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GEOLOGICAL AND SEISMOLOGICAL EVALUATION OF EARTHQUAKE HAZARDS AT RIRIE DAM, IDAHO

by

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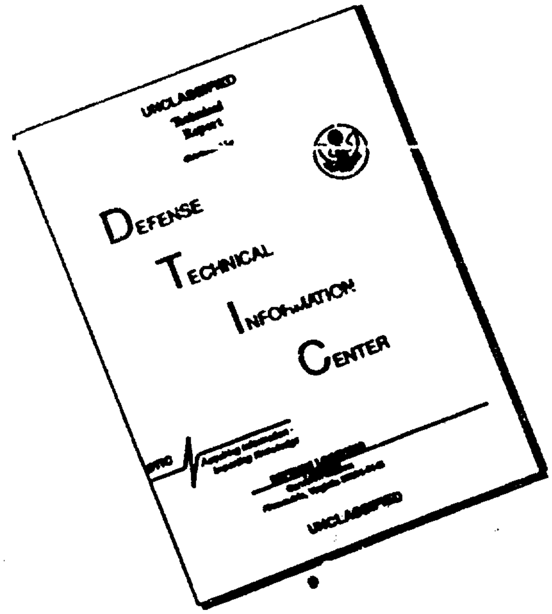

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Ririe Dam is in an area of active faults that is capable of generating severe earthquakes. Horizontal peak motions for Maximum Credible Earthquakes at the dam were interpreted as:

Earthquake	M	MM I_s	Acceleration cm/sec^2	Velocity cm/sec	Duration ≥0.05 g/sec
Local	7.0	IX	1200	68	22
4-8 km	7.5	X	1200	120	33
80 km	7.5	VIII	280	25	65

An Operating Basis Earthquake was assigned with motions of 280 cm/sec^2, 25 cm/sec, and 65 sec.

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PREFACE

The US Army Engineer Waterways Experiment Station (WES) was authorized to conduct this study by the US Army Engineer District, Walla Walla, by Appropriation Order No. E86860001 dated 4 October 1985.

This study was prepared by Dr. E. L. Krinitzsky and Mr. Joseph B. Dunbar of the Earthquake Engineering and Geosciences Division (EEGD), Geotechnical Laboratory (GL), WES. Illustrations were prepared by Mr. Dale Barefoot, EEGD. Field investigations at Ririe Dam and vicinity were made by Dr. Krinitzsky; Dr. David B. Slemmons, and Mr. A. R. Rameli, Consultants of Reno, Nevada; and Mr. Fred J. Miklancic of the Walla Walla District. The project was under the general supervision of Dr. A. G. Franklin, Chief, EEGD, and Dr. W. F. Marcuson III, Chief, GL.

The Commander and Director of WES is COL Larry B. Fulton, EN. The Technical Director is Dr. Robert W. Whalin.

CONTENTS

GEOLOGICAL AND SEISMOLOGICAL EVALUATION OF EARTHQUAKE HAZARDS AT RIRIE DAM, IDAHO

PART I: INTRODUCTION

Background

This report supplements and updates a previous Waterways Experiment Station report on the geology and seismicity of Ririe Dam in Idaho. The earlier report by Patrick and Whitten (1981) was presented as a Miscellaneous Paper (GL-81-7) under the title "Geological and Seismological Investigations at Ririe Dam, Idaho." The current report incorporates new data and viewpoints developed in this region for Blackfoot Dam (Krinitzsky, 1987), Palisades Dam (Piety et al., 1985 and Adhya, 1983) and work done by Slemmons (1980) and Slemmons and Ramelli (1986).

Purpose and Scope

The purpose of this investigation is to define the maximum potential for earthquakes at Ririe Dam and to provide appropriate ground motions for earthquake shaking at the dam. These ground motions are for use in the design analysis of the present earth dam and associated structures.

This investigation includes both a geological and seismological study and consists of the following parts: (a) an examination of the local and regional geology including an evaluation of active faulting, (b) a review of the historic seismicity of the area under study, and (c) the determination of the source and magnitude of maximum earthquake(s) that may affect the damsite and the attenuated peak ground motions that would be produced at the damsite.

Study Area

The area covered by this study includes that portion of the western United States in which earthquakes have occurred that might be felt at the damsite, roughly the area enclosed by a circle with a 200 km (125 miles) radius with the damsite located at the center of the circle. The study area includes portions of Idaho, Wyoming, Utah, and Montana. Extremely severe earthquakes, centered outside the study area, are examined on an individual basis to determine their effects, if any, in relation to the damsite.

Ririe Dam is located in southeastern Idaho on Willow Creek, a tributary to the Snake River. The damsite is located in Bonneville County, approximately 25 km (15 miles) northeast of Idaho Falls, the nearest major city. Construction of the dam was begun in 1967 and was completed ten years later. The dam was designed and constructed by the U.S. Army Engineer District, Walla Walla, and in 1978 was transferred to the U.S. Bureau of Reclamation for operation.

The dam embankment is 76.5 m (251 ft) high, 256 m (840 ft) long, and 12.2 m (40 ft) wide at the crest. The lake at its maximum pool elevation of 5119 ft has a storage capacity of approximately 100,000 acre-ft. The dam serves for flood control, recreation, and irrigation.

PART II: GEOLOGY

Regional Geology

Introduction

Ririe dam and reservoir are located on the northern margin of the Basin and Range Province (see Figure 1). Less than 5 km (3.1 miles) to the north is the southern edge of the Snake River Plain, a vast lava plain stretching across the entire width of southern Idaho. The eastern portion of the Snake River Plain adjoins the Yellowstone and Island Park Calderas. Calderas, the sites of former volcanic activity, are large volcanic depressions which are more or less circular in shape. East of the damsite is the western boundary of the Rocky Mountains, which is separated from the Basin and Range Province by a nearly continuous north-south fault zone composed of the Grand Valley, East Cache, and Wasatch faults.

Along this north-south zone, there is a broader zone of seismicity which is known as the Intermountain Seismic Belt. The fault boundary marks the edges between subplates of the North American Plate (Smith and Sbar, 1974). The Yellowstone and Island Park Calderas are sites of geologically very recent volcanism. Ririe dam and reservoir are situated within this active zone of seismicity and volcanism as will be noted in more detail later.

Snake River Plain

The Snake River Plain extends along Idaho's southern border for about 500 km (310 miles) in length and 80 to 110 km (50 to 68 miles) in width. The plain derives its name from the Snake River which flows west along most of its southern boundary. As the name implies, the Snake River Plain is relatively flat in comparison to the rugged mountain ranges that border it. The plain ranges in elevation from approximately 1585 m (5200 ft) above sea level on the east, in the vicinity of Ririe Dam, to approximately 670 m (2200 ft) above sea level on its western margin, near Boise.

Malde (1965) describes the Quaternary stratigraphic section in the Snake River Plain as about 1500 m (4900 ft) thick and involving the interplay of volcanism and alluvial sedimentation. The eastern and western parts of the plain differ both in structure and physiography. Gravity and magnetic data identify a distinct structural contrast between the eastern and western

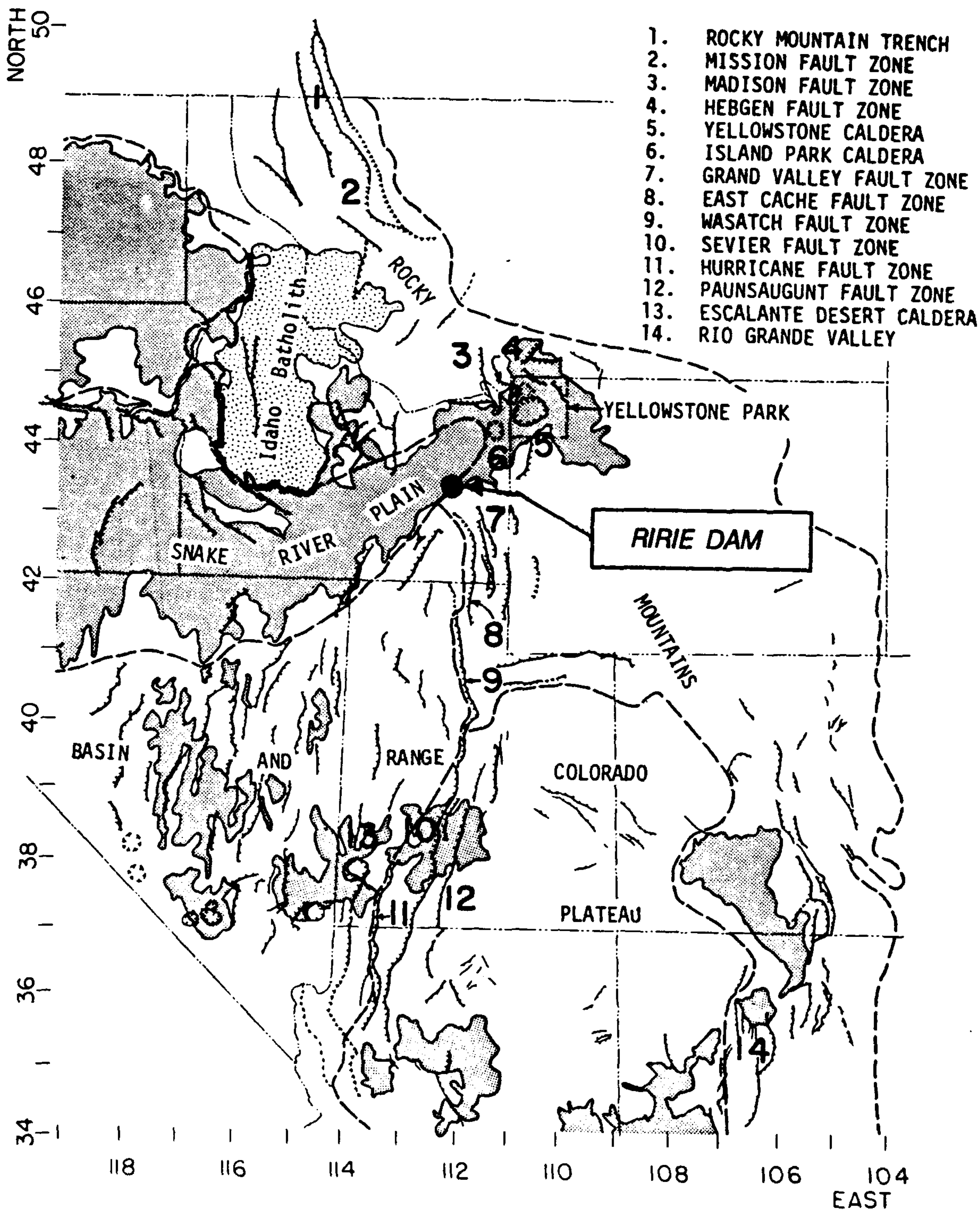


Figure 1. Location of Ririe dam and reservoir and major geologic features (from Smith and Sbar, 1974)

portions. The difference in physiography between the eastern and western portions is primarily caused by the Snake River. The western portion of the plain has been deeply dissected by the Snake River and much of the Quaternary deposits that make up the plain in its deep valley are exposed. The eastern portion of the plain, in contrast is nearly level and composed of extensive basaltic lava flows which are primarily Quaternary in age.

The geologic complexity of the eastern portion of the Snake River plain is shown in Figure 2 (from Malde, 1965). The bulk of the rock comprising the eastern portion of the plain is volcanic in origin. The geology near Ririe Dam consists of rocks ranging in age from Late Tertiary to the present. The most recent rocks are of volcanic origin, most notably those related to Yellowstone Park. The trend of the eastern Snake River Plain is toward the northeast at an oblique angle to the general north-south trend of the older deformed sedimentary rocks which border the plain. The evolution of the Snake River Plain is believed to have begun during the Late Tertiary, in Miocene time (Leeman, 1982). The age distribution of volcanic deposits comprising the plain show a definite age relationship with location on the plain. The volcanic rocks become progressively younger toward the east (Armstrong, Leeman, and Malde, 1975; Luedke and Smith, 1983; and Kuntz et al, 1986). The most recent location for volcanic activity is the Yellowstone Park area.

The character of the underlying subsurface geology of the eastern Snake River Plain is only partially understood, with information primarily from gravity and magnetic surveys (Mabey, 1978a, 1978b, and 1982). A gravity survey defines changes in the mass properties of the underlying rock, which relates to variations in subsurface density. Included on the geologic map of the eastern Snake River Plain in Figure 2 is a generalized Bouguer gravity map (after Hill et al., 1961 and LaFehr, 1962). The map identifies an anomalous gravity high over the plain. Note that the values over the plain are less negative than over the surrounding area.

A more detailed Bouguer gravity map of southeastern Idaho is presented in Figure 3 (after Mabey, 1978b; from Mitchell et al., 1980). Also shown is an interpreted boundary between the plain and the adjacent physiographic provinces. Contours over the plain range from a negative 120 to a negative 160 mgals, in contrast to the region surrounding the plain, which range from 160 to 180 mgals and higher. Ririe Dam is located on the margin of a pronounced

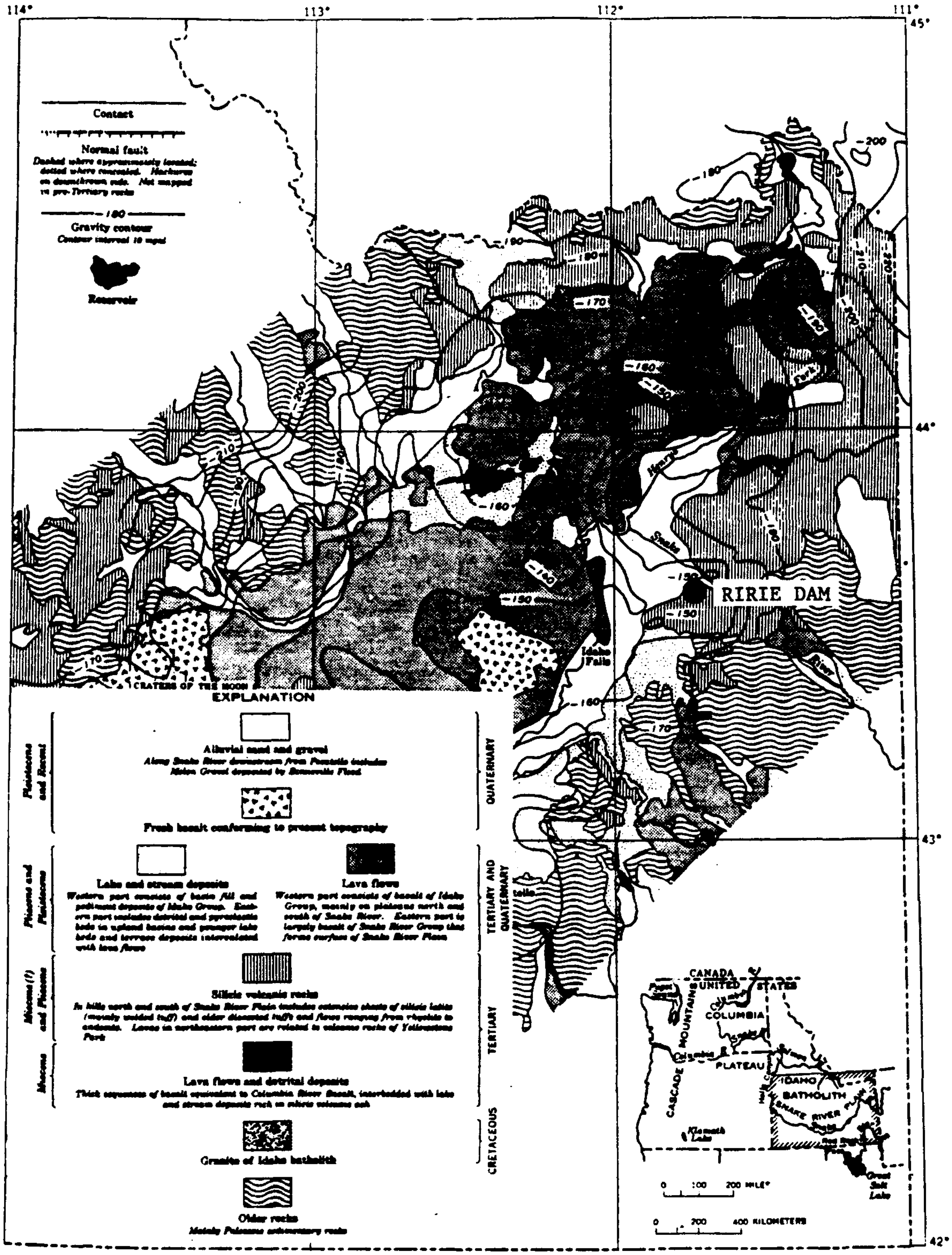


Figure 2. Generalized geology and gravity map of the Snake River Plain (from Malde, 1965)

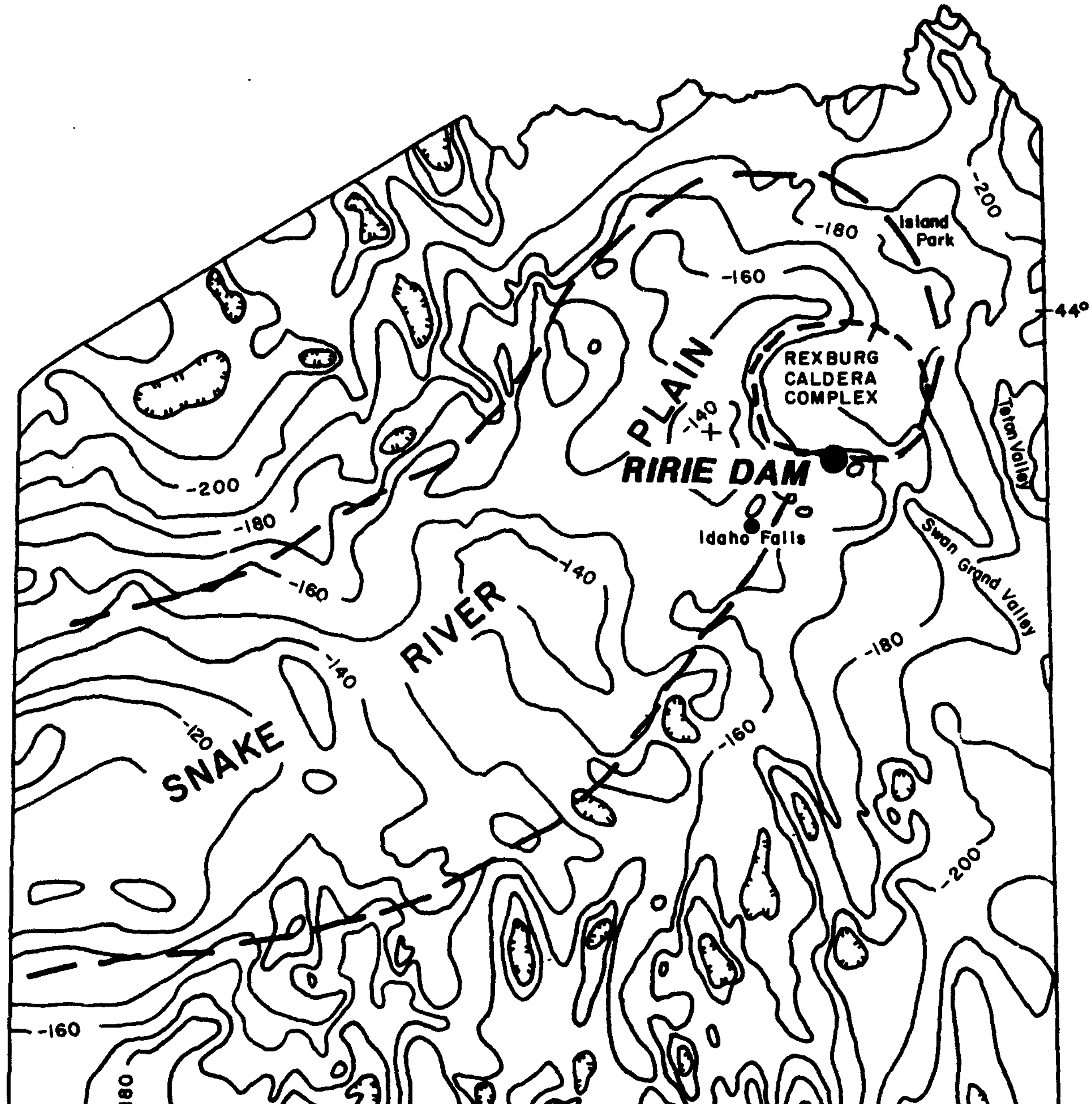


Figure 3. Bouguer gravity map of southeastern Idaho
(from Mabey, 1978a and Mitchell et al., 1980)

gravity low which is defined as the Rexburg caldera complex and a more linear low over Swan and Grand Valleys. The Rexburg caldera is discussed in greater detail in the following section. Swan and Grand Valleys are fault-bounded graben valleys.

Figure 4 shows an aeromagnetic map of southeastern Idaho (from Mabey, 1978a), which complements the gravity map presented above. Flight elevations for the survey on which the map is based are 2750 to 3700 meters above sea level. A magnetic survey measures variations in the intensity of the earth's magnetic field. These variations are related to major differences in rock types in the earth's crust and reflect the concentrations of magnetic minerals, primarily magnetite. The aeromagnetic map shows a series of structures beneath the Snake River Plain that are anomalous compared to the adjacent areas. The Snake River Plain is characterized by a complex of local highs and lows. Ririe Dam is situated between a magnetic high and a pronounced low near the intersection of Swan and Grand Valleys with the Snake River Plain (area bounded by the dashed line). The low corresponds to the Rexburg caldera.

Mabey (1978a and 1982) interpreted the gravity and magnetic data to indicate crustal thinning under the eastern portion of the Snake River Plain. The crust beneath the plain consists of a thin upper layer overlying a thick block. Composition of the upper layer is primarily volcanics as illustrated by the numerous calderas (Rexburg and Island Park) and the magnetic anomalies. Formation of the thin upper layer is by extensive flows of basaltic lavas. The thick lower block is poorly understood, but is believed to represent magmatic material. A mantle hot spot or plume may have generated the lower block as the volcanic activity in the plain moved during very recent geologic time to its present position at Yellowstone (Mabey, 1982; Smith and Sbar, 1974; and Leeman, 1982). Mabey (1982) concluded about the Snake River Plain:

> "The Snake River Plain is a major feature in the crust. Active volcanism, open fissures, and evidence of continued subsidence show that the plain is an active structure that continues to develop."

Rexburg Caldera

The large, circular, negative gravity anomaly beneath the city of Rexburg and near Ririe Dam has been interpreted as a volcanic caldera based on geologic and geophysical evidence (Prostka and Embree, 1978 and Mabey, 1978b). A detailed Bouguer gravity map of the Rexburg caldera is presented in Figure 5

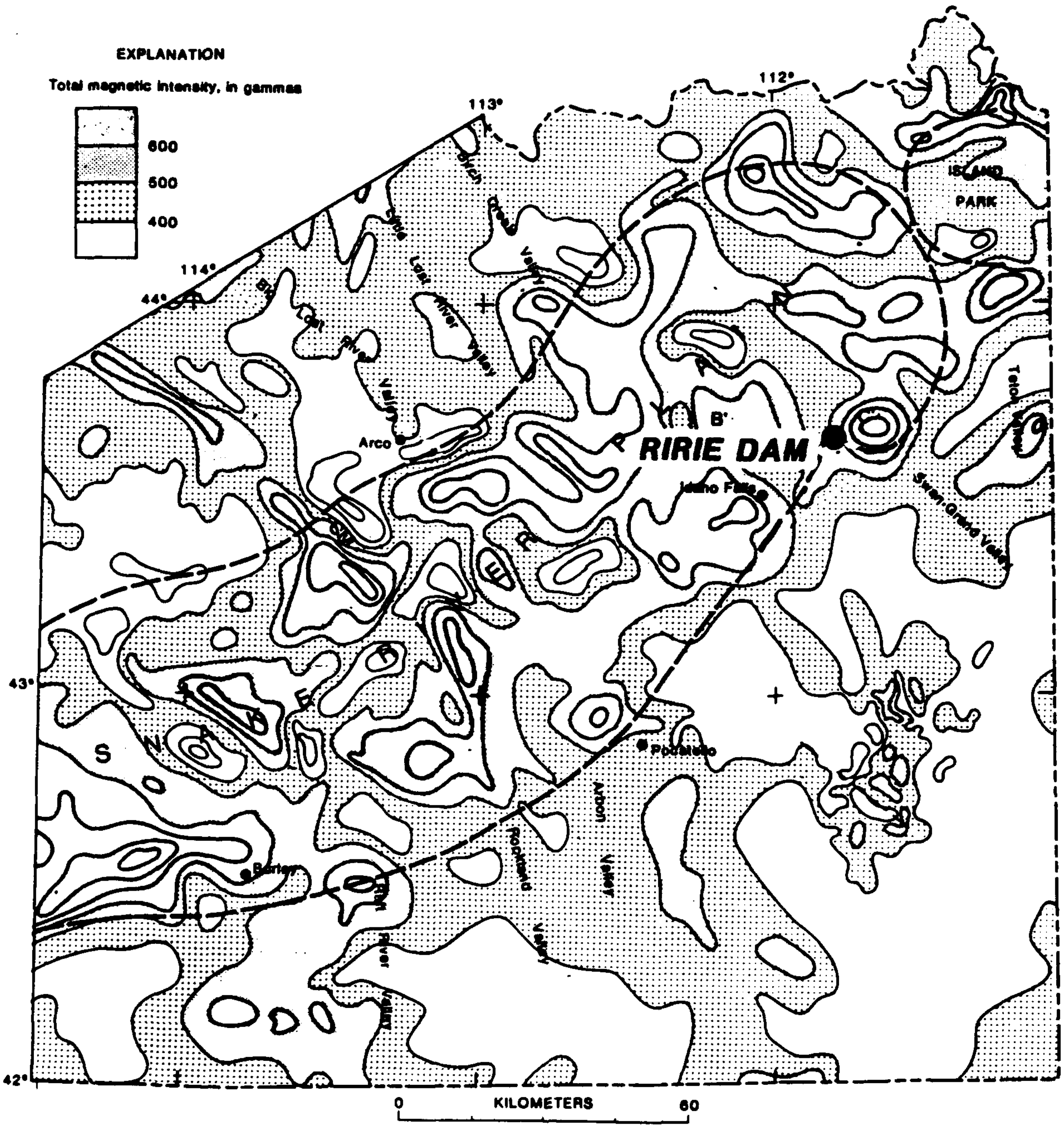


Figure 4. Total intensity aeromagnetic map of southeastern Idaho (from Mabey, 1978a)

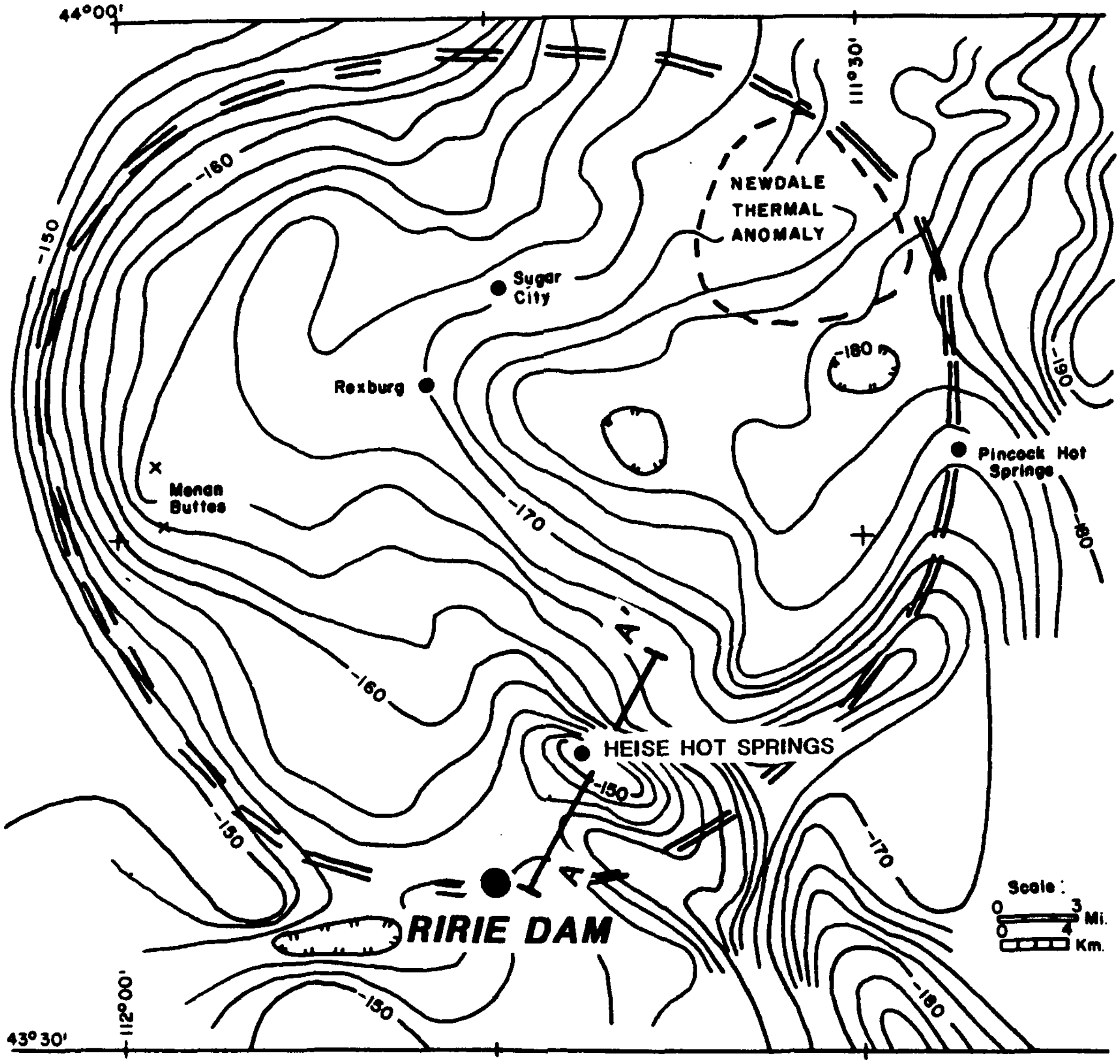


Figure 5. Bouguer gravity map of the Rexburg area
(after Mabey, 1978b; from Mitchell et al., 1980)

(after Mabey, 1978b; from Mitchell et al., 1980). The circular pattern of the anomaly is clearly identified by the gravity map. Contours range from a high of a negative 150 mgal along the margins of the caldera, to a low of a negative 180 mgal at Menan Buttes near the western side of the caldera. A gravity high at Heise Hot Springs and a linear low that trends to the northwest-southeast are located on the southern margin of the caldera.

The Rexburg caldera complex is 55 km in diameter and was active approximately 6.5 million years before the present (Embree et al., 1982). Tertiary volcanics associated with the complex are exposed around the margins of the caldera and are mapped as the Tuff of Spring Creek. The steep gravity gradients on the southwestern margin of the caldera suggest, according to Mabey (1978b), that the caldera is filled with 1.0 to 2.5 km of low density materials.

<u>Heise Hot Springs</u>

Heise Hot Springs, a popular resort area along the Snake River, are approximately 8 km (5 miles) northeast of Ririe Dam. Heise is situated along a northwest trending fault zone that has experienced movement during Pleistocene time (Witkind, 1975b, and Slemmons and Ramelli, 1986; see Appendix C). Heise fault in Swan and Grand Valleys is an extension of the faults of the Basin and Range structures. The Heise fault forms a southwest facing scarp with as much as 300 m (985 ft) of relief. The scarp is uneroded and youthful in appearance with patches of travertine from recently active springs. It is parallel to and near the crest of the gravity and magnetic anomalies examined in the preceding figures (Mabey, 1978b). The intent of this discussion on the Heise Hot Springs is to identify and define one of the important regional geologic and structural features that is in close proximity to the dam. A more detailed evaluation of faulting near the damsite, including the Heise fault, will be presented in a later section of this report.

A prominent magnetic and gravity high within the Rexburg caldera is coincident with the Heise Hot Springs. Mabey (1978b) interpreted the geophysical evidence as indicating that the magnetic high in Figure 6 was produced in part by a large buried intrusive body. The geology tends to support this interpretation as Mesozoic sedimentary rock overlain by Tertiary rhyolite flows and tuffs outcrop on the fault scarp. In addition, rhyolite dikes are locally abundant. East of the Heise Hot Springs, at a distance of

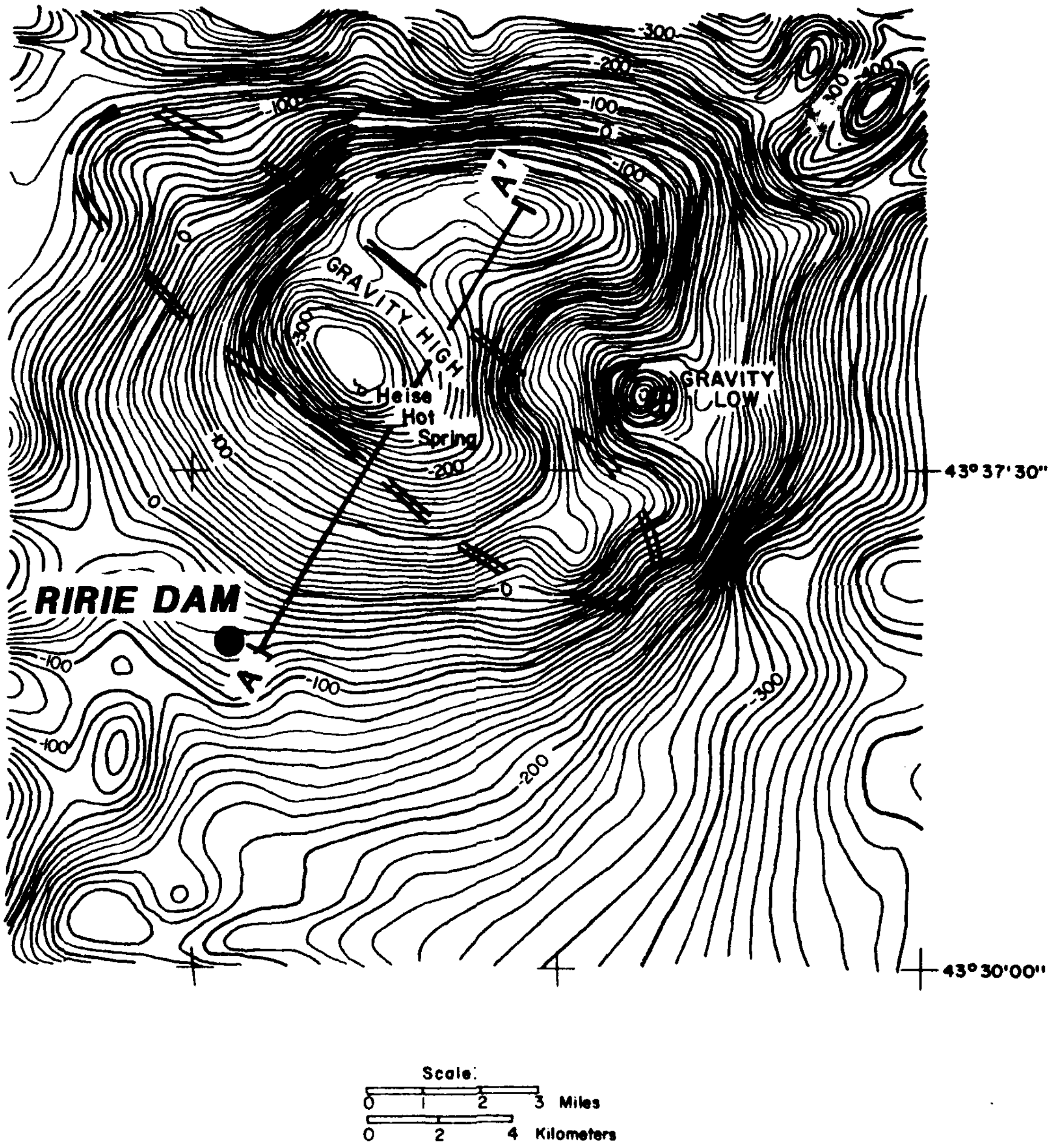


Figure 6. Residual aeromagnetic map of the Heise Hot Springs area (after Mabey, 1978b; from Mitchell et al., 1980)

approximately 8 km, are coincident gravity and magnetic lows interpreted as different density and magnetization from what is found in the surrounding rock mass (Mabey, 1978b).

Figure 7 presents an interpretation of the geophysical data for the Heise Hot Springs (after Mabey, 1978b; from Mitchell et al., 1980). The profile indicates that the area of the Snake River Valley to the southwest of Heise is composed of a thick sequence of Cenozoic rock. The gravity high at Heise corresponds to a thin layer of Cenozoic rock under which is located the apex of the intrusive mass. The Cenozoic rock southwest of Heise is in the structural low which corresponds to the Swan and Grand Valleys which intersect the Rexburg caldera. The exact age of the underlying intrusive mass is unknown, but it may be the same as the rhyolite dikes which are locally abundant.

Local Geology and Stratigraphy

The rocks underlying Ririe Dam and reservoir consist primarily of volcanics of Tertiary age. The geology for the damsite and surrounding area is shown in Figure 8. A detailed legend for the map is presented in Appendix A (after Ross and Forrester, 1947). Five major lithologic and stratigraphic units occur at the damsite. These units are exposed in the valley walls of Willow Creek or are covered with either Holocene or Pleistocene alluvium, colluvium, or loess.

The foundation for Ririe Dam was excavated along the centerline of the dam to rock. The foundation ranges from bedrock along the centerline of the dam, to in-situ coarse sands and gravels beneath the upstream and downstream toes of the dam. The alluvium underlying the dam varies in thickness from a few feet along the right and left abutments, to more than 70 ft at the deepest portions of Willow Creek Canyon. The valley fill at the damsite consists of sandy gravels overlain by 5 to 10 ft of soft, silty clays and clayey silts.

Overlying the flat uplands that border Willow Creek Canyon is a thin veneer of Pleistocene loess. Beneath the loess are five major geologic units (after U.S. Engineer District, Walla Walla, 1977). The major units from youngest to oldest are:

(a) An intracanyon basalt flow composed of blue-gray to black porphyritic, vesicular basalt having a columnar structure.

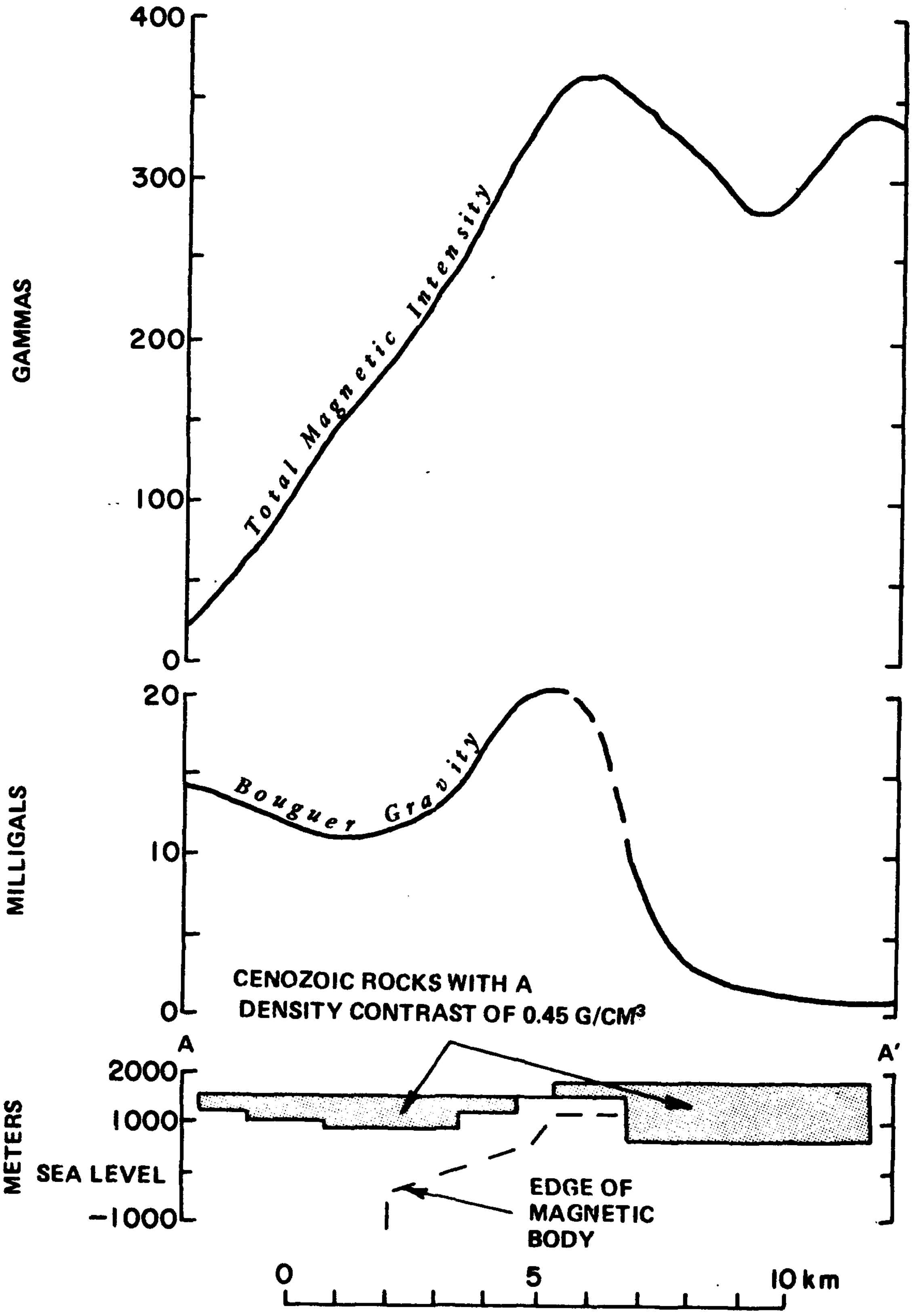


Figure 7. Gravity and Magnetic intensity profile across the Heise Hot Springs area and subsurface interpretation (after Mabey, 1978b; from Mitchell et al., 1980)

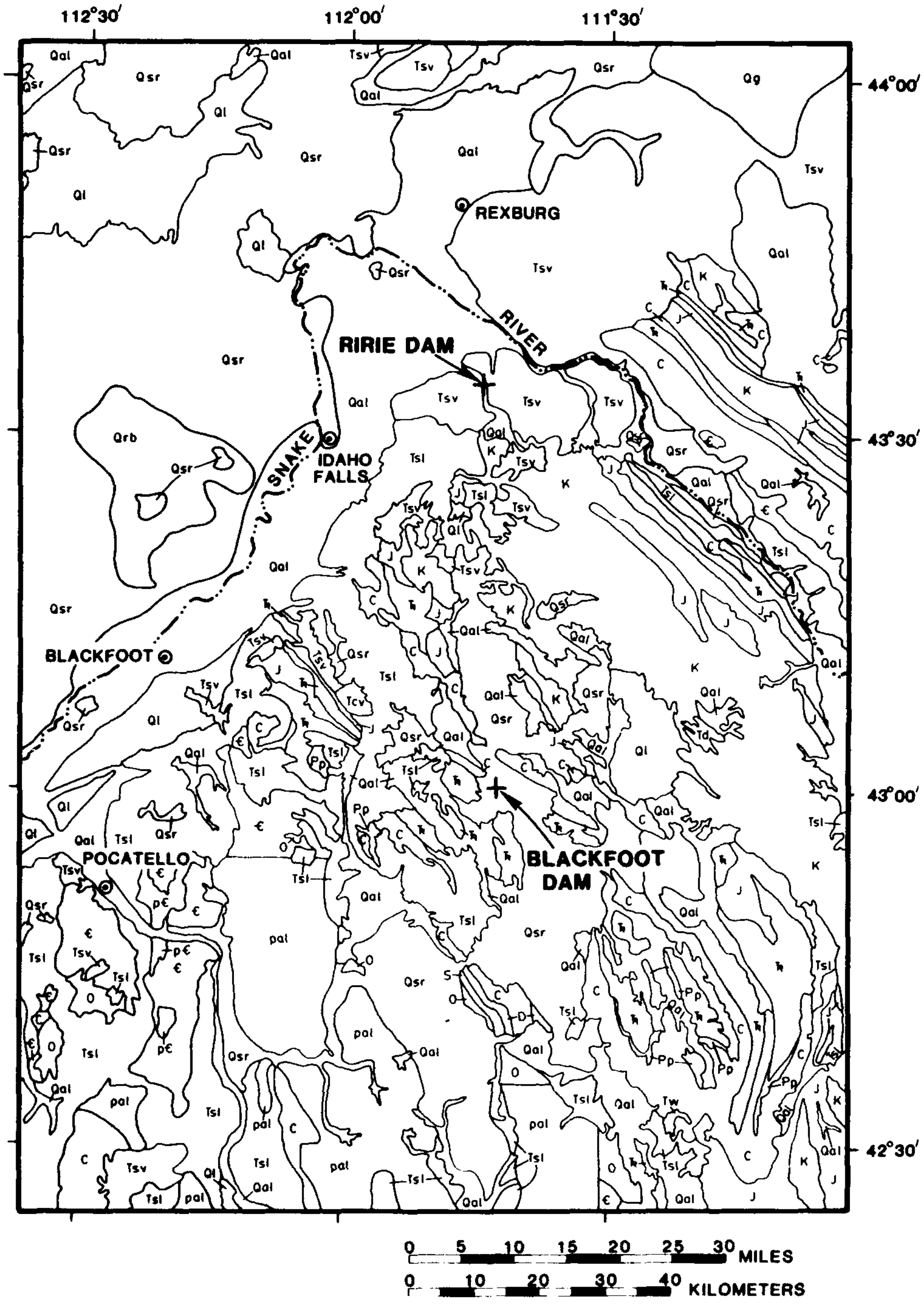


Figure 8. Geology of Ririe Dam and vicinity (from Ross and Forrester, 1947)

(b) Rhyolite which is moderately hard to soft, pink to gray in color, fine-grained, with needle-shaped crystals generally with a thin (plus or minus five foot) layer of volcanic ash at the bottom of the flow.

(c) Channel gravels which are found upstream of the dam axis in the right abutment and consist of cross-bedded sand, gravels, and clay.

(d) Basaltic lava flows which are porphyritic and vesicular, intercalated with sedimentary interbeds of clay, silts, and flow breccia.

(e) The Salt Lake Formation, locally called Basal Sediments, composed of a series of sandstones, siltstones, and claystones, with at least one known intercalated rhyolite flow.

A detailed description of each major unit and its relationship to the overall damsite stratigraphy is presented in Appendix B. Descriptions in Appendix B are taken from the earlier Patrick and Whitten (1981) report on Ririe Dam. Also included in Appendix B is a large-scale geologic map of Ririe Dam (Figure B1, from Prostka and Hackman, 1974) and a detailed stratigraphic section (Figure B2, from U.S. Army Corps of Engineers, Walla Walla, 1977) for the dam. The latter identifies the principal stratigraphic horizons within each geologic unit. Included in the stratigraphic column is the minimum, maximum, and average thickness for each of these units as well as their relative ages based on potassium/argon dating techniques (from Patrick and Whitten, 1981).

Figure B3 in Appendix B shows the locations of 5 geologic cross-sections constructed from foundation borings (Figures B4 through B9, from Patrick and Whitten, 1981). The five cross-sections are constructed along the centerline of the dam (profile 1), upstream of the dam and normal to Willow Creek (profile 2), parallel to Willow Creek and normal to the dam (profiles 4 and 5), and near the vicinity of the right abutment (profile 3). The generalized sections identify the stratigraphic complexity of the underlying geology and identify faulting beneath the dam (profiles 1 and 2). The entire vertical section defined by the geologic profiles measures approximately 122 meters (400 ft), as measured between the flat upland surface bordering Willow Creek and the deepest boring beneath the dam.

The rock units comprising the foundation of the damsite are examined in great detail in the original foundation report with several types of geologic data examined, including numerous borings, seismic surveys, test pits, and field mapping. The results from these detailed studies show that the basalt units which form the foundation for the dam dip in a southwesterly direction from 5 to 30 degrees.

Regional Faults

Mapped Faults

The patterns formed by the major faults in southeastern Idaho and adjacent states are shown on Figure 9. The faults were compiled from several sources: the Idaho state geological map by Ross and Forrester (1947), the Wyoming state geological map by Love, Weitz, and Hose (1955), the Utah state geological map by Stokes (1962), and the Montana state geological map by Ross, Andrews, and Witkind (1958); also used were active fault maps for the states of Idaho and Wyoming by Witkind (1975a and 1975b) and the Quaternary fault map of the Basin and Range and Rio Grande Rift by Nakata et al. (1982). Included on Figure 9 are the locations of historic earthquakes of MM intensity VI or greater (data from Stover et al., 1986). These earthquakes will be discussed in greater detail in a later section of this report.

Two contrasting tectonic processes are imprinted onto the region shown in Figure 9. The first was a period of compressive stresses in the crust that occurred during the late Mesozoic and early Cenozoic (approximately 150 to 50 million years before the present) and that produced major thrust faulting throughout Wyoming, Idaho, and Utah (Wiltschko and Dorr, 1983 and Woodward, 1986). The second period began sometime in the middle Cenozoic, approximately 30 million years before the present in the middle Tertiary, and continues on into the present. This later tectonism was marked by a change in crustal stress that produced normal faulting, volcanism, and created the Basin and Range Province. Regional extension of the northern Basin Range Province became apparent during the later part of the Tertiary, about 17 million years before the present (Mabey et al., 1983).

Formation of the Snake River Plain began during the second tectonic period. The Snake River Plain is a crustal depression produced by rifting related to regional plate tectonics, downwarping, and normal faulting along the margin of and parallel to the plain (Gable and Hatton, 1983). Downwarping of

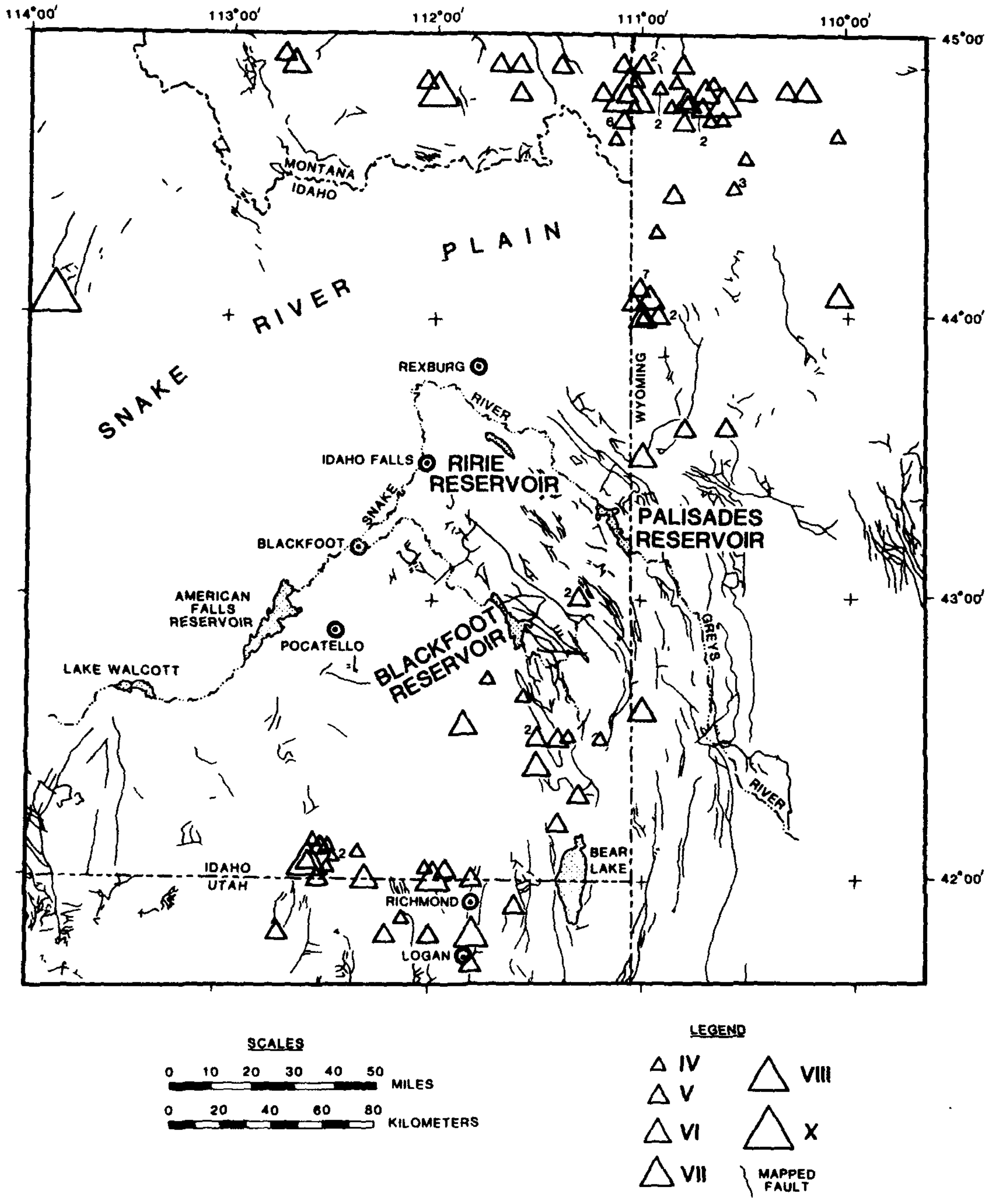


Figure 9. Major faults and earthquakes of MM intensity VI and greater

the plain was produced by isostatic adjustments of the dense magmatic fill that was previously cited. The Basin and Range Province, in contrast, has experienced continuous uplift during the late Tertiary and Pleistocene (from 2 million years to 10,000 years before the present). Uplift has continued in the Holocene (10,000 years to the present) and is continuing today. Associated with this uplift has been extensive normal faulting.

Gable and Hatton (1983) identify the rate of uplift at the Ririe Dam area as 1 mm per year. This value is for the region surrounding the Island Park caldera. The uplift is as much as 14 mm per year for the Yellowstone caldera. The rates identified on their map are based on leveling data obtained during the last 60 years.

The general trend of faulting in southeastern Idaho is north-northwest to south-southeast. The Snake River Plain abruptly truncates this pattern of faulting and the plain is itself essentially devoid of faulting. Equally absent from the plain are earthquakes comparable to those in the adjacent areas. The absence of major faulting and significant earthquakes in the eastern Snake River Plain indicate that the earth's crust in this area is in a state of low stress. The lack of faults and of earthquakes, as well as high heat values that are associated with the plain, suggest that the release of strain energy beneath the plain may be occurring by creep rather than the sudden subsurface crustal ruptures that produce earthquakes (Pennington, et al., 1974 and King and Doyle, 1982).

A schematic cross-section showing the geologic structure near Ririe Dam is contained in Figure 10 (after Dixon, 1982). Ririe Dam is situated adjacent to the Grand and Swan Valley graben which becomes the Palisades graben to the southeast. To the west of Ririe Dam is the Bear Lake graben. A graben is a structurally formed fault bounded valley with the faulting parallel to the long sides of the valley. As shown by the geologic cross-section, the structure of the northern Basin and Range Province is complicated by intense subsurface regional faulting. Many of these faults are listric meaning that they flatten at depth and become extremely low-angle. The deep, nearly horizontal faults are regional thrust faults related to the tectonism associated with compressive stresses during the late Mesozoic. Under the present tectonism, these faults are believed to be reactivated as extensional faults. The near surface, more vertical-dipping faults are the result of the

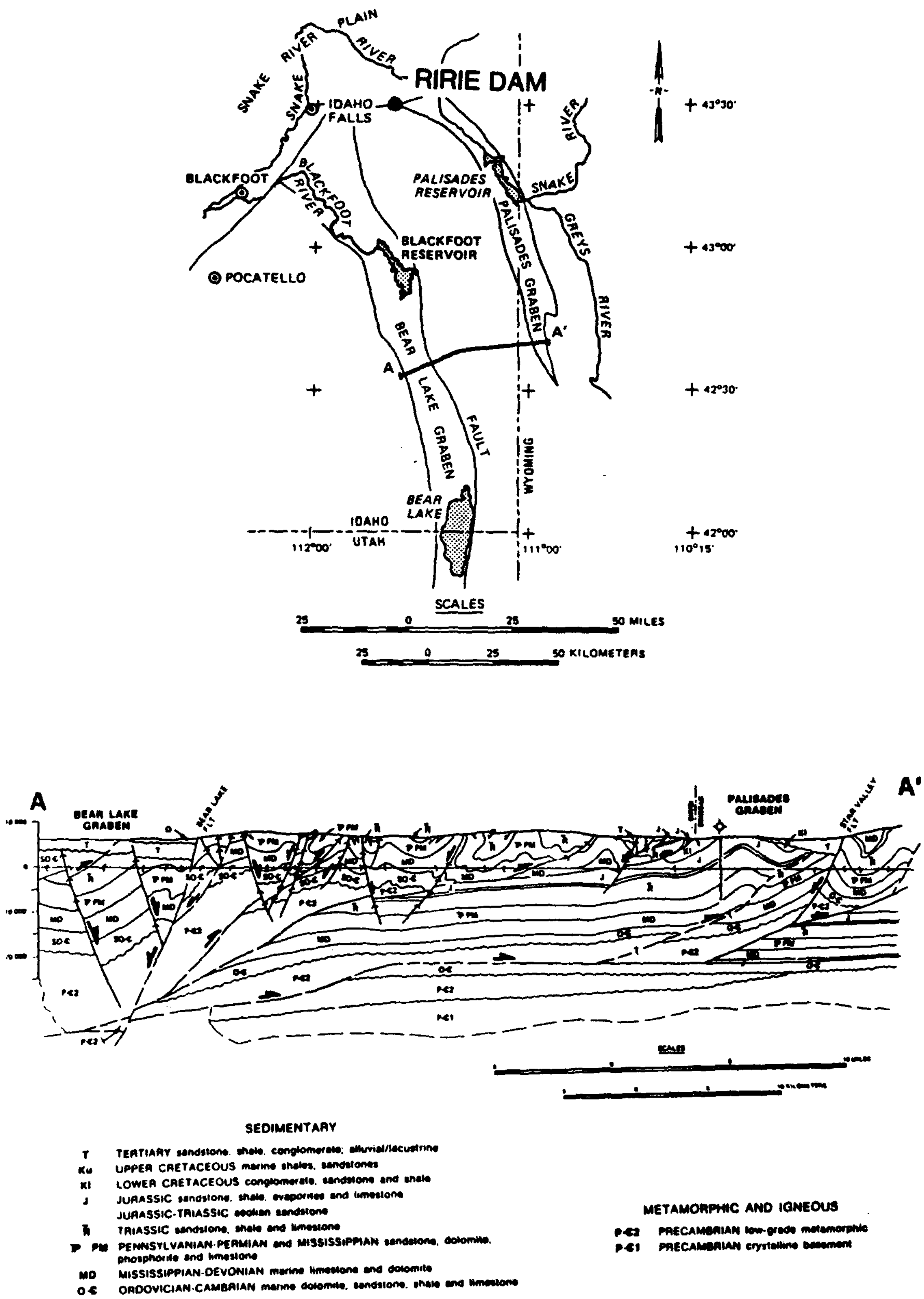


Figure 10. Generalized structure and geology of northern Basin and Range province showing Bear Lake and Palisades Grabens (after Dixon, 1982)

late Cenozoic extension. This extension is responsible for forming the graben valleys identified on the section. Quaternary valley fill and volcanic deposits were introduced into these structurally controlled valleys. The rock types underlying these grabens range in age from the Precambrian (before 600 million years) to the present.

Active Faults

Major active faults in the region surrounding Ririe Dam are shown in Figure 11. The faults were mapped primarily by Witkind (1975a and 1975b) with slight modification to the faulting near the damsite by Slemmons (1986). The information provided by Witkind for the individual faults shown in Figure 11 are presented in Table 1. Table 1 lists the type of faulting, the age of latest movement, direction of movement, the length of the fault segment, the earthquake potential for each fault, and relevant characteristics of each fault. Figure 12 presents the nomenclature of the major fault valleys. Figure 13 presents the fault trends along with their most recent movement.

Within a 50 km (31 mile) radius of the damsite the major faults are almost entirely associated with the main Snake River or Grand Valley faults. These faults represent activity ranging from the late Cenozoic to the Holocene. Faulting within a 50 km radius of the damsite consists of the Snake River fault (No. 23), Grand Valley fault (No. 22), Heise-Rexburg fault (No. 98), the unnamed fault along the west side of Teton River Valley (No. 87), and numerous smaller unnamed and unnumbered faults within Swan Valley.

The Grand Valley, Heise-Rexburg, and several smaller unnamed segments collectively form the Grand Valley Fault system. This system begins near Rexburg on the Snake River Plain and extends southeast along the eastern side of the graben valley through Antelope Flat, Swan Valley, and into Star Valley. The Grand Valley fault system extends in a discontinuous manner for approximately 160 km (100 miles). The western side of Grand Valley is bounded by the Snake River fault which is not included in the Grand Valley fault system.

Grand Valley Fault

Holocene age movement is shown on the Witkind map (1975b) of Idaho for three segments of the Grand Valley fault: about 20 km (12 miles) southeast of the dam (fault No. 22), and further to the southeast, beginning approximately 80 km (50 miles) from the damsite (No. 20 and 21) (see Figure 11). Closer to

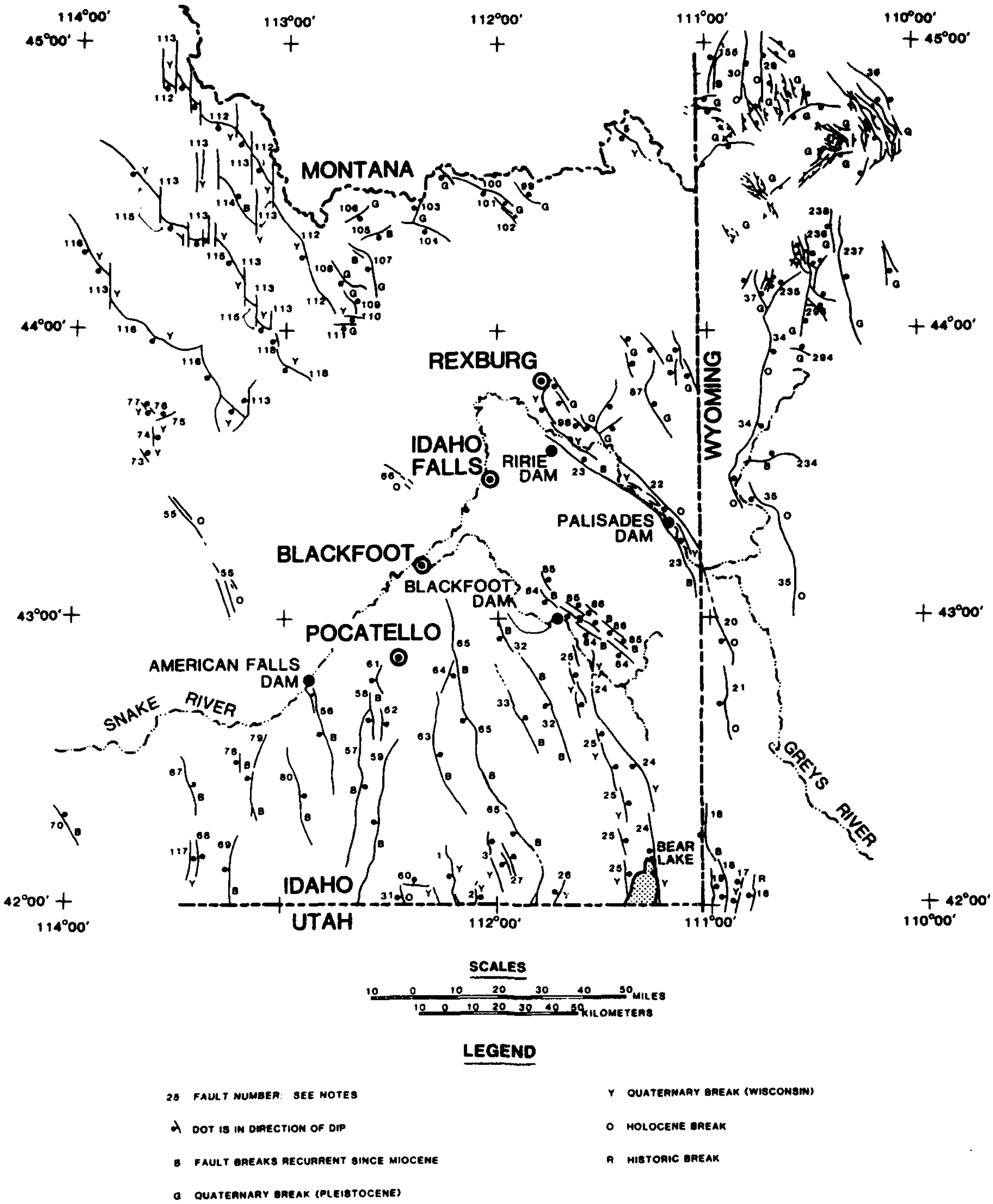


Figure 11. Active faults near Ririe Dam, see Table 1 for the descriptions of the individual faults (after Witkind, 1975a and 1975b)

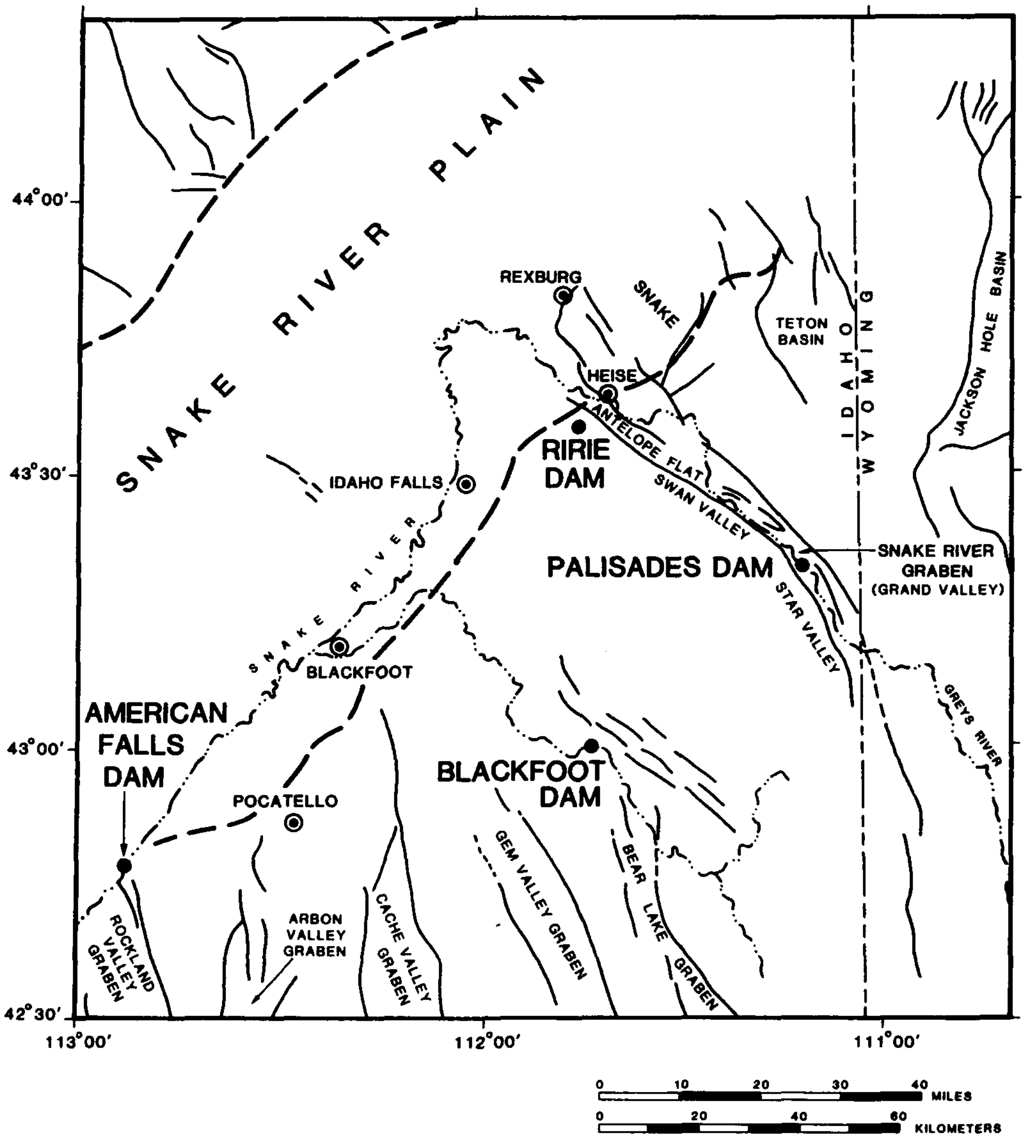


Figure 12. Nomenclature of major structural features in the area of Ririe Dam

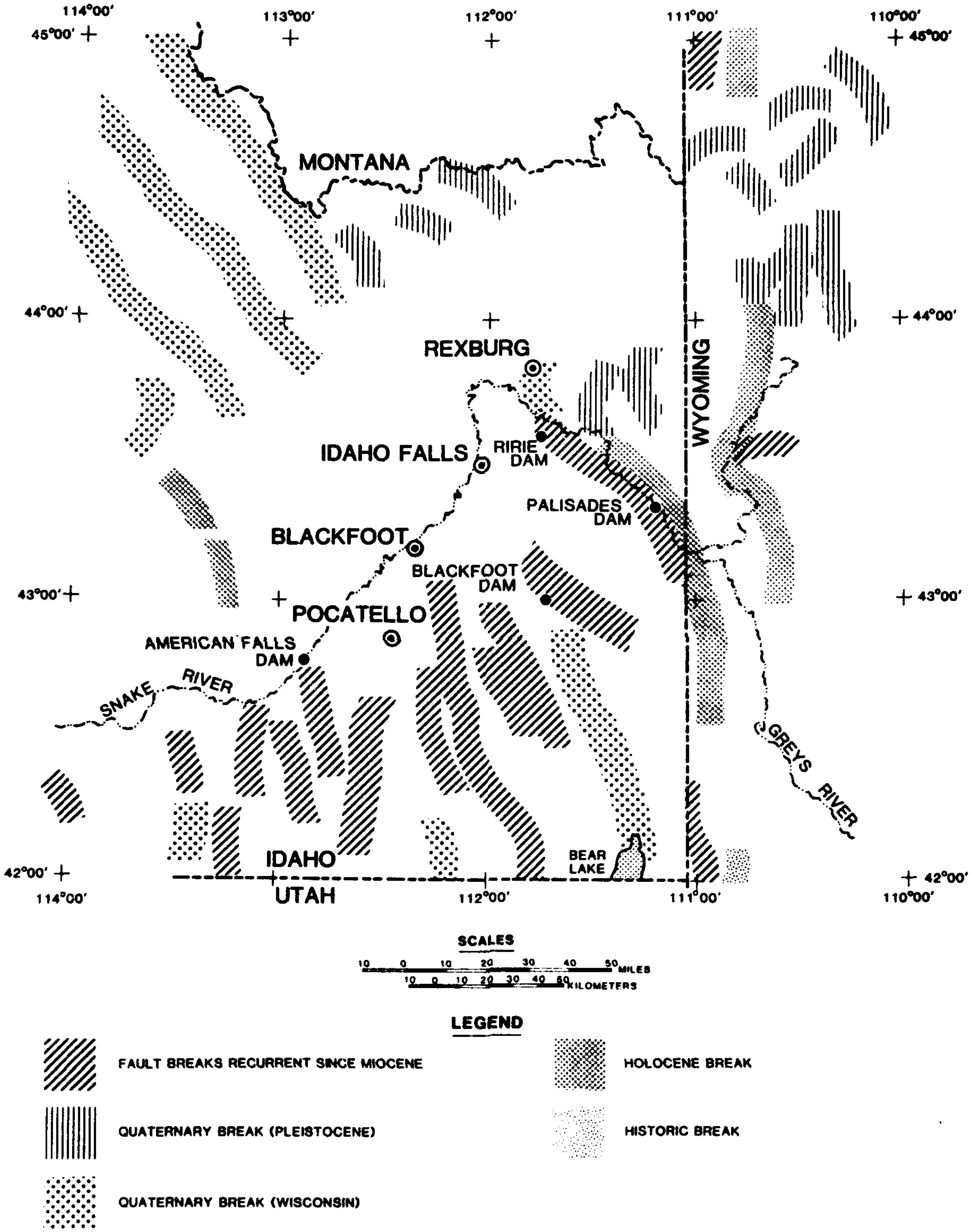


Figure 13. Major fault zones and ages of most recent movement

the damsite, Pleistocene movement is shown for the segment near the damsite. This fault along its entire length is identified as a high angle normal fault with the west side downthrown. A view along a segment of the Grand Valley fault near the damsite is shown in Figure 14. The photograph shows the great amount of relief on the fault scarp. The view in the photo is 24 km (15 miles) almost due east of the damsite at Antelope Flat, at the mouth of Black Canyon.

The descriptions accompanying fault segment No. 22 of the Witkind map (see Table 1) indicate that the latest movement occurred in the late Cenozoic, with no mention of the Holocene activity which is identified on the map. Patrick and Whitten (1981) noted the inconsistency between the map and the accompanying descriptions in their report. They concluded, after discussions with various USGS personnel, that the Holocene classification was "...subjective and was not based upon definitive stratigraphic or seismological evidence." They further stated that the Holocene classification may have been related to earthquake activity associated with loading of Palisades Reservoir. It was felt that the discrepancy in age may have been due either to error or somehow related to induced seismicity on the fault from Palisades reservoir. On the other hand, physiographic evidence in the fresh, uneroded scarp and the fresh patches of travertine along the scarp strongly suggest Holocene activity.

Further to the southeast, Holocene movement is identified for two segments forming the Grand Valley fault system. These two segments are part of the Star Valley fault (No. 20 and 21) and show displacements in Holocene beds. Figure 15 shows a photo of the Star Valley fault segment. It would be unlikely that Holocene movement could occur in this part of the valley and not be possible throughout the entire valley. Thus, Holocene movement can be inferred as a possibility on this basis in the Heise area.

North of the damsite, trenching was done by Williams and Embree (1978) along a segment of the Rexburg fault (No. 98). This fault extends en echelon to the Heise fault south of Rexburg, and continues en echelon into the main trunk of the Grand Valley fault in Antelope Flat. The surface trace of the Rexburg fault segment measures approximately 18 km (11.5 miles) in length. The configuration of the Rexburg fault shown in Figure 11 is based upon mapping by Slemmons (1986). Trenching by Williams and Embree identified a 1.6 m displacement in middle to late Pleistocene deposits that were unconformably overlain by younger alluvial deposits that were not offset. It was determined

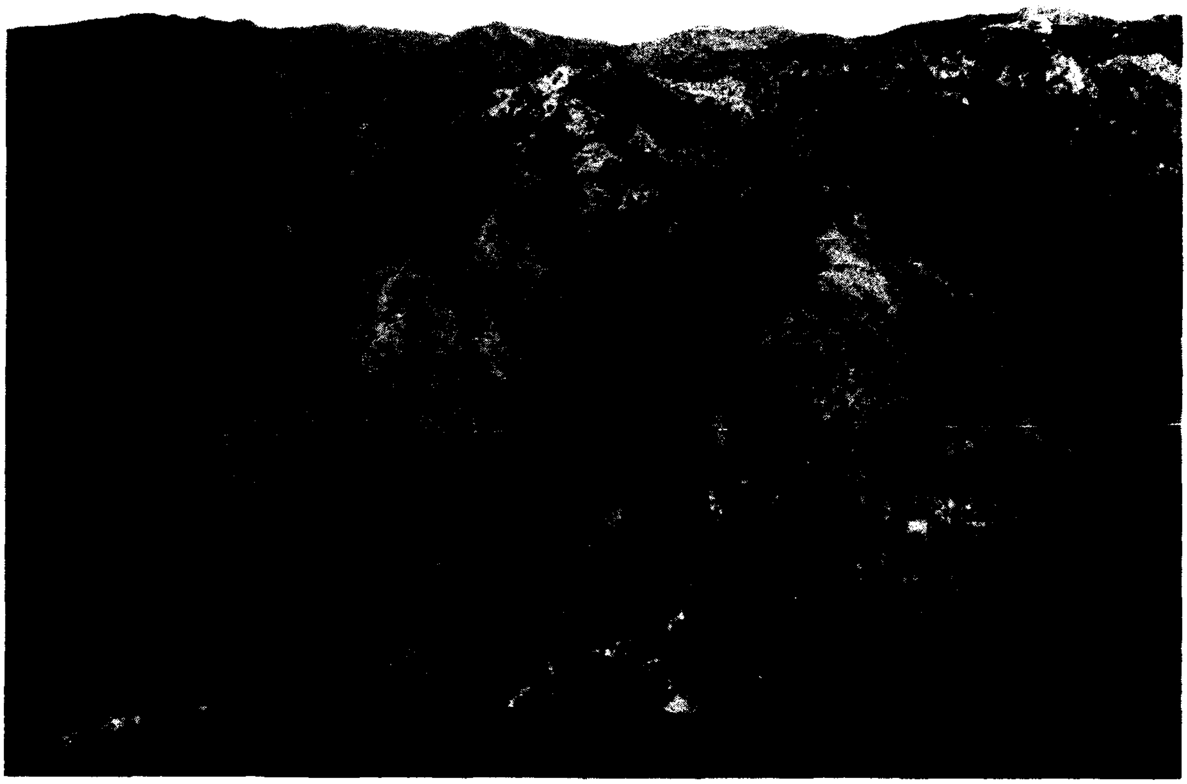


Figure 14. A view of the Grand Valley fault at Antelope Flat

Figure 15. A view of the Grand Valley fault in Star Valley

by Williams and Embree that the average slip rate during Pleistocene time, based on a total offset as measured on the Huckleberry Ridge Tuff, a key marker bed, was 1 m per 20,000 years for that portion of the fault.

A view of the Rexburg fault is shown in Figure 16. The fault scarp abruptly cuts the nearly flat, featureless surface of the southeastern Snake River Plain. Approximately 30 m (100 ft) of relief occurs at the location shown in the photo. The youthful age of the Rexburg scarp is shown from the drainage channels that intersect the scarp face. The young age of the scarp is indicated by an absence of alluvial fans at the bases of these channels. In addition, these channels have failed to significantly erode into the highly erosive loess-covered surfaces on the upper block of the fault which would be the case if the scarp was Pleistocene in age. The physiographic evidence suggests that the scarp may be Holocene in age. The Pleistocene dating by Williams and Embree (1978) may have been of a different poriton of the fault or of another fault.

Figure 17 shows a view along the Heise segment of the Grand Valley fault. The location is southeast of Rexburg at Heise Hot Springs. The relief between the base and the crest of the fault scarp is approximately 20 m (66 ft). The fault cuts greatly shattered and erodable volcanics. The total relief along segments of the Heise scarp are in excess of 330 m (1000 ft) at several locations. At the location shown in Figure 17 are thermal springs and travertine deposits. It was noted in a previous section of this report that locally the Heise Hot Springs are the site of gravity and magnetic anomalies. These anomalies are partially explained by the occurrence of a magmatic intrusion in the shallow crust beneath Heise. The active hot springs and the freshness of the fault scarp despite the easily erodable materials in the scarp are suggestive of extremely youthful fault movement.

<u>Snake River Fault</u>

The Snake River fault (No. 23) is the nearest major fault to the damsite and forms the west bounding fault on the Grand Valley or Snake River graben. The eastern side of this fault is downthrown and it extends southeast from the Snake River Plain for approximately 80 km (50 miles). Witkind (1975b) identifies the Snake River fault as having recurrent movement since the Miocene. No movement is reported for this fault in the Pleistocene. Figure 18 shows a segment of the exposed fault partially covered by talus at its base,

Figure 16. A view of the Rexburg fault south of Rexburg

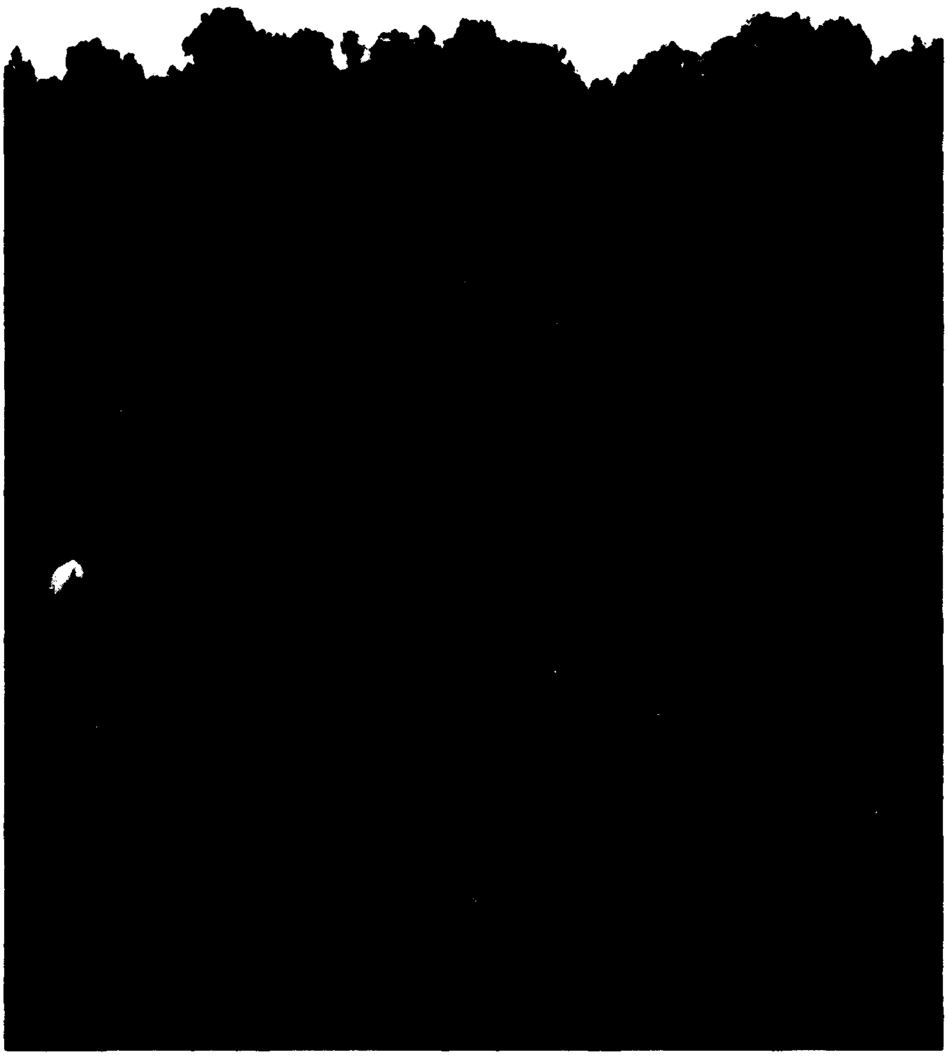


Figure 17. A view of the Heise fault near Heise Hot Springs

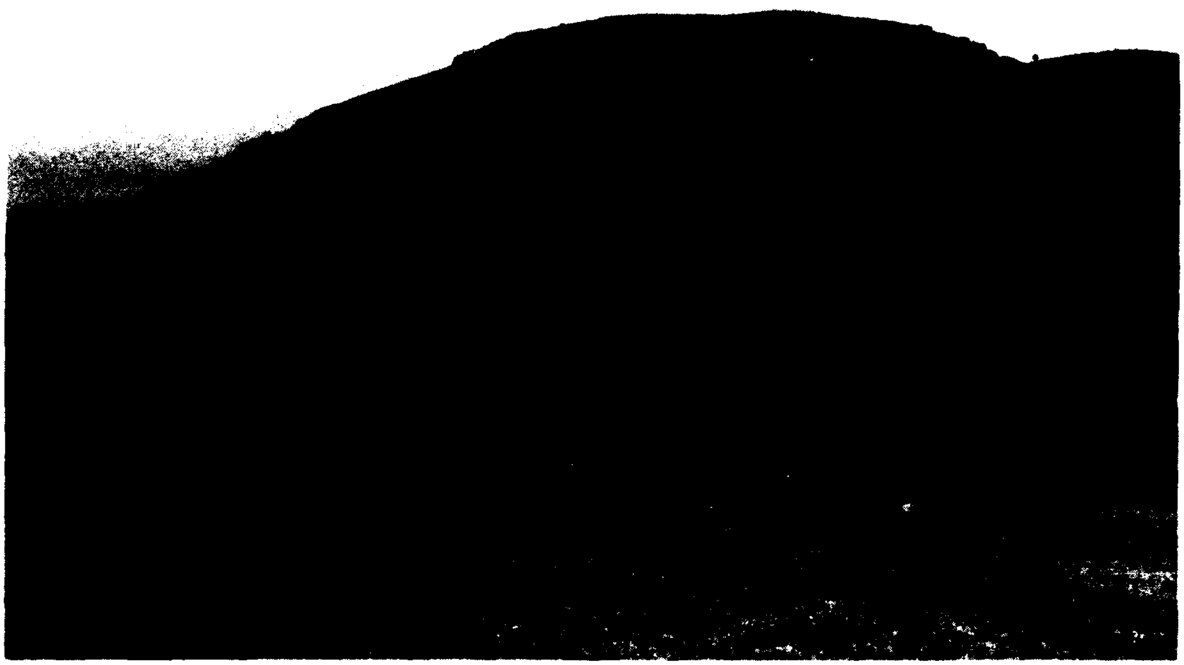


Figure 18. A view of the Snake River fault north of Pritchard Creek

approximately 2.5 km (1.5 miles) north of Pritchard Creek and southeast of the damsite 30 km (18.5 miles).

Teton Basin Faults

The remaining unnamed faults within a 50 km radius of the damsite, and not associated with the Grand Valley or Snake River graben, are located east of the damsite in the Teton Basin. These faults are mapped and described by Witkind (1975a) as being Quaternary age (essentially Pleistocene) and they trend in a northwesterly direction. Faulting in the Teton Basin consists of several unnumbered and unnamed smaller faults and one longer fault. The longer fault is Witkind's unnamed fault No. 87. The longer fault (No. 87) measures approximately 30 km (19 miles) in length while the smaller faults in this same vicinity measure between 10 and 15 km (6 to 9 miles).

Other Faults

Major faults located beyond a 50 km radius from the damsite are numerous (see Figure 11). These faults occur in the many fault-bounded valleys that parallel the general northwest-southeast trend of the Snake River graben. Major faults in these structurally formed valleys include Jackson Hole (No. 34 and 35), Enoch (No. 84, 85, and 86), Bear Lake (No. 24 and 25), Gem (No. 32 and 33), and Marsh Creek (No. 63 and 65) Valleys.

Faults in the Vicinity of the Dam

Lineaments

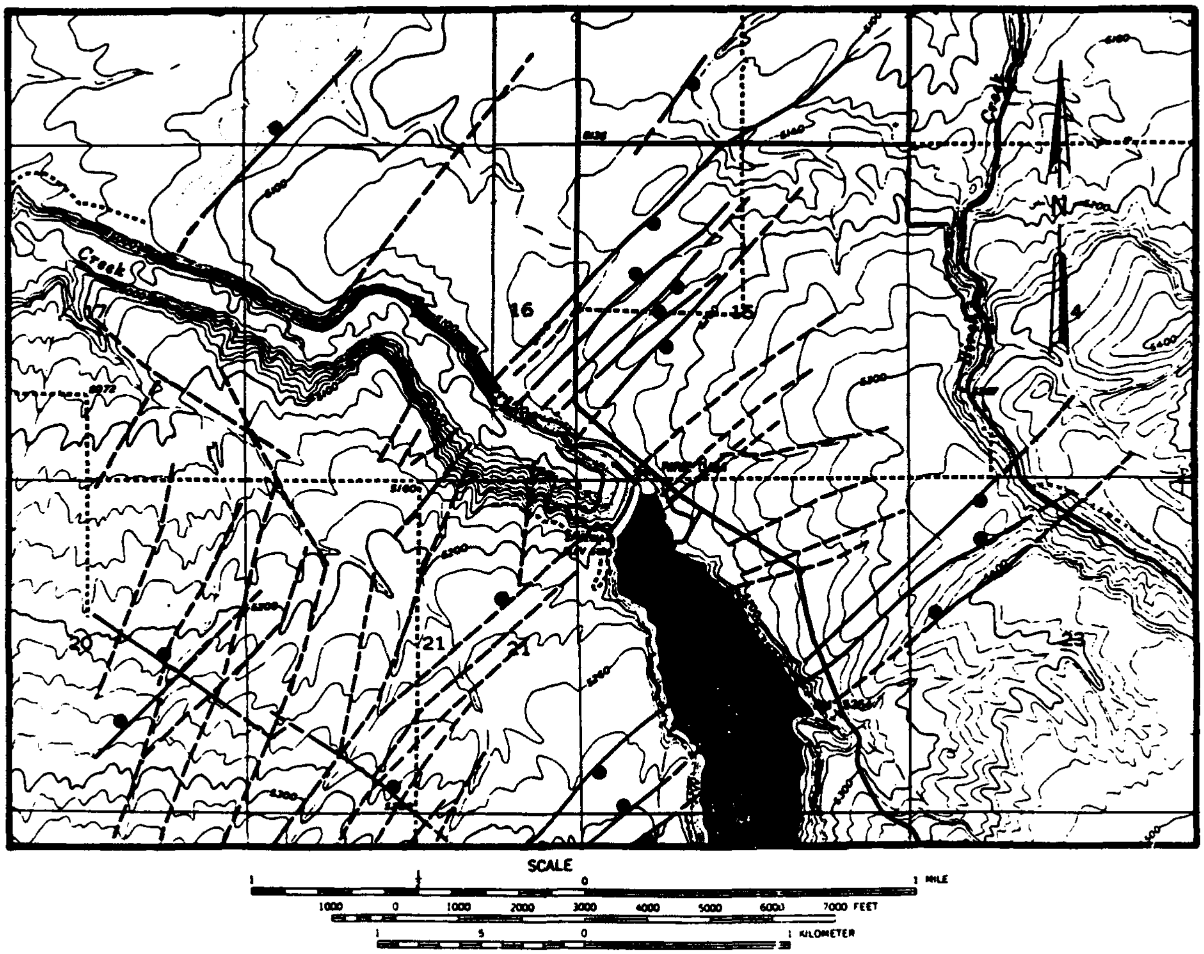
The patterns formed by lineaments and possible faults near the damsite are identified by the small scale aerial photograph in Figure 19. The interpretation of the linear features shown on the photograph is presented on the topographic map in Figure 20 (from Slemmons, 1986). The surface expression of these linears is masked in part by loess soils. A detailed assessment of surface faulting near the damsite is presented in Appendix C in a report by Slemmons and Ramelli titled, "Seismotectonic Setting and Design Earthquakes at Ririe Dam."

A close-up view of a lineament is shown in Figure 21. The location is south of the damsite and the feature trends approximately N 45 degrees W. It is on a surface that is covered by loess soil. A close inspection along several of these linear features in the canyon wall of Willow Creek, including

0 1/2 1 Mile

SCALE

Figure 19. Aerial photograph of Ririe damsite showing pattern of lineaments



Linear with no apparent offset

Fault with barb on downthrown side

Figure 20. Topography of Ririe damsite with interpreted lineaments and faults (from Slemmons, 1986)

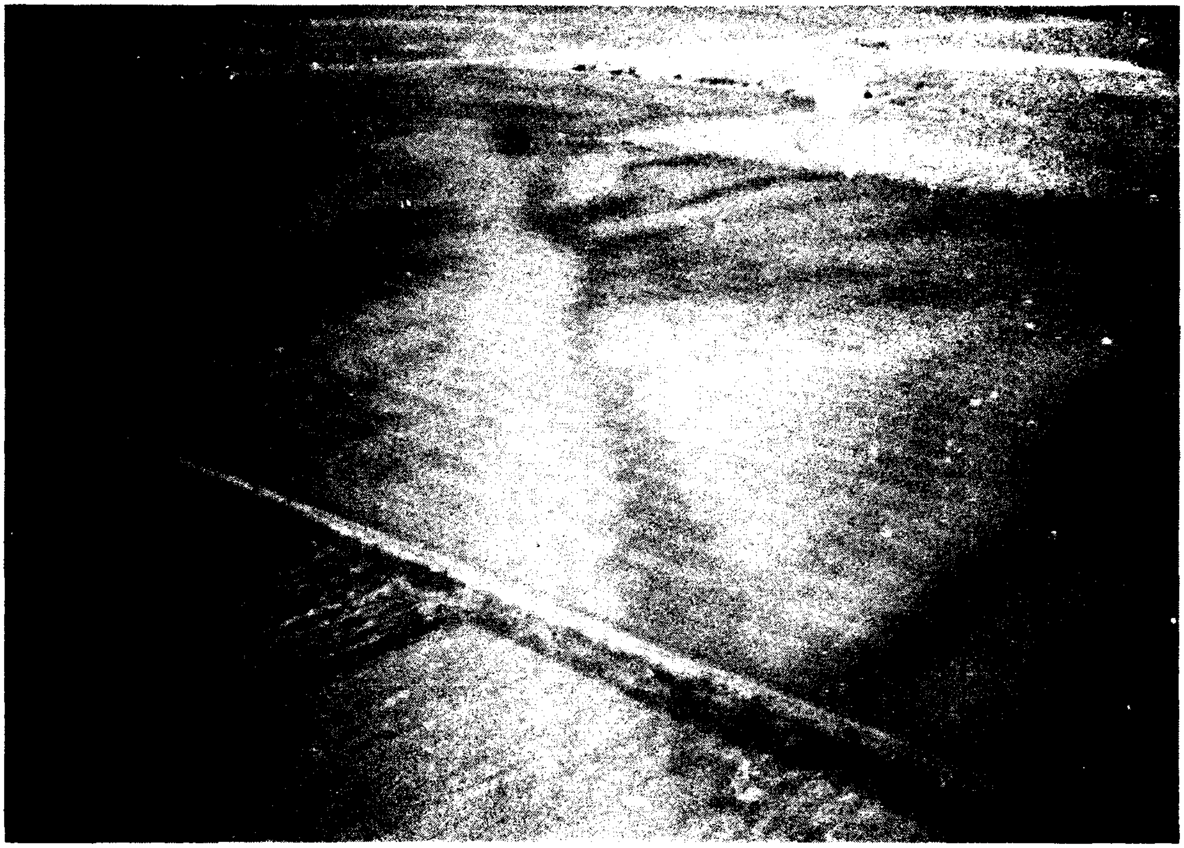


Figure 21. A close-up view of a linear near Ririe Dam

the one shown in the photograph, identified no offset on these features. Figure 22 is a view looking across a linear near the damsite and shows very little topographic expression associated with the lineament.

The lineaments which are shown passing through Ririe Dam (see Figures 19 and 20) have not offset the stratigraphy in the canyon walls of Willow Creek. Figure 23 and 24 are views of the right and left abutments. The thick light colored layer in the photograph of the left abutment (Figure 24) is a shotcrete cover and not an exposed lithological unit. As shown in both abutment photographs, no offset is apparent on either valley wall.

The lack of vertical structural displacement on the plateau surface is continuous throughout the rim of the canyon in which the reservoir is contained. This stability suggests that the reservoir is in no danger of an activated fault throw that could result in overtopping of the dam.

A possible explanation for the lineaments in the loess soils is that they represent cooling fractures in the underlying volcanic rock instead of being tectonic or structural in origin. Another possibility is that they indicate vents through which lava was extruded onto the surface of the plateau. Figures 25 and 26 lend support to a volcanic origin instead of a tectonic one. Figure 25, a view of the right abutment along a portion of the dam's spillway, clearly shows the general horizontal layering of the volcanic stratigraphy. In contrast, Figure 26, a view at the end of the spillway, shows an abrupt thickening of the volcanic units at what may be the vent from which they issued.

Surfa(Faults

The faults shown in Figure 20 are described by Slemmons (Appendix C) as being of Quaternary age as they cut the Huckleberry Ridge Tuff, a volcanic deposit having been extruded approximately 2.0 million years ago, very near the Tertiary-Quaternary boundary (Christiansen, 1982). The lengths of these short faults near the damsite are less than 5.6 km (3.4 miles) with displacements of 2 to 3 m (5-10 ft). Two ages of faulting are reflected in the patterns shown in Figure 20, an older northwest-southeast series of faults and a younger northeast-southwest series of faults.

The age of these faults is suggested by the thickness and displacement in the loess deposits. The older northwest-southeast trending faults parallel and are associated with the faults along the Grand Valley graben. The younger

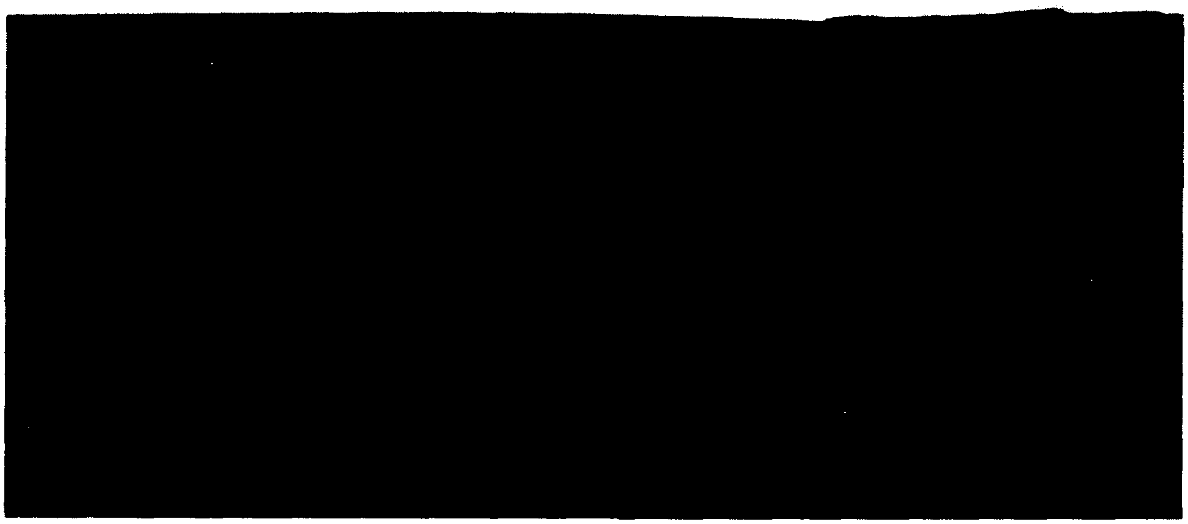


Figure 22. A view looking across a lineament near Ririe Dam showing little topographic relief

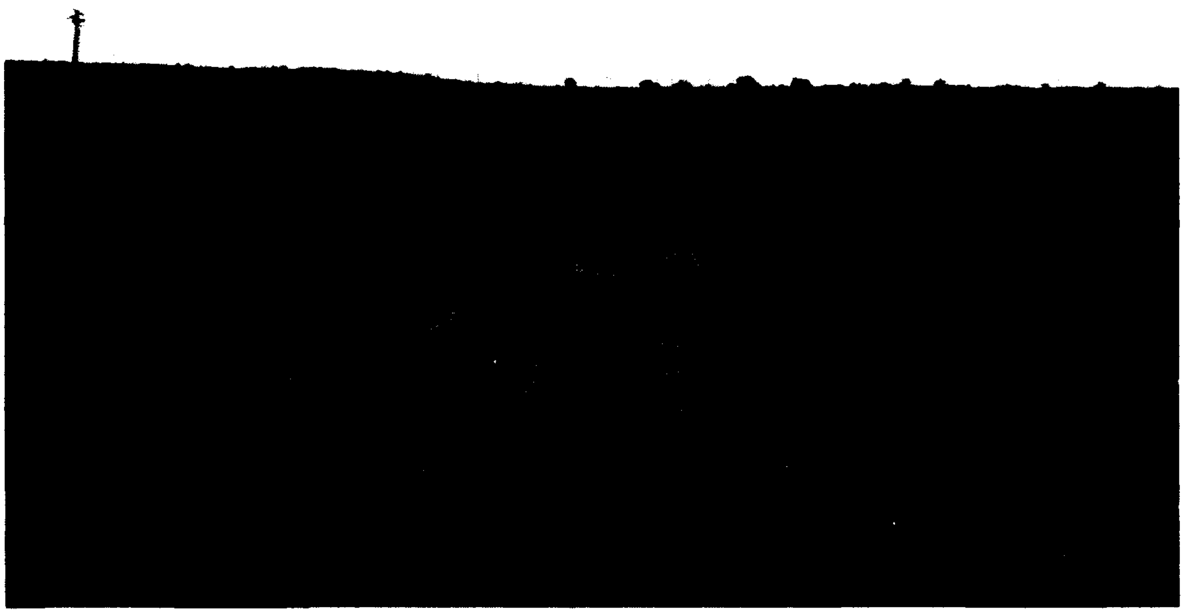


Figure 23. A view of the right abutment showing the stratigraphy in the canyon wall of Willow Creek

Figure 24. A view of the left abutment showing the stratigraphy in the canyon wall of Willow Creek

Figure 25. A view of the right abutment spillway showing the horizontal stratigraphy

Figure 26. A view of the right abutment at the end of the spillway showing the change in lithology and orientation

northeast-southwest trending faults are described by Slemmons (Appendix C) as being secondary features related to subsidence of the Snake River Plain. Supporting a subsidence origin for these faults is the attitude of the Huckleberry Ridge Tuff. The Huckleberry Ridge Tuff dips to the north, toward the Snake River Plain. The direction of dip indicates that subsidence and warping has been a continuous process in the Quaternary.

Subsurface Faults

Faulting beneath the dam has received a very close examination on at least two separate occasions: during the construction of the dam, and again, later in the study by Patrick and Whitten (1981). Three subsurface faults were identified at the damsite during construction. Two faults were identified beneath the dam and a third occurred beneath the intake tower. Only the faulting beneath the dam is shown by the cross-sections in Appendix B. No extension of the faulting beneath the dam was visible on aerial photography nor was there any evidence to be seen in the field reconnaissance studies that were made.

The major fault nearest the right abutment of the dam is shown in a geologic section (centerline section) in the foundation report as a normal fault with the downthrown side occurring on the right abutment block (U.S. Army Corps of Engineers, Walla Walla, 1977). Geologic profile 1 (Appendix B, Figure B4) is very similar to this section (Patrick and Whitten, 1981). Although this fault is shown as a normal fault by Patrick and Whitten, it is described in the original foundation report as a reverse fault, striking approximately N 40 degrees W and dipping toward the southeast at 42 to 56 degrees, with approximately 60 or more feet of vertical displacement. The interpretation of reverse faulting was discounted by Patrick and Whitten on the basis that the present tectonism for the entire region is characterized by normal faulting.

The remaining two faults at the damsite, the smaller fault beneath the dam near the left abutment and the fault beneath the intake tower, upstream from the dam, were not described in any detail in the foundation report. The left abutment fault was believed to be associated with the major fault closest to the right abutment. The third fault at the damsite was located beneath the intake tower, striking approximately normal to the axis of the valley, with displacement limited only to the older basalt (Qbo) and not the overlying rhyolite (Qyh). Since the overlying younger rhyolite was not displaced, it was concluded that the intake tower fault was a dead fault based on the age of the rhyolite flow (Patrick and Whitten, 1981).

Interpretation of Subsurface Faults

The significance of the faulting beneath the dam was examined in great detail by Patrick and Whitten (1981). Their study included additional drilling, radiometric age dating of major stratigraphic units by potassium-argon methods, and structural and isopach mapping of various key stratigraphic horizons. The results from the radiometric dating of the major stratigraphic horizons are included on the stratigraphic column in Appendix B (Figure B2).

The geological interpretation and identification of the structure at Ririe Dam is complicated by the thin veneer of loess covering the bluff surface and also by the dam and filled reservoir which covers locations of interest. Surface expression of the faulting beneath the dam is not visible in the canyon walls of Willow Creek. A primary objective of the drilling program in the Patrick and Whitten study was to establish the age of the faulting and its lateral extent away from the dam.

The drilling was confined chiefly to the part of the valley near the right canyon wall, a short distance downstream from the dam. The strike (N 40 degrees W) of the major fault beneath the dam was believed to extend to this location where the fault was projected in a downstream direction. A minimum age could be determined for the faulting beneath the dam by locating the fault in drill holes, and showing that it did strike into the canyon wall in the subsurface, and from detailed mapping of the layers exposed in the canyon wall where there is no displacement. This minimum age would establish whether the fault is recent enough to be considered capable of generating earthquakes.

The conclusions from the exploratory drilling program indicated that the major fault could not be dated by direct stratigraphic techniques, and it was determined that the fault did not extend into the canyon wall. Furthermore, the results of this drilling strongly suggested that a topographic surface was indicated rather than a fault scarp. Patrick and Whitten proposed that the displacements were those of a past landslide. As partial support of this interpretation, they cite Prostka and Hackman's geologic map (1974) for the area, which shows that numerous landslides have occurred along Willow and Meadow Creeks.

To establish whether the presumed fault beneath the dam was a slip face or detachment plane from a gravity slump or landslide, Patrick and Whitten contoured and constructed isopach maps of the numerous marker horizons from the available boring data to define the continuity and thickness of the various marker horizons. In addition, they reconstructed the prefaulting stratigraphy to logically explain the present structure. The landslide interpretation had to explain the evidence for faulting which in the foundation consisted of dislocations of marker horizons in borings, dislocations of marker horizons in the foundation excavation, and the presence of a shear zone in the foundation excavation. Their final conclusion is presented below:

> "The integration of data derived from the structural contour and isopach maps with the information derived from the examination of field relations does not support the existence of faults in the foundation. The abrupt change in strike of the major offset downstream from the dam, the significant topographic variation on the basal sediments and younger surfaces, the inability to reconstruct rational prefault conditions, the lack of sheared or gouge zones, and the presence of landslides strongly support the conclusion that the identified offsets in the foundation are topographic and that there are no active or capable faults at the damsite."

Thermal Springs

Thermal springs provide additional evidence for present-day tectonism as they identify regions of shallow volcanic activity or areas of anomalous crustal heat. Near Ririe Dam are located numerous thermal springs. Sites of thermal springs and wells are shown in Figure 27 with data for these locations presented in Table 2 (from Mitchell, et al., 1980). The listings in Table 2 for the wells and springs are grouped by county, followed by numbered location in each county.

Often associated with thermal springs are travertine deposits that can develop great thickness over relatively short periods of time. One such example of rapid development occurred in a newly drilled well at Soda Springs, Idaho, where flows built a circular mound over 60 ft in diameter and 4-1/2 ft high in six years (Krinitzsky, 1984). Travertine deposits may provide additional confirmation of tectonic activity, even long after the spring has ceased flowing. As was noted earlier, Heise Hot Springs is the site of thermal

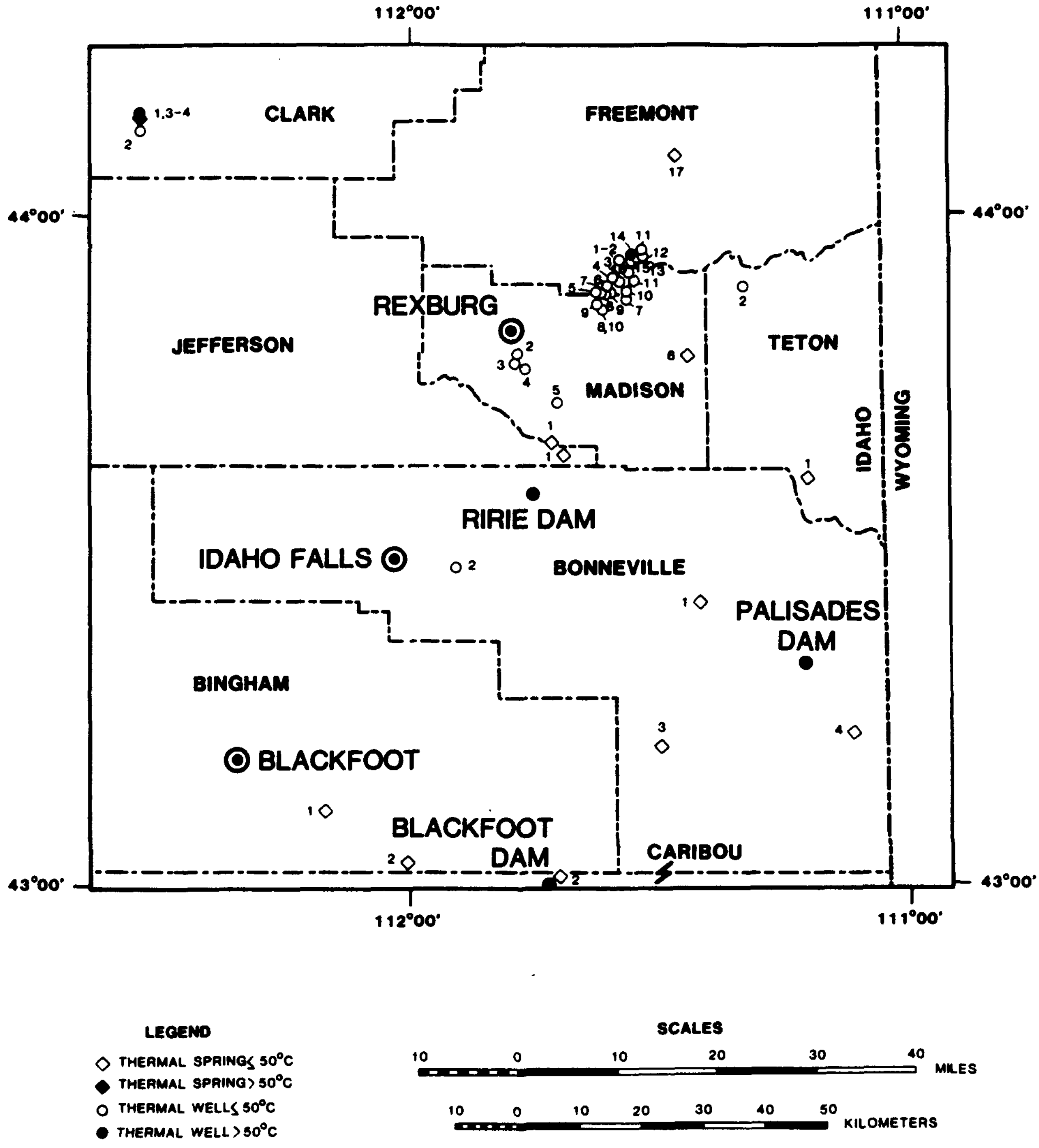


Figure 27. Locations and temperatures of hot springs and wells near Ririe dam (after Mitchell et al., 1980)

springs and there are travertine deposits on the fault scarp. Both are in close proximity to the damsite.

The temperatures for the majority of thermal wells and springs near Ririe Dam are less than 50 degree C. At only two locations are water temperatures greater than 50 degrees. Both locations are on the Snake River Plain, in Clark County and in Freemont County. The high concentration of thermal wells in southern Freemont and northern Madison Counties are primarily a function of population density and related drilling. Mitchell et al. (1980) associates the thermal anomaly at this location to the Rexburg Caldera complex which underlies this area.

PART III: SEISMICITY

Distribution of Historic Earthquakes

The distribution of historic earthquakes for a portion of the Intermountain Seismic Belt (ISB) is shown in Figure 28 for earthquakes of magnitude 3 and greater (from Piety et al., 1985). Ririe Dam is located along the western margin of this zone, which extends in a general north-south direction from Arizona into northwestern Montana (Smith and Sbar, 1974). The ISB is a zone of pronounced seismicity in the western United States. It is characterized by numerous small to very large magnitude earthquakes. They are generally shallow, the majority being less than 15 km in focal depth.

The earthquake record for this area in the western United States is the shortest in the contiguous United States. The record dates from 1871 for the area covered by this study, 109.5 to 114.0 degrees west longitude and 41.0 to 45.0 degrees north latitude, and from 1854 for the larger area covered by the ISB. A listing of earthquakes of Modified Mercalli (MM) Intensity VI or greater is presented in Appendix D (see Figure 9 for earthquake locations). Included in Appendix D is the MM Intensity scale identifying the different levels of earthquake severity. The list of earthquakes was derived from the USGS Hypocentral Data Search Program on United States Seismicity Files by Stover, Reagor, and Algermissen (1986).

Earthquakes less than MM VI were not considered in this review since there are numerous moderate to major earthquakes in this area and the patterns for minor earthquake activity have been studied extensively (Smith and Sbar, 1974 and Piety et al., 1985). The catalogue in Appendix D lists 31 events between 1884 and 1983 that are greater than MM VI. The majority of earthquakes are of MM VI, six earthquakes are of MM VII, three earthquakes are of MM VIII, and two earthquakes are of MM X. Of the six MM VII events, the 1884 earthquake at Bear Lake has been interpreted also as MM VIII (Arabasz and others, 1979) and is shown as MM VIII in Figure 29. The locations of all historic earthquakes of MM VII or greater for Idaho and adjacent states are shown in Figure 29. An MM VIII earthquake is the threshold for which damage begins to occur in buildings of good design and construction. The earthquakes in Figure 29 are randomly distributed throughout the area and they do not identify any

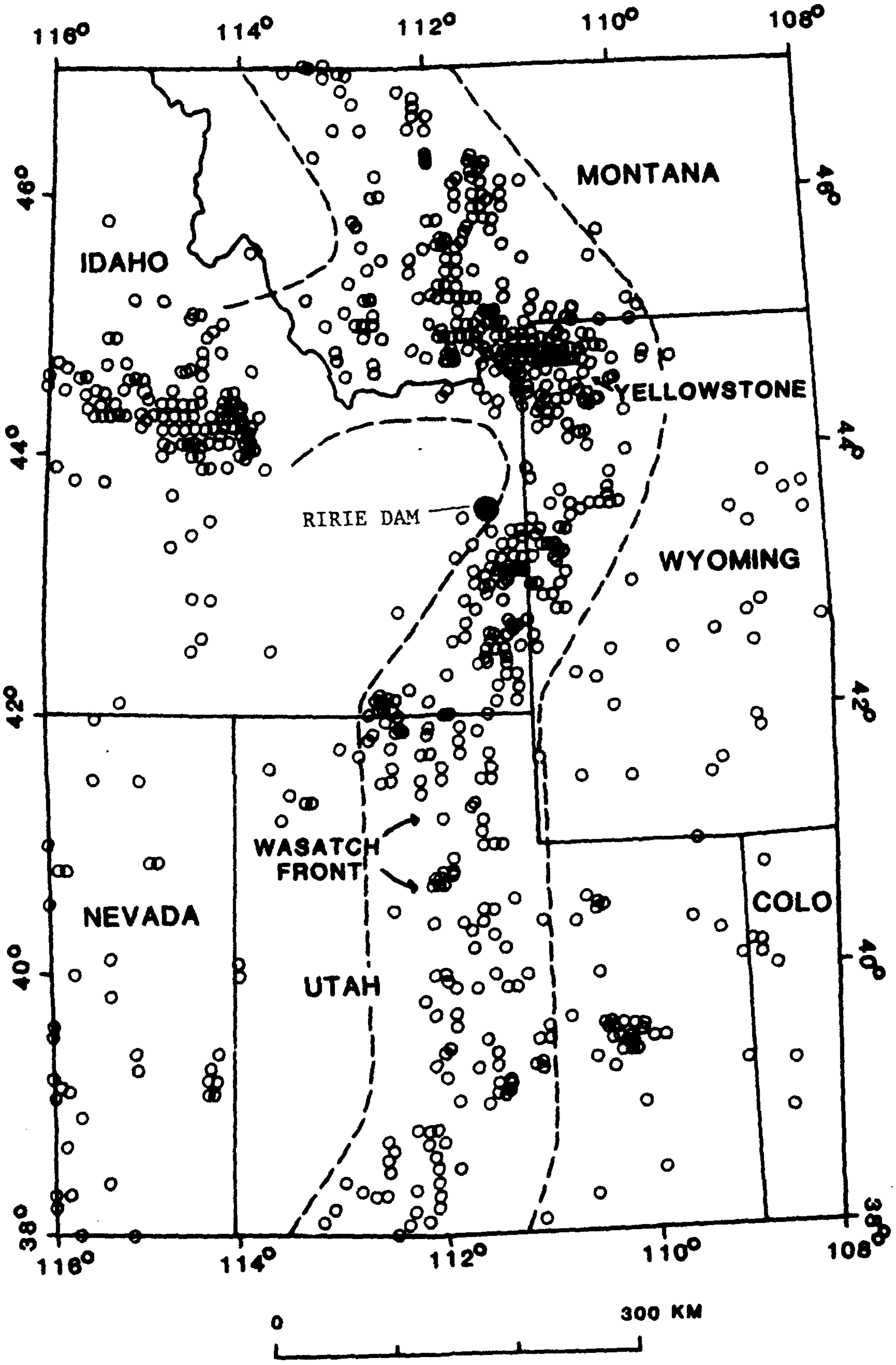


Figure 28. Patterns of historic seismicity from a section of the Intermountain Seismic Belt for earthquakes of magnitude 3.0 and greater (from Piety et al., 1985)

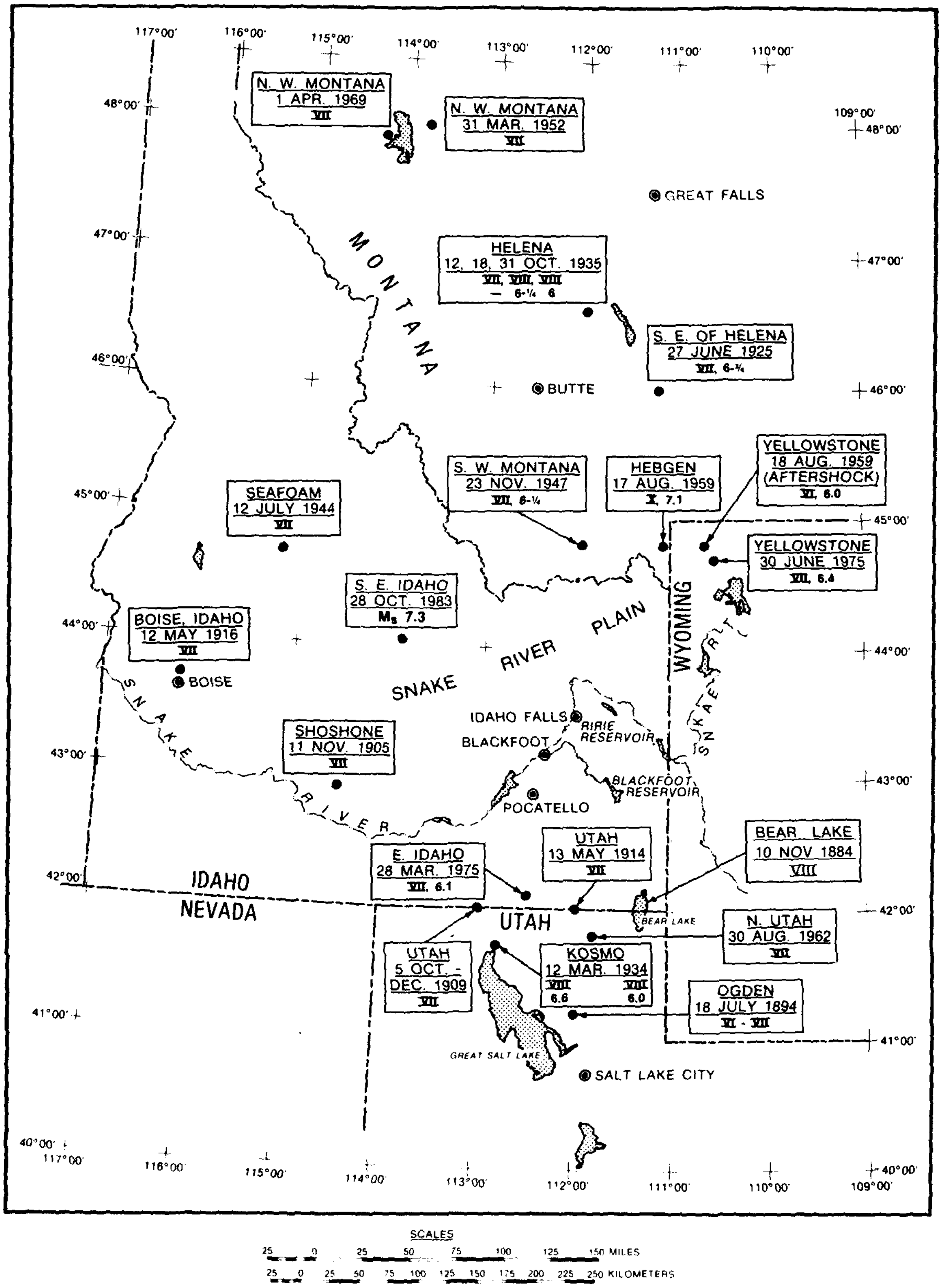


Figure 29. Historic felt earthquakes greater than MM Intensity VII (from Krinitzsky, 1987)

dominant trends or major geologic structures.

Relation of Seismicity to Geology

Smith and Sbar (1974) interpreted the pronounced seismicity along the ISB to movement along subplates which comprise the North American plate. The earthquakes occurring in this belt are associated primarily with normal faulting and with strike-slip components of movement.

Fault plane solutions for earthquakes in the ISB are shown in Figure 30 (from Smith and Sbar, 1974). Earthquakes generated near the damsite are characterized by normal faulting. Two major earthquakes greater than M = 7 have occurred in less than 30 years within 200 km (125 miles) of Ririe Dam. These earthquakes are the Hebgen Lake and Borah Peak earthquakes. These two earthquakes are the two largest in the historic catalogue for the study area.

The geodetic and seismological evidence from these two earthquakes strongly suggest that both events occurred on normal faults dipping from 45 to 60 degrees (Doser, 1985 and Stein and Bucknam, 1985). At Hebgen Lake, the vertical displacement was 6.7 m (22 ft), while the Borah Peak earthquake produced 2.7 m (8.9 ft) of displacement. Single event displacements associated with mapped Quaternary faults are comparable to displacements associated with these two major historic earthquakes. This suggests that the Hebgen Lake and Borah Peak earthquakes are representative of large events that have produced faulting near the damsite during the Quaternary.

The relationship between earthquake magnitude and surface rupture for the ISB is based upon the historic record. From the few incidents of surface rupture in the historic record, as compared to those incidents where no rupture has occurred, a threshold magnitude is identified for the ISB which ranges from M = 6-1/2 to 6-3/4 (Piety et al., 1985). The rate of occurrence for these events are so infrequent however, that their association with any particular fault or structure cannot be determined. In the entire Basin and Range Province (California, Nevada, Utah, Idaho, and Arizona), only six major earthquakes have occurred over the last 100 years with magnitudes greater than 7 (Stein and Bucknam, 1985). Of these six, two are within the area of this investigation.

In summary, the potential for faults to generate earthquakes in the Ririe

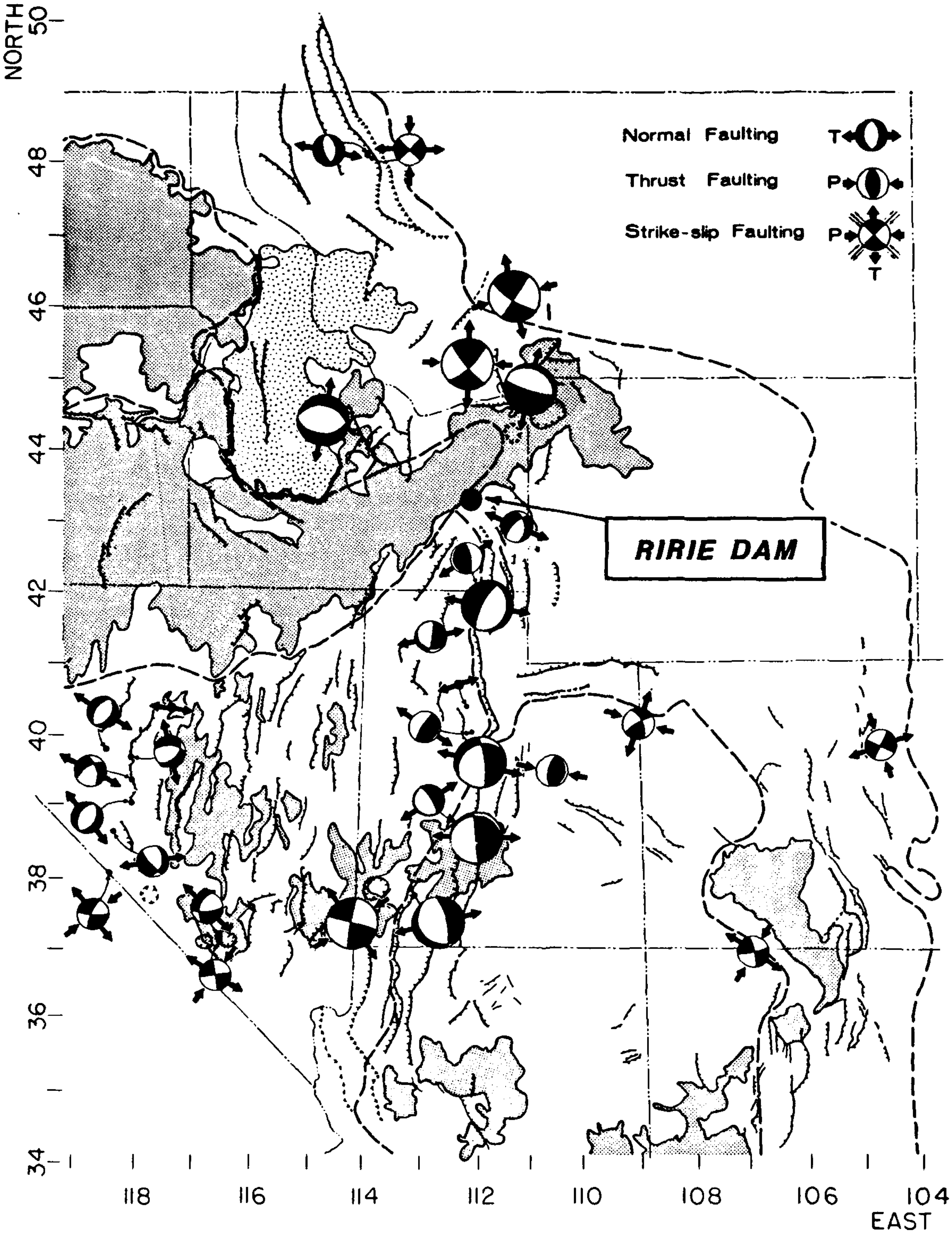


Figure 30. Focal mechanisms of earthquakes in the Intermountain Seismic Belt (from Smith and Sbar, 1974)

Dam are has to be based on geologic and other evidence rather than a reliance on the short record of seismicity. Nonetheless, the seismic history shows that the faults in this area have been generating major earthquakes and are capable of doing so in the future.

Microearthquakes

Distribution

Microearthquakes are small earthquakes, too small to be felt, but may be recorded by sensitive instruments. Such events are useful for interpreting tectonic activity in an area. Microearthquakes are useful in identifying and defining important crustal characteristics. These include areas where crustal stresses are concentrated, the patterns of earthquake focal depths, the geometry of major geologic structures, a clue to rates of earthquake occurrence, and identification of mechanisms of fault movement.

Numerous studies of microearthquake activity have been conducted for the Snake River Plain and for the northern Basin and Range, but the most detailed monitoring program for the region was conducted by the Bureau of Reclamation for Palisades Dam (Piety, et al., 1985). Their monitoring program initially covered the Caribou, Snake River, and Salt River Ranges, the Grays Lake region, and the boundary with the Snake River Plain, including the Ririe Dam area. The Bureau's monitoring program covered a total area of approximately 10,000 square km (3,860 square miles) for a period of 60 days during the summer of 1982. Their network was twice reorganized during this initial monitoring program to respond to areas of pronounced microseismicity. In its final configuration, the network encompassed only a portion of the Snake River Valley.

A second, less extensive monitoring program was initiated in the winter of 1983 following the occurrence of a magnitude 4.2 earthquake less than 3 km south of Palisades Dam. No damage was done to the dam. More than 60 small aftershocks were recorded during this monitoring program following the main shock.

Approximately 600 microearthquakes were reported from both monitoring programs with a location accuracy of less than 4 km (2.5 miles). The patterns produced by microearthquakes from the Bureau's monitoring activity are shown in Figure 31 (from Piety et al., 1985). Also shown is the major Quaternary

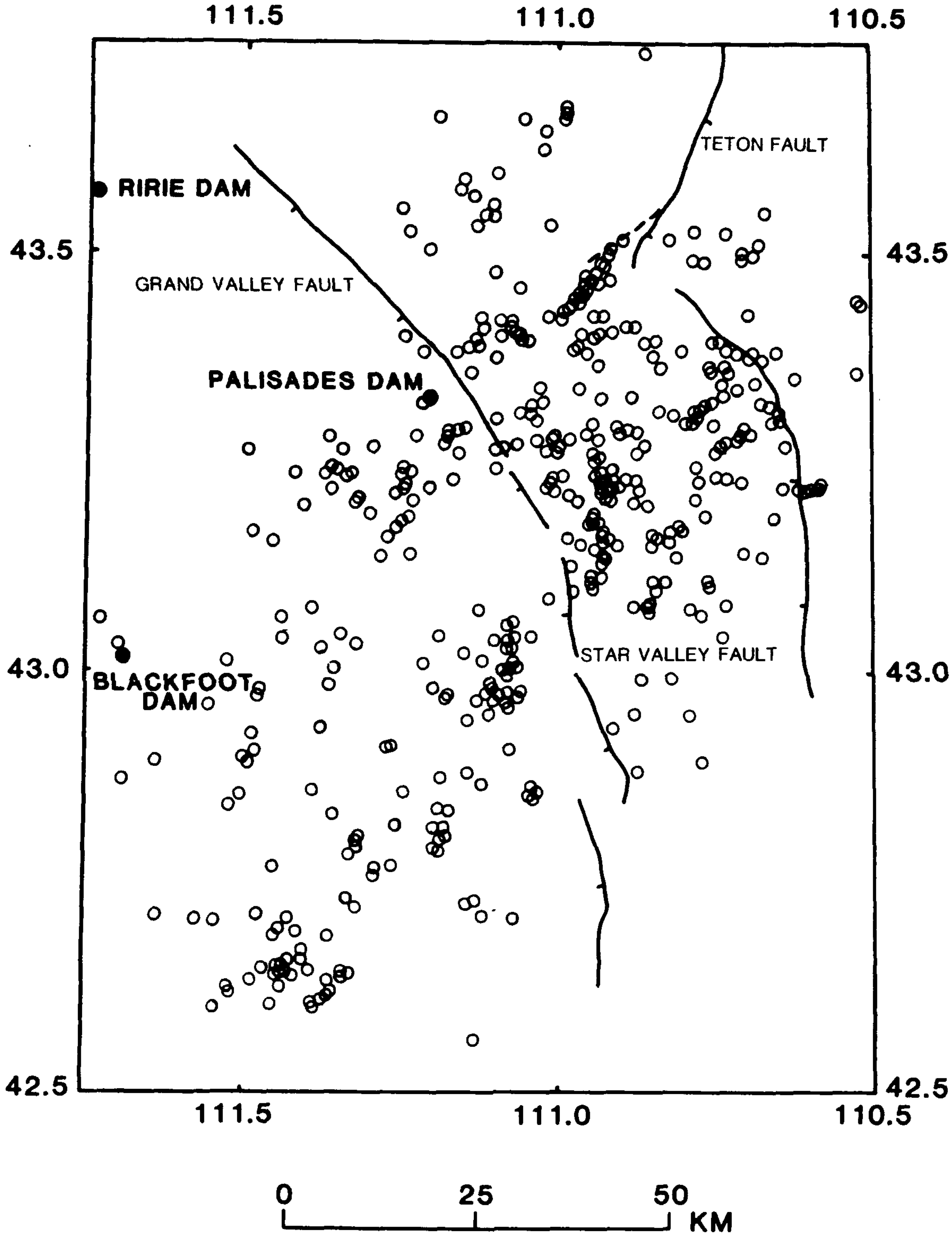


Figure 31. Earthquake epicenters recorded during 1982 and 1983 Bureau of Reclamation studies on Palisades Dam. Epicenters have a location uncertainty of less than 4 km (from Piety et al., 1985)

faulting described by Witkind (1975a and 1975b). The general pattern of microearthquakes is oriented northeast-southwest and northwest-southeast.

The Bureau concluded from their limited monitoring program that the distribution of earthquake epicenters did not generally reflect locations of mapped Quaternary faults and that seismicity was "diffused and scattered." Two possible exceptions were noted. First, a possible linear trend was identified for the southern end of the Teton fault (fault No. 34 from Witkind, see Figure 11), and second, the aftershocks associated with the magnitude 4.2 earthquake near Palisades Dam were located down-dip of and possibly associated with the Grand Valley fault.

The occurrence of earthquake activity as a result of reservoir loading at Palisades Dam was considered in an earlier paper by Schleicher (1975). He concluded after examining the local seismicity for the period 1960 to 1969, that seasonal reservoir fluctuations were causing induced seismicity. It is unknown whether the magnitude 4.2 earthquake recorded above is related to reservoir loading or crustal disparities. Schleicher cites two cases where M = 6+ earthquakes were attributed to reservoir loading.

The general pattern of microseismicity established by the Bureau's brief monitoring program indicated that the Grand and Star Valley faults (fault No. 20, 21, and 22) were not readily distinguishable on the basis of seismicity alone, even though this fault trend shows pronounced Holocene scarps. The Bureau concluded that this lack of correlation is caused either by too short an observation period, or that microseismicity for this area is not a precise indicator of active faults.

Other monitoring programs of microseismicity include work by King and Doyle (1983). Microearthquake monitoring of the eastern plain has been going on since 1971. King and Doyle reported results obtained between 1972 and 1982. Seismic activity is sharply diminished near and almost entirely absent on the Snake River Plain. Seventy-eight events were located by their array from which 59 events were located outside of the Snake River Plain. As mentioned earlier, the aseismicity of the Snake River Plain has been attributed to aseismic creep by plastic deformation under conditions of high crustal heat (Pennington et al., 1974 and King and Doyle, 1983).

Focal Depth of Microearthquakes

Focal depths for the earthquakes in the ISB are mostly 20 km or less.

The frequency distribution of 350 earthquakes between 1961 and 1970 is shown in Figure 32 (from Smith and Sbar, 1974). The full range of focal depths for the ISB extends to 45 km.

Closer to Ririe Dam, the Bureau examined the distribution of focal depths from their monitoring programs in 1982 and 1983 at Palisades Dam. Using only those depths that were from data that could be calculated accurately, approximately 10 percent of the Bureau's data set, they determined that the majority of events occurred at focal depths less than 10 km. An abrupt decrease in events occurred at 10 to 12 km and below 16 km there were no events recorded.

In an earlier study by Dixon (1982) of the Western Overthrust Belt using seismic reflection profiles, listric faulting (curvilinear and usually concave upward) was identified throughout the Paleozoic sediments comprising the Grand Valley graben (see Figure 10 and Figure C6, Appendix C). Listric faulting generally did not extend into the underlying basement rock. In contrast, the hypocenter depth plots for the microearthquake data from Palisades Dam were determined to extend into the basement rock using several different velocity models. Microseismic monitoring at Palisades Dam defined earthquake activity that extended deeper into the crystalline basement rocks than was previously thought. Basement rock near Ririe and Palisades Dams occurs at depths of less than 10 km. Seismic activity extends well below this level as shown by Figure 33 (from Piety, et al., 1985, sections after Dixon, 1982). As shown by the three sections, seismic monitoring identified possible fault zones that extended into the basement rocks.

The identification of earthquakes in the basement rocks near the dam suggests that appreciable stress drops can be produced. Large stress drops are necessary for producing large earthquakes such as those that occurred at Hebgen Lake and Borah Peak.

Recurrence

The recurrence of earthquakes in the ISB has been defined by Smith and Sbar (1974) as

$$\text{Log } N = 6.4 - 1.06\,M$$

where N is the number of earthquakes and M is the Richter magnitude. Their

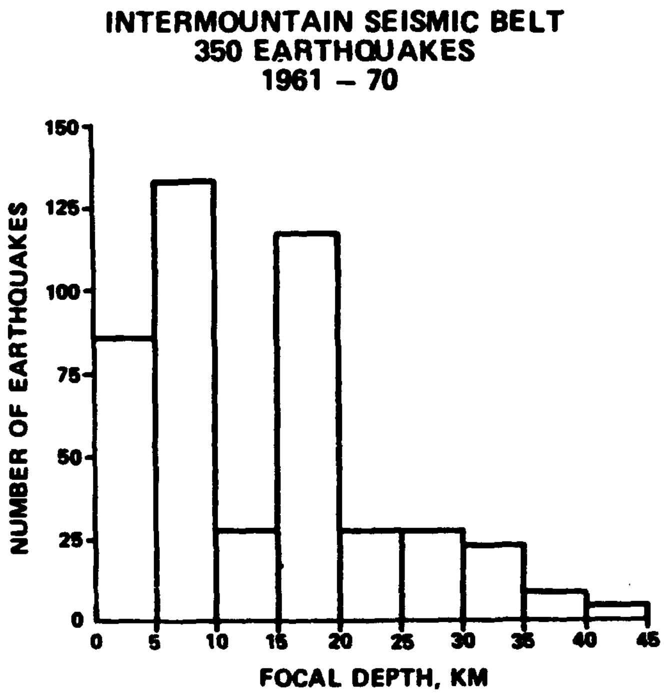


Figure 32. Histogram of focal depths of felt earthquakes, 1961-1970, in the Intermountain Seismic Belt (from Smith and Sbar, 1974)

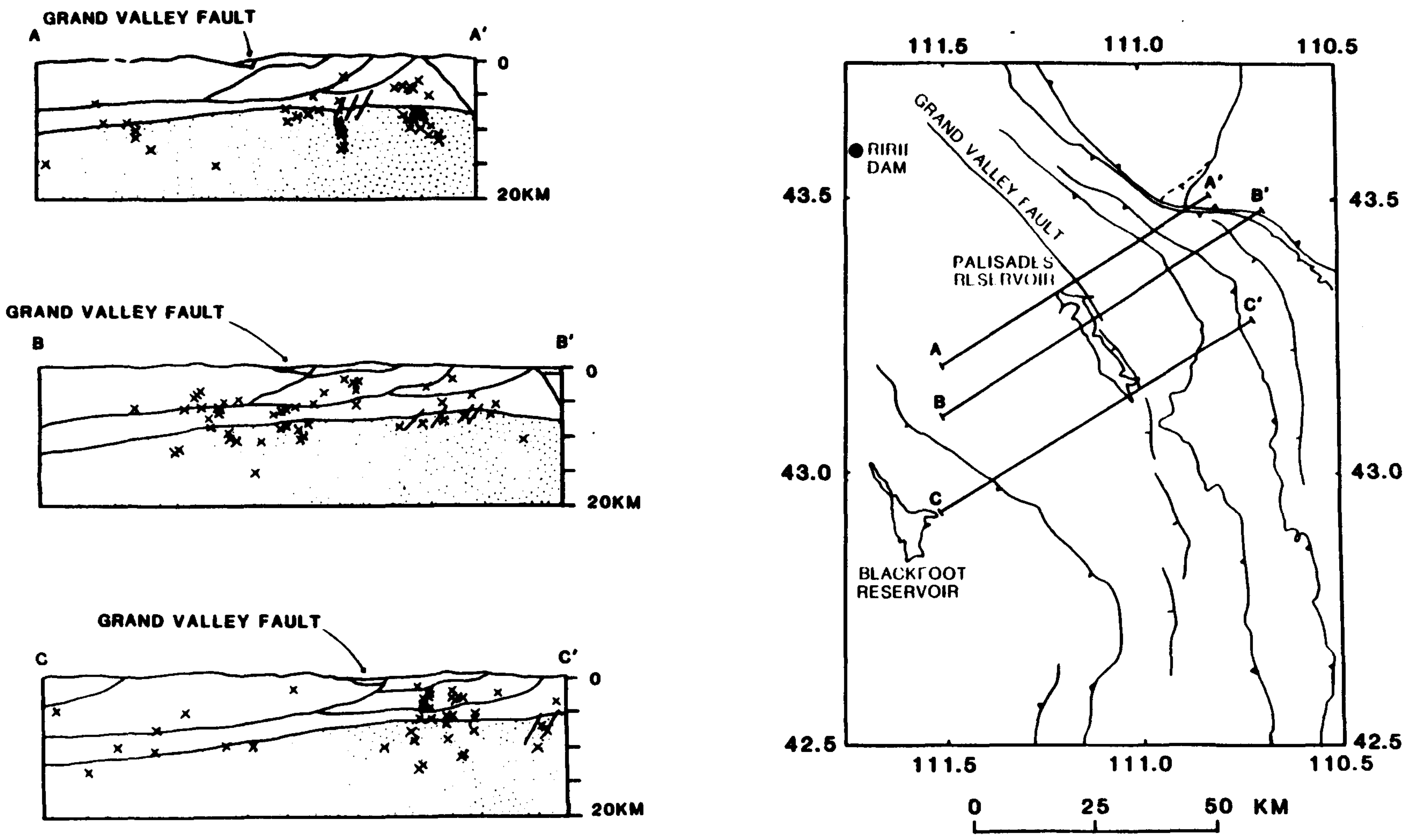


Figure 33. Geology and focal depths from microearthquake monitoring near Palisades Dam (after Piety et al., 1985; geology from Dixon, 1982)

plot is based on 350 earthquakes of magnitude 3 or greater between 1961 to 1970. Smith and Sbar calculated a b value of 1.06. The Bureau of Reclamation calculated a b value of 0.96 for the portion of the ISB that they studied, approximately a 55,000 square km area in the tri-state area of Idaho, Wyoming, and Utah (Piety et al., 1985).

The Bureau's recurrence estimates for Palisades Dam are based on magnitude 3 and larger earthquakes beginning with events occurring after 1873. The various scales of magnitude and intensity in the historic record were converted to a common magnitude scale using empirical relationships. A cumulative annual recurrence relation is presented in Figure 34 and is based on 240 events. The data defines the relation between the number of events of a given M_L per unit of time (years). The basic assumption made in constructing this recurrence curve is that earthquakes were evenly distributed in the ISB. Extending this assumption further, the earthquakes were taken to be evenly distributed for smaller subgroups such as the 55,000 square km area examined by the Bureau.

The magnitude-recurrence curve is shown plotted in Figure 34 with the average data point in each interval and the range in the 95 percent confidence levels (identified by the vertical bars) for each magnitude interval. The Bureau of Reclamation's report on Palisades Dam points out that considerable uncertainty occurs in each magnitude interval. This fact is very apparent for a magnitude 6.5 earthquake. The statistical probability of this magnitude earthquake occurring ranges from 40 to over 1000 years with the average value at nearly 100 years.

For the Ririe Dam area, the occurrence of moderate to major earthquakes within the confines of the study area (200 km radius) is significant. As indicated earlier, there were six earthquakes of MM VII, three of MM VIII and two of MM X. The two MM X (magnitude 7 plus) earthquakes occurred in a time span of less than 30 years, in an area where the probability of occurrence, by extrapolation of the curve in Figure 34, predicts only one event of magnitude 7 plus at approximately 1000 years.

In summary, the probability of recurrence for a major event at Ririe Dam cannot be estimated statistically because of the extremely short and incomplete historic record.

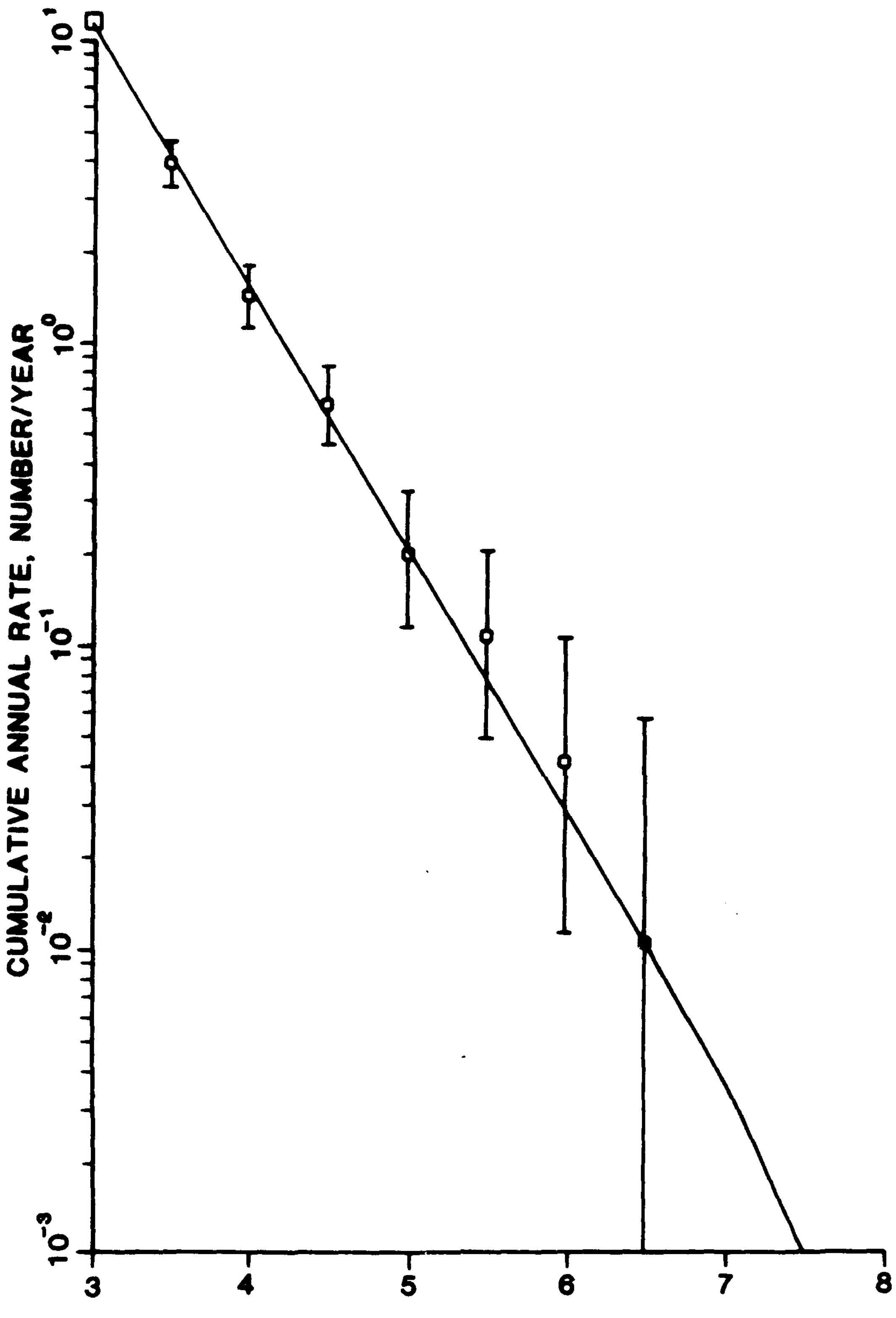


Figure 34. Cumulative recurrence relation for area of approximately 55000 square kilometers (between 110 - 113 degrees West Longitude and 41- 44 degrees North Latitude). The cumulative relation indicates the annual number of events of M_L or larger (from Piety et al., 1985)

Earthquakes Felt at Ririe Dam

A list of historic earthquakes that can be interpreted as having been felt at Ririe Dam is presented in Appendix D. These are moderate to major earthquakes, greater than MM VI, that have occurred over approximately the last 100 years. Included with this listing of earthquakes are the epicentral distances for each event from the damsite and the attenuated intensities. The intensities felt at the damsite were estimated using the "Cordilleran Province" intensity attenuation curves from Chandra (1979).

The most severe earthquake felt at the damsite is judged to have been the Hebgen Lake, Montana, earthquake of 1959 which was MM X at its epicenter 145 km to the north of Ririe Dam and MM VIII at the damsite. This earthquake was felt over an area of approximately 1,554,000 square km (600,000 square miles). The other MM X earthquake occurred at Borah Peak in 1983 and is judged to have been felt at Ririe Dam as an MM VII event. The nearest moderate intensity earthquake, MM VI, occurred 62 km due east of the damsite and is judged to have been felt as an MM V event (see Figure 9 for location).

PART IV: EARTHQUAKE MOTIONS AT RIRIE DAMSITE

Recommended Peak Motions

Maximum Credible Earthquake

The major active faults in the area under investigation are shown on Figure 11 and are summarized by Figure 13. It is an area in which tectonic activity is so great that all Cenozoic faults, whether they have been mapped as active or not, must be regarded as being active and capable of generating earthquakes.

In a general sense, the severity of an earthquake is in proportion to the size of fault rupture, where the greater the surface rupture, the greater the earthquake. The problem with this relationship is that there is an enormous dispersion in the data. Recent charts by Bonilla (1983), see Figure 35, show the general relationships between fault displacement, length of surface rupture along faults, and earthquake magnitude. The dispersion in the data is one to two orders of magnitude and there is no significant relation in these curves as to type of faulting, whether normal, reverse, or strike-slip. The best that can be done is to treat these relationships in a reasonably encompassing way.

Reference to Figures 11 and 20 shows two trends in faulting near Ririe Dam that show Quaternary offset. The first of these trends is identified on Figure 20 and consists of several short fault segments oriented in a general northeasterly direction. The maximum fault length that can be mapped is only 5.6 km (3.4 miles). A fault length of 10 to 15 km (6 to 9 miles) is probably a more realistic and a conservative assumption for local faulting in this area (Slemmons and Ramelli, 1986). A fault length of 10 to 15 km by the curves by Bonilla indicate an earthquake of magnitude $M_s = 7.0$.

The second pattern of faulting identified near Ririe Dam consists of the regional pattern of northwesterly trending faults (see Figure 11). These faults include the bounding faults of the Grand Valley or Snake River graben, that is the Grand Valley (No. 22), Star Valley (No. 20 and 21), and Snake River (No. 23) faults, and those faults extending onto the Snake River Plain, the Heise-Rexburg fault (No.98). The latest movement along fault segments of the Grand Valley graben ranges from the late Tertiary to the late Holocene. The faults along this entire zone are regarded as active and capable of generating

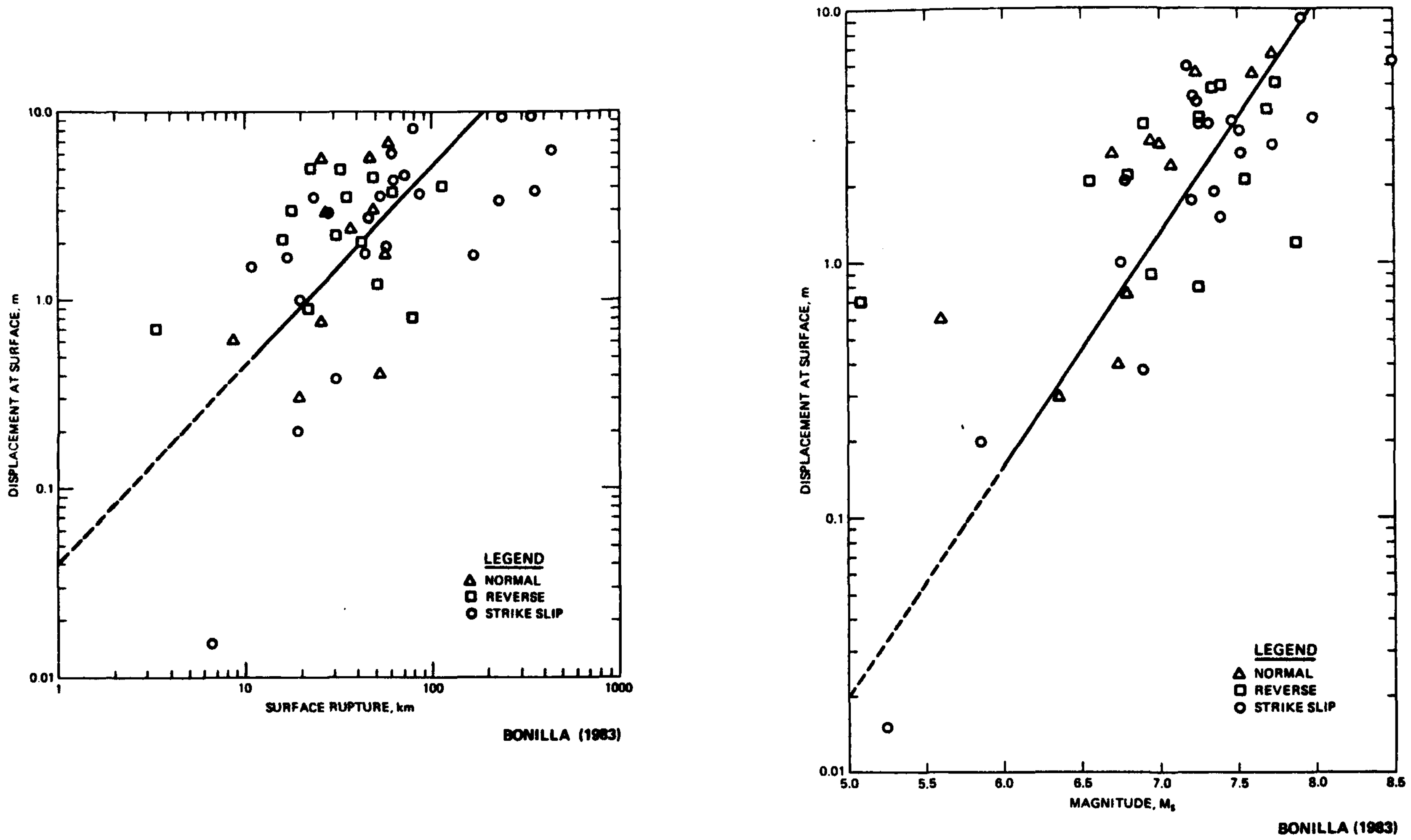


Figure 35. Relations between displacement at surface, length of surface fault rupture, and earthquake magnitude, M_s (from Bonilla, 1983)

earthquakes.

The length of mapped fault segments in the Grand Valley graben varies from 20 to 90 km (13 to 56 miles). It does not follow that movement during an earthquake would be restricted to only an individual segment. Assuming a length of 50 km (31 miles), inclusive of movements along several segments orparts of segments, the Bonilla charts would provide an interpreted magnitude of $M_s = 7.5$.

Field Conditions

In terms of earthquake intensity using the Modified Mercalli (MM) scale, ground motions from the above identified sources and felt at Ririe Dam should be regarded as of two general types: near field and far field. Near field sources are characterized by a large range and high values for peak motions. The near field contains complex reflection and refraction patterns, resonance effects, impedance mismatches and high frequency components of motion. In contrast, far field conditions reflect more orderly wave patterns, lower peak motions and more predictable values.

The relationship between earthquake magnitude (M_s), epicentral intensity (I_o), and limits of the near field are given in the following set of relations (from Krinitzsky and Chang, 1977).

M_s	MM Maximum Intensity, I_o	Radius of Near Field, km
5.0	VI	5
5.5	VII	15
6.0	VIII	25
6.5	IX	35
7.0	X	40
7.5	XI	45

Attenuation of MM intensity can be done by using curves from Chandra (1979) that are presented in Figure 36. The curve for the Cordilleran Province was selected for prediction of the attenuated intensities at Ririe Dam from the above sources.

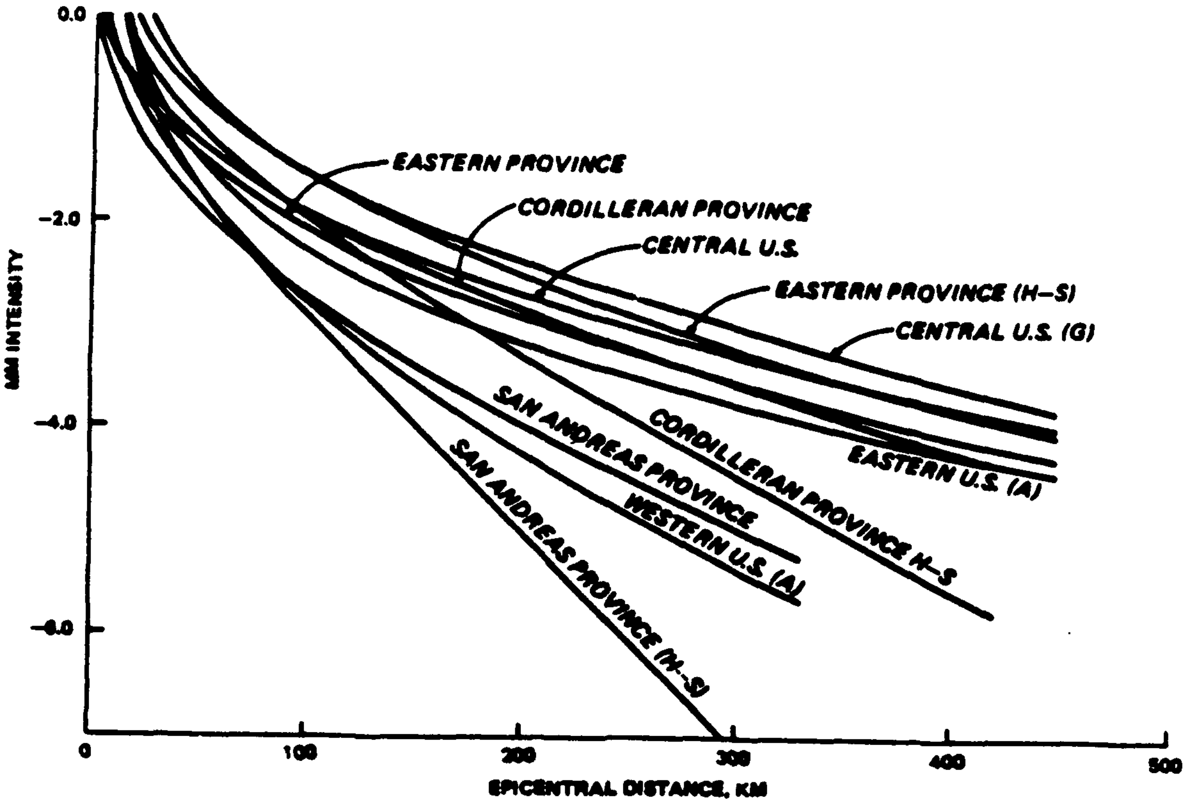


Figure 36. Attenuation of MM intensities with distance (A=Anderson; G=Gupta; H-S=Howell-Schultz, from Chandra, 1979)

Peak Motions

Peak motions for the appropriate MM intensity at the Ririe damsite were obtained from a series of charts by Krinitzsky and Chang (1988). These charts relate MM intensity to the principal parameters for horizontal motion: acceleration, velocity, and duration. The charts are based on a selected collection of 1,000 accelerograms for which values were calculated for the mean, mean plus one standard deviation, and the mean plus two standard deviations for the observed range in MM intensities. The charts were prepared for near field and far field, and for hard and soft sites. The level of motions recommended for Ririe Dam are presented below and are taken at the mean plus one standard deviation or 84 percentile. The 84 percentile is regarded as a level that puts one in a conservative position. Figures 37 and 38 present the relations between MM Intensity and acceleration, velocity, and duration, respectively, for a hard site in the near field and a hard site in the far field. Values for the respective source areas and field conditions are as follows:

Earthquake Source (Distance from Site to Source)	MM Intensity Source (I_o)	Site (I_s)	Acceleration Mean + 1S.D. (cm/sec^2)	Velocity Mean + 1S.D. (cm/sec)	Duration Mean + 1S.D. (sec.$\geq$0.05g)
Local Source Near Field (Vicinity)	IX	IX	1200	68	22
Grand-Swan Valley Near Field (4-10 km)	X	X	1200	120	33
Grand-Swan Valley Far Field (80 km)	X	VIII	280	25	65

The above parameters are suitable for shaping time histories for use in dynamic analyses.

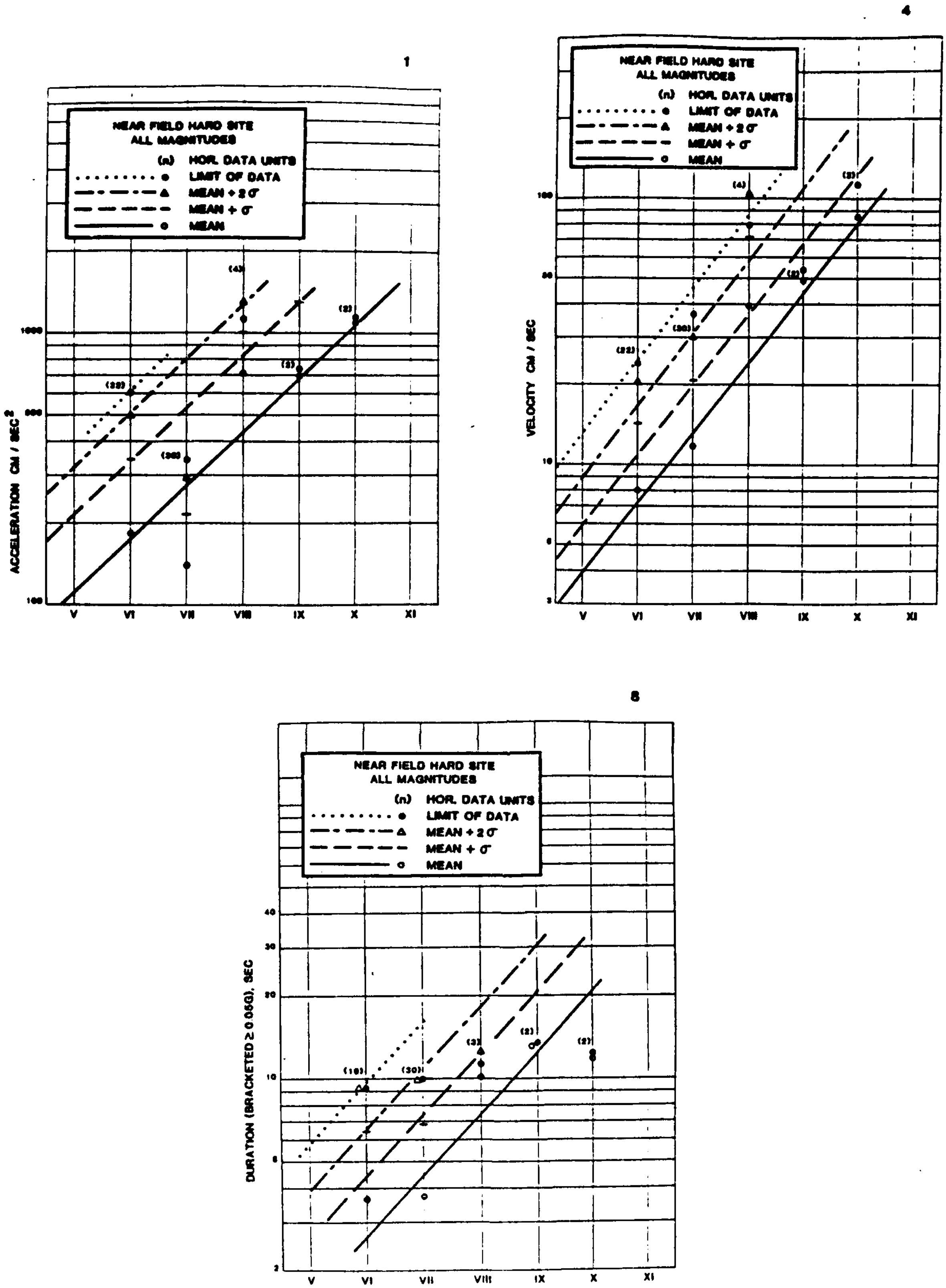


Figure 37. Relations between MM Intensity and acceleration, velocity, and duration in the Near Field, Hard Site (from Krinitzsky and Chang, in press)

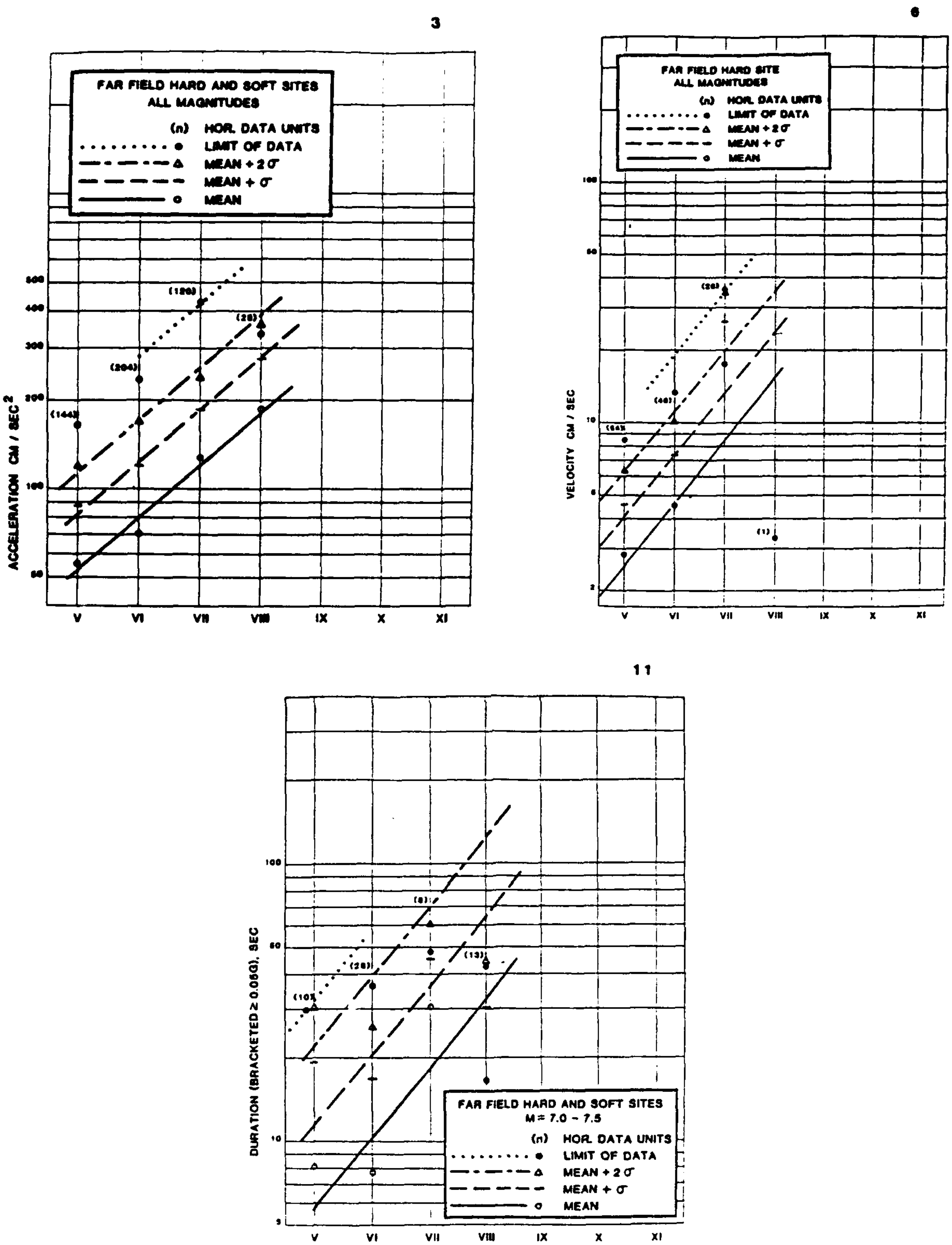


Figure 38. Relations between MM Intensity and acceleration, velocity, and duration in the Far Field, Hard Site (from Krinitzsky and Chang, in press)

Operating Basis Earthquake

The operating basis earthquake at Ririe Dam cannot be related to the probability of recurrence since the historic data are insufficient for calculating probabilities. A reasonable alternative may be to relate the operating basis earthquake to the severest shaking felt at the damsite during the past 100 years. Appendix D shows that MM Intensity VIII is the severest that has been experienced at the damsite. The shaking resulted from the 1959 Hebgen Lake earthquake which was interpreted to be $M_L = 7.7$ by Bolt (see Appendix D of this report). The Hebgen Lake earthquake occurred at a distance of 145 km from the Ririe damsite. Using the Krinitzsky and Chang charts in Figure 37 for the far field at the mean plus one standard deviation, yields values for peak acceleration of 280 cm/sec^2, velocity of 25 cm/sec and duration of 65 sec.

PART V: CONCLUSIONS

The geologic and seismic evidence indicates that Ririe Dam is in an area of active faults capable of generating severe earthquakes. Local faulting has been identified near the damsite. The local faulting is interpreted to be capable of producing an earthquake of $M_s = 7.0$ and MM intensity of IX. Another earthquake can be postulated for the Grand Valley or Snake River graben, a fault-bounded valley nearly 100 km in length which lies at 4 to 10 km from the damsite. Pleistocene and Holocene age faults have been identified for fault segments within the Grand Valley graben. The entire zone is interpreted as active. The zone is capable of producing earthquakes of M_s = 7.5. A distant earthquake along this zone is taken at 80 km. Motions for maximum credible earthquakes originating from these three sources are as follows:

Earthquake Source (Distance from Site to Source)	MM Intensity Source (I_o)	MM Intensity Site (I_s)	Acceleration Mean + 1S.D. (cm/sec^2)	Velocity Mean + 1S.D. (cm/sec)	Duration Mean + 1S.D. (sec. $\geq$ 0.05g)
Local Source Near Field (Vicinity)	IX	IX	1200	68	22
Grand-Swan Valley Near Field (4-10 km)	X	X	1200	120	33
Grand-Swan Valley Far Field (80 km)	X	VIII	280	25	65

An operating basis earthquake is based on motions appropriate to the severest shaking experienced at the damsite during the past 100 years. These motions correspond to a far field MM Intensity VIII with values for peak acceleration of 280 cm/sec^2, velocity of 25 cm/sec, and duration of 65 sec.

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Table 1

Description of Major Active Faults in the General Region of Ririe Dam From Witkind (1975a, 1975b). See Figure 11.

Fault No.	Name	Latest Movement (Age)	Type	Relative Movement	Length	Earthquake Potential	Remarks
1	Wasatch Fault	Late Quaternary	High angle normal	West side down	Major	High-prbably major eqk (7+)	Many scarps, 1/4 mile each side of main scarp. Northern edge of Wasatch fault.
2	Cache Valley Fault (West Cache Fault)	Probably latest Quaternary (faulting older than Wasatch)	High angle normal north trending fault	East side down	Many miles	Great	Many small scarplets, 1/4 mile each side.
3	Clifton-Oxford Fault	Late Quaternary	High angle normal	East side down	About 8 miles	Great	Many small scarplets and branches.
5	Unnamed						No data available. Identified on Witkind Map as Fault No. 5
16	Rock Creek Fault	Historic-100 years old	High angle normal	Down-thrown on west	24-25 miles	High	One scarp. Indications that fault has moved in past 100 years. Scarps 50-60 ft in alluvium.
17	En Echelon Series of faults	Late Cenozoic	High angle normal	Down-thrown on west	25 miles +	Low to moderate	En Echelon Series

(continued)

Table 1

Description of Major Active Faults in the General Region of Ririe Dam From Witkind (1975a, 1975b). See Figure 11.

Fault No.	Name	Latest Movement (Age)	Type	Relative Movement	Length	Earthquake Potential	Remarks
18	Unnamed fault, west side of Sublette Ridge	Late Cenozoic	High angle normal	Down-thrown valley-side (west side down)	45 miles ±	High	No modern movement. Connects with fault in UT along west front of Crawford Mountains.
19	Unnamed fault, west side Bear River Valley, east side Boundary Ridge, west of Cokeville	Late Cenozoic	High angle normal	East side (valley) down-thrown	About 10 miles	Low to moderate	No modern scarplets.
20	Star Valley Faults (North Star Valley Fault) determine west flank of Salt River Range	Cuts Holocene beds	High angle normal	West side (valley) down-thrown	Many miles	High	Modern scarplets. This fault connects with North Swan Valley fault.
21	Star Valley Faults (South Star Valley Fault)	Cuts Holocene beds	High angle normal	West side (valley) down-thrown	± 18 miles	High	Modern scarplet.

(continued)

Table 1

Description of Major Active Faults in the General Region of Ririe Dam From Witkind (1975a, 1975b). See Figure 11.

Fault No.	Name	Latest Movement (Age)	Type	Relative Movement	Length	Earthquake Potential	Remarks
22	Grand Valley Fault	Late Cenozoic	High angle normal	South-west block down (valley side down)	Joins Star Valley fault (No.20)	High	No scarplets, Seismic activity related to Palisades Reservoir.
23	Snake River Fault	Recurrent since Miocene	NE side down-thrown		About 55-60 miles long		No data available. Information from Witkind Surface Map.
24	East side, Bear Lake	Late Quaternary, major movement	High angle normal	West side down	55 to 60 mi, at least	High	Discontinuous fault, extends to Blackfoot Reservoir. Breaks basalt there at least 50,000 yrs old.
25	West side of Bear Lake	Probably major Late Quaternary	High angle normal	East side down-thrown	En Echelon Series of short breaks (55-60 miles)		Extends as far north as Blackfoot Reservoir.
26	Unnamed fault east of Franklin	Major Late Quaternary?	High angle normal, east side of basin	West side down-thrown			This is a major fault bounding the east flank of Cache Valley.

(continued)

Table 1
Description of Major Active Faults in the General Region of Ririe Dam
From Witkind (1975a, 1975b). See Figure 11.

Fault No.	Name	Latest Movement (Age)	Type	Relative Movement	Length	Earthquake Potential	Remarks
27	Clifton Hill Fault	Probably Late Cenozoic	High angle normal	North-east side (valley) downthrown	About 8 miles	Low	
29	Mammoth Fault	Generally breaks travertine, so probably Holocene	High angle normal	NE side down-thrown	8-10 miles	High	Fault butts Gardiner on north and extends into Wyoming - Eastern fault that bounds a graben - Western fault is Reese Creek (Gardiner) #30. Curving - faces NE - trends generally NW
30	Reese Creek Fault (East Gallatin Fault)	Holocene - latest movements cut glacial deposits	High angle normal-determines east face Gallatin Range	East side (valley) downthrown	About 20 miles	High	This fault butts into Gardiner Fault on North. Trends north, dips east
31	Unnamed faults along west side of Samaria Mtn	Holocene	High angle normal	West side down Pocatello Valley (not near Pocatello ID)	6-8 miles	High	Two faults.

(continued)

Table 1

Description of Major Active Faults in the General Region of Ririe Dam From Witkind (1975a, 1975b). See Figure 11.

Fault No.	Name	Latest Movement (Age)	Type	Relative Movement	Length	Earthquake Potential	Remarks
32	East Gem Valley Fault	Late Cenozoic	High angle normal	West side (Gem Valley) downthrown	28-30 miles	Low to moderate	No breaks in surface deposits.
33	West Gem Valley Fault	Late Cenozoic	High angle normal	Northeast side (Gem Valley downthrown)	22-25 miles		
34	Teton normal fault	Pleistocene and Recent movement	High angle normal	East block down	40 miles	High	Some small scarplets cut Pinedale (150-200 ft high).
35	Hoback normal fault	Pleistocene deposits cut Holocene	High angle normal	Southwest block down	35 miles		Scarplets in loess and silt. Scarplets about 50 ft high.
36	Lomar normal fault	Some movement during Quaternary	High angle normal	NE block downthrown	20 miles +	Low	Trends N50^{o} W, dips NE
37	Hering Lake fault system	During Quaternary	High angle normal	East block downthrown	About 10 miles	Low	Two parallel faults - shown as one. Trends about N20^{o} W, dips NE

(continued)

Table 1
Description of Major Active Faults in the General Region of Ririe Dam
From Witkind (1975a, 1975b). See Figure 11.

Fault No.	Name	Latest Movement (Age)	Type	Relative Movement	Length	Earthquake Potential	Remarks
55	Idaho Rift system	Holocene	Extensional	Gaps in fractures-extensional movement NE-SW	Three sets in Rift system - Northern one Craters of the Moon-Middle one Kings Bowl Rift set - Southern one Wapi Rift set	Low	Probably west - trends N35° W
56	Rockland Valley fault - west flank of Deep Creek Mtns	Late Cenozoic	High angle normal, dips valleyward (SW)	SW side downthrown	30 miles ±	Low to moderate	Trends about N20° W, dips SW
57	Unnamed-east side of Deep Creek Mountains	Late Cenozoic	High angle normal, dips valleyward, east side down	East side downthrown	40 miles	Low to moderate	
58	East side of Bannock Creek Valley	Late Cenozoic	High angle normal, dips valleyward	West side downthrown	12 miles	Low to moderate	

(continued)

Table 1

Description of Major Active Faults in the General Region of Ririe Dam From Witkind (1975a, 1975b). See Figure 11.

Fault No.	Name	Latest Movement (Age)	Type	Relative Movement	Length	Earthquake Potential	Remarks
59	East side Arbon Valley	Late Cenozoic	High angle normal, dips valley-ward	North-west side down-thrown	40-45 miles	Low to moderate	No mapping done in this general area.
60	Woodruff fault, north edge of Samaria Mountains	Probably major: Late Quaternary	High angle normal	Down-thrown on north	About 7 miles		May be strike-slip.
61	Unnamed fault, west side Bannock Range	Late Cenozoic	High angle dipping valley-ward	West side down-thrown	8 miles ±		
62	Unnamed in-ferred fault, west side of Rattlesnake Creek Valley	Late Cenozoic	High angle normal, dips valley-ward	East side down-thrown	About 8 miles	Low to moderate	
63	Unnamed fault, west side Marsh Creek valley	Late Cenozoic-Pliocene	High angle normal, dips valley-ward	East block down-thrown	32 miles ±	Low to moderate	

(continued)

Table 1

Description of Major Active Faults in the General Region of Ririe Dam
From Witkind (1975a, 1975b). See Figure 11.

Fault No.	Name	Latest Movement (Age)	Type	Relative Movement	Length	Earthquake Potential	Remarks
64	Unnamed fault, Rapid Creek Fault?	Late Cenozoic-Pliocene	High angle normal, dips valley-ward	East side down-thrown	About 8 miles	Low	
65	Unnamed fault, along east side of Marsh Creek	Late Cenozoic-Pliocene	High angle normal, dips valley-ward	South-west block down-thrown	65 miles	Moderate	
66	Unnamed fault along NW flank Hell's Half Acre (West of Idaho Falls)	Holocene	Exten-sional system		About 5± miles	High	Vent fissure, trends about N60° W
67	Unnamed fault - west flank Raft River Valley	Late Cenozoic	High angle normal	East side down-thrown	15 miles	Moderate	Considerable uncertainty about age of these faults - some ground breakage due to water withdrawal. Trends about N20° W, dips NE
68	Unnamed fault - West side Raft River Valley	Major Late Quaternary	High angle normal	East side down-thrown	8-10 miles		Geothermal area alluvial fans broken by faults. Trends north, dips east
69	Unnamed fault along west flank Strevell Range	Late Cenozoic	High angle normal	West side down-thrown	17-18 miles		Uncertain of age of fault. Spring at very northern tip of fault. Trends north, dips west

(continued)

Table 1

Description of Major Active Faults in the General Region of Ririe Dam
From Witkind (1975a, 1975b). See Figure 11.

Fault No.	Name	Latest Movement (Age)	Type	Relative Movement	Length	Earthquake Potential	Remarks
70	Unnamed fault near Oakley	Late Cenozoic	High angle normal	NE side down-thrown	16 miles ±	Low	Recent ground breakage along fault trace possibly due to water withdrawal by pumping. Several springs along fault trace have stopped flowing. Trends N35^{o} W, dips NE
73	Unnamed fault - Dry Fork Creek	Cuts alluvial fans - Probably Late Quaternary	High angle normal	Down-thrown on northeast	4 miles		Continuation to NW of Rift Zone. Trends N30^{o} W, dips NE
74	Unnamed fault - Dry Fork Creek	Cuts alluvial fans - Probably Major Late Quaternary	High angle normal	Down-thrown on east	5 miles		Trends due north, dips east
75	Unnamed fault - Antelope Creek	Cuts alluvial fans - Probably Major Late Quaternary	High angle normal	Down-thrown on NW	5 miles		Trends N50^{o} E
76	Unnamed - southern one in Cherry Creek	Cuts alluvial fans - Probably Major Late Quaternary	High angle normal	Down-thrown on SW	3 miles		Trends N35^{o} W, dips SW
77	Unnamed - north fault in Cherry Creek	Cuts alluvial fans - Probably Major Late Quaternary	High angle normal	Down-thrown on NE	3 miles		Despite being in Cherry Creek, it does not dip same way fault further south does (fault #76). Trends N35^{o} W, dips NE.
78	Unnamed - west of North Chapin Mtn	Late Cenozoic	High angle normal	Down-thrown on west	About 5 miles		Uncertain whether fault is present. Trends north, dips west (Valleyward)

(continued)

Table 1

Description of Major Active Faults in the General Region of Ririe Dam From Witkind (1975a, 1975b). See Figure 11.

Fault No.	Name	Latest Movement (Age)	Type	Relative Movement	Length	Earthquake Potential	Remarks
79	Unnamed - west side of Sublett Range	Probably Late Cenozoic	High angle normal	Down-thrown on west	22 miles		Uncertain whether fault is present. Several hot springs (Hot Springs and Butter Spring) suggest its presence. Trends about N20°E, dips west (curving fault
80	Unnamed - along east flank Sublett Range	Probably Late Cenozoic	High angle normal	Down-thrown on east	25 miles		No mapping in area. About N10°W, dips NE.
84	Enoch Valley Fault (En Echelon Series)	Probably Late Cenozoic	High angle normal	Southwest flank down	30 miles		
85	Lime Rock Fault (En Echelon Series)	Probably Late Cenozoic	High angle normal	Northeast block down	About 30 miles		
86	Unnamed fault, east side of Little Gray Ridge	Probably Late Cenozoic	High angle normal	Southwest side down-thrown	13 miles (En Echelon)		
87	Unnamed fault along west side Teton River Valley	Probably late Cenozoic	High angle normal	Down on NE		Moderate	Trends N30° W, dips NE

(continued)

Table 1

Description of Major Active Faults in the General Region of Ririe Dam From Witkind (1975a, 1975b). See Figure 11.

Fault No.	Name	Latest Movement (Age)	Type	Relative Movement	Length	Earthquake Potential	Remarks
98	Heise Fault	Major Late Quaternary	High angle normal	Southwest block downthrown	20-21 miles	Low to moderate	
99	Unnamed Cottonwood Creek (South flank Centennial Mtns)	Probably Major Quaternary	High angle normal	East side down	9 miles	Low	Trends about N30°W, dips NE
100	Unnamed - Along NE side West Camas Creek (Centennial Range)	Probably Major Quaternary	High angle normal - dips SW-SW down	SW side down	About 17 miles	Low	About N65°W, dips SW
101	Unnamed - along SW flank Camas Creek	Probably Major Quaternary	High angle normal	NE side downthrown	7 miles	Probably low	Trends about N40°W, dips NE
102	Unnamed	Probably Major Quaternary	High angle normal	NE side down	6 miles	Low	Trends about N40°W, dips NE
103	Unnamed	Probably Major Quaternary	High angle normal	NW side down	18 miles	Low	Trends N20°E, dips NW
104	Unnamed	Probably Major Quaternary	High angle normal	SW side downthrown	About 13 miles	Low	Trends about N70°W, dips SW
105	Unnamed	Probably Late Cenozoic	High angle normal	SE side down	About 18 miles	Low	Trends about N60°E, dips SE

(continued)

Table 1

Description of Major Active Faults in the General Region of Ririe Dam
From Witkind (1975a, 1975b). See Figure 11.

Fault No.	Name	Latest Movement (Age)	Type	Relative Movement	Length	Earthquake Potential	Remarks
106	Unnamed - Near Poison Gulch	Probably Major Quaternary	High angle normal	SE side down	About 7 miles	Low	Trends about N50^{o}E, dips SE
107	Unnamed - Near Lidy Hot Springs	Probably Major Quaternary	High angle normal	Down on west	About 16 miles	Low	Curving - trends N-NW, dips west
108	Unnamed - In Chandler Canyon	Probably in Major Quaternary	High angle normal	SW side down	13-15 miles	Low	Trends about N35^{o}W
109	Unnamed	Probably Major Quaternary	High angle normal	NE side down-thrown	About 7 miles	Low	Trends N25^{o}W, dips NE
110	Unnamed	Probably Major Late Quaternary	High angle normal	South side down	About 5 miles	Low	Fault may be Major Quaternary. Trends west.
111	Unnamed	Probably Major Quaternary	High angle normal	South side down-thrown	5 miles	Low	Trends west, dips south
112	Applies to a series of NW trending faults along SW flank of Beaverhead Mtns	Probably Major Late Quaternary	High angle normal	SW flank down	Many miles		Trends about N40^{o}W, dips SW

(continued)

Table 1

Description of Major Active Faults in the General Region of Ririe Dam From Witkind (1975a, 1975b). See Figure 11.

Fault No.	Name	Latest Movement (Age)	Type	Relative Movement	Length	Earthquake Potential	Remarks
113	Unnamed series of N-S trending faults that break NW-trending faults which bound Beaverhead Mtns	Probably Major Late Quaternary	Vertical strike-slip	Right lateral	Ranges from a few to many miles	Slight	Trends north - vertical
114	Unnamed fault - near Gilmore	Probably Late Cenozoic	High angle normal	NE side down	15 miles		Trends N40°W, dips NE
115	Unnamed series of faults along SW flank Lemhi Range	Probably Major Late Quaternary	High angle normal	SW block down-thrown	Many miles	Moderate to High	Fault scarp along range. Trends about N45°W, dips SW
116	Unnamed fault along SW flank Lost River Range	Probably Major Late Quaternary	High angle normal	SW block down-thrown	Many miles	Moderate to High	Trends N60°W, dips SW
117	Unnamed fault - east flank Jim Sage Mtns	Probably Major Late Quaternary	High angle normal	East block down-thrown	About 10 miles	Low to Moderate	Further west and higher in mountains than #68. Trends slightly east of North, dips valleyward - Eastward
118	Howe Fault	Probably Major Late Quaternary	High angle normal	SW block down-thrown	15-20 miles	Moderate to High	Trends about N60°W - but curves
155	West Gallatin Fault	Uncertain - Late Cenozoic, but may be younger	High angle normal	Down-thrown on west	25 miles ±	Low to Moderate	Trends about N20°E, dips NW

(continued)

Table 1

Description of Major Active Faults in the General Region of Ririe Dam From Witkind (1975a, 1975b). See Figure 11.

Fault No.	Name	Latest Movement (Age)	Type	Relative Movement	Length	Earthquake Potential	Remarks
234	Unnamed	Late Cenozoic	High angle normal	Down on north			
235	Huckleberry Ridge Fault	Cuts Huckleberry Ridge - Late Quaternary	High angle normal	Down on NW			
236	Unnamed	Major Quaternary	High angle normal	Down on east			
237	Unnamed	Major Quaternary	High angle normal	Down on east			
238	Unnamed	Major Quaternary	High angle normal				
293	Unnamed - east of Huckleberry Mtn	Probably Major Quaternary	Normal?	Uncertain	3 miles ±	Low	Trends about N70°W but curves
294	Unnamed fault near Two Ocean Lake	Probably Major Quaternary	High angle normal	NE side down	About 5 miles ±	Low	Convex to NE - trends about N75°W, dips NE

(continued)

Table 2

Characteristics of Thermal Springs near Ririe Dam
(from Mitchell, Johnson, and Anderson, 1980)

County	Map Location	Spring/Well Identification No. and Name	Discharge (ℓ/min)	Aquifer Age and Rock Type	Geologic Structure	Remarks	Gas	Deposition Sili-ceous	Deposition Carbon-ates	Well Depth (m)	Surf. Temp (^oC)	Aquifer Temp. (^oC)
Bingham	1	Yandell Springs 3S 37E 31DBB1S	5677	Pre-Tertiary limestone		Temperature Range 18-32 degrees C					32	35
Bingham	2	Alkali Flats WS 4S 38E 28DDD1S	37	Tufa in Quaternary alluvium			Yes				34	
Bonneville	1	Fall Creek Mineral SPG 1N 43E 8DCD1S	264	Quaternary alluvium with travertine deposits near Paleozoic limestone	Northwest trending fault	Spring vents extending along creek into section 8 and 17; sulfur odor; temperature range 23-25 degrees C	Yes		Yes		25	42
Bonneville	2	Richard Piggot Well 2N 39E 30ADC1									20	
Bonneville	3	Brockman Creek 2S 42E 26DCD1S	49								35	
Bonneville	4	Alpine WS 2S 46E 19CAD1S	94	Quaternary alluvium near Tertiary si-licic volcanics		Spring is now under Pali-sades Reservoir					37	61
Caribou	2	Wilson Lake, WS 5S 41E 6ABB1S				Not field checked; reported to have several spring vents					30	

County	Map Location	Spring/Well Identification No. and Name	Discharge (ℓ/min)	Aquifer Age and Rock Type	Geologic Structure	Remarks	Gas	Deposition Sili-ceous	Deposition Carbon-ates	Well Depth (m)	Surf. Temp (°C)	Aquifer Temp. (°C)
Clark	1	Lidy HS #1 9N 33E 2BBC1S	946	Pre-Tertiary limestone		Travertine deposition near spring vents					51	66
Clark	2	Wilson Bros. Well 9N 33E 2CDC1	3785	Pre-Tertiary limestone						213	50	
Clark	3	Lidy HS Well 10N 33E 35CCC1	6813	Pre-Tertiary limestone	Fault					125	58	68
Clark	4	Lidy HS #2 10N 33E 35CCC1S	189	Pre-Tertiary limestone	Fault						51	
Fremont	1	Keith Jergenson Well #1 7N 41E 13CAB1		Pleistocene sediments and basaltic lava		Not field checked				213	23	
Fremont	2	Keith Jergenson Well #2 7N 41E 13CAD1	4239	Pleistocene sediments and basaltic lava		Drillers log available				213	23	
Fremont	3	Donald Trupp Well 7N 41E 25CBD1	8706	Tertiary silicic vol-canic rock (?)						91	36	94
Fremont	4	Wayne Larson Well 7N 41E 26ACC1				Not field checked; re-ported tempera-tures					22	106
Fremont	5	Gordon Clark Well 7N 41E 33DDD1		Pleistocene sediments and basaltic lava		Drillers log available				73	22	

County	Map Location	Spring/Well Identification No. and Name	Discharge (l/min)	Aquifer Age and Rock Type	Geologic Structure	Remarks	Gas	Deposition Sili-ceous	Deposition Carbon-ates	Well Depth (m)	Surf. Temp (°C)	Aquifer Temp. (°C)
Freemont	6	Henry Harris Well 7N 41E 34ADD1		Tertiary silicic vol-canic rock (?)		Drillers log available				83	34	78
Freemont	7	Newdale City Well 7N 41E 34DCD1	2271	Tertiary silicic vol-canic rock (?)						91	32	81
Freemont	8	7N 41E 35CDD1		Tertiary silicic vol-canic rock (?)		Reported tempera-ture; not field checked			Yes	106	36	84
Freemont	9	Steter and Swindelman 7N 41E 35DCD1		Tertiary silicic vol-canic rock (?)		Drillers log available				100	37	
Freemont	10	Claude Haws Well 7N 41E 36DDA1		Tertiary silicic vol-canic rock (?)						193	34	63
Freemont	11	Dean Swindelman Well 7N 42E 8CAA1		Tertiary silicic vol-canic rock (?)							34	48
Freemont	12	Keith Jergenson Well #3 7N 42E 17BAC1									27	
Freemont	13	Keith Jergenson Well #4 7N 42E 17BBC1									39	
Freemont	14	Keith Jergenson Well #5 7N 42E 18BAA1	8327	Tertiary silicic vol-canic rocks		Drillers log available; not field checked				246	51	

County	Map Location	Spring/Well Identification No. and Name	Discharge (ℓ/min)	Aquifer Age and Rock Type	Geologic Structure	Remarks	Gas	Deposition Sili-ceous	Deposition Carbon-ates	Well Depth (m)	Surf. Temp (°C)	Aquifer Temp. (°C)
Freemont	15	Naomi Jergenson Well 7N 42E 18CAA1		Tertiary silicic vol-canic rocks		Drillers log available; not field checked				201	33	
Freemont	16	Remington Produce Well 7N 42E 19CCA	1892	Tertiary silicic vol-canic rock (?)		Drillers log available; not field checked				193	26	
Freemont	17	Ashton WS 9N 42E 23DAC1S		Pleistocene basalt		Two spring vents					26	91
Jefferson	1	Heise HS 4N 40E 25DDA1S	227	Tertiary silicic vol-canic rock		Two spring; extensive travertine deposition			Yes		49	79
Madison	1	Elkhorn WS 4N 40E 23CAD1S									22	
Madison	2	Lavere Ricks Well 5N 40E 5CBA1		Tertiary silicic vol-canic rocks		Temperature not confirmed; drillers log available				108	21	36
Madison	3	Mark Ricks Well 5N 40E 8BCC1		Tertiary silicic vol-canic rocks		Temperature not confirmed; drillers log available				56	26	44
Madison	4	Pauline Smith Well 5N 40E 9CCC1	12491	Tertiary silicic vol-canic rocks		Temperature not confirmed; drillers log available				135	21	30
Madison	5	Bill Webster Well 5N 40E 36BDB1	10977	Tertiary silicic vol-canic rocks		Drillers log available				405	22	

County	Map Location	Spring/Well Identification No. and Name	Discharge (ℓ/min)	Aquifer Age and Rock Type	Geologic Structure	Remarks	Gas	Deposition Sili-ceous	Deposition Carbon-ates	Well Depth (m)	Surf. Temp (^oC)	Aquifer Temp. (^oC)
Madison	6	Green Canyon HS 5N 43E 6BCA1S		Tertiary silicic volcanic rocks		Several spring vents; also known as Pincock HS; travertine deposits			Yes		44	72
Madison	7	Val Schwendiman Well 6N 41E 1ADD1		Tertiary silicic volcanic rocks		Drillers log available				201	29	
Madison	8	Walz Ent. Inc. Well 6N 41E 10ACC1				Temperature not confirmed					26	81
Madison	9	Wanda Wood Well #1 6N 41E 10BBB1				Temperature not confirmed				80	24	78
Madison	10	Wanda Wood Well #2 6N 41E 10DBB1				Temperature not confirmed					27	80
Madison	11	Bureau of Reclamation 7N 42E 30DBD1		Tertiary silicic volcanic rocks		Drillers log available; Teton dam site				200	34	
Teton	1	Taylor Springs 3N 45E 7BAA1S	946	Triassic Marine Sediments near thrust fault							20	
Teton	2	O. Neely Well 7N 43E 36AAC1		Triassic sediments beneath Cenozoic basalts (?)		Not field checked; temperature range 32-49 degrees C; drillers log available				353	49	

APPENDIX A

GEOLOGY AT RIRIE DAMSITE AND VICINITY

(to accompany Figure 8, from Ross and Forrester, 1947)

Quaternary

Qal Alluvial deposits - Unconsolidated and poorly consolidated sand, silt, and gravel, mainly in flood plains, fans, etc.; landslide deposits included locally. Windblown deposits included where bedrock is masked.

Qg Glacial deposits - Gravel, boulders, and sand, glacially worn and deposited. Only the largest masses shown.

Ql Late lake sediments - Chiefly silt.

Qrb Snake River basalt - Chiefly basalt flows. Closely allied rocks included locally. Distinctly recent flows distinguished as Qrb where possible.

Qsr Snake River basalt - Chiefly basalt flows. Closely allied rocks included locally.

Tertiary

Tcv Challis volcanics and associated rocks - Includes Challis volcanics, Kamiah volcanics, and other rocks, mostly near the Snake River Plain, that are similar in composition and apparent stratigraphic position to these formations. Mostly of intermediate composition, but some rhyolite and basalt are included.

Tsl Salt Lake formation and associated strata - Rather poorly consolidated sand, silt, and gravel of lacustrine and fluviate origin, including fan deposits. Minor quantities of rhyolitic flows and welded tuffs and of basalts are included. Some of the sediments are tuffaceous, and fresh-water limestone is locally present.

Tsv Silicic volcanic rocks associated with the Snake River basalt - Welded tuffs and flows of rhyolitic appearance.

Tw Wasatch formation - Largely conglomerate; some limestone.

Cretaceous

K Cretaceous sedimentary rocks - Includes Gannett group and Wayan formation. Conglomerate, limestone, sandstone, largely of fresh-water origin. Some age assignments tentative.

Jurassic

J Jurassic sedimentary rocks - Includes Nugget, Twin Creek, Preuss, Stump, and other units. Largely marine sandstone and limestone.

Triassic

Tr Triassic sedimentary rocks - Includes Wood, Deadman, Higham, Timothy, Portneuf, Fort Hall, Ross Fork, Woodside, and other units. Varied marine rocks, locally associated with volcanic strata. Schistose in a few places.

Permian

Pp Phosphoria formation - Phosphatic shale, limestone, and chert.

Carboniferous

C Carboniferous sedimentary rocks - Brazer, Madison, Milligen, Wells, Wood River, and other units. Dominantly marine and containing a large proportion of calcareous rocks, with some quartzite, etc. May include some Devonian beds.

Ordovician

O Ordovician sedimentary rocks - Fish Haven, Swan Peak, Saturday Mountain, Kinnikinic and other units, some of which are of doubtful age, Marine beds in which quartzite and argillaceous rocks are plentiful; some calcareous beds are included.

Cambrian

Є Cambrian sedimentary rocks - St. Charles, Nounan, Bloomington, Blacksmith, Bayhorse, Garden Creek, and other units. Marine beds in which limestone is plentiful, but quartzite and other rocks are also present. Some age assignments are tentative.

Undifferentiated Paleozoic

pal Undifferentiated Paleozoic sedimentary rocks

Pre-Cambrian

pЄ Pre-Cambrian (?) strata not correlated with the Belt Series-Hyndman formation, East fork formation, Albion Range group, and other units. Mostly metamorphosed limestone and other sedimentary rocks, but igneous rocks are included locally. Most age assignments are tentative.

APPENDIX B

STRATIGRAPHY AT RIRIE DAMSITE WITH GEOLOGIC SECTIONS

(from Patrick and Whitten, 1981)

Geology of Ririe Dam

Stratigraphy and Structure

The following descriptions and cross-sections of the major geologic units underlying Ririe Dam are taken from the earlier WES report on Ririe Dam by Patrick and Whitten (1981). The surface distribution and underlying stratigraphy of these units are presented in Figures B1 and B2, respectively. Figure B3 shows the locations for five generalized geologic cross-sections parallel and normal to Willow Creek (Profiles 1 through 5 in Figures B4 to B8, respectively).

Rock Unit Descriptions

Intracanyon flow (Qby)

Unconformably overlying the local channel gravels and rhyolite is approximately 72 ft of gray to black, porphyritic, and vesicular basalt. This unit exhibits feldspar phenocrysts and columnar jointing and was apparently extruded along a canyon ancestral to the present Willow Creek canyon. The contact between the intracanyon flow and the older basalts is along the north side of Willow Creek canyon approximately one mile downstream of the dam.

Rhyolite flow (Qyh)

Unconformably overlying the channel gravels and first flow basalt in the right abutment and only the first flow basalt in the left is a fine-grained, soft to moderately hard, pink to gray, rhyolite flow. This material is the gray rhyolite flow. The base of the flow consists of ash and locally obsidian. This material is the Huckleberry Ridge tuff of Prostka and Hackman (1974) who describe the unit as a rhyolite, welded, ash-flow tuff. These authors give the age of the material as Pleistocene.

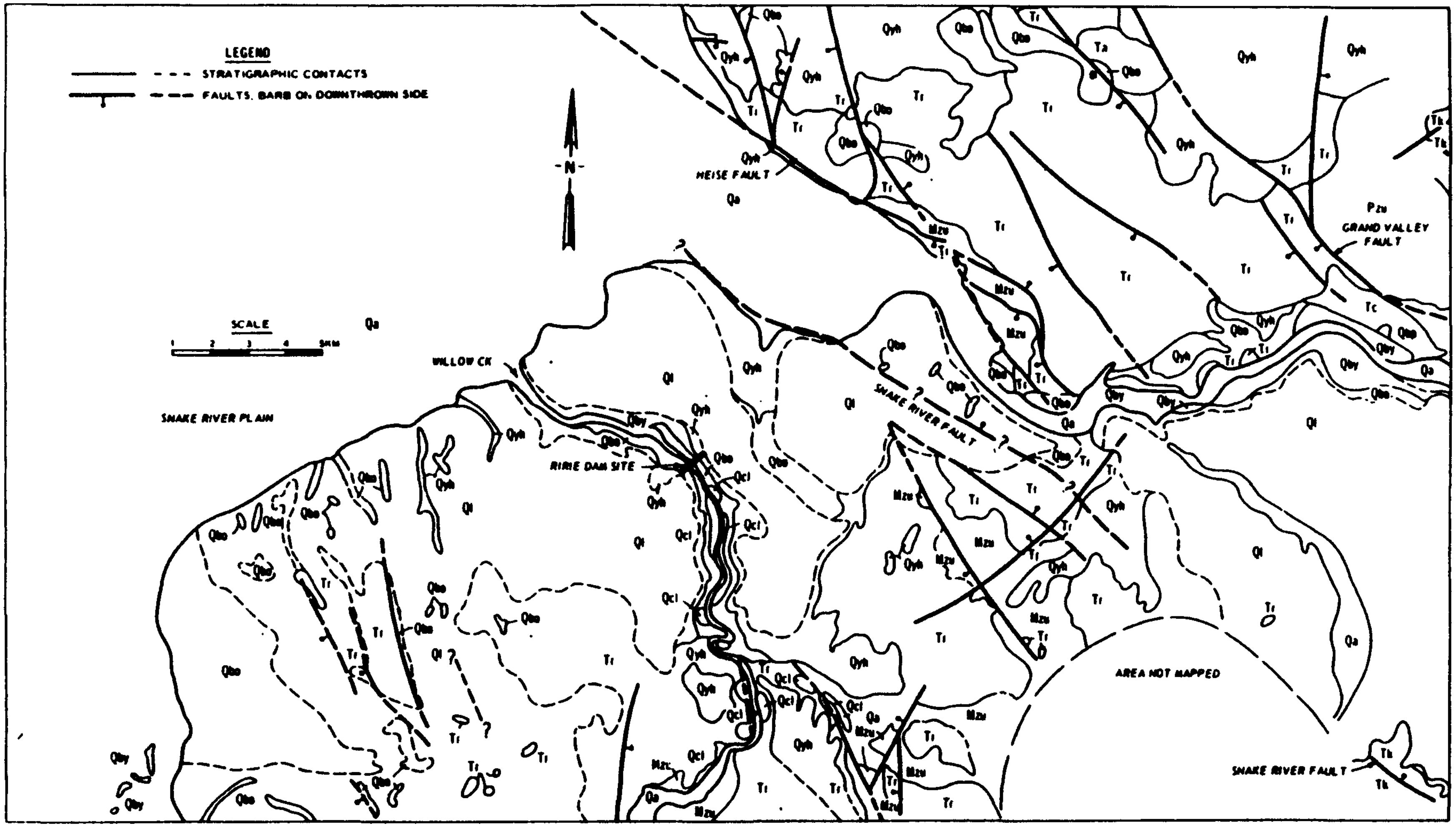

Figure B1. Geology of Ririe Dam and vicinity (after Prostka and Hackman, 1974; from Patrick and Whitten, 1981)

MAP SYMBOL*	POTASSIUM/ ARGON DATING (MILLION YEARS)	GEOLOGIC AGE	MARKER HORIZON NUMBER	LITHOLOGY	DESCRIPTION		THICKNESS IN FEET MIN	MAX	AVG
C	–	QUATERNARY (PLEISTOCENE)			LOESS	Tan, fine grained, wind blown silt. Occurs on upland areas.		~3	
Qbv	3.1 ± 0.2	TERTIARY (PLIOCENE)			INTRACANYON FLOW	Characterized by large (average length 0.4 inches) tabular feldspar crystals. The rock is blue gray to black in color and vesicular in texture. It is generally columnar in structure and is only evident on the right abutment above 5020 elevation where it forms cliffs. This flow makes contact with materials forming the older erosional surface. As such, it overlies both channel gravels and volcanic flows, and the contact could include other alluvial materials.	15	128	72
Qvh	3.2 ± 0.2				RHYOLITE	Fine grained with needle shaped crystals. It is soft to moderately hard and its color varies from pink to gray. A thin layer of ash is often found at the base of the rhyolite. This material can rest on the basalt flows or the channel gravel.	4	88	30
–	–				CHANNEL GRAVELS	Confined to a buried channel exposed along the right abutment during the stripping contract. They extend an unknown distance into the hillside. The deposit consists of lenticular and intertongued clays, silts, sands, and gravels. The exposed channel extends from DH 13 through DH 24.	34	49	43
Qbo	6.7 ± 0.7				BASALT (FIRST FLOW BASALT)	Flow is a marker bed because of the unusual arrangement of the feldspar crystals. These crystals are 0.2 to 0.3 inches in length and are arranged in clusters or rosettes. The rock is vesicular and gray in color.	9	55	31
	–		12		BASALT	Hard, fine grained with vesicles ranging in size from 0.5 inches to "pin hole". It is dark gray in color.	12	93	71
			13, 13a		CONTACT BRECCIA / CLAY	The clay is gray green to gray and is very plastic. It contains thin lenses of silts and sands. There is a 2 foot contact breccia zone capping the clay bed. The breccia is orange to brown in color and has inclusions of basalt fragments.	1 / 2	7 / 38	2 / 24
			14		BASALT	Hard, medium grained, slightly vesicular and dark gray in color. Feldspar crystals appear as white lathes in the rock.		76	50
			15, 15a		CONTACT BRECCIA / CLAY	This clay is generally gray green to yellow green and is plastic. It is capped by a contact breccia zone.	2 / 1	11 / 23	7 / 8
			16		BASALT	Hard, fine grained, slightly vesicular and dark gray in color.	13	41	30
	7.3 ± 0.4		17, 17a		FLOW BRECCIA / BASALT	The basalt is similar to flow 16-17 except that it is capped by a flow breccia zone.	2 / 9	15 / 52	8 / 18
Tr	–	?	18		BASAL SEDIMENTS	Considered to be part of the Salt Lake Formation. They are clay and silty clays, soft to moderately hard and are red brown to tan in color. Beds of the Salt Lake Formation are exposed in the canyon wall several miles upstream from the damsite.	UNDETERMINED DEPTH (ESTIMATED AT 1000'S OF FEET)		

* SYMBOLS ON GEOLOGIC MAP (FIGURE) AFTER USGS.
OTHER SYMBOLS SHOWN ON GEOLOGIC MAP BUT NOT SHOWN HERE ARE:
Qa ALLUVIUM, Qcl LANDSLIDE MATERIAL, Mz UNDIFFERENTIATED MESOZOIC SEDIMENTS

Figure B2. Stratigraphy underlying Ririe Dam (after U.S. Army Corps of Engineers, 1977; from Patrick and Whitten, 1981)

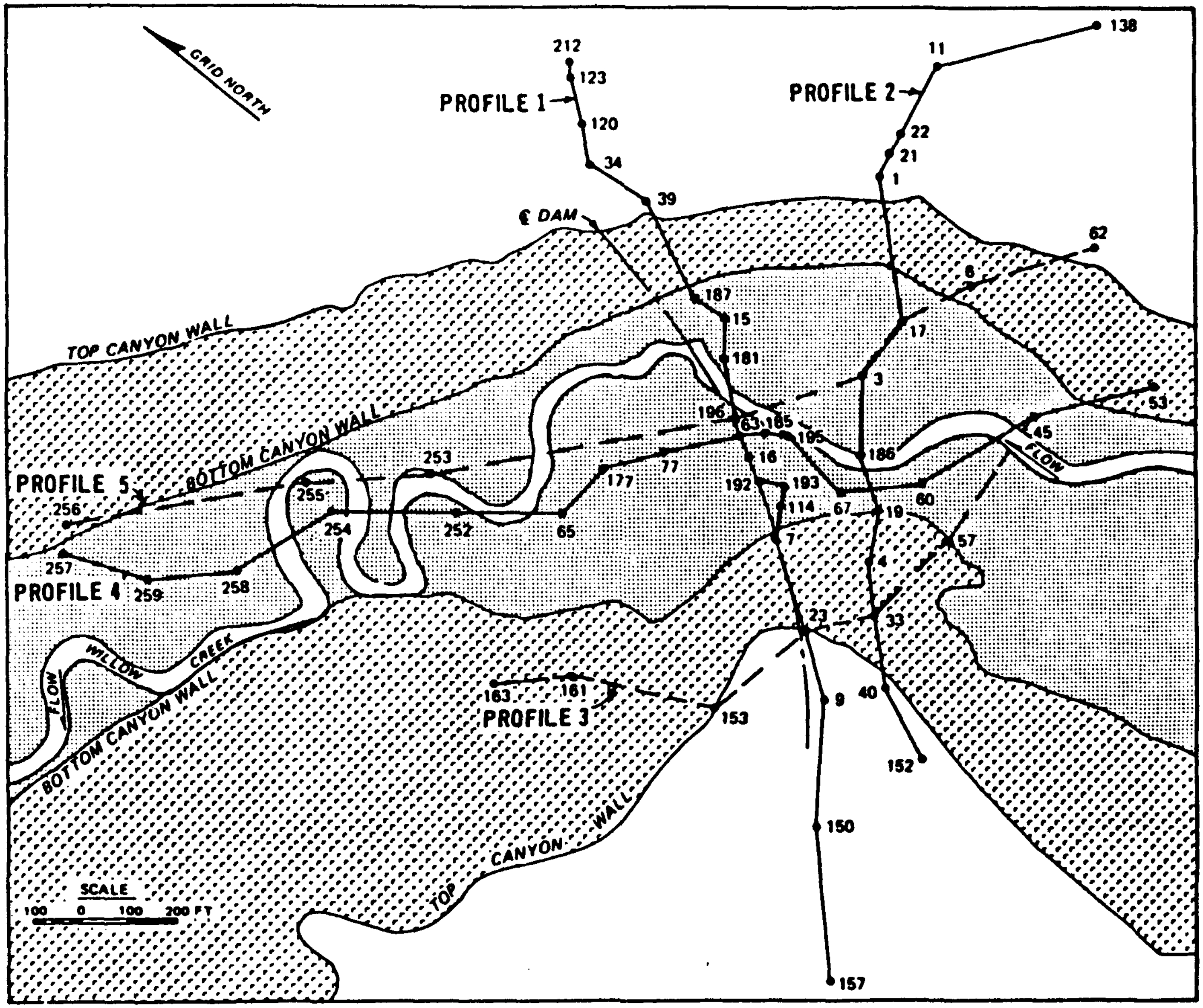

Figure B3. Location of geologic cross-sections (Profiles 1 to 5)
(from Patrick and Whitten, 1981)

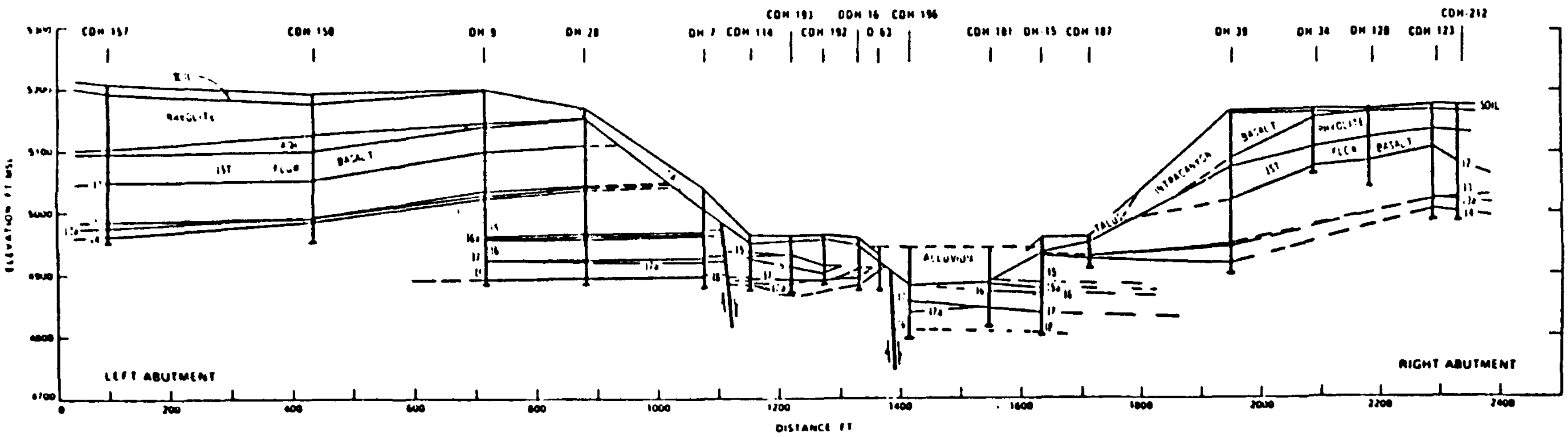

Figure B4. Geologic profile 1 of the volcanic units (from Patrick and Whitten, 1981)

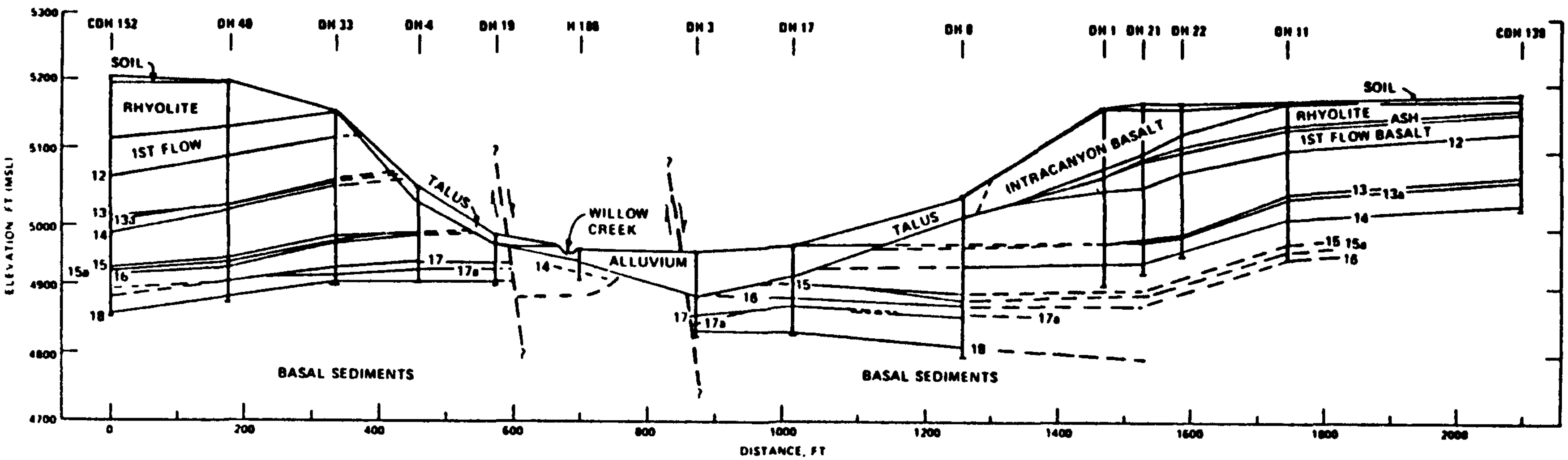

Figure B5. Geologic profile 2 of the volcanic units (from Patrick and Whitten, 1981)

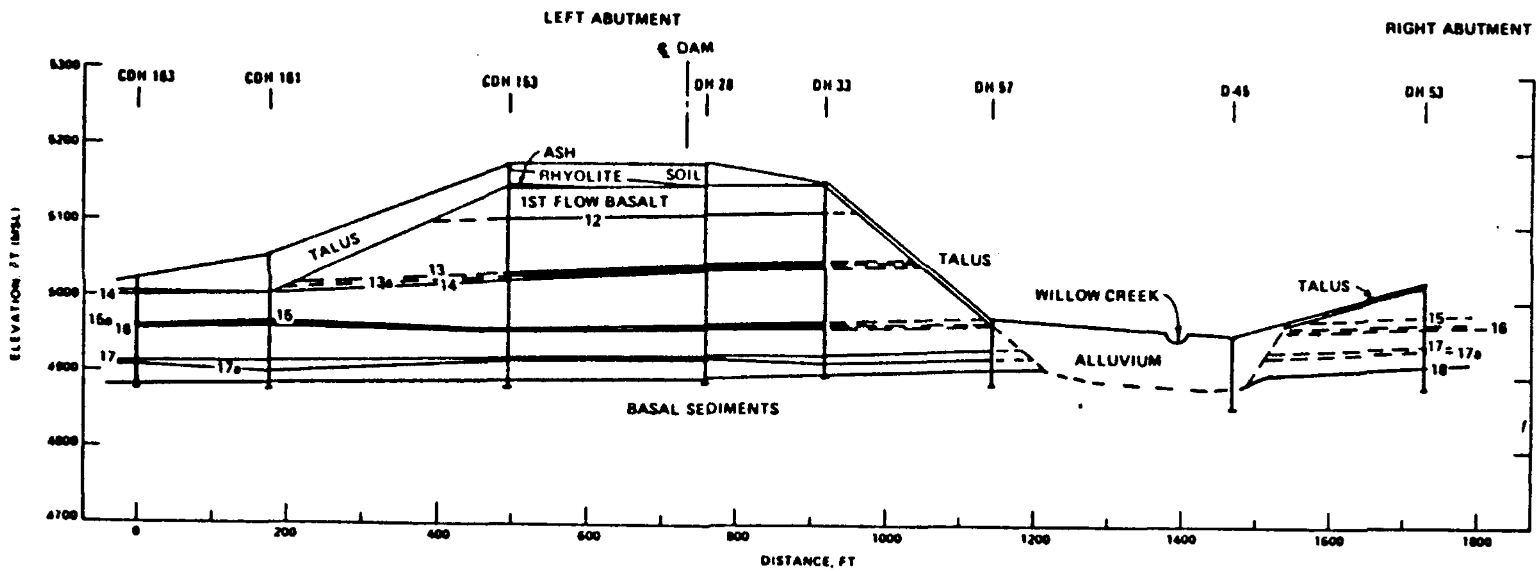

Figure B6. Geologic profile 3 of the volcanic units (from Patrick and Whitten, 1981)

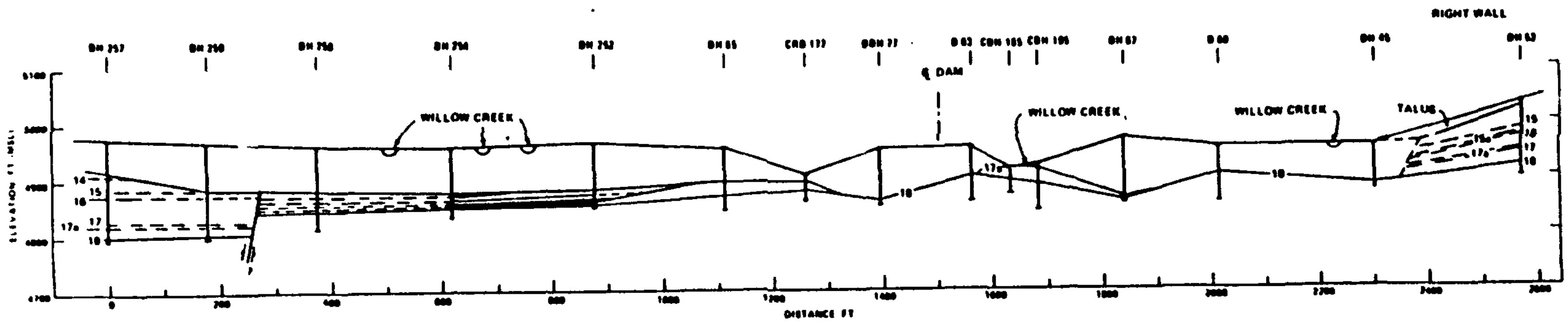

Figure B7. Geologic profile 4 of the volcanic units
(from Patrick and Whitten, 1981)

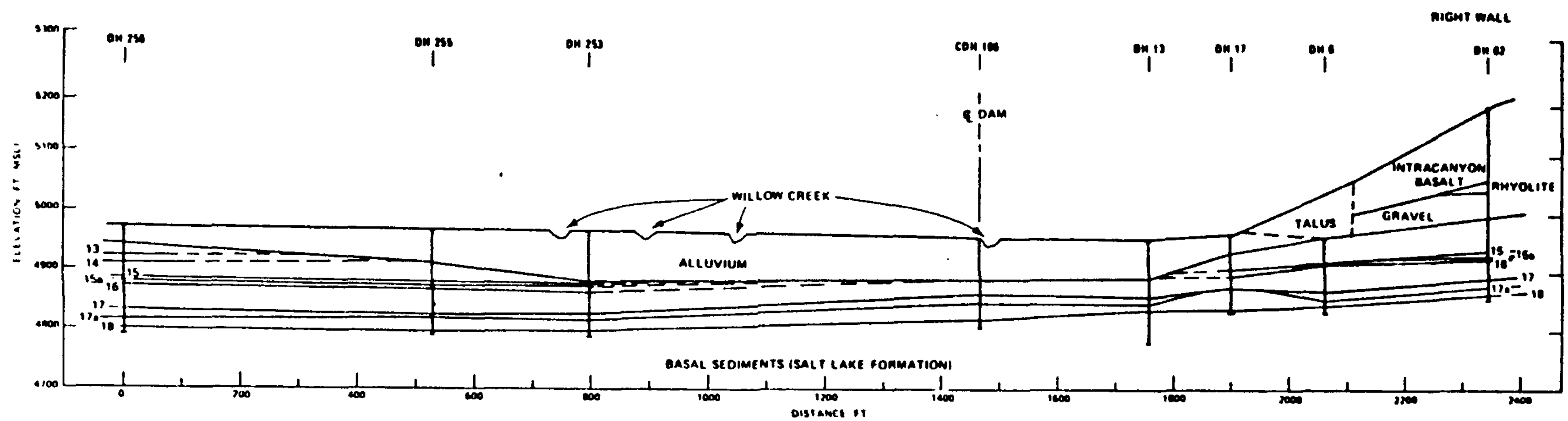

Figure B8. Geologic profile 5 of the volcanic units
(from Patrick and Whitten, 1981)

Channel gravels

Exploratory drilling for the emergency spillway in the right abutment revealed the presence of approximately 40 ft of predominant gravel interbedded with sand, silt, and clay. The drilling logs indicated that these gravels, which are presumed to represent a channel deposit, underlie both the rhyolite and the youngest rock unit, the intracanyon basalt. The channel gravels lie unconformably upon the older basalt flows and represent downcutting to at least horizon 14 (see Figure 2) in the older basalt flows.

Older basalt (Qbo)

Unconformably overlying the basal sediments and underlying both the rhyolite flow and the channel gravels are approximately 251 ft of basalt flows. These basalt flows are labeled "Qbo" on Prostka and Hackman's (1974) map and are considered by them to be of the Quaternary age. At the damsite the unit consists of predominant hard, dark gray, fine-grained, vesicular basalt. This sequence of basalts has been lithologically and stratigraphically divided into five individual flows or flow units on the basis of interbedded clays, flow or contact breccias, and lithologic dissimilarity. Ten key marker horizons have been identified and are shown on the stratigraphic column and on the cross sections. Generally these marker horizons can be identified throughout the vicinity of the dam. However, the examination of boring logs revealed that marker horizons 17 and 17A are least continuous. These interbedded clays and associated contact or flow breccia zones apparently indicate surfaces of unconformity upon which successive flows were extruded. Horizon 12 reflects a distinct change in lithology in terms of the appearance of clustered plagioclase phenocrysts, which appear above horizon 12 and not below it. This porphyritic basalt is termed the "first flow basalt." This horizon is not a surface of unconformity.

Basal sediments (Tr)

This unit is termed "basal sediments" in the foundation reports and is presumed to be approximately equivalent to the Salt Lake formation. This material is mapped as "Tr" on Prostka and Hackman's (1974) map and is Pliocene (Tertiary) in age. The unit consists of rhyolitic welded tuffs, lava flows, and nonwelded tuffs. Exposures of this unit in Meadow Creek, an upstream tributary of Willow Creek, consist of volcanic ash beds (nonwelded tuffs), silts, and sands. The surfaces upon which these individual volcanic and non-volcanic materials were deposited are apparently quite irregular as indicated by steep primary dip. These materials are unweathered as exposed in Meadow Creek, but the basal sediments encountered in boreholes under and near the dam consist of silt and clay that most probably resulted from the devitrification and weathering of the volcanic glass. This unit is believed to be quite thick, perhaps thousands of feet thick. However, the deepest exploratory penetration of this unit was approximately 100 ft.

APPENDIX C

SEISMOTECTONIC SETTING AND DEISGN EARTHQUAKES
AT RIRIE DAM

(Report by D. B. Slemmons and A. R. Ramelli, 1986)

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Received April 1, 1987

Dr. Ellis L. Krinitzsky
Geotechnical Laboratory
U. S. Army Engineer Waterways Experiment Station
P. O. Box 631
Vicksburg, Miss. 39180

Dear Ellis:

The accompanying report summarizes my observations on the seismotectonic setting at Ririe Dam, Idaho. The earthquake magnitudes that are proposed are for the three main fault systems at or near the site. The listric normal faulting has been verified by Dixon (1982) for the Snake River graben from Antelope Flat through Swan Valley, Palisades Reservoir and Star Valley, and also for the Bear Lake graben. It is not certain that the Heise and Rexburg faults are listric, nor whether or not they are part of the southeastern border zone of the Snake River Plain.

The surface wave magnitudes are from the linear regressions of Bonilla, et al., 1984, and Slemmons, 1982. The maximum magnitudes that were observed for normal faults in the region are: Hebgen Lake (Ms = 7.6) and Pleasant Valley (Ms = 7.6). The geologic setting and structures for both of these areas is more conspicuous than for either the Snake River graben near Ririe Reservoir, or for the Bear Lake graben near Blackfoot Reservoir. The estimated maximum magnitudes for various fault segments that are tabulated in the accompanying report is about Ms = 7 1/2.

Please do not hesitate in writing or calling me for any addition information that you may require.

Sincerely,

David B. Slemmons

SEISMOTECTONIC SETTING AND DESIGN EARTHQUAKES AT RIRIE DAM, IDAHO

by

D. B. Slemmons and A. R. Ramelli

2995 Golden Valley Road
Reno, Nevada 89506

Prepared for
Geotechnical Laboratory
U. S. Army Engineer Waterways Experiment Station
P. O. Box 631, Vicksburg, Mississippi 39180

for the

U. S. Army Engineer District, Walla Walla

21 February 1986

ABSTRACT

Ririe Dam and Reservoir are situated in southeastern Idaho in an area of active tectonism which includes geologically recent volcanism, hot springs and active faults. Two earthquakes are postulated for design purposes:

(1) Local and Near Field: Snake River Plain Border Zone.

Distance = 0, Ms = 7

(2) Local and Near Field: Swan Valley Graben.

Distance = 5 km; Ms = 7 1/2

(3) Far Field: Star Valley Graben.

Distance = 40 km; Ms = 7 1/2

PART I: SEISMOTECTONIC SETTING

Ririe Dam, in southeastern Idaho (fig. C1), is located in the Intermountain Seismic Belt (Smith and Sbar, 1974). In this region, tectonic activity has been operating throughout the Quaternary along N-S to NW-SE trending extensional fault systems and the NE-SW trending Snake River Plain. The regional geologic, tectonic and seismic setting is summarized by Krinitzsky (1984) for the nearby Blackfoot Reservoir.

Basin and Range extensional faulting was initiated in the Miocene and continues today. Recent studies (e.g. Dixon, 1982) have shown that thrust faults of the Sevier (late Mesozoic) orogenic event have been reactiviated by this extension, thus developing listric (i.e. flattening with depth) normal faults. The Grand Valley-Star Valley fault system (Snake River graben) has been described as having 9 km (5 1/2 mi) of net slip and 6 km (3 1/2 mi) of horizontal extension during the late Cenozoic (Royse, 1983). Due to the west-facing thrust ramps, major graben systems in this region generally have the vast majority of their fault displacement on the east or northeast sides and much lower displacement and activity to the west or southwest. This results in tilting and rotation of the valley floor toward the more active southeastern side.

The Snake River Plain was later overprinted on the graben system partly in the form of early caldera formation, with subsequent basaltic volcanism filling and burying the older calderas. Thus, the older volcanic deposits of the Snake River Plain are mostly of acidic composition and the younger ones are mostly basalts. This system becomes younger toward the northeast and may be due to movement of the North American continental plate over a "hot spot"

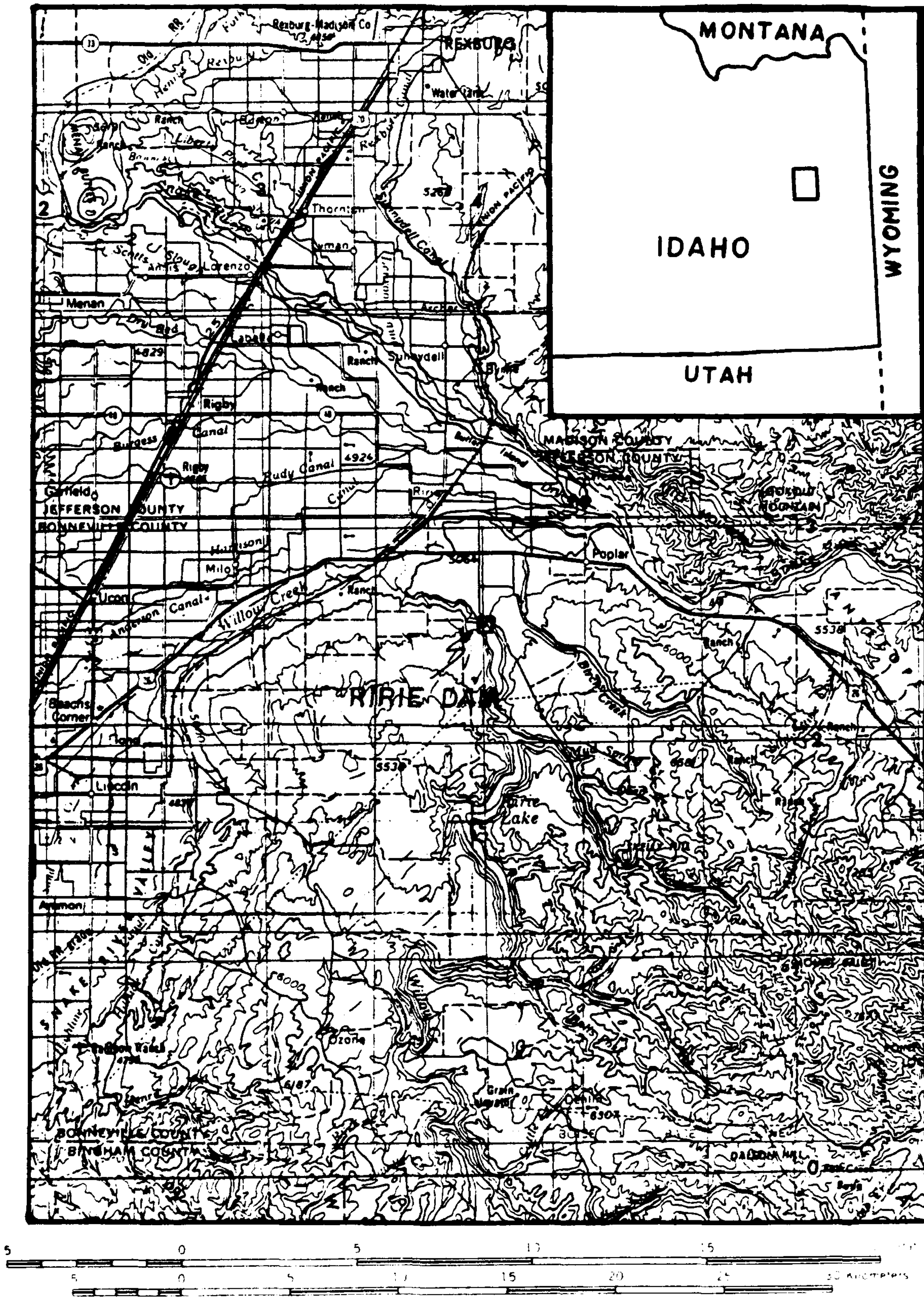


Figure C1. Location map for Ririe Dam, Idaho that is responsible for present-day volcanic and seismic activity in the Yellowstone area (Armstrong, et al., 1975).

Ririe Dam is located along the southeastern edge of the Snake River Plain, where subsidence of the plain has caused warping and/or faulting of mostly extrusive volcanic units. Most of these units are the rhyolitic products of the caldera systems (in particular the Rexburg and Island Park calderas). Very little Quaternary fault activity has been described for the plain boundary, but our aerial and ground reconnaissance, and inspection of large-scale aerial photography shows evidence for recent fault activity along fault segments of up to 5 km.

PART II: SOURCE AREAS

Faulting in the Ririe Dam Area, Along the Snake River Plain

Several faults are shown on the 1:20,000 scale, aerial photographs and maps (figs. C2 and C3). These are present on a surface of loess-covered Huckleberry Ridge Tuff, a deposit dated at about 2.0 million years ago, which erupted from the Island Park Caldera, (Christiansen, 1982). This unit thus provides a datum plane that is very near the Tertiary/Quaternary boundary, estimated at about 1.8 m.y. All faults showing surface expression are assumed to be Quaternary in age, since they cut the Huckleberry Ridge Tuff. The oldest faults are those with NW or NNE trends (fault numbers 1, 2, 3, and 4; fig. C4), which includes the SE bounding fault of the Snake River graben (fault 1). This fault has a thick, uneven cover of loess, as opposed to the younger, N 45 E trending faults (fig. C5), which have a much smaller amount of offset and a uniform cover of loess, probably indicative of faulting events that post-date the majority of loess accumulation. These faults are believed to be late Quaternary and possibly Holocene in age. They generally have offsets of about 2-3 m (5-10 ft) or less, indicating low activity. They parallel the Snake River Plain boundary and are likely secondary features due to warping caused by subsidence of the plain. This is supported by the lack of a through-going fault zone. The surface of the Huckleberry Ridge Tuff dips toward the plain at about 5 to 10 degrees, indicating that such warping processes have been operating throughout much of the Quaternary.

Fault zone lengths are difficult to determine for swarms of faults such as these, but a short length would be expected, given the amounts of offset,

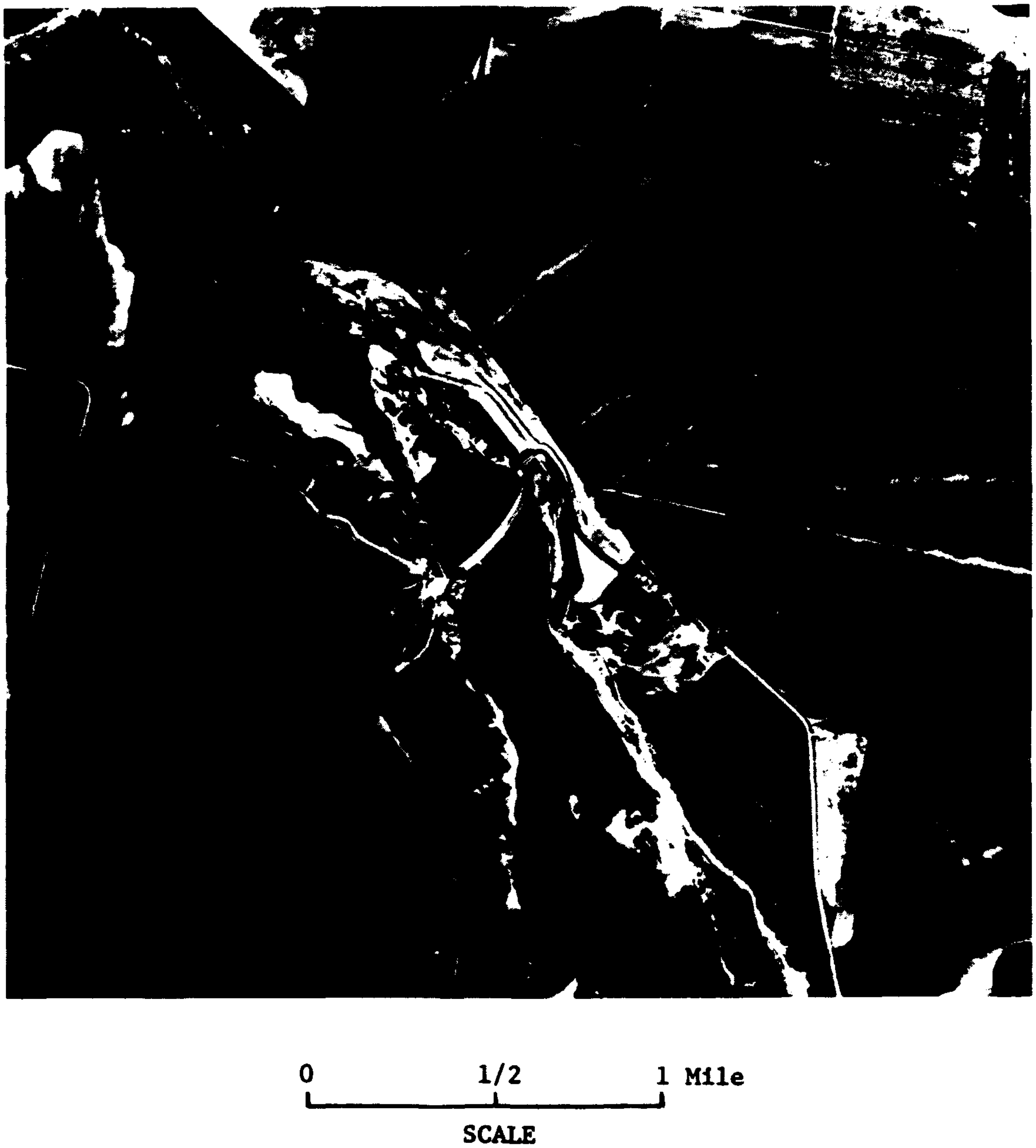
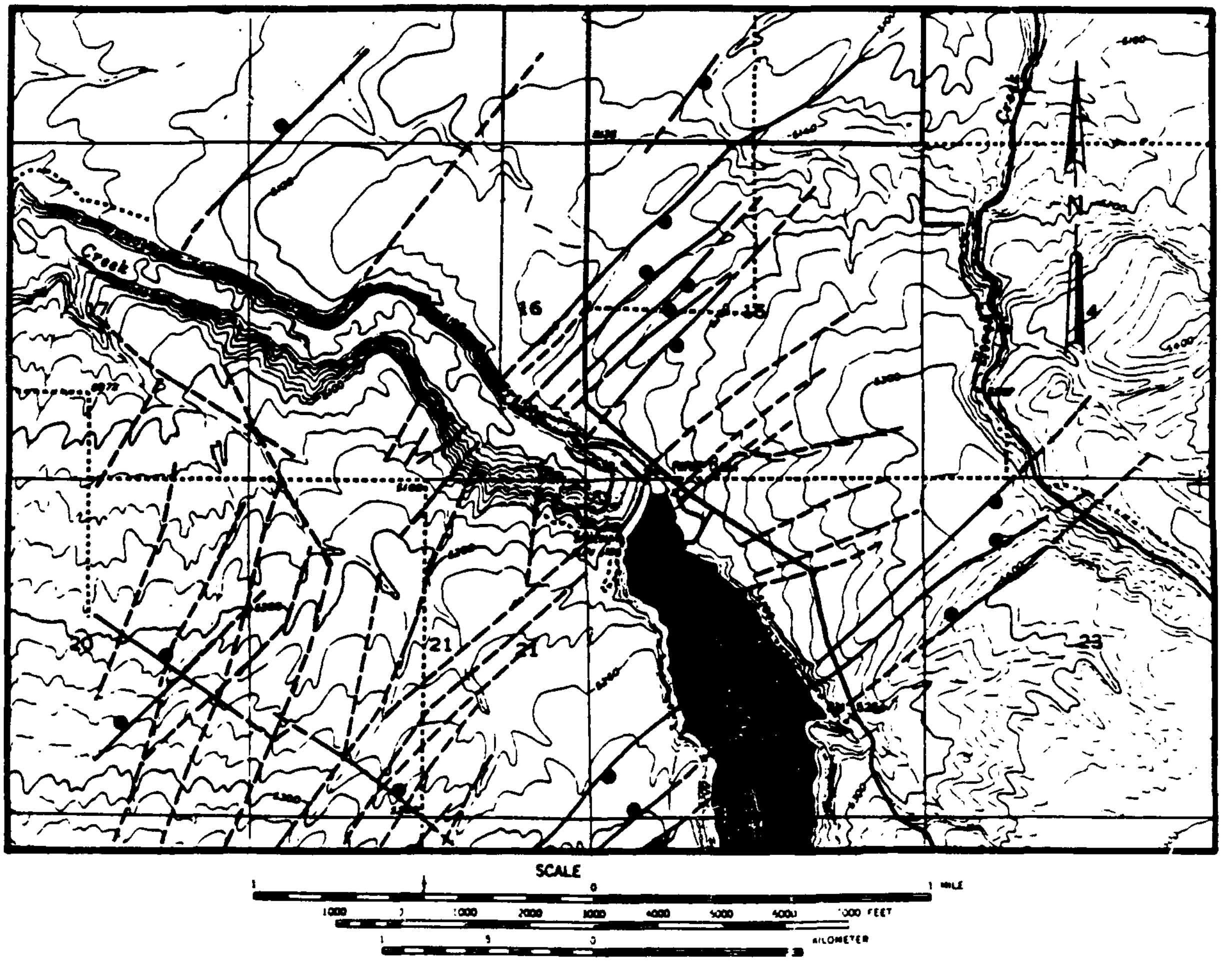


Figure C2. Aerial photograph of Ririe Dam and vicinity showing pattern of lineaments



Linear with no apparent offset

Fault with barb on downthrown side

Figure C3. Interpretation of linear features at Ririe Dam.

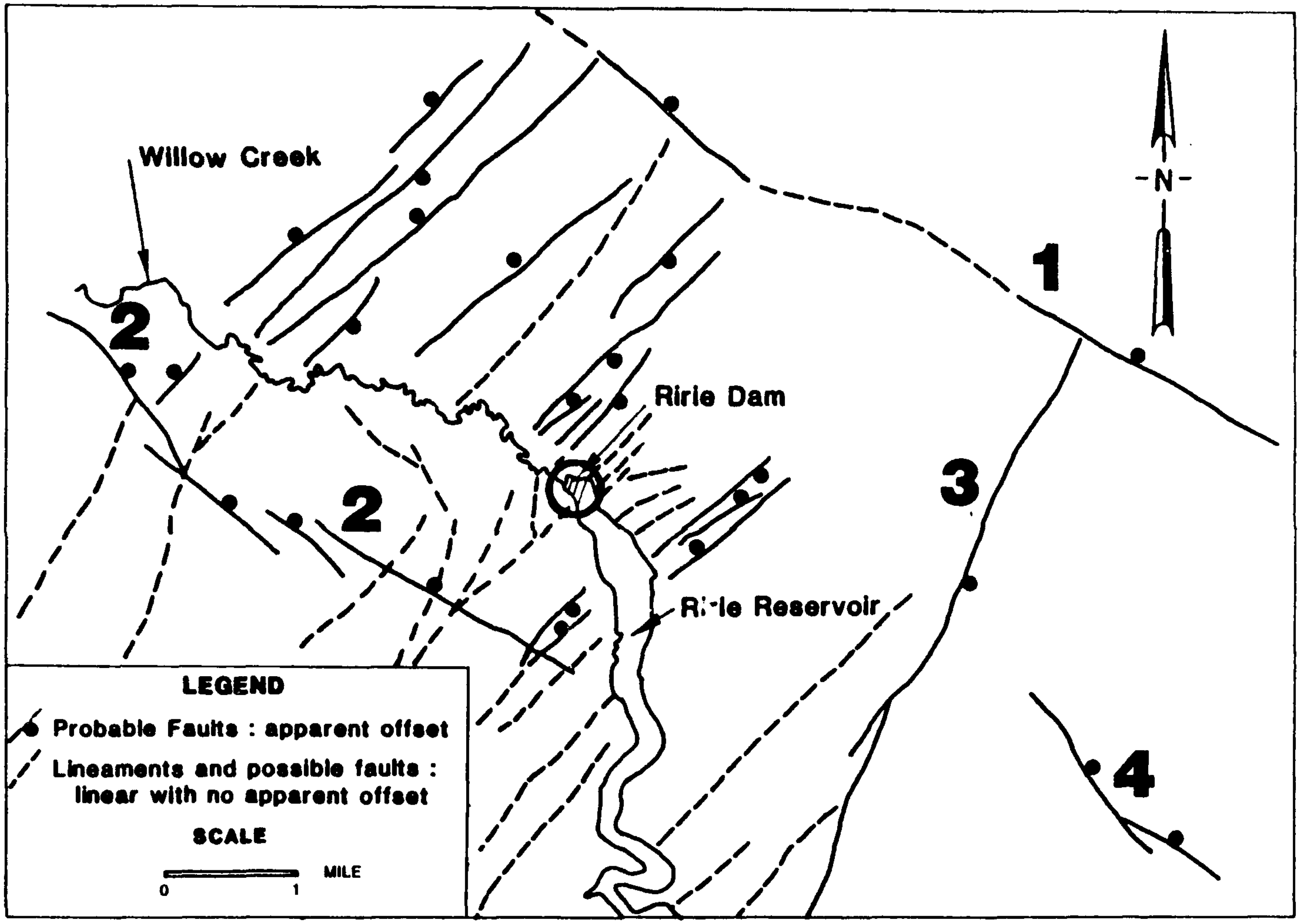


Figure C4. Faults and lineaments, Ririe Dam area.

Figure C5. Aireal photograph of northeast trending faults in loess.

thereby limiting the size of maximum seismic events that could be expected. The greatest length that can be traced for a single fault is about 5.6 km (3.4 mi), but a fault zone length of 10-15 km (5-10 mi) is probably more realistic and a conservative assumption.

Orientations and relative ages determined for these faults agree fairly well with those described by Allmendinger (1982) for the south 1/2 of the Ammon 15 minute quadrangle to the SW of this location. This type of situation is likely to hold true for much of the Snake River Plain's southeastern boundary. Numerous normal faults with small offsets were observed in a quarry about 6 1/2 km (4 mi) south of Ammon. The faulted units in this location are probably the "Tuff of Heise" dated at 4.3 plus or minus 0.15 m.y. (Armstrong, et al., 1980).

Faults near Ririe Dam change greatly in appearance across Willow Creek (figs. 2 to 4). The most evident offsets are on fault traces to the NE of Willow Creek, while the area to the SW is characterized by numerous linear drainages with no apparent offset. This change in appearance may be due to faulting along Willow Creek, as described by Patrick and Whitten (1981).

Our aerial reconnaissance south of the town of Ririe showed that these scarps had steep, fresh-appearing slopes that are probable Holocene age. The total scarp height precludes numerous events, so the recurrence interval is probably ten thousand or more years.

For a fault length of 10 to 15 km, linear regression formulas indicate an earthquake of 6 1/4 to 6 3/4 (Bonilla, et al., 1984, and Slemmons, 1982), with a scatter of about 1/4 magnitude for one standard deviation. The magnitude may be too high if this faulting results from warping and is not a deep-rooted system. Regression formulas indicate that earthquakes of this magnitude could lead to maximum surface displacements of about 1/2 to 1 meter, but if the magnitudes are lower, smaller displacement should be expected. Also the complex pattern may be characterized by a series of smaller offsets.

The maximum earthquake for this fault zone is conservatively assumed to be at Ms = 7, this magnitude is based on a length that is about six times greater than any of the late Quaternary fault scarps of this zone, but is somewhat greater than the maximum fault displacements that were observed near Ammon and at Ririe.

Faults of the Snake River Graben and the Bear Lake Grabens

Faults along the NE edges of the Snake River (Swan Valley/Palisades/Star Valley) and Bear Lake grabens (i.e. Grand Valley and Bear Lake fault systems) appear to be highly active (Note: Snake River graben and Snake River Plain are separate features). The hypothesis that these faults have their base on listric, reactivated, subhorizontal thrusts (e.g. Dixon, 1982) is strongly supported by geomorphic evidence, in particular, the tilting of valley floors to the NE.

The historical record of extensional faulting in western United States, including Borah Peak (1983), Dixie Valley (1954), Fairview Peak (1954), Hebgen Lake (1959), Pleasant Valley (1915), and two events on Rainbow Mountain (1954), shows faulting ruptures that have segment lengths that were defined by step-overs, cross-structures, and changes in graben width and fault orientation. Based on these relations, segments of about 30 to 50 km (20 to 30 mi) are assigned for the Snake River and Bear Lake graben systems. These lengths are in agreement with historical normal fault rupture lengths in western United States. Seven segments are identified for the Snake River graben between the Snake River Plain and the southern end of Star Valley, and three for the

Bear Lake fault system between Blackfoot Reservoir and Bear Lake at the Idaho-Utah border. These segments are summarized in Table C1, with their estimated seismic parameters.

Earthquake magnitudes that could be expected with these fault lengths, based on linear regression (e.g. Slemmons, 1982), are not likely to exceed 7 1/2. If these faults are shallow and connect to detachment surfaces at depths of a few kilometers, the magnitudes may be lower, although the seismogenic behavior of listric normal faults has not been evaluated.

Since the northwesternmost of Dixon's (1982) profiles is a few kilometers southeast of Ririe Dam, it is not certain that the Heise fault is listric. If it is listric, or the listric faults of Swan Valley graben extend beneath Ririe Dam, the fault plane would be about 4 1/2 km (2 3/4 mi) deep, based on Dixon's (1982) cross section 1 which is located about 6 km to the SE, see Figure 6. The Heise-Rexburg fault could yield and earthquake of about 7 1/2 magnitude in a zone that is about 5 km from Ririe Dam. Recurrence intervals can not be determined precisely without detail study of timing of events, but an approximation is possible. Along the Rexburg-Heise fault, which appears to represent one segment, one event of about 1 2/3 m (5 1/2 ft) displacement occurred between 250,000 and 25,000 years B.P., probably much closer to the 25,000 years date (Williams and Embree, 1980 and personal communication). The Huckleberry Ridge Tuff has been shown to be offset about 150 m (500 ft) near Rexburg (Embree, et al., 1982). This indicates a displacement rate of about 0.07 mm/yr. If a fault displacement of about 1 2/3 m (5 1/2 ft) is characteristic for this fault segment (although it should be noted that total offset increases southeastward along the Heise fault), a recurrence interval of more than 20,000 years is suggested.

Table C1

Fault Segments and Seismic Parameters for Segment and Site

Fault Segment	Estimated Segment Length (km)	Displacement Total (m)	Displacement Per Event (m)	Distance from Site (km)	Earthquake, Magnitude Ms	Displacement Rate (mm/yr)	Age of Most Recent Offset (yrs)	Estimated Recurrence Interval (yrs)
S. Boundary Faults of Snake R. Plain	<15	2-3	<0.5-1.0	<0.5	7	<<0.1	Late Quaternary	$\pm 10^4$
Heise-Rexburg	25	~150	~1.5	8	7 1/2	0.07	>25,000	>20,000
Antelope Flat	35	---	---	18	7 1/2	very low	Probably >100,000	Currently inactive?
Swan Valley	35	>300	<4	30	7 1/2	>0.2	Holocene	±5,000
Palisades	35	>300	<4	60	7 1/2	>0.2	Holocene?	±5,000
N. Star Valley	45	>300	<4	85	7 1/2	>0.2	Holocene	±5,000
S. Star Valley	45	>300	<4	120	7 1/2	>0.2	Holocene	±5,000
Snake R. Fault incl. SW side	40	---	---	4	7 1/2	very low	?	Currently inactive
Bear Lake Flt.	50	>300	<4	180	7 1/2	>0.2	late Holocene	<5,000
Montana	35	>250	<4	145	7 1/4	>0.2	Holocene	±5,000
Soda Springs	25	>250	<4	125	7 1/4	>0.2	Holocene	±5,000
Soda Springs-Blackfoot	35	>250	<4	90	7 1/4	>0.2	Holocene	±5,000
Blackfoot grabens	30, or less	~100	<3	30+	<7 1/4	?	Quaternary to Holocene	>10,000

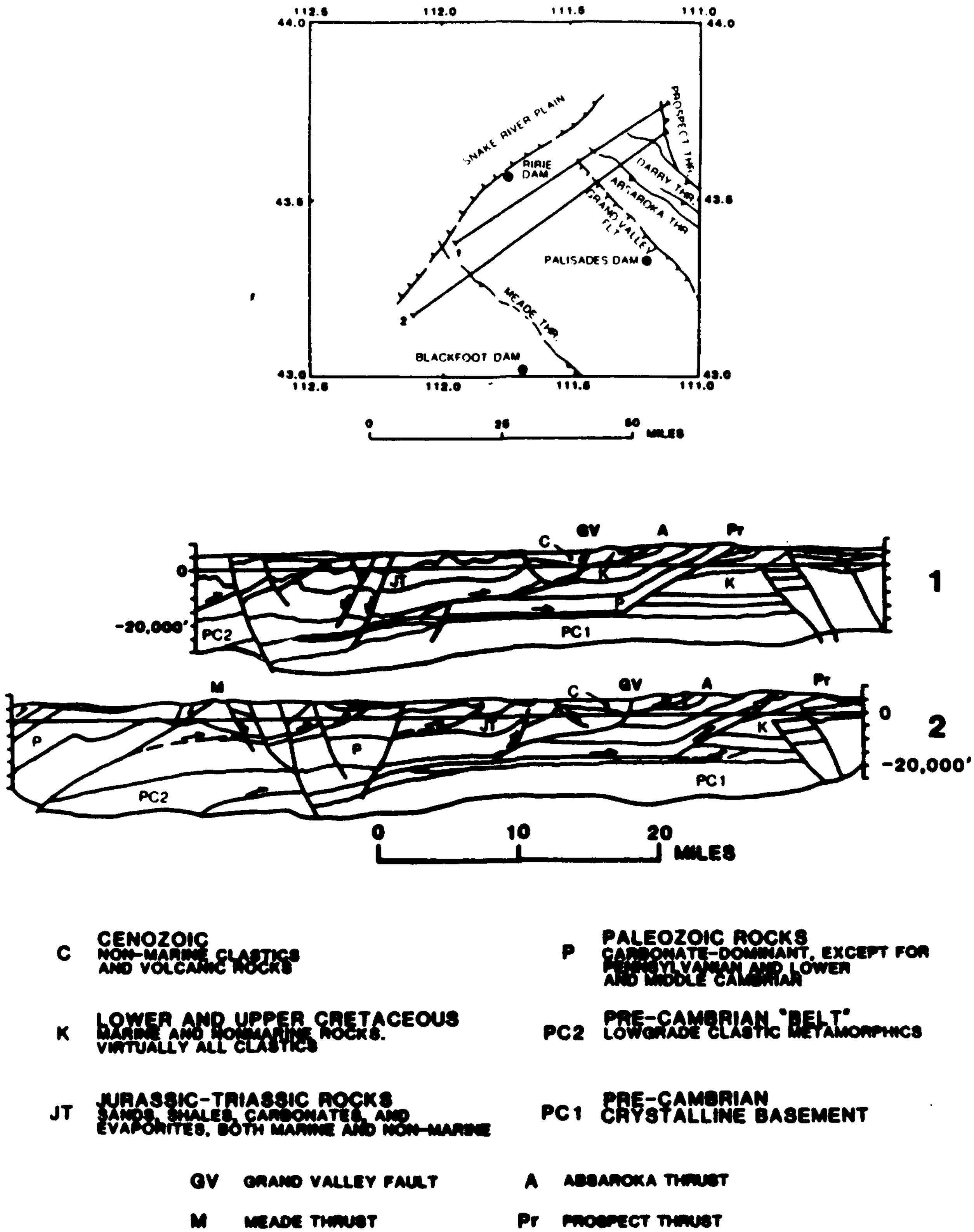


Figure C6. Geologic cross sections 1 and 2 of Dixon (1982).

The rest of the fault system, with the exception of Antelope Flat, has a higher rate of activity. Along Antelope Flat, between the Heise fault and Swan Valley, this fault system does not appear to have been active during the late Quaternary. Basalt flows that are offset a minimum of 100 m (300 ft) at Swan Valley show no offset where they extend up Pine Creek along the NE edge of Antelope Flat. These flows probably originated in the Snake River Plain, where the uppermost flows are mostly Quaternary in age. A date of 0.8 plus or minus 0.1 m.y. is given for a basalt flow west of Swan Valley (Armstrong, et al. 1975). A normal magnetic polarity is described for this flow, so it is likely to post-date the Matuyama reverse polarity epoch which ended about 0.73 m.y. B.P., although a short period of normal polarity also existed from 0.97 to 0.90 m.y. B.P. (Mankinen and Dalrymple, 1979). If this is an accurate date for the surficial flow of Antelope Flat (although it is not indicated as such), a minimum rate of displacement of about 0.14 mm/yr is indicated. An additional age date of 0.2 plus or minus 0.2 m.y. is given for a basalt flow capping Table Rock at the northwest end of Antelope Flat (Armstrong, et al., 1980). If this is the surficial flow, a rate 2 to 3 times greater is probable and is more likely, given the net fault slip reported by Royse (1983) see section I). Offset of these basalts is surely much greater than 100 m (300 ft). The young fault extends from the southeast along the eastern side of Swan Valley and crosses the graben and dies out rapidly at Conant Valley. A side stream (Pritchard Creek) of this rectangular shaped valley was observed to have multiple (at least four) sets of uplifted terraces. The northwestern side of the fault was upfaulted at Antelope Flat to form a natural dam across the Snake River. This caused thick accumulations of sediment in an upstream direction. A sediment thickness of 50 percent of the exposed offset is assumed to be conservative, suggesting a rate of over 0.2 mm/yr is a better approximation than 0.14 mm/yr. Detailed study of basalt flows and fault offsets could greatly refine this estimate. A recurrence interval of a few thousand years is suggested. These parameters appear to apply for the rest of the fault system south to Star and Thomas Fork Valleys in Wyoming. The southwestern side of the Snake River graben system, including the "Snake River fault" (see Witkind, 1975), has a much lower rate of activity, with displacement much less than 0.1 mm/yr and a recurrence interval of at least several tens of thousands of years. This fault does not noticeably offset a thick, uneven cover of loess.

The Bear Lake graben system has a rate of activity similar to the Snake River graben system, but differs in character. At Bear Lake, activity is highest and occurs along a narrow fault zone. Late Holocene displacement is indicated for this part of the fault by the presence of a very steep free face on a fault scarp. Activity remains on a narrow fault zone north to Blackfoot Reservoir, where it diffuses into a wide zone of extensional faults of smaller, more distributed ruptures. Activity along the Snake River graben is on a discreet fault zone to where it intersects, and is truncated by the Snake River Plain. Events in the diffuse graben system at the Blackfoot Reservoir are probably smaller in magnitude than those to the south, but some faults of this area appear quite active and young (e.g. along Tin Cup Creek, 8 km (5 mi) east of Wayan).

The Ms magnitude indicated by the linear regressions of Bonilla, et al. (1984), and Slemmons (1982) indicate magnitudes of about 7 1/4, and this value has a standard deviation of about 1/4 a magnitude value to give a maximum earthquake of about 7 1/2. The two highest magnitude earthquakes for normal faulting in western United States is slightly over 7 1/2 (Hebgen Lake in 1959 and Pleasant Valley in 1915). The maximum earthquake is assumed conservatively assumed to equal this value, although the 7 1/4 magnitude is based on an average fit for the data.

Parameters for faults discussed above are summarized in Table 1. The values given in this table are estimations only, but are within an order of magnitude.

PART III: CONCLUSIONS

Evidence for Quaternary activity exists near Ririe Dam along the edge of the Snake River Plain and along extensional graben systems. Fault swarms paralleling the Snake River Plain were observed to show geologically recent, probably Holocene offset within 0.3 km (0.2 mi) of the damsite. While two lineaments pass through the dam, they do not exhibit obvious offset. The faults around the dam are believed to be shallow features due to warping of the plain boundary and are assigned earthquake magnitudes of less then Ms = 7.

The major fault systems on the Snake River (Swan Valley and Star Valley) and Bear Lake graben systems appear to be listrically faulted and broken in segments of 50 km (30 mi) or less in length. The earthquake magnitudes for these faults are likely to be about Ms = 7 1/2 or less. The nearest of these segments is the Heise-Rexburg fault, at about 8 km (5 mi) surface distance from the site.

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APPENDIX D

FELT EARTHQUAKES IN THE GENERAL VICINITY OF RIRIE DAM (MM INTENSITY VI OR GREATER)

(from Stover, Reagor, and Algermissen, 1986, and Coffman, Von Hake, and Stover, 1982)

YEAR	DATE	TIME (GMT)	NORTH LATITUDE	WEST LONGITUDE	DEPTH	MAGNITUDE*	MM INTENSITY	DISTANCE FROM DAM-SITE (KM)	MM ATTENUATED INTENSITY
1884	10 NOV	850	42.00	111.30			VII	180	IV
1894	18 JUL	2250	41.20	112.00			VI	270	III
1909	06 OCT	241	41.80	112.70			VII	215	IV
1914	13 MAY	1715	41.20	112.00			VII	270	IV
1930	12 JUN	915	42.60	111.00			VI	130	IV
1932	26 JAN	1013	43.50	110.70			VI	87	IV
1934	12 MAR	1506	41.50	112.50		6.60UK	VIII	240	V
1934	12 MAR	1820	41.50	112.50		6.00UK	VII	240	IV
1934	15 MAR	1201	41.50	112.50		5.10ML	VI	240	III
1934	06 MAY	810	41.50	113.00		5.50UK	VI	255	III
1936	15 JAN	440	44.00	111.00			VI	75	IV
1947	23 NOV	946	44.80	112.00		6.20UK	VIII	137	VI
1948	24 FEB	2390	43.50	111.00			VI	62	V
1950	28 JUN	431	44.80	110.50			VI	170	III
1959	18 AUG	637	44.82	111.20		7.70ML	X	145	VIII
1959	18 AUG	842	44.80	110.70		6.00UK	VI	160	IV
1959	23 AUG	840	44.80	111.20			VI	145	IV
1959	05 SEP	1210	44.80	111.20			VI	145	IV
1959	13 SEP	1950	45.00	111.50			VI	160	IV
1959	03 NOV	1703	44.80	111.20			VI	145	IV
1960	07 AUG	1627	42.40	111.50	49.00		VI	136	IV
1962	30 AUG	1335	42.04	111.74	7.00	5.70ML	VII	172	III
1963	08 MAR	836	44.80	110.20	33.00	3.8mb	VI	185	III
1965	06 JAN	201	44.77	112.75	10.00	5.1mb 5.00Mn	VI	155	IV
1975	28 MAR	231	42.06	112.52	5.00	6.1mb 6.0Ms	VIII	187	V
1975	30 JUN	1854	44.68	110.62	2.00	5.6mb 5.9Ms	VII	152	V
1976	19 DEC	1710	44.77	110.80	5.00	4.9mb 4.5ML	VI	150	IV
1977	19 OCT	1651	44.77	111.81	10.00	4.7ML	VI	130	IV
1978	24 OCT	2031	42.55	111.84	7.00	4.2mb 4.1ML	VI	110	IV
1982	14 OCT	410	42.59	111.43	7.00	4.6mb 4.7ML	VI	114	IV
1983	28 OCT		44.05	113.89		7.3Ms	X	180	VII

* mb = Body-wave (Guttenburg and Richter, 1956)
ML = Local (Richter, 1958)
Mn = Nuttli (1973)
Ms = Surface-wave (Bath, 1966 or Guttenburg, 1945)
UK = Unknown magnitude

MODIFIED MERCALLI INTENSITY SCALE OF 1931

(Abridged)

I. Not felt except by a very few under especially favorable circumstances.

II. Felt only by a few persons at rest, especially on upper floors of buildings. Delicately suspended objects may swing.

III. Felt quite noticeably indoors, especially on upper floors of buildings, but many people do not recognize it as an earthquake. Standing motor cars may rock slightly. Vibration like passing of truck. Duration estimated.

IV. During the day felt indoors by many, outdoors by few. At night some awakened. Dishes, windows, doors disturbed; walls made cracking sound. Sensation like heavy truck striking building. Standing motor cars rocked noticeably.

V. Felt by nearly everyone; many awakened. Some dishes, windows, etc., broken; a few instances of cracked plaster; unstable objects overturned. Disturbance of trees, poles and other tall objects sometimes noticed. Pendulum clocks may stop.

VI. Felt by all; many frightened and run outdoors. Some heavy furniture moved; a few instances of fallen plaster or damaged chimneys. Damage slight.

VII. Everybody runs outdoors. Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable in poorly built or badly designed structures; some chimneys broken. Noticed by persons driving motor cars.

VIII. Damage slight in specially designed structures; considerable in ordinary substantial buildings with partial collapse; great in poorly built structures. Panel walls thrown out of frame structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned. Sand and mud ejected in small amounts. Changes in well water. Disturbed persons driving motor cars.

IX. Damage considerable in specially designed structures; well designed frame structures thrown out of plumb; great in substantial buildings, with partial collapse. Buildings shifted off foundations. Ground cracked conspicuously. Underground pipes broken.

X. Some well-built wooden structures destroyed; most masonry and frame structures destroyed with foundations; ground badly cracked. Rails bent. Landslides considerable from river banks and steep slopes. Shifted sand and mud. Water splashed (slopped) over banks.

XI. Few, if any (masonry), structures remain standing. Bridges destroyed. Broad fissures in ground. Underground pipe lines completely out of service. Earth slumps and land slips in soft ground. Rails bent greatly.

XII. Damage total. Waves seen on ground surfaces. Lines of sight and level distorted. Objects thrown upward into the air.

Figure D1. Modified Mercalli Intensity Scale of 1931 (abridged) (from Barosh, 1969)