SEISMIC HAZARD EVALUATION
RIDGWAY DAM AND RESERVOIR SITE
DALLAS CREEK PROJECT, COLORADO

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March 1980
Seismic Hazard Evaluation
Ridgway Dam and Reservoir Site
Dallas Creek Project, Colorado

SUMMARY

The following conclusions and recommendations are the result of a seismic hazard study performed by the Seismotectonic Section, Geologic Services Branch, for Ridgway Dam, Dallas Creek Project, Colorado. This study is based on the latest available geological and geophysical data and is consistent with current Water and Power Resources Service standards for such studies.

Conclusions

1. The Ridgway fault is considered active based on the association of microearthquake hypocenters with the projected subsurface trace of the fault. The Ridgway fault is a high-angle normal fault with about 450 m (1500 ft) of displacement, 8 km (5 mi) from the damsite.

2. Branch faults in the reservoir area are considered active based on a structural relationship with the Ridgway fault, association of microearthquake epicenters, and apparent tectonic displacements in Quaternary deposits.

3. Maximum credible earthquakes which may affect Ridgway damsite are tabulated below. Earthquake recurrence relationships for the selection of other design earthquakes are shown on Figure 9.
Maximum Credible Earthquakes

<table>
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<tr>
<th>Tectonic structure</th>
<th>Maximum Credible Earthquake (MCE)</th>
<th>Epicentral distance</th>
<th>Focal depth</th>
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<tr>
<td>Ridgway fault</td>
<td>6.5</td>
<td>8 km</td>
<td>7 km</td>
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<tr>
<td>Branch faults</td>
<td>6.0</td>
<td>2 km</td>
<td>7 km</td>
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4. A maximum surface displacement of 0.5 to 1.0 m (1.6 to 3.3 ft) may be associated with the MCE on the Ridgway fault. A maximum surface displacement of 10 to 35 cm (0.3 to 1.1 ft) may be associated with the MCE on the branch fault closest to the dam.

5. Landslides covering areas as large as about 0.56 km² (0.22 mi²) have been mapped along the western margin of the reservoir (Fig. 4). Analysis of the hazard posed by activation of existing or additional slope instabilities in the reservoir area due to ground shaking associated with the MCE is beyond the scope of this report.

6. Due to the lack of penetration resistance data, the susceptibility of foundation materials to liquefaction cannot be evaluated.

Recommendations

1. Since surface displacements through the dam foundation cannot presently be precluded, geologic mapping of the core trench should be performed to determine if faulting is present. In addition, foundation materials should be examined for indications of liquefaction susceptibility.
2. Establish and maintain a seismic monitoring program at Ridgway Dam to accomplish the following objectives:

   a. To determine the natural level of seismicity of the reservoir area as background data for b and c.

   b. To provide additional information on the seismic activity of the faults in the vicinity of Ridgway Dam.

   c. To determine if filling and subsequent operation of the reservoir will induce earthquakes. Although Ridgway Dam and reservoir will not meet the statistical size criteria accepted for induced seismicity (Woodward-Clyde Consultants, 1977), there are active faults in the reservoir area.

   d. To provide seismic instrumentation on the Colorado Plateau to improve earthquake detection and location for the province.

Details and cost estimates are provided in Appendix II.
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Terminology and Correlation of Quaternary Glacial Deposits in the San Juan Mountains
Ridgway Microseismic Data
Maximum Credible Earthquakes for Ridgway Damsite
Velocity Model
Seismograph Station Parameter
Schedule of Station Operations
INTRODUCTION

Scope

This report summarizes the results of a Water and Power Resources Service seismotectonic study of the Ridgway Dam and reservoir site, Dallas Creek Project, Colorado. The objectives of this study were to:

1. Define the regional geology and tectonic setting of the project area.

2. Evaluate the historic seismicity of the region.

3. Assess the age and earthquake potential of the Ridgway fault and related faults.

4. Estimate the magnitude and location of design earthquakes.

5. Evaluate the potential for other seismically induced hazards.

Studies were based on: (1) a review of existing geological and seismological literature; (2) interpretation of panchromatic, color, and false-color infrared aerial photography; (3) geologic mapping; and (4) a 3-month, five-station microseismic monitoring program. The information gathered during this study was supplemented by the Service's Geologic Specifications Design
Data - Dallas Creek Project, Ridgway Dam and Reservoir (1979). The conclusions and recommendations presented in this report are considered adequate by current standards for design, construction, and operation of Ridgway Dam, Reservoir, and related facilities.

Location and Physiography

Ridgway Dam will be constructed across the Uncompahgre River in the SE 1/4, section 17, and the SW1/4, section 16, Township 46 north, Range 8 west. Ridgway, Colorado (population 150), lies 10 km (6 mi) upstream of the dam near the upper end of the reservoir; Montrose, Colorado (population 6,413), a major regional population center, lies 31 km (19 mi) downstream at the confluence of the Uncompahgre and Gunnison Rivers. The dam and reservoir are located on the Dallas and Ridgway 7.5-minute topographic quadrangles published by the U.S. Geological Survey.

The Ridgway Dam and reservoir area is dominated by three major physiographic elements: (1) the massive San Juan Mountains to the south and east, (2) the Uncompahgre Plateau to the northwest, and (3) the Uncompahgre River canyon flowing from south to north through the area. Near the town of Ridgway, the Uncompahgre canyon widens into a broad east-west trending valley bounded on the north by a 300-m (1000-ft) high bedrock escarpment forming the south side of Log Hill Mesa. North of this escarpment, the river resumes its course through a canyon incised into the southeasterly extension of the Uncompahgre Plateau. In general, relief decreases northward from the bedrock escarpment north of Ridgway to the damsite. Elevations at the damsite range from 2024 m (6640 ft) along the river to 2195 m (7200 ft) at the canyon rim, relief of over 170 m (560 ft).
Vegetation cover is typical of semiarid regions of western Colorado, consisting of willows and cottonwood along the major drainages and sagebrush, pinon, juniper, and scattered ponderosa pine at the higher elevations.

**Proposed Construction and Hazard Classification**

Ridgway Dam, the primary water impoundment structure for the Dallas Creek Project, will be a zoned earthfill embankment with a height of 79 m (259 ft) and a crest length of 732 m (2400 ft). The reservoir will have a total capacity of 9.9 x 10^7 m^3 (80,000 acre-ft). The river outlet works, a 2.7-m (8.9-ft) diameter pressure conduit with a discharge capacity of 36.8 m^3/s (1300 ft^3/s), will be located in a bedrock bench east of the existing river channel. The spillway will consist of 5.0-m (16.4-ft) diameter reinforced concrete shaft and inclined conduit located beneath the dam embankment on a sidehill cut in the right abutment. The uncontrolled spillway will have a capacity of 255 m^3/s (9000 ft^3/s).

To the best of our knowledge, no downstream flood inundation map has been prepared in the event of catastrophic failure of Ridgway Dam. Numerous ranches and homes are scattered along the Uncompahgre Valley immediately downstream of the dam; and the city of Montrose, 31 km (19 mi) to the north, lies in the potential flood path. U.S. Highway 550, a major transportation route connecting Montrose, Ridgway, Ouray, Silverton, and Durango, parallels the Uncompahgre River downstream of the dam. Catastrophic release of Ridgway reservoir, therefore, may result in significant property damage and loss of life.
REGIONAL TECTONIC SETTING

Regional Geology

The Ridgway site is located virtually on the boundary between the Colorado Plateau and the Southern Rocky Mountain tectonic/physiographic provinces (Fig. 1). The Colorado Plateau, encompassing about 400 000 km² (154,000 mi²) in western Colorado, southeastern Utah, northern Arizona, and northwestern New Mexico, is characterized by large-scale, but comparatively gentle, folds and locally faulted monoclinal flexures. In some areas, notably eastern Utah and western Colorado, the sedimentary rocks have been deformed and intruded by igneous rocks and diapirically emplaced salt. The Hurricane, Toroweep, and Wasatch faults form the seismically active boundary between the Colorado Plateau and the Basin and Range Province further to the west.

The Southern Rocky Mountains, on the other hand, are characterized by north-south trending, Precambrian-cored, anticlinal mountain ranges. These ranges, reaching elevations of over 4267 m (14,000 ft), are commonly fault-bounded and separated by relatively narrow intermontane, sedimentary basins. Local volcanic centers have extruded hundreds of meters of volcanic rock. One of these volcanic centers, the San Juan Mountains, lie a few miles south and east of the damsite.

Although within a few miles of the San Juan Mountains, the geology of Ridgway damsite is predominantly that of the Colorado Plateau. The site is located on a 160-km (100-mi) long by 50-km (31-mi) wide, northwest trending, northeast tilted block called the Uncompahgre Plateau. It is bounded on the northeast by a sharply flexed faulted monocline and on the southwest by a
series of relatively large displacement normal faults. Uplift of the Uncompahgre Plateau, evidenced by thick accumulations of Pennsylvanian and Permian sedimentary rocks in the Paradox Basin adjacent to its southwestern flank, began during Pennsylvanian time as a part of the uplift of the ancestral Rockies. Following intermittent movement during the Mesozoic, Cretaceous strata including the Burro Canyon, Dakota, Mancos, and Mesa Verde, and lower Tertiary formations (Cater, 1970) were deposited over the crest of the present Uncompahgre uplift.

Regional Seismicity

Earthquake epicenters through 1978 and within a 320-km (200-mi) radius of the damsite (NOAA, 1977; NOAA, 1973; NEIS, 1978; Hadsell, 1968) are plotted on Figure 1. All magnitudes reported herein are Richter (1958) magnitudes (M), and all intensities are Modified Mercalli. Body-wave magnitudes (mb) available in the literature were converted to Richter magnitudes by an empirically derived formula. Both Richter and body-wave magnitudes have been reported for 16 earthquakes in the study area. These events are plotted and listed in figure 2. A curve was fit to these data by a least-squares technique. The formula has the form:

\[ M = 1.76 \, mb - 4.07 \]

with a correlation coefficient of 0.94. This curve fits the data well for the magnitude (M) range 3.0 to 6.0 and should not be extended much beyond this range. Earthquakes with body-wave magnitudes less than 4.0 were considered to have Richter magnitudes less than 3.0 (specific numeric values were not assigned). For some earthquakes, only Modified Mercalli intensities
are reported in the literature. To develop a recurrence relation (Earthquake Recurrence, page 33), it was necessary to convert the intensities of these events to Richter magnitude. This conversion was performed using the Gutenberg and Richter (1956) formula:

\[ M = 1 + \frac{2}{3} I. \]

This relation is plotted in Figure 3 along with the magnitude-intensity data available for the study area. A curve fit to the data by a least-squares technique yields lower magnitudes at all intensities greater than \( I = III \), but has a correlation coefficient of only 0.68. Due to the low number of data points, their scatter, and the low correlation, it is prudent in this case to utilize the well accepted and more conservative Gutenberg and Richter formula.

Seismicity of the Colorado Plateau is, in general, of moderate magnitude and tends to be concentrated near the boundary of the province. The largest recorded earthquakes in the province are two intensity VII events (\( M \) approximately 5.7) of 1906 and 1912 in the vicinity of Flagstaff, Arizona. Other events of Richter magnitude 5.0 or greater on the Colorado Plateau include the following: 1950 (\( M = 5.25 \)) in the Uinta Basin; 1960 (\( M = 5.5 \)) near Ridgway, Colorado; 1966 (\( M = 5.5 \)) near Dulce, New Mexico; and 1976 (\( M = 5.0 \)) near Gallup, New Mexico. The events near Dulce, New Mexico, are all related to the January 23, 1966 (\( M = 5.5 \)) event (von Hake and Cloud, 1968) and are associated with structures on the northeast rim of the San Juan Basin. The 1960 Ridgway event is apparently associated with the Ridgway fault and related structures (Site Seismicity, page 17), and the 1906 and 1912 Flagstaff earthquakes occurred on the Oak Creek Canyon fault system (Giardina,
1977). The concentration of seismic activity near Price, Utah, is largely related to coal mining (Smith and others, 1974). Four events of 1941 (M = unknown), 1967 (M = unknown), 1967 (M = 3.0) and 1970 (M = 3.2) occurred 60 to 80 km (37 to 50 mi) southwest of the damsite. The poor accuracy of these locations [at least +20 km (12.5 mi)] suggests that these events may be related to any of several structures in the area. The northwest-southeast trend of the epicenters is similar to that of salt anticlines in the region (Cater, 1970) suggesting that the earthquakes may be related to salt movements and/or collapse features. No surface collapse features are present in the immediate area of the epicenters, however. Other small events in the province are scattered and do not delineate specific seismogenic structures.

Earthquakes in part of the Southern Rocky Mountains Province are also shown on Figure 1. The cluster of events near Denver that occurred during the 1960's are associated with fluid waste disposal at the Rocky Mountain Arsenal well (Major and Simon, 1968). The seismic history of the Rio Grande rift in Colorado is short and sparse. The only macroearthquakes associated with this portion of the rift are the intensity VII event of 1901 near Buena Vista and the events of 1961 (I = IV) and 1965 (M = 3.5). Short-term microearthquake surveys in the upper Arkansas valley (Crompton, 1976; Lange, 1977; Water and Power Resources Service, 1980) and the San Luis Valley (Keller and Adams, 1976) reported only 15 events in a total monitoring period of 115 days. The rate of activity indicated by the historical earthquake record is rather low; however, activity in the New Mexico portion of the rift is considerably higher and includes the intensity VII and VIII events of 1869, 1893, 1906, and 1918 (Sanford and others, 1979). Other historic earthquakes in the province are small, scattered, and do not delineate specific seismogenic structures.
SITE GEOLOGY AND SEISMICITY

Bedrock Stratigraphy

Bedrock exposed at the surface throughout most of southwestern Colorado, north and west of the San Juan Mountains, is Cretaceous coastal and marine sediments including the Dakota Sandstone and Mancos Shale with the underlying Jurassic Morrison Formation and older sedimentary rocks exposed in the deeper canyons. The southeastern portion of the Uncompahgre Plateau is capped by Dakota Sandstone with Mancos Shale locally preserved beneath a protective cap of glacial gravels. Further to the northeast, in the Gateway area, the Precambrian core of the Uncompahgre Plateau has been exposed, unconformably overlain by a Mesozoic sedimentary section.

Ridgway Dam and reservoir will occupy a 6-km (3.7-mi) long portion of the Uncompahgre River canyon north of the town of Ridgway. This portion of the Uncompahgre canyon is incised into a Jurassic to Cretaceous age sedimentary section summarized in the legend for Figure 4. The erosion-resistant rim of the canyon is formed by sandstones, conglomerates, and interbedded shales of the Dakota and Burro Canyon formations undivided. The abutments and foundation of the dam will be constructed in the underlying Morrison formation comprising about 250 m (820 ft) of variegated siltstones and shales with interbedded sandstones. Mancos Shale is preserved locally on Log Hill Mesa, in the area east of the reservoir and around the town of Ridgway. Quaternary deposits, due to their importance in assessing fault activity, are discussed in detail in the following section.
Quaternary Deposits

The relationship of Quaternary deposits across a fault can provide geologic evidence of its Quaternary displacement history. Near Ridgway, Quaternary glacial deposits are present both north and south of the Ridgway fault. Above the Uncompahgre River valley, tills are present both on Log Hill Mesa and Miller Mesa, north and south of the Ridgway fault. In addition, moraines are present on the valley bottom south of the fault and remnants of outwash deposits are present downstream of the moraines on the valley sides north of the fault. If these deposits could be correlated across the fault, the late Quaternary displacement history of the fault could be outlined.

A summary of Quaternary mapping in the Ridgway area is presented in this section as well as a discussion of the differing terminology used by various workers in reconstructions of the glacial history of the San Juan Mountains. It is concluded that our present understanding of Quaternary relationships in the Ridgway area precludes definitive conclusions regarding the Quaternary displacement history of the Ridgway fault; however, possible indications of Quaternary displacement are presented.

Quaternary glacial deposits in the Ridgway area have been divided into three major "age" groups called Cerro, Durango, and "Wisconsin" by Atwood and Mather (1932) based largely on present topographic position. Subsequently, more detailed geologic investigations in the San Juan Mountains have challenged some of the correlations and age relationships of Atwood and Mather (1932). Table I provides a synthesis of current published and unpublished terminology related to the glacial sequence in the San Juan Mountains.
<table>
<thead>
<tr>
<th></th>
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<th>San Juan Mountains Uncompahgre River (Ridgway) (Lee, 1978)</th>
<th>This report (Figure 4)</th>
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<tr>
<td><strong>Late</strong></td>
<td>Pinedale Late Middle Early</td>
<td>Wisconsin of Atwood and Mather (1932)</td>
<td></td>
<td>Qt₄</td>
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<tr>
<td><strong>Wisconsin</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Early</strong></td>
<td>Bull Lake Late Early</td>
<td>Some Durango of Atwood and Mather (1932)</td>
<td>Wisconsin of Atwood and Mather (1932)</td>
<td>Qt₃</td>
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<tr>
<td><strong>Illinoian</strong></td>
<td>Sacagawea Ridge Type end moraine, Durango, Atwood and Mather (1932)</td>
<td></td>
<td></td>
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<tr>
<td><strong>Kansan</strong></td>
<td>Cedar Ridge</td>
<td>Durango of Atwood and Mather (1932)</td>
<td></td>
<td>Qt₁, Q₅₀</td>
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<tr>
<td><strong>Nebraskan</strong></td>
<td>Washakie Point</td>
<td>Cerro of Atwood and Mather (1932)</td>
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In the following portions of this section, recent work pertinent to the age and correlation of the deposits of each major age group is presented.

**Older deposits (locations shown on Fig. 7).** - Howe and Cross (1906) and Cross and others (1907) first recognized and interpreted evidence for multiple Pleistocene glaciations in the Uncompahgre region. In addition to a discussion of the features of recent glaciation, they described gravel deposits 16 km (10 mi) west of Ridgway both on West Baldy Peak and further north on Horsefly Peak. These peaks are erosional remnants of Mancos Shale capped by gravels. They are aligned along the north-northeasterly trending fold of the Dallas Divide which separates the San Miguel and Uncompahgre watersheds. Horsefly Peak, at an elevation of 3154 m (10,347 ft), lies to the north of Log Hill Mesa on the upthrown side of the Ridgway fault; West Baldy, at an elevation of 2977 m (9766 ft) is 8 km (5 mi) south of Horsefly Peak on Howard Flats on the downthrown side of the Ridgway fault.

These gravel deposits are described as pebbles, boulders, and blocks of volcanic material up to 3 to 4.5 m (10 to 15 ft) across (Howe and Cross, 1906). A large part of this material was reported to be volcanic clasts of the Potosi Volcanic Series. These rocks are the youngest of the Tertiary volcanic rocks in the Uncompahgre region and remain today only as thin flows capping the highest peaks of the adjacent Sawtooth Range of the San Juan Mountains (Howe and Cross, 1906). These authors discount a landsliding or weathering-in-place origin for these deposits and conclude they are tills of considerable age.
In their comprehensive work on the Quaternary deposits of the San Juan Mountains, Atwood and Mather (1932) extended the occurrence of these deposits to South Baldy, a 2993-m (9821-ft) peak about 13 km (8 mi) southwest of West Baldy in the Dallas Creek drainage and to large areas west and northwest of Cimmaron Ridge, a narrow north-trending mesa capped by San Juan tuff, extending from the San Juan Mountains almost to the Gunnison River, about 15 km (9 mi) northeast of Ridgway (Fig. 7). They name this oldest glacial deposit Cerro till and describe the type section at Cerro Summit about 35 km (22 mi) northeast of Ridgway. Dickinson (1965) restudied the Cerro Summit area in 1965 and concluded that the glacial deposits at Cerro Summit mapped by Atwood and Mather (1932) as Cerro till appear to be landslide deposits derived from Poverty Mesa on the upthrown side of the Cimmaron fault north of Cerro Summit.

Intermediate-age deposits (locations shown on Fig. 4). — Intermediate level till and outwash deposits were recognized by Atwood (1915) and Atwood and Mather (1932) and attributed to a Durango stage glaciation. About 3 km (2 mi) north of Ridgway on the upthrown side of the Ridgway fault (Fig. 4), these tills (Qtl) occur in two localities. One is on the southeast side of Log Hill Mesa at an elevation of about 2408 m (7900 ft) where they preserve a thin veneer of the Mancos Shale above the Dakota Sandstone (fig. 4). To the east of the Uncompahgre River, also on the upthrown side of the Ridgway fault, similar gravels cap a hill of Mancos Shale at an elevation of about 2377 m (7800 ft) (Qt1 on Fig. 4). These deposits are thought to represent the approximate location of Durango "stage" terminal moraine (Atwood and Mather, 1932). They map
additional deposits of intermediate-age till intermittently along the Uncompahgre River canyon to the south (Qt₁ on Fig. 4) and on the margins of Miller Mesa southwest of Ridgway (south of Fig. 4).

Atwood (1915) interpreted nine exposures of gravel around the margins of Miller Mesa (Qso on Fig. 4) and one exposure on Log Hill Mesa (Qso on Fig. 4) to be an Eocene age till he named the Ridgway till. Subsequent work by Van Houten (1957) and Mather and Wengerd (1965) established that these deposits consist of landslide debris and, in the localities shown on Figure 4, in-place Durango till. These deposits are described as a chaotic assemblage of Mancos shale and weathered Telluride conglomerate and a basal section of in-place Durango till. They interpret the upper section of these exposures to represent the base of a large landslide and debris flow extending north from Whitehurst Mountain (Fig. 7) across Miller Mesa and onto Log Hill Mesa south of the Ridgway Fault.

In measured sections along the northeastern margin of Miller Mesa, Mather and Wengerd (1965) show in-place Durango till at the base of the exposure mapped as Qso on Figure 4 at elevations of 2331 m (7650 ft) and 2345 m (7700 ft). The Dakota sandstone rim on the southern margin of Log Hill Mesa at an elevation of 2438 m (8000 ft) intervenes between the exposures on Miller mesa (Qso) and exposures of Durango till (Qt₁ and Qso on Fig. 4) on Log Hill mesa at elevations ranging from 2420 m (7940 ft) to 2304 m (7560 ft). If the correlation among deposits mapped as Durango till (Qt₁ and Qso) could be more definitively established, an explanation for the elevation difference of the deposits would be Quaternary displacement on the Ridgway fault.
Atwood (1915) and Atwood and Mather (1932) conclude that a remnant of the valley train (Qoc) associated with the Durango terminal moraine (Qt₁) is preserved downstream on the interstream divide between the Uncompahgre River and Cow Creek above the right abutment of Ridgway Dam. This deposit is about 8 m (25 ft) thick and lies about 107 m (350 ft) above modern stream level.

**Youngest deposits** (located on Fig. 4). - The youngest deposits of the tripartite glacial sequence described by Atwood and Mather (1932) were called "Wisconsin." In the Uncompahgre region, Cross and Howe (1907), Howe and Cross (1906), Atwood (1915), and Atwood and Mather (1932) considered the "great moraine" or the complex of terminal moraines just north and east of Ridgway about 1.6 km (1 mi) south of the Ridgway fault line scarp to be Wisconsin in age. This morainal complex is 3.2 km (2 mi) long, 1.6 km (1 mi) wide, and up to 122 m (400 ft) high in places (Fig. 4).

Unpublished mapping by Lee (1978) and air photograph interpretation by the Seismotectonic Section suggests that this "great moraine" consists, in part, of deposits older than the Wisconsin glaciation of the midcontinent (Qt₂, Qt₃, Qt₄ on Fig. 4 and Table I). Similarities in morphology, elevation above modern stream level, and relative size suggest that deposits within the "great moraine" may correlate with the Pinedale (Qt₄), Bull Lake (Qt₃), and Sacagawea Ridge (Qt₂) deposits described by Richmond (1965) near Durango, Colorado.

Richmond (1965) studied the moraines along the Animas River at Durango, Colorado, and concluded that there was evidence for three Pinedale, two Bull Lake, and three pre-Bull Lake stades. He concluded that the end
moraine of the type Durango till of Atwood and Mather (1932), a broad, gently sloping ridge on a rock bench 91 to 107 m (300 to 350 ft) above the Animas River east of Durango, correlates with deposits of the Sacagawea Ridge Glaciation in the Wind River Mountains (Table I).

A continuous alluvial terrace (Qoa on Fig. 4) about 15 m (50 ft) above modern stream level can be traced downstream from mapped Pinedale end moraines within the "great moraine" (Lee, 1978) near Ridgway (Qt4 on Fig. 4). Downstream from the older deposits within this complex, no higher terrace levels are conspicuous. However, two gravel deposits east of the Uncompahgre River 2.4 and 4.8 km (1-1/2 and 3 mi) north of the great moraine have been worked by Ouray County. These cuts have exposed well-stratified sands and gravels overlain by a well-developed, pre-Wisconsin age soil. Lee (1978) indicates that these outwash deposits (Qob on Fig. 4), at about 137 m (450 ft) above stream level, may be remnants of a valley train associated with the largest and oldest of the moraines east of Ridgway. This moraine (Qt2 on Fig. 4) is about 122 m (400 ft) high and may correlate with Richmond's (1965) Sacagawea Ridge till in the Durango area. The base of this moraine is at about 2195 m (7200 ft), 91 m (300 ft) above modern stream level. If a correlation between the outwash deposits (Qob) and the moraine (Qt2) could be definitively established, then the elevation difference between the outwash deposits and the base of the moraine would be evidence for late Quaternary displacement on the Ridgway fault.
Structure

Ridgway damsite is located on the northeast flank of the Uncompahgre Plateau. Structure in the vicinity of the damsite is expressed as a northwest-trending tilted block with a broad, gently dipping northeastern flank and an abrupt, fault-terminated southwestern escarpment. Bedrock in the foundation and abutments of the dam and in most of the reservoir area strikes about north 40° west and dips northeasterly at angles ranging from 4° to 10°.

The southwest flank of the plateau, 8 km (5 mi) south of the damsite, is formed by the Ridgway faultline escarpment (Fig. 4). The Ridgway fault is the southeastward extension of a fault system bounding the Uncompahgre Plateau extending from Gateway, Colorado to Ridgway. This high-angle normal fault juxtaposes Mancos Shale on the downthrown block to the south against Morrison and Dakota-Burro Canyon Formations on Log Hill Mesa to the north. Sense of displacement is down to the south. Differential erosion across the fault is responsible for the steep escarpment north of the town of Ridgway.

The southeastern portion of the Uncompahgre Plateau both on Log Hill Mesa and southeast of the Uncompahgre River is disrupted by a series of subparallel, north-south trending, normal faults, referred to later in the report as branch faults. These branch faults appear to be terminated by the Ridgway fault on the south. This style of faulting has resulted in the formation of a series of asymmetric horsts and grabens oriented normal to the strike of the Ridgway fault. The predominant sense of displacement is down to the west toward the western portion of the Ridgway fault and down to the east on the
eastern portion. This pattern of displacement suggests that the faulting is a consequence of the accommodation of the resistant beds of the Uncompahgre Plateau to the varying amount of slip on the Ridgway fault.

Site Seismicity

Ground motion due to three earthquakes has been reported in the vicinity of Ridgway damsite. Intensity VI damage was reported in Cimmaron, Lake City, Montrose, Ophir, Ouray, Placerville, Powderhorn, Ridgway, and Telluride, Colorado, for the magnitude 5.5 (maximum intensity VI) earthquake of October 11, 1960 (Talley and Cloud, 1962). The isoseismal map (Fig. 5) illustrates the distribution of reported intensities of ground shaking for this event. Ground shaking was experienced in Cimmaron, Montrose, and Ridgway, Colorado, during the intensity V earthquake of February 5, 1962 (Lander and Cloud, 1964). This event was instrumentally located 14 km (9 mi) east of the damsite. The limited felt reports do not allow accurate determination of the intensity of ground shaking at the damsite; however, the damsite is certainly within the limits of the felt area. The November 11, 1913 event was historically located 6 km (3.7 mi) from the damsite. No damage reports are available within 27 km (17 mi) of the site; however, similar intensities of ground shaking were reported at Montrose [27 km (17 mi) to the north] and Ouray and Telluride [27 to 30 km (17 to 19 mi) to the south] (NOAA, 1973) indicating it is likely that intensity V shaking also occurred at the damsite. Two other events were located within 15 km (9 mi) of the Ridgway damsite. These earthquakes occurred in 1966 (M = 3.3) and 1967 (M = 3.8).

Simon (1969, 1972) and Presgrave (1979) reported 60 earthquakes at Montrose, Colorado, and 13 at Sheep Mountain (Fig. 6). These source areas are within
30 km (19 mi) of the damsite. Given their location techniques, it is possible that some of these events occurred much nearer to the damsite. At the very least, their data indicate that a significant number of earthquakes occur in the region of the damsite.

All of the events discussed above as well as those of 1965 (M = 3.8), 1967 (M = undetermined), 1977 (M = 4.0) (Fig. 1), and Grand Valley and Mount Wilson (Fig. 6) (Presgrave, 1979) were located on or near the boundary of the Uncompahgre Plateau. The largest of these earthquakes and greatest number of them occurred at the southeast end of the plateau. The epicenters of the macroearthquakes shown in Figure 7 demonstrate an apparent geometric relation to the Ridgway fault and associated branch faults. It will be demonstrated later in the Geophysical Investigations section that these faults are the site of significant microearthquake activity.

SEISMOTECTONIC FIELD INVESTIGATIONS

This section describes field investigations conducted by the Seismotectonic Section during the spring of 1979.

Geologic Investigations

Previous work. - Dickinson and others (1968) suggest that major movement on normal faults bounding the southwestern flank of the Uncompahgre Plateau and, hence, its development as a distinct structural unit took place during the late Cretaceous. Cater (1966, 1970) offers evidence based on geologic mapping and geomorphic interpretation in the Gateway and Unaweep Canyon areas for uplift along the southwestern margin of the
Plateau during the Pliocene and early Pleistocene. This localized Plio-Pleistocene uplift of the Uncompahgre Plateau follows the Miocene epeirogenic uplift of the Colorado Plateau and subsequent entrenchment of the master streams (Hunt, 1956). Based on Cater's work (1966, 1970), Kirkham and Rogers (1978) included the faults on the southwestern flank of the Uncompahgre Plateau on their map of potentially active faults of Colorado and indicated they have experienced Quaternary movement.

Based on their field studies, Mather and Wengerd (1965) concluded that the outcrops of Eocene Ridgway till described by Atwood and Mather (1915) are actually remnants of a Quaternary landslide and debris flow overlying Durango till.

In this study, they find inconclusive evidence for Quaternary movement on the Ridgway fault. A detailed discussion of this evidence follows in the section on Quaternary deposits.

Initial field reconnaissance. - During the summer of 1978, a field reconnaissance by members of the Seismotectonic Section disclosed possible active faulting in the Ridgway area (travel report dated July 27, 1978). Exposures in a gravel pit just east of the reservoir revealed Quaternary displacements of 0.5 to 3 m (1.6 to 9.8 ft) apparently associated with a bedrock fault. Based on this exposure and its possible relationship to the Ridgway fault, it was decided to undertake phase II geologic studies in the Ridgway area.

These studies included thorough review of pertinent geologic literature, review of bedrock fault mapping in the area based on air photographic
interpretation and field inspection of bedrock faults for evidence of their Quaternary history, and an evaluation of the geomorphic evidence for Plio-Pleistocene uplift of the Uncompahgre Plateau in the Ridgway area.

Tectonic structures. - This section describes the results of the geologic investigations by the Seismotectonic Section in the study area.

Roubideau Creek fault. - Kirkham and Rogers (1978) described a series of normal faults along the southwestern flank of the Uncompahgre Plateau as potentially active faults. They concluded that one of these faults, the 10-km (6-mi) long normal fault in section 21, T. 48 W., R. 12 W. on the USGS Davis Point 7-1/2-minute topographic quadrangle, displaces Holocene landslide deposits. Because this fault is considered the best evidence for Quaternary faulting on the Uncompahgre Plateau (Kirkham and Rogers, 1978), a reconnaissance investigation was made in the area. Reconnaissance revealed that this fault strikes west-northwest across Roubideau Creek with the offset visible in the Dakota Group on the western side of the creek. A scarp or fault-line scarp clearly extends through an area of Quaternary landslides on a bench formed in the Morrison Formation on the eastern side of the creek. Reconnaissance suggests that interpretations other than Holocene fault movement may explain the presence of this scarp. Since this fault is 40 km (24 mi) from Ridgway damsite, the activity or inactivity of this fault was not determined.

Ridgway fault. - The Ridgway fault, 8 km (5 mi) south of Ridgway damsite, is a high-angle normal fault forming a fault-line scarp 300 m (984 ft) high just north of the town of Ridgway. 150 m (490 ft) of
Mancos Shale is reported to overlie the Dakota Sandstone near Ridgway; therefore, maximum displacement on the Ridgway fault is 450 m (1475 ft) near the center of the mapped trace. Tweto and others (1976) show a mapped trace 25 km (15.5 mi) in length based on the diminishing height of the fault line scarp to the east and west.

As discussed in the section Quarternary Deposits, two lines of indirect evidence suggest that the Ridgway fault has experienced Quaternary movement.

Assessing these lines of evidence requires thorough understanding of the glacial sequence in the Uncompahgre Valley. Although various interpretations of the glacial sequence appear in the literature, as discussed in a previous section, no sufficiently detailed morphologic and stratigraphic correlation studies are presently available with which to assess the Quaternary history of the Ridgway fault.

Thorough study of the Ridgway fault on air photographs and limited study in the field did not reveal the presence of fault scarps in the Pinedale glacial deposits in Pleasant Valley near the Uncompahgre River. Although some linear features are present at the base of the Ridgway fault-line scarp further west toward Dallas Divide, field examination of these features indicates they probably do not represent fault displacements. The linear features are asymmetric ridges composed of angular blocks of Dakota Sandstone displaying no consistent attitudes. The blocks appear to have fallen or slid to their present position following undermining of the resistant Dakota caprock due to erosion of the Morrison formation as described by Atwood and Mather (1932). Similarly, east of the Uncompahgre River, the presence of a bedrock fault is clear from the
juxtaposition of bedrock stratigraphic units, but evidence for Quaternary faulting in the form of scarps, vegetation alignments, or ground-water barriers in the recent alluvium is lacking.

**Branch faults.** - On the geologic map of Tweto and others (1976), a series of generally north-south trending normal faults, interpreted in this report to be related to movement on the Ridgway fault, disrupt the mesas on the upthrown side of the Ridgway fault. Review of both black and white and color photography confirmed the presence of these previously mapped faults and revealed additional faults both on Log Hill Mesa and in the reservoir area. Following the remapping and field checking of bedrock faults, careful attention was given to exposures of Quaternary deposits overlying the traces of bedrock faults where direct evidence of Quaternary displacement might be revealed.

The best geologic evidence for Quaternary displacement in the vicinity of Ridgway damsite occurs in an Ouray County gravel pit located in the NW1/4 sec. 3, T. 4 S., R. 8 W. This gravel pit is about 1060 m (3500 ft) east of the Uncompahgre River at an elevation of about 2240 m (7330 ft) (Fig. 4), 137 m (450 ft) above the modern channel of the river.

This deposit comprises about a 15-m (50-ft) thickness of stratified gravels with clasts 7.5 cm (3 in) and smaller in a sand and silt matrix, interbedded with discontinuous lenses of sand and silt. Underlying the gravels is an unknown thickness of well-sorted fine sand exposed in the east wall, around the margins of the pit, and in a small excavation in the center of the gravel pit. Although the surface soil has been disturbed by continuing excavation, the deep red color of the B horizon
and the 2-m (6-ft) thick Cca horizon suggest a pre-Wisconsin age for this deposit. As indicated in figure 4, this gravel deposit is on the west-facing slope of a narrow north-south trending graben. Directly south of the gravel pit is an escarpment capped by Dakota Sandstone and a veneer of Mancos Shale. Structural relations and the presence of extensive travertine deposits at the base of the escarpment indicate the presence of a bedrock fault trending through this gravel pit with the sense of displacement down to the west.

Narrow, vertical zones of shingled gravel, in some cases cemented by carbonate, extending from near the original ground surface to the base of the excavation were first observed in this gravel pit during the Phase I reconnaissance (travel report dated July 27, 1978). During the course of the field studies, repeated visits were made to this gravel pit to observe the changing exposures generated by the continuing excavation. On the north face of the excavation, a series of four vertical, shingled zones persisted as the face was moved back. The strike of these features varied from N2°W to N26°E dipping consistently 90° from top to bottom of the excavation, a distance of about 15 m (50 ft). Measurements of the offset of sand and silt lenses on two of the shingled zones indicates displacements of 0.3 and 1.2 m (1 and 4 ft). A lack of correlative stratigraphy prevented the measuring of displacement on the other shingled zones.

Just prior to completion of field studies, excavation on the east face of the gravel pit revealed the largest displacement observed in the gravel pit. In this exposure, the stratigraphic contact between the bedded gravel unit and the underlying fine sand was offset 3 m (10 ft) along a
north-south trending vertical plane. Additional exposures west and south of this face confirmed this interpretation. Color prints of the exposures described in the preceding paragraphs are available from Seismotectonic Section files.

The topographic position of this deposit suggests that the observed displacements could have resulted from landsliding or slumping. However, the displacement planes described in the preceding paragraphs do not flatten with increasing depth nor is there evidence for lateral extension as might be expected if they were related to mass movement. The planes are vertical to a depth of about 12 m (40 ft). The bedding planes in the gravel deposit are nearly horizontal, dipping slightly (1° to 2°) to the north, indicating that they have not been rotated. Although a mass movement origin for the observed displacement cannot be ruled out, available evidence suggests that the deformation in the gravel pit should be considered the late Quaternary expression of movement on the branch fault trending through the exposure.

Field reconnaissance of other branch faults on Log Hill Mesa revealed no direct evidence of Quaternary displacement although the preservation of such evidence in the limited late Quaternary alluvial and colluvial deposits along the stream channels is unlikely. The "Busted Boiler" fault (located on Fig. 7) is a down-to-the-west normal fault with about 30 m (100 ft) of displacement on Log Hill Mesa. Along the strike of this fault in the NW1/4 sec. 27, R. 9 W., T. 6 N. (USGS 7-1/2-minute Ridgway quadrangle), McKenzie Creek is apparently offset about 0.4 km (1/4 mi) south-east along the north-northwest strike of the fault before resuming its
east-northeast orientation down the Dakota dipslope on Log Hill Mesa. However, just 0.8 km (1/2 mi) to the southeast, the parallel east-northeast channel of Fisher Creek continues uninterrupted across the fault trace, precluding a component of right lateral strike-slip movement as an explanation for the apparent offset of McKenzie Creek. A possible explanation is that McKenzie Creek previously occupied Busted Boiler Draw flowing north along the strike of the "Busted Boiler" fault as a tributary to Horsefly Creek. It was subsequently captured by headward erosion of its present lower course across the upthrown side of the fault. The elevation difference of less than 6 m (20 ft) between the floor of Busted Boiler Draw and the modern channel of McKenzie Creek indicates relatively recent capture. Any possible relationship between movement of the fault and the timing of the capture is uncertain.

Faulting in the foundation. - The Uncompahgre River Valley is about 1000 m (3300 ft) wide in the damsite area. The 150-m (450-ft) and 100-m (300-ft) high valley sides are capped by the sandstones of the Dakota Group dipping 4° to 10° to the northeast in the vicinity of the damsite (Fig. 4). Stratigraphic projection of correlative beds within the Dakota Group across the valley along the dam axis precludes displacements of 50 m (160 ft) or more within the dam foundation. However, due to the distance across the valley and local variations in the dip of the sandstones in the Dakota Group, displacements similar to those found on the branch faults in the damsite area cannot be ruled out. Exposures of unfaulted Dakota Sandstone capping the valley sides north and south of the damsite restrict the length of any possible fault passing through the Ridgway site to a 5- to 8-km (3.1- to 5-mi) stretch within the
Uncompahgre River Valley. Careful examination and mapping of beds within the Morrison Formation in the core trench excavation will be required before a definitive conclusion is reached concerning faulting in the dam foundation.

Geophysical Investigations. -

Microseismic studies. - A five-station microseismic network (Fig. 7) was installed in the vicinity of Ridgway damsite in December of 1978. Continuous monitoring for microearthquakes utilizing Sprengnether MEQ No. 800 smoked paper seismographs began January 2 and ended March 30, 1979. During the 87-day study, 66 separate identifiable events with S-P times less than 6 seconds were recorded. The majority of these earthquakes occurred in two distinct swarms. The first swarm of events began about 0900 (G.M.T.) on January 12, 1979, and continued for 24 hours. Twenty-two microearthquakes having well defined S-P times consistently between 1.5 and 2.0 seconds were recorded at station PVY. Three of these events were of sufficient amplitude to be locatable using HYPO-71, a computer program designed to compute the hypocenters of local earthquakes recorded at three or more stations. The epicenters of these located events are in proximity to and just south of the surface trace of the Ridgway fault. The temporal relationship and similar character, as observed at station PVY, between the located and nonlocated events of this first swarm lead one to suggest the existence of a spatial relationship as well. Station PVY, due to anomalous site conditions, was a low-gain station. Large amplitude teleseisms as recorded at the other stations were recorded with significantly reduced amplitudes at station PVY.
Therefore, to detect ground motions at station PVY, an earthquake must be of relatively large magnitude (in comparison to the detection threshold of the other stations in the array) or the epicenter must be within several kilometers of the station. The recorded trace amplitudes at station PVY of the three located events were significantly larger than the amplitudes of these events as recorded at the other stations. In addition, most of the first swarm events were only recorded at station PVY. Thus, this amplitude phenomenon not only supports the location accuracy of the three located events, but also provides justification for the spatial relationship between all events of the first swarm.

This location criteria also applies to the second swarm of microearthquakes which began at 1341 (G.M.T.) on January 29, 1979, and continued until 0406 (G.M.T.) on February 1, 1979. Eight microearthquakes recorded during this 2.5-day period were accurately located south of the Ridgway fault, and an additional 10 microearthquakes were recorded on at least the PVY station. All 22 events of the first swarm and all 18 events from the second swarm are believed to be associated with movement on the Ridgway fault. In addition, two located and five nonlocated individually occurring events recorded during the study are believed to be Ridgway fault related microearthquakes.

In further support of the association between this microseismic activity and the Ridgway fault, Figure 8 illustrates a plot of focal depth versus horizontal distance from the surface fault trace for all epicenters located near station PVY. A steeply dipping ($72^\circ$) fault plane fits the data and is in good agreement with the known geology of the area. An attempt was made to derive a fault plane solution for the
Ridgway fault events. Due to the low number of located earthquakes (13) and their spatial distribution with respect to the network, no unique solution could be determined.

Seven microearthquakes recorded during the study were located north of the Ridgway fault and east of the Uncompahgre River. The three northernmost events were located with only fair to poor quality and could not be associated with any known structure. The epicenters of the other four events, however, are within 5 km (3 mi) of known surface exposures of the north-trending branch faults and are on trend with the faults. In general, good solutions were obtained for these four events even though no stations were in the immediate vicinity to provide the degree of control available in locating the PVY events. It is postulated the north-northeast linear trend defined by these earthquakes may indicate northward extension of the branch faults beyond that mapped on Figure 7.

Five microearthquakes were located outside the array to the south and southeast where numerous mines and quarries exist. Blasting has been suggested as a possible source of these events, though no known blasting has occurred anywhere within the study area with the exception of one blast set by the State Highway Department on March 5, 1979. All located earthquakes are listed in Table II and plotted in Figure 7. Technical information regarding the microseismic net and hypocenter determinations can be found in Appendix A.
Table II. - Ridgway microseismic data

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<th>Date</th>
<th>Time</th>
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<th>Longitude</th>
<th>Depth</th>
<th>Mag</th>
<th>Q</th>
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<td></td>
<td>(G.M.T.)</td>
<td>(N)</td>
<td>(W)</td>
<td>(km)</td>
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<td>20:46</td>
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<td>14</td>
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<td>02:53</td>
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<td>5.0</td>
<td>2.73</td>
<td>B</td>
</tr>
<tr>
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<td>2/01/79</td>
<td>04:06</td>
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<tr>
<td>15</td>
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<td>02:54</td>
<td>38° 0'.28&quot;</td>
<td>107° 41'.66&quot;</td>
<td>13.7</td>
<td>0.82</td>
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<td>16</td>
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<td>03:14</td>
<td>37° 58'.96&quot;</td>
<td>107° 47'.56&quot;</td>
<td>20.1</td>
<td>0.87</td>
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<tr>
<td>17</td>
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<td>38° 7'.64&quot;</td>
<td>107° 52'.66&quot;</td>
<td>7.2</td>
<td>-0.25</td>
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<tr>
<td>18</td>
<td>2/11/79</td>
<td>07:07</td>
<td>38° 15'.32&quot;</td>
<td>107° 41'.76&quot;</td>
<td>1.2</td>
<td>0.99</td>
<td>B</td>
</tr>
<tr>
<td>***</td>
<td>2/15/79</td>
<td>22:41</td>
<td></td>
<td></td>
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<td>19</td>
<td>2/16/79</td>
<td>05:49</td>
<td>38° 13'.99&quot;</td>
<td>107° 42'.22&quot;</td>
<td>1.3</td>
<td>0.56</td>
<td>C</td>
</tr>
<tr>
<td>20</td>
<td>2/17/79</td>
<td>06:43</td>
<td>38° 4'.22&quot;</td>
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<td>6.3</td>
<td>1.03</td>
<td>C</td>
</tr>
<tr>
<td>***</td>
<td>2/19/79</td>
<td>12:37</td>
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<td>21</td>
<td>2/22/79</td>
<td>10:55</td>
<td>38° 8'.57&quot;</td>
<td>107° 53'.42&quot;</td>
<td>1.1</td>
<td>0.11</td>
<td>C</td>
</tr>
<tr>
<td>***</td>
<td>2/23/79</td>
<td>07:05</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>***</td>
<td>2/23/79</td>
<td>07:07</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>2/25/79</td>
<td>08:09</td>
<td>38° 17'.04&quot;</td>
<td>107° 41'.03&quot;</td>
<td>1.1</td>
<td>1.16</td>
<td>C</td>
</tr>
<tr>
<td>23</td>
<td>2/29/79</td>
<td>00:49</td>
<td>38° 22'.75&quot;</td>
<td>107° 44'.49&quot;</td>
<td>9.1</td>
<td>0.65</td>
<td>C</td>
</tr>
<tr>
<td>24</td>
<td>3/04/79</td>
<td>04:46</td>
<td>38° 17'.60&quot;</td>
<td>107° 45'.05&quot;</td>
<td>6.4</td>
<td>1.04</td>
<td>D</td>
</tr>
<tr>
<td>***</td>
<td>3/13/79</td>
<td>12:41</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>3/16/79</td>
<td>02:34</td>
<td>38° 13'.15&quot;</td>
<td>107° 43'.05&quot;</td>
<td>1.4</td>
<td></td>
<td>B</td>
</tr>
</tbody>
</table>

1/ Richter Magnitudes, calculated using the Coda Duration Method.

2/ Q refers to the quality of the epicenter solution based on HYPO 71 output parameters and record condition:

- A = Excellent
- B = Good
- C = Fair
- D = Poor
Footnotes for Table II - continued

* Swarm of 18 unlocatable events occurring between 0900 and 1600 hours, believed to originate near station PVY.
** Swarm of four unlocatable events occurring between 1300 and 1400 hours, believed to be associated with events No. 7 and 8 (i.e., possible quarry blasts).
*** Unlocatable event believed to originate near station PVY and similar in character to the swarm events of 1/12/79.
**** Swarm of seven unlocatable events occurring between 2200 hours on 1/30/79 and 1800 hours on 1/31/79 believed to originate near station PVY.
SEISMOTECTONIC HAZARDS

Seismotectonic hazards significant to the design and operation of Ridgway Dam and Reservoir include ground shaking from design earthquakes, surface faulting, liquefaction, slope stability, reservoir seiche, and reservoir-induced seismicity.

Fault Activity

Ridgway fault. - The spatial association of 13 located hypocenters (Figs. 7 and 8) with the Ridgway fault leads to the conclusion that this fault is active. An additional 34 unlocated events (Table II) appear to be associated with the Ridgway fault.

A group of five historical earthquakes in the Ridgway area are plotted on Figure 7. The isoseismal plot of Figure 5 for the M = 5.5 event in 1960 indicates that the epicenter for this event may actually be further south than the instrumental epicenter. Although the unequivocal association of these events with particular mapped faults is not possible due to the ±20-km (12-mi) errors of the epicentral locations, it does seem likely that these historical events are associated with the faults in the Ridgway area.

The largest historical event in the vicinity of Ridgway damsite is an M = 5.5 in 1960 which places a lower bound for an MCE on the Ridgway fault. Fault length-earthquake magnitude relations for a normal fault 25 km (15.5 mi) in length yield magnitudes from 6.5 to 7.0 (Mark and Bonilla, 1977; Slemmons, 1977). We conclude that the MCE on the Ridgway fault has a Richter magnitude of 6.5 at an epicentral distance of 8 km (5 mi).
Branch faults. - The occurrence of four located microseismic events northeast of the reservoir, the Quaternary displacements in the gravel pit east of the reservoir, and the association of these faults with an active fault, the Ridgway fault, lead to the conclusion that the branch faults southeast of the dam must be considered active. Two of these faults are within the reservoir (Fig. 4).

As noted above, the largest historical event in the vicinity of Ridgway damsite is an $M = 5.5$ in 1960 which also places a lower bound for an MCE on the branch faults. Due to the greater cumulative displacement on the controlling structure in the region, the Ridgway fault, we feel that an MCE associated with the branch faults should be less than that assigned to the Ridgway fault. Therefore, we assign an MCE of $M = 6.0$ within 2 km (1.2 mi) of the damsite on the north-south trending branch faults in the reservoir.

Maximum Credible Earthquakes

Table III summarizes the MCE's proposed for estimation of potential ground motion at Ridgway damsite:

<table>
<thead>
<tr>
<th>Tectonic structure</th>
<th>Maximum Credible Earthquake (MCE)</th>
<th>Epicentral distance</th>
<th>Focal depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ridgway fault</td>
<td>6.5</td>
<td>8 km (5.0 mi)</td>
<td>7 km (4.4 mi)</td>
</tr>
<tr>
<td>Branch faults</td>
<td>6.0</td>
<td>2 km (1.2 mi)</td>
<td>7 km (4.4 mi)</td>
</tr>
</tbody>
</table>
Richter magnitudes are used in the above table. Epicentral distances are measured from the closest approach of the tectonic structure to the site. The concentration of microearthquakes near a depth of 7 km (4.4 mi) in Figure 10 resulted in the selection of this focal depth for the design earthquakes.

**Design Earthquakes**

Other design earthquakes for the Ridgway and branch faults can be selected from the recurrence relations in Figure 9. The focal depths and the epicentral distances for these earthquakes are the same as those for the MCE's.

**Earthquake Recurrence**

A magnitude recurrence relation has been developed for the Colorado Plateau province by the extreme value method. The relationship is illustrated in Figure 9 and fits the straight line on a semilogarithmic graph represented by:

\[
\log_{10} (N) = 4.67 - 1.1 (M + 0.4)
\]

where \(N\) is the number of events per year and \(M\) is Richter magnitude. The parametric \(b\) value of 1.1 is the slope of the resultant curve and is at the high end of the empirical range of values. High \(b\) values indicate a large proportion of small to large shocks and relatively low ambient stress. Historically, the Colorado Plateau exhibits only a moderate level of seismicity (maximum recorded magnitude 5.5). This may, in part, be due to a lack of instrumentation, low population density, and/or long recurrence
times for large earthquakes. On the other hand, the historical record may indeed be an indication of the actual rate of seismicity. The above recurrence relation was derived for the entire Colorado Plateau province. Therefore, it yields a conservative estimate of recurrence interval for any specific fault within the Colorado Plateau. However, there are not enough data for any specific fault on the Colorado Plateau to determine a magnitude recurrence relation for any one fault in the province. The Colorado Plateau relationship is used directly for the Ridgway fault and is scaled for the branch faults to yield the same return period for the MCE's on the two structures.

Surface Faulting

Based on the rupture length-displacement and magnitude-displacement curves of Slemmons (1977), a magnitude 6.5 earthquake occurring on the Ridgway fault may be associated with a surface displacement of 0.5 to 1.0 m (1.6 to 3.2 ft). As the Ridgway fault is outside the proposed Ridgway damsite and reservoir area, this surface rupture would not pose a hazard.

The branch fault closest to the dam is within the proposed Ridgway reservoir. Based on the same curves (Slemmons, 1977) a surface displacement of 10 to 35 cm (0.3 to 1.2 ft) may be associated with the MCE on this fault.

Liquefaction

USBR (1979) drilling data indicate that up to 30 m (100 ft) of unconsolidated alluvial and colluvial deposits will underly portions of the embankment.
Liquefaction susceptibility of foundation materials will be evaluated as the core trench is excavated.

**Slope Stability**

A number of late Pleistocene or Holocene age landslides have been mapped along the west side of the Uncompahgre river canyon in the vicinity of Ridgway Dam and reservoir. These slides occur along the northeast dipping bedding planes in the shales of the Morrison formation. In addition to about six slides, each covering an area of less than 0.1 km² (0.04 mi²), a slide mass covering an area of about 0.13 km² (0.05 mi²) is mapped in the left abutment of the dam and a slide covering an area of about 0.56 km² (0.22 mi²) is mapped along the western margin of the reservoir (Fig. 4 and USBR, 1979). Although these slides do not appear to have been active in historic time, a Richter magnitude 6.5 event could reactivate the existing slides and trigger additional slope instabilities in the dam and reservoir area. Analysis of the hazard posed by slope instabilities is beyond the scope of this report.

**Reservoir Seiche**

Seiche due to vibratory ground motion, landsliding, and surface faulting can be expected in Ridgway reservoir. Wave generation due to ground motion alone, however, is believed to be of minor consequence. Vertical fault displacements of up to 35 cm (1.2 ft) and reactivated landslide masses moving into the reservoir could create significant seiche waves. Analysis of these effects are beyond the scope of this report.
Reservoir-induced Seismicity

Reservoir-induced seismicity has been empirically related to reservoirs with the following general characteristics: (1) water depth in excess of 92 m (300 ft), (2) water volume in excess of $10^{10} \text{m}^3$ (8.1 million acre-ft), and (3) active faults in the reservoir (Woodward-Clyde Consultants, 1977). The proposed Ridgway Reservoir with a maximum water depth of 67 m (220 ft) and a volume of $9.9 \times 10^7 \text{m}^3$ (80,000 acre-feet) meets only one of these criteria; namely, active faults in the reservoir. In the event earthquakes are induced by reservoir filling, we believe they would not exceed the MCE's in Table III.

CONCLUSIONS

1. The Ridgway fault is considered active based on the association of microearthquake hypocenters with the projected subsurface trace of the fault. The Ridgway fault is a high-angle normal fault with about 450 m (1500 ft) of displacement, 8 km (5 mi) from the damsite.

2. Branch faults in the reservoir area are considered active based on structural association with the Ridgway fault, association of microearthquake epicenters, and apparent tectonic displacements in Quaternary deposits.

3. MCE's which may affect Ridgway damsite are tabulated below. Earthquake recurrence relationships for the selection of other design earthquakes are shown on Figure 9.
### Maximum Credible Earthquakes

<table>
<thead>
<tr>
<th>Tectonic structure</th>
<th>Maximum Credible Earthquake (MCE)</th>
<th>Epicentral distance</th>
<th>Focal depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ridgway fault</td>
<td>6.5</td>
<td>8 km</td>
<td>7 km</td>
</tr>
<tr>
<td>Branch faults</td>
<td>6.0</td>
<td>2 km</td>
<td>7 km</td>
</tr>
</tbody>
</table>

4. A maximum surface displacement of 0.5 to 1.0 m (1.6 to 3.3 ft) may be associated with the MCE on the Ridgway fault. A maximum surface displacement of 10 to 35 cm (0.31 to 1.2 ft) may be associated with the MCE on the branch fault closest to the dam.

5. Landslides covering areas as large as about 0.56 km² (0.22 mi²) have been mapped along the western margin of the reservoir (Fig. 4). Analysis of the hazard posed by activation of existing or additional slope instabilities in the reservoir area due to ground shaking associated with the MCE is beyond the scope of this report.

6. Due to the lack of penetration resistance data, the susceptibility of foundation materials to liquefaction cannot be evaluated.

### RECOMMENDATIONS

1. Since surface displacements through the dam foundation cannot presently be precluded, geologic mapping of the core trench should be performed to determine if faulting is present. In addition, foundation materials should be examined for indications of liquefaction susceptibility.
2. We recommend that a seismic monitoring program be established at Ridgway Dam to accomplish the following objectives:

   a. To determine the natural level of seismicity of the reservoir area as background data for b. and c.

   b. To provide additional information on the seismic activity of the faults in the vicinity of Ridgway Dam.

   c. To determine if filling and subsequent operation of the reservoir will induce earthquakes. Although Ridgway Dam and reservoir will not meet the statistical criteria accepted for induced seismicity (Woodward-Clyde Consultants, 1977), there are active faults in the reservoir.

   d. To provide seismic instrumentation on the Colorado Plateau to improve earthquake detection and location for the province.

Details and cost estimates are provided in appendix II.

ACKNOWLEDGEMENTS

The installation and operation of the five seismometer stations were conducted by Rudolf Angeli, Cecil Womack, Donald Harriman, and James Whiteman of the Dallas Creek Project staff. We also wish to thank James Whiteman of the Project staff and Mark Bliss, rotation engineer, for their assistance with the geologic field investigations.

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FIGURE 1 - Historical seismicity and geologic provinces in the vicinity of Ridgway damsite.

Modified Mercalli Intensity

Richter < 3.0  3.0-3.9  4.0-4.9  5.0-5.9

Magnitude o  o  o  o

Undetermined o

\(\text{\textbullet} \text{Ridgway damsite}

\(\text{\textbullet} \text{Fault, hachures on downthrown side.}

\(0 50 100 \text{km}

COLORADO PLATEAU

SOUTHERN ROCKY MOUNTAINS

Ridgway damsite

Ridgway fault
Figure 3 - (a) Plot of Richter Magnitude vs. Modified Mercalli Intensity for the Colorado Plateau and the Southern Rocky Mountains in Colorado.
(b) List of the earthquakes plotted in (a).
Figure 2 - (a) Plot of Richter Magnitude vs. body-wave magnitude for the Colorado Plateau and the Southern Rocky Mountains in Colorado and their linear relationship. 
(b) List of the earthquakes plotted in (a).
FIGURE 4 Geology and fault pattern in the vicinity of Ridgway dam site. Quaternary displacements exposed at locality A.

TERTIARY

San Juan Tuff (Miocene). - Predominantly a gray tuff breccia containing intermixed sandy tuff and tuff conglomerate erupted from calderas in the San Juan Mountains (Luedke and Burbank, 1962). This unit does not appear within the area of figure 4.

Telluride Conglomerate (Oligocene?). - Gray to red, well indurated conglomerate with a silty to sandy matrix. Rounded cobbles and boulders of the conglomerate vary in diameter up to 1 foot (Luedke and Burbank, 1962). This unit does not appear within the area of figure 4.

MESOZOIC

Km - Mancos Shale (Cretaceous). - Dark gray to dark brown clay shale; local calcareous, gypsiferous or sandy. 0 to 700 m (0 to 2000 ft) thick.

Kd - Dakota Group (Cretaceous). - Consists of two formations: the Dakota and underlying Burro Canyon. The Dakota consists of light gray to light brown medium grained, thin to medium bedded, uniform, crossbedded, resistant sandstone; some dark gray carbonaceous shale; coal beds, and chert-pebble conglomerate. The Burro Canyon Formation consists of light gray, lenticular, chert pebble conglomerate and coarse-grained sandstone and light to green claystone. 38 m (125 ft) thick.

Jm - Morrison Formation (Jurassic). - Variegated mudstones, shales, and sandstones in the Brushy Basin Member and light gray sandstones in the underlying Salt Wash Member. Approximately 244 m (800 ft) thick.

Geologic contacts

Faults (dashed - location approximate, bar and ball on downthrown side)
STRATIGRAPHIC COLUMN AND LEGEND FOR FIGURE 4.
Description from USBR (1979) unless otherwise indicated.

QUATERNARY

HOLOCENE

Qa1 - Alluvium. - Stream fill, low-level terraces, and flood plain deposits consisting mainly of stream deposited, rounded gravels, cobbles, and boulders with sand and minor amounts of silt and clay.

Qc - Colluvium. - Heterogeneous mixture of angular cobbles, boulders, and blocks in a silty matrix deposited by mass wasting and intermittent surface runoff.

Qcg - Gravel colluvium. - Colluvium with rounded gravels, cobbles, and boulders.

Qs - Landslide deposits. - Colluvium deposited on steep slopes by gravity movement under wet or saturated conditions.

Qt - Travertine. - Brown to white, layer calcium carbonate. (Flowing hot springs occur within this deposit.)

PLEISTOCENE - reconnaissance studies indicate no significant differences in lithology among these glacial deposits. These deposits are distinguished by morphology and modern elevation.

Possible Correlations

Qt4 - Till Qoa - Outwash
Qt3 - Till Qob - Outwash
Qt2 - Till Qoc - Outwash
Qt1 - Till

Qso - This deposit includes: 1) Pleistocene landslide debris consisting of shale fragments, rounded gravels and angular blocks of volcanic tuff and 2) a basal section of in place Durango till at exposures included on this figure. These exposures were originally mapped as Eocene Ridgway Till by Atwood (1915).
Figure 5. - Isoseismal Map of the Earthquake of October 11, 1960. The triangle indicates the instrumental location (Talley and Cloud, 1962).
Figure 6. - Earthquakes of Colorado from January 1966 through August 1973 (Presgrave, 1979).
FIGURE 7 - Earthquake Epicenters and Seismometer Station Locations
FIGURE 8
PLOT OF FOCAL DEPTH VS. HORIZONTAL DISTANCE FROM RIDGWAY FAULT TRACE
Figure 9. - Magnitude recurrence relation for the Colorado Plateau province and the Ridgway and associated branch faults.
APPENDIX I

Technical Information Regarding Microseismic Survey

The microseismic survey conducted during this investigation involved 87 days of continuous monitoring for microearthquakes occurring within the vicinity of Ridgway damsite. Five portable, high-gain Sprengnether MEQ 800 seismographs were installed within 17 km (10.5 mi) of the damsite (Table V), at an average station spacing of 20 km (12 mi) (Fig. 7). Ground motions detected by 1 Hz vertical component geophones (Mark Products L-4c) were amplified 90 to 102 dB and displayed on smoked paper records. Maximum deflection was set to 25 mm (1 in) with low- and high-cut filters set at 5 and 10 Hz, respectively. Timing was provided by internal crystal clocks synchronized with portable digital crystal clocks at the beginning and end of each 24-hour period. The portable master clock was synchronized with WWV (time standard broadcast by the National Bureau of Standards) in the morning before going to the stations and again at the completion of the route, typically 5 hours later. The master clock drift, usually between 10 and 30 milliseconds, was linearly interpolated to determine appropriate corrections to be made to the MEQ 800 drifts as determined at each station. The seismograph clocks were found to drift 10 to 50 milliseconds over a 24-hour period. This deviation from WWV was linearly interpolated over the entire record to arrive at the appropriate net drifts for each recorded event. Due to the extreme cold, wooden boxes with heaters were built to house the seismographs and thereby helped to minimize the resultant clock drift. Earthquake arrival times were manually determined using a precision micrometer that had inherent picking
errors of less than 20 milliseconds. The overall accuracy of the arrival time was \(\pm 0.05\) and \(\pm 0.1\) second for P and S waves, respectively. Due to the widespread distribution of Quaternary deposits and Mancos Shale, accessible outcrops of solid bedrock were difficult to find and less than desirable geophone sites had to be accepted for stations PVY, ONC, and OWL. At one station, OWL, a concrete slab needed to be poured to insure adequate coupling between the geophone and Mancos Shale. Large snowfalls necessitated the use of snowmobiles to reach stations PVY and OWL. In all cases, the geophones and cables were buried to reduce wind-generated noise.

Stations PVY and GTS were operational the entire length of the study, whereas MMS, ONC, and OWL experienced mechanical difficulties intermittently in January and/or February. See Table VI for a schedule of daily operational status.

The hypocenter of events recorded at three or more stations were determined by computer program HYPO-71, revised (Lee and Lahr, 1975). The program uses Geiger's method (Geiger, 1912) to compute latitude, longitude, and focal depth by minimizing the residuals between observed and calculated arrival times in terms of least squares. The calculated arrival times result from assuming a horizontal multilayer velocity model and a trial hypocenter by a technique developed by Eaton (1969).

A compressional wave velocity model for the Colorado Plateau in southwestern Colorado was developed (McGetchin and others, 1979) from data of the Transcontinental Refraction Survey. The P-velocity model used to locate microearthquakes in this study (Table IV) is based, in part, on this model and on a model derived from refraction data from Climax, Colorado.
### Table IV. - P - Velocity model

<table>
<thead>
<tr>
<th>Layer</th>
<th>Velocity (km/s)</th>
<th>Depth to top of layer (km)</th>
<th>Thickness (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.5</td>
<td>0.0</td>
<td>1.0</td>
</tr>
<tr>
<td>2</td>
<td>5.0</td>
<td>1.0</td>
<td>7.0</td>
</tr>
<tr>
<td>3</td>
<td>6.4</td>
<td>8.0</td>
<td>17.0</td>
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<tr>
<td>4</td>
<td>6.8</td>
<td>25.0</td>
<td>15.0</td>
</tr>
<tr>
<td>5</td>
<td>7.8</td>
<td>40.0</td>
<td></td>
</tr>
</tbody>
</table>

### Table V. - Station parameters for the Ridgway seismic network

<table>
<thead>
<tr>
<th>Station</th>
<th>Lat (N) deg min</th>
<th>Lon (W) deg min</th>
<th>Elevation (m)</th>
<th>Delay (s)</th>
<th>System gain (dB)</th>
<th>Site conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>GTS</td>
<td>38 17.64</td>
<td>107 52.74</td>
<td>2300</td>
<td>0.06</td>
<td>96-102</td>
<td>Outcrop - Dakota sandstone</td>
</tr>
<tr>
<td>MMS</td>
<td>38 05.46</td>
<td>107 47.22</td>
<td>2640</td>
<td>0.15</td>
<td>96-102</td>
<td>Outcrop - San Juan tuff</td>
</tr>
<tr>
<td>ONC</td>
<td>38 19.68</td>
<td>107 45.36</td>
<td>2025</td>
<td>-0.02</td>
<td>90-96</td>
<td>Boulder in Quaternary gravel</td>
</tr>
<tr>
<td>OWL</td>
<td>38 10.68</td>
<td>107 37.68</td>
<td>2530</td>
<td>0.12</td>
<td>96</td>
<td>Concrete slab in. Mancos Shale</td>
</tr>
<tr>
<td>PVY</td>
<td>38 10.02</td>
<td>107 52.56</td>
<td>2550</td>
<td>0.13</td>
<td>96-102</td>
<td>Boulder in slide debris from Ridgway fault scarp</td>
</tr>
</tbody>
</table>
Pakiser, 1965). In addition, the velocity of the upper 1 km (0.6 mi) of Paleo- zoic and Mesozoic strata was determined from a one-sided refraction line shot during this study and from the stratigraphic section as described by Larson and Cross (1956) and Kottlowski (1957). A blast initiated by the State Highway Department on March 5, 1979, near Ridgway damsite served as the source for the refraction line (travel report dated August 28, 1979). Station delays were computed based on a velocity of 3.5 km (11,500 ft) per second and the difference between station elevation and a datum of 2100 m (6890 ft) above sea level. As a check on the validity of the velocity model, the blast was located by HYPO-71 using arrival times from the network stations. The computed epicenter, based on P-waves, was within 1 km (0.6 mi) of the blast site. Due to the nature of the time-delayed blast, no S-wave arrivals were distinguishable on the records. With the additional control provided by S-wave data from the real earthquakes, sufficiently accurate locations were computed using this velocity model.

The magnitudes of located microearthquakes, as computed by HYPO-71, is based on the duration of the coda and is a good estimate of the Richter magnitude provided an empirical relation of the form $Md = a_1 + a_2 t \log t + a_3 d + a_4 h$ can be determined (Lee and Stewart, 1979). In this equation, $Md$ is the duration magnitude, $t$ is the signal duration in seconds, $d$ is the epicentral distance in kilometers, and $h$ is the focal depth in kilometers. $a_1$, $a_2$, $a_3$, and $a_4$ are empirical constants determined by comparing signal duration with Richter magnitudes for a set of earthquakes, accounting for focal depth and epicentral distance. With respect to the MEQ 800 seismograms, the signal duration was defined as the time in seconds from the onset of the P-wave arrival to the point where the peak to peak amplitude of the trace falls below 1 mm.
(0.04 in). This point is approximately where the signal to noise ratio declines to about two. During the 3-month study, the occurrence of earthquakes with widely differing Richter magnitudes was too low to enable one to solve for the empirical constants. Therefore, we used the constants derived for central California by Lee, Bennet, and Meagher in 1972 to arrive at estimates of Richter magnitudes. The appropriate equation is $M_d = -0.87 + 2.0 \log t + 0.0035d$. Using this formula, the magnitudes of all located microearthquakes fell between -0.25 and 2.7. It should be emphasized that these values are only crude estimates of Richter magnitudes and are important in representing only the relative size of an event versus the other located microearthquakes recorded during this study.
APPENDIX II

Recommendations for Seismic Monitoring

Seismicity of the Colorado Plateau is, at best, a poorly understood phenomena. The sparse recorded seismic history may be a result of low population density, long recurrence intervals for large earthquakes, and/or naturally low to moderate seismicity. The seismic record is also affected by a lack of instrumentation of the Colorado Plateau. Presently, only events of $M = 4.5$ or greater are being recorded for the Colorado Plateau with location accuracies of approximately $\pm 20$ km (12.5 mi) because seismograph station spacing is several hundred km. There is not sufficient instrumentation to accurately define seismic sources on the plateau. We recommend that a seismic monitoring program be established at Ridgway Dam for several reasons:

1. To determine the natural level of seismicity of the reservoir area as background data for 2 and 3

2. To provide additional information on the seismic activity of the faults in the vicinity of Ridgway Dam

3. To determine if reservoir fluctuations are inducing earthquakes

4. To provide seismic instrumentation on the Colorado Plateau to improve earthquake detection and location for the province

Two alternative approaches for seismic monitoring at this site are presented. The first is to install a three-station seismic array around the reservoir which would be capable of detecting and locating microearthquakes on the
Ridgway and branch faults. Data from all three seismometers would be transmitted to Denver on existing Water and Power microwave circuits. Data from one of these would also be transmitted to the U.S. Geological Survey in Golden to be included in the national seismic monitoring network. Total cost would be approximately $30,000 for equipment and installation and $2,500 maintenance each year after installation.

The other alternative is to install one seismic station near Ridgway Dam. Data from this station could be transmitted via Service microwave circuits to the U.S. Geological Survey in Golden where it would be included in the national seismic network. Earthquakes in the Ridgway area could not be located with only one station; however, events near the reservoir could be counted. Cost for equipment and installation would be about $14,000 with an annual maintenance cost of about $2,000.

In either case, data would be telemetered from the seismic stations to Montrose, Colorado, where it would be transmitted to Denver and Golden on available microwave circuits. Marvin Carlson of the U.S. Geological Survey has expressed an interest in monitoring a seismic station in western Colorado. Mory Laberten, Department of Energy, Montrose, Colorado, also indicated that the telemetry system could be maintained by the Department of Energy. As data transmission circuits and maintenance personnel are available within the Federal Government, Ridgway is a very cost effective location for a seismic monitoring program.