REMEDIAL ACTION PLAN AND SITE DESIGN FOR STABILIZATION OF THE INACTIVE URANIUM MILL TAILINGS SITES AT SLICK ROCK, COLORADO

Attachment 2, Geology Report

Preliminary Final

March 1994

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OF THE INACTIVE URANIUM MILL TAILINGS SITES
AT SLICK ROCK, COLORADO**

**ATTACHMENT 2
GEOLOGY REPORT**

Preliminary Final

March 1994

**Prepared for
U.S. Department of Energy
UMTRA Project Office
Albuquerque, New Mexico**

**Prepared by
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LIST OF ACRONYMS AND ABBREVIATIONS

ATC	Applied Technology Council
DOE	U.S. Department of Energy
EPA	U.S. Environmental Protection Agency
FE	floating earthquake
ft	foot
ft/ft	feet per foot
g	acceleration of gravity
in	inch
km	kilometer
LSA	low sun angle
m	meter
ME	maximum earthquake
mi	mile
mm	millimeter
MMI	Modified Mercalli Intensity
MSL	mean sea level
NRC	U.S. Nuclear Regulatory Commission
PHA	peak horizontal acceleration
RAC	Remedial Action Contractor
TAC	Technical Assistance Contractor
TAD	Technical Approach Document
UMTRA	Uranium Mill Tailings Remedial Action
USGS	U.S. Geological Survey

1.0 INTRODUCTION

1.1 CRITERIA AND DEFINITIONS

This section presents definitions and criteria used to perform site hazard evaluations. These are presented to standardize usage throughout this section and are pertinent to the seismic hazard evaluation because of the wide range of interpretation or usages of certain seismological terms.

Design life. As specified by the U.S. Environmental Protection Agency (EPA) standards for remedial actions at inactive uranium processing sites (40 CFR Part 192 (1993)), the controls implemented at Uranium Mill Tailings Remedial Action (UMTRA) Project sites are to be effective for up to 1000 years, to the extent reasonably achievable, and in any case for at least 200 years. In the case of assessing seismic and geomorphic hazards, the criteria established and the methodologies applied seek to ensure that the reclaimed wastes will not be damaged by earthquake ground motions, related ground rupture, or erosional encroachment for up to 1000 years.

Design earthquake. The magnitude of the earthquake that produces the largest on-site peak horizontal acceleration (PHA) is the magnitude of the design earthquake. This controlling earthquake could be the floating earthquake (FE) or an earthquake whose magnitude is derived from a relationship between capable fault rupture and/or fault length and maximum magnitude.

Capable fault. A capable fault is defined as a fault that has exhibited one or more of the following characteristics:

- Movement at or near the ground surface at least once within the past 35,000 years, or movement of a recurring nature within the past 500,000 years.
- Macroseismicity instrumentally determined with records of sufficient precision to demonstrate a direct relationship with the fault.
- A structural relationship to a capable fault such that movement on one fault could be reasonably expected to cause movement on the other.

This definition is essentially the one adopted by the U.S. Nuclear Regulatory Commission (NRC) for siting nuclear power plants (10 CFR Part 100 (1993) Appendix A).

Acceleration. Acceleration is defined as the mean of the peaks of the two horizontal components of an accelerogram record. The exact term used is "peak horizontal acceleration." Design accelerations for the western United States are determined from the constrained attenuation relationship based on distance and magnitude developed by Campbell (1981) and adopted by the *Technical Approach Document (TAD)* (DOE, 1989).

Duration of strong earthquake ground motion. For the purposes of UMTRA Project studies, duration is defined by Krinitzsky and Chang (1977) as the bracketed time interval in which the acceleration is greater than 0.05 gravity (g). The methodology of Krinitzsky and Chang (1977) is applied in estimating the duration of strong ground motion at a particular site. The acceleration used is the peak horizontal ground acceleration.

Magnitude and intensity. Magnitude was originally defined by C. F. Richter as the base-10 logarithm of amplitude of the largest deflection observed on a torsion seismograph located 62 miles (mi) [100 kilometers (km)] from the epicenter. This local magnitude value may not be the same as the body-wave and surface-wave magnitudes derived from measurements at teleseismic distances. Unless specified otherwise, Richter magnitude values are used in the seismic hazard evaluations.

Intensity is the index of the effects of an earthquake on the human population and made-made structures and is based on the Modified Mercalli Intensity (MMI) scale.

Because preinstrumental earthquakes are reported in intensity and more recent instrumental records are in magnitude, there may be a need to relate these values. Several equations have been proposed. Unless otherwise specified, the relationship developed by Gutenberg and Richter (1956) is applied. This equation is as follows:

$$M = 1 + 2/3 I_o$$

where M = magnitude in the Richter scale and I_o = MMI in the epicenter area.

It is generally acknowledged that some confusion prevails in the use of various magnitude scales in the engineering and seismic literature. This results from the lack of instrumental data in many places such as the Colorado Plateau, limitations of the instruments themselves, the complex nature of seismic phenomena, and the fact that different scales are used for different purposes. The M_L scale is used primarily in the western United States and the m_b scale is considered more appropriate for the central and eastern United States.

This is because the M_L and m_b scales are proportional to the ground motion amplitudes near one second period, which is the part of the ground motion spectrum of most interest to engineers (Nuttli and Herrmann, 1982). Magnitudes of design earthquakes for the UMTRA Project will be specified in terms M_L for earthquakes of less than magnitude 6.5. Above 6.5 magnitudes are sometimes expressed as M_s , depending on the method used to calculate maximum earthquakes (ME).

The fault length versus magnitude relationship is taken from Bonilla et al. (1984), who compiled statistical relationships of surface rupture length and fault displacement to surface wave magnitude (M_s). The following relationship of Bonilla et al. (1984) was used for plate interiors:

$$M_s = 6.02 + 0.729 \log L$$

where L = mapped fault rupture length.

Maximum earthquake. An ME is the earthquake associated with specific seismotectonic source areas or provinces that would cause the most severe vibratory ground motion or foundation dislocation capable of being produced at the site under the currently known tectonic framework. It is typically adopted from published literature and based on all known regional and local geological and seismological data.

Floating earthquake. An FE is the largest earthquake within a specific seismotectonic province that is not associated with a known tectonic structure. Before assigning the FE magnitude, the earthquake history and tectonic character of the province are analyzed.

The magnitude of the FE is an estimate of the threshold magnitude at which ground breakage occurs and, thus, a maximum magnitude for the FE. An event of larger magnitude will produce ground breakage and, by the above definition, is not an FE. The conservative value of $M_L = 6.2$ is recommended and adopted by UMTRA. This value is in general agreement with arguments of Krinitzky and Chang (1975) and Campbell (1981). The FE is located at a radial distance of 9.3 mi (15 km) from the site.

1.2 SCOPE OF WORK

Detailed investigations of geologic, geomorphic, and seismic conditions at the Burro Canyon site were conducted by the U.S. Department of Energy (DOE) as a disposal site for the tailings at two processing sites near the Slick Rock, Colorado, post office. The purposes of these studies are basic site characterization and identification of potential geologic hazards that could affect long-term site stability. Subsequent engineering studies (e.g., analyses of hydrologic and liquefaction hazards) used the data developed in these studies. The geomorphic analysis was employed in the design of effective erosion protection. Studies of the regional and local seismotectonic setting, which included a detailed search for possible capable faults within a 65-km radius of the site, provided the basis for seismic design parameters.

The scope of work performed included the following:

- Compilation and analysis of previous published and unpublished geologic literature and mapping.

- Review of historical and instrumental earthquake data.
- Review of site-specific UMTRA Project subsurface geologic data, including logs of exploratory boreholes advanced in the site area.
- Photogeologic interpretations of existing LANDSAT and conventional aerial photography.
- Low-sun-angle (LSA) aerial reconnaissance of the site region.
- Ground reconnaissance and mapping of the site region.

The site and the immediately surrounding area out to a radius of 1 mi (2 km) are referred to in this section as the site area. The surrounding region, encompassing west-central Colorado and adjoining eastern Utah, will be referred to as the site region. The following topics relevant to the stabilization of mill tailings at the Slick Rock alternative site are discussed:

- Characterization of the regional geologic setting and its correlation to site geology.
- Identification of geomorphic hazards and suggestions for mitigative measures.
- Seismotectonic evaluation to provide initial design earthquake and acceleration parameters. Subsequent engineering analyses to fully assess the liquefaction potential and slope stability.
- On-site fault rupture potential.
- Potential for damage by earthquake-induced natural slope failure.
- Potential impact of geothermal and volcanic activity, subsidence due to tectonic causes, and reservoir-induced seismicity.
- Analysis of mineral resource potential and the possible impact on site stability of future mineral resource development.

Geomorphic evaluation

The purpose of the geomorphic evaluation of UMTRA Project sites is to characterize the current geomorphic conditions and to assess the impact of geomorphic processes on the long-term stability of the uranium mill tailings piles. These evaluations are restricted to the assessment of natural geomorphic processes and the geomorphic effects of past land-use activities, but do not address future human activities or potential hazards related to site hydrology.

Schumm and Chorley (1983) prepared a detailed publication presenting a theoretical discussion of geomorphic processes which may affect a tailings site. Nelson et al. (1983) present a handbook approach to specific methods for site assessment, engineering procedures for mitigation, and confidence levels for hazard predictions over periods of 200, 500, and 1000 years. The methodologies and criteria presented in these publications were used as guides for the geomorphological investigations of UMTRA Project sites.

Compilation and analysis of previous work

A review of all pertinent stratigraphic, lithologic, tectonic, seismologic, geophysical, geomorphic, mineral resource, and soils literature and mapping of the site region was performed by the TAC. A search of government agencies was made for unpublished seismic hazard evaluations for large engineered structures. Personal communications were established with experts on seismic evaluation and persons knowledgeable about fault systems.

Earthquake data compilations

Historical earthquake data for the area within a 124-mi (200-km) radius of the disposal site were obtained for the initial phase of this study (NGDC/NOAA, 1985). Subsequent data for this region were updated from the earthquake data file for a nearby UMTRA Project site (NGDC/NOAA, 1989). The complete NOAA data file is included as Attachment 1. Additional seismic data for the Ridgway Dam and reservoir site (Sullivan et al., 1980) were obtained from the U.S. Bureau of Reclamation.

Published probabilistic seismic hazard studies for the United States (Liu and DeCapua, 1975; ATC, 1978; Algermissen and Perkins, 1976; Algermissen et al., 1982; Coffman et al., 1982) were also reviewed.

Studies of estimated earthquake magnitudes derived from fault length and surface area parameters were reviewed for their applicability to the study region. Ground motion attenuation relationships were also reviewed for selection of the best relationship for the seismotectonic characteristics of the region.

ME values for remote seismotectonic provinces, such as the Intermountain Seismic Belt and Rio Grande Rift, were taken from published studies. In addition, two regional epicentral compilations were also obtained from the National Geophysical Data Center (NGDC/NOAA, 1985, 1989) for use in calculating the ME value and recurrence interval for the Colorado Plateau and in compiling of the regional seismic map.

Surface geologic data

On-site and local geologic and geomorphic investigations consisted of detailed mapping of site geology and geomorphology and investigating nearby geologic,

geomorphic, and fault features. Geologic field investigations were conducted in the summer of 1986 and in February and June 1990. The surficial geology at the proposed site of the disposal cell was mapped and all areas of potential geologic hazards were noted and investigated. All faults within a 3-mi (5-km) radius were investigated. Studies were also conducted of selected faults with possible Quaternary activity within a 40-mi (65-km) radius of the site.

Subsurface geologic data

Subsurface geologic data obtained in the site area for this study consist of logs of 16 well boreholes, 13 core holes, and 20 backhoe test pits advanced on the site during 1990 and 1993. Boreholes were drilled to depths ranging from 80 to 430 feet (ft) (20 to 130 meters [m]) to assess ground water conditions, subsurface stratigraphy, and engineering characteristics. Test pits were advanced to depths of 3 to 10 ft (1 to 3 m). Logs of all boreholes and test pits were compiled by representatives of the Technical Assistance Contractor (TAC) and by the Remedial Action Contractor (RAC) for the 1993 activities, and samples were acquired for testing and classification. Disturbed and undisturbed samples were obtained from the boreholes using standard sampling and penetration techniques. Disturbed bulk samples were obtained from the test pits. Logs of test pits and boreholes are included in Appendix B of Attachment 3.

Photogeologic interpretation

Studies of existing remote sensing imagery for the Slick Rock area included review of LANDSAT satellite images, high-altitude aerial photographs, and low-altitude stereo aerial photographs.

Low-sun-angle aerial reconnaissance

LSA reconnaissance was flown by the DOE on May 20 and 21, 1986. A high-wing Cessna 206 Turbo aircraft was used for reconnaissance of a 65-km radius of the site at flight altitudes of 1000 to 2000 ft (300 to 600 m) above the ground. The low-sun-angle method is described by Glass and Slemmons (1978).

During the LSA aerial reconnaissance missions, all known faults within 9.3 mi (15 km) of the site were inspected and an intense low-altitude search for undetected faults within 6.2 mi (10 km) of the site was made. All faults of over a few miles (kilometers) in length within a 65-km radius of the site were inspected and any topographic structures that could result from faulting were inspected. All regional structures that could be capable of large or great earthquakes within 124 mi (200 km) of the site were also examined.

2.0 REGIONAL GEOLOGY

2.1 REGIONAL PHYSIOGRAPHY

The Burro Canyon site is in the northeastern part of the Colorado Plateau physiographic province, near its boundary with the Southern Rocky Mountains province (Figure 2.1). The site area lies in the Canyon Lands section of the Colorado Plateau province. The eastern part of the Canyon Lands section, which includes the site, is characterized by large-scale folds, unwarped plateaus, lava-capped mesas, deep and narrow river canyons, and laccolithic mountains (Hunt, 1974). South of and parallel to the Uncompahgre Plateau is the northwest-trending, folded belt of the broad Paradox Basin. Principal physiographic elements within the study area include the Dolores River valley; the San Juan River valley; the La Sal, Abajo, and San Miguel Mountains; and the Uncompahgre Plateau. Collapsed salt anticline features include the Paradox Valley, Libson Valley, Gypsum Valley, and Spanish Valley.

South of the site is a high plain that rises gradually from the southwest to the gently arched Dolores anticline. At the site area, the land surface drops to a relatively low elevation along the synclinal Disappointment Valley. The land surface just west of the site area is deeply incised by the antecedent (or superimposed), generally north-flowing Dolores River, and by tributary canyons. Physiographic features of the Dolores River drainage basin are shown on Figure 2.2.

The Burro Canyon site region lies in the folded belt of the Paradox Basin between the Uncompahgre Plateau and the uplifted laccolith mountains of the La Sal and Abajo Mountains to the west. The La Sal Mountains rise to elevations of about 13,000 ft (4000 m). East of this range, the land surface slopes gradually toward the deeply entrenched Dolores River. Uplift of the region in the late Tertiary resulted in downcutting of the river from the upper plateau elevation of about 8000 ft (2400 m) to the current river surface elevation of about 5500 ft (1700 m). In the folded belt of the Paradox Basin, sedimentary strata of Mesozoic age are folded into a series of broad, northwest-trending, faulted anticlines and synclines. The salt-cored, collapsed anticlinal valleys bordered by faulted, parallel ridges alternate with broad, flat synclinal valleys including Disappointment Valley, where the site valley elevations range from 5000 to 6000 ft (1500 to 1800 m) and ridges of upturned sedimentary rocks rise to elevations of about 7000 ft (2100 m). The salt-cored structures occupy an area from the edge of the Dolores River near Slick Rock, northeastward to the edge of the uplifted Uncompahgre Plateau.

Regional geomorphology

Geomorphic features and Quaternary deposits in the Slick Rock area reflect the interaction of geologic and climatic variables. The physiography, topography, and Quaternary deposit record attest to the predominance of fluvial and eolian

**BURRO CANYON
SITE**

National Parks and Monuments

1. Dinosaur Nat. Mon.	13. Rainbow Bridge Nat. Mon.
2. Black Canyon of the
Gunnison Nat. Mon.	14. Capitol Reef Nat. Mon.
3. Colorado Nat. Mon.	15. Bryce Canyon Nat. Park
4. Arches Nat. Mon.	16. Cedar Breaks Nat. Mon.
5. Canyonlands Nat. Park	17. Zion Nat. Park
6. Natural Bridges Nat. Mon.	18. Grand Canyon Nat. Park
7. Hovenweep Nat. Mon.	19. Wupatki and Sunset Crater
Nat. Mons.
8. Mesaverde Nat. Park	20. Walnut Canyon Nat. Mon.
9. Aztec Ruins Nat. Mon.	21. Petrified Forest and
Painted Desert Nat. Mon.
10. Chaco Canyon Nat. Mon.	22. Montezuma Castle Nat. Mon.
11. Canyon de Chelly Nat. Mon.	23. Tuzigoot Nat. Mon.
12. Navajo Nat. Mon.
(Betatakin and Kiet Seel)	

*Escarments at South End
of High Plateaus*

- pc. Pink Cliffs
wc. White Cliffs
vc. Vermilion Cliffs

Other Prominent Features

- wf. Waterpocket Fold
er. Elk Ridge
cr. Comb Ridge
mv. Monument Valley
ng. Agathla Peak
sr. Shiprock
cb. Cabezón Peak

FROM HUNT, 1974.

**FIGURE 2.1
PHYSIOGRAPHIC MAP OF THE COLORADO PLATEAU**

FIGURE 2.2
PHYSIOGRAPHIC FEATURES OF THE
BURRO CANYON SITE REGION, COLORADO

erosion as well as mass movement processes operating in a semiarid to temperate climate during Quaternary time. Glacial deposits on high-elevation mountains in the region indicate climatic fluctuations.

Numerous geologists have investigated the development of drainage patterns, terraces, pediments, and glacial moraines in the site region. The following discussion is excerpted from articles by Hunt (1956), Lohman (1981, 1965), Yeend (1969), Sinnock (1981a,b; 1978), and Shawe et al. (1968).

Since about 10,000 years ago, fluvial erosion processes have been the dominant geomorphic force in the region. Late Cenozoic uplift of the Colorado Plateau has been the major driving force in the evolution of the landscape, triggering landscape rejuvenation, stream channel incision, and removal of massive amounts of sedimentary bedrock. At least 5000 ft (1520 m) of regional downcutting of major rivers into sedimentary rocks of Early Tertiary to Late Cretaceous age has occurred since uplift began (Yeend, 1969).

Downcutting has produced long steep slopes, oversteepened cliffs, and narrow canyons. Extremes in elevation, slope exposure, and range of bedrock types allowed varied geologic processes to operate through time and produce very different effects on the landscape. Geomorphic studies in the Paradox Basin (W-C, 1982a) indicate that the regional incision processes were interrupted several times during which landscape stability and stream aggradation allowed the deposition of Quaternary sediments and soil formation. These periods of landscape stability were probably caused by Quaternary climatic fluctuations.

In the site area, the regional base level for streams is the Colorado River, and incision has generally occurred in response to the lowering of the Colorado River. In the Paradox Basin area, erosion since Pliocene time has removed most of the Tertiary deposits and carved canyons up to 1500 ft (460 m) deep in the Mesozoic and Paleozoic rocks (W-C, 1982a). Integration of the present Colorado River drainage system occurred about 5 million years ago (McKee and McKee, 1972). Prior to the establishment of a through-going drainage system, the Paradox Basin was probably drained by local interior basin streams (Hunt, 1956).

Until perhaps Pliocene time, the Grand Junction area and adjacent parts of the Colorado Plateau were undergoing erosion by the ancestral Colorado River. The course of the Colorado River may have been established by the end of the Miocene. Differential uplift of the Uncompahgre Plateau was renewed during the Pliocene, causing major changes in the drainage patterns of the Colorado and Gunnison Rivers.

High-elevation gravel deposits of probable Early Pleistocene age overlie a deeply weathered Mancos Shale erosion surface east of the Dolores River (Shawe et al., 1968). Younger terrace gravel deposits of the Dolores River occur at levels 100, 350, and 650 ft (30, 110, and 200 m) below the Mancos Shale erosion surface, indicating rapid downcutting of the river since the Early Pleistocene (Shawe et al., 1968). At least some of this rapid downcutting was a reaction to structural upwarping of the district.

The Dolores River traverses the site area from south to north in a deep canyon. Throughout most of its length, the canyon is markedly sinuous; with little doubt, the sinuositities are entrenched meanders inherited from the stream that flowed on the flat Miocene surface. Terraces at various levels in the canyon record periods during which lateral cutting locally predominated over downcutting.

Landforms indicative of glacial processes are present only in areas of the region higher than about 9000 ft (3000 m) above mean sea level (MSL). Glacial and periglacial activity occurred as recently as 10,000 years ago in the La Sal, Abajo, and San Juan Mountains. Significant amounts of sediment were added to drainages during glacial periods, resulting in cyclic deposition of gravel in valleys throughout the region (W-C, 1982a). Evidence of multiple Pleistocene glaciations is present in the La Sal Mountains (Richmond, 1962); however, the Abajo Mountains exhibit only periglacial processes (Witkind, 1964). No evidence is present to suggest that glacial or periglacial processes occurred in areas at the elevation of the Slick Rock sites or the valleys of the Paradox Basin salt anticline area (W-C, 1982a).

Active geomorphic processes operating within the site region are fluvial erosion and deposition, eolian deposition, and mass movement. Fluvial processes are influenced by the semiarid and arid climate of most of the region. The high relief and sparse vegetation of the Paradox Basin result in rapid surface water runoff and active erosion. Sheetwash and the development of rills and gullies in fine-grained alluvium occur throughout the region. Within integrated drainage networks, sediment is ultimately transported to the Colorado River.

Mass movement processes are currently active on many slopes in the region. These occur as rock falls, debris slides and slumps, debris flows, and rock and soil creep. Rock falls from cliff walls and bedrock ledges are a dominant mechanism of cliff retreat and talus formation in the site area. Talus accumulations formed at the base of cliffs by rock falls usually weather rapidly and are removed by surface water flow and gravitational downslope movement. Falls involving sandstone units of the Burro Canyon Formation and the Salt Wash Member have occurred in the last few decades along steep cliffs next to the Dolores River (Shawe et al., 1968). The falls probably were initiated by erosional oversteepening of the less resistant strata underlying the sandstone blocks.

Extensive soil development studies have been conducted in the region at the La Sal Mountains (Richmond, 1962) and at Spanish Valley and the Paradox Basin (W-C, 1982a). Soils in the Paradox Basin area are developed on Pleistocene and Holocene deposits that have been subject to periods of accretion and erosion. Soil development correlations are thus difficult to achieve between discontinuous deposits. Soils developed in Pleistocene deposits commonly have well developed argillic horizons and distinct carbonate accumulations (W-C, 1982a). Carbonate soils occur on virtually all fluvial and eolian deposits at elevations below 7000 ft (2100 m). Soils developed on Holocene fine-grained deposits lack buried A horizons and significant humic material in the

surficial A horizons (W-C, 1982a). This suggests prevailing arid conditions during the last 10,000 years.

Rates of denudation

In reference to the possible influence of the long-term erosion processes upon reclamation design, a discussion of the rates of denudation and stream downcutting is provided below. The rates of denudation are the rates at which a land surface is being lowered as a result of erosional processes.

Evidence of the long-term predominance of erosional processes on the Colorado Plateau since the Late Tertiary time is provided by canyon topography and the great amounts of Tertiary and Cretaceous strata (3500 to 13,000 ft) (1100 to 4000 m) that have been removed from much of the plateau surface. The relatively low strengths of Tertiary and Cretaceous bedrock facilitate the Late Tertiary and Quaternary erosion (Schumm and Chorley, 1966). Features of the landscape of the upper Colorado River Basin that suggest continuing erosion at a moderately rapid rate include high relief and deep, narrow, vertical-walled canyons; the absence of significant desert varnish on many cliff faces; the lack of talus accumulation below cliffs; and progressively less well-developed soils on successively lower terraces along streams (W-C, 1982a). Since Late Miocene time, erosion rates have been controlled by the Colorado River, which acts as the regional base level for streams. Potassium-argon dates of basalt flows indicate that the Colorado River drainage above Grand Junction was established about 10 million years ago (Larson et al., 1975), whereas drainage integration through the Grand Canyon occurred by about 5 million years ago (McKee and McKee, 1972; Damon et al., 1978).

Relatively rapid erosion has resulted from the combination of mechanically weak bedrock (Schumm and Chorley, 1966) and rapid tectonic uplift (Hunt, 1969; Luchitta, 1972; Larson et al., 1975). Broad spatial and temporal variations in erosion rates are due to differences in local rock type, changes in uplift rate, and climatic fluctuations.

Potential amounts of erosion at the site during the next 1000 years were estimated from several data types. Average stream channel incision and scarp retreat rates, calculated for periods on the order of millions of years, reflect the progressive development of major geomorphic features such as valleys and canyons. Modern denudation rates have been calculated from sediment yield and reservoir sedimentation rates for large sections of the Colorado Plateau and for small test watersheds on the Mancos Shale. Future erosion rates at and near the site were estimated from local geomorphic features. These types of data represent greatly differing scales of space and time and, therefore, are not directly comparable. Moreover, each data type involves simplifications and measurement problems, so that the resulting erosion rates are approximations. However, these data collectively indicate that future erosion at the site will be relatively low.

Regional erosion rates

Average incision rates were calculated for most sites in the northeastern Colorado Plateau where radiometrically dated units are closely associated with stream channels. However, a few sites have minimum ages based on reversed paleomagnetic polarity (Johnson, 1982) or estimated age ranges based on geomorphic relationships. The maximum long-term incision rates are about 1 ft (0.3 m)/1000 years; however, most of the rates fall between 0.3 and 0.7 ft (0.1 to 0.2 m)/1000 years. Some regional variation is apparent when rates for the same time interval are compared. The rates also are subject to change with time in a single area, as illustrated by the Roaring Fork River, where the average incision rate varied as follows: 0.98 ft (0.30 m)/1000 years (10 to 8 million years before present), <0.1 ft (0.03 m)/1000 years (8 to 1.5 million years before present), roughly 0.75 ft (0.23 m)/1000 years (1.5 to 0.62 million years before present), and 0.52 ft (0.16 m)/1000 years (0.62 million years before present to present).

Channel incision rates also vary on shorter time scales, as indicated by pediments and terraces occurring at several levels above the Colorado, Gunnison, Uncompahgre, and Dolores Rivers (Lohman, 1965; Yeend, 1969; Sinnock, 1981a, 1978; Cole and Sexton, 1981; Shawe, 1968). These surfaces most likely formed during glacial intervals when larger sediment loads temporarily prevented channel incision. No incision rates were calculated from the heights of these surfaces because their ages are not well known. However, the presence of these surfaces indicates that incision rates have been more variable than the long-term averages indicate, and perhaps were several times higher during times of postglacial drainage adjustment.

Long-term average rates of scarp retreat are less well known than channel incision rates due to greater difficulties in dating, the episodic nature of the retreat (Schumm and Chorley, 1966), and local variations in rate for salients, re-entrants, and tributary mouths (Haman, 1983). Most of the calculated rates are on the order of a few feet in 1000 years. An exceptionally rapid rate for the Book Cliffs at the northwestern end of the Uncompahgre Plateau, 74 ft (23 m)/1000 years (Hunt, 1969), may be erroneously high. Possibly valley widening at this location began earlier than assumed, along the tributary stream that later captured the Colorado River (Lohman, 1965).

Historic denudation rates for large parts of the Colorado Plateau are based on sediment yield and reservoir sedimentation measurements. Rates that include all components of sediment load (suspended, dissolved, and bed) mostly range from 0.3 to 0.8 ft (0.09 to 0.2 m)/1000 years. These rates are similar to long-term average channel incision rates, but the similarity must be partly fortuitous because the different time scales should reflect the controls of climate and tectonics in very different ways.

Holocene erosion rates in the site area

Holocene erosion and incision rates have not been studied in the site area, but relative rates can be inferred from studies conducted in nearby areas. Erodibility studies for similar rock types in the Paradox Basin area (W-C, 1982a) can be applied to the area.

Incision processes in the Paradox Basin probably involve periods of virtually no downcutting alternating with periods of active incision. Little bedrock incision appears to have occurred during the last 8000 to 10,000 years (W-C, 1982a). Exposures in the area show multiple cut-and-fill events, indicating that successive cycles of erosion and deposition have occurred during the past 10,000 years. Bedrock elevations in stream channels appear to have remained constant. Historic surface denudation rates range from 0.3 to 3.1 ft (0.09 to 0.94 m)/1000 years for lithologic units similar to those in the site area (W-C, 1982a). Geomorphic relationships within the Paradox Basin show the same range of erosion rates (W-C, 1982a). The rates show considerable variability based on local climatic conditions, different time intervals used in calculations, and variations in lithology, drainage basin area, topographic setting, and human activities. Within the site area, the most resistant rock types consist of silica-cemented sandstones (Burro Canyon and Dakota Sandstone Formations). Decreasingly resistant rock types are, respectively, massive, friable sandstone with predominantly calcite cement (Entrada Sandstone, Navajo Sandstone, Wingate Sandstone, and Kayenta Formations); sandstone with interlayered siltstone (Salt Wash Member of the Morrison Formation, and Summerville Formation); and siltstone with bentonitic mudstone (Brushy Basin Member of the Morrison Formation). Estimates of rates of scarp retreat in bedrock units in the site region range from 0.8 to 1.8 ft (0.2 to 0.55 m)/1000 years (W-C, 1982a) in formations similar to those at the site area. Considerable variations in rates occur throughout the area due to differences in lithology. Incision and scarp retreat will occur most readily in those units composed of less resistant siltstone, mudstone, and calcite-cemented sandstone. Silica-cemented sandstone units will have low scarp recession rates. Bedrock incision rates and rates of scarp retreat may increase if changing climatic conditions result in lower mean annual temperatures and higher stream discharges.

Climate and vegetation

Annual precipitation at the site is 7 to 10 inches (in) (200 to 250 millimeters [mm]) (NOAA, 1975) and reflects a seasonal variation with the majority of the rainfall occurring from June to October. Higher elevation areas outside of the Dolores River valley average 15 to 20 in (380 to 500 mm) of annual precipitation (Shawe et al., 1968).

The area is in a transitional vegetation area characterized by sagebrush and other desert shrubs, small cacti, pinon-juniper woodland, and scattered pine trees (Shawe et al., 1968). Along the Dolores River and near springs, cottonwoods and yellow pines commonly occur. Sagebrush dominates the

lower slopes of the valley, while thick stands of pinon and juniper dominate the higher elevation mesas. Open plains at elevations of about 7000 ft (2200 m) are covered with sagebrush. Small stands of aspens and spruce trees grow at elevations higher than 8000 ft (2400 m).

The Holocene climate

Broad changes in postglacial climate have been documented for the western United States. Following a period of transitional climate, changes in average temperature for periods on the order of hundreds to thousands of years were most likely $\pm 4^{\circ}\text{F}$ ($\pm 2^{\circ}\text{C}$) (Knox, 1983). However, few of the paleoenvironmental data available have been used to derive quantitative estimates of climate change.

The time following the last glaciation has been divided into three climatic intervals:

- A transitional period from 14,000 to 7000 years.
- A slightly warmer period ending around 4000 years.
- A slightly cooler period continuing to the present.

Evidence for the Middle Holocene warm period is abundant in surrounding areas but is poor in Colorado, perhaps because the sites studied are insensitive to small climatic changes (Baker, 1983).

Short periods during the Holocene of greater effective moisture are documented in parts of the southwestern United States. These studies associate more pluvial conditions with intense, warm-season precipitation, triggering major periods of landscape instability, erosion, and sedimentation (Gile et al., 1981). Observation in the Paradox Basin (W-C, 1982a) indicates that the valley fill was removed and redeposited during multiple cut-and-fill episodes. Episodic fluctuations in Holocene surficial geologic processes in the Colorado Plateau area are indicated by periodic eolian deposition during neoglacial interstadices of the last 6000 years (Curry, 1976) and by incipient soil development on buried fine-grained fluvial deposits.

No data on Holocene climates are available for the Slick Rock sites area, but inferences may be drawn from pollen studies in surrounding areas (Baker, 1983). The closest and possibly most similar site, Alkali Basin (Markgraf and Scott, 1981), is located northwest of Gunnison, Colorado, on the flank of the West Elk Mountains. At an elevation of 9000 ft (2700 m), this site was not glaciated. The period from 10,000 to 4000 years is interpreted to be about 1.5°F (1°C) cooler and 50 percent more moist than the period from about 4000 years to the present.

During the last few centuries, tree-ring studies (Fritts, 1971) have shown significant variability in climate during periods ranging from a few years to a few decades and longer. Historic records (Bradley, 1976), although shorter, corroborate these short-term fluctuations.

Relative changes in effective moisture for the Colorado Plateau have been interpreted for the last several centuries from tree-ring data (Stockton and Jacoby, 1976). This study included data from several sites in western Colorado. A synthetic hydrograph, developed for the discharge of the San Juan River near Bluff, Utah, integrates local variations in moisture over a large area. An important aspect of this hydrograph is its short-term variability, which may illustrate the potential variability in the site area. The strongest periodicities in the hydrograph were 50 and 5 years, but weaker periodicities of 3 and 2 years also occurred.

Historical climatic records for several stations in the San Juan Mountains have been analyzed in detail (Bradley and Barry, 1976). The resulting trends indicate the general magnitude of short-term variations that could be expected in the site area. At the most carefully studied station (Durango from 1900 to 1970), the 9-year weighted-mean temperature varied by about 3.3°F (1.8°C). In contrast, the nine-year weighted-mean precipitation varied by a factor of 1.7, from 13.5 to 23 in (343 to 580 mm); the annual mean precipitation varied by a factor of more than 2. Variations also occurred in the seasonal distribution of temperature and precipitation and in the frequency of rainfall events in particular size classes.

General trends in temperature indicated regional cooling from the late 1860s until about 1930, followed by regional warming. General trends in precipitation were roughly inverse to those in temperature but were much less consistent.

For the next few hundred to a thousand years, average temperature and precipitation will most likely fluctuate within the same ranges as during the recent past.

2.2 STRATIGRAPHIC SETTING

Stratigraphic units underlying the Burro Canyon site region range from a Precambrian basement complex to a thick sequence of marine and continental rocks of Cambrian to Cretaceous age, overlain by igneous rocks of Tertiary age and unconsolidated Quaternary deposits. The combined thickness of sedimentary rocks in the region is about 13,000 ft (4000 m) and, prior to erosion in the late Tertiary and Quaternary, may have been as much as 18,000 ft (5500 m) (Shawe et al., 1968). The sedimentary units in the site region are folded into broad, parallel, northwest-trending anticlines and synclines intruded by evaporite rocks into the axial parts of the anticlines. The west and south parts of the region contain localized laccolith igneous centers. A generalized composite stratigraphic section of the site region is shown in Figure 2.3. Detailed descriptions of the stratigraphic units cropping out in the immediate site area are given in Table 2.1.

Paleozoic sedimentary rocks in the region are underlain by a Precambrian igneous and metamorphic basement complex, generally at depths of 2000 to 4000 ft (600 to 1200 m) below sea level (Shawe et al., 1968). The Paleozoic

Erathem	System	Rock Unit	
CENOZOIC	Quaternary	Alluvial, Eolian, Colluvial and Glacial Deposits	
	Tertiary	Igneous Rock	
MESOZOIC	Cretaceous	Mesaverde Group	
		Mancos Shale	
		Dakota Sandstone	
		Burro Canyon Formation	
	Jurassic	Morrison Formation	
		San Rafael Group	Bluff Sandstone
			Summerville Formation ?
			Curtis Formation ?
			Entrada Sandstone
		Glen Canyon Group	Navajo Sandstone
			Kayenta Formation
			Wingate Sandstone
	Triassic	Chinle Formation	
PALEOZOIC	Permian	Moenkopi	
		Cutler Group	White Rim (De Chelly) Sandstone
			Organ Rock Shale
			Cedar Mesa Sandstone
			Elephant Canyon Formation
	Pennsylvanian	Hermosa Group	Honaker Trail Formation
			Paradox Formation
			Pinkerton Trail Formation
	Mississippian	Molas Formation	
		Leadville Limestone (Redwall equivalent)	
	Devonian	Ouray Limestone	
		Elbert Formation	Upper Elbert Member,
			McCracken Sandstone Member
		Aneth Formation	
	Cambrian	Lynch Dolomite ?	
		Muav Limestone	
		Bright Angel Shale	
		Ignacio Formation (quartzite)	
Pre-Paleozoic	Pre-Cambrian	Basement Complex of Igneous and Metamorphic Rock	

BURRO CANYON
DISPOSAL SITE

SLICK ROCK
PROCESSING SITE

FROM W-C, 1982a.

FIGURE 2.3
STRATIGRAPHIC SECTION OF THE
BURRO CANYON SITE REGION, COLORADO

Table 2.1 Description of stratigraphic units in the Burro Canyon site area

Age	Unit	Approximate thickness in site area [ft (m)]	Description
Quaternary	Quaternary deposits	Varying thickness	Consists of landslide deposits, terrace gravels, alluvial fan deposits, and minor soil, loess, alluvium, colluvium, and talus.
Upper Cretaceous	Mancos Shale	0-860 ft (0-260 m)	Dark gray carbonaceous calcareous shale with abundant silt and sand. Remnants of the formation are found in the lower portion of Disappointment Valley.
Lower and Upper Cretaceous	Dakota Sandstone	130 ft (40 m)	Light brown to dark gray, thin-bedded to massive, cross-bedded, arenaceous sandstone with common carbonaceous material and gray and brown conglomerate with chert, sandstone, and quartzite pebbles. Thin, evenly-bedded carbonaceous shale and mudstone and thin coal layers occur between the upper and lower sandstone units. In the site area, the lower contact is marked by a carbonaceous shale that is in conformable contact with the Burro Canyon Formation. At other locations there is an unconformable contact.
Lower Cretaceous	Burro Canyon Formation	400 ft (120 m)	White, gray, red, and light brown fluvial sandstone and conglomerate interbedded with green and purple lacustrine siltstone, shale, and mudstone. Forms cliffs and steep, even slopes.
Upper Jurassic	Morrison Formation	750 ft (230 m)	Variegated fluvial channel and floodplain deposits of shale, mudstone, and sandstone with thin limestone and conglomerate lenses. Divided into the Brushy Basin shale member and the Salt Wash sandstone member. Brushy Basin shale member: Gray, pale green-red, and light purple bentonitic mudstone, fluvial sandstone, and conglomerate lenses. Mudstones are evenly bedded and sandstone lenses are cross-bedded.

Table 2.1 Description of stratigraphic units in the Burro Canyon site area (Continued)

Age	Unit	Approximate thickness in site area [ft (m)]	Description
Upper Jurassic	Summerville Formation	120 ft (37 m)	<p>Salt Wash sandstone member: Light buff to light reddish-brown lenticular fluvial sandstone and cross-bedded sandstone intercalated with reddish-brown floodplain mudstone layers and thin, discontinuous limestone beds near base. Generally forms a transitional contact with the underlying Summerville Formation. Minor uranium deposits occur in the lower part of the Salt Wash member. The upper part of the member contains the major uranium-vanadium deposits of the region.</p> <p>Greenish-gray argillaceous, horizontally bedded sandy siltstone and mudstone changing to a reddish-brown, horizontally bedded sandy siltstone and mudstone below a thin marker bed of reddish-brown to brown very fine-grained silty sandstone with oscillatory ripple marks. Lower part of the formation consists of reddish-brown and greenish-gray, very fine-grained laminated sandstone interbedded with thin layers of claystone, mudstone, or siltstone. Base of unit is transitional to the underlying Entrada Sandstone.</p>
Middle Jurassic	Entrada Sandstone: Slick Rock and Dewey Bridge Members	90-155 ft (30-47.2 m)	<p>Buff, brown, and reddish-brown, fine-grained quartzose sandstone and reddish-brown clayey siltstone with a localized chert pebble conglomerate at the base. Divided into the fine-grained, horizontally bedded to massive to cross-bedded. Sandstone of the Slick Rock Member at the top and the clayey siltstone and sandstone of the Dewey Bridge Member at the base. The upper sandstone unit forms cliffs and the lower siltstone unit weathers to low mounds. Forms a disconformable contact with the underlying Navajo Sandstone.</p>

Table 2.1 Description of stratigraphic units in the Burro Canyon site area (Continued)

Age	Unit	Approximate thickness in site area [ft (m)]	Description
Lower Jurassic(?)	Navajo Formation	100 ft (30 m)	Buff and reddish-brown, fine-grained eolian sandstone with large scale tangential cross-beds. Forms sheer cliffs. Contact with the underlying Kayenta Formation is irregular.
Lower Jurassic(?)	Kayenta Formation	180 ft (55 m)	Reddish-brown to purple-gray, thin-bedded to cross-bedded fine- to coarse-grained sandstone, shaly sandstone, shale, and pebble conglomerate. Forms steep, closely-spaced ledges and occasional sheer cliffs.
Lower Jurassic(?)	Wingate Sandstone	250 ft (76 m)	Reddish-brown, orange-brown, buff, fine-grained, massive thick-bedded, cross-bedded eolian sandstone. Forms prominent, vertical cliffs with red and black desert varnish on weathered surfaces.
Upper Triassic	Chinle Formation	550 ft (170 m)	<p>Terrestrial red to orange-red siltstone with interbedded lenses of red sandstone, shale, and limestone-pebble and clay-pellet conglomerate. Lenses of quartz-pebble conglomerate and grit at base. Rests unconformably on Cutler Formation rocks. Divided into Church Rock, Petrified Forest, and Moss Back members. Contains uranium and vanadium.</p> <p>Church Rock Member: Mainly reddish-brown, purple, and gray shaly siltstone, mudstone, and sandstone with thin layers and lenses of cross-bedded to horizontally-layered pebble conglomerate.</p> <p>Petrified Forest Member: Grayish-green mudstone, siltstone, and shale with minor reddish-brown mudstone and greenish-gray sandstone and conglomerate. Limestone and mudstone pebble conglomerate is, in places, cross-bedded.</p> <p>Moss Back Member: Greenish-gray limey arkosic and quartzose sandstone and conglomerate with minor beds of greenish-gray to reddish-brown mudstone, siltstone, and shale.</p>

Table 2.1 Description of stratigraphic units in the Burro Canyon site area (Concluded)

Age	Unit	Approximate thickness in site area [ft (m)]	Description
Permian	Cutler Formation	3,000 ft (900 m)	Cross-bedded and horizontally bedded, coarse-grained, reddish-brown to brown arkosic sandstone forming a prominent ledge. Contains siltstone, mudstone, and shale in lower part of unit. Transitional between marine sediments to the west and terrestrial sediments to the east. Upper 240 ft (73 m) exposed in Dolores River Canyon.

Ref. Adapted from Shawe et al., 1968.

rocks are composed of 5000 ft (1500 m) or more of marine carbonates and evaporites interbedded with clastic sedimentary units.

In the subsurface, the most significant Paleozoic formation is the extremely thick deposit of the Hermosa Group, including the Paradox salt formation. This Pennsylvanian age deposit consists of evaporite deposits of halite, gypsum, and phosphate minerals. Its depositional extent determines the area of the Paradox Basin and resulted in the formation of the salt core anticlines of the region.

Outcropping units include the upper part of the Cutler Formation of Permian age; the Chinle Formation and Wingate Sandstone of Triassic age; the Kayenta Formation of Triassic age; the Navajo Sandstone of Triassic and Jurassic age; the Entrada Sandstone, Summerville Formation, Junction Creek Sandstone, and Morrison Formation of Jurassic age; and the Burro Canyon Formation, Dakota Sandstone, and lower part of the marine Mancos Shale of Cretaceous age (Shawe et al., 1968).

Unconsolidated sediments in the region consist of terrace gravels, mudflows, landslides, alluvial fans, loess, soil, colluvium, talus, and floodplain deposits. Igneous rocks occur as dikes on Glade Mountain and near the southeastern part of Disappointment Valley; as a thick sill in the salt unit of the Paradox Member of the Hermosa Group; and as laccolith bodies in the La Sal and Abajo Mountains (Shawe et al., 1968; W-C, 1982a).

2.3 STRUCTURAL SETTING

The Burro Canyon site is in the northeastern portion of the Colorado Plateau, a stable intracontinental subplate characterized by a thick cover of relatively flat-lying Phanerozoic sedimentary rock overlying a complex Precambrian igneous and metamorphic core. The central, stable portion of the Colorado Plateau exhibits characteristics of cratonic areas, while the margins of the subplate exhibit crustal structure similar to more highly active bordering provinces. The Colorado Plateau is bordered on the east, south, and west by the extensional, block-faulted regime of the Rio Grande Rift and the Basin and Range Province (Figure 2.4).

The principal present-day structural elements of the Colorado Plateau are as follows (Hunt, 1956):

- Broad west and northwest-trending basins such as the Piceance, Uinta, San Juan, and Navajo Basins.
- Clusters of uplifts that lie between these broad basins, including the Uncompahgre, Monument, San Rafael Swell, Circle Cliffs, Kaibab, Defiance, and Zuni Uplifts.

- Northwest-trending anticlines and faults of east-central Utah and southwestern Colorado, including the Paradox Basin, underlain by thick salt deposits.
- North-trending fault blocks of the high plateaus in Utah and Arizona. These features represent a zone of transition between the Colorado Plateau and Basin and Range Provinces.
- Domes and folds related to laccolithic intrusions, most of which are in the central part of the Plateau.

The present structural elements of the plateau are principally the result of Cenozoic deformation, but follow, at least in part, the trends of older features. Structures in the Precambrian basement have undoubtedly influenced the later tectonic history of the plateau. However, relatively little is known of the Precambrian structure. Precambrian rocks are exposed only in the Uncompahgre Uplift, Grand Canyon, Zuni Mountains, and Defiance Uplift. These rocks consist of a complex series of metasedimentary and metavolcanic rocks cut by a series of large intrusions. During much of Paleozoic and Mesozoic times, the plateau region was a stable continental shelf area. From the Late Mississippian to Permian time, the "Ancestral Rockies" disturbance affected parts of the eastern plateau and the Rocky Mountain region to the east. The Uncompahgre Uplift rose during this time, while the Paradox Basin received large volumes of Pennsylvanian and Permian redbeds and evaporite deposits (Cater, 1970, 1966). The Zuni Mountains and Defiance Upwarps probably were also uplifted at this time (Hunt, 1956). The Late Cretaceous-Eocene Laramide Orogeny produced a series of monoclines and fault-bounded uplifts and basins within the plateau (Tweto, 1980). From the end of the Eocene until Miocene or Pliocene times, the plateau was undergoing erosion by the ancestral Colorado River. Since Late Tertiary time, the plateau has been experiencing gradual uplift at an average rate of 2 mm/year (Gable and Hatton, 1983). This uplift is regional in character and appears to produce relatively little internal deformation.

The major regional structural and tectonic features of the site region are the Uncompahgre Uplift, the salt anticline region of the Paradox Basin, and the laccolithic centers of the La Sal, Abajo, and Ute Mountains (Figures 2.4 and 2.5).

The Uncompahgre Uplift (or Uncompahgre Plateau) is a large, northwest-trending, asymmetrical block composed of a complex Precambrian igneous and metamorphic core overlain by Mesozoic sedimentary units. The uplift is bounded on the northeastern and southwestern flanks by abrupt, locally faulted monoclines. The northwest-trending salt anticlines of the Paradox Basin lie to the southwest, paralleling the trend of the uplift. On the northeast, the uplift is flanked by the valleys of the Colorado, Gunnison, and Uncompahgre Rivers, Grand Mesa, and the Piecance Basin. The southeast end of the uplift is terminated by the Ridgway Fault (Tweto, 1979; Sullivan et al., 1980) and the San Juan volcanic field. To the northwest, the uplift plunges beneath the Tertiary sedimentary sequence of the Uinta Basin.

REF: FROM SHAW, 1970.

NOTE: STRUCTURE CONTOURS ARE ON THE BASE OF THE DAKOTA SANDSTONE FM. HEAVY LINES INDICATE INFERRED DEEP-SEATED FAULTS.

- EXPLANATION
- Approximate location of zero thickness of saline facies (Boundary of Paradox Basin)
 - Anticline in which intrusive salt (Paradox Formation) is exposed
 - Igneous intrusive center, generally a domal uplift
 - Overthrust margin of Uncompahgre Uplift; barbs on overthrust block
 - Anticline within area of potash deposition
 - Limit of major potash deposition

REF: FROM WOODWARD-CLYDE, 1983.

FIGURE 2.5
GEOLOGIC STRUCTURE OF THE BURRO CANYON SITE
REGION AND AREA, COLORADO

The Uncompahgre Uplift has experienced recurrent activity since at least the end of the Paleozoic and may be controlled by deep-seated faults that were established during Precambrian time. The uplift was a prominent structural feature during the "Ancestral Rockies" disturbance in Late Paleozoic (Mississippian-Permian) time. Movement also occurred on bounding faults and monoclines during the Laramide Orogeny in Late Cretaceous to Eocene times. The modern Uncompahgre Uplift is a northeast-tilted block that has apparently experienced considerable Neogene Uplift. The timing of Neogene deformation is uncertain. Movements apparently began during the Miocene or Pliocene and may have persisted well into the Pleistocene (Cater, 1966; Lohman, 1981; Sinnock, 1981b; Kirkham and Rogers, 1981).

Kirkham and Rogers (1981) indicate that deformation of the Uncompahgre Uplift may be continuing at the present time. Their study identified 25 faults of Late Cenozoic age flanking the uplift on the northeast and southwest. These faults range in length from 5 to 25 mi (8 to 40 km). Faults identified as "potentially active" by Kirkham and Rogers (1981) on the northeastern flank lie at distances ranging from 56 to 75 mi (90 to 120 km) from the site. Faults lying along the southwestern flank are about 30 mi (50 km) from the site.

The salt anticline region of the Paradox Basin south of the Uncompahgre Plateau includes the Sinbad, Paradox, Spanish, Lisbon, Gypsum, and Disappointment Valleys (Figure 2.5). Each of these features is the result of folding of sedimentary rocks, flowage of evaporite bodies, erosion, and faulting. The salt anticline region generally lies within a northwest-trending trough, which may have originated as a wide graben in Precambrian igneous and metamorphic sediment rocks between the Uncompahgre Plateau and a Precambrian platform to the west and south (Shawe et al., 1968). This trough may have been an important ancestral control on the deposition of thick Paleozoic and Mesozoic sediments in the Paradox Basin.

The Paradox Basin is a northwest-southeast-trending structural and sedimentary basin bounded on the northeast and east by the Uncompahgre Plateau and the San Juan Mountains, on the south by the Defiance Plateau, and on the west by the Circle Cliffs and San Rafael Swell (Ohlen and McIntyre, 1965). The basin is 200 mi (320 km) long and 80 mi (130 km) wide. Five major northwest-trending salt anticlines ranging from 30 to 70 mi (50 to 110 km) long occur within the basin and are characterized by structurally complex centers 2 to 6 mi (3 to 10 km) wide and salt cores 4100 to 13,700 ft (1300 to 4180 m) thick (Elston and Landis, 1960). The Dolores anticline to the west of the site and the Gypsum Valley anticline to the east have salt core thicknesses of 4000 and 10,000 ft (1200 and 3000 m), respectively, while the Disappointment Valley syncline, in which the site is located, has a relatively thin layer of only 1000 ft (300 m) (Shawe et al., 1968).

The Paradox Basin formed in Pennsylvanian time along a dominant set of northwest-trending faults of pre-Pennsylvanian age. Basin subsidence, accompanied by uplift of the ancestral Uncompahgre highland, resulted in the

deepest part of the basin occurring adjacent to the present-day Uncompahgre Plateau (Chenoweth, 1984). Terrestrial and marine sediments, including the salt-bearing unit of the Paradox Member of the Hermosa Group, were deposited in this subsiding basin, creating a wedge of sediment thickening to the northeast to greater than 20,000 ft (6000 m).

The sedimentary rocks in the Paradox Basin are folded in a series of broad, northwest-trending anticlines and synclines generally parallel to the southwestern edge of the Uncompahgre Plateau (Figure 2.5). The folding is related to both the uplift of the plateau and the flowage and intrusion of evaporite rocks into the axial parts of the anticlines (Shawe et al., 1968). Crustal movement associated with the uplift of the Uncompahgre highland ceased by the end of deposition of the Cutler Formation in the Late Permian, although minor upwelling of the evaporites occurred during the Triassic and Jurassic (Chenoweth, 1984; Elston and Landis, 1960). Upwelling of evaporite deposits resulted in steeper dips on successively older formations on the flanks of the anticlines and deposition of younger formations across the upturned and truncated edges of the older formations. The process of upturning, erosion, and deposition of overlapping younger formations continued until the Late Jurassic, when salt from the adjacent synclines had been squeezed out and exhausted (Chenoweth, 1984).

Relaxation of stress during the Cretaceous Period caused initial collapse of the crest of anticlines in the Paradox Basin. Middle and Late Tertiary uplift of the Colorado Plateau reactivated axial graben formation in the salt anticlines. As a consequence of differential overburden pressure, evaporite deposits were extended upward from, and moved laterally by, flowage along the axial regions of the anticlines, and locally were removed by solution processes by incised river valley (Cater, 1970). The axial regions of the anticlines collapsed as grabens bounded by longitudinal faults or fault zones along the limbs of the structures (Shawe et al., 1968). Many of the graben collapse features are expressed as huge, backward-rotated slump blocks flanking the axial valleys of the eroded anticlines. Basin-like downwarps and sags within the Paradox Basin areas also appear to be the result of salt removal by flowage (Chenoweth, 1984). Continuing removal of salt by flowage toward the deeply incised stream valley in the Paradox Basin indicates that graben development in the anticlines is directly related to downcutting of the Dolores River (Cater, 1970). Faults associated with collapse of salt-cored anticlines in the site region are not tectonically controlled, but result from downdropping of sedimentary rocks overlying areas of salt removal by flowage and solution.

Some laccolithic centers and associated structural features appear to be controlled by the northwest-trending basement structure that results in the alignment of the Uncompahgre Uplift (Cater, 1970). Major laccolithic mountains in the region are the La Sal, the Abajo, and the Ute Mountains (Figure 2.5). Minor intrusive bodies occur in the Klondike, Disappointment Valley, and Glade Mountain areas. Laccolithic igneous intrusions in the La Sal Mountains are of Tertiary age and occur in the midst of the series of salt anticlines and synclines.

The folding and associated faulting are the result of Late Cretaceous or Early Tertiary deformation and original structures have been complexly modified by repeated plastic deformation of evaporite beds (Hunt, 1958). Middle Tertiary laccolith intrusions postdate the folding. Local Late Tertiary and Quaternary deformations and faulting of Pleistocene and Holocene deposits are related to continued flowage of salt bodies.

Laccolithic igneous intrusions in the Abajo Mountains do not seem to be related to the fold and fault structures of the nearby Paradox Basin, Blanding Basin, or Monument Upwarp. Formation of the Abajo Mountains, by doming of flat-lying sedimentary rocks by forcible igneous intrusions, occurred during the Middle Tertiary (Witkind, 1964). A zone of high-angle, normal faults trending eastward across southeastern Utah and southwestern Colorado forms grabens on the north and south flanks of the Abajo Mountains. The Shay and Verdure grabens crossing the Abajo Mountains appear to antedate the laccolithic intrusion and uplift of the mountain area (Witkind, 1964), and were probably formed between Late Cretaceous and Middle Tertiary time. Evidence of possible displacement of a Quaternary gravel-covered pediment on the north side of the Shay Mountain suggests a possible rejuvenation of the graben system since laccolith emplacement in the Oligocene (W-C, 1982a). Quaternary movement on the graben-bounding faults has not been conclusively demonstrated, although geomorphic evidence suggests it. The age of last movement on the Verdure graben on the south flank of Abajo Mountain may be Oligocene, but overlying Quaternary pediment gravel deposits may be offset by later fault movement (W-C, 1982a).

In the site region, igneous intrusions also occur at Glade Mountain, Disappointment Valley, and Klondike Ridge at the southeast end of Gypsum Valley (Shawe et al., 1968). A fault-bounding the Glade graben near the top of Glade Mountain localized intrusion along an igneous dike. A sill intruded into the Paradox Member of the Hermosa Formation is connected with the dike. Igneous intrusions at Klondike Ridge are also connected, with sills occurring in the Mancos Shale and Dakota Sandstone in Disappointment Valley. Dikes and sills in these areas were probably localized by pre-existing north-south faults and were emplaced sometime between Early Cenozoic and Miocene times (Shawe et al., 1968). In Disappointment Valley, syncline development most likely continued for a short time after intrusion of the igneous sills.

2.4 SEISMOTECTONICS

Seismic hazard studies in much of the southwestern United States are hampered by the lack of a reliable long-term historical record. Movements on major fault systems in the region may have recurrence intervals on the order of tens to hundreds of thousands of years, while the historical record dates back only to the middle or late 19th century. The historical record for Arizona dates back to 1776 (DuBois et al., 1982); for Utah to 1850 (Arabasz et al., 1979); and for Colorado to 1870 (Kirkham and Rogers, 1981). Reliable and reasonably complete instrumental records generally date back only to the early 1960s. As

a general rule, the historical record is probably reliable for moderate to large earthquakes since 1900 to 1910, while the instrumental record is most likely reliable for earthquakes of magnitude 4.5 or greater since the early 1960s (Von Hake, 1984).

In the absence of a reliable long-term historical record, probabilistic analyses of seismic risk are of limited use. Therefore, seismic risk analyses are largely based on studies of the geologic and seismotectonic setting, Cenozoic geologic history, and geomorphic evidence of Late Tertiary and Quaternary fault movements. Fortunately, erosion rates are slow and vegetation is generally sparse in the arid to semiarid climates that prevail in most of the region. Long faults, which are necessary for large earthquakes, will not remain undetected if careful geologic investigations are made (Krinitzky and Chang, 1975).

The site is near the northeast edge of the Colorado Plateau physiographic and seismotectonic province. The boundaries of seismotectonic provinces in the site region, as defined for this study, are shown on Figure 2.4. The boundaries are determined on the basis of published studies of Neogene faulting, regional seismicity trends, areas of Cenozoic igneous activity, geophysical data, and the distribution of major physiographic provinces. In Colorado, adjacent to the Colorado Plateau province on the east, lies the Western Mountains seismotectonic province (corresponding to the west part of the southern Rocky Mountains physiographic province). Figure 2.6 shows a plot of historical and instrumentally-located earthquake epicenters (for events of magnitude ≥ 4 and intensity (I_{MM}) $\geq V$) for the Colorado Plateau region. These data were provided by the National Geophysical Data Center/National Oceanic and Atmospheric Administration (NGDC/NOAA, 1989).

Beyond the border zones, the Colorado Plateau is surrounded on three sides by the extensional, block-faulted regime of the Basin and Range and Rio Grande Rift Provinces. The Colorado Plateau, Basin and Range, Rio Grande Rift, and Sierra Nevada appear to be parts of an interrelated system that has experienced major uplift and extension during the last 20 million years (Thompson and Zoback, 1979). Within the Basin and Range and Rio Grande Rift bounding the plateau are found geologic and geomorphic evidence of repeated surface faulting events associated with large earthquakes during Quaternary time. These areas have experienced some of the largest historical earthquakes in the entire United States. These regions are characterized by large volumes of Cenozoic intrusive rock, thinner crust, higher heat flow, and stress fields oriented differently than the modern stress field in the interior of the Colorado Plateau (Thompson and Zoback, 1979). The boundary of the Colorado Plateau and the Basin and Range Province on the west is marked by the Wasatch Frontal Fault system in Utah, which forms a major segment of the Intermountain Seismic Belt (Smith and Sbar, 1974). The transition zone in northern and central Arizona is referred to in this study as the Arizona border zone. Some of the largest historical earthquakes of the Colorado Plateau have occurred in this region (DuBois et al., 1982). The Rio Grande Rift and the eastern Colorado Plateau border zone in New Mexico and southwestern Colorado have also been the

FIGURE 2.6
EPICENTRAL COMPILATION OF ALL RECORDED EARTHQUAKES FOR THE
COLORADO PLATEAU AND ADJACENT SEISMOTECTONIC PROVINCES

focus of elevated seismicity in historical times. A swarm of moderate to large earthquakes occurred in the Dulce, New Mexico, region during 1966, and may be related to the movement of magma at depth.

The border zone of the Colorado Plateau and Western Mountain Provinces in southwestern Colorado, which includes the site region, has also experienced a moderate, broadly-distributed level of seismicity during historical times. An area of persistent seismic activity near Montrose, Colorado, may be related to the Ridgway fault, which terminates the southeast end of the Uncompahgre Uplift (Sullivan et al., 1980; Kirkham and Rogers, 1981). To the north, the Colorado Plateau is bordered by the Wyoming Basin, a series of broad basins and uplifts that are structurally and tectonically similar to the Plateau. The transition zone is not marked by elevated seismicity, except for probable mining-related events in the eastern Utah coal-mining belt (Smith and Sbar, 1974). Seismotectonic characteristics of the Colorado Plateau and adjacent provinces are listed in Table 2.2.

Colorado Plateau seismotectonic province

The modern Colorado Plateau is composed of a stable interior portion bounded on the west, south, and east by more highly active border zones. For this study, the interior and border zones are defined as separate subprovinces, and the boundary is drawn at the 25-mi (40-km) crustal thickness contour. The border zones lie within the physiographic boundary of the Colorado Plateau but are characterized by elevated seismicity, thinner crust, higher heat flow, common normal faulting, and elevated levels of Tertiary and Quaternary volcanism relative to the interior. Nearly all of the larger historical earthquakes of the Plateau have occurred within the border zones.

The Colorado Plateau is a major continental plate that has been uplifted since Late Tertiary time at a rate of between 0.08 to 0.12 in/year (2.0 to 3.0 mm/year) (Gable and Hatton, 1983). The plateau has experienced little internal distortion in contrast with the more tectonically active border regions of the plateau that includes the Rio Grande Rift, the Arizona Basin and Range province, and the Intermountain Seismic Zone. Major seismotectonic characteristics of the Colorado Plateau interior province are listed in Tables 2.2 and 2.3. Average thickness of the earth's crust beneath the region is 25 mi (40 km) (Wong et al., 1987). Lithosphere thickness averages 50 mi (80 km). Earthquake focal depths of 3 to 16 mi (5 to 26 km) have been recorded for seismic events within the province interior (Giardina, 1977). The faulting mode is primarily strike-slip and thrust with a north-northeast direction of least principal horizontal stress (Zoback and Zoback, 1980).

Neogene faulting is generally rare within the interior portion of the Colorado Plateau, except for faulting associated with the Uncompahgre Uplift and the collapsed salt anticlines of the Paradox Valley. Earthquakes are rare. The historical seismicity of the interior portion has been classified by Wong (1984) as very low level, having events of small to moderate magnitude with diffusely

Table 2.2 Seismotectonic characteristics of the Colorado Plateau and adjacent provinces

Province	Crustal thickness ^{a,b} km (miles)	Lithosphere thickness ^{a,c} km (miles)	Earthquake focal depth km (miles)	Direction of least principal horizontal stress ^{d,c}	Primary mode of faulting ^{d,b}	Maximum recorded earthquake	Maximum earthquake
Colorado Plateau Interior (Northern Arizona)	42 (26)	80 (50)	5-26 (3-16) ^e	NNE	Strike slip and thrust	M = 5.5 ^f	M = 6.5
Basin and Range (Central and North Central Arizona)	30 (19)	60 (37)	10-15 (6-9) ^g	WNW to E-W	normal	M = 5.75 ^f	M = 6.5
Intermountain Seismic Belt - (Southern Utah)	24 (15)	30 (19)	15 (9) ^h	ENE	normal	M = 6.5 ⁱ	M = 7.5
Rio Grande Rift - (Northwestern New Mexico)	40 (25)	60 (37)	40-43 (25-27) ^j	WNW	normal	M = 6.3 ⁱ	M = 6.5
Southern Rocky Mountains	45-50 (28-31)	100 (62)	--	E-W	normal	M = 5.5 ^k	M = 6.5

^aThompson and Zoback, 1979.

^bSmith, 1978.

^cKeller et al., 1979.

^dZoback and Zoback, 1980.

^eGiardina, 1977.

^fDubois et al., 1982.

^gEberhart-Phillips et al., 1981.

^hSmith and Sbar, 1974.

ⁱArabas et al., 1979.

^jWong, 1984.

^kKirkham and Rogers, 1981.

Table 2.3 Probabilistic estimates of maximum acceleration, velocity, and intensity in the site area

Source	Return period or probability	Maximum acceleration (g)	Maximum velocity (cm/s) ^a	Maximum Modified Mercalli intensity
Liu and DeCapua (1975)	100 years	0.02 to 0.03	--	IV-V
Algermissen and Perkins (1976)	90% probability of not being exceeded in 50 years	0.03 to 0.04	--	--
Applied Technology Council (ATC, 1978)	--	0.04 to 0.05	--	--
Algermissen et al. (1982)	90% probability of not being exceeded in 10 years	< 0.04	< 2	--
Algermissen et al. (1982)	90% probability of not being exceeded in 50 years	0.04 to 0.05	2	--
Algermissen et al. (1982)	90% probability of not being exceeded in 250 years	0.10 to 0.12	4-6	--

^acm/s = centimeters per second.

distributed epicenters. The largest instrumentally recorded earthquakes within the interior portion have fallen in the magnitude range 4.5 to 5.0.

The largest historical earthquakes recorded within the Colorado Plateau have occurred in the border zones. These include the following:

- Events of estimated magnitudes 5.5 to 5.75 (M_L) at Lockett Tanks, Arizona, in 1912 and Fredonia, Arizona, in 1959 (DuBois et al., 1982). These events occurred within the Arizona border zone separating the Colorado Plateau from the Basin and Range Province to the south.
- The Dulce, New Mexico, earthquake of January 23, 1966, of magnitude (M_b) 5.5 (NGDC/NOAA, 1985). This event occurred in the zone of transition between the Colorado Plateau and Rio Grande Rift (Herrmann et al., 1980).
- The earthquake of October 11, 1960, of magnitude 5.5, northeast of Ridgway, Colorado, which was strongly felt in the Ridgway-Montrose area. This event may be associated with the Ridgway fault, which terminates the southeastern end of the Uncompahgre Uplift, marks the northwestern boundary of the San Juan volcanic field, and may be the boundary between the Colorado Plateau and Western Mountain Provinces (Sullivan and Martin, 1981; Kirkham and Rogers, 1981).

Recurrence intervals have not been established for large earthquakes within the Colorado Plateau. They may be on the order of tens to hundreds of thousands of years.

Kirkham and Rogers (1981) have identified several faults with apparent Quaternary movement associated with the Uncompahgre Uplift and the salt anticline regions of the Colorado Plateau. Along the northeast flank of the Uncompahgre Uplift, an east-west-trending fault offsets Quaternary pediment gravels about 4 ft (1.2 m) and the underlying Mancos Shale is offset about 10 ft (3 m). Ely et al. (1986) reported a magnitude 2.9 earthquake on this fault in 1985 and concluded the fault was active. Other faults along the northeastern flank of the uplift appear to be no younger than Laramide age. Faults expressing Quaternary movement also occur along the southwestern flank of the Uncompahgre Uplift. The Ute Creek graben-bounding faults appear to have been active during the Late Pliocene and Early Pleistocene and may be active today. Other faults exhibit indications of Quaternary movement, the most important of which is the Ridgway fault bounding the southern end of the uplift. The Ridgway fault offsets Quaternary gravels and is associated with historical earthquakes. Nontectonic faults associated with the collapse of salt anticlines are common in the Paradox Basin. These faults are the result of salt flowage and are unlikely to generate earthquakes larger than magnitude 4 or 5 (Kirkham and Rogers, 1981). Wong et al. (1987) observed that the nature of seismicity in salt anticlines in the potash mining area near Moab, Utah, was less than magnitude 3.0.

Two faults along the flanks of Abajo Mountain, west of Slick Rock, have probable Quaternary movement. The Shay graben faults north of the mountain and the Verdure graben faults on its south flank were initially formed during emplacement of the Abajo Mountain laccolith. Geomorphic evidence (W-C, 1982a) suggests that parts of the Shay graben faults have experienced Quaternary movement. Renewed movement on the Verdure graben faults may also have occurred, but the geologic evidence is less certain.

The area of western and southwestern Colorado, which includes the Slick Rock sites, does not display some of the significant characteristics of the typical Colorado Plateau border zones (e.g., thinner crust and higher heat flow). Physiographically, this transition is also marked by increasing elevation within the uplifted areas adjacent to the Rocky Mountains, in contrast to the marked elevation decreases characteristic of the transitions to the Basin and Range and Rio Grande Rift Provinces. The transition is marked, however, by a marked increase in the level of seismicity relative to the Colorado Plateau interior. This seismicity is broadly centered over the Colorado Plateau/Western Mountain Province transition zone (Kirkham and Rogers, 1981). Geologic and geomorphic evidence has been interpreted as showing that certain structures in this region, notably the Uncompahgre Uplift, experienced considerable Late Tertiary uplift that may be continuing today.

Analysis of the historical and instrumental seismic record for this region indicates that activity on the eastern half of the Colorado Plateau may be associated with a series of parallel, northwest-trending structural features (Figure 2.6). The closest such seismic trends are labeled as No. 1 and No. 2 and are briefly described as follows:

- An apparent feature extending from the Dulce, New Mexico, area along the south flank of the San Juan Mountains, through the boundary of the Paradox Basin and the Uncompahgre Uplift. This feature may mark a hinge line separating the Uncompahgre Uplift from the Paradox Basin. The north end of this lineament slightly extends into the 65-km radius site region.
- An apparent feature lying about 62 mi (100 km) north of lineament 1, which passes through the central portion of the San Juan Mountains, through the seismicity in the Ridgway-Montrose, Colorado, area (possibly associated with the east-west-trending Ridgway fault), and along the northeast side of the Uncompahgre Uplift. This feature may mark a hinge line separating the Uncompahgre Uplift toward Piceance Basin. This lineament lies about 50 mi (80 km) northeast of the site.

These features cut across the roughly north-south-trending boundary between the Colorado Plateau and the Western Mountain Province of Kirkham and Rogers (1981) and Southern Rocky Mountains of Hunt (1967). This indicates that the seismicity of this region may coincide with deep-seated, northwest-trending, active structural features that cut across the province border.

The northeast-trending Colorado Lineament (Warner, 1980; Brill and Nuttli, 1983) is not apparent as a controlling seismic feature in the study region on the basis of seismicity trends. Warner (1980) concluded that the Colorado Lineament represents a system of wrench-faults of Late Precambrian age. He estimated that movement on this system may have virtually ceased about 1700 million years ago. However, Brill and Nuttli (1983) believe the Colorado Lineament to be one of the source zones for the larger historical earthquakes of the west-central United States. Hite (1975) described features within the Paradox Basin, which he determined to be evidence of extensive movements on northeast-trending faults as late as Eocene time. The presence of major northeast-trending basement faults concealed at depths beneath younger sediments in the site region cannot be ruled out entirely. However, the predominant structural and tectonic grain of surface geologic features is northwest-trending. The apparent correspondence of northwest-trending structural features and seismicity trends seems to indicate that seismicity in the site region is not directly associated with the northeast-trending Colorado Lineament.

Intermountain Seismic Zone

Seismicity throughout the Intermountain Seismic Zone is characterized by earthquake focal depths less than 9 mi (15 km) (Smith and Sbar, 1974). Most major faults trend north to northwest. The general direction of least principal horizontal stress is east-northeast (Table 2.2). Fault movement is mainly normal slip. The current stress regime of northwest-southwest extension appears to control historic surface faulting.

The entire zone has experienced more than 15 earthquakes of magnitude 6.0 or greater since the mid-1800s (Wong, 1984). The largest recorded event was the 1959 Hebgen Lake, Montana, earthquake of magnitude 7.1. Seismicity near Salt Lake City is anomalously low. In southern Utah, historic earthquake intensities have ranged from III to VI (NGDC/NOAA, 1985). Earthquake epicenters generally have poor correlation with Late Cenozoic faults (Wong, 1984). This may be caused by listric faulting and the occurrence of earthquakes on curved fault surfaces at depth. Offset of Quaternary deposits along some fault zones is evident. The maximum recorded earthquake in southern Utah was a magnitude 6.5 event near Richfield in 1901 (Table 2.2). Historical earthquake epicenter distributions for the Intermountain Seismic Belt are shown on Figure 2.6.

The Intermountain Seismic Belt, which lies outside the site region, includes the Wasatch Frontal Fault System and other major potentially active faults of northern and central Utah. This zone is highly seismic and capable of large earthquakes up to local magnitude (M_L) 7.5 (Arabasz et al., 1979).

Arizona Basin and Range Province

The Arizona Basin and Range Province lies south and west of the Colorado Plateau rim. Because of the distance from the site 300 mi (500 km), the seismicity from the region is not significant.

Rio Grande Rift

The Rio Grande Rift section of the border zone lies in western New Mexico along the eastern edge of the Colorado Plateau (Figure 2.4). The rift zone is 140 mi (230 km) from the site and will not have a significant effect on the seismic characterization of the site.

Western Mountains Province

The mountainous areas to the west of the Rio Grande Rift province form the Western Mountains Province of the Colorado Plateau (Figure 2.4). Included in this province are the San Juan Mountains, Elk and West Elk Mountains, west flank of the Sawatch Range, White River Uplift, and Gunnison Uplift. The Sawatch and White River Uplifts lack pre-Laramide expression, but their borders may be controlled, in part, by older basement faults (Tweto, 1980). Neogene faults are scarce in this province. Most faults expressing Neogene movement are associated with evaporite flowage or caldera collapse (Kirkham and Rogers, 1981). Despite the apparent absence of major Neogene faults, numerous earthquakes have been recorded within the province. The nearest approach to the site of this province is approximately 65 mi (110 km). The largest historical earthquake felt in the province was a magnitude 5.5 event near Montrose (Kirkham and Rogers, 1981). No major tectonic faults have been proven to have had Quaternary activity. Crustal thickness of the Southern Rocky Mountains region averages 28 to 31 mi (45 to 50 km) thick (Table 2.2). Earthquake focal depths have not been calculated from seismic events. Most faults have normal slip movement.

Review of seismic data for the Colorado Plateau

Epicentral compilation

An epicentral compilation for use in derivation of seismic parameters for the Colorado Plateau was obtained for this study from the NGDC/NOAA earthquake data file in 1985 and updated in 1989 by the data file for the nearby Dry Flats site near Naturita, Colorado (NGDC/NOAA, 1989).

Table 2.4 was derived from this list and represents all instrumentally located earthquakes within the Colorado Plateau (interior and border zones) of magnitude ≥ 4.0 since January 1, 1960. The list contains 70 events. Of these, 15 occurred either in the eastern Utah coal mining belt or in the oil and gas fields near Rangely, Colorado. These are considered to be artificially induced events caused by mining or oil and gas withdrawal (Smith and Sbar, 1974).

Table 2.4 Earthquakes of $M \geq 4.0$ since 1960 in the Colorado Plateau

Date			Time			Location		Depth	Magnitude				Intensity
yr	mo	da	hr	min	sec	lat(N)	long(W)	km	mb	ms	other	local	
1960	10	11	08	05	30.5	38.3	107.6				5.5		VI
1963	06	19	08	38	47.5	37.9	112.6	33	4.2				
1963	07	07	19	20	42.4	39.5	111.9		4.9				VI
1963	07	09	20	25	27.5	40.0	111.2	33	4.1				
1963	07	10	18	32	50.6	39.9	111.4		4.2				V
1963	09	02	17	40	15.4	39.6	110.1	33	4.1				
1963	09	11	11	59	41.0	33.2	110.7		4.2				
1964	06	06	12	46	59.9	39.4	110.2	30	4.2				
1965	01	18	20	08	14.4	37.4	113.1	33	4.0				IV
1965	03	21	22	56	39.7	39.5	110.3		4.0				IV
1965	03	26	00	51	24.5	39.5	110.3		4.3				V
1966	01	23	01	56	38.0	37.0	107.0	14	5.5				VII
1966	01	23	06	14	15.6	36.9	107.2	5	4.2				V
1966	01	23	07	44	35.7	36.9	107.3	5	4.6				
1966	01	25	10	38	05.0	36.8	107.1	5	4.0				

Table 2.4 Earthquakes of $M \geq 4.0$ since 1960 in the Colorado Plateau (Continued)

Date			Time			Location		Depth	Magnitude				Intensity
yr	mo	da	hr	min	sec	lat(N)	long(W)	km	mb	ms	other	local	
1966	01	23	11	01	07.1	36.9	107.2	Dulce, NM (RGR Border Zone)	5	4.3			V
1966	01	23	23	48	08.1	36.9	107.0	Dulce, NM (RGR Border Zone)	5	4.6			V
1966	01	23	19	43	19.7	36.9	107.1	Dulce, NM (RGR Border Zone)	5	4.5			V
1966	04	23	20	20	54.5	39.2	111.4	Wasatch Zone, Utah (IMSB Border Zone)	33	4.4			
1966	04	30	18	29	13.8	39.6	110.4	EUT Coal Mining Belt (Mining-Induced)	3	4.0			V
1966	05	04	05	40	37.5	36.8	107.1	Dulce, NM (RGR Border Zone)	5	4.1			
1966	05	08	17	23	37.8	36.9	106.9	Dulce, NM (RGR Border Zone)	5	4.5			V
1966	05	08	17	50	35.6	37.0	106.8	Dulce, NM (RGR Border Zone)	5	4.2			V
1966	05	09	02	08	53.5	36.9	106.9	Dulce, NM (RGR Border Zone)	5	4.2			V
1966	05	09	02	57	23.6	37.0	106.9	Dulce, NM (RGR Border Zone)	5	4.4			V
1966	05	19	00	26	42.2	36.9	107.0	Dulce, NM (RGR Border Zone)	5	4.6			
1966	05	20	13	40	48.8	37.9	112.1	SW Utah (IMSB Border Zone)	18	4.3			
1966	06	02	21	59	11.5	36.9	107.0	Dulce, NM (RGR Border Zone)	5	5.0			VI
1966	06	21	05	24	38.2	36.9	107.1	Dulce, NM (RGR Border Zone)	5	4.2			
1966	06	04	10	29	39.3	37.0	107.0	Dulce, NM (RGR Border Zone)	5	4.1			V
1966	07	06	05	47	08.3	40.2	108.9	Rangely, CO (Oil & gas withdrawal?)	5	5.4			V
1966	09	04	09	52	34.5	38.3	107.6	SW CO (Colorado Plateau/WMP Border Zone)	33	4.2			

Table 2.4 Earthquakes of $M \geq 4.0$ since 1960 in the Colorado Plateau (Continued)

Date			Time			Location		Depth		Magnitude				Intensity
yr	mo	da	hr	min	sec	lat(N)	long(W)	km	mb	ms	other	local		
1966	10	03	16	03	50.8	35.8	111.6	Coconino Co., AZ (AZ Border Zone)	33	4.4				V
1966	12	16	02	00	44.0	37.0	107.0	Dulce, NM (RGR Border Zone)	33	4.2				
1967	01	06	15	41	15.5	36.9	107.0	Dulce, NM (RGR Border Zone)	33	4.3				V
1967	01	12	03	52	06.2	39.0	107.5	SW CO (Colorado Plateau/ WMP Border Zone)	33	4.4				V
1967	01	16	09	22	45.9	37.7	107.9	Silverton, CO (WMP Border Zone)	33	4.1				V
1967	02	15	03	28	03.6	40.1	109.1	Rangely, CO (oil & gas withdrawal?)	5	4.5				V
1967	04	04	22	53	39.5	38.3	107.7	SW CO (Colorado Plateau/ WMP Border Zone)	33	4.5				V
1967	10	25	02	41	34.4	39.4	110.3	EUT Coal Mining Belt (Mining-Induced?)		4.0				V
1967	10	25	05	53	08.4	39.4	110.3	EUT Coal Mining Belt (Mining-Induced?)		4.0				V
1968	01	16	09	42	54.2	39.2	112.0	Wasatch Zone, Utah (IMSB Border Zone)	33	4.0				V
1968	08	04	06	23	36.4	39.1	111.4	Wasatch Zone, Utah (IMSB Border Zone)	15	4.0				V
1968	08	29	09	31	48.1	39.5	110.2	EUT Coal Mining Belt (Mining-Induced?)		4.2				V
1968	09	24	02	10	51.8	38.0	112.1	SW Utah (IMSB Border Zone)	33	4.0				V
1968	11	17	14	33	37.5	39.5	110.9	EUT Coal Mining Belt (Mining-Induced?)	6	4.6				V

Table 2.4 Earthquakes of $M \geq 4.0$ since 1960 in the Colorado Plateau (Continued)

Date			Time			Location		Depth		Magnitude				Intensity
yr	mo	da	hr	min	sec	lat(N)	long(W)	km	mb	ms	other	local		
1969	03	13	07	03	14.8	39.4	110.2	2	4.1					V
1969	05	23	05	24	53.6	39.0	111.8	31	4.0					V
1969	12	25	12	49	10.1	33.4	110.6	15	4.4			5.1		
1970	02	03 ^a	05	59	35.6	37.9	108.3	33	4.0					V
1970	04	14	10	40	54.2	39.7	110.8	13	4.2					
1970	04	18	10	42	11.9	37.8	111.6	10	4.4					
1970	04	21	08	53	52.4	40.1	108.9	4	4.3			3.9		V
1970	04	21	15	05	47.5	40.1	108.9	4	4.6					V
1970	05	23	22	55	22.4	38.0	112.3	3	4.6			4.9		
1970	10	25	07	46	42.1	39.2	111.4	5	4.3					V
1970	11	28	07	40	11.6	35.0	106.7	9	4.5					V
1971	01	04	07	39	06.7	35.0	106.7	9	4.7					
1971	01	07	20	39	52.1	39.4	107.3	33	4.3			3.8		
1973	07	16	06	36	42.8	39.1	111.5	10	4.2					

Table 2.4 Earthquakes of $M \geq 4.0$ since 1960 in the Colorado Plateau (Concluded)

Date			Time			Location		Depth	Magnitude				Intensity
yr	mo	da	hr	min	sec	lat(N)	long(W)	km	mb	ms	other	local	
1973	12	24	02	20	14.9	35.3	107.7	18	4.4				V
1975	01	30 ^a	14	48	40.3	39.2	108.6	5	4.4			3.7	
1975	10	06	15	50	46.9	39.0	111.4	5	4.2			3.2	II
1976	01	05	06	23	32.9	35.8	108.3	25	5.0			4.6	VI
1976	02	04	00	04	58.1	34.6	112.5	12	4.9		5.1	5.2	VI
1976	02	09	03	07	22.0	34.6	112.5	10	4.6			3.3	
1977	03	05	03	00	54.7	35.9	108.2	22	4.6			4.2	VI
1977	09	24	11	16	48.4	39.3	107.3	5	4.0			3.0	
1980	05	24	10	03	36.3	39.9	111.9	5	5.0			4.2	V
1981	05	14	05	11	04.1	39.4	111.0	1	4.0		4.0	3.5	V

^aColorado Plateau Interior.

REF. NGDC/NOAA, 1985.

They were not included in the subsequent analysis. Only two of 55 events occurred within the stable interior portion of the Plateau as defined for this study. These include events of magnitude (m_b) 4.0 in the Paradox Basin on February 3, 1970, and 4.4 near Grand Junction, Colorado, on January 30, 1975. The data indicate that 4 percent of the seismicity of the Colorado Plateau occurs in the stable interior. Those events that do occur appear to be associated with tectonically unique structures such as the Uncompahgre Uplift and Paradox Basin.

The remaining 53 events, representing 96 percent of the data, occurred in the border zones. Twenty-three events occurred in the Rio Grande Rift border zone, and of these, 18 were associated with the swarm of events near Dulce, New Mexico, from January 1966 to January 1967. Eighteen of the events are associated with the border zone of the Colorado Plateau and the Intermountain Seismic Belt in Utah and northern Arizona. Most of these events occurred along the Wasatch frontal fault system. Seven events occurred in the border zone between the Colorado Plateau and the Western Mountain Province. These include the event of October 11, 1960, of magnitude 5.5 near Montrose, Colorado. The remaining five events occurred in the Arizona Border Zone and include several events of magnitude (m_b) 5.5 to 5.75 in the Flagstaff area.

Graphical determination of ME

The data were plotted (see Figure 2.7) to determine the ME value for the Colorado Plateau. Obviously, due to the scarcity of data for the Colorado Plateau Interior, the data are representative of the border zones. The data show that there is no basis for any determination of the ME value for the interior from the instrumental seismic record. The historical record is also extremely limited and is most likely less reliable. The scarcity of recorded earthquakes of magnitude 5.0 and greater also limits the reliability of the ME determination for the border zones. The true ME value may lie anywhere within the range of 6.2 to 6.8. The average value of this range (magnitude 6.5) is a reasonably conservative value. This value is recommended as the ME value for the Colorado Plateau interior and border zones together. This value is also the value adopted by Kirkham and Rogers (1981) as the ME for the Colorado Plateau.

The data do not permit any estimate of the recurrence interval for the ME event within the interior province; however, it may be on the order of tens to hundreds of thousands of years. For the border zones, a reasonable estimate can be made on the basis of the historical record. Assuming the record for moderate to large earthquakes to be complete since 1900, the data base covers a period since that time. This value represents an absolute minimum recurrence interval for the border zones. If it is assumed, conservatively, that one magnitude 6.5 earthquake occurs every 85 years within the approximately 164,000-mi² (425,000-km²) area of the Colorado Plateau (interior and border zones), the probability of the occurrence of a magnitude 6.5 event within any 9-mi (15-km) radius within the region is 0.06×10^{-4} . The recurrence interval of an ME earthquake within any 9-mi (15-km) radius area is thus 51,106 years.

FIGURE 2.7
GRAPHICAL DETERMINATION OF ME MAGNITUDE
COLORADO PLATEAU INTERIOR AND BORDER ZONES

A graphical determination of the recurrence interval of the ME within the entire Colorado Plateau interior and border zone is represented in Figure 2.8. The results indicate a recurrence probability of 0.0019 ME events per year, or a recurrence interval of 526 years.

Determination of an floating earthquake magnitude

The definition of an FE adopted for use in UMTRA Project seismic hazard evaluations is "an earthquake within a specific seismotectonic province which is not associated with a known tectonic structure." It is important to distinguish between the terms ME and FE. The ME magnitude should be larger than the FE magnitude because large earthquakes are generally associated with ground breakage on known tectonic structures. The FE magnitude should never be greater than the ME.

The maximum magnitude of the FE should therefore be equal to the threshold magnitude at which ground breakage will occur. It is generally agreed that the threshold magnitude is 6.2 and that the distance of the FE from a site is assumed to be 9.3 mi (15 km). These assumptions were adopted by the TAD (DOE, 1989). The FE for the Colorado Plateau is selected as the 6.2 threshold earthquake which will have a resultant 0.21 g PHA based on a 9.3-mi (15-km) site radius (Campbell, 1981).

Effect of maximum earthquakes on other regional seismotectonic features

Remote seismotectonic provinces bordering the Colorado Plateau Province include the Western Mountain Province, at a distance of 62 mi (100 km); the Intermountain Seismic Belt, at a distance of 124 mi (200 km); the Wyoming Basin, at a distance of 186 mi (300 km); and the Rio Grande Rift, at a distance of 155 mi (250 km).

Based on the distance-attenuation relationship of Campbell (1981), a maximum earthquake of magnitude 8.2 at a distance of 65 km would result in a PHA at the site that would be less than for the FE for the region. Therefore, remote seismic source regions in excess of 65 km are not significant to the seismic stability analysis.

Western Mountain Province

Earthquake epicentral maps of the Colorado Plateau region show a heightened level of seismic activity possibly coinciding with the border zone along the contact with the Western Mountain Province, which is located roughly within 62 mi (100 km) of the sites. The ME magnitude for the Colorado Plateau, according to Kirkham and Rogers (1981), is 5.5 to 6.5, and for the Western Mountain Province is 6.5. Therefore, the ME associated with the border zone of the two provinces is assumed herein to have a magnitude of 6.5.

FIGURE 2.8
GRAPHICAL DETERMINATION OF RECURRENCE INTERVALS FOR
FLOATING EARTHQUAKE (FE) AND MAXIMUM EARTHQUAKE (ME),
COLORADO PLATEAU INTERIOR AND BORDER

The maximum horizontal acceleration in rock expected at the site area, from a possible ME event having a magnitude of 6.5, occurring within 65 km of the sites area, is 0.03 g, as detailed in Table 2.5.

Table 2.5 Estimated maximum peak horizontal ground acceleration at the site area from MEs on regional seismotectonic features

Source area	Maximum earthquake magnitude	Approximate distance from site area	Maximum free-field, nonamplified peak horizontal ground acceleration ^b expected at site area (fraction of unit gravity)
Paradox Basin	5.5 ^c	9.3 mi (15 km)	0.11
Intermountain Seismic Belt	7.0-7.5	137 mi (220 km)	0.02
Rio Grande Rift	6.5-7.5	155 mi (249 km)	0.02
Wyoming Basin	5.7-6.5	186 mi (299 km)	0.005
Colorado Plateau/Western Mountain Province Transition Zone	6.5	62 mi (100 km)	0.03

^aSee text for explanation of values assumed.

^bCalculated from acceleration/attenuation relationship of Campbell (1981).

^cCalculated from fault rupture area/magnitude relationship of Woodward-Clyde (W-C, 1982b).

Paradox Basin salt collapse structures

Major structural features within the Paradox Basin of concern to site design parameters consist of faulted salt anticline crests. Faults formed during collapse of the anticline crest during flowage of the salt cores are not tectonic features (Cater, 1970). Movement along these failure surfaces proceeds more as a gradual creep than sudden slip.

Wong (1984) listed 22 earthquake events within the Paradox Basin for the period 1853 to 1979. A program of microearthquake monitoring from 1979 to 1982 recorded 316 microearthquakes of magnitude (M_L) zero to 2.4 (Wong, 1984). Most of these events were associated with mine blasting or Colorado River-induced seismicity. The largest magnitude event occurred near Moab, Utah, and was a magnitude (M_b) of 3.8 (Wong, 1984).

2.5 MINERAL RESOURCES

Known economic mineral resources in the area are limited to uranium and vanadium ores and oil and gas deposits. The area has been extensively mined for uranium-vanadium deposits, but economically significant ore bodies are still present in the area. Oil and gas are produced from structural traps within the Paradox and Libson Valleys and other carbonate units within the salt anticline region of western Colorado and eastern Utah. Figures 2.9 and 2.10 show the location of resource development in the region (W-C, 1983).

Uranium-vanadium ore deposits in the Slick Rock district and the Uravan mineral belt occur mainly in the thick sandstone deposits of the Salt Wash Member of the Morrison Formation (Shawe et al., 1959). The upper sandstone in the Slick Rock area contains the majority of the ore deposits; however, small localized deposits also occur in the lower sandstones and mudstones as well as in the coarse conglomeratic sandstones of the lower part of the overlying Brushy Basin Member (Chenoweth, 1981). Both of these units crop out extensively in the area and have been mined since the early 1900s. Uranium-vanadium mines in the area of the sites are no longer operating. The nearest mine to the sites is the Burro Canyon mine, formerly operated by Umetco (Umetco, 1990). Figure 2.10 shows the area of underground workings and mining claims relative to the site. The nearest approach to the site is the mine vent 2300 ft (700 m) to the southwest. The mine was abandoned in 1983 (Umetco, 1990). Based on the elevations of the ore zone in the nearest exploratory hole logged by Umetco, this zone would be approximately 910 ft (280 m) below the site. The ore zone typically is in discontinuous lenses and pockets from 0.5 to 2.0 ft (0.2 to 0.6 m) thick. Occasionally there may be two zones up to 75 ft (23 m) apart (Umetco, 1990). Potential for future mining activity in the Slick Rock-Uravan mining district is dependent on uranium prices. A renewed market for uranium ores could stimulate new exploration and development for these deposits in the area.

Extensive oil and gas resources have been developed in the salt anticline region surrounding the Slick Rock area. Most production has been in the Paradox Basin, north of the Libson Basin in Utah and northwest of the site (Wiegand, 1981). Oil and gas occur in structural traps associated with Late Paleozoic salt-cored anticlines. Extensive undeveloped oil and gas deposits are believed to exist in the Paradox Basin area (Krivanek, 1981) and in the Egnar-Gypsum Valley area (Stokes and Phoenix, 1948). No known economic oil or gas deposits occur in the area of the Burro Canyon site, although exploration has occurred adjacent to the site. The mine vent shown on Figure 2.10 is erroneously shown on U.S. Geological Survey (USGS) topographic maps as an "oil" or "gas well."

Thin coal seams and carbonaceous shale occasionally are present in the Dakota Sandstone Formation but do not underlie the site. These deposits are impure and discontinuous and do not contain economically important coal reserves.

FIGURE 2.9
AREAS OF MINERAL RESOURCE DEVELOPMENT IN
BURRO CANYON SITE REGION, COLORADO

Although very minor amounts of metallic minerals occur with the uranium-vanadium ores, their low concentration precludes economic development (Shawe et al., 1959). No known potential for development of geothermal heat exists in the area of the sites.

3.0 SITE GEOLOGY

General geologic setting

The Burro Canyon site is named after nearby Burro Canyon, a steep-walled tributary canyon to the Dolores River Canyon. The Burro Canyon Formation was also named after the exposure of this strata in the canyon. The formation at this location, however, is different than in most other outcrops in the region and its lithologic occurrence is not useful as a type section (Shawe et al., 1968).

The site is near the axis of the Disappointment syncline at the northwest end of Disappointment Valley. The synclinal axis plunges southeast toward the center of the valley. The Mancos Shale Formation of Cretaceous age, the youngest bedrock in the region, is exposed on the surface in the lower part of the valley, but is completely eroded from higher elevations including the site area. The resistant Dakota Sandstone forms the cap rock around the perimeter of the synclinal valley (Figures 3.1 and 3.2).

The nearby Dolores River is a meandering stream, which was established on the soft rocks of the thick Mancos Shale or perhaps on overlying poorly consolidated Tertiary sediments. During regional uplift and folding, the stream was superimposed and entrenched across the folded belt without noticeable structural or stratigraphic controls. Because of the erosional resistance of various sandstone strata, all other topographic features in the area strongly reflect the structure of the Dolores anticline and the Disappointment syncline.

3.1 BEDROCK GEOLOGY

A map of the bedrock in the Burro Canyon area is shown in Figures 3.1 and 3.2. Cross sections of the stratigraphy below the site are shown on Figures 3.3, 3.4, 3.5, and 3.6. The full stratigraphic section is shown in Figure 2.3 and described in Table 2.1.

The lowest unit of the Dakota Sandstone Formation forms the foundation for the site. This lower unit is a black carbonaceous shale and mudstone that contains two persistent thin sandstone layers. Shawe et al. (1968) observe that locally this layer is in conformable contact with the uppermost unit of the Burro Canyon Formation. The carbonaceous shale underlies the main sandstone unit of the Dakota and is exposed on the eastern edge of the site, where it is moderately to severely weathered. The shale appears suitable for clean fill borrow material and offers a potential for geochemical attenuation of contaminant constituents. Locally, some lateral facies change from black shale to greenish-brown mudstone in the lower part of this unit.

The main sandstone unit (Kd3) forms the upper part of the formation and occurs as eroded outcrops on the ridge at the southeast side of the disposal site and along the north edge of the mesa. Its maximum thickness on the ridge is about 16 ft (4.9 m).

(MAP QUADRANT LOCATION: T44N, R18W)

LEGEND

MODIFIED FROM: SHAWE et al., 1968.

QUATERNARY

ALLUVIUM

LANDSLIDE

TERRACE GRAVEL

CRETACEOUS

MANCOS SHALE

DAKOTA SANDSTONE

BURRO CANYON FORMATION

JURASSIC

BRUSHY BASIN MEMBER, MORRISON FM.

SALT WASH MEMBER, MORRISON FM.

SUMMERVILLE FORMATION

ENTRADA FORMATION

JURASSIC-TRIASSIC

NAVAJO SANDSTONE

FAULT (DASH WHERE INFERRED)

STRIKE AND DIP

NORTH CONTINENT TAILINGS

UNION CARBIDE TAILINGS

2000 0 2000 4000 FEET

500 0 500 1000 METERS

FIGURE 3.1
SITE GEOLOGIC MAP, BURRO CANYON SITE, COLORADO

FIGURE 3.2
GEOLOGY AND TOPOGRAPHY OF BURRO CANYON DISPOSAL SITE

- NOTES: 1. HOLE #515 IS A COREHOLE.
2. ELEVATIONS ARE GIVEN IN FEET. TO CONVERT FROM FEET TO METERS, MULTIPLY FEET BY 0.3048.
3. SEE FIGURE 3.2 FOR CROSS SECTION LOCATION.

FIGURE 3.3
GEOLOGIC CROSS SECTION A - A'
AT THE BURRO CANYON DISPOSAL SITE, SLICK ROCK, COLORADO

LEGEND

BENTONITE SEAL INDICATES TOP OF SAND PACK FOR WELL AS REFERENCE FOR WATER LEVEL

PACKER TEST INTERVAL WITH PERMEABILITY DETERMINATION (CM/S)

K_d

DAKOTA SANDSTONE FORMATION

CONTACT

K_{bc}

BURRO CANYON FORMATION

100 0 200 FEET

50 0 50 100 METERS

NOTES: 1. ELEVATIONS ARE GIVEN IN FEET, TO CONVERT FROM FEET TO METERS, MULTIPLY FEET BY 0.3048.

2. SEE FIGURE 3.2 FOR CROSS SECTION LOCATION.

FIGURE 3.4
GEOLOGIC CROSS SECTION B-B'
AT THE BURRO CANYON DISPOSAL SITE, SLICK ROCK, COLORADO

- NOTES: 1. HOLE #515 IS A COREHOLE.
2. ELEVATIONS ARE GIVEN IN FEET. TO CONVERT FROM FEET TO METERS, MULTIPLY FEET BY 0.3048.
3. SEE FIGURE 3.2 FOR CROSS SECTION LOCATION.

LEGEND

BENTONITE SEAL INDICATES TOP OF SAND PACK FOR WELL AS REFERENCE FOR WATER LEVEL

PACKER TEST INTERVAL WITH PERMEABILITY DETERMINATION (CM/S)

Kd

DAKOTA SANDSTONE FORMATION

—

CONTACT, Kd - Kbc

Kbc

BURRO CANYON FORMATION

FIGURE 3.5
GEOLOGIC CROSS SECTION C-C'
AT THE BURRO CANYON DISPOSAL SITE, SLICK ROCK, COLORADO

FIGURE 3.6
GEOLOGIC CROSS SECTION D-D'
AT THE BURRO CANYON DISPOSAL SITE, SLICK ROCK, COLORADO

The two thin sandstone layers (Kd2 and Kd1) of this lower unit of the Dakota Sandstone and the underlying silicified claystone of the Burro Canyon Formation at the upper contact form the resistant rim rock of the small mesa on which the site is located. The thin sandstone strata vary from 1 to 6 ft (0.3 to 2 m) thick and the resistant silicified mudstone of the Burro Canyon contact zone is typically 2 ft (0.6 m) thick. These thin Dakota Sandstone units occur in the upper 5 to 10 ft (2 to 3 m) of the mesa surface and the upper (Kd2) unit was excavatable in most cases with a small backhoe.

The claystone of the Burro Canyon Formation is gray-green to blue-green in contrast to the drab yellow, browns, and dark gray of the Dakota Formation. In the steep slopes of the north and east sides of the mesa, the silicified contact bed of the Burro Canyon Formation appears distinctive in its color and strong resistance to undercutting erosion. In some areas below the site, however, the contact appears to be more gradational and less defined in borehole data.

Shawe et al. (1968) report that the top of the Burro Canyon is called a marker bed in this area because of its conspicuous outcrop and lateral persistence. That study describes it as a light greenish-gray stratum, 1 to 3 ft (0.3 to 1 m) thick, appearing to be a silicified silty claystone, and in places is chert-like. The rock contains numerous calcite crystals 1 mm in size, and contains kaolinite. This nonswelling clay differs from the bentonitic clay that characterizes the underlying Brushy Basin Member of the Morrison Formation (Shawe et al., 1968).

The upper 60 ft (18 m) of the Burro Canyon Formation and the lower 40 ft (12 m) of the Dakota Formation are exposed continuously around the north face of the mesa in the tributary of Nicholas Wash. The exposure shows the very gentle dip and the unfaulted structure of the mesa.

The upper claystone/mudstone unit of Burro Canyon ranges from 50 to 65 ft (15 to 20 m) thick. Packer test permeability determinations (shown in cross section in Figures 3.3 through 3.5) and core analysis indicate that this hydrologically confining unit is only moderately weathered with few fractures and is essentially impermeable in the lower two-thirds of the claystone unit. The assessment of this important unit is discussed in Attachment 3, *Ground water Hydrology Report*.

There are three sandstone/conglomerate units within the Burro Canyon Formation, whose tops are at roughly approximate depths below the site of 100, 200, and 300 ft (30, 60, and 90 m). The upper sandstone unit contains a partially saturated, low-yield water table, whereas the middle and lower units are fully confined artesian aquifers. Details of these units are discussed in Attachment 3. Shawe et al. (1968) report that in some areas of Disappointment Valley there are as many as six distinct sandstone units within the Burro Canyon. The intervals between the sandstone consist of strata of claystone and mudstone. The upper part of the formation contains thin, interbedded limestone and both silica and calcite cement occur in the sandstone

units. The silica cementation of the sandstone in some cases has altered it to quartzite (Shawe, 1968).

Burro Canyon Formation below the site is 400 ft (120 m) thick based on logs of on-site coreholes. Shawe et al. (1968) report that this location has one of the thickest sections in the region and gives a combined thickness of the Burro Canyon and the Brushy Basin Member of the Morrison Formation as 850 to 900 ft (260 to 270 m). This thickness is significant, because it marks the relative depth of the uppermost uranium-vanadium ore zone at the top of the Salt Wash Member of the Morrison Formation.

The upper and lower portions of the Morrison Formation are composed, respectively, of the Brushy Basin and the Salt Wash Members. The Brushy Basin Member consists mostly of thick units of mudstone interbedded with thin discontinuous sandstone units. The bentonitic clays in this formation form unstable slopes in the oversteepened river valley (Shawe et al., 1968).

The upper zone of the Salt Wash Member is the primary uranium-vanadium ore producing strata in this region; it outcrops along the Dolores River floodplain near the Slick Rock, Colorado, post office. Umetco (1990) reports that ore values in the exploration coreholes for the Burro Canyon mine approximately 0.5 mi (0.8 km) west of the site occur only within this zone (Figure 2.10).

Bedrock structure

Figure 2.5 shows the structure of the Disappointment syncline and the relationship to the salt core anticline within Paradox Basin. Based on strikes and dips shown on the map on Figure 3.2, the beds dip approximately 2 to 3 percent (1 degree) to the southeast below the site. The ground water flow gradient for each of the three sandstone units in the Burro Canyon Formation flows at slightly different southerly directions (see Attachment 4).

3.2 SURFICIAL GEOLOGY

Several drill holes and 20 test pits in the disposal site area indicate the soils consist of reddish-brown, sandy clay to clayey sand with thicknesses ranging from 0 to 1.5 ft (0.5 m) at the perimeter of the mesa top, to 3 to 4.5 ft (1 to 1.4 m) thick in the middle of the site. In most instances, the soil was found to be directly underlain by a thin sandstone stratum. In a few locations, the soil was underlain by a dark-gray, carbonaceous shale/claystone.

Figure 3.7 shows the surficial geology map of the site area; Figure 3.2 shows the resistant rocks that outcrop on the site. The area north of the site is deeply incised by tributaries of the Nicholas Wash and contains only thin Quaternary deposits within the confines of active drainages (Figures 3.7 and 3.8).

ALLUVIAL SILTS SAND AND GRAVEL IN ACTIVE DRAINAGE

ALLUVIUM AND COLLUVIUM DEPOSITS INCLUDING SHEET WASH DEPOSITS GREATER THAN 1 FT (0.3M) THICK

DAKOTA SANDSTONE FORMATION

BURRO CANYON FORMATION

FIGURE 3.7
SURFICIAL GEOLOGY
BURRO CANYON SITE AREA

LEGEND

- DRAINAGE DIVIDE
- - - DRAINAGE

FIGURE 3.8
DRAINAGE SYSTEMS
BURRO CANYON SITE AREA
SLICK ROCK, COLORADO

3.3 GEOMORPHOLOGY

The small mesa on which the site is located is isolated from upland runoff. Figure 3.8 shows the site basin relative to adjacent basin and drainage systems. The drainage north and east of the site is the Nicholas Wash Basin, trending along the axis of the Disappointment Valley. The site and basins south of the site drain into the Joe Davis Canyon. The site has two shallow drainages through the mesa center that drain by sheet flow until reaching the south edge of the mesa; there the flow concentrates into a well-defined gully where it incises the rim (Figure 3.2). The rim of the mesa on the west and north sides is also the drainage divide.

The soil-covered mesa top has a moderate cover of grass. Scattered juniper trees occur at the rim where sandstone outcrops. The average slope of the basin is approximately 0.033 feet per foot (ft/ft). The slopes below the rim of the mesa range from 0.145 ft/ft on the north slope, 0.118 ft/ft on the west slope, and 0.20 ft/ft on the south slope. Where the drainage exits the mesa on the south slope, the channel slope is 0.100 ft/ft (Figures 3.2, 3.7, and 3.8). Sandstone bedrock is exposed in this drainage, which is also armored with detritus of sandstone fragments. The rate of erosion in the channel is low, with no active gullies. Should the toe of the cell overlap the edge of the mesa, an engineering design will be required to stabilize the slopes. The steeper slopes below the rim of the mesa on the south and southwest sides are covered with a thin veneer of colluvium composed mostly of detritus from weathering of the two thin sandstone strata. Sandstone fragments from a few inches to slabs several feet across form a natural armor on the slopes, particularly at the head of minor gullies. The armor sustains a thin soil development and vegetation growth. Except for the outcrop of the sandstone, there are few bedrock exposures on the upper slopes.

The controlling influence in the development of geomorphic features at the site is the differential erosion of the claystone and shale units above and below the resistant rimrock contact strata of the Burro Canyon and Dakota Formations. The erosion of most of the 60-ft (20-m) thick claystone and mudstone of the upper Burro Canyon creates the relief of the mesa on which the site is located.

The upper sandstone unit of the Burro Canyon Formation is a silica-cemented quartzite that forms the floor of the broad valley west of the site. This unit also forms the bottom of the Nicholas Wash tributary drainage just north of the site.

The western slope below the edge of the mesa has the least thickness of sandstone rimrock. At the southeast corner of the mesa top, the upper of the two thin sandstone strata is missing from a 1-acre (0.4-ha) area (Figure 3.2). On the north, east, and southeast edges of the site, the remnants of the main (Kd3) sandstone unit of the Dakota Sandstone (up to 16 ft [4.9m] thick in the southeast ridge) provide stability to the edges of the mesa and stabilize the slopes of the deep arroyo formed by incision of the west fork tributary of Nicholas Wash (Figures 3.3 through 3.8).

The Dakota Sandstone Formation is missing from most of the area north of the Nicholas Wash tributary bordering the site. Similar small mesa tops in that area show that the silicified upper contact bed of the Burro Canyon Formation is resistant to gully formation (see Figures 3.1 and 3.6).

The nonswelling type of clay and the silica-altered cementation that characterizes the mineralogy of the Burro Canyon Formation (Shawe, 1968; Shawe et al., 1968) gives the mudstone a resistance to erosion that is significantly greater than that for similar claystone-mudstone units in the Mancos Shale, Dakota Sandstone, or Morrison Formations exposed in the area.

4.0 GEOLOGIC STABILITY

4.1 GEOMORPHIC STABILITY

The principal geomorphic processes in the site area are scarp retreat, reentrant penetration of tributaries into the bedrock mesa, and surficial erosion of soils. The rim of the site mesa, which also marks the drainage divide between the mesa top and sideslopes, has exposed bedrock around most of the full perimeter of the site (Figure 3.2). With no erosion potential from overland flow, the age of the mesa scarp is based on the rate of scarp retreat for the region. The age can be ascertained only in relative terms because retreat is dependent on the resistance of the outcropping formation. With rates presented in Section 2.1 ranging from 0.8 to 1.8 ft (0.2 to 0.55 m)/1000 years for some studies (Schumm and Chorley, 1966; and Haman, 1983) to 74 ft (23 m)/1000 years in another study (Hunt, 1969), it can be concluded that retreat has been in the lower range of these rates and the site has been geomorphically stable for the last 1000 years.

Potential hazards for the long-term stability of the site are 1) the headcutting of the tributary below the site in the event that the cell might extend southward beyond the physical protection of the rimrock, and 2) the diversion of runoff from the cell cover over the edges of the mesa rim will expose the lower slopes to concentrated flow. The 100-ft (30-m) setback zone around the perimeter will require protection of the integrity of the cap rock with drainage control channels and stabilized aprons above and below the rimrock.

Flooding is not a concern, based on the 80-ft (25-m) height of the mesa above the north side tributary system of Nicholas Wash.

4.2 SEISMOTECTONIC STABILITY

Technical approach

The objectives of the seismic hazard analysis performed for this study are as follows:

- Select the design earthquake and estimate the on-site PHA for use in subsequent engineering analysis.
- Recognize any potential for on-site fault rupture.
- Recognize any potential for earthquake-induced landsliding or subsidence due to tectonic causes.

The technical analysis performed for this study involved a critical review of all the information developed during the investigation and a step-by-step approach to estimating seismic risk.

The first step was the determination of the magnitude of the FE in the seismotectonic province within which the site is located. This earthquake was then assumed to occur at a radial distance of 9 mi (20 km) from the site, and the resulting on-site acceleration was calculated using the acceleration/attenuation relationship of Campbell (1981) as discussed in the TAD (DOE, 1989).

Following the above analysis, the maximum on-site acceleration resulting from maximum magnitude earthquakes occurring in each of the remote seismotectonic provinces within the region of interest was determined. Individual faults within remote provinces were not analyzed, unless they lay within a radius of 65 km of the site. In a conservative approach, the closest remote province from the sites was measured first. The measurement was made using published maps and literature to delineate province boundaries. The estimated ME values for the remote provinces were based on published studies and personal communications from active researchers in the area. The ME earthquake was then assumed to occur at the closest approach of each remote province to the sites, and the resulting on-site acceleration was calculated.

After completion of the first two steps in the analysis, the on-site accelerations resulting from the FE within the province containing the sites were compared with the MEs at the closest approaches to each of the remote provinces. The largest value was taken as the critical acceleration during the subsequent capable fault analysis.

Based on the review of published and unpublished geologic data and the air-photo analysis, all mapped faults and air-photo lineaments within a radial distance of 65 km of the site were compiled. For faults of tectonic origin, the fault length/magnitude relationships of Bonilla et al. (1984) were used to determine the ME that each structure would produce if it were determined to be a capable fault. An on-site acceleration resulting from each fault was then calculated. These values were then compared to the critical acceleration determined during the previous analysis. Any features potentially capable of producing a larger on-site acceleration than the critical value were subjected to a detailed field investigation to determine if they were capable faults.

The capable fault investigation consisted of the analysis of the seismic record for evidence of micro- and macroseismicity associated with the fault, close inspection of the mapped fault trace on aerial photography, detailed ground reconnaissance for evidence of Late Quaternary or Holocene movements, and careful investigation of the indicated fault during the LSA aerial reconnaissance.

If any evidence indicated that a fault (or faults) is capable, the largest calculated on-site acceleration was recommended as the design acceleration value. The fault was designated as the controlling fault and the ME on that fault was specified as the design earthquake.

Previous studies

Several probabilistic earthquake maps, which plot contours of maximum horizontal accelerations, velocities, and intensities for various return periods, have been prepared for the contiguous United States. Examples of such studies are those by Liu and DeCapua (1975), Algermissen and Perkins (1976), the Applied Technology Council (ATC) (1978), and Algermissen et al. (1982). These studies were used to estimate the maximum value of each parameter for the site area. The resulting values are listed in Table 2.3.

Accelerations calculated in these previous studies are uniformly lower than the maximum values derived from this study. Previous studies are probabilistic analyses based on the rather brief historical record.

Fault and epicentral compilation

A compilation of all mapped faults and earthquake epicenters within 40 mi (65 km) of the sites is shown in Plate 2.1 of this document. In addition, all suspected faults and lineaments derived from aerial photographic interpretation were compiled. All faults and lineaments were observed at least once during the LSA aerial reconnaissance. Most features within 12 mi (20 km) of the site were field-checked during the ground reconnaissance phase of the study. Other features of regional significance outside this 12-mi (19-km) radius were also field-checked.

The majority of the faults within a 65-km radius of the site are associated with collapsed salt-cored anticlines. Faults resulting from collapse of the anticline crests are not considered tectonically active. Slow creep may be occurring on some of these faults as subsurface evaporite bodies continue to be removed by solutioning. Faults within the salt anticline region identified by Kirkham and Rogers (1981) as potentially active are associated with the collapse of anticline crests.

Fault swarms along the southwest side of the Uncompahgre Plateau lie within the northeast part of the 65-km radius of the site (Plate 2.1). The Uncompahgre Uplift may be an active seismotectonic feature. Geologic and geomorphic evidence indicates that the uplift has been a recurrently active feature since Late Paleozoic time, and may have experienced considerable uplift since Late Pliocene time (Cater, 1966; Sinnock, 1981b; Kirkham and Rogers, 1981). Many faults were identified as potentially capable by Kirkham and Rogers (1981). Regional seismic trends (Figure 2.6) also indicate the uplift has been the focus of a low-to-moderate level of seismicity during historical time. Ely et al. (1986) have associated a magnitude 2.9 earthquake with one of the faults in the uplift.

The most conservative approach is to consider all faults in the uplifts are capable.

All faults and linear features observed during the study are briefly discussed in Table 4.1 and shown in Plate 2.1. Faults for which the estimated on-site acceleration (resulting from the estimated ME) approached or exceeded the acceleration of 0.21 g (resulting from FE) were subjected to critical analysis. Fault segments with reported or suspected Quaternary movement were examined in the field.

These include fault groups numbered 1, 1A, 7, 9, and 10 (see Table 4.2). The faults initially determined to be the most critical for design potential are those of the 1A group and fault groups 1 and 9. Fault groups 2 and 3 are discussed because probable Quaternary movement has occurred along segments of their surface traces. Fault groups 8 and 11 are related to uplift of the Uncompahgre Plateau and may be capable, but do not have on-site accelerations in excess of the design value.

Fault group 1. This fault zone is mapped as parallel faults segments trending along the crest of the Lisbon Valley salt-cored anticline (Williams, 1964). Major valley-bounding faults extend to within 15 mi (24 km) of the site. Shorter bedrock faults of the southeast end of the valley extend to within about 0.6 mi (1 km) of the site. All faults are related to the collapse of the anticline crest following solutioning and removal of subsurface evaporite bodies. The Lisbon Valley-Moab fault zone probably experienced northeast-side-down displacement during the Pliocene and possibly Quaternary (W-C, 1982a). Earthquake monitoring (W-C, 1982a) in the vicinity of the Lisbon fault has detected no microearthquakes with magnitudes greater than $M_L = 1.0$. The absence of microearthquake activity, however, does not necessarily indicate that the structure is inactive. LSA reconnaissance over the structure showed no visible evidence of Quaternary displacement in the valley fill deposits. Detailed field inspection also revealed no surface evidence of Quaternary fault displacement. The absence of Quaternary fault activity has not been conclusively proven through geological techniques such as trenching. The fault is considered not tectonically capable. Any movement along salt anticline collapse fault surfaces would likely occur by slow creep, as previously discussed. Sudden fault shear activity along the entire length of the fault zone is not consistent with the geologic evidence of past fault movement.

Fault group 1A. Faults in group 1A are mapped on the Horse Range Mesa 7.5-minute geologic quadrangle map (Cater, 1955). Mapped faults up to 3 mi (5 km) long occur within about 4 mi (6 km) of the site area. All faults lengths within this group have estimated on-site accelerations greater than the design acceleration of 0.21 g. The faults appear to be related to the formation and collapse of the Lisbon Valley salt-cored anticline to the northwest and are nontectonic. LSA reconnaissance and ground inspection revealed no offset of Quaternary units. No faults in rock units younger than Cretaceous age were located. These faults are considered not capable.

Table 4.1 Summary of analysis of mapped faults and lineaments within a 65-km radius of the Burro Canyon site, Colorado

	Fault/lineament	Source	Length mi (km)	Distance from site mi (km)	Estimated ME ^a	Estimated on-site acceleration ^b	Comments
1.	Lisbon Valley	Williams, 1964); W-C, (1982a)	6 (10)	15 (24)	5.3 ^c	0.06g	Not potential design fault. Faulting related to salt anticline collapse. Not tectonically capable.
1A.	Summit Canyon faults	Cater, (1955a)	1.2-3.1 (1.9-4.9)	2 (3.2)	5.1 (max.)	0.33g (max.)	Not potential design faults. No Quaternary movement. Not capable.
2.	Verdure graben	Haynes et al. (1972); W-C, (1982a)	33 (53)	22 (35)	7.3	0.20g	Not potential design fault. May have minor Quaternary movement. May be capable.
3.	Shay graben	Williams, 1964); Haynes et al. (1972); W-C, (1982a)	25 (40)	23 (37)	7.2	0.18g	Not potential design fault. Has probable minor Quaternary movement. May be capable.
4.	Spanish Valley	Williams, 1964); W-C, (1982a)	6 (10)	33 (53)	5.3 ^c	0.02g	Not potential design fault. May have minor Quaternary movement related to salt anticline collapse. Not tectonically capable.
5.	Sinbad Valley	Williams, 1964);	7 (11)	27 (43)	5.3 ^c	0.03g	Not potential design fault. Faulting related to salt anticline collapse. Does not appear tectonically capable.
6.	Unnamed	Williams, 1964);	3 (4.8)	24 (39)	6.5	0.10g	Not potential design fault.
7.	Paradox Valley	Williams, 1964); W-C, (1982a)	16 (26)	13 (21)	5.6 ^c	0.09g	Not potential design fault. Faulting related to salt anticline collapse. Does not appear tectonically capable.

Table 4.1 Summary of analysis of mapped faults and lineaments within a 65-km radius of the Burro Canyon site, Colorado (concluded)

	Fault/lineament	Source	Length mi (km)	Distance from site mi (km)	Estimated ME ^a	Estimated on-site acceleration ^b	Comments
8.	Uncompahgre Uplift	Williams, (1964)	22 (35)	32 (51)	7.2	0.13g	Not potential design fault. May be capable.
9.	Big Gypsum Valley	Williams, (1964)	23 (37)	3 (4.8)	5.7 ^c	0.35g	Not potential design fault. Faulting related to salt anticline collapse. Does not appear tectonically capable.
10.	Unnamed	Haynes et al. (1972)	12 (19)	16 (21)	5.5 ^c	0.08g	Not potential design fault. Most faults related to collapse of salt structures. Does not appear tectonically capable.
11.	Uncompahgre Uplift	Williams, (1964)	29 (47)	30 (48)	7.2	0.13g	Not potential design fault. May be capable.
12.	Unnamed	Haynes et al. (1972)	14 (23)	37 (60)	7.0	0.09g	Not potential design fault.
13.	Unnamed	Williams, (1964)	16 (26)	31 (50)	7.0	0.12g	Not potential design fault. Related to diorite and andesite intrusive body.
14.	Unnamed	Haynes et al. (1972); Williams, (1964)	8 (13)	35 (56)	6.8	0.07g	Not potential design fault.
15.	Unnamed	Williams, (1964)	9 (14)	25 (40)	6.9	0.13g	Not potential design fault.

^aUsing fault length/magnitude relationship of Bonilla et al. (1984).

^bUsing acceleration/attenuation relationship of Campbell (1981).

^cUsing fault rupture area/magnitude relationship of Woodward-Clyde (W-C, 1982b).

Table 4.2 Duration of strong earthquake ground motion at the Burro Canyon site, Colorado

Fault	Distance to site mi (km)	ME	Duration (acceleration ≥ 0.05 g)
1	15 mi (24 km)	5.3	4 s
1A	0.7-2.4 mi (1.1-3.9 km)	5.1 (max)	5 s
7	14 mi (22.5 km)	5.6	6 s
9	16 mi (26 km)	5.7	7 s
10	14 mi (22.5 km)	5.5	5 s
FE	9.3 mi (15 km)	6.2	10 s

Note: Fault numbers refer to faults in Table 4.1. Method used to determine estimated duration follows procedure of Krinitzsky and Chang (1977) for rock sites. None of these faults are tectonically capable structures.

Fault groups 2 and 3. Both these faults are associated with the Abajo Mountain igneous intrusion. Doming of the Abajo Mountain area resulted in initial formation of the Verdure graben and Shay graben during the Oligocene. Geomorphic evidence suggests that parts of the faults forming the Shay graben have experienced renewed movement. Apparent displacement of Quaternary gravel-covered pediment occurs on the south Shay graben fault (W-C, 1982a). More detailed geologic investigations such as trenching would be required to substantiate the faulting activity. Field inspection of the fault area revealed no surface evidence of Quaternary fault scarps. Due to the distance of the fault zone from the site, the fault is not a potential design structure, although it may be a capable fault. No evidence was found for Quaternary movement on the Verdure graben faults.

Fault group 7. These faults occur along the crest of the collapsed anticline of the Paradox Valley about 14 mi (23 km) from the site. As with the Lisbon Valley faults, these features are the result of the collapse of rock units along the anticlinal crest during and following removal of subsurface evaporite bodies by solutioning. LSA reconnaissance flights over the Paradox Valley revealed numerous slump blocks along the ridges bounding the valley. The majority of mapped and observed faults occur along the slip surfaces of these slump blocks. Most of the numerous faults parallel to the valley trend are, therefore, the surface expression of the failure planes of the landslide slump blocks. Field inspection revealed no recent movement of the blocks nor geomorphic evidence of recent offset in Quaternary sediments. All bedrock faults are associated with the collapse of the anticline crest. No evidence of Quaternary movement on the bedrock faults was found. Although the valley-bounding faults may be experiencing slow creep, they are not considered tectonically capable.

Fault group 9. The Big Gypsum Valley faults exhibit the same general characteristics as the Paradox Valley faults. Most of the mapped faults are the surface expression of slump blocks along the sides of the valley formed by the collapsed anticline. Bedrock faults are the result of anticline crest collapse following removal of subsurface evaporite bodies. The 1970 earthquake epicenter $M = 4.0$ occurs at the southern end of this anticline structure where it converges with the San Juan Mountain uplift. LSA reconnaissance flights and ground inspection revealed no evidence of fault scarps in Quaternary deposits. The faults in Big Gypsum Valley are not tectonically capable.

Fault group 10. Faults in area 10 in Plate 2.1 appear to be related both to partial collapse of rock strata caused by salt flowage and to regional tectonic folding. The western faults are probably caused by salt-cored anticline formation and partial collapse. The eastern faults are bedrock faults apparently caused by structural folding during the Mid-Tertiary. LSA reconnaissance revealed no evidence of scarps in Quaternary deposits. Bedrock faults are not tectonically capable. Field inspection revealed no surface evidence of Quaternary movement.

Fault groups 8 and 11. Both these faults occur along the southwest side of the Uncompahgre Plateau. Based on their distance and rupture length either of these faults are potential design faults for the site. The Uncompahgre uplift is a recurrently active feature that has experienced considerable uplift since the Late Pliocene. The faults located along the southwest side of the plateau may be capable, but have not been proven to have experienced Quaternary movement. The most conservative approach is to consider them as capable faults. None of the faults in these areas are potential design faults for the site.

Structures delineated during the LSA aerial reconnaissance and photogeologic studies

The area within a 65-km radius of the site was thoroughly examined for indications of capable faulting. This area was also checked for undefined regional structures that could affect the seismic risk evaluation at the site.

Regional joint patterns are prominent on aerial photos of the site region. Joints within the Paradox Basin area are related to the regional deformation produced by folding during the Paleozoic. Joint sets show northeast and northwest orientations. Studies of regional lineaments and joint patterns (W-C, 1982a; Shawe, 1970) indicate they were formed during multiple episodes of folding and were enhanced at the surface by Cenozoic erosion. Lineaments do not appear to be rejuvenated ancestral fractures in Precambrian rocks (W-C, 1982a). Surface enhancement has been greatest on northeast-trending joints.

The balance of lineaments and structures delineated by the interpretation of aerial photos and during LSA aerial reconnaissance correlated to mapped faults and fold structures in the compilation of Williams (1964), Haynes et al. (1972), and Kirkham and Rogers (1981).

Epicentral compilation

Only one earthquake epicenter is listed in the NGD NOAA earthquake data file for magnitude 4.0 or Intensity I events within the 65-km radius of the sites. The epicenter of this event is plotted in Plate 2.1. Two other microseismic events with unknown magnitudes or intensity were located near Egnar, Colorado, by other sources: one in October 1971 (Arabasz et al., 1979), $M = 2.3$ (estimated); and one in May 1941 (Kirkham and Rogers, 1981). Because this area is intensely mined for uranium and vanadium, it is expected that the events may be related to mining. Another explanation may be the relationship to salt core adjustment in the Dolores anticline. There does not appear to be a relationship to known faults in the area.

The February 3, 1970, earthquake event north of Lone Cone 32 mi (51 km) from the site may be related to the bedrock faults flanking the mountain or by deep subsurface adjustment of a magma body. The estimated magnitude is 4.0 with a focal depth of 21 mi (33 km) (Kirkham and Rogers, 1981). No Quaternary fault movement has been observed on the Lone Cone faults. The faults are not capable and are not critical to design acceleration for the site.

The Summit Canyon fault is the only mapped fault that could produce larger accelerations at the site than the FE at a radius of 9 mi (15 km) if it were tectonically capable. Field analysis of this potential design fault indicates that it is not capable of tectonically induced movement.

On the basis of this seismotectonic analysis of faults within a 65-km radius of the site, the FE should be adapted as the design fault. This fault is assumed to occur at a radial distance of 9 mi (15 km) from the sites. A design earthquake of magnitude (M_L) 6.2 occurring at this distance would produce a free-field, nonamplified, peak horizontal ground acceleration at the site of 0.21 g.

Potential for on-site fault rupture

As discussed above, there are no indications of any capable faults in the immediate site area. No faults pass through the Burro Canyon site for the stabilized tailings pile. The closest mapped fault lies about 1.1 mi (1.8 km) from the site. This feature was carefully examined during the site investigations and showed no indication of Quaternary movement.

Potential liquefaction hazard

The unsaturated bedrock foundation of the site is not susceptible to liquefaction.

Reservoir-induced seismicity

A review of the previous literature by Meade (1982) indicates that the phenomenon occurs only where faults are associated with deep reservoirs with large storage capacity.

There are no large reservoirs with sufficient depth or volume to induce seismic activity in the region of the Burro Canyon site at the present time. The largest reservoir is the McPhee Reservoir on the Dolores River near Dolores, Colorado, approximately 36 mi (58 km) from the site. There are no known active faults associated with this reservoir or within the alignment of the Dolores River. The reservoir does not meet the other minimum criteria of depth in excess of 302 ft (92.1 m); and volume in excess of 1 million ft (1200 m³) (W-C, 1979). The limited storage capacity and drainage area of other impoundments in the region preclude the likelihood of their triggering seismic events. Therefore, there is no probability of reservoir-induced seismicity in the area.

Duration of strong earthquake ground motion

For UMTRA Project studies, duration is defined as the bracketed time interval in which the acceleration is greater than 0.05 g at the sites. The definition and method of estimating the duration for soil and rock follow the procedure of Krinitzsky and Chang (1977).

The proposed stabilized pile will rest on shale and sandstone bedrock. The duration values for ground motion at the sites are therefore determined using the method for a rock site. Durations of strong earthquake ground motion are given in Table 4.2 for those faults closest to the sites and for an FE event.

5.0 GEOLOGIC SUITABILITY

This section discusses the geological site conditions that are considered potential deficiencies in meeting requirements for long-term stability.

5.1 FOUNDATION MATERIALS

The potential problems with the bedrock are primarily related to transient water drainage of the cell and the potential for perching and migration (see Attachment 3). Because of the volume of transient drainage, unless final calculations can be shown as not of concern it is recommended that the thin cap rock sandstone units be excavated and dissected on the downslope (south) edge of the cell to prevent possible seepage migration off the site through these strata. The mostly silica mineralogy of the bedrock is considered nonreactive to tailings leachate. The carbonaceous (organic) shales in the lower Dakota Formation are expected to aid in attenuating chemical concentrations levels.

5.2 SURFACE DRAINAGE AND EROSION

The cell cover may be drained onto the apron, resulting in flow being diverted over the crest of the rimrock or being concentrated between the cell and the sandstone ridge at the southeast corner of the site. Since the perimeter flow will naturally concentrate on the cell apron at certain locations, the apron surface should be designed to collect runoff and armored to protect against erosion of the soft bedrock areas.

The apron on the south and southeast edge of the cell will be underlain by the soft weathered, black carbonaceous shale that is especially susceptible to gullyng with concentrated flows. Erosion protection for concentrated flows should be extended to the lower slope of the mesa.

It is especially important to maintain a 100-foot (30-m) setback from the edge or scarp of the mesa rim as a protection against scarp retreat for the long-term stability of the site. This zone should be protected against any excavations that might substantially fracture the edge or make it more vulnerable to erosion. If regrading the buffer zone for drainage is necessary, the grade should be raised by filling so that the resistant edges of the mesa are left intact as much as possible.

5.3 SEISMICITY

The design earthquake is based on an FE of magnitude 6.2 and has resultant peak horizontal acceleration of 0.21 g at the site. There are no concerns of instability due to design seismic parameters or from regional nontectonic sources.

5.4 UNEXPLOITED NATURAL RESOURCES

There is a potential for development of uranium and vanadium ore below the site. The depth of the ore, at 900 ft (300 m), and the thin zones in which it occurs make it very unlikely to affect the integrity of the site. Calculations for the potential effects of mining below the site, based on nearby conditions in the Burro Canyon Mine (Umetco, 1990), indicate that no detrimental effects to the long-term stability of the cell will occur. The calculation (SRK-90-03-03-00) is presented in the appendix to this attachment.

5.5 VOLCANIC HAZARDS

Volcanic and igneous activity do not present a hazard to the site area. No Quaternary volcanic rocks occur in the area. The closest center of Quaternary volcanic activity is near Cameron, Arizona, over 100 mi (200 km) from the site. The youngest igneous intrusive rocks are Early Miocene in age and occur in the Abajo and La Sal Mountains in eastern Utah.

5.6 POTENTIAL FUTURE IMPACT OF SALT-COLLAPSE PHENOMENA

The site is in the salt anticlines region of southwestern Colorado. The salt anticlines consist of a series of large anticlinal folds having intrusive cores of salt and gypsum derived from the Paradox Member of the Pennsylvanian Hermosa Formation (Shawe et al., 1968; Cater, 1970). The salt-cored anticlines and inter-synclines are northwest-trending folds lying on the southwestern flank of the Uncompahgre Uplift, extending from southwestern Colorado into Utah (Figure 2.4). Collapse of the crests of the anticlines due to salt core flowage has created nontectonic faults and slump block zones trending parallel to the folds.

Shawe (1968) shows that the Gypsum Valley collapse anticline has 10,000 ft (3000 m) of salt core and the uncollapsed Dolores anticline has a 4000-ft (1200-m) thick salt core. The Disappointment syncline has only 1000 ft (300 m) of salt. Most of the underlying salt layer has apparently been squeezed out from beneath the syncline, and the site area is not susceptible to the development of salt-collapse features.

Normal faults associated with the Dolores/Lisbon Valley anticline lie within 2.5 mi (4 km) to the southwest of the site (Plate 2.1 and Figure 2.5). The displacements on faults nearest to the site are generally less than 100 ft (30 m). Cater (1970) states that these faults may have formed in response to either collapse of the salt core of the Dolores/Lisbon Valley anticline or to tensional stresses developed during folding. Several northeast-trending faults on the northeast end of the Disappointment Valley syncline lie within 1 mi (1.6 km) to the north of the site. The Gypsum Valley anticline collapse faults are within 2 miles (3.2 km) to the northeast of the site.

No fault has been recognized in the immediate site location, and none of the faults in the surrounding area have been shown to be active. Therefore, it is unlikely that any faulting related to the salt core collapse or dissolution will occur at the site during the design life of the proposed facilities.

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CODE OF FEDERAL REGULATIONS

10 CFR Part 100, *Seismic and Geologic Siting Criteria for Nuclear Power Plants*, U.S. Nuclear Regulatory Commission, 1993.

40 CFR Part 192, *Health and Environmental Protection Standards for Uranium and Thorium Mill Tailings*, U.S. Environmental Protection Agency, 1993.

APPENDIX A
EVALUATION OF SUBSIDENCE POTENTIAL
(BURRO CANYON)

CALCULATION COVER SHEET

CALC NO. SRK04-90-03-03-00 DISCIPLINE GEOTECH. ENGINEERING NO. OF SHEETS 17

PROJECT:

UMTRA

SITE:

SLICK ROCK

FEATURE:

EVALUATION OF SUBSIDENCE POTENTIAL
(BURRO CANYON)

SOURCES OF DATA:

UMETCO MINERALS CORP. MINE MAP
U.S. Geological Survey Paper 576-A, "Stratigraphy, Slick
Rock District and Vicinity, Colo.
Slick Rock Geology Report (Burro Canyon), in preparation.

SOURCES OF FORMULAE & REFERENCES:

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PRELIMINARY CALC. ☐ FINAL CALC. ☒ SUPERSEDES CALC. NO. _____

REV. NO.	REVISION	CALCULATION BY	DATE	CHECKED BY	DATE	APPROVED BY	DATE	

PROBLEM STATEMENT:

Evaluate the potential for subsidence due to mining beneath the Burro Canyon site. Assess the effect of this estimated subsidence on the integrity of a disposal cell.

METHOD:

The method used to predict subsidence is by Abel and Lee, (1977). Estimate the amount of subsidence from underground room and pillar mining for two mining scenarios: 1) smaller panels with higher extraction ratios and smaller pillars; and 2) wider panels with lower extraction ratios and wider pillars. Using the higher amount of subsidence predicted, apply British National Coal Board (1975) methods to estimate the subsidence profile. Based on this profile, use the equation by Lee and Shen (1969) to predict the potential cracking of the disposal cell cover.

ASSUMPTIONS:

The empirical correlations by Abel and Lee (1977) and the National Coal Board (1975) developed mostly from coal mining data are applicable to this case. This is a conservative assumption because the unconfined compressive strengths of sandstones (the strata being mined) are usually about four times that of coal. Subsidence at the site would be due to pillar failure; with higher strengths, failure would be less likely for sandstones than coal under the same conditions.

The beam analogy for cracking (Lee and Shen) is applicable and the radon/infiltration barrier represents the stiff layer in the cover most susceptible to cracking. The Slick Rock tailings are predominantly cohesionless sands that would shift in response to foundation subsidence but would not crack; tensile strains would be transferred to the cover.

DATA SOURCES:

Umetco Minerals Corp. mine map for their Burro Canyon mine

U.S. Geological Survey Professional Paper 576-A, "Stratigraphy, Slick Rock District and Vicinity, Colo."

Slick Rock Geology Report for proposed Burro Canyon site (in preparation)

CALCULATIONS:

Evaluated previous mining in the site area (Umetco Minerals Corp.--about one mile to the southwest) to estimate the following mining characteristics: 1) depths of mined zones; 2) number of zones; 3) thickness of mined zones; 4) widths of pillars and panels; and 5) extraction ratios. The following conclusions can be made as to reasonable mining scenarios that could potentially affect a disposal cell at the Burro Canyon site:

Case	Panel width (ft)	Pillar width (ft)	Extraction ratio (%)
1	200	10	80
2	600	50	50

Based on the strike and dip of the Salt Wash (the unit being mined) and the depth of previous mining, the estimated depth of potential mining zones underneath the Burro Canyon site will be 900 feet. Two potential ore zones, approximately 50 feet apart and less than five feet thick have been mined (mining equipment removed about ten feet of the ore bearing sand-stone). For this analysis, two zones with mining thicknesses of ten feet will be used and the results superimposed. It might be noted that there was not extensive overlap of the two zones excavated during previous mining in the area.

DATE 4/16/90

 SUBJECT SUBSIDENCE
EVALUATION

 SHEET NO 3/17

 BY JMM CHKD. _____

JOB NO _____

Case 1) $L_{max} = \frac{K D}{1 - R}$ where K = overburden pressure (constant)
 D = mining depth (900 ft)
 R = extraction ratio (80%)

$$= \frac{(0.226 \text{ MPa}_m)(275 \text{ m})}{1 - (.8)}$$

$$L_{max} = 31.1 \text{ MPa}$$

$$\begin{aligned} \% \text{ Subsidence} &= 8.47 + 11.95 \ln [L_{max} (H/W)] \quad (\text{Abel and Lee, 1977}) \\ &= 8.47 + 11.95 \ln [31.1 (3 \text{ m}/3 \text{ m})] \quad \begin{array}{l} H = \text{mining height (10 ft)} \\ W = \text{pillar width (10 ft)} \end{array} \\ &= 49.5 \% \text{ of mining height} \\ &\quad \text{use } 50\% \end{aligned}$$

$$\text{Subsidence (s)} = .5 (10 \text{ ft}) = 5 \text{ ft}$$

Panel correction factor

$$\text{Width} = 61 \text{ m}; \text{ Depth} = 275 \text{ m}$$

$$\text{From Fig. 3 (NCB, 1976)} \quad \text{correction factor} = 0.08$$

$$\text{Then } S_{max} = .08 (5 \text{ ft}) = 0.4 \text{ ft}$$

Limited face advance factor

$$\text{Face advance (L)} = 2W = 2(61 \text{ m}) = 122 \text{ m} \quad (\text{Assumption})$$

$$\text{Depth (H)} = 275 \text{ m}$$

$$L/H = 122 \text{ m}/275 = 0.44$$

$$\text{From Fig. 4 (NCB, 1976)} \quad \text{factor} = 0.4$$

$$\text{Corrected } S_{max} = 0.4 (.4 \text{ ft}) = \underline{0.16 \text{ ft}}$$

Figure 3. Subsidence above room-and-pillar workings following pillar squeeze or failure.

Case 2) $L_{max} = \frac{K D}{1-R}$ $D = 900 \text{ ft}$
 $R = 50\%$

$$= \frac{(0.0226 \text{ MPa/m})(275 \text{ m})}{1-(.5)}$$

$$L_{max} = 12.43 \text{ MPa}$$

$$\% \text{ Subsidence (S)} = 8.47 + 11.95 \ln [L_{max} (H/W)]$$

$$= 8.47 + 11.95 \ln [12.43 (3 \text{ m} / 15 \text{ m})] \quad \begin{matrix} H = 3 \text{ m} \\ W = 15 \text{ m} \end{matrix}$$

$$= 19.4 \% \text{ of mining height}$$

use 20%

$$S = .2 (10 \text{ ft}) = 2 \text{ ft}$$

Panel Correction Factor

$$\text{Width} = 183 \text{ m} ; \text{Depth} = 275 \text{ m}$$

$$\text{From Fig. 3 (NCB, 1976) correction factor} = .67$$

$$\text{Then } S_{max} = .67 (2 \text{ ft}) = 1.34 \text{ ft}$$

Limited face advance is not applicable

$$\underline{S_{max} = 1.34 \text{ ft}}$$

Use 1.34 ft for max. subsidence

ANGLE OF DRAW

Percent sandstone in overlying rock $\approx 30\%$

From Fig. 2 (Abel & Lee) Angle of draw = 25°

Distance from ribside to zero subsidence (definition of angle of draw)
 $= \tan \text{angle (Depth)}$
 $= \tan 25^\circ (900 \text{ ft})$
 $= 420 \text{ ft}$

Subsidence Profile

Ratio of Panel: WIDTH = 600 ft ; height = 900 ft

$w/h = 600/900 = .67$ use .68 for Table 1 (NCB, 1976)

$s/s =$ ratio of predicted subsidence to max. subsidence

From Table 1 (NCB, 1976)

0 subsidence is expected 1.04 (height) away from panel center line

$1.04(900 \text{ ft}) - (300 \text{ ft})$ $300 \text{ ft} = \frac{1}{2} \text{ panel width}$

$= 636 \text{ ft}$ away from ribside (Based on 35° angle of draw)

To correct profile for increased angle of draw (25° vs 35°)

use ratio $420 \text{ ft} / 636 \text{ ft} = .66$

Subsidence predicted to occur at distances less than one-half of the panel width do not have to be corrected, i.e. over the panel.

FIG. 2--Reported angle of draw versus percent sandstone and limestone.

TABLE 1: Relationship between w/h and d/h for various points on a subeidence profile

w/h RATIO OF PANEL	DISTANCES FROM PANEL CENTRE IN TERMS OF DEPTH									
	0.05	0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90
2.0	1.61	1.39	1.29	1.24	1.19	1.16	1.12	1.08	1.03	0.96
2.4	1.41	1.29	1.19	1.14	1.10	1.06	1.02	0.98	0.93	0.85
2.2	1.31	1.19	1.09	1.04	1.00	0.96	0.92	0.88	0.83	0.75
2.0	1.21	1.09	0.99	0.94	0.90	0.86	0.82	0.78	0.73	0.65
1.8	1.11	1.00	0.90	0.84	0.80	0.76	0.72	0.68	0.63	0.55
1.6	1.01	0.90	0.80	0.74	0.70	0.66	0.62	0.58	0.53	0.45
1.4	0.91	0.80	0.70	0.64	0.60	0.56	0.52	0.48	0.43	0.35
1.3	0.86	0.75	0.65	0.59	0.55	0.51	0.47	0.43	0.38	0.30
1.2	0.81	0.70	0.60	0.54	0.50	0.46	0.42	0.38	0.33	0.25
1.1	0.77	0.65	0.55	0.50	0.45	0.42	0.38	0.34	0.29	0.21
1.0	0.72	0.61	0.51	0.45	0.41	0.37	0.33	0.29	0.24	0.18
0.98	0.71	0.60	0.50	0.44	0.40	0.36	0.32	0.28	0.23	0.17
0.96	0.70	0.59	0.49	0.43	0.39	0.35	0.32	0.27	0.23	0.16
0.94	0.69	0.58	0.48	0.42	0.38	0.34	0.30	0.26	0.22	0.15
0.92	0.68	0.57	0.47	0.41	0.37	0.33	0.30	0.25	0.20	0.14
0.90	0.68	0.57	0.46	0.40	0.36	0.32	0.28	0.24	0.20	0.13
0.88	0.67	0.56	0.45	0.40	0.36	0.32	0.28	0.24	0.20	0.13
0.86	0.66	0.55	0.45	0.39	0.35	0.31	0.27	0.23	0.19	0.12
0.84	0.65	0.54	0.44	0.38	0.34	0.30	0.26	0.22	0.18	0.11
0.82	0.64	0.53	0.43	0.37	0.33	0.29	0.25	0.21	0.17	0.10
0.80	0.63	0.52	0.42	0.36	0.32	0.28	0.24	0.20	0.16	0.11
0.78	0.63	0.52	0.42	0.36	0.32	0.28	0.24	0.20	0.16	0.11
0.76	0.62	0.51	0.41	0.35	0.31	0.27	0.23	0.19	0.15	0.10
0.74	0.61	0.50	0.40	0.34	0.30	0.26	0.22	0.18	0.14	0.10
0.72	0.61	0.50	0.40	0.34	0.30	0.26	0.22	0.18	0.14	0.10
0.70	0.60	0.49	0.39	0.33	0.29	0.25	0.21	0.17	0.13	0.09
0.68	0.60	0.49	0.38	0.32	0.28	0.24	0.20	0.17	0.13	0.09
0.66	0.60	0.48	0.38	0.32	0.28	0.24	0.20	0.17	0.13	0.09
0.64	0.59	0.48	0.37	0.31	0.27	0.23	0.19	0.16	0.12	0.08
0.62	0.59	0.47	0.37	0.31	0.27	0.23	0.19	0.16	0.12	0.08
0.60	0.59	0.47	0.36	0.30	0.26	0.22	0.18	0.15	0.12	0.08
0.58	0.59	0.47	0.35	0.30	0.25	0.22	0.18	0.15	0.12	0.08
0.56	0.59	0.47	0.35	0.29	0.25	0.21	0.18	0.15	0.12	0.08
0.54	0.59	0.47	0.34	0.29	0.25	0.21	0.18	0.15	0.12	0.08
0.52	0.59	0.47	0.34	0.28	0.24	0.21	0.17	0.15	0.12	0.08
0.50	0.59	0.47	0.34	0.28	0.24	0.21	0.17	0.15	0.12	0.08
0.48	0.59	0.47	0.33	0.28	0.23	0.20	0.17	0.15	0.12	0.08
0.46	0.59	0.47	0.33	0.28	0.23	0.20	0.17	0.15	0.12	0.08
0.44	0.59	0.47	0.33	0.28	0.23	0.20	0.17	0.15	0.12	0.08
0.42	0.59	0.47	0.33	0.28	0.23	0.20	0.17	0.15	0.12	0.08
0.40	0.59	0.47	0.34	0.28	0.24	0.21	0.18	0.15	0.12	0.08
0.38	0.60	0.48	0.35	0.29	0.24	0.21	0.18	0.15	0.12	0.08
0.36	0.60	0.48	0.35	0.29	0.25	0.21	0.18	0.15	0.12	0.08
0.34	0.60	0.49	0.36	0.30	0.25	0.22	0.19	0.16	0.13	0.09
0.32	0.61	0.50	0.37	0.31	0.26	0.22	0.18	0.15	0.12	0.08
0.30	0.61	0.50	0.38	0.32	0.27	0.23	0.19	0.16	0.13	0.09
0.28	0.61	0.51	0.39	0.33	0.28	0.24	0.20	0.17	0.14	0.09
0.26	0.62	0.52	0.41	0.35	0.30	0.26	0.22	0.18	0.15	0.10
0.24	0.62	0.53	0.43	0.36	0.32	0.28	0.24	0.20	0.16	0.11
0.22	0.63	0.55	0.46	0.39	0.34	0.30	0.26	0.22	0.17	0.11
0.20	0.64	0.57	0.48	0.41	0.37	0.32	0.28	0.23	0.19	0.13

(TABLE 1 → 35°) (25°)			
s/s	Dist. from Panel G (ft)	Dist. from Ribside (ft)	Distance from Ribside (ft)
0	(1.04)(900') = 936'	936' - 300' = 636'	.66(636') = 420'
.10	(.49)(900') = 441'	441' - 300' = 141'	.66(141) = 93'
.20	(.38) = 342'	= 42'	.66(42') = 28'
.30	(.32) = 288'	= -12'	Use = -12' INSIDE OF PANEL RIBSIDE
.40	(.28) = 252'	= -48'	Use Distances are less than 1/2 panel width
.50	(.24) = 216'	= -84'	
.60	(.21) = 189'	= -111'	
.70	(.17) = 153'	= -147'	
.80	(.14) = 126'	= -174'	
.90	(.10) = 90'	= -210'	
.95	(.07) = 63'	= -237'	

Max. slope occurs from s/s: 0.3 to 0.8 where S = 1.34 ft

$$\text{Slope} = \frac{(.8 - .3)(1.34')}{-174' - (-12')} = \frac{.67'}{162'} = .004 \text{ ft/ft}$$

for one 10' ore zone mined

Cracking Potential

$m = \frac{2}{3} H \alpha \quad (L \ll S_{km}) \text{ where } m = \text{horizontal movement}$

$H = \text{thickness of stiff layer}$

$\alpha = \text{slope of surface due to}$

subsidence

$m = \frac{2}{3} (3') (.008)$

$\text{average effect of mining two years}$

$\text{therefore } \alpha = (.004 \text{ ft/ft}) (2)$

$= .016 \text{ ft}$

$\text{Tensile strain } (\%) = .016 \text{ ft} / 162 \text{ ft}$

$162' = \text{length of max.}$

$\text{differential subsidence}$

$= .001 \%$

From Leonard & Nairn (1963), 0.05% was the lowest

tensile strain that resulted in cracking of any soil

type tested. $.01\% \ll .05\%$ Therefore, the most rea-

sonable, potential mining scenario in the vicinity of

the proposed disposal that could cause subsidence

would be well below the threshold of potential damage

to the cell cover.

Most conservative case

Assume same mining thickness (32m), number of zones (2) and depth (275 m). These assumptions are valid for uranium and vanadium mining previously conducted in the Black Rock area. Increase extraction ratio (R) to 75%, and decrease pillar width (W) to 7.5 m for case number 2, which was the worst case analyzed.

$$L_{max} = \frac{KD}{1-R} = \frac{(0.226 \text{ MPa/m})(275)}{1-.75} = 24.86 \text{ MPa}$$

$$\begin{aligned} \% \text{ Subsidence} &= 8.47 + 11.95 \ln [L_{max} (3/7.5)] \\ &= 35.9\% \quad \text{use } 36\% \end{aligned}$$

$$S = .36 (10') = 3.6'$$

Panel correction factor = .67

$$S_{max} = .67 (3.6') = 2.4 \text{ ft}$$

Same subsidence profile is applicable, determine slope for s/s from .3 to .8.

$$S_{\text{slope}} = \frac{(.8-.3)(2.4)}{-174' - (-12')} = .007 \text{ ft/ft} \quad (\text{for one zone mined})$$

DATE _____

SUBJECT _____

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BY _____

CHKD. _____

JOB NO. _____

Cracking potential

$$m = \frac{2}{3} H \alpha$$

$$= \frac{2}{3} (3') (.015)$$

$$m = .03 \text{ ft}$$

slope (α) is doubled for mixing of two zones

$$\text{Tensile strain (\%)} = \frac{.03 \text{ ft}}{164 \text{ ft}}$$

$$= .02 \% \ll .05 \%$$

Tensile strain is still well below threshold for cracking.

CONCLUSIONS:

Based on previous mining in the area and using conservative assumptions for analysis, potential mining of the upper Salt Wash Formation for uranium and vanadium would not adversely affect the long-term stability of the proposed disposal cell at Burro Canyon. In order to cause an impact to the integrity of the disposal cell cover, underground mining would have to be much closer to the surface. Presently, there are no known economical ore deposits in either the Burro Canyon or Morrison Formation in the vicinity of the proposed Burro Canyon site. These are the formations overlying the Salt Wash.

TABLE 1, Uniaxial Compressive and Tensile Strengths
For Typical Rocks
(Farmer, 1963 and Jaeger & Cook, 1969)

Rock	Compressive Strength (psi) from - to	Tensile Strength (psi) from - to	Ratio of Comp. Str. to Tens. Str. from-to
Pierre shale	70- 2,530		
Bearpaw shale	550- 1,250		
Shale ¹	1,400-14,000	280-1,400	5 - 10
Granite	14,000-36,000	1,000-3,600	10 - 14.5
Dolerite	28,000-71,000	2,000-5,800	10 - 13.5
(Diabase)			
Basalt	21,000-43,000	1,400-3,600	12 - 15
→ Sandstone ¹	2,800-24,000	500-3,600	5.5- 6.5
Limestone ¹	4,300-36,000	700-3,600	6 - 10
Quartzite	21,000-67,000	1,400-4,300	10 - 15.5
Marble	14,000-36,000	1,000-2,800	11 - 14
→ Coal ¹	700- 7,000	280- 700	2.5- 10
Diorite	25,000-43,000	2,000-4,300	10 - 12
Gabbro	25,000-43,000	2,000-4,300	10 - 12
Dolomite ¹	11,500-36,000	2,000-4,300	5.5- 8.5
Gneiss ¹	7,000-28,000	700-2,800	10
Slate ¹	14,000-28,000	1,000-2,800	10 - 14

TABLE 2, Elastic Modulus (Stiffness) for Typical Rocks
(Farmer, 1968)

	Modulus (E) (psi x 10 ⁶) from - to
Pierre shale	0.02 - 0.14
Bearpaw shale	0.018
Shale ³	1.5 - 5
Granite	3 - 8.5
Dolerite (Diabase)	11.5 -15.5
Basalt	8.5 -14
Sandstone ^{2,3}	0.5 -11.5
Limestone ³	1.5 -11.5
Coal ³	1.5 - 3
Diorite	10 -14
Gabbro	10 -15.5
Dolomite	5.5 -12
Microgranite	4 -11.5
Syenite	8.5 -11.5
Mudstone ³	3 - 7

Notes: ¹ Tensile strength across bedding and(or) foliation may be too low to measure.

² Grain packing may be critical.

³ Modulus very different across bedding and along bedding.

UNITED STATES DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

EXPLANATION

Light-gray or light-buff
sandstone

Light-reddish-brown
sandstone

Mostly greenish-gray
mudstone

Mostly reddish-brown
mudstone

Limestone

Carbonaceous shale

Coal

DV-119
Diamond-drill hole
number

109° 15'

109° 00'

108° 45'

108° 30'

108° 15'

38° 45'

38° 30'

38°15

38°00

37°45

37°45'—

109° 00'

108° 45'

PLATE 2.1 FAULT AND EPICENTER M BURRO CANYON SITE, COLO

8 Fault or fault system, dashed where inferred, dotted where concealed, ball on downthrown side.

Major Fault Systems Enclosed By Dashed Lines

CONTOUR INTERVAL 200 FEET
WITH SUPPLEMENTARY CONTOURS AT 100 FEET

Major Fault Systems Enclosed
By Dashed Lines

Areas Of Closely Spaced
Small Faults

Fault or fault system, dashed
where inferred, dotted where
concealed, ball on downthrown
side.

NGDC/NOAA EPICENTER (1989)
Earthquake epicenter
with date.

PLATE 2.1
FAULT AND EPICENTER MAP
BURRO CANYON SITE, COLORADO

DATE

FILMED

4/20/94

END