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United States Department of Energy

Remedial Action Plan and Site Design for Stabilization of the Inactive Uranium Mill Tailings Site at Durango, Colorado

Attatchment 2, Geology Report

Revised Final

December 1991

Appendix B of the Cooperative Agreement No. DE-FC04-81AL16257

MASTER

Uranium Mill Tailings Remedial Action Project

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ATTACHMENT 2

GEOLOGY REPORT

DISCLAIMER

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1.0 INTRODUCTION

Detailed investigations of geologic, geomorphic, and seismic conditions at the Bodo Canyon disposal site were conducted. The purpose of these investigations was basic site characterization and identification of potential geologic hazards that could affect long-term site stability. Subsequent engineering studies, such as 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 kilometer (km) (40-mile) 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- Compilation and analysis of previous published and unpublished geologic literature and maps.
- Review of historical and instrumental earthquake data.
- Review of site-specific subsurface geologic data, including lithologic and geophysical logs of exploratory boreholes advanced in the site area.
- Photogeologic interpretations of existing conventional aerial photographs.
- Ground reconnaissance and mapping of the site region.

The Bodo Canyon site and the immediately surrounding area, out to a radius of about 1.6 km (one mile), by definition of the Technical Approach Document (TAD) (DOE, 1989) are referred to in this section as the "site area." The surrounding region, to a radius of 65 km, will be referred to as the "site region." The area is not identified as "Bodo Canyon" on topographic maps, but rather is taken from the name of the former landowner.

The following topics relevant to the stabilization of mill tailings at the Bodo Canyon disposal 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 assess the liquefaction potential and slope stability fully.
- Identification of other geologic hazards, including secondary seismic hazards, impacts from future mineral resources development, and problems related to site stratigraphy or unconsolidated deposits, fractures, or structures.

This document represents a compilation of several reports by the U.S. Department of Energy (DOE) as listed below, on the characterization of the Durango and Bodo Canyon sites. This geology attachment is presented in a revised format adopted in 1990 for consistency. In addition, data and interpretation resulting from field investigations conducted in the fall of 1989 were used to revise and update the earlier reports. The procedures used in the seismic stability analysis followed the technical approach in use in 1985 and precede the adoption of the current technical approach formulated in 1986 (DOE, 1986). The findings, however, provide essentially the same conservative design that the current approach would give.

The following publications were used to compile this report and are subsequently superseded with regard to site geologic characterization. The full title of the publications can be found in the reference list at the end of this document.

DOE, 1984a	DOE, 1985c
DOE, 1984b	DOE, 1985d
DOE, 1985a	DOE, 1985e
DOE, 1985b	DOE, 1986

1.1 CRITERIA AND DEFINITIONS

The following is a discussion of the standards and definitions that were applied to the evaluation of geologic hazards at the Bodo Canyon disposal site.

- Design life. As specified by the U.S. Environmental Protection Agency (EPA) standards for remedial actions at inactive uranium processing sites (10 CFR 40), 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 stabilized materials will not be damaged by earthquake ground motions, related ground rupture, or erosional encroachment for up to 1000 years.

- Capable fault. A capable fault is 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 the siting of nuclear power plants (10 CFR 100, Appendix A, 1975).

o <u>Acceleration</u>. Within the context of the UMTRA Project studies, 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." The design acceleration may be determined by probabilistic and deterministic techniques or may be based on attenuation-magnitude relationships as appropriate for the database and seismotectonic characteristics for the region, consistent with standard practices.

o <u>Magnitude and intensity</u>. Magnitude was originally defined by C. F. Richter as the base-10 logarithm of the amplitude of the largest deflection observed on a torsion seismograph located 100 km (62 miles) 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, local magnitude (M_L) values are used in the UMTRA Project seismic hazard evaluations.

  Intensity is the index of the effects of an earthquake on the human population and structures. The Modified Mercalli Intensity (MMI) scale is used in the UMTRA Project studies.

  Because pre-instrumental 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 on the Richter scale and I_o = Modified Mercalli Intensity (MMI) in the epicentral area.

o <u>Maximum Earthquake</u>. The term Maximum Earthquake (ME) was defined by Krinitzsky and Chang (1977) as "the largest earthquake that is reasonably expected" on a given structure or within a given area. That definition is applied in UMTRA Project seismic hazard studies. No recurrence interval is specified for such an event. Essentially, the ME is equivalent to the Maximum Credible Earthquake (MCE) event as defined in 10 CFR 40, Appendix A, Criterion 4(e).

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 disposal cell. These evaluations are restricted to the assessment of natural geomorphic processes and the geomorphic effects of past land-use activities, but do not address the effect of future human activities.

Schumm and Chorley (1983) have prepared a detailed publication presenting a theoretical discussion of geomorphic processes that 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 geomorphic investigations of the Bodo Canyon disposal site.

1.2 SCOPE OF WORK

Compilation and analysis of previous work

A review of all pertinent stratigraphic, lithologic, tectonic, seismologic, geophysical, geomorphic, mineral resource, soils literature, and maps of the site region was performed. A GeoRef data search was employed to ensure complete coverage of all published information.

The study region is covered by the published state geologic map, by $1^{\circ} \times 2^{\circ}$ quadrangle maps, and by several 7.5- and 15-minute quadrangle maps. Copies of all published maps and open-file reports covering a 65-km radius of the site were obtained and employed in the fault compilation. All faults identified during the survey were compiled onto a single base map for use in subsequent analyses. A search was also made for other unpublished seismic evaluations for large engineered structures (dams, power plants, waste disposal areas, and the like).

Earthquake data compilations

Historical earthquake data for the area within a 200-km (124-mile) radius of the Bodo Canyon disposal site were obtained for this study. Published probabilistic seismic hazard studies for the United States were reviewed, as were ME estimates for remote seismotectonic provinces, such as the Colorado Plateau and Rio Grande Rift.

Subsurface geologic data

Subsurface geologic data obtained in the site area for this study consist of logs of boreholes and backhoe test pits advanced on the site. Boreholes were drilled to depths ranging to 400 feet to assess groundwater conditions, subsurface stratigraphy, and engineering characteristics. Test pits were advanced to depths of 4.5 to 10 feet. Numerous wells and test pits were completed.

Ground reconnaissance

Ground reconnaissance and field verification of geologic and geomorphic features in the site region were performed by geologists concurrently with the other phases of this study, including site selection process, and investigations at the processing site.

Mapped faults and unmapped faults and lineaments within 40 km of the site were delineated by an inspection of aerial photographs and by field inspections. This included faults that could potentially be design faults. Particular attention was paid to potential geomorphic hazards at the site, including gully erosion, landslides, and mudflows.

Photogeologic analysis

Photogeologic analyses performed for the Bodo Canyon site included analysis of conventional stereo-pair aerial photographs, both color and black and white. The aerial photographs were also used in the geomorphic characterization of the site and during identification of potential geomorphic hazards.

2.0 REGIONAL GEOLOGY

2.1 REGIONAL PHYSIOGRAPHY

The Bodo Canyon disposal site is located southwest of the city of Durango in La Plata County, Colorado. The site lies in the Colorado Plateau just south of the boundary with the Southern Rocky Mountains physiographic province (Figure 2.1). The Animas and La Plata Rivers, tributaries of the San Juan River, flow through the area from the San Juan Mountains portion of the Southern Rocky Mountains province to the north. The San Juan River, a major tributary of the Colorado River, drains the San Juan Basin portion of the Colorado Plateau province (Hunt, 1974).

The northern San Juan Basin located within the Navajo section, Colorado Plateau, is characterized by southwest-trending "hogback" (ridge and valley) topography. These hogbacks generally have steep northern slopes and gentler southern slopes. The highest ridges in the site area are over 8000 feet above mean sea level, with relief exceeding 1200 feet.

The valleys between the hogbacks are drained by intermittent or ephemeral streams that trend parallel to the hogbacks and roughly perpendicular to the Animas and La Plata Rivers. Although they generally carry little water, these drainages have eroded deep gullies into the alluvium and shales underlying the valleys.

Geomorphic setting

The Bodo Canyon disposal site is along the Hogback Monocline, which forms the northwest edge of the San Juan Basin. Bedrock types in this region include alternating sandy and shaley formations that range in age from Cretaceous to early Tertiary. The dips are generally south to southeast and decrease toward the basin center.

On a broad scale, the geomorphic features of this region reflect the monoclinal structure, the varying resistance of the bedrock formations to erosion, and Quaternary incision of the Animas and La Plata drainage systems. Hogback ridges with steep northern slopes and gradual southern slopes, underlain by relatively erosion-resistant sandstones, are separated by strike valleys cut into softer shales.

Segments of the drainage system typically run either parallel or oblique to the structural trend. Stream capture appears to have played an important role in the development of drainage patterns.

During Quaternary and possibly late Tertiary time, fluvial incision has been influenced by repeated glaciations in the La Plata and San Juan Mountains. Cyclic changes in river behavior have produced a series of glaciofluvial outwash terraces along each river and along some of the larger tributaries. Along the Animas River, the gradients of the terraces decrease from late Pliocene to middle Pleistocene time, suggesting continued tectonic uplift in the San Juan Mountains (Gillam et al., 1984). However, the gradients of late Pleistocene terraces and the present Animas River gravel are very similar, so that the uplift appears to have slowed

National Parks and Monuments

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

Escarpments 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
ag Agathla Peak
sr Shiprock
cb Cabezon Peak

REF: AFTER HUNT, 1967.

50 0 50 100
SCALE IN MILES

FIGURE 2.1
PHYSIOGRAPHIC SKETCH MAP OF THE COLORADO PLATEAU

or terminated. Therefore, the Durango area was considered tectonically inactive for the scope of this investigation.

Climatic setting

Paleoclimatic trends, although difficult to determine, indicate the general range of climatic conditions that may occur during the next 1000 years, and thus provide a basis for assessing the effects of climatic change on the tailings site and the impoundment structure.

Unfortunately, paleoclimatic reconstructions are imprecise because they measure the indirect responses of biological or geological phenomena; in turn, these phenomena have varying sensitivities and response times and may reflect different climatic variables. Recent research has suggested that the seasonal distribution of temperature and precipitation, as well as annual mean values, significantly affect geomorphic processes. However, seasonal influences are not yet sufficiently clear to be evaluated on a practical level.

One source of error in paleoclimatic reconstructions is natural, local climatic variability. In an analysis of historical precipitation records for the Rocky Mountains, Bradley (1976) notes that local conditions in adjacent areas often deviate from historical records or from regional trends. Therefore, inaccuracies may result from extending paleoclimatic interferences too far from the site of data collection.

Present climate

The climate of the Durango area is semiarid, with minor local variations resulting from differences in elevation, sun exposure, and wind channelization. Because little climatic data are available for the surrounding area, historical measurements at Durango are considered to be broadly representative.

For Durango, the mean annual temperature is 46.0° to 46.7° F and mean annual precipitation is 15.6 to 19.2 inches (NOAA, 1985; SCS, 1954). During 1982, when a meteorological station was operated at the Bodo Canyon site, the daily temperature range was only slightly greater than at Durango, but the mean annual temperature was identical.

Monthly precipitation is slightly higher during the summer and fall. Snow may occur from October to May, and is most abundant in December and January. Potential evapotranspiration exceeds precipitation from April to October.

Postglacial climate

The contrast between glacial and interglacial climates should be greater than the maximum long-term shift in climate that could be expected in the Durango area during the next 1,000 years. The last full glacial period in the southwestern United States was probably a pluvial period with increased precipitation, cool summers, and relatively mild winters, or it may have been characterized by very cold temperatures and precipitation similar to today's.

The difficulty of isolating changes in temperature and precipitation has been summarized by Barry (1983) from data on southwestern lake levels during the last glaciation. Water balance calculations have shown that the glacial high level of Warner Lake, in southern Oregon, could have been maintained with a 9° F temperature reduction and a 33 percent precipitation increase. Lake Estancia, New Mexico, could have existed with a temperature reduction as great as 18° to 20° F, even if precipitation decreased 10 to 20 percent. Lake Bonneville could have been maintained either with a temperature decrease of 13° F and a precipitation increase of 90 percent, or with a temperature decrease of 29° F and a precipitation decrease of 50 percent. Brakenridge (1978) suggests there was a cooling of at least 13° to 14° F in the southwest during the last glaciation.

In the northern Rocky Mountains, the magnitude of snow-line depression suggests temperature decreases of as much as 25° to 31° F during the last glaciation (Porter et al., 1983).

Three types of data have been analyzed to identify climatic trends in the Four Corners region. These include: 1) pollen ratios (spanning the entire postglacial period); 2) tree ring growth records (for the last few hundred years); and 3) historical records (for the last century). These are discussed below.

Changes in climate can be identified by comparing ratios of fossil pollen species to characteristic ratios of the same species in various modern environments. Typically, the pollen is collected from lakes where it has accumulated continuously during sedimentation. Several pollen studies in the Four Corners region have used changes in the elevation of treeline as an indicator of past climate. Because treeline is most sensitive to summer temperature, a rise in treeline indicates increasing warmth.

The pollen studies include the following areas: Molas Lake (Maher, 1961), Hurricane Basin (Andrews et al., 1975), Lake Emma (Carrara et al., 1984), La Plata Mountains (Peterson and Mehringer, 1976), and Chuska Mountains (Wright et al., 1973).

The individual pollen records can clarify broad trends in summer temperature for intervals from less than one hundred years to several hundred years. When compared, the records yield a generalized sequence of changes during the last 15,000 years. Approximate dates for intervals were estimated from radiocarbon dates and from lake sedimentation rates. The temperature changes were not fully consistent or synchronous between the various pollen sites, but provide a general indication of concurrent trends near Durango.

The maximum glacial-interglacial temperature contrast appears to have been about 6° to 16° F in the Four Corners region and 8° to 10° F at Durango. Glacial-interglacial precipitation changes in the Four Corners region are not available. However, Leonard (1984) concludes that air circulation and storm track patterns near the San Juan Mountains did not change significantly.

The thickness of annual growth rings of trees is related to both temperature and precipitation. A tree ring data series, showing relative variations in ring width through time, is synthesized from several trees and may span hundreds of years. From comparisons of historic tree ring and climatic data, equations have been developed for estimating climatic conditions from the widths of prehistoric rings. In the Four Corners area, most studies have emphasized the determination of former moisture levels.

Relative changes in effective moisture as interpreted from tree ring data in the San Juan Mountains area (Fritts, 1965) were compared to historic data (Bradley, 1976) for the period 1855 to 1935. Bradley concludes that historic data support the tree ring record for the period after 1900, but partly conflict for the period between 1855 and 1900.

Stockton and Jacoby (1976) examined tree ring data series from 30 sites in the Colorado River basin, including several sites near Durango. From the series, Stockton and Jacoby inferred a sequence of moisture changes from 1500 to 1964 A.D.

Historical and climatic records for several stations in the San Juan Mountains, including Durango, have been analyzed in detail by Bradley and Barry (1976). Selected 19th century data provide a rough indication of contemporaneous trends at Durango (correlation coefficients between Durango and other stations range from 0.6 to 0.8). Twentieth-century data for Durango are presented as nine-year weighted means and as seasonal means. From 1900 to 1970, the nine-year weighted-mean temperature varied slightly from 44.3° to 47.6° F, while the nine-year weighted-mean precipitation varied significantly from 13.5 to 23 inches. During this period, variations also occurred in the seasonal distribution of temperature and precipitation, in winter precipitation as a percentage of total annual precipitation, and in the frequency of rainfall events in particular size classes. The following description of temperature and precipitation trends is paraphrased from their report.

General trends in temperature indicate regional cooling from the late 1860's until about 1930, followed by regional warming. In detail, temperature rose markedly during the late 1850's and 1860's to a high around 1867; fell slowly until 1890 and possibly during the next 10 years (no records available); declined to about 1920, and then warmed until 1930. High average temperature peaks that occurred around 1905 and 1956-58 at Durango were almost 4° F warmer than the 1930 low.

General trends in precipitation tend to be inversely related to those in temperature, thus enhancing variations in effective moisture. Several stations in the area are characterized by rapid transitions between relatively wet and dry intervals. Precipitation is least variable in the winter and most variable in the spring and fall. Droughts are typically associated with periods of low winter precipitation.

In detail, 19th century precipitation records suggest a possible rising trend from the 1860s to the 1890s; the 1860s may have been as dry as the period from 1931 to 1960. Precipitation reached a major low around 1900 and then rapidly increased until about 1908; at Durango this peak was more than twice as moist as the 1900-1901 low. Another minor low in about 1916 was followed by an increase until 1919 to 1922, a drastic fall to a period low from 1929 to 1932, and then a dramatic rise that peaked from 1936 to 1938. Minor lows occurred from 1945 to 1946 and from 1961 to 1962, with intermediate peaks from 1948 to 1951 and 1956 to 1957.

Summary of climatic data

The maximum long-term glacial-interglacial temperature change in the Durango area was probably between 6° and 16° F, and may have been about 8° to 10° F. No local data are available for concurrent precipitation changes, but Schumm and Chorley (1983) suggest an increase of about 10 inches occurred during the last glaciation for the southwestern United States, about a 53 percent increase compared to present levels at Durango.

Long-term climatic fluctuations during post-glacial time have probably been a moderate fraction of the glacial-interglacial changes, and have been on the order of a few degrees in temperature or a few inches of precipitation.

Historical records show that annual climatic variability is high compared to short-term averages; some of the variability may occur in cycles from a few years to twenty years in length.

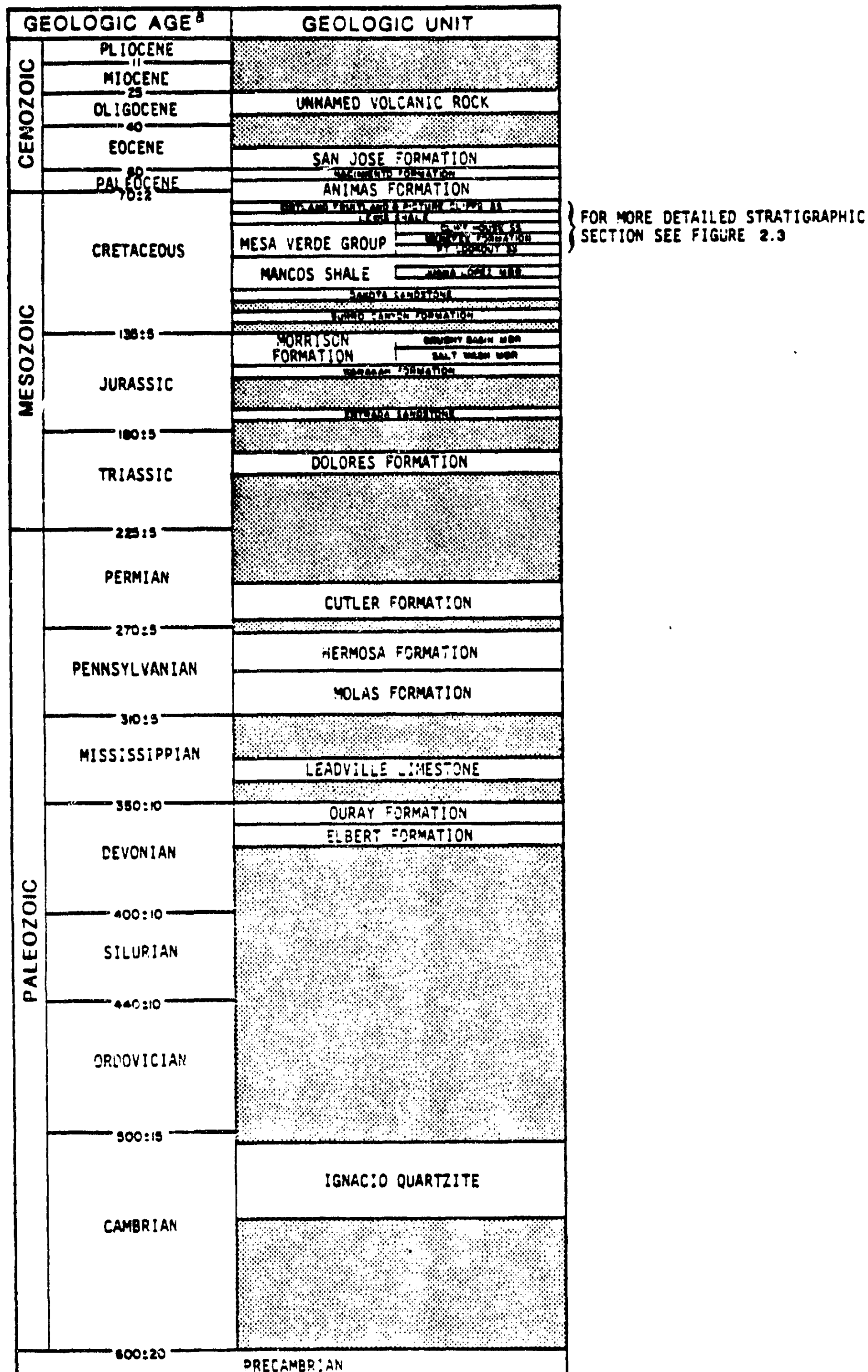
Average values for longer periods during postglacial time, on the order of a hundred to several hundred or perhaps even a thousand years, probably fall within the range of historical values. However, extreme events, representing the maximum range of variation with respect to these very long-term averages, may have fallen beyond the range of modern variation, and these events usually have important geomorphic effects.

2.2 STRATIGRAPHIC SETTING

The Colorado Plateau is a structural province containing a thick, nearly flat-lying sequence of Paleozoic, Mesozoic, and Cenozoic rocks. Rocks ranging in age from Precambrian (more than 600 million years old) to Quaternary (less than one million years old) underlie the area and crop out within 20 miles of the site (Figure 2.2). The upper several thousand feet of bedrock southwest of Durango consist only of Cretaceous sandstone, shale, and siltstone. In some areas this Cretaceous bedrock is overlain by a thin veneer of Quaternary surficial materials. Because only geologic units of Cretaceous and Quaternary age would be affected by the remedial actions, only rocks of these ages are discussed in detail.

The detailed stratigraphy of the Cretaceous bedrock at the Bodo Canyon site area is shown in Figure 2.3. The lowermost Cretaceous units are the Dakota Sandstone and the Burro Canyon Formation. These sandstone and conglomerate units comprise one of the major groundwater and oil and gas reservoirs of southwestern Colorado. The 200-foot-thick Dakota also contains potentially economic coal resources.

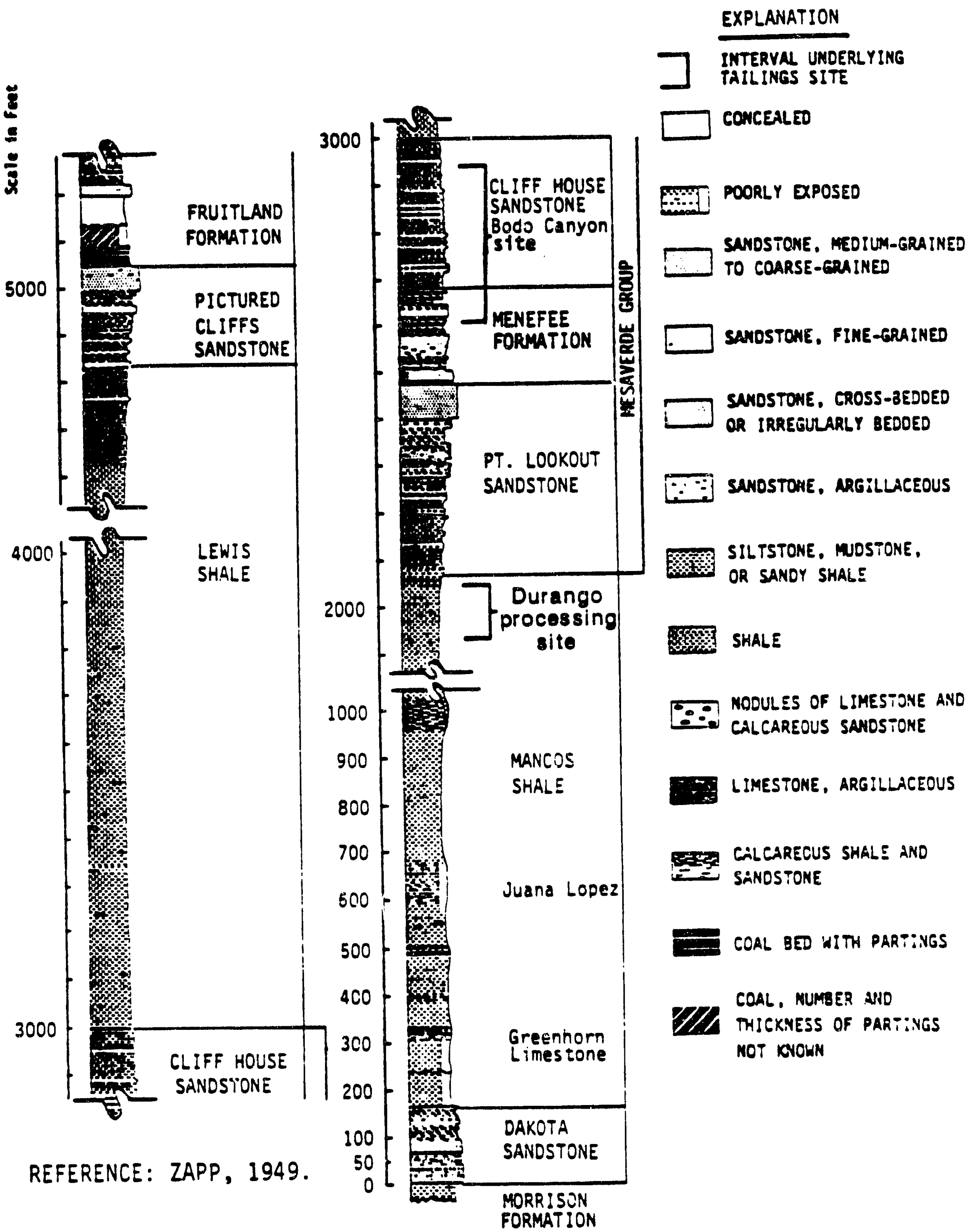
Overlying the Dakota Sandstone is a thick (1900 feet), dark gray, silty shale called the Mancos Shale (Zapp, 1949). Thin limestone (25 feet thick) and sandy shale (80 feet thick) marker beds within the Mancos have



REFERENCE: CGS, 1974; STEVEN et al., 1974.

[a] IN MILLIONS OF YEARS

FIGURE 2.2
GENERALIZED STRATIGRAPHY
BODO CANYON SITE REGION, COLORADO



REFERENCE: ZAPP, 1949.

FIGURE 2.3
STRATIGRAPHY OF CRETACEOUS ROCKS
BODO CANYON SITE AREA, COLORADO

been named the Greenhorn Limestone and Juana Lopez Member, respectively (Steven et al., 1974).

The Mesaverde Group, which overlies the Mancos Shale, is divided into three separate rock units (Zapp, 1949). The lowermost Mesaverde rock unit is the Point Lookout Sandstone, a light-colored, thin-bedded to massive, 400-foot-thick sandstone unit. The erosion-resistant Point Lookout Sandstone caps the Smelter Mountain hogback north of the site. Overlying the Point Lookout Sandstone is a complex assemblage of lenticular sandstone beds, dark-colored shale and siltstone beds, and coal beds called the Menefee Formation. The Menefee Formation ranges from 250 to 350 feet in thickness and contains the major coal resources. This formation, together with the Point Lookout Sandstone, forms the major bedrock aquifer in the area; the aquifer is utilized by the Durango West and Rafter J subdivisions located about eight miles west of the Bodo Canyon site. The Cliff House Sandstone, overlying the Menefee Formation, consists of interbedded calcareous sandstone, siltstone, and silty shale. Although it is a resistant, ledge-forming unit in the vicinity of Mesa Verde National Park, the Cliff House Sandstone southwest of Durango is much less resistant to erosion than are the underlying Point Lookout Sandstone and the overlying Pictured Cliffs Sandstone. The Bodo Canyon site is underlain by the Cliff House Sandstone (described above) and the Menefee Formation, which consists primarily of sandy shale, siltstone, shaley sandstone, and sandstone beds with occasional thin coal beds (Figure 2.3).

The Lewis Shale, characterized by poorly vegetated slopes composed of dark gray to black, almost homogeneous shale, overlies the Mesaverde Group (Zapp, 1949). The basal contact is very sharp with black clay shale overlying gray mudstone or sandy shale of the Cliff House Sandstone, while the upper 300 feet of the Lewis Shale is sandy and transitional upward into the Pictured Cliffs Sandstone (Zapp, 1949).

Overlying the Lewis Shale is a light-colored, massive, resistant sandstone that closely resembles the Point Lookout Sandstone and has been named the Pictured Cliffs Sandstone (Zapp, 1949). This sandstone is 200 feet thick and caps a hogback (Basin Mountain) parallel to, but south of, the Point Lookout hogback. Also, like the Point Lookout Sandstone, the Pictured Cliffs Sandstone forms an aquifer in the subsurface.

Several additional Cretaceous bedrock units are found in the Durango area, but all lie stratigraphically above the disposal site; therefore, they have not been described in detail.

Widespread deposits of Quaternary alluvium, colluvium, loess, and glacial outwash overlie the Cretaceous bedrock southwest of Durango. The Animas River Valley contains deposits of bouldery cobble gravel, sand, and silt that may reach 80 feet in thickness (Zapp, 1949). The former Durango processing site is partially underlain by these alluvial gravels. Four Quaternary gravel terraces have been mapped at elevations of 40 to 370 feet above the present levels of the Animas and La Plata Rivers (Moore and Scott, 1981). These terraces are composed primarily of 20 to 120 feet of igneous- and metamorphic-rich cobble gravel formed by glacial outwash. Thin deposits of sheetwash alluvium, derived from these glacial outwash terraces, have formed in some of the shale valleys. Where not overlain by alluvium, the shale in the valleys is generally covered by a thin veneer of colluvium and weathered bedrock.

The Bodo Canyon site is underlain by as much as 65 feet (Dames & Moore, 1983a) of clayey to sandy silt, alluvium, and colluvium.

2.3 STRUCTURAL SETTING

The Bodo Canyon site is located in the eastern portion of the Colorado Plateau, a large, relatively stable continental platform centered in the Four Corners area. The site area is considered to be within the interior portion of the Plateau, which contains thick sequences of Paleozoic and Mesozoic sedimentary rocks that are flat-lying to gently folded. The broad, gentle folds form several downwarps in the central and eastern Plateau (Figures 2.4 and 2.5), including the Uinta Basin, the Black Mesa Basin, and the San Juan Basin (King, 1959). The San Juan Basin extends into the Durango and Bodo Canyon site area in a southeast-dipping fold called the Hogback Monocline. This monocline, with dips ranging from 35 degrees to nearly flat-lying, forms the northwestern rim of the San Juan Basin (Woodward and Callender, 1977).

The eastern portion of the Colorado Plateau is characterized by a lack of faulting except in areas bounding major uplifts. One such uplift, the Uncompahgre Uplift, formed the highlands between the Uinta (Piceance Basin) Basin to the northeast and northwest, respectively; and the Paradox Basin to the southwest during the deposition of the early-Tertiary Green River "oil shale." The boundary between the Uncompahgre Uplift and the Paradox Basin, marked by a series of northwest-trending faults, is located 120 km (75 miles) northwest of Durango.

A second area of prominent faulting occurs 160 km (100 miles) east of Durango in the Rio Grande Rift Zone. The rift contains numerous north-south trending "basin and range" style block faults, which are described by Kirkham and Rogers (1981) as the most active faults in Colorado.

The northern San Juan Basin, including the Hogback Monocline, contains relatively few faults. In the immediate area of the Bodo Canyon site, however, the sedimentary rocks of the monocline have been folded into a relatively sharp, southwest-plunging anticline and syncline. These folds, called the Durango Anticline and the Perins Peak Syncline, are bounded on the southeast by several northeast-trending normal faults. Displacements along these faults are small, ranging from 30 to 300 feet. These structures are discussed in more detail in Section 2.4.

The Paradox Basin, outlined on Figure 2.5, is a Paleozoic basin defined by the limits of the Paradox Salt Formation. Its eastern boundary just slightly overlays the site area. The several thousand foot thick salt formation that causes structural deformation in the salt core anticline region is only 100 feet thick in the site area. The structural provinces that border the Colorado Plateau nearest to the site are the Southern Rocky Mountains province 16 km (10 miles) northeast and the Rio Grande Rift Province, 105 km (75 miles) to the east southeast.

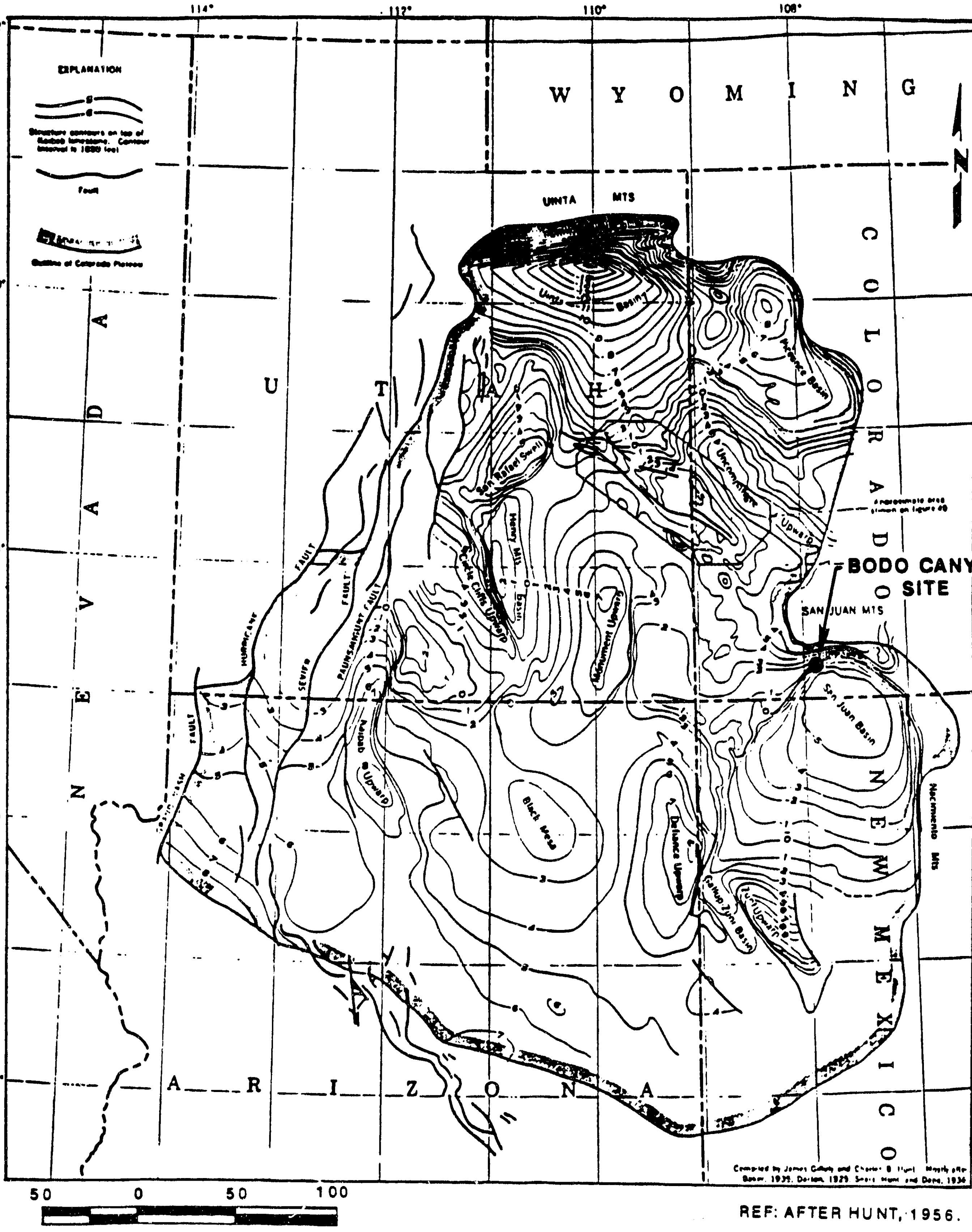


FIGURE 2.4
STRUCTURE CONTOUR MAP OF THE COLORADO PLATEAU
BODO CANYON SITE

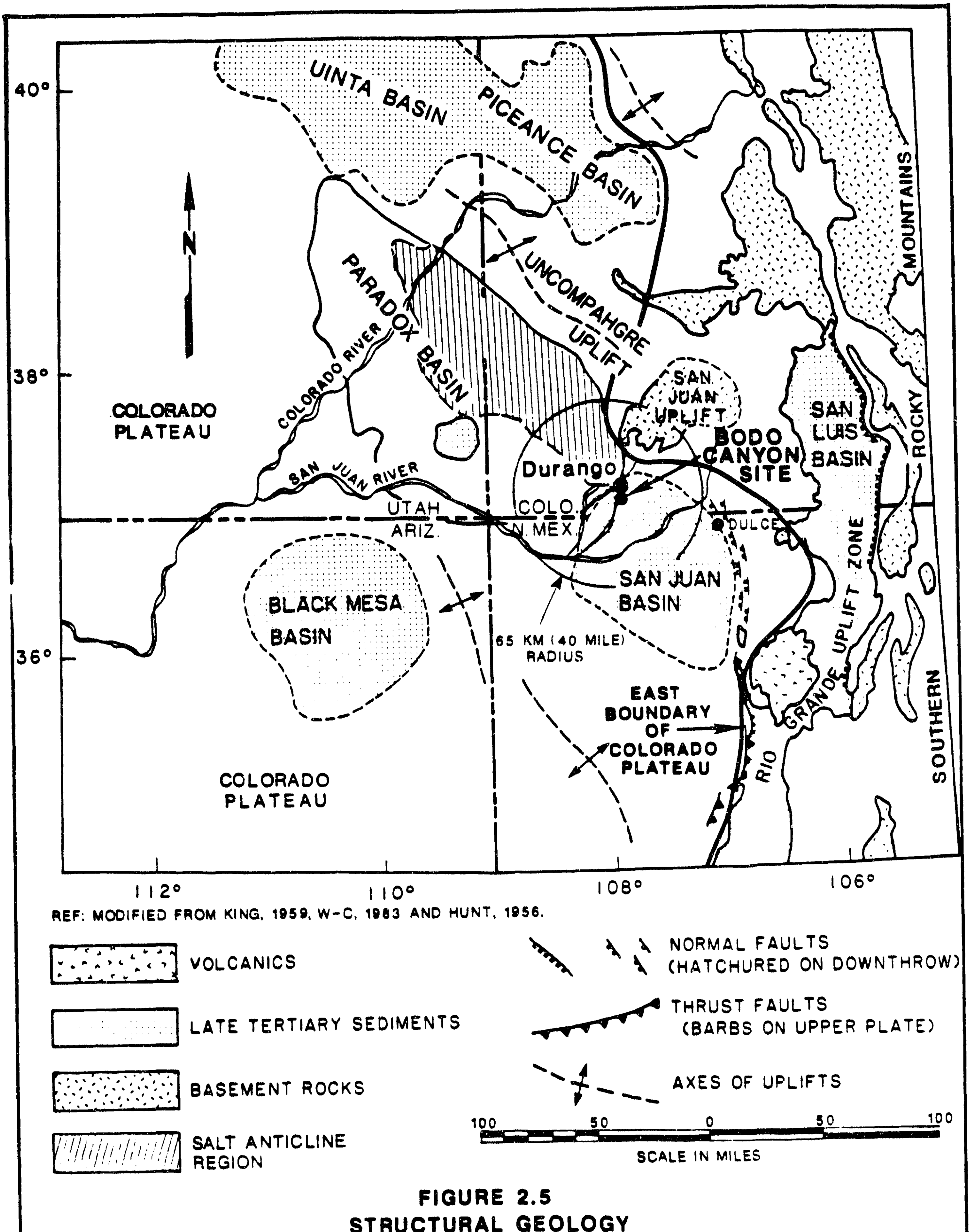


FIGURE 2.5
STRUCTURAL GEOLOGY
OF THE BODO CANYON SITE, COLORADO

The Bodo Canyon site lies on the southeast limb of the Durango anticline, which is a relatively minor structural feature superimposed on the Hogback Monocline along the north-northwest boundary of the San Juan Basin (Figure 2.5). The bedrock in the Bodo Canyon area dips to the southwest at an angle that varies between five and 15 degrees. Dips farther to the south of the site are in the same direction but range up to as much as 40 degrees from the horizontal.

2.4 SEISMOTECTONICS

The first recorded earthquake in Colorado occurred in 1870, so the historical record covers only 114 years, which is too short a period for use in developing a completely reliable database for the analysis of future seismic risk. The length of the record for the adjoining states is comparable. The historical record for New Mexico dates to 1849 (Sanford et al., 1981), for Arizona, to 1776 (DuBois et al., 1982), and for Utah, to 1850 (Arabasz et al., 1979). The instrumental record is considerably shorter, generally dating to the early 1960s. As a general rule, the historical record for the region is probably reliable for earthquakes of magnitude greater than 4.5 occurring after 1960 (von Hake, 1984). In order to predict future earthquakes associated with faults that may have recurrence intervals of thousands to tens of thousands of years, studies of the geologic and seismotectonic setting, recent geologic history, and evidence of recent fault movements are required.

Colorado has been divided into seismotectonic provinces by Kirkham and Rogers (1981), based on the distribution and characteristics of Neogene faults, historical earthquakes, major structural and physiographic regions, and interpretations of earthquake potential. Those provinces that are significant to a seismic hazard evaluation of the Durango area are shown on Figure 2.6, which also delineates the major seismotectonic provinces in the neighboring states of New Mexico, Arizona, and Utah. The site area lies near the eastern margin of the Colorado Plateau province, in a zone that is transitional with the neighboring Western Mountain province, and lies within about 105 km (65 miles) of the Rio Grande Rift province.

The dominant seismotectonic feature of the Durango region is the Rio Grande Rift, a major intracontinental extensional feature that appears to be related to most of the Neogene or younger faulting and associated igneous activity of Colorado and New Mexico. The Rio Grande Rift is, therefore, the major potential source region of large earthquakes that could impact the disposal site area. Other source areas of significance to Durango are the Uncompahgre Uplift and other specific source zones within the Colorado Plateau, an unexplained seismic source near Dulce, New Mexico, and the boundary zone of the Colorado Plateau and Western Mountain provinces.

Due to the limits of the historical and instrumental records, the maximum credible earthquakes (MCEs) for specific seismogenic sources, such as the Uncompahgre Uplift or the unknown features responsible for the Dulce events, can only be estimated based on geologic and geomorphic criteria. Recurrence relationships and estimates of the probability of various ground accelerations occurring at the sites as a result of earthquakes associated with these specific features can be developed, but not with a high level of

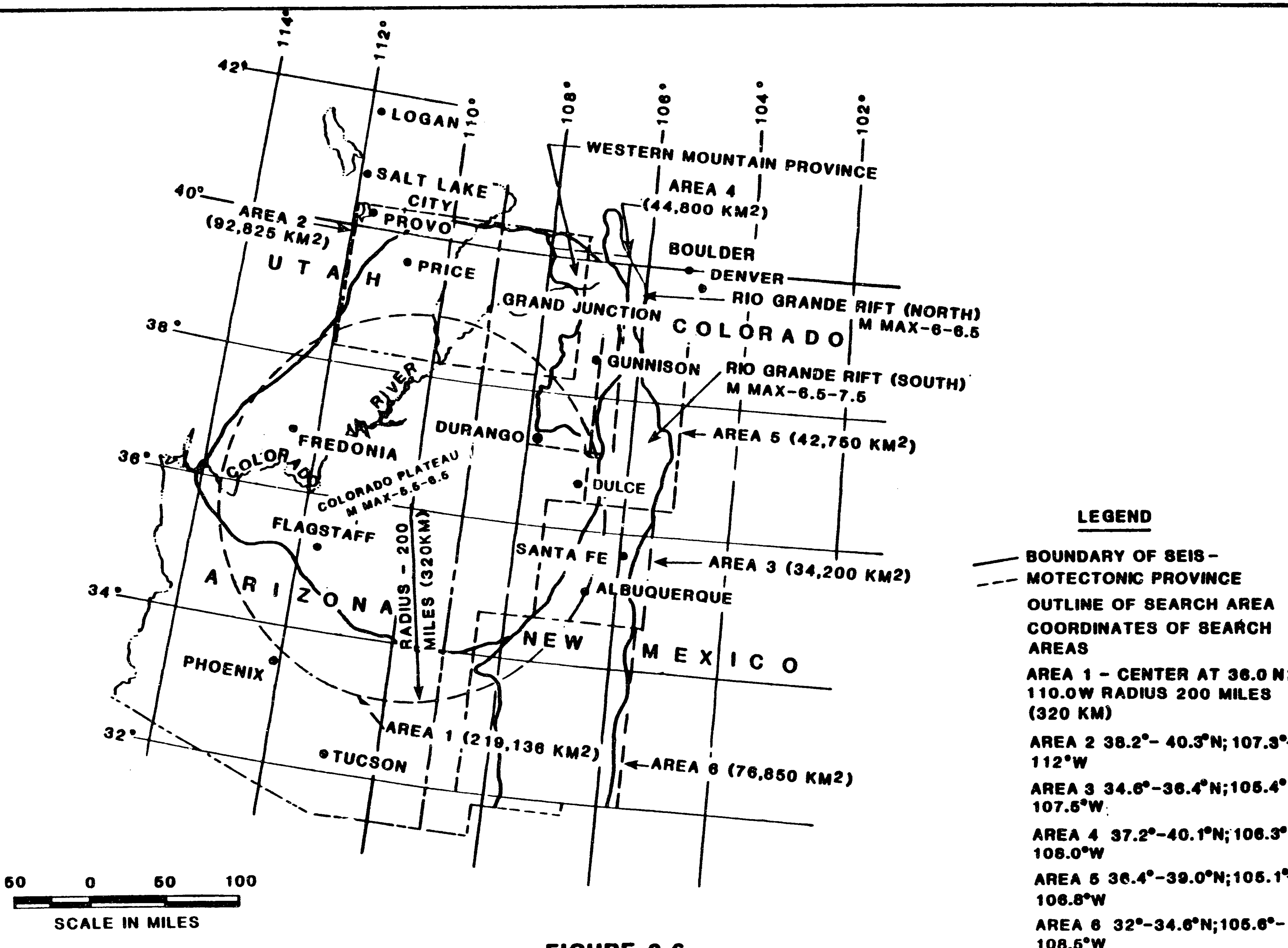


FIGURE 2.6
SEISMOTECTONIC SETTING BODO CANYON SITE REGION, COLORADO

confidence. The MCEs and recurrence relationships can be more reliably estimated for larger areas, such as seismotectonic provinces, and probabilistic estimates can be developed for them with a higher degree of confidence.

Colorado Plateau province

The Colorado Plateau is a major tectonic block composed of Paleozoic and Mesozoic rock, underlain by a core of Precambrian rock, that has been uplifted at a rate of about two millimeters per year since late Tertiary time (Gable and Hatton, 1980). It covers an area of approximately 114,000 square miles (295,000 square km) in western Colorado and adjoining areas of New Mexico, Arizona, and Utah. The site area lies near the eastern margin of the plateau. Neogene faulting is generally rare within the region of the Colorado Plateau surrounding the site, except for faulting associated with the Uncompahgre Uplift located approximately 97 km (60 miles) north of the site, the salt anticlines region located approximately 105 km (65 miles) northwest of the site, and an undefined earthquake source located near Dulce, New Mexico, approximately 80 km (50 miles) southeast of the site.

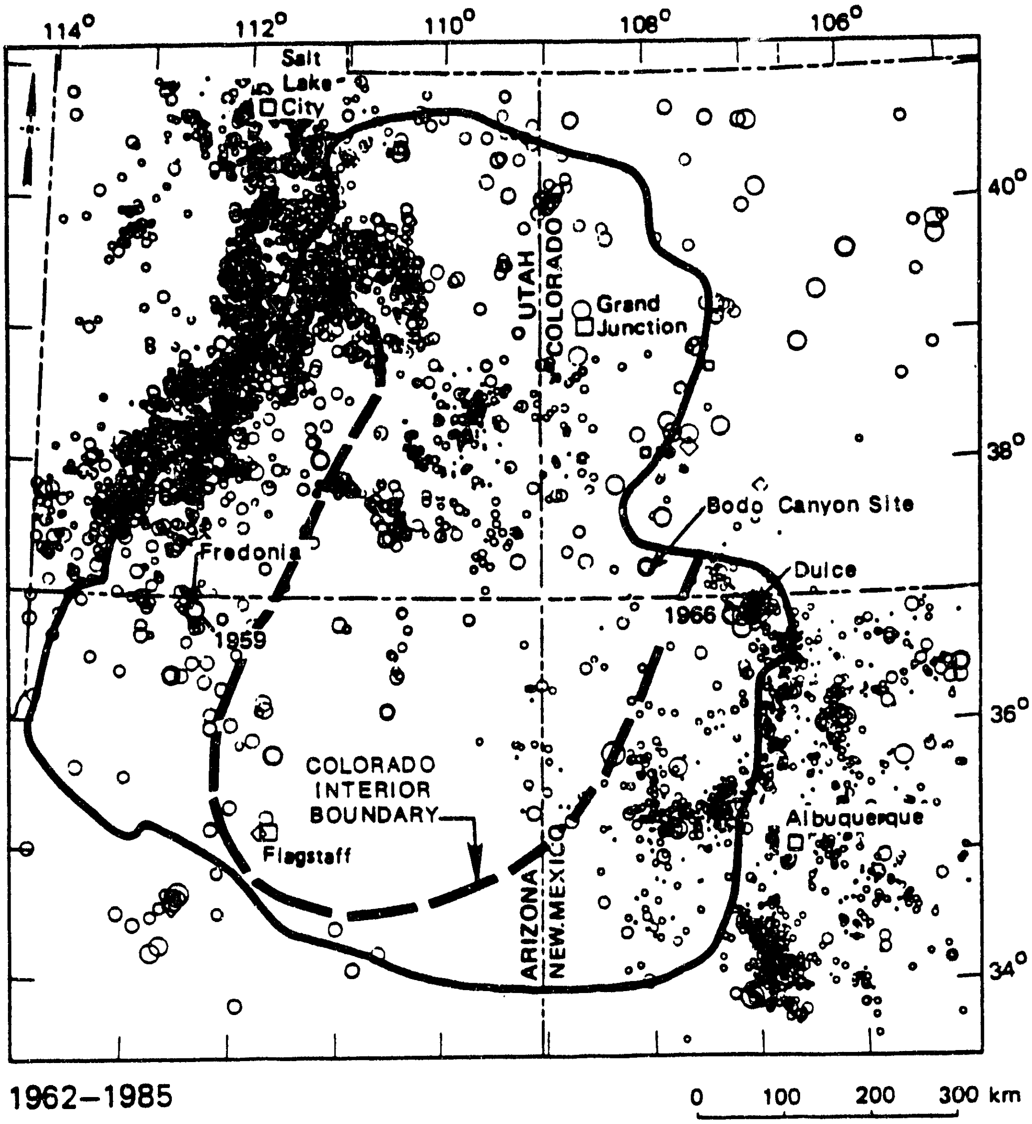
Surface wave dispersion and seismic refraction data show that the crust of the interior of the Colorado Plateau is approximately 45 km thick (Keller et al., 1979). Crustal thicknesses in the Basin and Range province bounding the plateau on the west and south, and in the Rio Grande Rift, generally average 30 to 35 km. Seismic data indicate that the thinner crust extends as much as 100 km into the plateau. Keller et al. (1979) conclude from this data that the zones of crustal extension or rifting bounding the Colorado Plateau appear to be growing. The Colorado Plateau is bordered by a marginal zone of increased seismic activity that includes the site area, as shown in Figures 2.7 and 2.8. The site area is considered to lie in a zone of elevated seismic risk relative to the interior of the plateau.

The highest earthquake magnitude recorded within the Colorado Plateau is estimated to be 5.5 to 5.75 (DuBois et al., 1982). This event occurred on July 21, 1959, near Fredonia, Arizona. Slemmons (1985) concludes that a magnitude of 5.7 to 6.0 is the MCE for the plateau.

San Juan Basin

The Durango area lies on the northern margin of the San Juan Basin, a thick section of sedimentary rock of Jurassic to Tertiary age located within the Colorado Plateau, that extends southward into New Mexico. The basin has not been associated with significant historical seismicity, with the exception of the Dulce, New Mexico, events (Sanford et al., 1981). No potentially active faults are presently recognized within the San Juan Basin (Kirkham and Rogers, 1981; Howard, 1978), excluding the unexplained structures responsible for the Dulce events.

A swarm of over 500 instrumentally detected earthquakes, about 40 of which were felt, occurred in the Dulce area beginning on January 23, 1966.



LEGEND

Earthquake epicenters

Magnitude M_L	Intensity MM
○ ≥ 6	◇ ≥ VI
○ = 5	◇ = V
○ = 4	◇ = IV
○ = 3	◇ = III
○ = 2	◇ = II
○ = 1	◇ = I

Symbol sizes are on a continuous nonlinear scale.

REF: WONG AND HUMPHREY, 1989

NOTE: HISTORICAL SEISMICITY, 1849 TO 1961
CONTEMPORARY SEISMICITY, 1962–1985

FIGURE 2.7
SEISMICITY MAP OF THE COLORADO PLATEAU

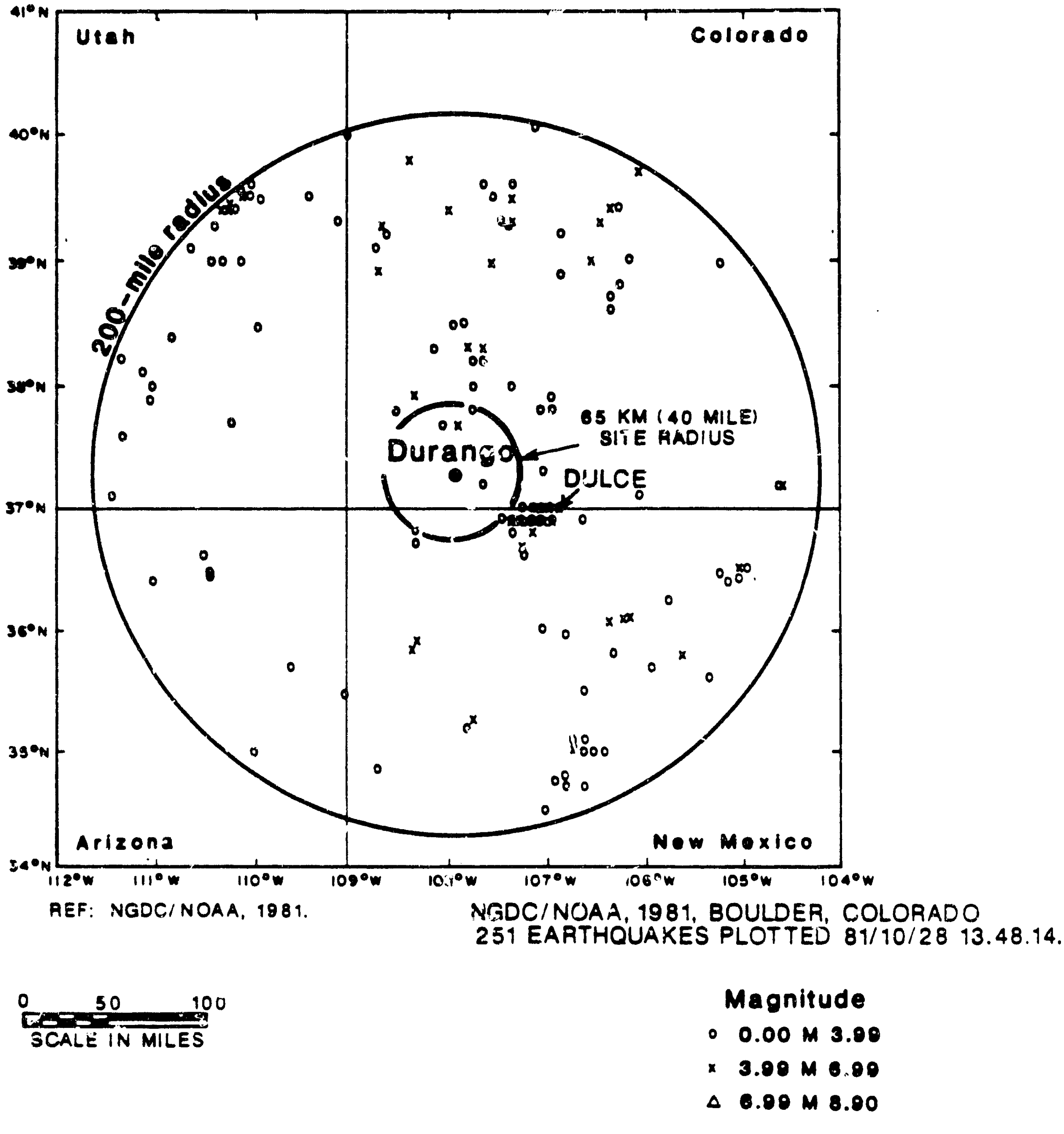


FIGURE 2.8
EARTHQUAKE EPICENTERS WITHIN A 200-MILE RADIUS OF BODO CANYON SITE, COLORADO

The maximum magnitude recorded was 5.5. Movement apparently occurred as a result of reactivation of one or more of a family of north-northwest-trending normal faults that had previously experienced a period of maximum activity in Miocene time (Herrmann et al., 1980). Northrup (1976) has suggested that the epicentral region might be similar tectonically to the Rio Grande Rift, and Zoback and Zoback (1980) have noted that the east-west orientation of tensional axes characteristic of the Rio Grande Rift extends well into the Colorado Plateau in this region.

The northern San Juan Basin shows evidence of extensive faulting along its northeastern and eastern boundaries, but areas along its northwestern boundary, including the Hogback Monocline, have not been subjected to major faulting. However, a series of northeast trending faults, thought to have been formed during the Laramide Orogeny, have been mapped in the Durango area. Among these, a northeast trending fault, herein called the "Ridges Basin Fault," has been mapped (Zapp, 1949) from Ridges Basin into Bodo Canyon. It has been postulated by some (CGS, 1981) that the Ridges Basin Fault may extend into or near the Bodo Canyon disposal site. Several small faults with displacements of less than 10 feet are exposed in a man-made cut slope to the south of the site, but are not thought to be related to the fault mapped by Zapp since their displacements are in the opposite direction (Dames and Moore, 1983b). Thus, all evidence available at this time indicates that the fault dies out just south of the site. This has been confirmed by field reconnaissance, low sun angle aerial reconnaissance, and trenching at the Bodo Canyon site.

It is possible that the Dulce region, though lying within the physiographic limits of the Colorado Plateau, is experiencing tectonic processes representative of the Rio Grande Rift. Since no surface fault ruptures have been recognized in the Dulce area, the actual MCE cannot be estimated using correlations between magnitude and fault characteristics. The upper-bound magnitude of 6.5, assigned to the Colorado Plateau by Kirkham and Rogers (1981), probably represents a conservative estimate for events on defined structures within the plateau or undefined structures within border zones. On this basis, the seismic source zone at Dulce is assigned an MCE magnitude that would result in a maximum acceleration in the site area of approximately 0.04g, as indicated in Table 2.1. Assuming an MCE magnitude of 7.5, the accepted upper bound value for the Rio Grande Rift, the larger maximum acceleration of 0.09g is obtained. A magnitude 7.5 event may represent an unreasonably high MCE for the Dulce area, as it assigns to a specific feature the upper bound magnitude that is applied to the Rio Grande Rift as a whole. A magnitude 6.0 event, the MCE event for the Colorado Plateau assumed by Slemmons (1985), would result in an acceleration of 0.03g.

Since no specific seismogenic sources are recognized in the Dulce area and the historical earthquake record in the area is insufficient, no recurrence relationship for this area was derived. Therefore, calculation of the probability that a given ground acceleration could be exceeded in the future was not attempted.

Table 2.1 Estimated maximum horizontal rock acceleration at site area

Source area/fault	Maximum credible earthquake magnitude[a]	Distance from center of site area	Maximum horizontal acceleration in rock expected at site area (fraction of unit gravity)[b]
Rio Grande Rift	7.5	65 miles (105) km)	0.06
Uncompahgre Uplift	6.5[c] 7.1[d]	60 miles (97 km)	0.03 0.05
Dulce, New Mexico	6.0[e] 6.5[c] 7.5[f]	51 miles (83 km)	0.03 0.04 0.09
Boundary Zone of Colorado Plateau and Western Mountain Province	6.5	10 miles (16 km)	0.3[g]

[a]See text for explanation of values assumed.
[b]Extrapolated from Seed and Idriss (1982).
[c]Kirkham and Rogers (1981) upper bound value for the Colorado Plateau.
[d]Based on rupture length equal to 1/2 fault length and relationships in Slemmons et al. (1982).
[e]Using upper bound value for Colorado Plateau estimated by Slemmons (1985).
[f]Using Kirkham and Rogers (1981) upper bound value for the Rio Grande Rift.
[g]See discussion in this section.

Uncompahgre Uplift

The Uncompahgre Uplift is a large, northwest-trending, asymmetrical block within the Colorado Plateau composed of Precambrian igneous and metamorphic rock overlain by Mesozoic sedimentary rock. It rose during the Neogene from the crest of an older, much larger highland that was a prominent structural feature during the Late Paleozoic (Cater, 1966). The modern Uncompahgre Uplift is a northeast-tilted block that has experienced considerable movement during the Pliocene and Quaternary along bounding faults and monoclines.

Kirkham and Rogers (1981) have identified 25 northwest-trending faults of Late Cenozoic age that flank the Uncompahgre Uplift (Figure 2.5). They are located between 97 and 103 km (60 and 120 miles) to the north-northwest of the site area. The closest is the Ridgeway fault, which bounds the southern end of the uplift approximately 97 km (60 miles) to the north of the site area. Studies of the Ridgeway fault and associated faults (Sullivan et al., 1980) identified two distinct swarms of microearthquakes occurring in 1978 and 1979 with epicenters centered on the Ridgeway fault. Small faults offset pre-Wisconsin aged Quaternary gravel exposed in a pit within the Ridgeway fault system. The combined evidence of modern seismicity and Quaternary activity requires that the Ridgeway fault system be considered active. Other faults considered to be active are located along the southwestern and northeastern flanks of the uplift at slightly greater distances from the site area.

Applying methods delineated by Slemmons (1977) and Slemmons et al. (1982), which use mapped fault segment lengths and assume a one-half fault length rupture during an MCE, the Uncompahgre Uplift is assigned an MCE magnitude of 7.1. This value is somewhat higher than that derived by Kirkham and Rogers (1981). The site area can expect to experience a maximum rock acceleration of 0.05g during an MCE event within the Uncompahgre Uplift. Recurrence relationships for use in probability estimates were not computed because of the lack of a detailed historical earthquake record associated with this source.

Salt anticlines region

The Pennsylvanian-aged Paradox Basin is located to the northwest of the site area, and southwest of the Uncompahgre Uplift. Associated with this basin are northwest-trending, salt-cored anticlines that collapsed along their crests in a graben-like fashion during the Neogene. The anticlines are believed to be controlled by large subsurface faults which apparently have experienced several episodes of activity since the Late Paleozoic. The anticlines themselves experienced movement in the Quaternary and may well be active today (Cater, 1970; Hunt, 1956). The current episode of collapse may have begun when the Colorado Plateau was uplifted during the Miocene, during which the anticlines were breached and their cores exposed by erosion. Rapid dissolution and flowage followed exposure, causing complex faulting.

It is unlikely that these features can generate earthquakes having a magnitude larger than four or five (Kirkham and Rogers, 1981). Considering their distance from the site area, they do not appear to represent a critical factor in seismic hazard analysis. However, the large subsurface faults which control the locations of the anticlines are not exposed, and it is not known if they are still active. They might represent a potential source of typical Colorado Plateau earthquakes.

Western Mountain province

The Western Mountain province comprises the mountainous areas to the west of the Rio Grande Rift extending as far as the border of the Colorado Plateau. This province is approximately the same as the Rocky Mountain Physiographic Province of Hunt (1956). This province includes the San Juan, Elk, and West Elk Mountains, the west flank of the Sawatch Range, and the White River and Gunnison uplifts. Relatively few Neogene faults are known in this province. Neogene rocks in the San Juan Mountains are offset by faults related to caldera collapse, but these are not considered to be active faults (see Figure 2.9).

Minor evidence of Neogene reactivation of west-to-northwest-trending Precambrian faults such as the Cimarron fault (Fault No. 94 of Kirkham and Rogers, 1981), and a few other Neogene faults scattered throughout the province, has been identified but none are major tectonic faults that have experienced any known significant Quaternary activity. The closest potentially active faults to the site area are collapse features of the Lake City Caldera.

Border zone of Colorado Plateau and Western Mountain province

Earthquake epicentral maps of the Colorado Plateau region show a generally heightened level of seismic activity within the narrow border zone along the contacts with the adjoining provinces (Figure 2.9). For this reason, the border zone of the Colorado Plateau and Western Mountain provinces, which is located within 16 km (10 miles) of the site area, is considered to represent a zone of higher seismic hazard. The MCE 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 MCE associated with the border zone of the two provinces is assumed herein to have a magnitude of 6.5.

The maximum horizontal acceleration in rock expected at the site area, from a possible MCE event having a magnitude of 6.5, occurring within 10 miles of the site area, is 0.3g, as detailed in Table 2.1. This value represents one of the higher calculated accelerations, but recurrence relationships and probabilities cannot be calculated separately. The probability of a magnitude 6.5 event occurring within 10 miles of the site area is considered in the probability analysis of Section 4.2.

Rio Grande Rift

The Rio Grande Rift is a north-south-trending extensional graben feature of great length and tectonic significance. It extends from Chihuahua, Mexico, through west Texas, New Mexico, and most of central Colorado, almost to the Wyoming state line. The rift was initiated in

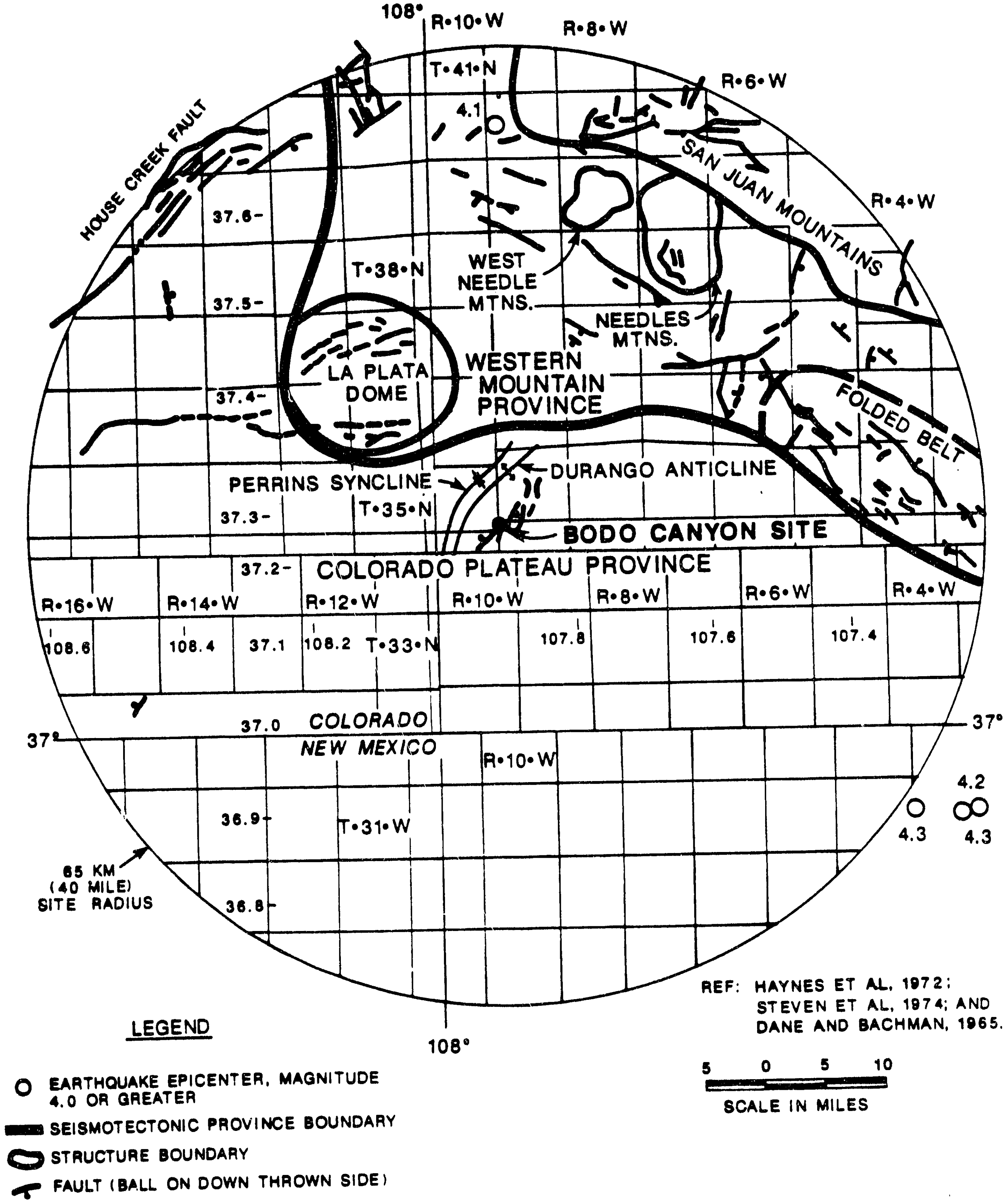


FIGURE 2.9
FAULT AND EPICENTER MAP
BODO CANYON SITE REGION, COLORADO

Neogene time and has experienced continued activity through the Quaternary. It is characterized by fault scarps in young alluvium; abrupt mountain fronts that exhibit faceted spurs; deep, narrow, linear valleys; Neogene basin-fill sedimentary rocks; and a bimodal suite of mafic and silicic igneous rocks.

A high percentage of all the potentially active faults in Colorado and New Mexico lie within the Rio Grande Rift province. The rift has been subdivided into northern and southern subprovinces in Colorado by Kirkham and Rogers (1981) on the basis of young faulting. Well-defined evidence of repeated Late Quaternary movement is abundant on several faults in the southern subprovince, whereas such evidence is obscure in the northern subprovince.

Within the southern rift subprovince, several potentially active fault systems with lengths in excess of 161 km (100 miles) exist. The closest of these to the site area is the north-northwest-trending Sangre de Cristo fault, which lies at the base of the Sangre de Cristo Mountains along the east side of the San Luis Valley, about 210 km (130 miles) east of the site area. The west flank of the valley is locally broken by small displacement faults.

Strong earthquakes within the Rio Grande Rift are generally associated with earthquake swarms, which worldwide are generally associated with active volcanoes and areas that have had volcanic activity in geologically recent times (Richter, 1958). Earthquake swarms in the Rio Grande Rift may be associated with the injection of magma into the crust (Sanford et al., 1979; 1977). Earthquake swarms in the Rio Grande Rift are generally located in central New Mexico (Sanford et al., 1981) and would not significantly impact the site area at such distances. However, the strongest recorded New Mexico earthquake in the era of accurate instrumental data (1962 to present) was the January 23, 1966, event at Dulce, which occurred within the Colorado Plateau province. Several investigators (Herrmann et al., 1980; Zoback and Zoback, 1980; Northrup, 1976) have suggested that the Dulce event might be considered representative of the tectonic processes operating within the Rio Grande Rift rather than the Colorado Plateau. This would imply an extension of the east-west oriented tensional tectonic stress regime of the rift into the margin of the Colorado Plateau.

The estimated magnitude of an MCE associated with the Rio Grande Rift in Colorado (Kirkham and Rogers, 1981) is 6.5 to 7.5. The nearest approach of the rift to the site area is about 105 km (65 miles). An event of magnitude 7.5 occurring at this distance from the site area would result in a horizontal rock acceleration of 0.06 g, as detailed in Table 2.1.

Regional seismicity

No known Neogene or younger faults occur within 50 miles of Durango (Kirkham and Rogers, 1981), and only minor seismicity has been recorded during the past 100 years near Durango. Locations and dates of the largest known earthquakes within a 200-mile radius of Durango during the past 100 years are listed in Table 2.2. Figure 2.8 and Tables 2.3 through 2.8 show the epicenters and all known macroseismic events for this radius.

Table 2.2 Largest earthquakes within a 200-mile radius of the Bodo Canyon site

Date	Modified Mercalli Intensity (Richter magnitude)	Epicentral location	km (miles) from site
1941 Aug. 29	V (?)	Bayfield, CO	26 (16)
1966 Jan. 25	?	Bayfield, CO	26 (16)
1967 Jan. 16	V (4.1)	Purgatory, CO	45 (28)
1966 Jan. 23	? (4.6)	Dulce, NM	66 (41)
1882 Nov. 23	IV (?)	Silverton, CO	68 (42)
1966 Jan. 23	VII (5.5)	Dulce, NM	84 (52)
1966 June 2	VI (5.0)	Dulce, NM	88 (55)
1928 Apr. 20	V (?)	Creede, CO	111 (69)
1955 Aug. 3	VI (?)	Lake City, CO	111 (69)
1913 Nov. 11	V (?)	Ouray, CO	114 (71)
1976 Jan. 5	VI (5.0)	Gallup, NM	164 (102)
1918 May 28	VIII (?)	Cerrillos, NM	228 (142)
1980 Sept. 11	V (3.1)	Cimarron, NM	256 (159)

Data from NGDC/NOAA, 1981; and von Hake, 1975; Hadsell, 1968.

According to the National Oceanic and Atmospheric Administration's (NOAA) earthquake data file (NGDC/NOAA, 1981), the closest event to the site was recorded on August 29, 1941, having an epicenter located 26 km (16 miles) east of Durango. Although no magnitude or intensity was given in the data file for this event, Hadsell (1968) estimated that the event had a Modified Mercalli Intensity (MMI) of V. The Coast and Geodetic Survey (NGDC/NOAA, 1981) recorded a second event with the same epicentral location on January 24, 1966. No magnitude or intensity is listed for the 1966 event.

The nearest MMI VI (Richter magnitude 5.0) event to the site occurred on June 2, 1966, near Dulce, New Mexico. This event, located 88 km (55 miles) southeast of Durango, was probably one of a number of aftershocks that occurred in the Dulce area following the January 23, 1966, MMI VII (magnitude 5.5) Dulce earthquake. The latter event was located 84 km (52 miles) southeast of Durango and was the largest event located within 161 km (100 miles) of the site during the period from 1873 to 1981.

The only MMI VIII event listed (NGDC/NOAA, 1981) within 200 miles of the site occurred on May 28, 1918, near Cerrillos, New Mexico, 228 km (142 miles) away. This earthquake was within the Rio Grande Rift (von Hake, 1975), a north-trending zone in New Mexico and Colorado that is more seismically active than the northern San Juan Basin. No events larger than

MMI VIII or magnitude 5.5 have been recorded by NOAA within a 322 km (200-mile) radius of the site.

Relationship of earthquakes to tectonic structures

According to Kirkham and Rogers (1981), only one fault system in southwestern Colorado, the Uncompahgre Uplift boundary fault, is thought to be capable of generating large earthquakes (magnitude seven to eight). A magnitude 5.5 (MMI VI) event occurred on this fault on October 11, 1960. This fault system is located, however, at least 121 km (75 miles) from the Durango area. Based on estimates of maximum horizontal acceleration in rock versus distance from a causative fault (Schnabel and Seed, 1972), the maximum acceleration for a magnitude 7.6 earthquake at a distance of 121 km (75 miles) is less than seven percent of gravity (0.07g).

The San Luis Valley, approximately 95 miles east of Durango, is located along the Rio Grande Rift Zone, a fault-bounded, down-dropped block containing thick Cenozoic alluvial and volcanic deposits. The eastern boundary fault of the San Luis Valley, the Sangre de Cristo fault, is a major, high-angle, normal fault zone with many thousands of feet of Cenozoic displacement. The last major surface rupture along this fault may have occurred during the past 2000 to 5000 years, with displacements averaging 8.5 feet and recurrence intervals ranging from 3000 to 30,000 years (Kirkham and Rogers, 1981). Using these criteria, the maximum magnitude that could be generated by this fault has been estimated at 7.5 by Kirkham and Rogers (1981). Again, using Schnabel and Seed, the maximum horizontal acceleration in Durango for a 7.6 magnitude event on the Sangre de Cristo fault (a distance of approximately 100 miles) would be less than 0.04g.

The largest historic earthquake in the northern San Juan Basin was the January 23, 1966, Dulce, New Mexico, event. This event was also the largest magnitude event recorded in New Mexico since 1938 (Herrmann et al., 1980). Although Kirkham and Rogers (1981) state that no Neogene faults or folds are known to exist in the Dulce area, several authors (Herrmann et al., 1980; Hoffman and Northrup, 1977; Cash, 1975) indicate that the event and its aftershocks may have occurred on reactivated, 10 million-year-old normal fault within the Precambrian basement. Using Schnabel and Seed's technique (Schnabel and Seed, 1972), a magnitude 5.6 event occurring at a distance of 80 km (50 miles) would create a maximum horizontal acceleration of 0.03g in Durango.

Figure 2.9 shows the epicenter of earthquakes of magnitude $m_b = 4.0$ within a 65-km site radius relative to the known faults, structures, and seismotectonic provinces of the site region.

Potential seismic hazards

The Durango site lies within Zone 1, described in the Uniform Building Code (ICBC, 1982) as follows:

Table 2.3 Recorded seismic history for Colorado Plateau - Area 1

---Date--- YR	MO	DA	---Time--- HR	MIN	SEC	---Location--- LAT(N)	LONG(W)	Depth km	-------Magnitude------- mb	ms	OTHER	LOCAL	Int	Loca-tion	Distance* km (miles)
1963	06	19	08	38	47.5	37.9	112.6	33	4.2						
1965	09	11	11	59	41.0	33.2	110.7	33	4.2						
1966	01	18	20	08	14.4	37.4	113.1	33	4.0				IV		
1966	01	23	01	56	38.0	37.0	107.0	14	5.5				VII	Dulce	88 (55)
1966	01	23	06	14	15.6	36.9	107.2	5	4.2				V	Dulce	80 (50)
1966	01	23	07	44	35.7	36.9	107.3	5	4.6					Dulce	72 (45)
1966	01	25	10	38	05.0	36.8	107.1	5	4.0					Dulce	88 (55)
1966	01	23	11	01	07.1	36.9	107.2	5	4.3				V	Dulce	80 (50)
1966	01	23	23	48	08.1	36.9	107.0	5	4.6				V	Dulce	96 (60)
1966	01	23	19	43	19.7	36.9	107.1	5	4.5					Dulce	88 (55)
1966	05	04	05	40	37.5	36.8	107.1	5	4.1					Dulce	96 (60)
1966	05	08	17	23	37.8	36.9	106.9	5	4.5				V	Dulce	96 (60)
1966	05	08	17	50	35.6	37.0	106.8	5	4.2				V	Dulce	80 (50)
1966	05	09	02	08	53.5	36.9	106.9	5	4.2				V	Dulce	96 (60)
1966	05	09	02	57	23.6	37.0	106.9	5	4.4				V	Dulce	93 (58)
1966	05	19	00	26	42.2	36.9	107.0	5	4.6					Dulce	96 (60)
1966	05	20	13	04	48.8	37.9	112.1	18	4.3						
1966	06	02	21	59	11.5	36.0	107.0	5	5.0				VI	Dulce	96 (60)
1966	06	21	05	24	38.2	36.0	107.1	5	4.2					Dulce	88 (55)
1966	06	04	10	29	39.3	37.0	107.0	5	4.1				V	Dulce	88 (55)
1966	10	03	16	03	50.8	35.8	111.6	33	4.4				V		
1966	12	16	02	00	44.0	37.0	107.0	33	4.2					Dulce	88 (55)
1967	01	06	15	41	15.5	36.9	107.0	33	4.3				V	Dulce	88 (55)
1968	09	24	02	10	51.8	38.0	112.1	33	4.0				V		

*distance shown for epicenters if within 60 km (100 mile) site radius.

Table 2.3 Recorded seismic history for Colorado Plateau - Area 1 (Concluded)

---Date---			---Time---			---Location---		Depth	-------Magnitude-------					Loca-	Distance*
YR	MO	DA	HR	MIN	SEC	LAT(N)	LONG(W)	km	mb	ms	OTHER	LOCAL	Int	tion	km (miles)
1969	12	25	12	49	10.1	33.4	110.6	15	4.4			5.1			
1970	02	03	05	59	35.6	37.9	108.3	33	4.0				V	North-west	84 (52)
1970	04	18	10	42	11.9	37.8	111.6	10	4.4						
1970	05	23	22	55	22.4	38.0	112.3	3	4.6			4.9			
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						
1973	04	19	16	59	42.7	34.3	112.6		4.5				V		
1973	12	24	02	20	14.9	35.3	107.7	18	4.4				V		
1974	03	14	20	59	57.2	34.2	112.7	18	4.1				V		
1976	01	05	06	23	32.9	35.8	108.3	25	5.0			4.6	VI	South-west	161 (100)
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	South-west	160 (99)

Notes:

1. Area 1 defined by a circle of 200-mile (300-km) radius with center located at 36.0N, 110.0W.
2. Listing restricted to events with M > 4.0 occurring after 1960.
3. Data Source: NOAA Earthquake Data File.
4. Average Depth = 14.9 km.

*distance shown for epicenters if within 60 km (100 mile) site radius.

Table 2.4 Recorded seismic history for Colorado Plateau - Area 2

---Date---			---Time---			---Location---		Depth	-------Magnitude-------					Loca-	Distance*
YR	MO	DA	HR	MIN	SEC	LAT(N)	LONG(W)	km	mb	ms	OTHER	LOCAL	Int	tion	km (miles)
1960	10	11	08	05	30.5	38.3	107.6				5.5		VI		
1963	07	07	19	20	42.4	39.6	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	33	4.2				V		
1963	09	02	17	40	15.4	39.6	110.1	33	4.1						
1964	06	06	12	46	59.9	39.4	110.2	30	4.2						
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	04	23	20	20	54.5	39.2	111.4	33	4.4						
1966	04	30	18	29	13.8	39.6	110.4	3	4.0				V		
1966	07	06	05	47	08.3	40.2	108.9	5	4.5				V		
1966	09	04	09	52	34.5	38.3	107.6	33	4.2						
1967	01	12	03	52	06.2	39.0	107.5	33	4.4				V		
1967	02	15	03	28	03.6	40.1	109.1	5	4.5				V		
1967	04	04	22	53	39.5	38.3	107.7	33	4.5				V		
1967	10	25	02	41	34.4	39.4	110.3		4.0				V		
1967	10	25	05	53	08.4	39.4	110.3		4.0				V		
1968	01	16	09	42	54.2	39.2	112.0	33	4.0				V		
1968	08	04	06	23	36.4	39.1	111.4	15	4.0				V		
1968	08	29	09	31	48.1	39.5	110.2		4.2				V		
1968	11	17	14	33	37.5	39.5	110.9	6	4.6				V		
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		
1970	04	14	10	40	54.2	39.7	110.8	13	4.2						

Table 2.4 Recorded seismic history for Colorado Plateau - Area 2 (Concluded)

---Date---			---Time---			---Location---		Depth	-------Magnitude-------					Loca-	Distance*
YR	MO	DA	HR	MIN	SEC	LAT(N)	LONG(W)	km	mb	ms	OTHER	LOCAL	Int	tion	km (miles)
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	10	25	07	46	42.1	39.2	111.4	5	4.3				V		
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						
1975	01	30	14	48	40.3	39.2	108.6	5	4.4			3.7			
1975	10	06	15	50	46.9	39.0	111.4	005	4.2			3.2	II		
1977	09	24	11	16	48.4	39.3	107.3	005	4.0			3.0			
1980	05	27	10	03	36.3	39.9	111.9	005	5.0			4.2	V		
1981	05	14	05	11	04.1	39.4	111.0	1	4.0		4.0	3.5	V		

Notes:

1. Area 2 defined by a rectangle bounded by coordinates 38.2 to 40.3N; 107.3 to 112.0W.
2. Listing restricted to events with M > 4.0 occurring after 1960.
3. Data Source: NOAA Earthquake Data File.
4. Average Depth = 16.7 km.

Table 2.5 Recorded seismic history for Western Mountain Province - Area 3

---Date---			---Time---			---Location---		Depth	-------Magnitude-------						
YR	MO	DA	HR	MIN	SEC	LAT(N)	LONG(W)	km	mb	ms	OTHER	LOCAL	Int	Loca-tion	Distance* km (miles)
1965	05	30	17	31	04.1	39.4	106.3	33	4.3				V		
1066	09	04	09	52	34.5	38.3	107.6	33	4.2						
1966	12	19	20	52	33.3	39.0	106.5	5	4.6				V		
1067	01	12	03	52	06.2	39.0	107.5	33	4.4				V		
1067	01	16	09	22	45.9	37.7	107.9	33	4.1				V	North	48 (30)
1967	04	04	22	53	39.5	38.3	107.7	33	4.5				V		
1971	01	07	20	39	52.1	39.4	107.3	33	4.3			3.8			
1977	09	24	11	16	48.4	3.93	107.3	5	4.0			3.0			

Notes:

1. Area 3 defined by a rectangle bounded by coordinates 34.6° to 36.4°N; 105.4° to 107.5°W.
2. Listing restricted to events with $M > 4.0$ occurring after 1960.
3. Data Source: NOAA Earthquake Data File.
4. Average Depth = 26.0 km.

Table 2.6 Recorded seismic history for Rio Grande Rift in south-central Colorado and northern New Mexico - Area 4

---Date---			---Time---			---Location---		Depth	-------Magnitude-------					Loca-	Distance*
YR	MO	DA	HR	MIN	SEC	LAT(N)	LONG(W)	km	mb	ms	OTHER	LOCAL	Int	tion	km (miles)
1966	05	08	17	50	35.6	37.0	106.8	5	4.2				V		
1966	12	19	20	52	33.3	39.0	106.5	5	4.6						

Notes:

1. Area 4 defined by a rectangle bounded by coordinates 37.2 to 40.1N; 106.3 to 108W.
2. Listing restricted to events with M > 4.0 occurring after 1960.
3. Data Source: NOAA Earthquake Data File.
4. Average Depth = 5 km.

Table 2.7 Recorded seismic history for Rio Grande Rift in north-central New Mexico - Area 5

---Date---			---Time---			---Location---		Depth	-------Magnitude-------					Loca-	Distance*
YR	MO	DA	HR	MIN	SEC	LAT(N)	LONG(W)	km	mb	ms	OTHER	LOCAL	Int	tion	km (miles)
1969	07	04	14	43	34.0	36.1	106.1	10	4.4				V		
1970	11	28	07	40	11.6	35.0	106.7	9	4.5			3.8	VI		
1971	01	04	07	39	06.7	35.0	106.6	9	4.7						
1971	04	28	11	36	52.7	35.8	105.6	5	4.0			3.0	V		
1971	12	06	05	18	13.7	36.1	106.3	5	4.2			3.2			
1973	03	17	07	43	05.5	36.0	106.1	6	4.5				V		

Notes:

1. Area 5 defined by a rectangle bounded by coordinates 36.4 to 39.0N; 105.1 to 106.8W.
2. Listing restricted to events with M > 4.0 occurring after 1960.
3. Data Source: NOAA Earthquake Data File.
4. Average Depth = 7.33 km.

Table 2.8 Recorded seismic history for Rio Grande Rift in south-central New Mexico - Area 6

---Date---			---Time---			---Location---		Depth	-------Magnitude-------					Loca-	Distance*
YR	MO	DA	HR	MIN	SEC	LAT(N)	LONG(W)	km	mb	ms	OTHER	LOCAL	Int	tion	km (miles)
1969	01	30	05	17	37.8	34.3	106.9	8	4.1				V		
1982	09	20	03	55	17.2	33.9	107.0	11	5.0		3.5	2.9	IV		
1983	03	02	23	22	19.4	34.3	106.8	4	4.3		4.3	4.1	VI		

Notes:

1. Area defined by a rectangle bounded by coordinates 32.0 to 34.6N; 105.6 to 108.5W.
2. Listing restricted to events with M > 4.0 occurring after 1960.
3. Data Source: NOAA Earthquake Data File.
4. Average Depth = 9 km.

"Minor damage; distant earthquakes may cause damage to structures with fundamental periods greater than 1.0 second; corresponds to intensities V and VI of the Modified Mercalli Intensity Scale of 1931."

The seismic zone map in the Uniform Building Code (UBC) shows the boundary between Zone 1 and Zone 2 approximately on the Colorado-New Mexico border south of Durango. The Dulce area, the site of most of the earthquake epicenters in the Durango region since 1966, is located in Zone 2, which is described in the UBC as "Moderate damage; corresponds to intensity VII of the MMI Scale."

Work by Algermissen et al. (1982) indicates that the maximum magnitude of an event in the Durango area will be in the range of approximately 6.5 to 7.3. According to Algermissen et al.'s (1982) preliminary map of horizontal acceleration (expressed as percent of gravity) in rock with a 90-percent probability of not being exceeded in 250 years, it is estimated that the maximum acceleration that could be expected to occur at the disposal site would be between 0.08 and 0.10g. The seismic event capable of producing a horizontal acceleration of 0.10g has a calculated mean recurrence interval of approximately 2400 years. Magnitudes of ground motion in the range from 0.08 to 0.10g are approximately equivalent to an MMI VI event.

2.5 MINERAL RESOURCES

Mineral resources in the northern San Juan Basin around Durango and the Bodo Canyon site area include coal, oil, gas, sand, and gravel. In 1980, La Plata County produced 93,619 tons of coal; 68,446 barrels of oil; and 26.7 billion cubic feet of natural gas (CDM, 1981; COGCC, 1981).

The 1980 coal production figures represented an increase of 265 percent since 1977. Coal production in La Plata County during the first nine months of 1981 was 109,979 tons (CDM, 1981). These figures show the increasing demand for, and mining of, coal in the Durango area.

The primary sources of coal in the northern San Juan River region coal resources district are the Fruitland Formation and the Menefee Formation. The Dakota Sandstone Formation is a limited potential source (Murray, 1981). The Bodo Canyon site is located stratigraphically below the Fruitland Formation but overlies the Menefee and Dakota Formations.

The Menefee Formation underlies the Cliff House Sandstone at a shallow depth (100 to 200 feet) below the Bodo Canyon site. According to sections measured by Zapp (1949), coal beds ranging in thickness from 0.7 to 4.5 feet occur in the upper 50 feet of the Menefee Formation in Bodo Canyon. Lateral extents of these beds cannot be determined because of the limited amount of subsurface information available for the area. According to Zapp (1949), a rather extensive bed having an approximate thickness of 4.6 feet occurs at a depth of about 140 feet below the top of the formation. Therefore, this coal bed could be from 250 to 300 feet below the ground surface at the Bodo Canyon site. Based on Zapp's total resource calculations, the Bodo Canyon site could be underlain by as much as 400,000 tons of potentially recoverable coal.

At least eight abandoned prospects and small coal mines in the Menefee Formation are located within a one-mile radius of the Bodo Canyon site. These mines produced a relatively high-quality bituminous coal with an average ash content of seven percent, an average sulfur content of 0.8 percent, and an as-received heating value of 14,000 British Thermal Units per pound. As stated by Zapp (1949), the coal within a six-mile radius of Durango is of sufficiently high quality to be used as coking coal; the coal underlying the Bodo Canyon site is within this radius (Ladwig, 1981). The mines only occur where the coal beds of the Menefee Formation crop out. There is no information on their underground workings. The nearest mine entrance is 0.6 miles east northeast of the site in Bodo Canyon. Based on evidence of mine tailings, the mines are small and it is unlikely that there are any mine tunnels approaching within 0.25 mile of the site.

Woodward-Clyde (W-C, 1983) shows that the nearest gas field, the Ignacio Blanca, is approximately five km (three miles) south of the site and the nearest oil field is 19 km (12 miles) to the southwest.

One dry oil and gas exploration well was drilled across the Animas River from the Durango site. No known wells have been drilled in Bodo Canyon, so the potential for oil or gas production is unknown. However, an oil and gas exploration well drilled about 1.5 miles south-southwest of the Bodo Canyon site was dry. Wells have been drilled in the Long Hollow area north and south of the Ute line. None of these wells produced economically significant quantities of oil or gas (CGS, 1981).

Other mineral resources found in the Durango area include sand and gravel, base and precious metals, and uranium. The nearest potential base and precious metals (copper, lead, zinc, silver, and gold), uranium, and vanadium resource area to the Bodo Canyon site is located four miles north in the La Plata mining district (Haynes et al., 1972). No mines are known to be currently producing in this district. Even if mining activity were renewed, those activities would not affect the disposal cell areas.

3.0 SITE GEOLOGY

The Bodo Canyon site geology was characterized initially during the alternate site selection process. Additional hydrological data gathered in the fall of 1989 for a demonstration of compliance with the proposed groundwater standards have been incorporated into this report.

3.1 BEDROCK GEOLOGY

Bedrock formations that crop out in Bodo Canyon include the Point Lookout, Menefee, and Cliff House Sandstone Formations of the Mesa Verde Group, and the Lewis Shale (listed from oldest to youngest), all of Upper Cretaceous age (Figure 3.1). The Colorado Geological Survey (1981) mapped the Cliff House Sandstone at the site and shows the underlying Menefee Formation only in the bottoms of drainages northeast and southeast of the site. This mapping apparently represents a reinterpretation of the gradational boundary between the Cliff House Sandstone and the Menefee Formation, because earlier maps (Steven et al., 1974; Zapp, 1949) show the bedrock at the site as Menefee Formation. Lewis Shale underlies the main part of Bodo Canyon south of the site. Figure 3.2 shows the approximate contour on the top of the Menefee Formation and its area of outcrop at the site. Figures 3.3 and 3.4 show geologic cross sections below the site and the approximate contours of the Cliff House and Menefee Formations. The Menefee Formation contact is distinguished primarily by the uppermost evidence of coal and carbonized fragments. Otherwise, the gross lithology of the two formations is very similar.

In general, the Cliff House Sandstone consists of calcareous sandstone, siltstone, and shale, but shale predominates in the transitional part of the formation at the site. Two distinct units of the Cliff House Sandstone were recognized at the site during this study. The lower unit, which contains sandstone beds up to three feet thick, forms the small ridge along the north side of the site, passes beneath the small valley in the middle of the site, and crops out in the lower slope along the south drainage. The upper unit, which contains fewer and thinner sandstone beds, caps the north and south drainages.

3.2 SURFICIAL GEOLOGY

Distribution and types of surficial deposits in the Bodo Canyon area are related to geomorphology. The most widespread deposits are colluvium on bedrock slopes and alluvium along drainageways. The colluvium is very thin, but the alluvium may be tens of feet thick in small sub-basins where several streams join. Landslide deposits occur locally along the hogback ridge south of the canyon, whereas terrace gravels and fan alluvium occur along the Animas River (Gillam et al., 1984; CGS, 1981).

Along the drainages north and south of the site, the alluvium consists mostly of silty sand with smaller amounts of sand and pebbly sand. The cross-bedded and lenticular nature of the deposits suggests that they accumulated in small, shifting channels with low-velocity flows. Angular cobble gravel occurs only at the base of the alluvium and is interpreted as

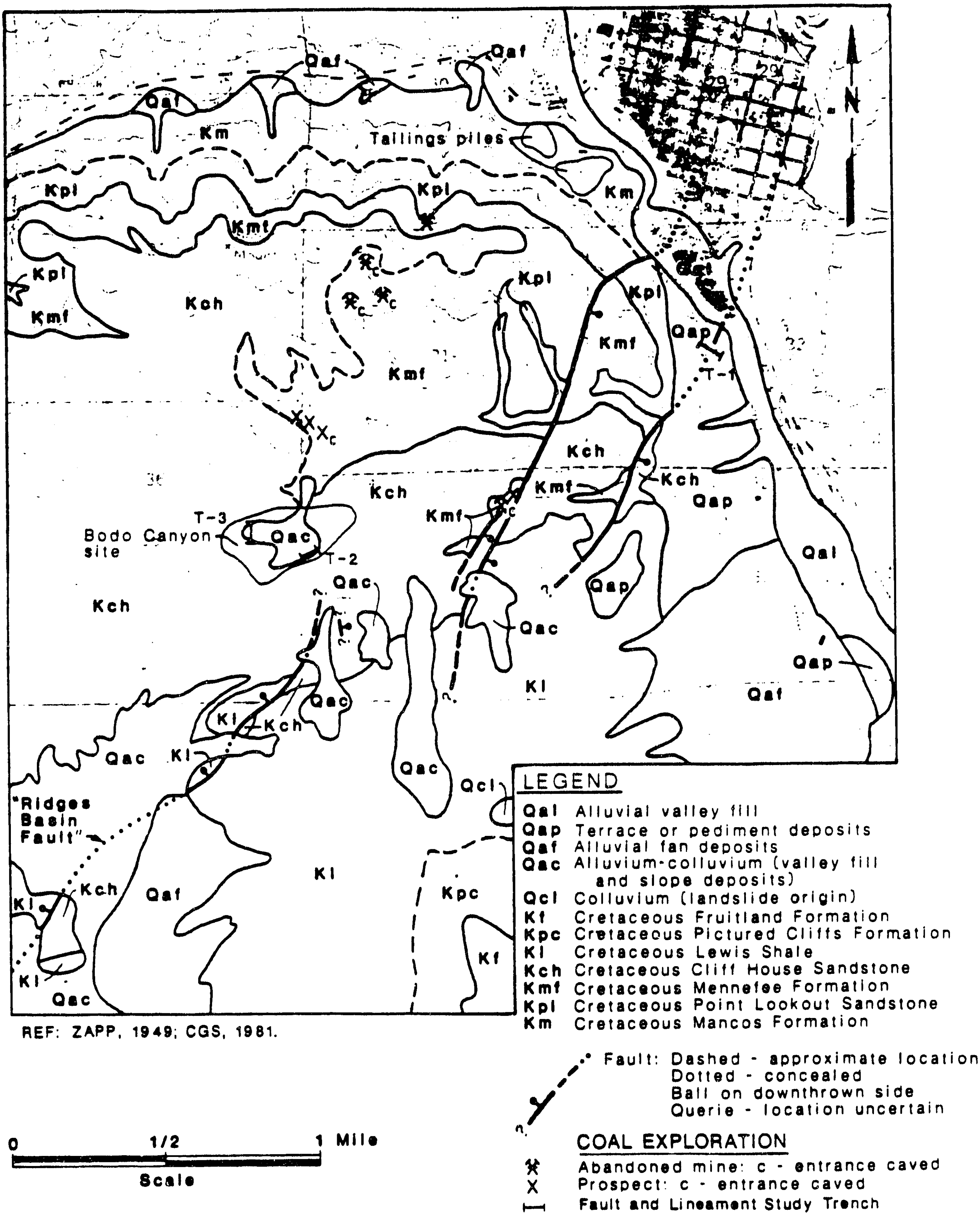


FIGURE 3.1
GEOLOGIC MAP OF BODO CANYON SITE AREA, COLORADO

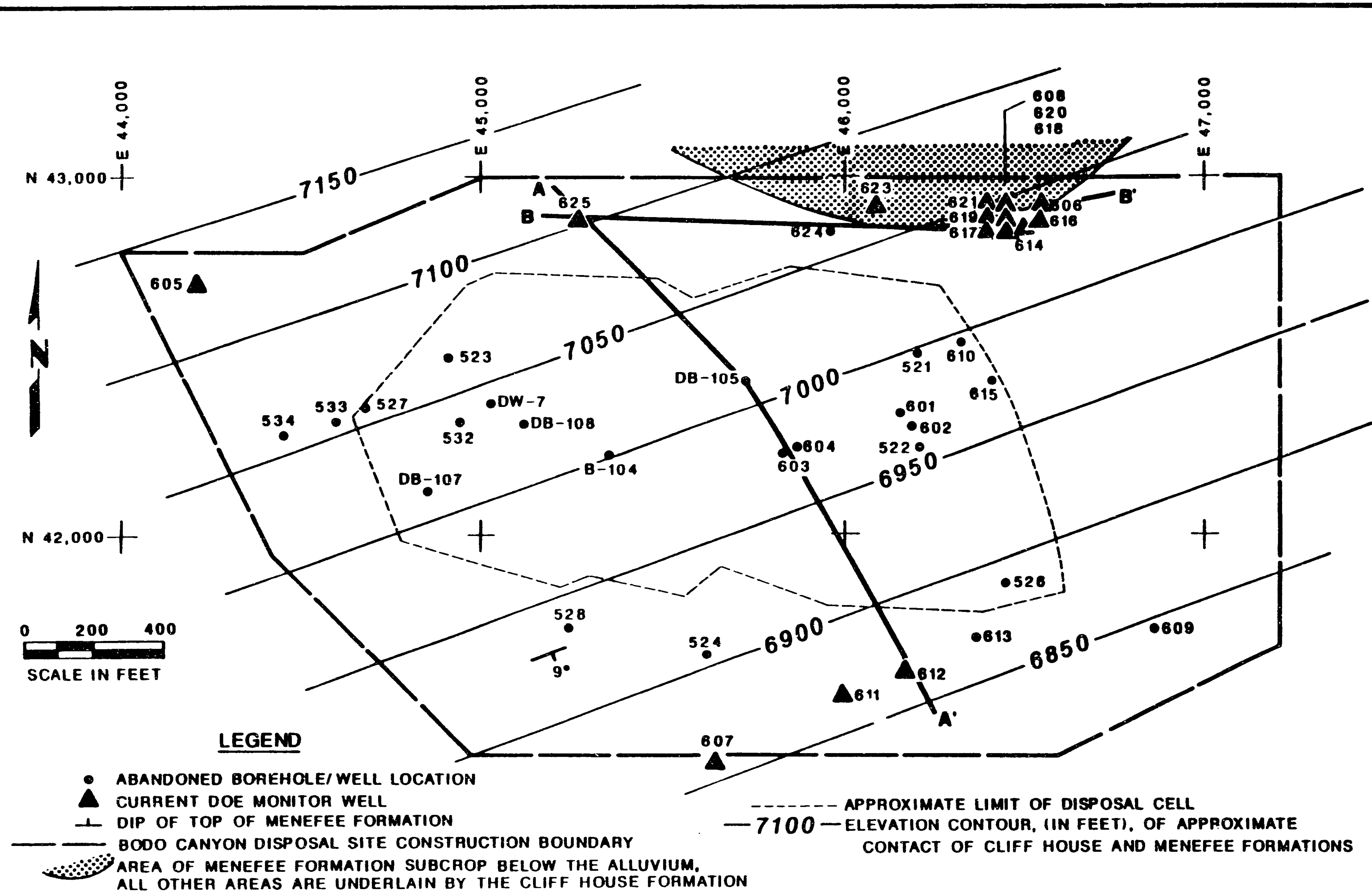
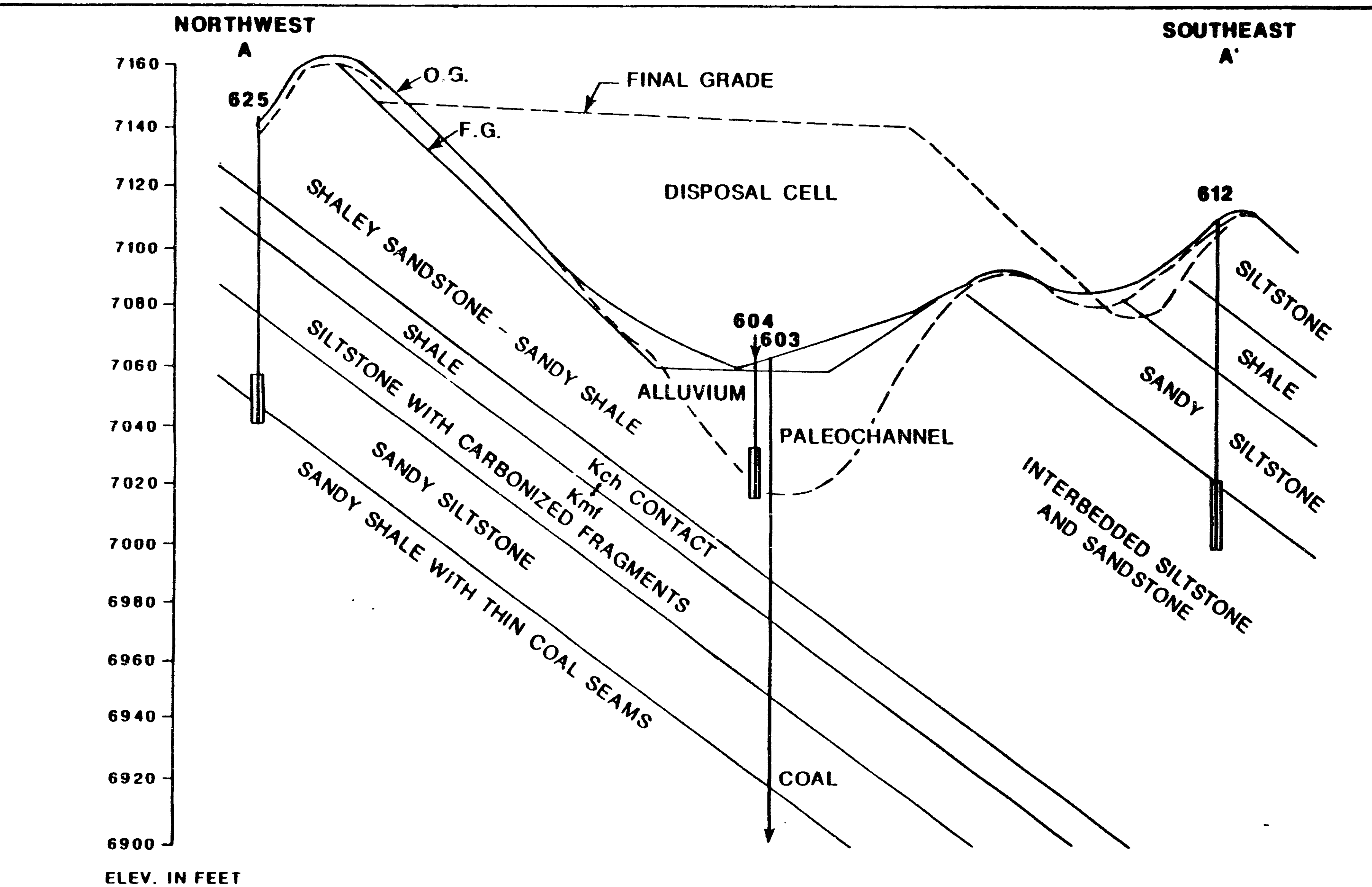


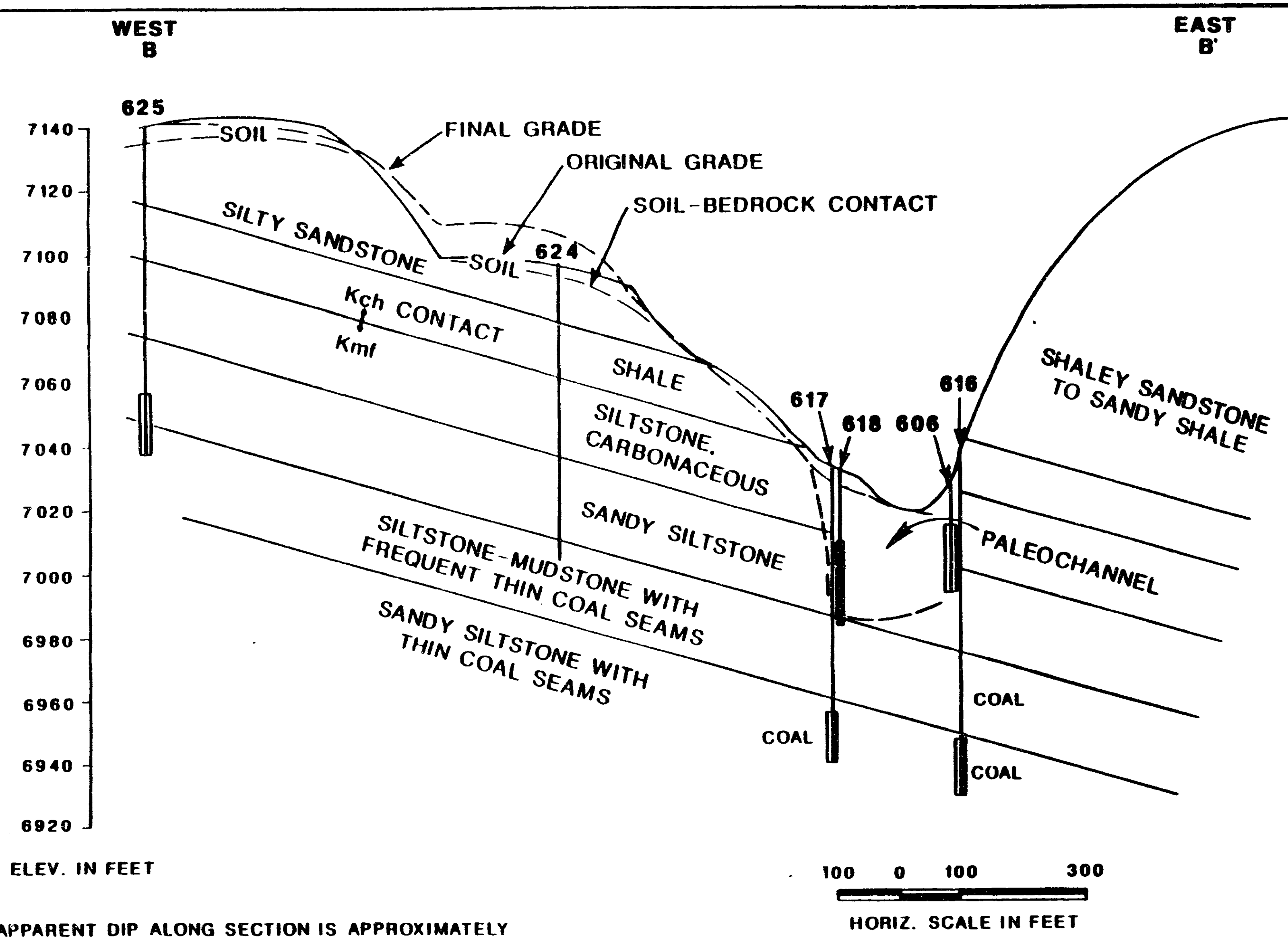
FIGURE 3.2
CROSS SECTION LOCATIONS AND STRUCTURAL CONTOUR OF TOP OF MENEFEE FORMATION
BODO CANYON DISPOSAL SITE, COLORADO



NOTE: APPARENT DIP ALONG SECTION IS APPROXIMATELY 8.5 DEGREES (TRUE DIP IS ABOUT 9.5 DEGREES)

O.G. - ORIGINAL GRADE
Kch - CLIFFHOUSE SANDSTONE
Kmf - MENEFEE FORMATION

FIGURE 3.3
CROSS SECTION A-A' THROUGH CENTER OF DISPOSAL CELL
BODO CANYON SITE, COLORADO



NOTE: APPARENT DIP ALONG SECTION IS APPROXIMATELY 3.3 DEGREES (TRUE DIP IS ABOUT 9.5 DEGREES)

LEGEND

Kch - CLIFFHOUSE SANDSTONE

Kmf - MENEFEE FORMATION

FIGURE 3.4
CROSS SECTION B-B' NEAR POINT OF COMPLIANCE, NORTH SIDE BODO CANYON SITE, COLORADO

a lag deposit (composed of bedrock fragments that fell into the channel and were concentrated by the erosion of fine-grained material before alluviation began). A few thin grayish layers within the alluvium probably are buried A soil horizons and indicate that the deposition was episodic. A weak A horizon also occurs at the surface, suggesting a late Holocene age for the uppermost deposits.

The surficial deposits within the central sub-basin of the site are poorly exposed, but have been described as consisting of silty clay, silt, and sand that locally contains sandstone and shale fragments. These deposits are thin to absent on the margins of the sub-basin, and reach a maximum thickness of 65 feet near its center (Figure 3.3) (DOE, 1984b).

Figures 3.5 and 3.6 show the approximate depth and location of a paleochannel whose existence is indicated by the abrupt thickness change of the surficial deposits. Figure 3.6 shows the approximate gradients toward the north side drainage. The evidence of the fault study trench (No. 3) suggests this paleochannel was nearly filled with fluvial deposits before being beheaded by the south side drainage (DOE, 1985b). Consequently the deposits are a mixture of fine-grained clayey sediments as well as coarser grained active stream deposits. The well-developed south channel and the depth of paleochannel fill prior to being beheaded suggest early Pleistocene or perhaps late Tertiary age when the channel was incised to its maximum depth.

The paleochannel is significant to the groundwater characterization since it contains a perched alluvial groundwater system and is the uppermost saturated zone where seepage from the cell would first appear. This is described more fully in the groundwater hydrology report, Attachment 4.

The Falfa clay loam soil, mapped in the site area, is formed on eolian (windblown) deposits that are relatively old. Elsewhere in La Plata County, this soil series has also been mapped (SCS, 1985) on eolian deposits that are more than six feet thick and have probably been accumulating for at least 200,000 years (Gillam et al., 1984). Underlying materials probably are alluvial and colluvial as previously stated.

3.3 GEOMORPHOLOGY

The site occupies about 80 acres in a gently sloping sub-basin in the northwest part of Bodo Canyon, and is nearly encircled by two deeply incised, ephemeral streams herein referred to as the north and south drainages. Geomorphic processes that affect the site occur either within the site, along these ephemeral drainages, or on the intervening slopes. The south drainage is the main north-branching tributary at the head of the Bodo Canyon drainage.

Bodo Canyon, southeast of the Bodo Canyon disposal site, together with Ridges Basin forms a strike valley that has developed along the outcrop belt of the Lewis Shale. The south slope of Smelter Mountain, a hogback ridge, is underlain by formations that collectively are more resistant to erosion (the Cliff House Sandstone, Menefee Formation, and Point Lookout Sandstone). The present pattern of tributary drainages in this area has probably developed during late Pleistocene time (Figure 3.8).

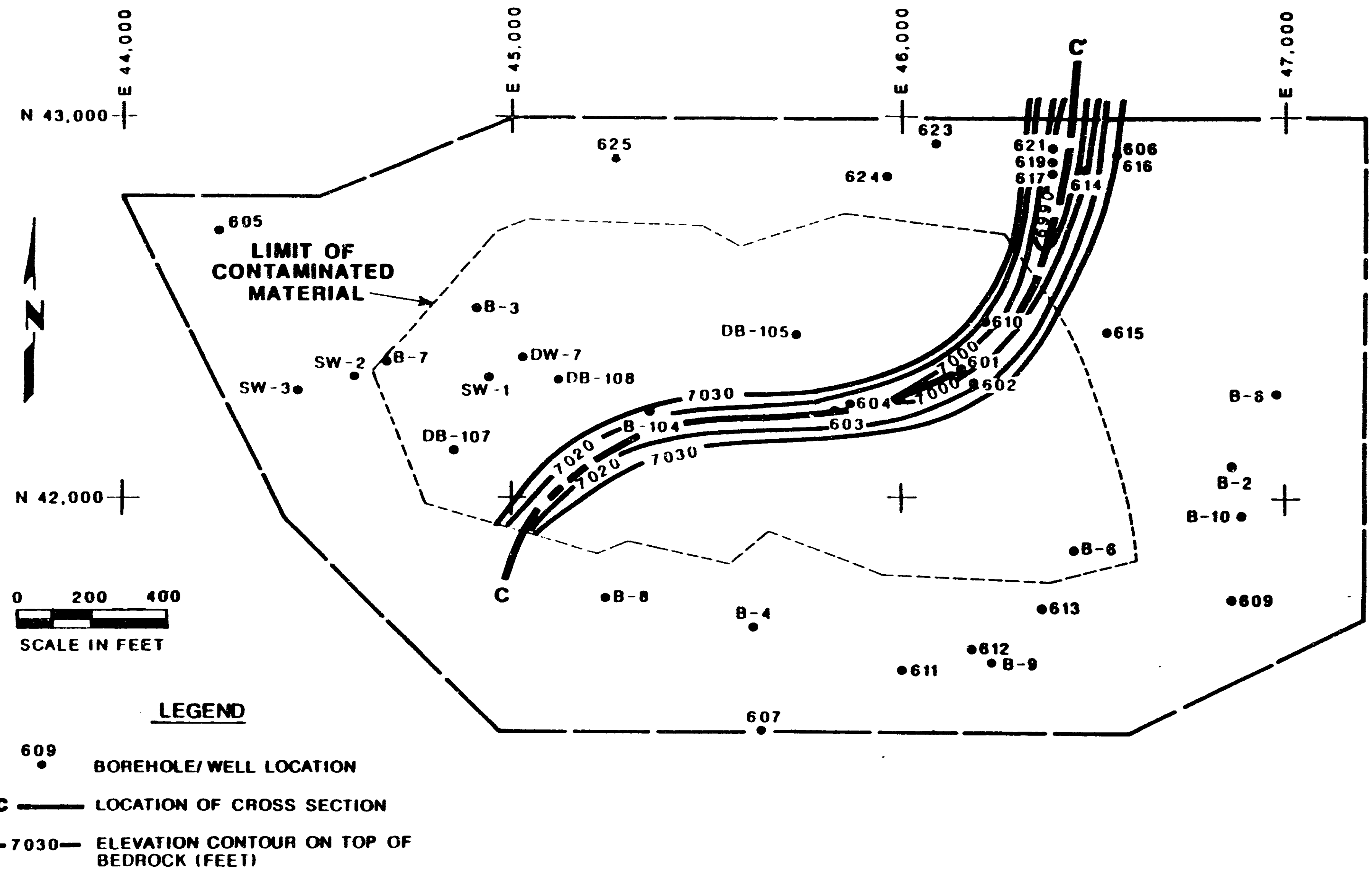


FIGURE 3.5
PALEOCHANNEL ALIGNMENT BELOW CELL AREA
BODO CANYON DISPOSAL SITE, COLORADO

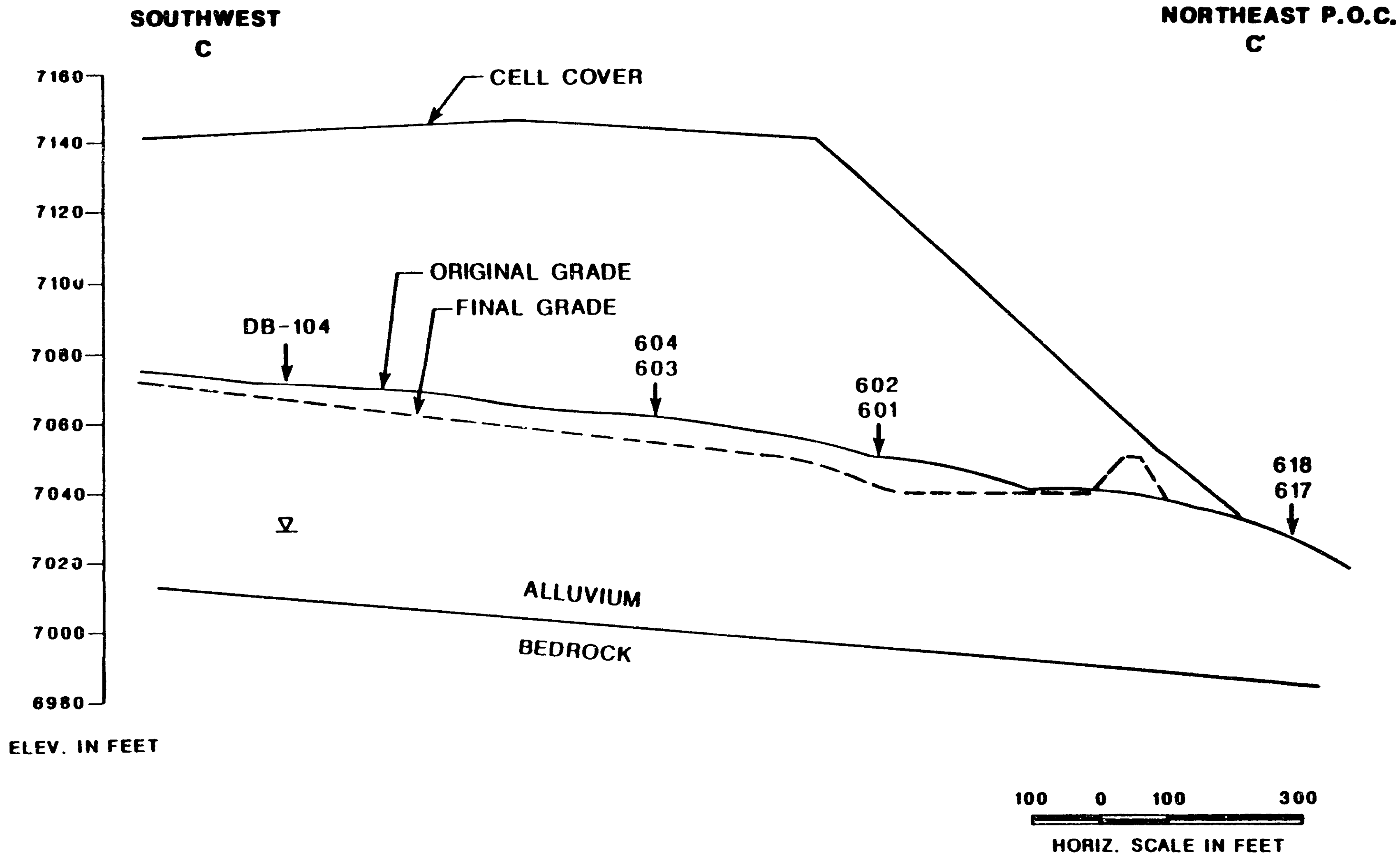


FIGURE 3.6
CROSS SECTION C-C' ALONG PALEOCHANNEL ALIGNMENT (THALWEG)
BODO CANYON, COLORADO

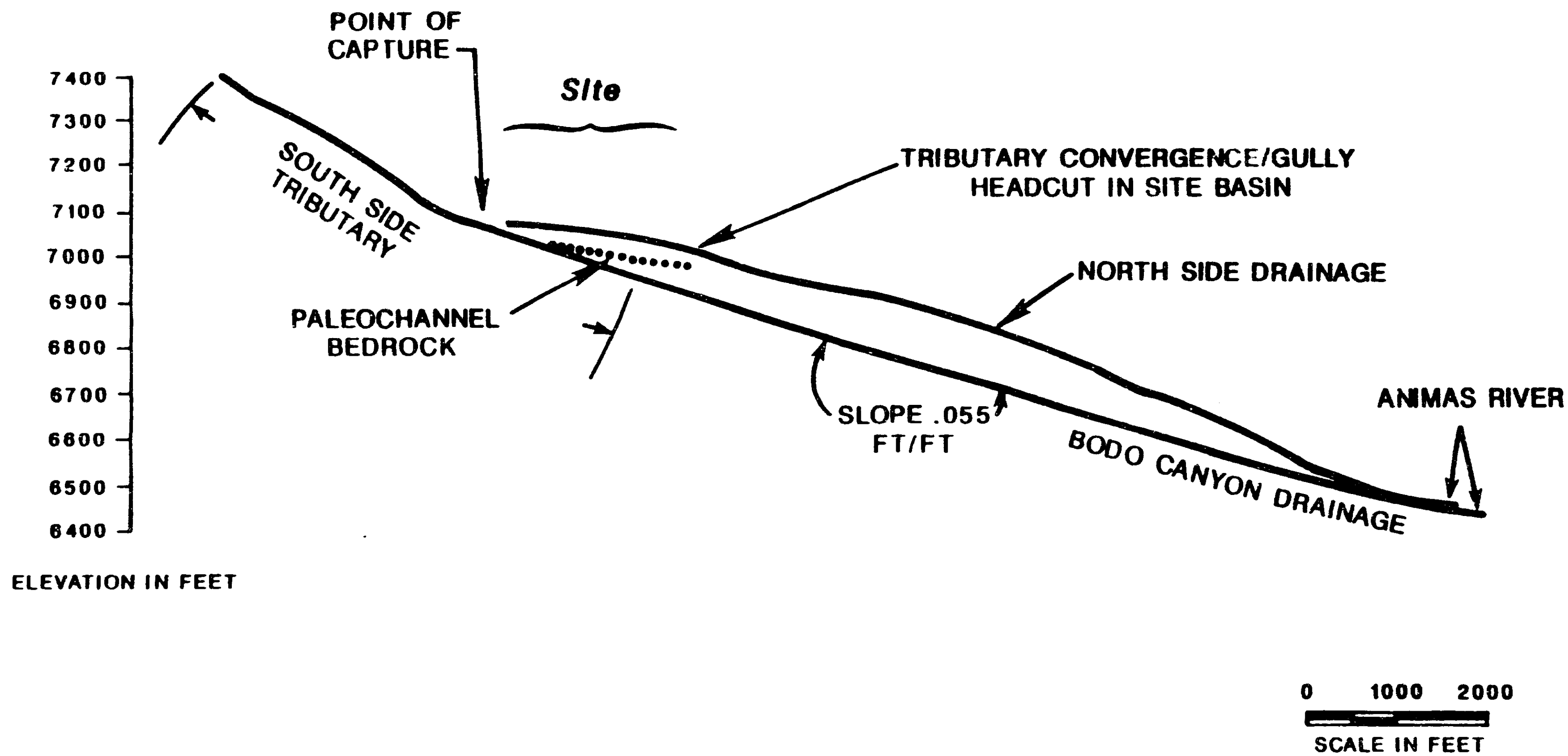
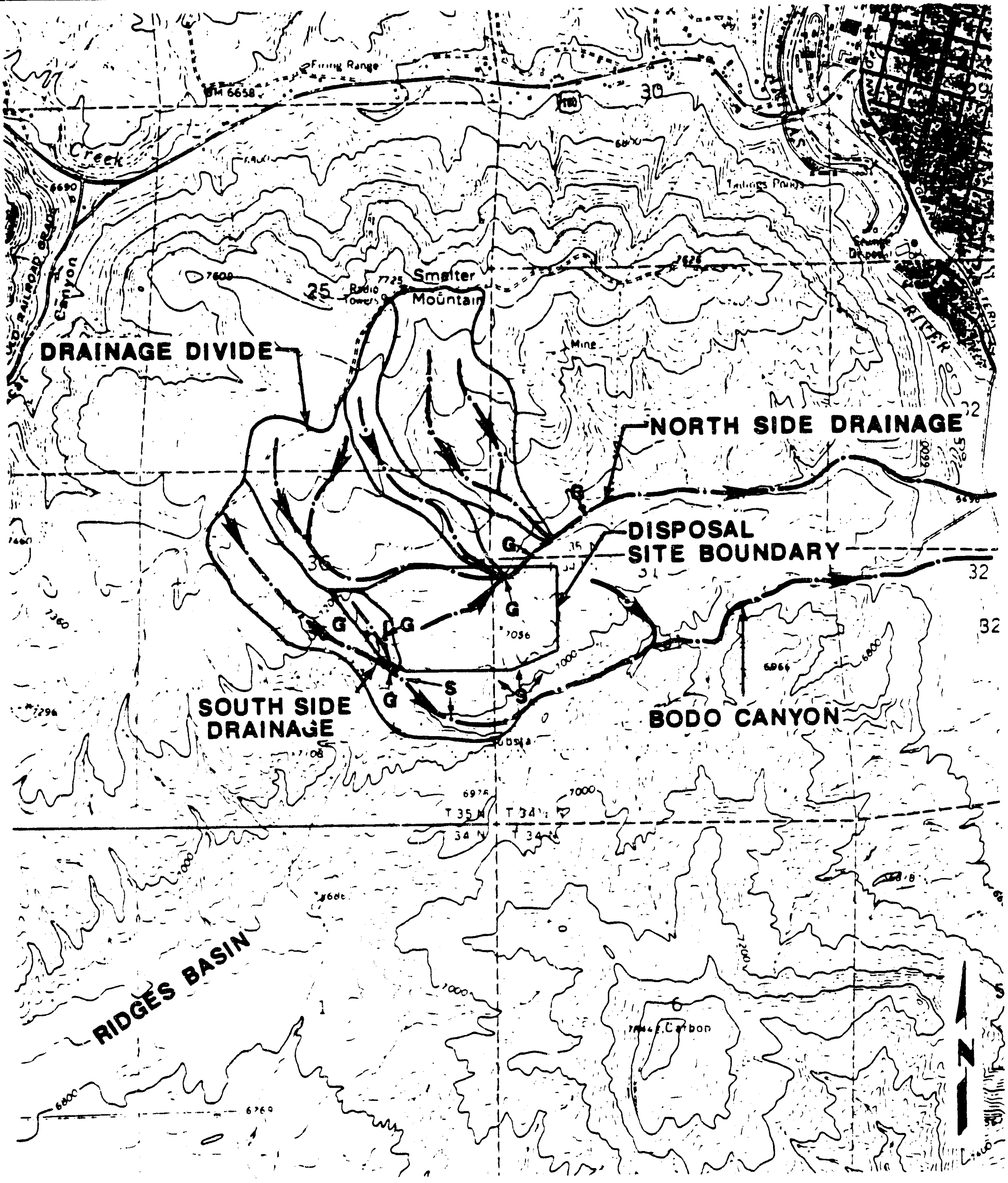


FIGURE 3.7
PROFILES OF NORTH AND SOUTH SIDE DRAINAGES
BODO CANYON SITE, COLORADO



LEGEND

G = GULLY

S = RAPID SLOPE EROSION

0 2000 SCALE IN FEET

FIGURE 3.8
GEOMORPHIC FEATURES, BODO CANYON SITE, COLORADO

Smelter Mountain may once have drained south across the site toward the middle of Bodo Canyon. The north drainage may have developed later by headward erosion along a more direct route to the Animas River, and captured the flow from tributaries on Smelter Mountain (see Figures 3.7 and 3.8). If so, the saddle east of the site, toward which the faults at the electrical substation apparently project, could be erosional rather than structural in origin.

The north and south drainages are only 3.4 and 3.7 km (2.1 and 2.3 miles) long, respectively, from their confluence with the Animas River to their common divide near the west end of the site. Their gradients (Figure 3.7) are relatively steep, 310 and 286 feet per mile. The south drainage, which flows almost entirely on Cliff House Sandstone, has a smooth, slightly concave profile. In contrast, the concave profile of the north drainage has segments of differing slope where it crosses formations of varying erodibility. Both profiles display numerous knickpoints, as much as a few feet high and a few tens of feet apart, where they cross relatively resistant sandstone beds.

Slopes along the north and south drainages typically have lower straight segments and upper convex segments. Maximum slope angles are roughly 25 to 30 degrees.

The site differs geomorphically from the main part of Bodo Canyon. The central sub-basin has relatively gentle slopes (one to 10 degrees) and resembles a small upland plateau when compared with the lower and more hilly area to the south. This contrast results from the effect of bedrock erodibility on the geomorphic development of the two areas. As the Animas River gradually deepened its valley during middle and late Pleistocene time, tributary streams easily dissected the Lewis Shale. However, downcutting along the north and south drainages was retarded by the sandstone beds in the older formations.

The periods of calculated peak discharges for the north and south drainages are comparable to the average daily discharges of the Animas River in May, June, and August, the months of highest runoff. The associated peak velocities would be capable of transporting cobbles and boulders, and thus would quickly erode any unprotected alluvium in the north and south drainages. Associated channel degradation and widening could lead to rejuvenation and accelerated erosion of other parts of the drainage network.

The fine texture of the alluvium in the north and south drainages indicates that flows of this magnitude have not occurred during late Holocene time. However, because the deposits are very young, their texture does not preclude the possibility that very large flows may have occurred during a longer time period.

Geomorphic processes

Because the Bodo Canyon site is in an upland area, only the following geomorphic processes need to be considered: degradation, knickpoint migration, and bank erosion in the channels; rejuvenation, extension, and deposition in the drainage network; denudation and retreat, dissection, and mass failure in the slopes; and wind erosion. A previous publication described the erosion potential as moderate (CGS, 1981).

Channel erosion

Remnants of late Holocene alluvium are present along the north and south drainages, indicating that both channels have recently incised their own earlier deposits to a depth ranging from 10 to 20 feet. This incision probably occurred relatively rapidly (possibly within a few hundred years or less) and may have been associated with the gully erosion described in the following section.

Future incision rates will probably be much less. The south channel locally contains minor amounts of sandy to cobbly alluvium, but is essentially flowing on bedrock along its entire length. Similar conditions exist along the north channel west of the site. Although the north channel is within alluvium near the site, further incision is prevented by a knickpoint that is downstream in resistant bedrock. Thus, future incision rates along both channels are likely to be less than the rate of base-level lowering along the Animas River. Since the last glaciation, this rate has averaged roughly one foot per 1000 years.

Lateral migration and bank erosion along both channels are minimal because of the relative straightness of the channels, the confining bedrock slopes, the relative scarcity of alluvial banks, and the small ephemeral discharges. However, a few bedrock-confined meanders, with amplitudes less than 20 feet, locally undercut adjacent bedrock slopes.

The recent channel incision and local bank erosion have steepened adjacent slopes and lowered the base level for gullies and rills, thus rejuvenating the drainage system and accelerating erosion rates.

Drainage network erosion

Drainage network rejuvenation and extension have been expressed as recent gully erosion in parts of Bodo Canyon. To date, this gullying has not been severe for several reasons: 1) the greater resistance of the underlying bedrock to erosion; 2) the greater permeability of the bedrock and surficial deposits, which reduces the relative intensity of runoff; and 3) the relatively dense vegetation, which further reduces runoff intensity and stabilizes the surface. Nevertheless, gullies have developed or are beginning to develop at several locations in and around the site. This section discusses the mechanics of gully erosion, the distribution and recent behavior of gullies at the site, the probable causes and recent rate of gully erosion, and the probable impact of the disposal cell on future gully behavior.

A gully is a relatively deep, recently formed, eroding channel that occurs where no well-defined channel previously existed (Nelson et al., 1983). The valley-floor gully is an extension of the channel from alluvium onto adjacent bedrock and colluvium. Gullies can form inside a site, or they can form outside a site and grow toward it. Apart from the potential for gully initiation on the disposal cell, the main process that may affect the site is from headward growth of gullies that now exist or that may form along the margins of the site (gullies within the site would be buried and rendered inactive by the disposal cell).

The gullies in Bodo Canyon extend headward by the retreat of a knickpoint at the head of the incised channel. This retreat is controlled primarily by localized hydrologic processes (Nelson et al., 1983). Therefore, gullies can continue to extend after the conditions that initiated the gullying (such as overgrazing and drought) have ceased to exist, and after downstream segments of the drainage network have been stabilized (for example, by artificial or bedrock barriers to channel incision). Valley-floor gully erosion also tends to be self-perpetuating because channel incision lowers the water table in adjacent alluvium, thereby preventing plant regeneration (Euler et al., 1979).

Existing gullies in and adjacent to the site are shown in Figure 3.8. A system of valley-floor gullies has developed within alluvium along the upper, more gently sloping part of the north drainage. Branching valley-floor gullies extend up all the major northern tributaries along alluvium that is too narrow to be shown on the geology map (Figure 3.1). A few valley-side gullies also extend up the bedrock ridge to the south, but are less prominent because the bedrock is more resistant to erosion.

A gully incising the paleochannel fill initially extended well into the site, branching off from the north drainage, but was partly filled when two earthen dams were constructed within the site basin. This artificial fill extended below the lower dam to the existing deep headcut. Below the headcut, the channel depth rapidly increases downstream from about five to 15 feet. Because the dams greatly reduced the flow reaching this headcut, its rate of headward extension appears to have decreased dramatically compared to pre-dam conditions.

Gully erosion is occurring on a smaller scale in other parts of the site. On the northwest slope of the site basin, several small gullies have developed in eolian deposits. These gullies flow into the south drainage. Several well-defined valley-side gullies occur south and east of the site on bedrock slopes above the south drainage. At the heads of the divides separating these gullies from the central basin, numerous shallow rills are forming within the surficial deposits.

Gully erosion in many areas of the southwest is thought to have begun during the nineteenth century as a result of overgrazing by cattle and short-term climatic change. Euler et al. (1979) summarize previous work on this subject. Gullying apparently began during the 1840's along the Rio Puerco, New Mexico, and around the late 1880's in most other areas. The majority of authors conclude that the gullying began during a brief period of decreasing moisture and that it was triggered by overgrazing. However, some authors believe that the gullying would have occurred somewhat later without overgrazing as a result of the drought alone.

The relative magnitude of the 1891 drought cannot be established because no historic precipitation data were collected at Durango until

1895. However, tree ring data for the Four Corners region indicate that the late nineteenth century was relatively dry.

If the gullies in the Bodo Canyon area have developed during the last 100 years, it is possible that the site could become more severely gullied in a relatively short time.

Estimated rates of headward extension were calculated for the main valley-floor gully along the north drainage, based on the following assumptions: gullying began in 1891 or 1910; and by about 1950, a gully headcut had migrated from the east end of the alluvium to the northeast corner of the site, a distance of about 3200 feet. The resulting average rates of headcut migration from these assumptions are 54 and 80 feet per year, respectively. The actual rates probably decreased upstream as the drainage area and discharge above the headcut also decreased. In comparison, recent maximum rates of headcut migration in the alluvium within the site have probably been a few feet per year, or less.

Minor processes

Minor geomorphic processes that may affect the Bodo Canyon site include: 1) slope erosion; 2) mass movements; 3) wind erosion; and 4) frost heave and solifluction. These are discussed by number below.

1. The Colorado Geological Survey (CGS, 1981) mapped the slopes northeast and southeast of the site, along the north and south drainages, as unstable. For this study, the slopes on all sides of the site were examined to identify the areas of greatest instability, to estimate maximum erosion rates, and to evaluate potential impacts on the site.

   The slopes at the site vary in height from roughly 60 to 100 feet. Typically, the upper parts are convex and moderately steep, whereas the lower parts are straight and steep, with maximum gradients as large as 25 to 30 degrees.

   The north-facing site slopes tend to be more stable because of thicker vegetation (roots bind the soil and plant litter impedes runoff). However, litter and surface soils are being stripped from the steeper northeast slope, which has been undercut by the north drainage.

   The south-facing site slopes are more active, partly because of the discontinuous vegetation. Particularly unstable areas include the lower, steeper parts of the slopes and the steep heads of active valley-side gullies, where intensified erosion in some cases extends nearly to the crests of the slopes. Colluvium is typically absent in these steeper areas. In contrast, the upper slopes in other areas retain a colluvial mantle, support slightly thicker vegetation, and appear relatively stable.

   Potential rates of hillslope erosion were estimated from data for the site area and for the southwestern United States. On the steep slopes south of the site, erosion has partly exposed the roots of juniper trees on their downhill sides. A few trees have even been uprooted. For two old stumps, the depth of root exposure was divided by the number of growth rings to obtain maximum rates of sheet and rill erosion of about 20 feet per 1000 years. If the trees were cut as much as 100 years ago, these rates would be closer to 10 feet per 1000 years. For comparison, historically measured rates of scarp retreat in the southwestern United States are about 6.5 to 43 feet per 1000 years in shale and two feet per 1000 years in sandstone (Schumm and Chorley, 1983).

Mechanical weathering is sufficiently rapid to allow moderate erosion rates, at least locally. Slope erosion is most likely to affect those parts of the impoundment that overlap or abut externally draining slopes. As presently designed, most of the impoundment margin lies inside the minor drainage divides that separate the central sub-basin from the externally draining slopes.

Discharge channels that cut through drainage divides will release most runoff from the site onto bedrock slopes well beyond the edges of the impoundment. Any channel incision or extension that may occur is not likely to cut through the bedrock divides to the impoundment. Minor undercutting could occur at the downstream ends of the channels, but would not be likely to impair their function.

Recent incision along the north and south drainages could rejuvenate existing valley-side gullies and create new channels that would dissect the slopes. Such rejuvenation is probably contributing to more rapid erosion along the slopes northeast and southwest of the site, where the proportion of sandstone beds is relatively low. However, the greater proportion and thickness of sandstone beds along the southeast slope will probably inhibit rejuvenation and dissection.

2. Mass movements have been identified along the hogback ridge south of Bodo Canyon (CGS, 1981), and may have occurred within the canyon in areas underlain by the Lewis Shale. However, no mass movements have been observed within or bordering the site.

   A few shallow soil slips, roughly tens of feet in diameter, have occurred along the south drainage east of the site where channel meanders have locally undercut the adjacent slopes. Future channel incision more directly south of the site might cause similar small failures, but these probably would not extend far enough uphill to impact the site and could be prevented by the relatively thick sandstone beds in the basal slopes.

3. Windblown materials are present in Bodo Canyon and on geomorphically stable surfaces in the Animas and La Plata river valleys (SCS, 1985; Gillam et al., 1984; Moore and Scott, 1981). The wide distribution and similarity of the materials suggest that they were derived primarily from the Colorado Plateau to the southwest, and that regional wind velocities are capable of

transporting silt and fine sand for at least 50 miles and probably much farther.

In local areas within the San Juan Basin, a part of the windblown material has probably been derived from nearby bedrock exposures and unconsolidated surficial deposits. Such local contributions have recently been demonstrated for areas north of Chaco Canyon (Schultz, 1983, 1980).

In the Bodo Canyon site area, geomorphic features of wind erosion (such as blow outs, yardangs, or ventifacts) do not occur, indicating that fluvial erosion dominates. However, locally measured wind velocities (DOE, 1984b) are sufficient to transport silt and sand particles in the tailings.

Wind erosion of the tailings and the overlying radon/infiltration barrier will be prevented by the cover.

4. During the winter, the maximum frost penetration depth in the Durango area is about four feet, although the depth can be much less if a persistent, early snowfall insulates the ground from cold air temperatures (SCS, 1954). Thus, frost heave and solifluction can occur in the area under favorable conditions.

   Frost heave is the vertical displacement of matter in response to freezing. The process requires that adequate moisture be present to form ice lenses within a fine-grained soil. Further water percolation and growth of the ice lenses causes upward expansion, displacing the surface. In the disposal cell, ice lenses could form in the upper part of the radon attenuation layer. The process can be mitigated by using a radon/infiltration barrier that is sufficiently impermeable to prevent significant water penetration, and a sufficiently porous aggregate covering to restrict water buildup over the clay.

   Solifluction is the slow flowage of saturated soils above frozen subsoils (Ritter, 1978). The saturation prerequisite for this process can also be mitigated by using permeable aggregate and impermeable radon barrier materials.

4.0 GEOLOGIC STABILITY

4.1 GEOMORPHIC STABILITY

At the Bodo Canyon site, the relative intensity of various natural geomorphic processes differs over short distances. Therefore, the geomorphic processes that may affect the disposal cell depends strongly on its specific location and design. The following comments pertain to the cell and to its proposed 1000-year lifetime.

The most significant geomorphic processes that may affect the site are from catastrophic flooding (represented by the Probable Maximum Flood, or PMF), gully erosion, and slope erosion. Some slopes peripheral to the site have recently been rejuvenated by channel incision along the north and south drainages, whereas the effect on other slopes will probably be mitigated by resistant sandstone layers in the bedrock. No significant risks appear to be associated either with further channel changes along the north and south drainages (except for possible local effects of the PMF in the north drainage, as discussed below) or with large-scale mass movements.

Geomorphic processes that could occur locally on the impoundment include frost heave, solifluction, and erosion by rainsplash, sheetwash, gully incision, and wind. These processes are not discussed because they will be controlled by the design of the disposal cell, cover material, and drainage.

The geomorphic processes that now occur naturally at the site appear to be well controlled by the proposed location and design, although a few minor suggestions are presented below.

The perimeter of the disposal cell has been placed on gentle or moderate, relatively stable slopes that drain toward the center of the basin. This placement avoids the slopes draining toward the north and south drainages, which are generally steeper, less stable, and more susceptible to rejuvenation.

The cell is placed across low areas where the perimeter truncates existing drainage channels. After construction, only runoff falling on the cell will enter these channels. This will substantially decrease present natural discharges into the channels, thus reducing incision rates. Because the crest of the south side of the cell is relatively close to the underlying natural drainage divide, the proportional reduction in discharge will probably be smallest for this channel. However, present incision along the channel is relatively slow because of the bedrock and low discharge.

The most significant potential for channel erosion would occur at the north end of the cell. Headward extension of the gully could continue.

The runoff from the Probable Maximum Precipitation (PMP) on the disposal cell would have significant erosive power, as indicated by the area of the cell, when compared to the areas and peak discharges of the three sub-basins used to model the PMF. The impacts of PMP-generated runoff are likely to be most significant at the downstream ends of the two drainage ditches mentioned above, and at the bases of the disposal cell. The possibility of unusually high runoff emphasizes the need to provide adequate erosion protection at these points, particularly to prevent undercutting at the north.

Gully erosion can breach an improperly protected impoundment in less than 100 years (Nelson et al., 1983). However, the plan for drainage dispersion from the cell at the site will prevent further extension and incision of the gullies described above. Embankments will be constructed where the perimeter crosses existing channels and rilled divides. Drainage will be diverted via ditches and will be released onto bedrock slopes beyond the perimeter of the disposal cell. With the natural flows in the channels and rills severely reduced, erosion rates will become insignificant.

4.2 SEISMOTECTONIC STABILITY

As previously discussed in section 2.4, there are no known capable faults in the Colorado Plateau or the Western Mountain seismotectonic provinces, which make up the portions of the site region. The group of faults that comprise the Ridges Basin-Durango fault group is the most critical to the site in terms of ground rupture hazards and on-site acceleration (Figures 2.9 and 3.1). The association and alignment with the Durango anticline and Perrin syncline folded structures suggest a similar Laramide Orogeny age for the faults. The following sections present the evaluation by the DOE (1985b) of this fault system.

Assessment of fault capability

The group of en echelon faults near the site was studied to determine the age of last movement. The four faults, with two small spurs, were first mapped by Zapp (1949) and included on subsequent geologic maps of the region. The faults and their possible extension were examined by low-sun-angle aerial reconnaissance over a 16-km (10-mile) radius of the site and also by the use of stereo-pair aerial photographs to determine if surficial Quaternary deposits were dissected by fault movement. This was followed by examination of the traces on the ground and selection of sites for trench excavation to expose the oldest undissected Quaternary deposits (DOE, 1985b).

Two of the faults, which are parallel to each other and whose trends dissect the east end of Smelter Mountain trends and are buried below Quaternary deposits in the Animas River, are the most prominent. The largest of these, called Fault No. 1, has an east-side-down displacement that could be as much as 300 feet (Zapp, 1949) and Fault No. 2 has a similar displacement of bedrock of several tens of feet. Both faults were found to have been intruded by dikes of fine-grained olivine basalt rock that were sheared by subsequent movement. The basalt dikes are apparently associated with volcanism that occurred in the area in the Late Cretaceous to Early Miocene.

Trench No. 1 was excavated across Fault No. 1 in the Durango processing site approximately 200 feet from the Animas River. Four Quaternary alluvium units directly overlying the faulted bedrock were found to be undisturbed. The alluvium along the terraces of the river are composed of glacial outwash representing the Pinedale glaciation that is dated as possibly older than 30,000 years (Gillam et al., 1984). Similar deposits were observed overlying the trace of Fault No. 2.

Trench No. 2 examined the combined north trace of Fault No. 3, and a spur called Fault No. 4, as mapped by Zapp (1949), that appeared to enter the east end of the Bodo Canyon disposal site. Fault 3 has an inferred length of approximately 2.0 km (1.2 miles), extending from Ridges Basin into the head of Bodo Canyon drainage and was interpreted by Zapp to have a west-side-down displacement. Field inspection of the trace indicates that no faulting has occurred along the mapped trace within one mile from the Bodo Canyon disposal site. If Fault 3 does exist, its maximum displacement is estimated at no more than 20 feet. Late Holocene alluvium that overlies the fault in Ridges Basin is not displaced. Paleochannels up to two feet deep were found in the alluvium (see Figure 3.1).

Trench No. 3 was made on the west end of the disposal site on the trend of lineation interpreted from aerial photos. The trench did not reach bedrock but exposed seven units of surficial deposits. Several paleochannels were observed to dissect these units. One paleochannel had a width of 30 feet and a depth of four feet. No evidence of faulting was found.

In Trenches 2 and 3 the presence of multiple buried soils and the topographic changes implied by the development and abandonment of the paleochannel drainages indicated a minimum age of the oldest units of 100,000 to 200,000 years.

The conclusion of the study of the faults from the various methods of investigations is that there is no evidence of movement on any fault in the Bodo Canyon area during at least the Late Quaternary and probably not since the end of the Tertiary. The fault system is considered to be noncapable.

For the purposes of the analysis of regional seismicity, it was concluded that the greatest seismic hazard in the site area is associated with undesignated faults within the Colorado Plateau/Western Mountain province transition zone and the Rio Grande Rift; specific known faults within the Colorado Plateau, including faults in the Uncompahgre Uplift and salt anticlines areas; and the unidentified seismic source in the Dulce, New Mexico, area. Maximum expected accelerations in the site area associated with the specific known features are discussed in Section 2.4. Due to the lack of detailed information of the seismic history, it is not possible to calculate recurrence relationships for these features, or to apply probabilistic techniques.

Therefore, the deterministic approach was supplemented by a probabilistic analysis based on the regional historical record. Historical earthquake data for the seismotectonic provinces of interest were obtained from the NOAA earthquake data file. The provinces were represented as six circular or rectangular search areas as shown on Figure 2.6, and complete listings of all historical and instrumentally detected earthquakes for each of the six areas were obtained. Because of the questionable reliability of the record for events of magnitude ≤ 4.5 occurring before 1960, it was originally intended to use only events of magnitude ≥ 4.5 occurring after 1960 in the analysis. This resulted in too small a data set for reliable analysis. In order to develop a larger data base without introducing major errors, all events of magnitude ≥ 4.0 occurring after 1960 were used. The resulting data sets for each of the six areas are listed in Tables 2.4 through 2.9. Recurrence relationships were determined graphically for each of the six areas.

Various published acceleration-attenuation relationships were used in successive runs using the computer code ACC.LINE.AREA (Chiang et al., 1984). The attenuation relationship, which resulted in site accelerations most consistent with the other analyses employed in this study, is that developed by Donovan (1973) based on an analysis of worldwide events:

$$A = 1320e^{0.58M}(R+25)^{-1.32}$$

Where M = magnitude, R = hypocentral distance (km), and A = peak ground acceleration (gravity).

The computer code ACC.LINE.AREA computes the probability of exceedance of a given peak ground acceleration at a specific site due to identified line or area seismic sources. Line sources are typically representative of known or suspected faults, and circular area sources are representative of regions that do not include recognized faults having a strong correlation between epicentral locations and fault locations.

Details of the program development are presented in Chiang et al. (1984). The seismic sources are characterized by normalized log-linear recurrence relationships based on historical data. The recurrence relationship defines the mean number of events of magnitude greater than the selected M per unit area and unit time. This quantitative relationship represents the past seismic history of the source. It is typically bilinear, and the computer code allows definition of an upper limit cutoff magnitude for a given source.

Future forecasting is based on the application of the Poisson statistical model to seismic activity. This model assumes that major seismic events are spatially and temporally independent. The Poisson probability model further assumes that the probability of two seismic events taking place at the same location and at the same instant in time approaches zero. The mean rate of occurrence defined by the normalized recurrence relationship for a source is used directly in the Poisson model, arriving at an expression that directly computes the probability of occurrence of at least one event of magnitude greater than the selected M in a given time period.

For a specific site, an attenuation function is substituted for acceleration in the probability relationship. The computer code then integrates the resulting relationship over an input time period for the specific source or sources considered to arrive at a probability distribution function for acceleration. In the integration process, the hypocenter, rather than the epicenter, is utilized, thus considering the possible variation in depth for different seismic sources.

Results of probability analysis

Data input and results of the probability analysis are included in the computer listings (DOE, 1985a). Magnitude values used in the probability analysis are body-wave magnitudes (m_b) because these are the values generally listed in the NOAA earthquake data file.

The probabilities were calculated for time periods of 10, 50, 200, 250, and 999 years (approximately for 1000 years). The probabilities calculated are consistent with previous seismic zoning studies and the historical record.

For the 10-year time period, there is a 90 percent probability that an acceleration of 0.015g to 0.02g will be experienced at the site area. For an acceleration of 0.02g to 0.03 g, the probability varies from 90 to 46 percent for the same time period. The probability of the acceleration exceeding 0.05g is less than 10 percent for the 10-year time period. Several accelerations in the range of 0.01g to 0.02g have been experienced in the site area since 1960. The analysis results are in good agreement with the acceleration contours of Algermissen et al. (1982) as presented in Table 2.3.

For the 50-year time frame, there is about a 10 percent probability that an acceleration of 0.046g to 0.07g will be experienced, which is consistent with the study by Algermissen and Perkins (1976) and slightly higher than Algermissen et al. (1982).

For a 200-year time period, the minimum planned design life of the uranium mill tailings disposal facilities, the calculated probability that an acceleration of 0.035g to 0.045g will occur is nearly 100 percent. This reduces to approximately 50 percent for an acceleration of 0.05g to 0.07g, and to near zero for an acceleration of 0.10g or greater. Bearing in mind the practical limitations of the analytical method being employed, it should be assumed that a low probability (approximately 10 percent) is associated with the occurrence of an acceleration of 0.08g to 0.1g for a 200-year time period. The probability of an acceleration greater than 0.1g is apparently very low (less than 10 percent), but is not zero.

Probability values were calculated for a 250-year time interval to facilitate comparison with the study of Algermissen et al. (1982). Both studies determined the probability of occurrence of an acceleration of 0.09g to 0.10g to be less than 10 percent.

For a 1000-year time interval (approximated as 999 years for the computer analysis), which is the maximum required stable design life of the planned disposal cell, a nearly 100 percent probability of occurrence of an acceleration of 0.05g was determined. The probability of occurrence of an acceleration greater than about 0.12g during the 1000-year time period is very low, but is not zero. An acceleration of 0.16g is considered as having zero probability. The results of the probability analysis are represented graphically in Figure 4.1.

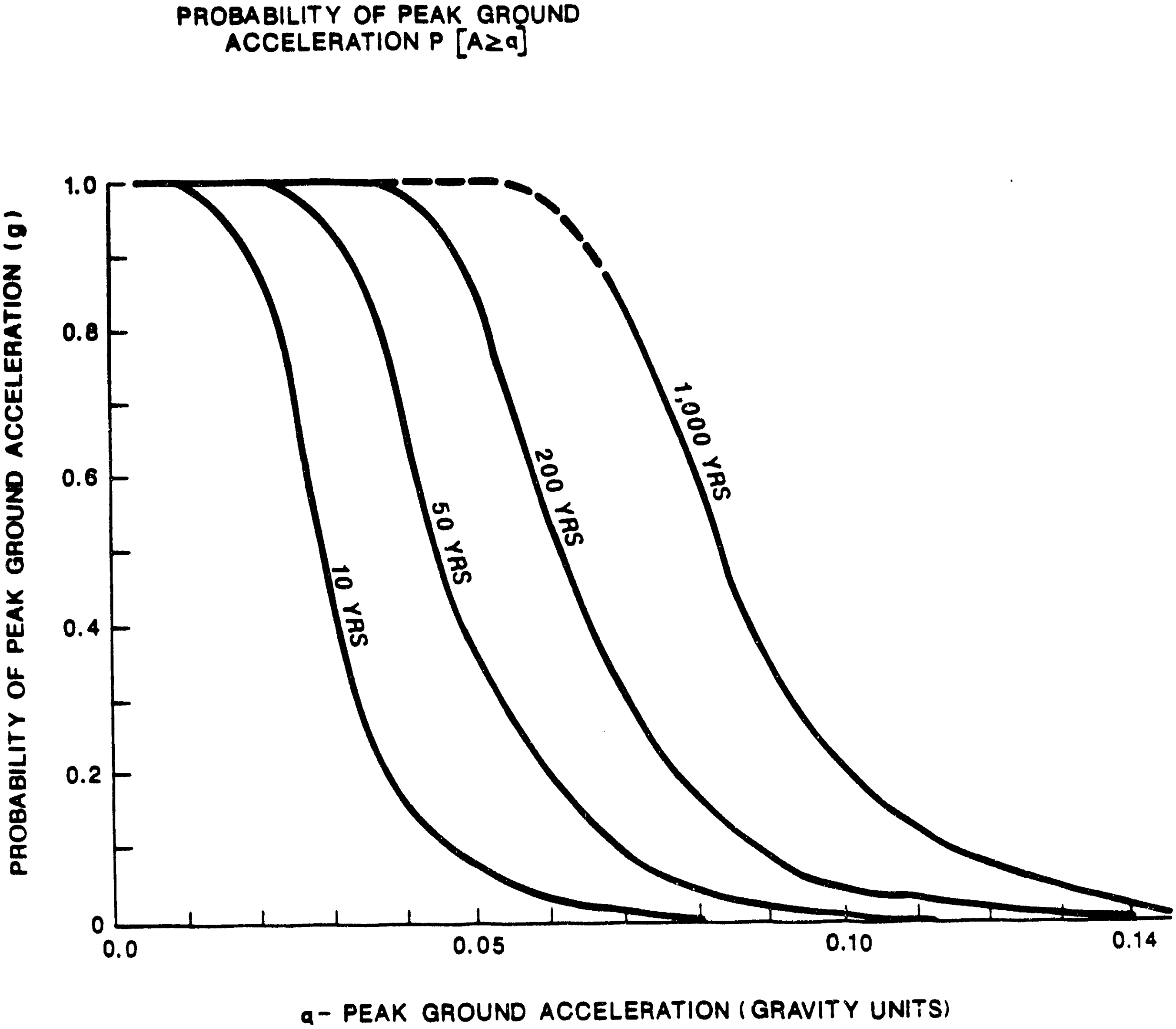


FIGURE 4.1
GRAPHICAL PLOT OF PROBABILITY OF ESTIMATED PEAK HORIZONTAL ACCELERATIONS AT BODO CANYON SITE, COLORADO

Seismic design

Based on the probabilistic approach, the maximum horizontal acceleration at the site for a 200-year period is 0.10g and for a 1,000- year design life is 0.16g. This method does not require the determination of a design earthquake magnitude. Seed and Idriss (1982) show that this design on-site acceleration of .16g on bedrock is equivalent to a design of a magnitude 5.5 earthquake at a distance of 15 km (9.3 miles) or a magnitude 6.2 earthquake at a distance of 26 km (16 miles) from the site.

Although there is a substantial depth of unconsolidated surficial deposits in the narrow paleochannel fill, the site is underlain by bedrock over 70 percent of the cell area.

The seismic coefficient for the long-term design life is 0.16g and for the short-term design is 0.05g. Figure 4.1 shows that there is less than 10 percent probability that an 0.05g acceleration will occur in 10 years.

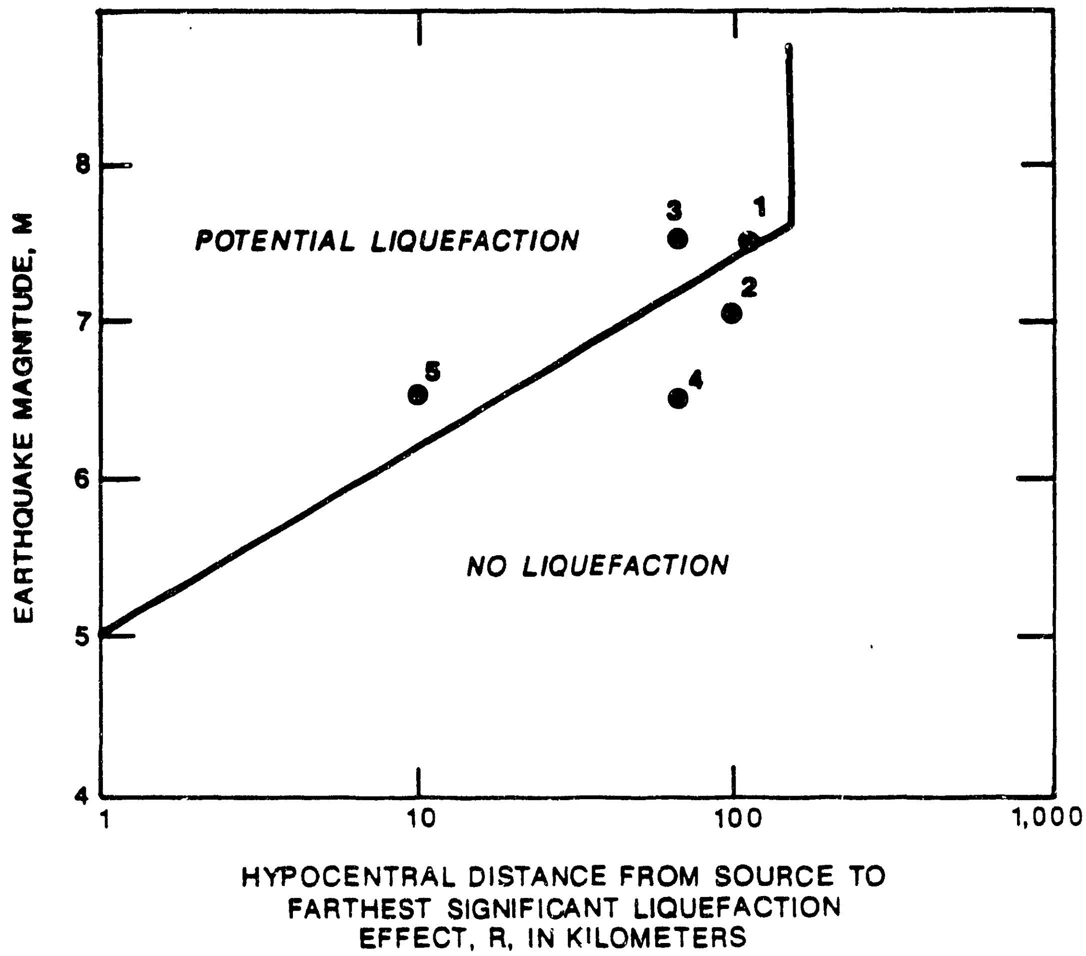
Potential for soil liquefaction at the site area

A review of published earthquake reports by Youd and Hoose (1977) indicates that shallow, saturated, Holocene fluvial, deltaic and aeolian deposits, and poorly compacted artificial sand fills have the highest susceptibility to liquefaction and subsequent ground failure. Holocene alluvial fan, alluvial plain, beach, terrace, and playa deposits were found to be less susceptible. Pleistocene sand deposits are generally even less susceptible, and glacial till, clay rich, and pre-Pleistocene deposits are usually immune to liquefaction. The degree of sorting, the degree of compaction during sedimentation or construction, and the grain-size distribution are major factors controlling liquefaction potential. The greater the sorting and the looser the packing, the greater the liquefaction potential. Most episodes of liquefaction have developed at relatively shallow depths (probably less than 10 meters) and in areas where the water table (free or perched) was located within a few meters of the ground surface.

The potential for liquefaction also depends on the degree of seismic shaking. The opportunity for ground failure in a given area is a function of the seismicity of the area and the rate of occurrence of earthquake ground motions of sufficient intensity to produce ground failure in susceptible materials. The maximum distance from a seismic source to potentially damaging ground failures as a function of earthquake magnitude was determined by Youd and Perkins (1978) as plotted in Figure 4.2. Liquefaction is not likely to be produced by earthquakes of magnitudes less than 5.0 or at a distance greater than 47 to 94 miles (75 to 150 km) from the hypocenter.

Five hypothetical earthquakes that might affect the Bodo Canyon site area are shown on Figure 4.2. It is apparent that only the largest possible events at the theoretical closest approaches would be capable of producing liquefaction in susceptible materials.

The Bodo Canyon site is underlain by colluvial and alluvial deposits that are generally very thin, but have a thickness of 45 to 65 feet along a narrow paleochannel. The deposits mainly consist of clayey and gravelly



LEGEND

EVENTS SHOWN ON GRAPH

1 CLOSEST APPROACH OF MCE - 7.5 IN RIO GRANDE RIFT.
2 MCE - 7.1 ON UNCOMPAGHRE UPLIFT
3 M - 7.5 EVENT IN DULCE, NEW MEXICO AREA.
4 M - 6.5 EVENT IN DULCE, NEW MEXICO AREA.
5 M - 6.5 EVENT IN COLORADO PLATEAU/WESTERN MOUNTAIN PROVINCE BORDER ZONE.

REF: YOUD AND PERKINS, 1978

FIGURE 4.2
GRAPHICAL PLOT OF LIQUEFACTION POTENTIAL
BODO CANYON SITE, COLORADO

sands with occasional cobbles and gravels, buried soil horizons, silty clays, and possibly some eolian silts. The water table is perched within the bottom of the paleochannel. The saturated sand deposits may be susceptible to liquefaction, but due to their limited extent and the criteria that were used in the design, the potential for liquefaction at this site is extremely small.

Other hazards

Volcanic activity, which occurred in the San Juan Mountains volcanic center, has not occurred in the Bodo Canyon region since late Miocene to early Pliocene time (Larkin et al., 1980). The last activity occurred in the border area with the Rio Grande Rift zone. No future activity is expected under the Quaternary tectonic regime within the Colorado Plateau or Western Mountain provinces.

REFERENCES

Algermissen, S. T., and D. M. Perkins, 1976. A Probabilistic Estimate of Maximum Acceleration in Rock in the Contiguous United States, U.S. Geological Survey Open-File Report 76-416, U.S. Department of the Interior, Washington, D.C.

Algermissen et al. (S. T. Algermissen, D. M. Perkins, P. C. Thenhaus, S. L. Hanson, and B. L. Bender), 1982. Accelerations and Velocity in Rock in the Contiguous United States, U.S. Geological Survey Open-File Report 82-1033, U.S. Department of the Interior, Washington, D.C.

Andrews et al. (J. T. Andrews, P. E. Carrara, F. B. King, and R. Struckenrath), 1975. "Holocene Environmental Changes in the Alpine Zone, Northern San Juan Mountains, Colorado: Evidence From Bog Stratigraphy and Palynology," in Quaternary Research, Vol. 5, pp. 173-197.

Arabasz et al. (W. J. Arabasz, R. B. Smith, and W. D. Richins), 1979. Earthquake Studies in Utah, 1850 to 1978, University of Utah Seismograph Stations, Department of Geology and Geophysics, University of Utah, Special Publication 5527, Salt Lake City, Utah.

ARPC (Animas Regional Planning Commission), 1976. Surficial Deposits, Geologic Hazards, and Mineral Resources for Durango West, Basin Mountain, and Kline Quadrangles, Animas Regional Planning Commission, Durango, Colorado.

ATC (Applied Technology Council (Associated with the Structural Engineers Association of California)), 1978. "Tentative Provisions for the Development of Seismic Regulations for Buildings," Applied Technology Council Publication ATC-3-06, also National Bureau of Standards Publication 510, National Science Foundation Publication 78-8, 506 pp., 2 pl.

Barry, R. G., 1983. "Late-Pleistocene Climatology," in Porter, S.C., ed., Late-Quaternary environments of the United States, Vol. 1: The Late Pleistocene, University of Minnesota Press, pp. 390-407, Minneapolis, Minnesota.

Bradley, R. S., 1976. Precipitation History of the Rocky Mountain States, Westview Press, 334 p., Boulder, Colorado.

Bradley, R. G., and R. Barry, 1976. "Historical Climatology," in Steinhoff, H. W. and Ives, J. D., eds., Ecological Impacts of Snowpack Augmentation in the San Juan Mountains, Colorado, San Juan Ecology Project, Final Report, pp. 43-67, Colorado State University, Fort Collins, Colorado.

Brakenridge, G. R., 1978. "Evidence for a Cold, Dry Full-Glacial Climate in the American Southwest," in Quaternary Research, Vol. 9, pp. 22-40.

CDM (Colorado Division of Mines), 1981. Personal communication with Paul Smith, Sergent, Hauskins & Beckwith, Geological Services, Phoenix, Arizona, dated December 2, 1981.

CGS (Colorado Geological Survey), 1981. Preliminary Report on Potential Sites Suitable for Relocation and/or Reprocessing of the Durango Uranium Mill Tailings Pile, Open-File Report 81-1, prepared by the Colorado Geological Survey, Denver, Colorado, with assistance from Robert M. Kirkham and the Four Corners Environmental Research Institute.

CGS (Colorado Geological Survey), 1974. Colorado Stratigraphic Correlation Chart, Denver, Colorado.

COGCC (Colorado Oil and Gas Conservation Commission), 1981. Personal communication with Paul Smith, Sergent, Hauskins & Beckwith, Geological Services, Phoenix, Arizona, dated December 2, 1981.

Campbell, K. W., 1981. "Near-Source Attenuation of Peak Horizontal Acceleration," in Bulletin of the Seismological Society of America, Vol. 71, pp. 2039-2070.

Carrara et al. (P. E. Carrara, W. N. Mode, M. Rubin, and S. W. Robinson), 1984. "Deglaciation and Postglacial Timberline in the San Juan Mountains, Colorado," in Quaternary Research, Vol. 21, No. 1, pp. 42-55.

Cash, D. J., 1975. "The Focal Mechanism of the Dulce, New Mexico, Earthquake of January 23, 1966," in Transactions of American Geophysical Union, Vol. 56, No. 12, p. 1022.

Cater, F. W., Jr., 1970. "Geology of the Salt Anticline region in southwestern Colorado," U.S. Geological Survey Professional Paper 637.

Cater, F. W., Jr., 1966. "Age of the Uncompahgre Uplift and Unaweep Canyon, West-Central Colorado," U.S. Geological Survey Professional Paper 550-C, Washington, D.C., pp. C86-C92.

Chiang et al. (W. Chiang, G. A. Guidi, C. P. Mortgat, C. C. Shoof, and H. C. Shah), 1984. Computer Programs for Seismic Hazard Analysis, a User Manual, John A. Blume Earthquake Engineering Center, Department of Civil Engineering, Report No. 62, Stanford University, Palo Alto, California.

Coffman, J. L., and C. A. von Hake, eds., 1973. "Earthquake History of the United States," U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Publication 41-1.

Crutchfield, R. L., 1976. "Geologic Feasibility Report, Ridges Basin Inlet System and Durango Pumping Plant, Animas - La Plata Project, Colorado," U.S. Bureau of Reclamation, Western Colorado Project Office, Durango Planning Division, Report No. DG 19, Durango, Colorado.

DOE (U.S. Department of Energy), 1986. "Remedial Action Plan and Site Design for Stabilization of the Inactive Mill Tailings Site at Durango, Colorado, December 1986," UMTRA-DOE/AL-050503.0000, DOE UMTRA Project Office, Albuquerque Operations Office, Albuquerque, New Mexico.

DOE (U.S. Department of Energy), 1985a. Seismic Risk Evaluation, Durango UMTRAP Sites, Uranium Mill Tailings Remedial Action Project, DOE UMTRA Project Office, Albuquerque Operations Office, Albuquerque, New Mexico.

DOE (U.S. Department of Energy), 1985b. "Supplemental Seismic and Geomorphic Evaluation, Bodo Canyon Area E Alternative Site Area, Durango, Colorado, Uranium Mill Tailings Remedial Action Project," prepared by the DOE UMTRA Project Office, Albuquerque Operations Office, Albuquerque, New Mexico.

DOE (U.S. Department of Energy), 1985c. "Final, Disposal Site Characterization Report for the Alternate Uranium Mill Tailings Disposal Site in Bodo Canyon near Durango, Colorado," UMTRA-DOE/AL-050103.0001, DOE UMTRA Project Office, Albuquerque Operations Office, Albuquerque, New Mexico.

DOE (U.S. Department of Energy), 1985d. Final Environmental Impact Statement: Remedial Actions at the Former Vanadium Corporation of America Uranium Mill Site, Durango, La Plata County, Colorado, DOE/EIS-0111F, DOE UMTRA Project Office, Albuquerque Operations Office, Albuquerque, New Mexico.

DOE (U.S. Department of Energy), 1984a. "Draft Environmental Impact Statement - Uranium Mill Tailings Remedial Action Program, Durango Site, Durango, La Plata County, Colorado," DOE/EIS-0111D, DOE UMTRA Project Office, Albuquerque Operations Office, Albuquerque, New Mexico.

DOE (U.S. Department of Energy), 1984b. "Disposal Site Characterization Report for the Alternate Uranium Mill Tailings Disposal Site in Bodo Canyon Near Durango, Colorado," DOE UMTRA Project Office, Albuquerque Operations Office, Albuquerque, New Mexico.

Dames & Moore, 1983a. Geotechnical Investigation for Bodo Canyon Uranium Mill Tailings Remedial Action Program, Durango, Colorado, prepared for the U.S. Department of Energy, Albuquerque Operations Office, Albuquerque, New Mexico.

Dames & Moore, 1983b. "Preliminary Draft Environmental Impact Statement - Uranium Mill Tailings Remedial Action Program, Durango Site, Durango, La Plata County, Colorado," unpublished data prepared by Dames & Moore, Denver, Colorado, for U.S. Department of Energy, UMTRA Project Office, Albuquerque Operations Office, Albuquerque, New Mexico.

Dane, C. H., and G. D. Bachman, 1965. "Geologic Map of New Mexico," U.S. Geologic Survey, Denver, Colorado.

Donovan, N. C., 1973. "Earthquake Hazards for Buildings," in Building Practices for Disaster Mitigation, National Bureau of Standards Building Science Series, no. 46, pp. 82-111.

Dubois et al. (S. M. DuBois, A. W. Smith, N. K. Nye, and T. A. Nowak, Jr.), 1982. Arizona Earthquakes, 1776-1980, Arizona Bureau of Geology and Mineral Technology, Bulletin 193.

Euler et al. (R. C. Euler, G. J. Gumerman, T. N. V. Karlstrom, J. S. Dean and R. H. Hevly), 1979. "The Colorado Plateau: Cultural Dynamics and Paleoenvironment," in Science, Vol. 205, No. 4411, pp. 1089-1101.

FBDU (Ford, Bacon & Davis Utah, Inc.), 1977. "Engineering Assessment of Inactive Uranium Mill Tailings - Durango Site, Durango, Colorado," unpublished Report No. GJT-6 prepared for the U.S. Department of Energy, UMTRA Project Office, Albuquerque Operations Office, Albuquerque, New Mexico.

FBDU (Ford, Bacon & Davis Utah Inc.), 1981. Engineering Assessment of Inactive Uranium Mill Tailings, Durango Site, Durango, Colorado, DOE/UMT-0103, prepared for U.S. Department of Energy, UMTRA Project Office, Albuquerque Operations Office, Albuquerque, New Mexico.

FMFA (F. M. Fox and Associates, Inc.), 1978. Geotechnical Investigation for a Proposed Uranium Tailings Leaching Operation Near Durango, Colorado, Job No. 1-331-3634, prepared for Ranchers Exploration and Development Corporation, Albuquerque, New Mexico.

FOCERI (Four Corners Environmental Research Institute), 1978. Environmental Report, Proposed Uranium Mill Tailings Leaching Operation, Durango, Colorado, prepared for Ranchers Exploration and Development Corporation, Albuquerque, New Mexico.

Fritts, H. C., 1965. "Tree Ring Evidence for Climatic Changes in Western North America," in Monthly Weather Review, Vol. 93, pp. 421-443.

Gable, D., and T. Hatton, 1980. Vertical Crustal Movements in the Conterminous United States over the Last 10 Million Years, U.S. Geological Survey Open-File Report 80-180, U.S. Department of the Interior, Washington, D.C.

Gale Research Company, 1980. "Climate of Colorado," in Climates of the States (2nd edition), Vol. 1, Gale Research Company, Detroit, Michigan.

Gillam et al. (M. L. Gillam, D. W. Moore, and G. R. Scott), 1984. "Quaternary Deposits and Soils in the Durango Area, Southwestern Colorado," in Brew, D.C., ed., Field Trip Guidebook, 37th Annual Meeting, Rocky Mountain Section, Geological Society of America, Fort Lewis College, Four Corners Geological Society, Durango, Colorado, pp. 149-182.

Gutenberg, B., and C. F. Richter, 1956. "Earthquake Magnitude, Intensity, Energy, and Acceleration," Bulletin of the Seismological Society of America, Vol. 46, No. 1, pp. 105-145.

Hadsell, F. A., 1968. "History of Earthquake Activity in Colorado," in Colorado School of Mines Quarterly, Vol. 63, No. 1, pp. 57-72.

Harmon, C. E., 1983. State Conservation Agronomist, Soil Conservation Service, U.S. Department of Agriculture, Denver, Colorado, telephone conversation with Paul Smith, Sergent, Hauskins & Beckwith, Geological Services, Phoenix, Arizona, dated November 23, 1983.

Haynes et al. (D. D. Haynes, J. D. Vogel, and D. G. Wyant), 1972. "Geology, Structure, and Uranium Deposits of the Cortez Quadrangle, Colorado and Utah," U.S. Geological Survey, Miscellaneous Investigations Series, Map I-629, Scale 1:250,000.

Herrmann et al. (R. B. Herrmann, J. W. Dewey, and S. K. Park), 1980. "The Dulce, New Mexico Earthquake of January 23, 1966," in Bulletin of the Seismological Society of America Vol. 70, No. 6, pp. 2171-2184.

Hoffman, J. P., 1975. "The Seismic History of the Rio Grande Rift," U.S. Geological Survey, Earthquake Information Bulletin, Vol. 7, No. 3, U.S. Department of the Interior, Washington, D.C., pp. 8-13.

Hoffman, J. P., and S. A. Northrup, 1977. "The Dulce, New Mexico Earthquake, January 23, 1966," in Earthquake Notes, Vol. 48, No. 4, pp. 3-20.

Howard, K. A., 1978. "Preliminary Map of Young Faults in the United States as a Guide to Possible Fault Activity," U.S. Geologic Survey, Miscellaneous Field Studies Map MF-916.

Hunt, C. B., 1974. Natural Regions of the United States and Canada, W. H. Freeman & Co., San Francisco, California.

Hunt, C. B., 1967. Physiography of the United States, W. H. Freeman and Co., San Francisco, California.

Hunt, C. B., 1956. "Cenozoic Geology of the Colorado Plateau," U.S. Geological Survey, Professional Paper 279, U.S. Department of the Interior, Washington, D.C.

ICBC (International Conference of Building Officials), 1982. Uniform Building Code (1982 Edition), Whittier, California.

Keller et al. (G. R. Keller, L. W. Braile, and P. Morgan), 1979. "Crustal Structure, Geophysical Models and Contemporary Tectonism of the Colorado Plateau," in McGetchin, T.R., and Merrill, R.B., eds., "Plateau Uplift: Mode and Mechanism," in Tectonophysics, Vol. 61, pp. 131-147.

Kelley, V. C., and N. J. Clinton, 1960. "Fracture Systems and Tectonic Elements of the Colorado Plateau," in Geology, No. 6.

King, P. B., 1959. The Evolution of North America, Princeton University Press, Princeton, New Jersey.

Kirkham, R. M., and W. P. Rogers, 1981. "Earthquake Potential in Colorado, a Preliminary Evaluation," Colorado Geologic Survey Bulletin, No. 43.

Krinitzsky, E. L., and F. K. Chang, 1977. State-of-the-Art for Assessing Earthquake Hazards in the United States, Report 7: Specifying Peak Motions for Design Earthquakes," U.S. Army Corps of Engineers Waterways Experiment Station, Miscellaneous Paper J-73-1, Vicksburg, Mississippi.

Ladwig, L. R., 1981. "Coking Coals of Western Colorado," in Western Slope Colorado, ed. J. F. Callender, New Mexico Geological Society, Thirty-Second Field Conference, October 8-10, 1981, University of New Mexico Press, Albuquerque, New Mexico.

Larkin et al. (R. P. Larkin, P. K. Grogger, G. L. Peters), 1980. The Southern Rocky Mountains: Field Guide, K/H Geology Field Guide series, Kendall/Hunt Publishing Company, Dubuque, Iowa.

Leonard, E. M., 1984. "Late Pleistocene Equilibrium Line Altitudes and Modern Snow Accumulation Patterns, San Juan Mountains, Colorado, U.S.A.," in Arctic and Alpine Research, Vol. 16, No. 1, pp. 65-76.

Liu, H. L., and H. Kanamori, 1980. "Determinations of Source Parameters of Midplate Earthquakes from the Waveforms of Body Waves," in Seismological Society of America Bulletin, Vol. 70, pp. 1989-2004.

Liu, S. C., and N. J. DeCapua, 1975. "Microzonation of Rocky Mountain States," in Proceedings of the U.S. National Conference on Earthquake Engineering, Earthquake Engineering Research Institute, Ann Arbor, Michigan, pp. 128-135.

Maher, L. J., Jr., 1961. "Pollen Analysis and Postglacial Vegetation History in the Animas Valley Region, Southern San Juan Mountains, Colorado," Ph.D. Thesis, University of Minnesota, Minneapolis.

Merges, C. M., 1983. "The Neotectonic Framework of Arizona: Implications for the Regional Character of Basin-Range Tectonism," State of Arizona, Bureau of Geology and Mineral Technology, Open-File Report 83-19.

Moore, D. W., and G. R. Scott, 1981. Generalized Surficial Geologic Map of the Basin Mountain Quadrangle, Colorado, U.S. Geological Survey Open-File Report 81-1306.

Murray, D. K., 1981. "Upper Cretaceous (Campanian) Coal Resource of Western Colorado," in Western Slope Colorado, ed. J. F. Callender, New Mexico Geological Society, Thirty-Second Field Conference, October 8-10, 1981, University of New Mexico Press, Albuquerque, New Mexico.

NGDC/NOAA (National Geophysical Data Center/National Oceanic and Atmospheric Administration), 1984. Earthquake data file for the Durango, Colorado, region.

NGDC/NOAA (National Geophyisical Data Center/National Oceanic and Atmospheric Administration), 1981. "Radial Search 200 miles (320 km) Around Durango, Colorado," Earthquake Data File, U.S. Department of Commerce, Boulder, Colorado.

NOAA (National Oceanic and Atmospheric Administration), 1985. Climatological data, New Mexico: 1930-1980, National Oceanic and Atmospheric Administration, Environmental Data and Information Service, Asheville, North Carolina, Vol. 34-84, No. 13.

Nelson et al. (J. D. Nelson, R. L. Volpe, R. E. Wardwell, S. A. Schumm and W. P. Staub), 1983. "Design Considerations for Long-Term Stabilization of Uranium Mill Tailings Impoundments," U.S. Nuclear Regulatory Commission, NUREG/CR-3397 ORNL-5979.

New Mexico Geological Society, 1982. Physiographic map of New Mexico, in New Mexico Highway Geologic Map, Scale 1:3,500,000.

Northrup, S. A., 1976. "New Mexico's Earthquake History, 1849-1975," New Mexico Geologic Society, Special Publication 6, pp. 77-87.

Peterson, K. L., and P. J. Mehringer, Jr., 1976. "Postglacial Timberline Fluctuations, La Plata Mountains, Southwestern Colorado," in Arctic and Alpine Research, Vol. 8, No. 3, pp. 275-288.

Porter et al. (S. C. Porter, K. L. Pierce, and T. D. Hamilton), 1983. "Late Wisconsin Mountain Glaciation in the Western United States," in Porter, S. C., ed., Late Quaternary Environments of the United States, Vol. 1: The Late Pleistocene, University of Minnesota Press, Minneapolis, Minnesota, pp. 71-110.

Raleigh, C. B., and others, 1976. "An Experiment in Earthquake Control at Rangely, Colorado," in Science, Vol. 191, pp. 1230-1237.

Richter, C. F., 1958. Elementary Seismology, W.H. Freeman and Company, San Francisco, California.

Ritter, D. F., 1978. Process Geomorphology, Wm. C. Brown Company, Dubuque, Iowa.

SCS (Soil Conservation Service), 1985. "Soil Survey of La Plata County, Colorado," U.S. Department of Agriculture, Soil Conservation Service, Washington, D.C.

SCS (Soil Conservation Service), 1982. National Cooperative Soil Survey, La Plata County, Colorado, unpublished map, U.S. Department of Agriculture, Durango, Colorado.

SCS (Soil Conservation Service), 1979. Determining Capability Class of Soils, Agronomy Note No. 56, U.S. Department of Agriculture, Denver, Colorado.

SCS (Soil Conservation Service), 1975. Soil Taxonomy, Agriculture Handbook 436, U.S. Department of Agriculture, U.S. Government Printing Office, Washington, D.C.

SCS (Soil Conservation Service), 1954. "Colorado Heat and Moisture Indices for Use in Land Capability Classification," U.S. Department of Agriculture, Soil Conservation Service, Salt Lake City, Utah.

Sanford et al. (A. R. Sanford, K. H. Olsen, and L. H. Jaksha), 1981. Earthquakes in New Mexico 1849-1977, New Mexico Bureau of Mines and Mineral Technology, Circular 171, Socorro, New Mexico.

Sanford et al. (A. R. Sanford, K. H. Olsen, and L. H. Jaksha), 1979. "Seismicity of the Rio Grande Rift," in Rio Grande Rift: Tectonics and Magmatism, edited by R. E. Riecher, American Geophysical Union, Washington, D.C., pp. 145-168.

Sanford et al. (A. R. Sanford, R. P. Mott, Jr., P. J. Schuleski, E. G. Rinehart, F. J. Cavarella, R. M. Ward, and T. C. Wallace), 1977. "Geophysical Evidence for Magma Body in the Crust in the Vicinity of Socorro, New Mexico," in The Earth's Crust, Geophysical Monograph Series, 20, edited by J. G. Heacock, A.G.U., Washington, D.C., pp. 385-403.

Schnabel, P. B., and H. B. Seed, 1972. Acceleration in Rock for Earthquakes in the Western United States, Report 72-2, University of California Earthquake Engineering Research Center, Berkeley, California.

Schultz, J. D., 1983. "Geomorphology and Quaternary History of the Southeastern Chaco Dune Field, Northwestern New Mexico," in Wells, S. G., Love, D. W., and Gardner, T. W., eds., Chaco Canyon Country, American Geomorphological Field Group, 1983 Field Trip Guidebook, pp. 159-166.

Schultz, J. D. 1980. "Geomorphology, Sedimentology, and Quaternary History of the Eolian Deposits, West-Central San Juan Basin, Northwest New Mexico," University of New Mexico, Albuquerque, M.S. Thesis.

Schumm, S. A. and Chorley, P. J., 1983. "Geomorphic Controls on the Management of Nuclear Waste," U.S. Nulcear Regulatory Commission, NUREG/CR-3276RW.

Seed, H. B., and I. M. Idriss, 1982. Ground Motions and Soil Liquefaction During Earthquakes, Earthquake Engineering Research Institute Monograph, Berkeley, California, 134 pp.

Slemmons, D. B., 1985. Personal communications from D. B. Slemmons, Professor, University of Nevada, Reno, to Paul V. Smith, Sergent, Hauskins & Beckwith, Geological Services, Phoenix, Arizona, on various dates in 1985.

Slemmons, D. B., 1977. "Faults and Earthquake Magnitude," U.S. Army Engineer Waterways Experiment Station, Miscellaneous Paper S-73-1, Report 6.

Slemmons, D. B., and R. A. Whitney, 1980. "Evaluation of Potential for Surface Faulting and the Design Earthquake Parameters for the Church Rock Tailings Dam, United Nuclear Company, Church Rock, New Mexico," unpublished report prepared for Sergent, Hauskins & Beckwith, Consulting Geotechnical Engineers, Phoenix, Arizona.

Slemmons et al. (D. B. Slemmons, P. O'Malley, R. A. Whitney, D. H. Chung, and D. L. Bernreuter), 1982. "Assessment of Active Faults for Maximum Credible Earthquakes of the Southern California - Northern Baja Region," Lawrence Livermore National Laboratory Publication UCID-19125.

Smith, R. B. and M. L. Sbar, 1974. "Contemporary Tectonics and Seismicity of the Western U.S. with Emphasis on the Intermountain Seismic Belt," in Geologic Society of America Bulletin, Vol. 85, pp. 1205-1218.

Steven et al. (T. A. Steven, P. W. Lipman, W. J. Hail, Jr., F. Barker, and R. G. Luedke), 1974. Geological Map of the Durango Quadrangle, Southwestern Colorado, U.S. Geological Survey Miscellaneous Investigations Map I-764, U.S. Department of the Interior, Washington, D.C.

Stockton, C. W., and G. C. Jacoby, 1976. "Long-Term Surface Water Supply and Streamflow Trends in the Upper Colorado River Basin, Based on Tree-Ring Analyses," University of California, Los Angeles, Institute of Geophysics and Planetary Physics, Lake Powell Reservoir Project Bulletin 18.

Sullivan et al., 1980. "Seismic Hazard Evaluation - Ridgeway Dam and Reservoir Site - Dallas Creek Project, Colorado," unpublished report, U.S. Water and Power Resources Service, Seismotectonic Section.

Trifunac, M. D., and A. G. Brady, 1975. "On the Correlation of Seismic Intensity Scales with the Peaks of Recorded Strong Ground Motion," in Bulletin of the Seismological Society of America, Vol. 65, No. 1, pp. 139-162.

Tweto, Ogden, 1979. "Geologic Map of Colorado," U.S. Geological Survey, Special Map, Scale 1:500,000.

USDC (U.S. Department of Commerce), 1968. Climatic Atlas of the United States, Environmental Science Services Administration, Environmental Data Services, U.S. Government Printing Office, Washington, D.C.

von Hake, C. A., 1984. Personal communication from C. A. von Hake, National Geophysical Data Center (NGDC/DOAA), Boulder, Colorado, to Paul V. Smith, Sergent, Hauskins & Beckwith, Geological Services, Phoenix, Arizona.

von Hake, C. A., 1975. "Earthquake History of New Mexico," in Earthquake Information Bulletin, Vol. 7, No. 3, pp. 23-26.

W-C (Woodward-Clyde Consultants), 1983. Overview of the Regional Geology of the Paradox Basin Study Region, for Battelle Project Management Division, published by NTIS, Springfield, Virginia.

Wong, I. G., 1984. "Seismicity of the Paradox Basin and the Colorado Plateau Interior," technical report prepared for Office of Nuclear Waste Isolation, Battelle Memorial Institute.

Woodward, L. E., and J. F. Callender, 1977. "Tectonic Framework of the San Juan Basin," in 28th Field Conference Guidebook, New Mexico Geological Society, Albuquerque, New Mexico, pp. 209-212.

Wright et al. (H. E. Wright, Jr., A. M. Bent, B. S. Hansen, and L. J. Maher, Jr.), 1973. "Present and Past Vegetation of the Chuska Mountains, Northwestern New Mexico," Geological Society of America Bulletin, Vol. 84, pp. 115-1180.

Youd, T. L., and S. N. Hoose, 1977. "Liquefaction Susceptibility and Geologic Setting," in Proceedings of 6th World Conference on Earthquake Engineering, New Delhi, India, Vol. 6, pp. 37-42.

Youd, T. L., and D. M. Perkins, 1978. "Mapping Liquefaction-Induced Ground Failure Potential," in Journal Geotechnical Engineering Division, ASCE, Vol. 104, No. GT4, pp. 433-446.

Zapp, A. D., 1949. Geology and Coal Resources of the Durango Area, La Plata and Montezuma Counties, Colorado, U.S. Geological Survey Oil and Gas Investigations Map OM-109.

Zoback, M. L., and M. D. Zoback, 1980. "State of Stress in the Continuous United States," in Journal of the Geophysical Restoration, Vol. 85, pp. 6113-6156.

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