deeper, east-directed detachment accounts for hanging wall collapse of the carapace into Crater Flat basin. Model 2 of D.A. Ferrill *et al.* (CNWRA, written communication, 1995) accounts directly for the hanging wall rollover and imbricate faulting at Yucca Mountain by assuming that the Bare Mountain fault is the driving listric (detachment) fault and that Yucca Mountain faults are simply antithetic to the deep, master, east-directed Bare Mountain detachment. However, in this model, faults antithetic to the Bare Mountain listric fault are simultaneously listric faults synthetic to a breakaway fault located somewhere to the east in Jackass Flats. The result is a curious "bathtub" profile having listric faults at each end that merge at a common plane of detachment (D.A. Ferrill *et al.*, CNWRA, written communiction, 1995). It is not clear how slip is partitioned between the two apparently competing listric faults and along the common detachment surface.

These detachments are presumed to operate in the 6 to 8 km depth range. Shallow detachment at the Tertiary/Paleozoic contact can be ruled out. Numerous exposures throughout the area, as well as the Crater Flat seismic profile (Brocher and Hunter, 1996), combine to show that the Paleozoic contact is an unconformity locally cut by high-angle faults. We leave open the question of deep detachment within the brittle-ductile lower crust transition. Much geologic evidence, such as high-grade metamorphic facies and mylonite in lower plates exposed elsewhere, indicates that detachments typically occur in the ductile transition zone, and theoretical and experimental rheological considerations (e.g., Melosh, 1990) support the mechanism in this setting. However, the occurrence of normal fault earthquakes at depths of 19 km or greater (see section 3.1) indicates that strain at these depths is not effectively assimilated by detachment. And because most of our inferences of fault behavior rely on processes that involve the brittle part of the crust, we consider whatever is meant or envisioned by "detachment" in the lower crust to be simply part of poorly understood, quasi-viscous flow deformation.

The oldest deformation that can be attributed plausibly to detachment is block faulting of the Topopah Spring Tuff at about 12.7 Ma. At that time, Bare Mountain was already an elevated range that was shedding debris into Crater Flat basin. In fact, Yucca Mountain field work revealed evidence that Bare Mountain was shedding metamorphic rock debris prior to deposition of the Crater Flat Tuff and that Crater Flat was an aggrading alluvial plain prior to 14 Ma. The Bare Mountain fault was active well before deposition of the Paintbrush Group C.J. Fridrich, USGS, written communication, 1995). This means that uplift of Bare Mountain cannot have terminated a detachment at Yucca Mountain, and that there was no tectonic association of Yucca Mountain extension with the formation of the Bullfrog Hills.

In fact, the Bullfrog Hills formed from 2 to 3 m.y. after the initial phase of Yucca Mountain faulting, in a completely different tectonic setting. The Bullfrog Hills originated from a breakaway fault along the west side of Tram Ridge beginning about 12.7 Ma (C.J. Fridrich, USGS, written communication, 1995; Hoisch *et al.*, 1997). The transport vector of the Bullfrog Hills projects eastward to the Rainier Mesa caldera, diverging some 20 degrees counterclockwise from the orientation of the transport vector of Yucca Mountain.

The style and direction of deformation in Crater Flat clearly are diachronous, having shifted from mountain-wide imbricate block faulting around 11.4 Ma primarily to subsidence at the southwest corner of the basin beginning around 9 Ma. Beginning around 11 Ma, sporadic basaltic volcanism became an important component of tectonism in this area. The basaltic volcanism implies that fracturing and faulting in the upper crust repeatedly connected with deep mantle sources. If a detachment plane existed in this area, it was not an effective barrier for fractures that penetrated through the crust.

Exposed detachment faults typically show slices of the upper plate resting at a high dip angle (65°) against the detachment plane. The geometric relations among the steeply dipping faults in a moderately extended domain, especially one that has no clearly identified breakaway fault, such as Yucca Mountain, are highly idealized. Detachment model 2 of D.A. Ferrill *et al.* (CNWRA, written communication, 1995) requires severe curvature of the fault planes as they merge into the detachment fault at about 8 km depth. No explanation for this "special case" geometry is offered; it is a precondition of a listric model that is never seen in exposed detachment systems.

The domino mechanism of imbricate faulting is unable to resolve this geometry problem. If the block-bounding faults at Yucca Mountain are controlled by deep detachment, they cannot behave like dominos. The domino model requires rigid behavior and completely distributed simple shear; there can be no variable rollover or opposed slip. It is clear, however, that the big blocks at Yucca Mountain have some rollover and that there is local reversal of offset along strike on some of the bounding faults. Furthermore, domino rotation presumes uniform frictional slip across the entire width of the slip plane, unrealistic expectations to depths of 8 km at Yucca Mountain, even given extreme pore pressure. Nevertheless, a domino model is a more satisfactory explanation of hanging wall collapse against the Bare Mountain fault than is the quasi-listric geometry called for in model 2 of D.A. Ferrill *et al.* (CNWRA, written communication, 1995), which requires a listric geometry as a consequence of a competing breakaway fault at the east side of Yucca Mountain.

A major shortcoming of the detachment model is that no breakaway zone has been identified for the imbricate faults of Yucca Mountain. For example, no such fault has been reasonably shown in the vicinity of Fortymile Wash. On the contrary, a good case can be made, both from seismic reflection profile data and stratigraphy in well UE25J#13, for a down-to-the-east fault near Fortymile Wash (Carr, 1984). The gravity fault is inferred by D.A. Ferrill *et al.* (CNWRA, written communication, 1995) to be a candidate breakaway fault for Yucca Mountain. However, despite the array of small down-to-the-west normal faults (post-9 Ma) that cut Little Skull Mountain, the primary structure here is a north-dipping block, which indicates that structural rotations are referred to east-northeast-striking rotation axes. This geometry is even more pronounced in the Striped Hills, but totally absent from Yucca Mountain.

The Little Skull Mountain earthquake demonstrated that a seismogenic normal fault beneath Little Skull Mountain dips southeast and would project to the surface west of the inferred breakaway fault for Yucca Mountain. The aftershocks occurred up to nearly 5 km from the surface (K.D. Smith *et al.*, University of Nevada, Reno, written communication, 1995), suggesting that the hypocentral projection of this fault (cf. Meremonte *et al.*, 1995) can be projected across a west-dipping breakaway fault. Additional constraints on the cross-sectional geometry of the detachment model are the lack of any expression of listric geometry or a detachment plane in the USGS seismic reflection profile (Brocher and Hunter, 1996). A detachment plane would have a seismic reflection in Crater Flat basin as in other areas of the Basin and Range Province (Smith *et al.*, 1989). Another geometric constraint for any model is the elevation of Yucca Mountain. It is difficult to restore the fault blocks (W. B. Hamilton, written communication, 1995) unless the detachment plane mimics the elevation profile, or we appeal to depositional thickening or to displacements outside the plane of the section.

In fact, displacements outside the plane of the section must be factored into the model geometry because field data show that the block-bounding faults have a left-oblique component of slip. But when we consider the overall planimetric aspect of the structure of

Yucca Mountain, the detachment model faces its most serious problems. Among these problems is the fact that Yucca Mountain faulting is tied exclusively to the geometry of a subjacent basin. Left-lateral bounding accommodation zones are not indicated at the margin of this basin, nor does the model offer any explanation of vertical axis rotation in the basin. Indeed, an important function of the detachment model is to isolate the upper plate extensional structure from influence of a lower plate structure, such as a strike-slip fault that could impose a dextral torque on the surface fault pattern. To continue to operate as an extensional mechanism into Pleistocene time, a detachment plane must be a chronic locus of slip or of strain-decoupling; this is the fundamental meaning of the word detachment. It cannot behave this way and transmit shear stress from the lower crust to the upper plate. In other words, if a detachment fault were present, there could be no possibility of a 1932 Cedar Mountain type earthquake at Yucca Mountain: seismic slip below 6 to 8 km depth could never break ground.

If an inferred detachment system has operated at least intermittently for the past 12 m.y., we find it to be a contradiction that the geophysical signature of intrusive bodies such as the basalts in Crater Flat and even the calderas show no systematic offset. If the fault set at Pahute Mesa (Minor *et al.*, 1996) were genetically related to faults of Yucca Mountain, then the detachment model must be extended north though the caldera complex. This model does not explain how a detachment could operate within or near a volume of crust subject to large-scale magma flux during nearly 7 m.y.

In terms of mechanics, the detachment model must operate on assumptions that present difficult and even intractable problems concerning dynamics. Among these is the assumption that the ductility and vertical strength profile in the crust is the same today as it was in mid-Miocene time. Models that require shifts from east-directed to west-directed detachment or invoke uplift of Bare Mountain by several kilometers during a tectonic event that terminates one episode of detachment and initiates another are unconstrained by available data and understanding of tectonic processes that have been active in the southern Great Basin.

G.I. Ofoegbu and D.A. Ferrill (CNWRA, written communication, 1995) applied finite-element modeling to the problem of detachment-related fault slip. A five-layer linear elastic model was used, and the initial stress state included previous fault slip on simulated Yucca

Mountain fault planes. For the model to work, each fault was treated as a weakly cohesive or cohesionless layer at least 150 m thick and decoupled from confining rock. Slip was forced to occur on a selected fault by reducing its coefficient of static friction. Under applicable confining stress, a friction angle of 0.93 degrees is required. The model implies also that a significant proportion of fault displacement is taken up by deformation of the hanging wall and footwall. G.I. Ofoegbu and D.A. Ferrill *et al.* (CNWRA, written communication, 1995) found that slip rates in the detachment fault and in the steep, off-branching perturbed fault differed by six orders of magnitude. They concluded that a detachment fault is likely to slip aseismically in response to slip events that may occur at seismic rates on the off-branching steep faults. To reach this conclusion, however, the modeled mechanism appears to violate the concept of detachment faulting: steep fault perturbation is not supposed to generate strain in a detachment fault. Rather, the detachment is the master slip plane, and motion along it is supposed to generate slip along the faults of the upper plate and distribute strain among them by virtue of independent motion. In other words, the model did not demonstrate how detachment is supposed to control fault slip in the upper plate.

It is clear from the model, however, that detachment can work only along a weak layer that has an unusually low angle of friction and low cohesive strength. This is why detachments are common as slump mechanisms (undrained failure) in saturated sediments and in the marine environment (leaving apart the issue of low effective stress). It also explains why exposed detachments typically show evidence of ductile deformation in the lower plate. Given the present structure and physical conditions of the upper crust near Yucca Mountain, we consider it highly unlikely that there is a throughgoing subhorizontal weak layer having the required properties and thickness at mid-crustal levels beneath Yucca Mountain and Crater Flat. Observed focal mechanism data from the Basin and Range (Doser and Smith, 1989) do not reveal nodal plane populations that would be consistent with low-angle, listric faulting. The fact that focal mechanisms of normal to oblique slip normal faulting earthquakes in extensional regimes from a global record (Jackson and White, 1989) show no low-angle (detachment) slip further supports our conclusions. Therefore, detachment models do not figure in our analysis of local faults and they are not incorporated into the seismic source characterization model.

2.3 HALF GRABEN MODEL—CARAPACE EFFECT

The collapsed carapace model (actually a submodel, hereafter termed the *carapace effect*, of the half graben model) of Yucca Mountain defines two layers. Yucca Mountain is the morphological expression of a faulted layer about 2.5 km thick of volcanic rock (the carapace) that rests unconformably on a thicker crustal layer (15 to 20 km thick) of Paleozoic and Precambrian marine sedimentary and metasedimentary rocks. This configuration is important because the layers differ greatly in bulk material properties and have radically different stress histories. The sub-carapace structure is revealed at Bare Mountain, the Specter Range, and the core of the Calico Hills. We emphasize that the fault characteristics, including slip history, that we measure in the carapace may have little or no relationship to seismogenic faults in the Paleozoic substrate. If we discount the carapace effect, then all of the faults we characterize at Yucca Mountain are potentially seismogenic and each can be projected as continuous fault planes to seismogenic depth as an end-member idealization of the half-graben model. If we strongly weight the carapace effect, then perhaps only one, two, or three Yucca Mountain faults project deep into the crust. The others are confined to the carapace, or link to faults having different attitudes and aspect ratios below the unconformity. According to this interpretation, the bulk of the faults in the volcanic carapace either are postseismic strain adjustments, or reflect strain that originates within or at the base of the carapace. To understand such processes we must regard the carapace as behaving like a huge, fragmented, incipient slab slide, much like an arrested slab slide or avalanche. This structure requires a basal weak layer or some form of decoupling from the substrate.

Arrested slab slides typically are broken by anastamosing faults that are broadly concave-facing downslope and have high length-to-width ratios. In cross section the fault slices show a general slump-like sense of hanging wall rotation, but along strike they are variably tilted. Much of the fault pattern at Yucca Mountain has the structural characteristics of an arrested slab slide. The abundance of toreva blocks and graben-like splays, the presence of footwall slices that are only a kilometer or two wide and that pinch out and change elevation along strike, faults that die out or fray out along strike, that are better described as breccia zones than faults (such as the Ghost Dance fault), all constitute a pattern of local tearing, spreading, and extensile damage within which the traces of deep-seated faults that span the length of the mountain are not apparent (the trace of the Solitario Canyon fault being an exception).

The closest structural analog to Yucca Mountain is the faulted volcanic carapace exposed along the south and west flanks of Mid Valley, about 22 km to the northeast. There, the faulted blocks of Timber Mountain Group and Paintbrush Group tuffs closely resemble those at Yucca Mountain, except they are about half the scale. The carapace rests unconformably on an eroded substrate of well-exposed 13-Ma Wahmonie dacite flows that do not reflect the structural attitude of the overlying tilted slices. The Wahmonie volcanic substrate is analogous to the Paleozoic carbonate substrate beneath Yucca Mountain. Two features are important here: (1) the Mid Valley carapace has subsided and partly extended into Mid Valley basin; and (2) deep stream erosion has isolated the blocks, facilitating some local faulting and tilting. These features suggest that the fault pattern in the carapace is a local, slope-controlled phenomenon rather than one controlled by a system of deep-seated faults.

How could such a system be accounted for at Yucca Mountain? It could work only by way of a weak layer beneath the carapace. Strata beneath the volcanic carapace in Crater Flat basin are equivalent to Rocks of Pavits Spring, a pre-14-Ma unit well exposed near Pavits Spring in Rock Valley (Hinrichs, 1968). The Rocks of Pavits Spring include weakly consolidated volcaniclastic silts and fine-grained sands. Layers of the requisite compositions could include fine-grained, altered airfall tuffs. In a saturated state (normal hydrostatic stress), such sediment could be susceptible to undrained failure or abrupt loss of shear strength. The mechanism might be driven by cumulative seismic strain ("hydraulic jacking" and grain redistribution) during times of high groundwater flux (Castro and Poulos, 1977; Seed and Idriss, 1982). We emphasize that the mechanism involves transient reductions of effective stress, not wholesale grain repacking from a metastable condition as in liquefaction or quick behavior. For example, soft-sediment faults are exposed below the volcanic section at the base of the south flank of Skull Mountain. Extensive failure of this type is considered to have facilitated the collapse of the south flank of Skull Mountain into Rock Valley. Deformation of this type is well documented in the extensively collapsed Eocene lower Absaroka Volcanic Supergroup, Wyoming (Decker, 1990).

In Crater Flat, the extent of an inferred weak layer is unknown. The model assumes that the sediments form a continuous deposit that thins and perhaps pinches out against the Paleozoic rock that forms the relatively elevated eastern rim of Crater Flat basin. This distribution implies that the eastern margin of Yucca Mountain (east of the Paintbrush Canyon-Stagecoach Road fault) is anchored directly on the Paleozoic substrate, leaving the carapace to the west susceptible to deformation of the inferred weak layer.

The bulk movement we expect from weak layer failure is chiefly translational. Such motion could explain the relatively minor offset accompanied by extensive damage along some of the faults. For example, the Bow Ridge fault as seen in the Exploratory Surface Facility (ESF) is a zone about 2 m wide that dips 60 degrees west and contains sand- and gravel-size crush material. Likewise, the Drill Hole Wash fault, as projected into the ESF, is a breccia zone about 2 m wide that contains rotated blocks as much as a meter in diameter. The characteristic breccia that defines the Ghost Dance fault could also be of oblique extensional origin. We consider an early stage of failure and collapse in which the entire volcanic carapace pulled away from the caldera rim, like a shattered ice floe on a gelid stream, the various fault blocks extending, colliding, and subsiding upon the weak layer as Crater Flat basin widened and deepened to the southwest (cf. Fossen and Gabrielsen, 1996). Such motion explains Yucca Wash as a minor extensional structure, and accounts for the odd down-to-the-east offsets along the west side of the mountain. Extension of the carapace to the west is limited by the footwall of the Bare Mountain fault. In-situ stress measurements by Stock *et al.* (1985) reveal that the least compressive stress at Yucca Mountain is at the limit of normal fault slip, implying that the carapace may be held together by the strength of the strata on which it rests.

The carapace effect means that most or all of the faults at Yucca Mountain are distributed. It means that Yucca Mountain is high not because of footwall uplift, but because of original deposition. It implies that any buried fault in the Paleozoic substrate could have been overridden repeatedly and broken through the carapace in more than one place, thus explaining complex fault zone structure. It also implies that some of the slip budget can be attributed to creep or postseismic adjustment to weak layer deformation. It finally implies that exogenous effects, such as high groundwater flux, may be more important here, at least locally, than tectonic effects; that unknown aspects of high pore pressure and time-dependent seismic strain weakening could be significant controls on recurrent fault slip.

The carapace effect does not explain the long, throughgoing, nearly rectilinear trace of the Solitario Canyon fault, nor the major block-bounding aspect of fault segments such as the Windy Wash fault. Accordingly, our preferred interpretation is that the large block-bounding faults (the Paintbrush Canyon-Stagecoach Road fault, the Solitario Canyon, and Windy Wash faults) are through-the-crust seismogenic faults, and that many intrablock faults such as the Ghost Dance fault, probably are confined to the carapace.

The tectonic model for Yucca Mountain best supported by the data is that of a half graben that includes both axial faults in Crater Flat basin and faults antithetic to Bare Mountain. This model posits the block-bounding faults of Yucca Mountain and the Bare Mountain fault as discrete, single plane faults that descend to the base of the seismogenic crust. It also provides a mechanism for one or more of the block bounding faults to interact with the Bare Mountain fault at the deepest seismogenic level where basaltic magma intrusion may be facilitated by fault displacement or dilation, thus providing a mechanism for coupled volcano-seismic events. All or some of the faults west of the Solitario Canyon fault may be antithetic to the Bare Mountain fault, a structural configuration that reduces the capability of large-scale faulting with widths of the scale of the seismogenic crust thickness, thereby reducing maximum magnitude. This fundamental model provides for individual fault scenarios as well as linked and distributed fault scenarios.

We do not find evidence to support an active detachment fault, which is a form of special pleading for mechanisms that are not reasonably demonstrable at Yucca Mountain. In other words, the data set do not require these models; their only purpose is to explain a "hidden" structure or some hypothetical mechanism that could act at any time but that has no manifest or unequivocal history at Yucca Mountain.

We consider two modifications to our basic model that do take into account buried faults, however: the collapsed carapace effect and a dextral strike-slip fault external to Crater Flat that projects from the southeast into Crater Flat beneath the carapace. These modifications are not exclusive and they are supported by some data. They support linked and distributed fault scenarios as well as a buried seismic source. We do not weight these modifications; their physical presence accounts for seismic sources the activity of which is assessed separately. Because specific tectonic models are not explicitly weighted, we have no tectonic models logic tree; all our local seismic structural sources are referred to in our favored model.

3.0
SEISMIC SOURCES

Three kinds of seismic sources are considered in our analysis, in order of increasing scale and specificity: seismic source zones, regional faults, and local faults. Seismic source zones are geographic regions discriminated on the basis of tectonic style and the structural nature of the seismogenic faults contained therein. As seismic sources, these regions are noted for the maximum background earthquake each is capable of hosting. Regional faults are specific, identified structural sources within these zones that, on the evidence of past surface rupture, are capable of generating earthquakes of some estimable magnitude greater than background. We also include discussion of a possible buried strike-slip fault source with regional faults. Local faults are structural sources confined to Yucca Mountain. Because of their proximity to the potential repository, local faults are analyzed for both ground shaking and displacement hazard. The local faults are all close to each other relative to depth of the seismogenic crust so linking and distributed motion are important considerations. The potential dynamic interactions among local faults constrains estimates of earthquake magnitude and fault mechanics; for this reason, a tectonic model constitutes an important rationale for our estimates of local fault parameters.

3.1 FOCAL DEPTH DISTRIBUTION AND DEPTH OF THE SEISMOGENIC CRUST

The maximum depth distribution of earthquakes in the Yucca Mountain area was determined by analyzing focal depth data on well recorded earthquakes recorded by seismic networks within the region as well as checking this information against rheologic models of the seismogenic crust that constrain the depth to the brittle-ductile transition. We studied the focal depth distribution using filtered focal-depth plots determined by our own study employing the ZMAP (S. Weimer, Univerity of Alaska, Fairbanks, written communication, 1996, seismicity analysis program) and by focal depth data provided by Woodward-Clyde Federal Services from the Yucca Mountain catalog filtered to our specifications.

The composite Yucca Mountain earthquake catalog, encompassing a 300 km radius sort from the Yucca Mountain site, is the same catalog that was distributed by Woodward-Clyde Federal Services to all Yucca Mountain teams after revisions for removal of multiple events and non-tectonic events. Focal depths were filtered by focal-depth accuracy, assumed to be related to the hypocenter parameter, DMN. DMN is the distance to the nearest station and is the standard statistical parameter used in the seismograph network community for analyzing focal depth accuracies. DMN is generally an indicator of the depth for which the eigenvalue for a particular hypocenter is within a single solution space whose major and minor axes represent a source volume ellipsoid and are a measure of the error ellipse for the specified standard error of picking the appropriate phase, such as the first P wave arrival.

The Yucca Mountain earthquake catalog was first evaluated for important non-earthquake contributions such as nuclear explosions as well as mislocated epicenters. After finalizing the most complete catalog, the hypocenter files were filtered for earthquakes for most accurate focal depths in two categories: 1) with DMN equal to or less than 1, and 2) DMN equal to or less than 1.5. We finally used the focal depth constraint to be DMN equal to or less than 1.5 to constrain the depths as it gave a larger population necessary for the best statistical treatment and still retained accurately determined focal depths. We used the ZMAP seismicity analysis package (S. Weimer, University of Alaska Fairbanks, written communication, 1996) to sort the hypocenter data for the various source areas in the 300 km wide catalog window. We used the Woodward-Clyde focal mechanism data to check against ours using the same DMN criteria.

We first considered the local Yucca Mountain area, encompassing the site and the nearby faults from the Bare Mountain fault on the west to the Gravity fault on the east and from the south edge of the Timber Mountain caldera to approximately the Highway 95 (Figure SDO-1). However using this area only provided a limited number of accurate focal depths; and we expanded our window to include the region of Source Zone 1 (Figure SDO-2).

The sorting process provided data for epicenter maps, recurrence plots for the filtered data for a given DMN value, and focal depth distributions. For completeness and to compare our data, we also asked Woodward-Clyde to provide the same data which revealed reasonably the same distributions. We then proceeded to sort the earthquake data into bins that we consider representative of the region: 1) the Yucca Mountain site, 2) a zone which included the Yucca Mountain site and extended across the California-Nevada border on the south on a NW trending line that extended across the NTS site and extended ~150 km NW and 150 km SE, 3) a zone that extended southwest from California-Nevada border ~90 km and 120 km E-W, and 4) a zone that extended ~ 200 NE into the Basin-Range. We also made epicenter plots for various depths of the distribution to examine if the distribution characteristics varied across the zones. Note these are a little different from our final three seismic source zones within 100 km of the site, but were used to assess enough good focal depth data to give statistically useful distributions.

The filtered focal depth data revealed Gaussian shaped distributions, centered at depths of ~ 8 to 10 km, with a scarcity of hypocenters from 0 to 2 km and an exponential decay to maximum depths of ~ 19 km (Figure SDO-3). We note the scarcity of data in the 0-2 km depth range, a depth range that we consider to be incapable of radiating strong ground motion because of the reduced stress state.

Alternate Evaluations--As alternate evaluations we examined focal distributions for areas around the Yucca Mountain site out to distances of 300 km, but we use data primarily from an area with a radius of 100 km from the site, because we wanted the data as representative as possible for this area which constitutes the Yucca Mountain geologic setting. We did not consider seismic sources beyond 100 km in our source models as beyond this distance the peak ground accelerations would not be significant at the site for earthquakes in this region.

We based our final maximum-depth of earthquakes on the focal depth distributions (rather than a 80 to 90% focal depth cut-off as suggested in rheological arguments) with consideration to the uncertainties in focal depth. We define a distribution for the maximum depth of earthquakes weighted as follows:

Depth (km)	Weight
14 km	0.2
17 km	0.7
19 km	0.1

We assigned the minimum focal depth as the depth with the largest (minimum) error for depth in the distribution considering ± 2 km for well resolved focal depths. The average maximum depth is near 17 km (Figure SDO-4). This depth also is consistent with the observed M 7+ normal faulting distribution of the Basin-Range (Smith and Arabasz, 1991).

A maximum focal depth of 19 km was chosen by our team as the depth of the largest well recorded earthquakes in the Basin and Range. This depth was as determined from the top of the maximum depth source zone that was modeled to depths of 25 km for a dynamic source by Mendoza and Hartzel (1988) for the M 7.3, 1983, Borah Peak normal faulting earthquake. We recognize that it is deeper than 95% of the depths of background seismicity, but it was taken as an upper bound of depths that could plausibly occur in the Basin Range province.

Our focal depth distributions were also compared with idealized rheological models for the southern Basin-Range area considering the hypothesis that the focal depth distribution relates to the thickness of the seismogenic crust (the brittle layer). This depth has been shown to correlate with background seismicity at about the 80 percentile depth and was taken as indicator for the bottom of the background seismicity (Smith and Bruhn, 1984). It corresponds to Smith and Bruhn's (1984) model for extensional normal-faulting regimes in the Basin-Range, where the maximum focal depths of large normal-faulting earthquakes correlate approximately with the 80th percentile of focal depths for smaller background earthquakes. We followed the use of such indicators, which since the mid-1970s, have revealed that accurate hypocenter data acquired by regional and portable seismic networks in the Basin-Range region permit the construction of reliable focal-depth histograms (Sibson, 1982; Smith and Bruhn, 1984).

Seismogenic models based on theoretical depths were hypothesized for peaks in maximum shear stress at the boundary between the brittle upper crust and a quasi-plastic layer (Scholz, 1990). These models in a general way account for the maximum depths of nucleation of large normal faulting earthquakes and for the maximum depths of background seismicity, corresponding to the base of the seismogenic layer. The models involve a temperature-dependent, depth-varying power law for creep combined with a linear brittle-behavior criterion. Scholz (1990) predicts the thickness of the seismogenic layer, and hence the maximum focal depths of earthquakes, using both a similar temperature criterion as that described above and additional fault-velocity constraints.

Qualitative arguments of Sibson (1982) and Smith and Bruhn (1984) suggested that the theoretically derived transition depth from brittle to quasi-plastic flow for silica-rich rocks is controlled primarily by a critical temperature of approximately 350 °C to 450 °C and occurs at or near the depth of maximum shear stress. At this depth, short-term strain rates greater than 10^{-3} to 10^{-4}/sec are necessary to achieve brittle failure during earthquakes within the more ductile, intermediate-depth crustal material. In theory, this is the critical depth for nucleation of the largest magnitude earthquakes. For the Yucca Mountain site the critical depth or depth to the brittle-ductile transition is taken to be 10 to 15 km for a quartz to dry quartzite composition and for the relatively low regional strain rate of 10^{-17} per second (Eddington *et al.*, 1987).

Comparison of background focal depth data (Smith and Arabasz, 1991) for three of the best studied, scarp-forming normal faulting earthquakes of the Basin-Range (the 1959 M7.5 Hebgen Lake, the 1971 M7.1 Dixie Valley, and the 1983 M7.3 Borah Peak earthquakes) supports our evaluation of depth of nucleation of large, M7+ events at a few kilometers beneath the idealized brittle-ductile transition depth.

3.2 SEISMIC SOURCE ZONES

Seismic source zones are defined on the basis of tectonic style, structural pattern, and rates of deformation. On this basis, the source zones are equivalent to tectonic subprovinces or regional domains of the southern Great Basin. Three of these regional domains fall within a 100-km radius of Yucca Mountain and therefore qualify as source zones of potential ground shaking hazard at and near the mountain.

We determined three seismic source zones that include most, or large areas of, (1) the Walker Lane, (2) the Inyo-Mono terrane (or the Death Valley Zone), and (3) the Basin and Range Province. Figure SDO-2 shows the source zones in relation to the 100 km radius centered on Yucca Mountain.

Zone 1 comprises the Goldfield-Spring Mountain sections of the Walker Lane (Stewart 1988). It is characterized by a complex structural pattern that includes north-south-striking Basin-and-Range style normal faults, local basins, and Walker Lane style structures (northwest-striking dextral faults and northeast-striking sinistral faults). The northern part of the zone is dominated by volcanic rocks (tuffs of Miocene age); the southern part (Spring Mountains section) consists chiefly of little-extended Paleozoic rock. It is bounded on the west by the Furnace Creek-Death Valley fault zone and the Pahrump-Stewart Valley fault zone, and on the east by the Las Vegas Valley shear zone. North of Indian Springs, the eastern margin of the zone is structurally diffuse, but generally is distinguished by northwest-striking dextral faults.

Zone 2 is the Death Valley section (or the Inyo-Mono terrane), which is characterized by active strike-slip faulting. The zone extends west from the Furnace Creek fault to the Sierra Nevada block. The Mammoth Lakes area to the north is purposely excluded from this zone because recent high levels of seismicity are associated with the Long Valley caldera and potentially localized volcano-tectonic activity. The southern boundary is marked by the Garlock fault.

Zone 3 is the central Basin and Range zone, which is bounded on the south by the Intermountain Seismic Belt that extends westward from Utah at about 36 degrees latitude and on the north by the 300-km cut-off distance from the site.

Alternative zones - Our initial categorization identified the Yucca Mountain site as a separate source zone having its own fault and seismicity characteristics. This area was bounded on the west by the Bare Mountain fault and on the east by the gravity fault. The north boundary was defined by Yucca Wash and the rim zone of the Claim Canyon caldera; the south side was at the southern termination of the Solitario and Stagecoach Road faults (Figure SDO-1). Plots of the historical seismicity from the project catalog (Appendix D of the main report) reveal only about 30 local earthquakes in this zone. Because of the sparcity of earthquakes, we chose not to identify this as a discrete seismic source zone, but included it in our regional source Zone 1 that would be characterized by its historic seismicity data.

We also considered as a separate seismic source zone an area defined by the Little Skull Mountain earthquake and its aftershock distribution. We made this interpretation based on the length of the aftershock zone (~ 30 km), which would correspond to the lower bound of our maximum background earthquake distribution for the lowest standard of error with a corresponding magnitude 6.3. However, after considering how to sort the historical data in both time and space, and considering that this location has been the site of smaller earthquakes that reflect ongoing seismicity characterized by our Zone 1 seismicity, we ultimately chose not to identify this as a discrete source area.

3.2.1 Maximum Background Earthquake

The maximum background earthquake, or MBE, is a critical parameter for the Yucca Mountain site PSHA. For our seismic source zones we consider the MBE to mean the largest earthquake that reasonably could occur in each seismic source zone without producing a distinguishable shear displacement of the ground surface (although there could be considerable ground cracks, fissures, etc. such as those that occurred with the M 6.2, 1986 Chalfant Valley, Nevada-California border earthquake). MBE was evaluated by comparing the seismicity characteristics of the Yucca Mountain area with the Quaternary tectonics (faults, fault lengths, relations to other structures, etc.) of the region and other extensional tectonic regimes. We considered that the seismic sources vary as a function of the faults that lie within them.

We used the data from Doser and Smith (1989) and the USGS fault data from Pezzopane (Seismotectonic Framework report [USGS, written communication, 1996]) to assess the maximum background earthquake distribution. We constructed our own distribution of Basin-Range earthquakes according to the following criteria: for magnitudes of $M_S > 5.5$, and for all ground breaking events.

We identified the maximum magnitude for each source zone, but also qualified that parameterization for a source radius of 100 km to ensure completeness for the Yucca Mountain site (Table SDO-1, Figure SDO-5).

Using the analogy of no tectonic fracturing associated with the Chalfant Valley earthquake and the largest earthquake in the Basin and Range province without surface rupture, the 1925 Clarkston Valley, Montana, M 6.6 (Doser and Smith, 1989; C.M. dePolo, written communication, 1997, from field mapping) a density distribution was defined from magnitude 6.2 to 6.6 for the MBE. We define a M_{max} of 6.4 ± 0.2 within 100 km with a cumulative lognormal distribution of:

Magnitude (MBE)	Cumulative distribution
6.2	0.03
6.4	0.50
6.6	0.97

Allowing for uncertainty in the magnitude of the Clarkston Valley earthquake, the maximum magnitude may be somewhat higher, as large as 6.8.

Our magnitude distribution is in accordance with a compilation of data on the occurrence of surface rupture for normal faulting earthquakes from (Doser and Smith, 1989) that revealed a similar distribution of MBE for a range of $5.3 < M < 7.5$ earthquakes. They showed that 8 events in the Doser and Smith (1989) data set revealed rupture beginning as small as M 6.1 and that all events above 7.1 experienced rupture. These data support our MBE distribution.

3.2.2 Recurrence Rates

Recurrence models describe the relative frequency of large- and small-magnitude earthquakes. The exponential model is considered to be appropriate for seismic source zones. However, for fault sources, it is not clear whether an exponential model or a characteristic earthquake model (Youngs and Coppersmith, 1985) is appropriate. We chose a truncated exponential recurrence model for our recurrence rate determination using the maximum-likelihood method of calculating the recurrence values (see Section 3.1 of the main report). We used all of the earthquake data in the catalog from the smallest to the largest magnitudes in the Yucca Mountain catalog. The choice of the entire magnitude range was made to provide as complete as possible a range of recorded earthquakes in the region. We discuss the treatment of historical seismicity for calculation of earthquake recurrence rates for the seismic source zones in section 4.0.

3.3 REGIONAL FAULT SOURCES

Regional faults within 100 km of Yucca Mountain were reviewed for inclusion in the ground motion analysis. Potential regional fault sources (Figure SDO-6) were identified first from among the following data sources: Slemmons (1967); Dohrenwend *et al.* (1991, 1992); Piety (1995); Chapters 5 and 11 of the Seismotectonic Framework report (USGS, written communication 1996); Jennings (1994); Reheis (1992); and Reheis and Noller (1991). Candidate faults were screened on the basis of evidence of Quaternary displacement. The faults were further screened according to whether they are assessed to equal or exceed 0.05g in the analysis by Pezzopane (Seismotectonic Framework report, Chapters 8 and 11 [USGS, written communication, 1996]). All identified and possible Quaternary faults capable of magnitudes 6.4 ± 0.2 within 50 km were included. In the range of 50 to 100 km from Yucca Mountain, only faults with lengths equal to or greater than 20 km were included. This criterion was based on the potential peak ground accelerations estimated in chapter 11 of the Seismotectonic Framework report (USGS, written communication, 1996). A few faults having slightly lower ground motion potential also were included to account for potential uncertainties that could increase their ground motion, or because long-period ground motions from earthquakes along these faults may be important to the site. Two faults that generally lie beyond 100 km were included: the Panamint Valley fault zone and the Ash Hill fault zone (Figure SDO-6). These were included for their potential contribution to long-period ground motions. Most of the faults show clear evidence of Quaternary activity, such as fault scarps. For a few faults, the existence of Quaternary activity or the fault itself is equivocal. For these faults, a probability of Quaternary activity is assessed based on the degree of belief of fault activity (e.g., how likely the scarps observed along the Oasis Valley fault are from fault movement in the Quaternary).

In general, regional fault sources are characterized only on the basis of fault length for maximum magnitude and slip rate for earthquake recurrence, although a few have a maximum surface displacement as well. Maximum magnitudes were estimated using the scaling relations shown in Table SDO-2 and discussed further in Section 3.3.2. Each regional fault source is characterized according to the parameters in Table SDO-3.

Regional faults were compiled to a mylar overlay of Piety's (1995) map. Fault length estimates were measured on the mylar overlay. Faults were weighted as to whether or not they had Quaternary activity, by evaluating published studies of the individual faults. Maximum surface displacement measurements were taken from the published literature, such as the Seismotectonic Framework report (USGS, written communication, 1996). Fault dips for the regional faults are largely unknown. For the normal-slip faults, 60° was used; for strike-slip faults, 90° was used. Because the regional faults occur within three different seismic source zones, there is an implication that faults within each source zone should mirror a distinct tectonic framework, or structural geometry. However, the Gaussian distribution of epicenters through the seismogenic crust suggests that dynamic distinctions in fault behavior throughout the region are not significant enough to require a models-based explanation. Therefore, we use a simple, universal model for all the faults: they are planar fractures that descend to seismogenic depths, the depths to a maximum of 19 km being directly proportional to fault length.

3.3.1 Description

The Gravity Fault

Because of its tectonic significance as a domain-bounding structure, the "gravity fault" (Winograd and Thordarson, 1975, p. C85) was described in the section on tectonic models. Surface expression along this fault is meager, but available data suggest chiefly normal slip. A subtle fault scarp segment on an alluvial fan was recognized by Reheis and Noller (1991); thus, there is indication of Quaternary activity along it. The lack of fault scarps suggests slip rates on the order of 0.0005 to 0.005 m/ky, but the subtle scarp may support a slip rate of 0.005 to 0.05 m/kyr (see Section 3.3.3 on recurrence justification of slip rate estimates for faults where data is lacking). Thus, the potential range of slip rate is 0.0005 to 0.05 m/kyr, with a preferred median value of 0.005 m/kyr. The minimum and preferred length is estimated to be 45 km, from the hills in the middle of Jackass Flats where the gravity anomaly diminishes, south to the end of the scarps that are on a southerly projection in the Ash Meadows area. The gravity gradient is essentially continuous along this extent. The maximum length extends south about 55 km to where many scarps are at an angle to the gravity fault. Although the Ash Meadows fault zone continues on strike to the south of the gravity fault on the basis of surficial expression, we do not extend it southward because the defining gravity gradient becomes indistinct (Winograd and Thordarson, 1975).

Amargosa River Fault

The Amargosa River fault was mapped by D.E. Donovan (University of Nevada, Reno, written communication, 1991) as a series of fault scarps and lineaments in southwest Amargosa Valley that are considered related to a strike-slip fault. Anderson *et al.* (1995a) confirm Quaternary activity along this fault, suggesting that it is a reactivated Miocene and Pliocene? strike-slip fault. The minimum and preferred lengths are the distance of the fault scarps mapped by Donovan. This length can be measured from the east-northeast-trending scarps in Amargosa Valley, which may be a westward extension of the Rock Valley fault zone at the north end, to a near-intersection with the Ash Meadows fault along the south end. This is a distance of 16 km. The maximum length pushes the south end to an intersection with the Ash Meadows fault and continues north along a lineament, for a total distance of 29 km. Further extension to the north is plausible. No slip rate is reported for the Amargosa River fault; thus, a comparative methodology is employed to estimate the slip rate (see section 3.3.1.3).

Furnace Creek Fault Zone (Northern Death Valley Fault Zone)

The Furnace Creek fault zone is part of the Death Valley fault system, the largest and most active system in the Basin and Range province. The length, single-event displacements, and slip rate of this fault, as determined by R.E. Klinger and L.A. Piety (USBR, written communication, 1996), support this notion. The preferred length of the Furnace Creek fault zone is given by Klinger and Piety as 105 km as measured from the intersection with the central Death Valley fault zone to the Last Chance Canyon area. They suggest that this represents a single rupture segment, an impression supported by the conspicuous scarp trace lineament seen in the USGS Death Valley 1:250,000 SLAR image composite. The minimum length for the maximum event is estimated to be 85 km based on the nearly continuous scarps represented by Piety (1995). If the Furnace Creek fault is continuous with the northern Death Valley fault the length is 120 km by our estimate, and this is our preferred value. The maximum fault length includes both the

Furnace Creek and Fish Lake Valley fault zones, 195 km. Research by T.L. Sawyer and M.C. Reheis (Piedmont Consultants, written communication, 1997) suggests that a small restraining step in the system may control the total rupture length along the Fish Lake Valley fault. The restraining step through Last Chance canyon, which lies between the Fish Lake Valley and Furnace Creek fault zones, is the basis for considering the failure of both of these faults consecutively. The Last Chance restraining step apparently has not ruptured during the Holocene, while both the Furnace Creek and Fish Lake Valley fault zones had multiple displacements. Yet, if this restraining step were to fail when both faults zones are mature in their seismic cycles, it could create a cascading double-fault zone rupture. R.E. Klinger and L.A. Piety (USBR, written communication, 1996) measured the maximum single-event displacement as 6 m of lateral displacement, and an average single-event displacement of 4.5 m, but report no uncertainties for these. We infer a maximum surface displacement to range from 5.5 m to 6.5 m, with an estimated measurement uncertainty of 0.5 m. R.E. Klinger and L.A. Piety (USBR, written communication, 1996) estimated two slip rates for the Furnace Creek fault zone, one near Ubehebe Crater and one near Red Wall Canyon. The Ubehebe Crater site, located on the main strand of the Furnace Creek fault zone, is distinguished by an anticline that includes the Bishop Tuff (~ 760 ka). The anticline is offset, yielding a slip rate of 8 to 10 m/kyr . The slip rate estimate from the Red Wall Canyon site is 4 to 8 m/kyr. We use the overlapping value of the reported ranges (8 m/kyr) for the preferred rate (a decision suggested by R.E. Klinger, written communication, 1997), and use the reported range (4 to 10 m/kyr) for the minimum and maximum values. A good analog for earthquakes along the Furnace Creek fault zone is the 1872 Owens Valley earthquake, which had average surface displacements of 6 m and was about 110 km long (dePolo *et al.*, 1991). That earthquake had a moment magnitude of about 7.8.

Central Death Valley Fault Zone

The Central Death Valley fault zone is a right-normal, oblique-slip fault. The fault zone is part of a right step in the right-lateral Death Valley fault system. Recent work by R.E. Klinger and L.A. Piety (USBR, written communication, 1996) concluded that the Central Death Valley fault zone is the most active, dominantly normal-slip fault in the Basin and Range province. Klinger and Piety measured a minimum surface rupture length of 45 km along the Central Death Valley fault zone, and a total length of about 60 km. Our estimate of 75 km extends this rupture to the south. Because of the rate and the potential size of offsets during paleoevents, we use 75 km for the preferred length, considering that the surface expression is poor along the northern part of the fault zone. The maximum and preferred values are identical, because the fault is structurally intersected at either end. For maximum surface displacement, RE. Klinger and L.A. Piety (USBR, written communication, 1996) measure surface separations (which in this case are essentially equal to vertical displacements because of steep near-surface fault dips and shallowly dipping offset surfaces) of 2.5 to 3.5 m; we adopt these values as the minimum and preferred maximum surface displacement values. Our maximum value adds 1 m to the preferred value to cover surficial noise and possible local poor preservation. Thus, the maximum surface displacement considered is 4.5 m. The minimum, preferred, and maximum slip rates are 2.6, 3.8, and 7.4 m/kyr, respectively. These are based on late Holocene offsets and age estimations of alluvial fan deposits made by R.E. Klinger and L.A. Piety (USBR, written communication, 1996).

Rock Valley Fault Zone

The Rock Valley fault zone comprises at least three major strike-slip faults and numerous bridging oblique faults in a zone that extends from Frenchman Flat west through Rock Valley, and possibly to Jackass Flats south of the Striped Hills, although there is evidence that the faults veer south into the Specter Range. The major faults strike N65°-80°E, are dominantly left-slip to slightly oblique, transtensional faults expressed geomorphically as a series of intermittent fault scarps and vegetation lineaments. Late Pleistocene to possible Holocene faulting has been documented through surficial mapping and trenching studies (Chapter 4, Seismotectonic Framework report [USGS, written communication, 1996]). Fault lengths for the Rock Valley fault zone were measured from the compilation by Piety (1995). The minimum length is 32 km, based on the faults mapped in Frenchman Flat to the west end of the scarps in Rock Valley. The preferred length is 47 km, measured between the faults mapped in Frenchman Flat and faults that pass immediately south of Skeleton Hills (Chapter 4, Seismotectonic Framework report [USGS, written communication, 1996]). The maximum length, 68 km, is measured from faults east of Frenchman Flat to the west end of the north-northeast-trending scarps and lineaments that cross Amargosa Valley. Individual fault strands, as mapped and indicated by lineaments, are about 15 to 17 km long. The Rock Valley fault zone has some of the largest single-event displacements measured in the Yucca Mountain area (Chapter 4, Seismotectonic Framework report [USGS, written communication, 1996]). Paleoseismic events have produced a minimum displacement of 1.14 m to a maximum of 4.51 m. Preferred displacements range from 2.04 to 3.62 m. The second largest preferred displacement is 3.30 m. Because natural variations in surficial expression from earthquakes can be comparable to the difference between the two largest displacement values, we consider it reasonable to use the maximum value as the maximum surface displacement for maximum earthquakes along the Rock Valley fault. Slip rates along Rock Valley fault strands range from 0.05 m/kyr to < 0.002 m/kyr. Yount *et al.* (1987) estimate 0.02 m/kyr for the medial fault strand; we adopt this value as the preferred slip rate for the entire fault zone. The Seismotectonic Framework report (USGS, written communication, 1996) reports a long-term lateral slip rate of 0.084 m/kyr over the past 30 Myr, but suggests that much of this activity may have occurred during the Miocene, when the rates of tectonic activity were higher.

Mine Mountain Fault

The Mine Mountain fault is defined by a 3-km-long fault contact at Mine Mountain that sets Miocene tuff against Paleozoic limestone (Maldonado, 1985). The fault can be projected 3.8 km to the northeast and 26 km to the southwest, based on scattered outcrop evidence and aeromagnetic anomalies. The maximum length is about 35 km (Maldonado, 1985; S.R. Young *et al.*, CNWRA, written communication, 1992). We prefer a length of 21 km, which includes the Mine Mountain segment and the segment projected along Shoshone Mountain to near Kiwi Mesa (Maldonado, 1985). The fault strikes N35°E and dips from 90 to 60 degrees southeast; it is considered planar, based on aeromagnetic gradients and focal plane mechanisms to depths of 9 km. The fault is chiefly normal along Shoshone Mountain, but has a sinistral component along its entire length. No Quaternary offsets are mapped, but colluvium offset against caliche crust in a prospect pit at the southeast corner of Shoshone Mountain amounts to about 20 cm of dip slip. Total offset of surficial material at this site is about one meter, possibly having occurred within the past 100 ky D. O'Leary, USGS, written communication, 1996). Lineaments in old fan surfaces suggest degraded scarps of perhaps mid to early Pleistocene age. Carr (1984) reported an offset of the Paintbrush and Timber Mountain tuffs of about 1 km left-lateral on the south side of Mine Mountain. Assuming that this offset has occurred during the last 11.5 Myr, a slip rate of 0.09 km/Myr (m/kyr) can be calculated, which is considered the maximum slip rate. Because geomorphology along the Mine Mountain is more poorly expressed than along the Rock Valley fault zone, its preferred slip rate is estimated to be similar or slightly lower than for that fault zone, or about 0.01 m/kyr or less; we use a lower limit of 0.005. Recurrent clustered earthquakes beneath the hanging wall of the Mine Mountain fault and along Mine Mountain indicate overall transtension and a low strain threshold. The Mine Mountain fault is considered to be susceptible to normal-oblique, southeast-side-down slip at this time. All of these features suggest that the Little Skull Mountain earthquake was generated by the Mine Mountain fault zone. However, the Mine Mountain fault strikes consistently N35°E rather than N55°E (the strike of the Little Skull Mountain slip plane); therefore, we believe that the Little Skull Mountain earthquake was generated within the Wahmonie fault zone or represents a fault in the hanging wall of the Mine Mountain fault.

Cane Spring Fault

The Cane Spring fault is expressed as a well-defined fault-line scarp that strikes N50°-40°E along a hillslope (Poole *et al.*, 1965). The fault is a single-plane structure that evidently controls the location and flow of Cane Spring. The fault line scarp is only about 6 km long. Frizzell and Shulters (1990) show an additional inferred 5 km extending into Barren Wash, and 2 km projected to the south side of Skull Mountain. The fault is traceable as a lineament into Skull Mountain, but is truncated by and breaks down into a complex of more northeast-striking normal faults. Field examination by O'Leary found no evidence for Quaternary offsets at Skull Mountain, and no evidence that the Cane Spring fault connects with the Rock Valley fault zone. Northeast of Cane Spring ,the fault projects into an alluvial basin. Gross landforms suggest that the fault extends, buried, a considerable distance toward Yucca Flat; therefore our preferred length estimate is 26 km, following the interpretation of Cornwall (1972). The maximum cumulative lateral offset is about 1 km (Poole *et al.*, 1965). The cumulative vertical offset, if any, is unknown because latest movement on the fault is nearly pure strike-slip. The youngest offset unit is about 9.5 Ma which gives a slip rate as high as 0.105 m/kyr. Overall geomorphic character implies very low Pleistocene activity. Thus, the minimum, preferred, and maximum slip rates assigned to the Cane Spring fault are 0.005, 0.01, and 0.05 m/kyr, respectively. In light of its tectonic isolation, lack of late Quaternary expression, and weak correlation with significant slope breaks or boundaries, we rank its probability of activity as 0.8.

Wahmonie Fault Zone

The Wahmonie fault zone is represented by degraded scarp segments in alluvial fans along the north flank of Skull Mountain, which faces Jackass Flats, and as a zone of complex faults exposed in bedrock in the divide between Little Skull Mountain and Skull Mountain (Frizzell and Shulters, 1990). The zone projects directly toward the Striped Hills, which have left-lateral offset as great as 1.4 km along the projection. The projection can be carried even farther south, across Rock Valley and along the flanks of the Specter Range. The Wahmonie fault zone either truncates or intersects the Rock Valley fault zone in a relationship not understood. The structural interaction, which is considered to be related to the recurrent, clustered seismicity at the western end of Rock Valley. Quaternary activity is indicated by fault scarps and lineaments in deposits dated 270-740 ka, and by concealment beneath Holocene deposits (Swadley and Huckins, 1990). Possible Holocene movement is suggested by cracked and slightly offset caliche pavement (observed by O'Leary), and by a conspicuous dearth of precarious rocks at the east end of Little Skull Mountain (J. Brune, oral commun. PSHA workshop). The minimum length of the Wahmonie fault is 9 km. The preferred and maximum lengths are 15 km, which include the discontinuous series of scarps and lineaments in eastern Jackass Flats, just north of Skull Mountain (Swadley and Huckins, 1990). The minimum, preferred, and maximum slip rates assigned to the Wahmonie fault are 0.005, 0.01, and 0.05 m/kyr, respectively. Despite hints of late Pleistocene activity, evidence for significant Pleistocene offset for any appreciable distance along strike has not been noted. On this basis we rank the probability of activity as 0.8.

South Silent Canyon Fault

The South Silent Canyon fault (herein named) lies in the structural system north of the Timber Mountain caldera that is remarkably similar to the Yucca Mountain fault system (described in the section on Tectonic Models). This is only one of several faults in Pahute Mesa that are suspected to have Quaternary activity (i.e., Quaternary alluvium in fault contact with rhyolitic tuffs), but for which we have little information. Maps, such as that of Frizzell and Shulters (1990), show several of these faults bounding local

Quaternary alluvial deposits. The South Silent Canyon fault ruptured following an underground nuclear explosion and/or earthquakes that occurred following the blast. The minimum length is 10 km. A preferred distance of 14 km includes the entire fault zone; a maximum distance of 17 km includes faults in the tuffs farther north. Slip rate estimates are poorly constrained; on the basis of structural similarity to the Yucca Mountain faults, minimum, preferred, and maximum slip rates are assumed to be 0.001, 0.005, and 0.01 m/kyr, respectively. These rates suggest that the South Silent Canyon fault is more active than the Bow Ridge fault, but that the minimum value might be lower. The maximum value approaches the slip rate of the Solitario Canyon fault. Little is known about the Quaternary history of the South Silent Canyon fault. Because of sparse data and uncertainty, we rank its probability of activity 0.8.

Pahute Mesa #1 Fault

The Pahute Mesa #1 fault (herein named) lies just west of the South Silent Canyon fault and is part of the same system. Also similar to the South Silent Canyon fault, the Pahute Mesa #1 fault ruptured in association with an underground nuclear explosion. This fault has a few kilometers of fault-bounded Quaternary alluvium along it (Orkild *et al.*, 1969). The minimum length of the Pahute Mesa #1 fault is about 10 km, the distance of the fairly continuous single-plane trace. The preferred length of 13 km includes the entire fault zone. The maximum length of 16 km includes faults in tuffs farther north. The weak slip rate estimates are based on structural similarities to the Yucca Mountain faults. Thus, minimum, preferred, and maximum slip rates are interpreted to be 0.001, 0.005, and 0.01 m/kyr, respectively. These rates suggest that the Pahute Mesa #1 fault is more active than the Bow Ridge fault, but that the minimum value might be lower. The maximum value approaches the slip rate of the Solitario Canyon fault. The fault-bounded Quaternary alluvium indicates a likelihood that the Pahute Mesa #1 fault has experienced some Quaternary activity, but otherwise we rank its probability of activity the same as for the South Silent Canyon fault, for the same reasons..

Yucca-Butte Fault Zone

The Yucca-Butte fault zone is a down-to-the-east, normal-slip fault that extends across the middle of Yucca Flat (Yucca fault) into the hills north of the flat (Butte fault). Because of the continuity between the Yucca and Butte faults, they are treated here as a structurally linked fault zone. The minimum length of the Yucca-Butte fault zone is 26 km, the distance of the Yucca fault portion. The preferred value is 34 km, which includes the small range-front portion (the Butte fault) north of Yucca Flat. The maximum value, 41 km, includes scarps and lineaments north of the Butte fault. Fault scarps clearly indicate Quaternary activity (Swadley and Hoover, 1990). Fernald *et al.* (1968) measure a surface displacement of 15 m in the Quaternary alluvium. Using ages for surfaces mapped by Swadley and Hoover (1990) and correlations with surfaces that have been studied in the Yucca Mountain area, slip rates for the Yucca-Butte fault range from 0.015 to 0.053 m/kyr, with a preferred value of 0.026 m/kyr.

Peace Camp Fault

The Peace Camp fault has been mapped by Dohrenwend *et al.* (1991) as a northeast-trending, fault-controlled lineament; by Reheis (1992) as a prominent scarp or lineament in Quaternary deposits; and by Yount (unpublished mapping) as a fault in older Quaternary alluvial deposits. Its strike and location suggest that the Peace Camp fault may be a left-slip fault, part of a small system that includes the South Ridge Faults" of Piety (1995). This structural association apparently would require a left step of about 2 km. The minimum and preferred length for the Peace Camp fault, 12 km, represents its clear expression in Quaternary alluvium. The maximum length of 30 km includes the South Ridge faults. Although Dohrenwend *et al.* (1991) show the South Ridge faults as juxtaposing Quaternary alluvium against bedrock, lack of geomorphic expression along this eastern extension suggests that earthquakes likely are restricted to half of this maximum length (15 km). Extension of the Peace Camp fault to the west would require another left step and a change to a more northerly orientation. A westward extension would bring the Peace Camp fault into structural association with the West Spring Mountains fault.

Slip rates from the Mine Mountain fault are adopted for the Peace Camp fault, on the basis of similar geomorphic expression. Thus, the minimum, preferred, and maximum slip rates assigned to the Peace Camp fault are 0.005, 0.01, and 0.09 m/kyr, respectively.

West Spring Mountains Fault

The West Spring Mountains fault is a west-side-down, normal-slip fault that bounds the northwest side of the Spring Mountains. The fault has been mapped and studied by J. L. Hoffard (University of Nevada, Reno, written communication,1991). Quaternary activity is evidenced by fault scarps. The minimum length of a continuous fault is 30 km. The preferred length of 37 km accounts for a south scarp that is on strike, but separated by a small gap in surficial expression. The maximum length of the West Spring Mountains fault is 56 km, which includes the Eastern Pahrump Valley fault zone southward to an intersection with the Pahrump Valley fault zone. This south reach may have a right-lateral component, given its relatively linear nature and left-stepping patterns. Based on geomorphology, the north 30 to 37 km of the West Spring Mountains fault appears to be a single earthquake segment. J. L. Hoffard (University of Nevada, Reno, written communication, 1991) measured a vertical surface separation of 12 m, which has been corrected to a vertical offset of 13.2 m to account for the surface slope and fault dip. Different projections of the profile made by Hoffard yield potential uncertainties of - 2 and + 4 m. Hoffard estimates the age of this offset surface to be 200 ka, with a range of 130 to 500 ka. These data yield a range of slip rates from 0.02 to 0.2 m/kyr, with a preferred rate of 0.09 m/kyr.

Oasis Valley Fault Zone

The Oasis Valley fault zone is a normal-slip fault that lies along a steep north-south gravity gradient (Anderson *et al.*, 1995b). This fault zone lacks evidence for late Quaternary faulting (Anderson *et al.*, 1995b). A prominent lineament, however, may be evidence of minor early Pleistocene displacement (Anderson *et al.*, 1995b). The minimum length of 5 km represents the bold faults from Piety's (1995) map. The preferred length of 8 km accounts for other faults and/or lineaments on strike. The maximum length of 20 km is the total possible expression of this fault zone, including projected faulting in Oasis Valley. Overall lack of geomorphic expression suggests that the slip rate likely is low, perhaps similar to that of the Bow Ridge fault. A range of 0.0005 to 0.003 m/kyr is assigned to the Oasis Valley fault zone, with a preferred value of 0.001 m/kyr. The very weak evidence for Quaternary activity leads us to assign a probability of activity of 0.8.

Pahrump Valley Fault Zone

The Pahrump Valley fault zone is made up of a series of discontinuous, northwest-trending scarps, spring alignments, and lineaments that indicate a right-slip fault zone (J. L. Hoffard, University of Nevada, Reno, written communication, 1991; Anderson *et al.*, 1995b; and Louie *et al.*, University of Nevada, Reno, written communication, 1997). The fault zone lies along the center of Pahrump Valley (essentially along the Nevada/California state line); it extends from Black Butte at the south end to an apparent pull-apart basin, Stewart Valley, at the north. The minimum length (25 km) is the distance of continuous geomorphic features in north Pahrump Valley, extending into south Stewart Valley. The preferred and maximum lengths (61 and 67 km, respectively) extend the zone down to Black Butte, with a maximum rupture length that traverses all of Stewart Valley. To estimate slip rate, we compare this fault zone with the Rock Valley fault zone, which has a similar, zone-like, geomorphic expression, but sharper geomorphic features. We assign a preferred slip rate of 0.01 m/kyr, with a range of 0.005 to 0.1 m/kyr.

Bare Mountain Fault

The Bare Mountain fault is poorly exposed, probably because in Quaternary time erosion and deposition have far outweighed tectonic activity along the fault. Gravity and seismic reflection data indicate that the fault plane stands at least a kilometer out from the eroded range front at the north end of the mountain, and converges more closely to the range front toward the south. Younger activity of the fault is also indicated to the south. The fault (or faults, if several planes are involved) dips east at 50 to 70 degrees; displacement is chiefly normal, with an oblique dextral component prominent to the south (Reheis, 1988; Monsen *et al.*, 1992). The fault is at least 18 km long. At the northeast corner of Bare Mountain, the Bare Mountain fault loses throw and breaks into a group of faults that extend across tuffs of the caldera rim assemblage. The easternmost fault is the Tram Ridge fault; it extends about 10 km to the Rainier Mesa caldera. A smaller, less clearly defined fault 8 km long, east side down, bounds the tuffs and the alluvium of Crater Flat. This fault apparently is post-8 Ma (C. Fridrich, USGS, written communication). At the south end, near Steves Pass, the Bare Mountain fault abruptly loses throw and ceases to be a range-front fault. It becomes lost in a distributed zone that includes faults traceable to Yucca Mountain itself; although a set of northwest-striking, dextral oblique faults appears to dominate the fault structure in this area. Within this plexus, the Bare Mountain fault is not a single-plane structure and probably is not a major tectonic influence. Because it surfaces within surficial deposits for most of its length, there is no direct indication of total bedrock displacement. The fault does not appear to be segmented; surface rupture has occurred along a relatively linear, narrow zone on all or most of its (preferred) 23-km length. Surface-rupturing earthquakes on the fault occur infrequently. The recurrence of moderate- to large-magnitude, surface-rupturing earthquakes appears to be on the order of tens of thousands to a hundred thousand years or more. The most recent surface-rupturing event occurred no more recently than about 14 to 24 ka and could be as old as 100 ka (Seismotectonic Framework report [USGS, written communication, 1996]). Maximum surface displacement ranges from 1.2 m to 1.8 m; we adopt a preferred value of 1.5 m which is the value reported in the Seismotectonic Framework report (USGS, written communication, 1996). An uncertainty of ± 0.3 m is considered to encompass a potential range of measurements (projection uncertainties or variability of datums). The minimum slip rate (0.006g m/ky) is taken from a minimum offset measured by L. W. Anderson and R. E. Klinger (USBR, written communication, 1996a) of 2.2 m taken over their maximum estimated age of 400 ka. The preferred value of 0.01 m/ky is the value estimated from L. W. Anderson and R. E. Klinger (USBR, written communication, 1996a). Ferrill *et al.* (1996) suggest a higher slip (0.2 m/ky) based on indirect evidence; we adopt this as our maximum slip rate.

Keane Wonder Fault

The Keane Wonder fault is a west-side-down, normal-slip fault that bounds the southeast side of north Death Valley and part of the west side of the Grapevine Mountains. The minimum, preferred, and maximum lengths are 19, 27, and 29 km, respectively. The minimum length is the continuous central part mapped by Piety (1995); the preferred length extends this to the north and south along a range front. The maximum length extends the fault farther south along a fault trace that bounds a range front for some distance before trending into the range. Lack of a faceted range front and of fault scarps indicates a relatively low rate of activity. The preferred slip rate estimate is the approximate threshold of faults having fault scarps of 0.005 m/kyr. The fault appears to lack late Quaternary activity (Anderson *et al.*, 1995b); but an abrupt, rectilinear range front indicates possible early to mid-Quaternary activity. Given that deposition along the range front is fairly uniform at the front, some Quaternary activity is considered likely. Thus, we consider a minimum slip rate of 0.001 m/kyr. The maximum rate is 0.05 m/kyr, just a little higher than the maximum rate of the Solitario Canyon fault. We make it slightly higher to reflect our uncertainty, because the Keane Wonder fault is untrenched.

Eleana Range Fault

The Eleana Range fault is an east-side-down, normal-slip fault that bounds the northwest side of Yucca Flat and the east side of part of the Eleana Range. This fault is about 5 km west of, and is synthetic to, the Carpetbag fault. The Eleana Range fault appears to bound a small subbasin within Yucca Flat, just west of the Carpetbag fault (Frizzell and Shulters, 1990). Fault scarps along the Eleana Range fault are indicated by Swadley and Hoover (1990) and Dohrenwend *et al.* (1992); the latter authors indicate some of these scarps are in late Pleistocene deposits. The Eleana Range fault is considered to be limited to its range-front expression, 15 km. This value is used for both the preferred and maximum values. A minimum value of 11 km represents the central part of the fault that has scarps. No direct slip rates are available for the Eleana Range fault, so we used comparisons. Because fault scarps are present, we assigned a minimum value of 0.003 m/kyr. The preferred value is difficult to ascertain, but we consider it be comparable to the Solitario Canyon fault, about 0.01 m/kyr. The maximum value assigned to the Eleana Range fault is the approximate maximum value for the Yucca-Butte fault zone, 0.05 m/kyr.

Yucca Lake Fault

The Yucca Lake fault is a down-to-the-northeast, normal-slip fault that bounds a short section of the west side of Yucca Flat. The fault is shown to offset the buried upper surface of pre-Cenozoic rocks in the subsurface, and a potential right-lateral component is indicated by McKeown *et al.* (1976). No fault scarps are identified along the Yucca Lake fault, and Quaternary activity is uncertain, although Cornwall (1972) shows the fault in Quaternary deposits. Given the information at hand, this fault is given a 50% chance of having Quaternary activity. The minimum length is the trace portrayed by Piety (1995), 12 km. The preferred length, 20 km, considers an inferred extension to the northwest and southeast of the trace shown on Piety's map; and the maximum length, 23 km, includes an extension southward that intersects the Cane Springs fault. Slip rate estimates for the

Yucca Lake fault are based on the interpretation that the fault is active and lacks scarps. The minimum rate is estimated to be 0.001 m/kyr; the preferred rate is assigned at the approximate threshold of faults that have scarps, 0.005 m/kyr. The maximum rate is similar to the preferred rate of the Solitario Canyon fault, about 0.01 m/kyr.

Carpetbag Fault

The Carpetbag fault is part of the down-to-the east system of normal faults in Yucca Flat, including the Yucca-Butte fault zone and the Eleana Range fault. At the surface, the Carpetbag fault manifested as faulting induced by nuclear testing. This exposed a fault zone that apparently has a Quaternary history of fracturing, but that had no natural surface expression prior to nuclear testing (Shroba *et al.*, 1988). Subsurface work has further defined the extent of the Carpetbag fault by following an offset of the floor of the Yucca Flat basin (Carr, 1984). The fault is composed of two traces south of the induced surface expression; these are synthetic normal faults separated by about 1.5 km (Frizzell and Shulters, 1990). The minimum length of the Carpetbag fault, 18 km, is based on a simple geometric segment interpretation of the subsurface projection. The preferred length is the extent of the fault indicated by the extent of offset of the basin floor to the north margin of Yucca Flat and, in the south, to an intersection with the Yucca Lake fault. The maximum length, 37 km, includes some rupture along the southeast part of Quartzite Ridge, and some rupture along the south part of the fault, parallel to the Yucca Lake faults. Slip rate estimates for the Carpetbag fault are based on assuming that the fault is active and lacks scarps. The minimum rate is estimated to be 0.001 m/kyr; the preferred rate is assigned at the approximate threshold of faults with fault scarps, 0.005 m/kyr. The maximum rate is similar to the preferred rate of the Solitario Canyon fault, about 0.01 m/kyr.

Oak Spring Butte Fault

The Oak Spring Butte fault is a down-to-the-east, normal-slip fault that bounds the easternmost part of the Belted Range and forms the west side of Emigrant Valley. The fault is expressed as a zone of scarps and lineaments. Several of the faults offset rhyolitic volcanic flows, creating expressions similar to those of the Yucca Mountain faults. Several of these faults are considered to have possible Quaternary displacement (Reheis, 1992; Dohrenwend *et al.*, 1992). The orientation, sense-of-displacement, and position suggest that the Oak Spring Butte fault is an overlapping extension of the Yucca-Butte fault zone. The length of the Oak Spring Butte fault is difficult to assess, since it is part of a large fault swarm within the east part of the Belted Range and Emigrant Valley. The minimum length (9 km) is taken from a straight, central part of the fault. The preferred length, 16 km, extends this to the north and south, the north part along the physiographic expression of the Belted Range range front. The maximum length, 19 km, includes a small projection to the north and south. With the possible exception of some weak lineaments and/or scarps reported by Reheis (1992) along the north end, no Quaternary scarps are identified along the Oak Spring Butte fault. Slip rate estimates for the fault are based on assuming that the fault is active and lacks scarps. The minimum rate is estimated to be 0.001 m/kyr; the preferred rate is assigned at the approximate threshold of faults with fault scarps, 0.005 m/kyr. The maximum rate is similar to the preferred rate of the Solitario Canyon fault, about 0.01 m/kyr.

Belted Range Fault

The Belted Range fault is a down-to-the-west, normal-slip fault that bounds the west side of the Belted Range and the east side of Kawich Valley. This fault, which has been mapped by Reheis (1992) and Anderson *et al.* (1995b), shows evidence of latest Pleistocene to earliest Holocene faulting. The minimum length of the Belted Range fault is 22 km; this is the length of surface scarps mapped by Anderson *et al.* (1995b). The preferred length of 35 km includes much of the topographic expression of the fault. The maximum length is 47 km, which includes projections of the fault into the mountains along the south end of the fault and a north projection along weak lineaments or fault scarps in alluvium mapped along Lava Ridge by Reheis (1992). Slip rate estimates were assigned following Anderson *et al.* (1995b), who estimate a Holocene slip rate of 0.1 m/kyr (1 m of offset in 10 kyr) and a Pleistocene slip rate of 0.01 to 0.09 m/kyr (11.3 m total offset in 130 to 780 kyr). From this information, we adopt minimum and maximum slip rates of 0.01 and 0.1 m/kyr. A mid-range value of 0.05 m/kyr was adopted as the preferred rate, which is the same rate as indicated by the long-term offset of the 11.5- to 12.5-Ma Timber Mountain Tuff (Anderson *et al.*, 1995b).

Kawich Range Fault

The Kawich Range fault is a down-to-the-west, normal-slip fault that bounds the west side of the Kawich Range and the east side of Gold Flat. Anderson *et al.* (1995b) found latest Pleistocene fault scarps over only a small percentage of the length of this fault, but this confirms Quaternary activity. The minimum length is 23 km, as indicated by Piety (1995) and Anderson *et al.* (1995b). The preferred value, 33 km, includes much of the topographic expression of the fault. The maximum value, 46 km, extends the fault to the south along faults mapped by Reheis (1992) and to the north to intersect the next major strand of the Kawich fault. The total length of the Kawich Range system is not reported here. Slip rate estimates for the Kawich Range fault are based on the interpretation that the fault is active but lacks scarps. The minimum rate is estimated to be 0.001 m/kyr; the preferred rate is assigned at the approximate threshold of faults that have scarps, 0.005 m/kyr. The maximum rate is similar to the preferred rate of the Solitario Canyon fault, about 0.01 m/kyr. Although the Kawitch fault is a substantial range front fault, lack of Quaternary expression leads us to assess a low probability of activity of 0.8.

Western Pintwater Range Fault

The Western Pintwater Range fault is a west-side-down, range-bounding, normal-slip fault that bounds the west side of the Pintwater Range and the east side of Indian Spring Valley. Dohrenwend *et al.* (1991) indicate that this fault is likely early to mid-Quaternary in age. The minimum fault length is 33 km, considering only the most prominent central part that bounds Indian Spring Valley. The preferred length, 54 km, includes the entire western side of the Pintwater Range. The maximum length, 75 km, includes a north extension of the fault that bounds the west side of the north Desert Range. Dohrenwend *et al.* (1991) identify some fault scarps along the Western Pintwater Range, but they are generally short, discontinuous scarps in mid- to early Pleistocene deposits (J. Yount, written communication, 1996). Yount finds no evidence for faulting along much of the fault, including apparently faceted portions, limiting the potential slip rate estimate. The minimum slip rate of the Western Pintwater Range is 0.005 m/kyr, near the lowest slip rate for normal faults that have fault scarps. The maximum estimated rate is 0.05 m/kyr, the approximate threshold slip rate for faults that have fault facets. The preferred slip rate is estimated to be between these two, or 0.008 m/kyr.

Grapevine Mountains Fault

The Grapevine Mountains fault is a west-side-down, normal-slip fault that bounds the north side of the Grapevine Mountains (Reheis and Noller, 1991; Dohrenwend *et al.*, 1992). The fault is made up of two principal strands, a range-front trace and a piedmont trace that bounds some small hills along its east end. The fault is represented as a single trace for analysis purposes. The minimum and preferred lengths of the Grapevine Mountains fault are 25 km, which represents most of the easternmost part of the fault shown by Piety (1995). The maximum length, 32 km, includes a south extension of the fault that strikes into the Grapevine Mountains. Fault scarps in Quaternary alluvium are present along the piedmont trace of the Grapevine Mountains fault, but fault facets are not present. The minimum slip rate estimate, 0.003 m/kyr, is the lowest rate for a fault that has a fault scarp; the preferred slip rate, 0.01 m/kyr, is the middle of the range for faults having alluvial scarps but no fault facets; and the maximum slip rate, 0.05 m/kyr, is approaching the maximum rate of faults that lack fault facets.

Panamint Valley Fault Zone

The Panamint Valley fault zone is a major strike-slip fault that bounds the west side of the Panamint Range and the east side of Panamint Valley and has a normal-right-lateral sense of displacement. The fault zone has been discussed or mapped by several individuals (W. A. Bryant, CDMG, written communication, 1989; Zhang *et al.*, 1990). The minimum length of the Panamint Valley fault zone is 82 km, which is its extent from the south part of Panamint Valley north to a small reentrant in the range front. The preferred length, 90 km, extends the north part of the fault to the more westerly-trending Hunter Mountain fault. The maximum length, 104 km, considers an additional extension to the southmost part of Panamint Valley. A Holocene slip rate was determined by Zhang *et al.* (1990) from offset alluvial features. Their slip rate estimate is 2.36 ± 0.79 m/kyr; we round this off to 2.4 ± 0.8 m/kyr.

Hunter Mountain Fault Zone

The Hunter Mountain fault zone is basically a northward extension of the Panamint Valley fault zone, but its strike is 25 degrees more westerly, and it is separated by a gap in fault scarps (see W. A. Bryant, CDMG, written communication, 1989). The fault zone has a minimum length of about 46 km and a maximum length of 65 km. Our preferred length, 64 km, is close to the maximum value. The Hunter Mountain fault zone exhibits one of the finest series of right-laterally offset stream channels in the Basin and Range province, on the southwest flank of Hunter Mountain. The fault zone is a normal-right-oblique fault, with alternating downthrown sides, down-to-the-west in the south and down-to-the-east in the north. Slip rates for the Hunter Mountain fault zone are relatively high, ranging from 1.3 m/kyr to 2.7 m/kyr. Our preferred value is 2 m/kyr, comparable to the rate for the Panamint Valley fault. Slip rates for this fault were taken from Piety (1995), Schweig (1989), and Burchfiel *et al.* (1987).

Ash Hill Fault Zone

The Ash Hill fault zone is a right-slip fault zone that runs up the west side of Panamint Valley. W. A. Bryant (CDMG, written communication, 1989) provides the most detailed description of this fault. The Ash Hill fault zone appears to alternate downthrown sides along strike, being down-to-the-east along the south part and down-to-the-west along the north part. The Ash Hill fault zone appears to coincide with the western margin of Panamint Valley; if so, it apparently has a much stronger normal component than the north part. The minimum length estimated for the fault zone is 33 km, which is the minimum length of the relatively continuous "backfacing-scarp appearance." The preferred length, 55 km, extends the Ash Hill fault zone slightly on the north and substantially along the south. The south end is extended along the northeast flank of the Slate Range as a buried fault (only probable liquefaction grabens are portrayed by W. A. Bryant (CDMG, written communication, 1989) along this projection). A buried fault is inferred primarily because this range front is on strike with the mapped surficial expression, and some active tectonism along the range front is considered to account for its youthful appearance. The maximum length, 90 km, includes a small increase in length on the north and, again, a substantial increase in length to the south. This is to account for the continued on-strike potential southward, along the west side of Panamint Valley, to just north of Wingate Pass. The slip rate of the Ash Hill fault has been investigated by Densmore and Anderson (1994). They map an olivine basalt K/Ar dated at 4.05±0.15 Ma that is offset right laterally by 1.2 ±0.3 km, indicating minimum, preferred, and maximum slip rates of 0.21, 0.3, and 0.38 m/kyr, respectively.

West Specter Range Fault

The West Specter Range fault is a west-side-down, normal-slip fault just west of the Specter Range (Anderson *et al.*, 1995b). The north part of the West Specter Range fault is expressed as "small scarps and conspicuous lineaments on alluvial deposits"; the south part is made up of "discontinuous but prominent scarps on alluvial deposits and by lineations in Tertiary(?) bedrock" (Anderson *et al.*, 1995b). Anderson *et al.* indicate that fault scarps have as much as 1.4 m of surface offset in deposits of probable middle Pleistocene age. Small scarps along the north part have 0.3 to 0.5 m of surface offset on deposits that likely are latest Pleistocene in age (Anderson *et al.*, 1995b). The minimum length given to the West Specter Range fault is 10 km, which is the extent of faulting mapped by Anderson *et al.* (1995b). The preferred length, 19 km, extends this fault north across a small wash and south across Amargosa Valley. The maximum length, 25 km, extends the fault farther north up a crude linear valley and completely across the valley in the south. The slip rate is based on Anderson and *et al.*'s estimated maximum of 0.004 m/kyr. We adopt this as the preferred value and estimate 0.001 to 0.01 m/kyr for the minimum and the maximum slip rates. These values are identical to the values Anderson currently is using for his team's analysis (1997, this report).

Spotted Range Fault Zone

The Spotted Range fault zone represents a swarm of faults around the Spotted Range, the primary one of which was culled to represent the zone. This is the longest, most continuous fault of the group identified by Reheis (1992) and Piety (1995). This fault is a down-to-the-west, normal-slip fault that bounds the west side of a central ridge in the Spotted Range. Quaternary fault scarps and lineaments are indicated by Reheis (1992), supporting Quaternary activity. The minimum length of 17 km represents the central part of the fault, roughly the continuous expression mapped by Reheis. The preferred length, 30 km, extends the minimum to the south across a small wash and to the north along a series of discontinuous fault traces shown by Piety (1995). The maximum length is the same as the preferred because it is difficult to push the fault in either direction reasonably. Slip rates for this fault are difficult because of limited information. The minimum rate estimated, 0.001 m/kyr, is below the range of faults having no fault facets; the preferred value, 0.01 m/kyr, is typical of faults that have fault scarps and fault facets in the Great Basin; and the maximum value is 0.05 m/kyr.

Buried Hills Fault Zone

The Buried Hills fault zone generally bounds the west side of the Buried Hills and is a down-to-the-west, normal-slip fault (Reheis, 1992; Piety, 1995). The minimum length, 15 km, represent the central part of the fault zone as mapped by Reheis. The preferred length, 18 km, extends the minimum to the north and south along discontinuous fault traces. The maximum length, 25 km, extends the fault farther north along the southeast side of Papoose Lake flat. Slip rate estimates for this fault are difficult because of limited information. The Buried Hills themselves lack fault facets and have a relatively laid-back range front. Quaternary fault scarps and lineaments shown by Reheis (1992) are weakly to moderately expressed (Piety, 1995). The minimum slip rate estimated, 0.001 m/kyr, is below the range for faults having no fault facets; the preferred value, 0.01 m/kyr, is typical of faults that have fault scarps and fault facets in the Great Basin; and the maximum value is more than 0.05 m/kyr.

Northern Emigrant Valley Fault Zone

The Northern Emigrant Valley fault zone is made up of a swarm of more than 75 Quaternary fault scarps in the western part of an alluvial valley. The nature of the tectonism that gives rise to this pattern is uncertain, but it seems to be related or interconnected to adjacent faults in the surrounding hills. A few right-lateral offsets have been identified by Reheis (1992), suggesting that the pattern could represent the distributed expression of a lateral-slip fault. Because this system is more than 50 km from the site area, the exact mechanism of the fault is of lesser importance; thus, a right-lateral fault is assumed. The minimum length, 18 km, is the length of the main part of the fault swarm shown by Reheis (1992). The preferred length, 37 km, includes the fault scarps to the north and south. The maximum length, 45 km, considers possible extensions of the fault in the Papoose Lake area, and a small extension to the north. Evaluating the slip rate of this swarm is difficult. The slip rate was assumed to be similar to the Rock Valley fault zone; we adopt the Rock Valley fault zone's slip rates, 0.01, 0.02, and 0.08 m/kyr, for the Northern Emigrant Valley fault zone.

Eastern Pintwater Range Fault Zone

The Eastern Pintwater Range fault zone is an east-side-down, normal-slip fault on the east side of the Pintwater Range (Dohrenwend *et al.*, 1991; Reheis, 1992). Geomorphic expression along the Eastern Pintwater Range fault zone appears to be subtle, consisting of short fault scarps, lineaments, and abrupt alluvium/bedrock contacts. The minimum length, 28 km, is the central part of the fault zone. The preferred length of 36 km includes most of the range front that seems to be related to the fault. The maximum length, 57 km, includes the entire range front. The Eastern Pintwater Range fault zone appears to be near the threshold of geomorphic expression, specifically as regards fault scarps. The minimum slip rate, 0.001 m/kyr, is less than that for faults that have little expression. The preferred rate is 0.005 m/kyr, the middle value for faults with and without scarps. The maximum slip rate is 0.01 m/kyr, close to the rate of the Solitario Canyon fault.

Towne Pass Fault Zone

The Towne fault zone is a northwest-side-down, normal-slip fault that bounds the west side of the Panamint Range. This fault reportedly has weak Quaternary expression (W. A. Bryant, CDMG, written communication, 1989; Reheis, 1991; Piety, 1995), although W. A. Bryant (CDMG, written communication, 1989) suggests that two beheaded drainages indicate latest Pleistocene to Holocene displacement. The Towne Pass fault locally is a prominent west-facing scarp in dolomite (W. A. Bryant, CDMG, written communication, 1989) and may have some small fault facets. These, if they are facets, are highly eroded and occur only along small parts of the fault zone. The minimum length of the Towne Pass fault zone is 33 km, from the north end of the Panamint Range to the south end of the Holocene or latest Pleistocene activity indicated by Piety (1995). The preferred length of 38 km extends the fault a little farther south, to a point where the fault bifurcates, and most of the range-front expression is gone. The maximum length of 50 km includes the total mapped geologic fault, with some minor inferred faulting off the north end. There was little information for estimating slip rate, so we used a broad range, 0.005 to 0.1 m/kyr. This rate places the fault zone between the threshold of faults that generally lack fault scarps and the point at which fault facets may be expected. The preferred value is 0.03 m/kyr.

3.3.2 Maximum Earthquake Estimates

Maximum earthquakes were estimated for the regional faults using empirical magnitude versus length, magnitude versus length and slip rate, and, in a few cases, magnitude versus maximum surface displacement relationships (Table SDO-2). All fault lengths given are the estimated maximum earthquake segment lengths for these faults. For regional faults that have multiple earthquake segments, only the closest segment was analyzed; in all these cases the other segments were too far away to have a significant impact on Yucca Mountain. A distribution of earthquake magnitudes also is considered for these faults down to the maximum background earthquake; these events are distributed randomly along the maximum earthquake segment. Different relations for magnitude versus length and magnitude versus maximum displacement were used for normal-slip versus strike-slip faults. All relationships are weighted equally, except that of Anderson *et al.* (1996). A concern about how well the data used by Anderson *et al.* compares to the southern Great Basin caused us to give this relationship a weight of one-third that of the other relations. A more extensive discussion of scaling relations for estimating maximum magnitudes and the associated input fault parameters in general is included in Section 3.4.2

The maximum magnitude evaluation assumed a similarity of structural style and expected geometry of regional faults throughout the areas within the same part of the southern Basin and Range province. Therefore, we assumed that they nucleated under similar stress field of extension. We considered, for example, unless there were contradictory data, that the faults have planar geometries from the surface to the depth of the maximum focal depths discussed earlier.

3.3.3 Recurrence

The occurrence of the maximum earthquake along regional faults is expressed by estimating the strain accumulation interval for the maximum event. The minimum, preferred, and maximum fault lengths are associated with an average surface displacement using relationships from Wells and Coppersmith (1994). This average displacement is divided by the fault slip rate, providing the slip accumulation time, which is considered to be the average recurrence interval. This is then inverted for annual earthquake occurrence rate. Since there is significant uncertainty in making these kinds of estimations, the final weighting of the average earthquake recurrence intervals are set at the 10^{th} and 90^{th} percentiles for the minimum and maximum values, and hence a "0.3, 0.4, 0.3" weighting is used in a three-point discrete distribution. Slip rates were taken from or derived from the published literature where possible. Estimates generally were made by comparing faults having unknown slip rates with the structural and geomorphic characteristics of faults having known slip rates, and thereby making a comparative estimate of the potential slip rate for the former. For example, faults that have alluvial fault scarps but do not have facets tend to have rates around 0.01 m/kyr, whereas faults that have neither facets or scarps tend to have rates of 0.001 m/kyr or less (dePolo, written communication, 1997). Although a more rigorous approach is desired, most of these faults have moderate to low slip rates and their impacts on the final ground motion values at Yucca Mountain are likely small. Slip rates are similar to the local faults at Yucca Mountain and, thus, can be compared with these relatively well-studied local faults. For the more active faults, results from field studies generally were available.

Earthquake occurrence rates for events smaller than the maximum earthquake are estimated by assuming a combination of characteristic and a truncated exponential distributions, weighted 0.7 and 0.3, respectively. For both of these models, it is assumed that the occurrence of earthquakes smaller than the MBE (magnitude 6.2) is addressed by the regional source zones. Therefore, the size of earthquakes occurring on the regional faults is limited to magnitudes greater than or equal to **M** 6.2.

The approaches used to evaluate maximum magnitude and recurrence for other regional fault sources were used to evaluate both the possible buried strike-slip faults and the Carrara fault. Fault parameters used to characterize these faults are provided in Table SDO-3.

3.3.4 Buried Strike-Slip Fault Sources

The question of a buried strike-slip fault in Crater Flat or beneath Yucca Mountain was introduced in Section 2.0 on Tectonic Models. Although there is direct evidence that dextral strike-slip has influenced the structural development of Yucca Mountain, there is insufficient data to characterize a single-plane strike-slip fault source, particularly one active in Quaternary time. There are two ways we dealt with the issue: one was to assume that a strike-slip fault (after Schweickert and Lahren, 1997) passes beneath Yucca Mountain and that it will be undetectable until it generates an earthquake. We do not consider this a well-founded proposition; it precludes the use of many of the rational tools developed for the present evaluation, such as estimation of slip rate, estimation of recurrence, or parametric evaluation of magnitude. We have no means of assessing the likelihood that it could happen. Thus it cannot be treated the way we treat all the other fault sources.

A second way we deal with the issue of a buried strike-slip fault source is to build on the meager evidence we have. The pattern and history of deformation at the southern end of Crater Flat, including the alignment of basaltic volcanoes, the structure along the rampart that forms the southern end of Yucca Mountain and Crater Flat north of Highway 95, evidence of vertical axis rotation at Yucca Mountain, alignment and changes of fault and fault block geometry south of the hingeline, all suggest a zone of distributed dextral faulting. The hingeline represents a structural border to this zone, albeit a poorly defined one. It could indicate a buried fault or fault zone, or a series of linked faults of relatively small local displacement that die out to the northwest. We plausibly can characterize the hingeline as a strike-slip fault trace approximately 20 km long, having as much as a kilometer of cumulative offset. We plausibly can consider the hingeline as the northwest extension of the Pahrump Valley fault zone and, therefore, infer a maximum length of about 120 km and a cumulative lateral offset of at least 4 km for the inferred fault trace. However, our preferred length for such a fault projection is limited to its possible extent beneath Yucca Mountain and Crater Flat, 27 km.

The Pahrump Valley fault shows some evidence of Quaternary activity (Piety, 1995) but the hingeline projection does not. Therefore, we assign a slip rate to the inferred buried fault projection (0.005 m/kyr) and a probability of activity of 0.4. The important point about this buried fault is that it could generate a large earthquake external to Crater Flat that could propagate focused ground motion along strike into Crater Flat, perhaps triggering any number of faults at Yucca Mountain that are susceptible to slip. Because of the large degree of assertion and speculation involved in a multiple-fault scenario, we model only a single buried strike-slip fault. The hingeline seems to be the only candidate for a buried fault (in the sense that there is no recognized fault trace at the surface) that can be characterized by at least some of the basic fault parameters established for this analysis.

We assign a probability of 0.2 to the likelihood of a fault extending along the southwest side of Bare Mountain in Amargosa Wash (the Carrara fault proposed by D.B. Slemmons, oral commun.)(Figure SDO-6). No measurable evidence for such a fault is available; much of the area is covered by latest Quaternary alluvium. Plausible lengths range from 12 to 24 km. With no physical features on which to base an estimate of earthquake magnitude or recurrence, we have no means of arguing for either the existence of a fault or any seismogenic characteristics. We assign a provisional slip rate of 0.001 m/kyr to this hypothetical fault. This rate is so slow that surficial evidence, such as fault scarps, are generally lacking in the Great Basin.

3.4 LOCAL FAULT SOURCES

Local faults are those at Yucca Mountain and in Crater Flat. These faults are considered to be potential seismic sources on the evidence of Quaternary displacement; a number of these faults have been trenched to determine the amounts, recurrence, and ages of the Quaternary offsets. Local faults that have a history of Quaternary displacement are all normal to steeply left-lateral oblique (primarily west-dipping) faults. The faults are categorized, on the basis of length and cumulative offset, as block-bounding faults and intrablock faults. The block-bounding faults, which are the largest and most likely seismogenic, are inferred to descend through the seismogenic crust as more or less uniformly dipping, single plane faults, in keeping with our tectonic model. The intrablock faults tend to be curvilinear in plan, segmented or distributed, and only locally follow large slope breaks (i.e. have small paleo-offsets). This distinctive structural pattern is one of the primary reasons for invoking a carapace collapse effect in our preferred model. These latter faults may be confined to the volcanic carapace or linked to the block-bounding faults at relatively shallow depths. Of the numerous interconnected faults at Yucca Mountain (Figures SDO-7a, b), six are long enough to warrant consideration as penetrating the Paleozoic substrate. These six Quaternary faults are:

Paintbrush Canyon fault
Stagecoach Road fault
Solitario Canyon fault
Iron Ridge fault
Fatigue Wash fault
Windy Wash fault

Local fault parameters are listed in Table SDO-4, event scenarios are listed in Table SDO-5. All principal faults considered but the Iron Ridge and Fatigue Wash faults are considered block-bounding faults—faults that define major tilted panels of the carapace, and that are considered to penetrate to significant seismogenic depth without intersection. The Fatigue Wash and Iron Ridge faults are less confidently interpreted; the interpretations are discussed below. All local faults are considered 100 percent active, but some may be involved only in linked or distributed event scenarios (see Section 3.4.1 for further discussion of event scenarios).

Paintbrush Canyon Fault

Paintbrush Canyon fault is the easternmost block-bounding fault that cuts Yucca Mountain. It is distinguished by: (1) it coincides with the northern part of the gravity gradient that defines the eastern structural margin of Crater Flat basin; (2) it is the only Yucca Mountain fault that is continuously traceable north of Yucca Mountain, deep into the unextended caldera rim terrane (a maximum distance of about 12 km north of Yucca Wash); and (3) the footwall consists of segmented, variably tilted and dissected buttes or ridges, rather than the more or less coherent rotated panel typical of Yucca Mountain to the west, and the hanging wall is broken by horsts and graben and numerous splay faults. Despite this evidence of major fault displacement and a broad zone of fault damage, the Paintbrush Canyon fault is poorly exposed south of Paintbrush Canyon. Along Yucca Mountain, it lies buried along the east side of Midway Valley; it is questionable whether the main break has been observed or is anywhere exposed south of Yucca Wash. Estimates of down-to-the-west displacement of Tertiary volcanic strata range from 250 to 500 m (Lipman and McKay, 1965; Scott and Bonk, 1984). Average dip on the fault plane is about 70 degrees west, and slip along it has been left oblique (Simonds *et al.*, 1995). We divide the Paintbrush Canyon fault into two segments, a segment that extends along Paintbrush Canyon north of Yucca Wash (PC(N)), and a segemnt that extends along the east side of Midway Valley south of Yucca Wash (PC(S)). The preferred length of PC(N) is 6 km, and of PC(S) is 12 km. We add 2 km from the south end of Busted Butte to establish linkage with the Stagecoach Road fault, for a total maximum length of 20 km (the maximum total length is 26.3 km if we carry PC(N) as far north as seems reasonable). Paleoseismic studies at three sites--natural exposures of sand ramps on the west side of Busted Butte and one trench each at Fran Ridge and Alice Ridge--indicate that multiple Quaternary displacements have occurred. As many as five faulting episodes