Seismotectonic Study

for
Monks Hollow Dam and Reservoir Site
Central Utah Project, Utah

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SEISMIC SOURCES, MAXIMUM CREDIBLE EARTHQUAKES, AND RELATED SEISMIC HAZARDS FOR MONKS HOLLOW DAMSITE

Central Utah Project, Utah

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SUMMARY

The most likely sources for earthquakes in the vicinity of Monks Hollow Dam are the Wasatch fault with a Maximum Credible Earthquake (MCE) of M_S = 7 1/2 at a distance of 15 km, the Little Diamond Creek fault with an MCE of M_S = 6 3/4 at a distance of 6 km, and a random earthquake source with an MCE of M_L = 6 to 6 1/2 in the immediate vicinity of the dam. A north-trending normal fault has been identified in the foundation of the proposed dam, but geologic evidence shows that there has been no surface displacement on this fault since at least 350,000 years ago. Therefore, no surface *displacements should be considered in the design and analysis of the dam.*

Geologic studies have also shown that other north-trending normal faults in the vicinity of the dam need not be considered potential sources for large-magnitude earthquakes. Longitudinal stream profiles constructed from the correlation of middle and late Quaternary terrace remnants along the Diamond Fork River project across the Sams Canyon fault zone and the F-series faults. These profiles show no evidence of disruption, indicating that no surface displacements have occurred on these faults in at least the last 150,000 years. In addition, exposures of undisturbed, dated alluvial deposits overlying the F5 fault preclude surface displacements on this fault in at least the last 350,000 years. The faults in the vicinity of the dam are within and adjacent to the Diamond Fork anticline, a north-trending fold in the upper plate of the late Cretaceous Charleston thrust fault. The Sams Canyon fault zone displaces lower Tertiary rocks on the east margin of the anticline about 2 km west of the damsite; north-trending normal faults, the F-series faults, have been mapped in the crest of the fold in the immediate vicinity of the dam.

The ISB (Intermountain seismic belt) is a 100-km-wide zone of contemporary seismicity on the eastern margin of the Basin and Range Province that is considered to have the highest level of earthquake risk in the United States outside of California and Nevada. Physiography, north-trending late Cenozoic and late Quaternary normal fault patterns, and geologic and seismologic studies of historical earthquakes show that the late Cenozoic evolution of this region has been dominated by generally east-west crustal extension. Large-magnitude earthquakes (M > 6 3/4) have occurred at focal depths of 10 to 15 km on mapped faults with an identifiable history of late Quaternary (<125,000 years) surface displacements, and future large-magnitude earthquakes are also expected to occur on late Quaternary faults. Moderate-magnitude earthquakes (M < 6 3/4) have occurred at depths of 8 to 15 km on "blind" faults that have not been mapped at the surface, and future moderate-magnitude earthquakes can be expected to occur in the vicinity of any site in the ISB.

The proposed Monks Hollow Dam and Reservoir are located in the southern Wasatch Mountains on the Diamond Fork River, a tributary of the Spanish Fork which flows into Utah Lake south of Provo, Utah. Conceptual design studies for a 103 m (339 ft) high, 235 m (770 ft) long, double-curvature arch dam have been completed. The proposed 30,000 acre-ft reservoir will have a maximum water depth of about 70 m (230 ft). This report provides MCEs (Maximum Credible Earthquakes) for design and analysis of the dam, discusses other seismotectonic hazards to the dam and reservoir, and supersedes the preliminary assessment of earthquake hazards for Monks Hollow damsite

provided in our memorandum of August 12, 1981. The level of investigation conducted for this report, together with the Central Utah Regional Seismotectonic Study (Sullivan and others, 1986), are considered adequate for final design considerations. No further seismotectonic investigations are recommended at this time.

1. MAXIMUM CREDIBLE EARTHQUAKES AND RELATED SEISMIC HAZARDS

Maximum Credible Earthquakes (MCEs) for potential seismic sources of moderate- and large-magnitude earthquakes in the vicinity of Monks Hollow Damsite are: an MCE of M_S = 7 1/2 for the Wasatch fault at a distance of 15 km, an MCE of M_S = 6 1/2 to 6 3/4 for the Little Diamond Creek fault at a distance of 6 km, and an MCE of M_L = 6 to 6 1/2 for the random earthquake in the immediate vicinity of the dam (table 1). No additional, significant seismic hazards related to the construction of the dam have been identified.

Table 1 - Maximum Credible Earthquakes for Monks Hollow Dam

Earthquake Source	MCE (M_S)	Closest approach to site (km)	Focal depth (km)	Average Return Period (ka)
Wasatch fault	7 1/2	15	10-15	1.7 - 3.0*
Little Diamond Creek fault	6 1/2 to 6 3/4	6	10-15	25 - 100**
Random earthquake	6 to 6 1/2***	local	8-15	N/A

*Schwartz and Coppersmith (1984)
**estimated from data on other late Quaternary faults in the region (Sullivan and others, 1986)
*** M_L

1.1 Maximum Credible Earthquakes

Both seismologic and geologic studies indicate that normal faulting in response to east-west extension is the principal mode of deformation in the back valleys of the Wasatch Mountains where Monks Hollow Damsite is located. The Maximum Credible Earthquakes (MCEs) discussed in this section are considered dip-slip earthquakes that are associated with northerly trending normal faults. The focal depth of these earthquakes is estimated to be 10 - 15 km. The identification of these sources (fig. 1) and the estimates of MCEs for these sources are based on the results of previously published investigations and the results of unpublished seismological and geological investigations reported in the Central Utah Regional Seismotectonic Study (Sullivan and others, 1986).

1.1.1 Wasatch fault

An MCE of M_S = 7 1/2 is estimated for the Wasatch fault based on the detailed studies reported by Schwartz and Coppersmith (1984). These studies indicate that the single-event, late Quaternary rupture length of segments of the fault is > 30 km and that Holocene, single-event surface displacements have been > 2 m. These investigators concluded that paleoearthquakes with magnitudes of 6 1/2 to 7 1/2 occurred on the fault during the last few thousand years. We concur with this interpretation and assign an MCE of M_S =

7 1/2 to the Wasatch fault. At its closest approach, the surface trace of the Wasatch fault is 15 km from Monks Hollow Dam (table 1).

1.1.2 Little Diamond Creek fault

An MCE of M_S = 6 3/4 is estimated for the Little Diamond Creek fault. This fault is considered to be a potential seismic source because we infer that late Quaternary displacements have occurred on the fault. This fault has characteristics similar to other normal faults in the back valleys of the Wasatch Mountains where trench data has shown that late Quaternary surface displacements have occurred. Based on an estimated single-event, late Quaternary rupture length of 12 km, an MCE of magnitude M_S = 6 1/2 to 6 3/4 has been assigned to the Little Diamond Creek fault (Sullivan and others, 1986). At its closest approach, the Little Diamond Creek fault is 6 km from Monks Hollow Dam (table 1).

1.1.3 Random earthquake

A local, random earthquake of M_L = 6 1/2 that could occur on faults that are not expressed in the surface geology should be considered a potential seismic source for Monks Hollow Damsite and all sites within the Intermountain seismic belt (ISB). Calculations of probabilistic epicentral distances from geologic and seismologic data show that for annual probabilities of occurrence of 1/50 000 to 1/100 000 an earthquake of magnitude 6 or greater could occur within 5 km of any site in this portion of the ISB (Sullivan and others, 1986). As the threshold for surface faulting in the ISB is within the magnitude range 6 to 6 3/4, an MCE of M_L = 6 1/2 has been assigned to this random earthquake source (Sullivan and others, 1986). This random earthquake should be considered a local event that could occur in the immediate vicinity of Monks Hollow Damsite.

1.2 Surface displacement on faults in the dam foundation and reservoir

No potential for surface displacement on faults in the foundation and reservoir needs to be considered in the design and analysis of the proposed Monks Hollow Dam. Detailed mapping has shown that a series of north-trending normal faults are present at Monks Hollow Damsite (pl. 1). Although the strike of these faults suggests they may have developed as a result of Cenozoic extension (Young, 1978), they lack the topographic expression that characterizes late Quaternary faults in the back valleys of the Wasatch Mountains (Sullivan and others, 1986). The preliminary alignment of the dam axis showed the right abutment crossing one of the faults, the F5 fault (USBR, 1986). The dam alignment has not been finalized, but the current design plan is to place the right abutment of the dam downstream of the F5 fault. This fault is overlain by stratified gravel and sand deposits in a terrace remnant with an estimated age of at least 350, 000 years. This exposure provides direct evidence that, with resolution of a few cm, there has been no surface displacement on this fault in at least the last 350 ka. Although we have concluded that subsidence associated with moderate-magnitude events may be localized as discrete displacements on favorably oriented, preexisting faults in the ISB (Sullivan and others, 1986), the evidence provided by the undisplaced terrace deposits across the F5 fault shows that even small discrete displacements have not occurred on this fault in the last 350 ka. We conclude that surface displacement on this fault, in association

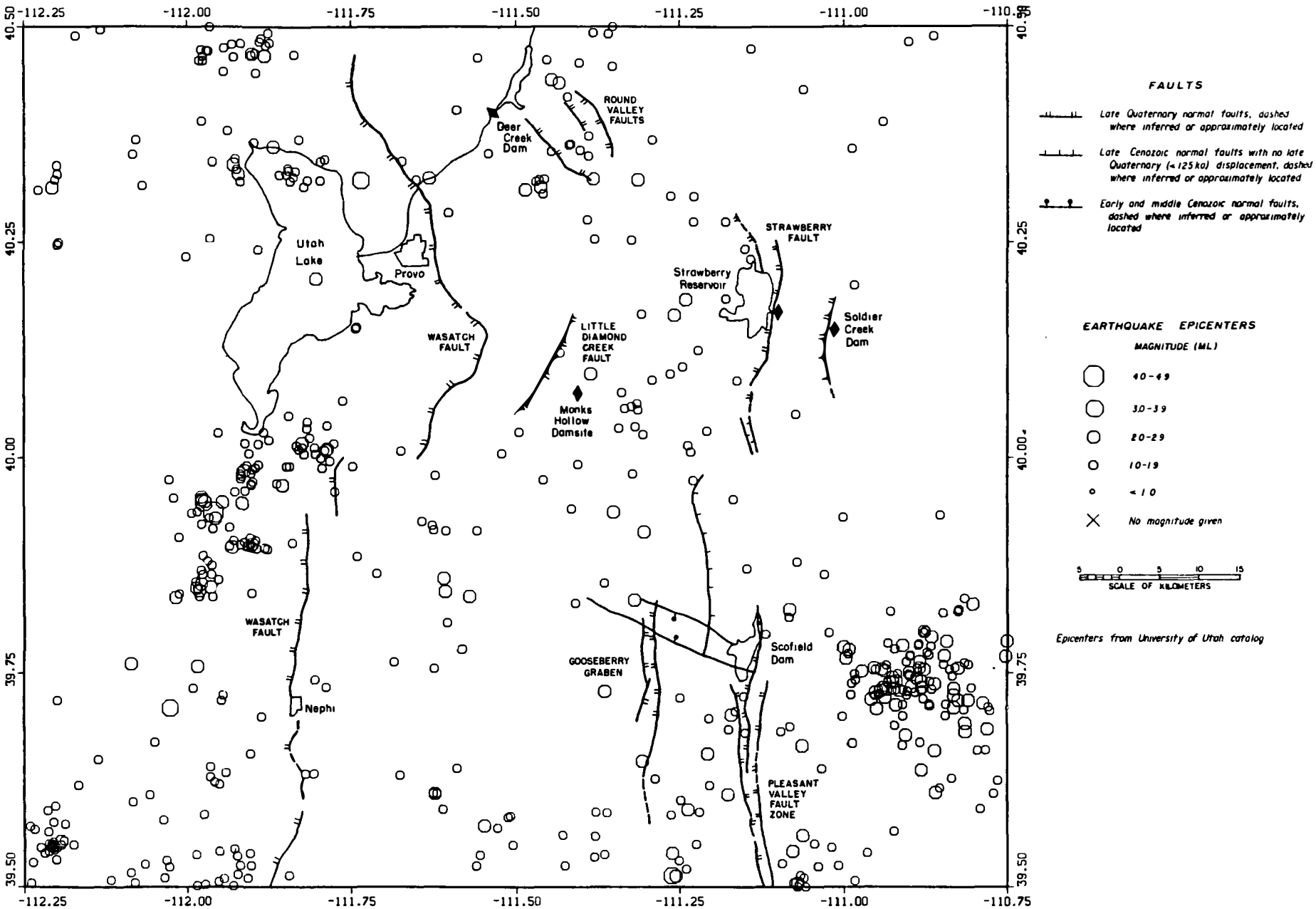


Figure 1 – Late Quaternary faults and historical seismicity (October, 1974 – March, 1986) in the vicinity of Monks Hollow Damsite. Late Quaternary fault are considered potential sources for large-magnitude earthquakes.

with any of the proposed MCEs, should not be considered in the analysis of Monks Hollow Dam.

1.3 Reservoir induced seismicity

Small- and moderate-magnitude earthquakes have resulted from the impounding of reservoirs (Sullivan and others, 1986). These earthquakes are thought to be naturally occurring events that are triggered prematurely by the presence of the reservoir. Large, deep reservoirs overlying young faults seem to be the most susceptible to reservoir-induced seismicity. Although faults are present in the proposed Monks Hollow Reservoir, investigation has shown that no surface displacements have occurred on these faults in at least the last 350 ka. The structural height of the proposed dam (103 m) is that of a large dam, but the reservoir volume (30,000 acre-feet) is small. Although induced seismicity is a possibility at Monks Hollow Damsite, the magnitudes of induced earthquakes are likely to be small. The largest induced earthquakes are not expected to exceed the MCE proposed for the random earthquake.

1.4 Scope of work

This seismotectonic report for Monks Hollow Damsite provided MCEs (Maximum Credible Earthquakes) for design and analysis of the dam, discussed other seismotectonic hazards to the dam and reservoir. These conclusions supersede the preliminary assessment of earthquake hazards for Monks Hollow Damsite provided in a memorandum of August 12, 1981. The conclusions presented in this report were developed from a review of published and unpublished literature, the results of USBR site geologic investigations, recently completed regional seismotectonic investigations in central Utah reported by Sullivan and others (1986), and field investigations in the area near the damsite. These field investigations included: 1) mapping of the Sams' Canyon and F-series faults (Pl. 1) by geologists from the Bonneville Construction Office and the Seismotectonic Section; 2) field checking of lineaments identified during a review of aerial photographs; 3) description of soil profiles in test pits; 4) preparation of a terrace profile along the Diamond Fork river; and 5) logging and sampling of a trench at the damsite.

The level of investigation conducted for this report, together with the investigations reported in the Central Utah Regional Seismotectonic Study (Sullivan and others, 1986), are consistent with previous USBR practice for dams in the ISB and elsewhere. The conclusions provided in this report are recommended for use in final design considerations for Monks Hollow Dam.

No further seismotectonic studies are recommended for Monks Hollow Damsite.

2. SEISMIC SOURCES IN THE BACK VALLEYS AND THE INTERMOUNTAIN SEISMIC BELT

Monks Hollow Damsite is located in the back valleys of the southern Wasatch Mountains where the late Quaternary displacement history of normal faults, considered together with the principal characteristics of historical seismicity in this Utah portion of the ISB, suggests that two types of seismic sources are important: 1) a large-magnitude source associated with normal faults that exhibit evidence of recurrent late Quaternary surface displacements, and 2) a moderate-magnitude source associated with subsurface, blind faults that are not expressed in the surface geology.

2.1 Late Quaternary faults in the back valleys of the southern Wasatch Mountains

Observations of both the late Quaternary geologic record and the record of historic surface ruptures in the ISB and the Basin and Range indicate that large-magnitude earthquakes occur repeatedly on normal faults with a history of late Quaternary surface displacements. MCEs for these faults are assumed to vary in magnitude from 6 1/2 to 7 1/2 depending on the length of late Quaternary surface rupture and the size of individual surface displacements. Identification of the faults which are the sources of these MCEs as well as estimates of the earthquake magnitude, the associated surface displacement (where needed), and the return period are based on geologic evidence from mapping and trenching studies. MCEs have been assigned to the late Quaternary faults in the vicinity of Monks Hollow Damsite--the Wasatch fault and the Little Diamond Creek fault.

Fault scarps have formed during three historic earthquakes in the ISB: the 1934 Hansel Valley earthquake of M 6.6 (Shenon, 1936), the 1959 Hebgen Lake earthquake of M 7.5 (Myers and Hamilton, 1964), and the 1983 Borah Peak earthquake of M 7.3 (Crone and Machette, 1984). These historic surface ruptures have occurred on faults with a history of recurrent late Quaternary surface displacement events. Doser (1985) concludes that large-magnitude earthquakes nucleate at or near the base of the seismogenic zone at a depth of about 15 km and rupture to the surface along planar normal faults dipping 45° to 60° forming fault scarps on the updip projection of the causative faults. These characteristics are assumed for the late Quaternary faults that are considered potential sources of large-magnitude earthquakes.

Potential sources of large-magnitude earthquakes have been identified in the back valleys of the southern Wasatch Mountains (Sullivan and others, 1986). The back valleys are Cenozoic basins bounded by normal faults that are a part of a zone of northerly trending normal faults in the transition zone on the eastern margin of the Basin and Range Province. The crust in the Basin and Range Province has been thinned by crustal extension accommodated by late Cenozoic and late Quaternary normal faults that bound linear, north-trending range blocks. Further east the thicker crust of the Colorado Plateau and the Middle Rocky Mountains has been disrupted by early Cenozoic reverse and thrust faults. The intervening transition zone is an area characterized by early Cenozoic thrust faults and northerly trending late Cenozoic and late Quaternary normal faults. This zone extends east of the Wasatch fault about 100 km into the Colorado Plateau and Middle Rocky Mountains Provinces. In the southern Wasatch Mountains, late Quaternary displacement has been demonstrated on the Wasatch fault, the Strawberry fault, and the faults of

the Joes Valley Graben and has been inferred on the Little Diamond Creek fault and the faults in Round Valley (figs. 1 and 2).

2.1.1 Wasatch fault

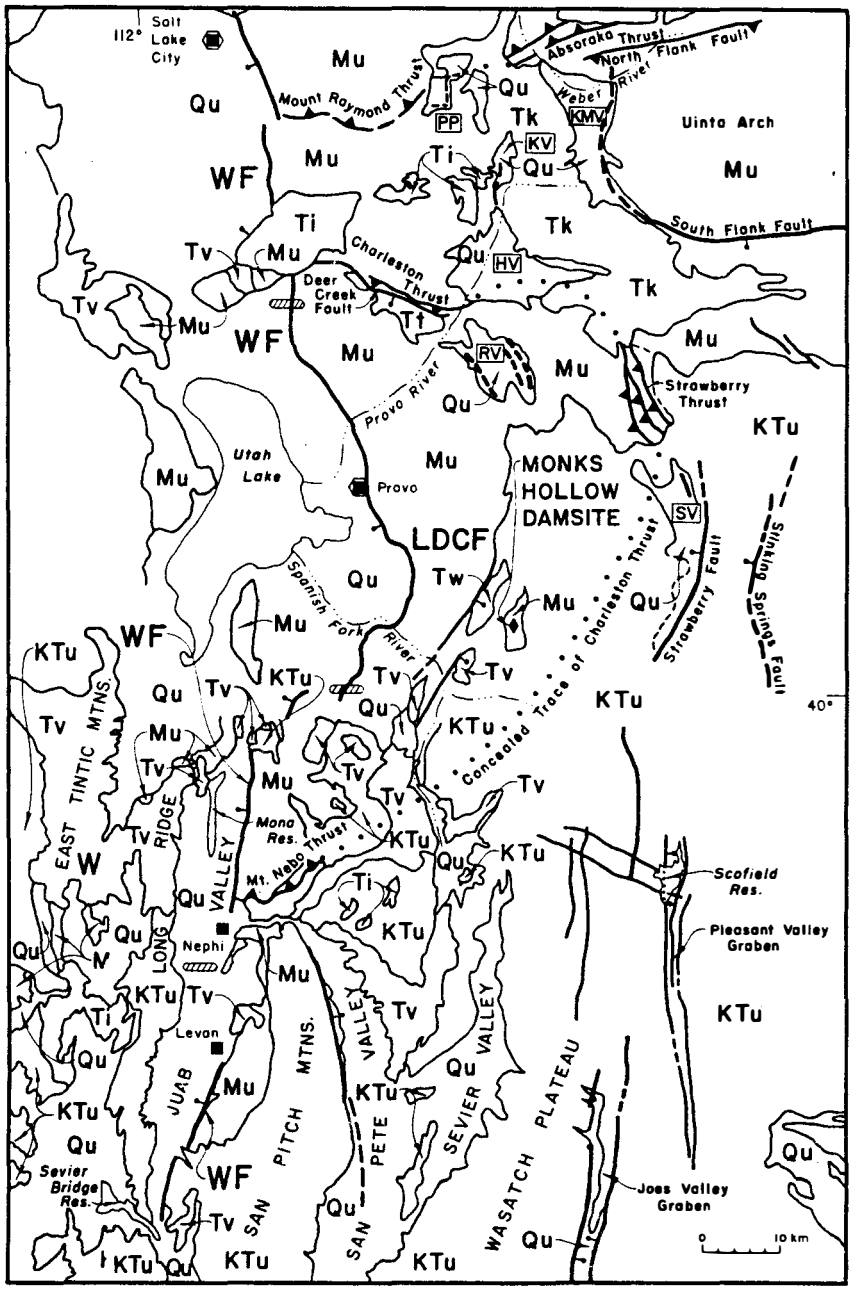
The Wasatch fault is the principal seismic source for large-magnitude earthquakes in the Utah portion of the ISB (figs. 1 and 2). Although other normal faults with evidence of recurrent late Quaternary surface displacements are known in the region, the Wasatch fault has experienced larger, Holocene, single-event surface ruptures and has a shorter estimated return period for surface displacements than other faults in the region.

The Wasatch fault is a major, late Quaternary, range-bounding normal fault marking the abrupt physiographic boundary between the Basin and Range and Colorado Plateau provinces. The fault extends 370 km north from Gunnison, Utah to Malad City, Idaho. The fault trace is mapped near the base of the triangular facets that form the west face of the Wasatch Mountains. Late Quaternary surface displacements are indicated by vegetation lineaments and scarps in lacustrine sediment of Lake Bonneville, late Pleistocene moraines and Holocene alluvial and colluvial deposits along the trace of the fault. Schwartz and Coppersmith (1984) recognize six major, segments of the Wasatch fault based on variability in timing of individual events, changes in scarp morphology, and fault geometry; Machette (1987) has more recently suggested that the fault may consist of as many as ten segments. Schwartz and Coppersmith (1984) suggest that characteristic, large earthquakes of similar size are associated with average surface displacements of 2 m or more and have an average recurrence interval for surface displacements of 444 yrs for the entire fault. The Provo segment of the fault, the closest to Monks Hollow Damsite, has an estimated recurrence interval for surface displacements of 1700 to 2600 years. Smith and Bruhn (1984) demonstrate a coincidence between some segment boundaries and location of lateral and sidewall ramps in late Cretaceous thrust faults, and suggest that pre-existing structure partly controls the position of segment boundaries of the Wasatch fault. They also present cross sections, based on seismic reflection profiles, depicting subsurface dips of the Wasatch fault that are less than the 60° to 80° dips of the surface scarps.

The lack of spatial correlation of earthquake epicenters with the mapped trace of late Cenozoic faults, particularly the Wasatch fault, has been a notable feature of the ISB in Utah since the initiation of earthquake monitoring. For the southern part of the Wasatch fault, based on local microseismic monitoring, McKee and Arabasz (1982) conclude that the lack of correlation of epicenters with the Wasatch fault is not simply due to poor epicentral resolution. Explanations currently under study relate to the orientation and behavior of the fault at depth. Zoback (1983) reviews and tabulates dips measured at the surface for the Wasatch fault and adjacent faults as well as focal mechanism solutions. McKee and Arabasz (1982, p. 143) present a "sanitized" section across the Wasatch fault based on proprietary seismic reflection profiles which depicts the fault shallowing in dip in the subsurface and becoming nearly horizontal at a depth of 6 to 7 km.

2.1.2 Little Diamond Creek fault

The southern segment of the Little Diamond Creek fault is considered a



EXPLANATION

Qu — Quaternary undivided
Tw — Middle or late Tertiary Wanrhodes volcanics
Tt — Middle Tertiary Tibbie Formation
Tk — Middle Tertiary Keetley volcanics
Ti — Middle Tertiary intrusives
Tv — Tertiary igneous rocks, undivided
KTu — Cretaceous and Early Tertiary sedimentary rocks, undivided
Mu — Jurrasic and older sedimentary rocks, undivided
▭ — Back valleys: PP = Parleys Park, KMV = Kamas Valley, KV = Keetly Valley, HV = Heber Valley, RV = Round Valley, SV = Strawberry Valley
— — Cenozoic normal faults, dashed where inferred, bar and bell on downthrown side, WF = Wasatch fault
▨ Wasatch fault segment boundaries (Schwartz and Coppersmith, 1984)
▲▲ Thrust faults, dotted where concealed

Figure 2 - Regional geology of north-central Utah including the back valleys of the Wasatch Mountains east of the Wasatch fault. The central Wasatch Mountains refers to the area between the Mount Raymond and Charleston thrusts. The southern Wasatch Mountains refers to the area south of the Charleston thrust and north of the Spanish Fork River. Monks Hollow damsite (◆) is in the center of the figure.

potential seismic source because geomorphic characteristics suggest that late Quaternary surface displacements have occurred on this portion of the fault (figs 1 and 2). The 12-km-long southern segment of the northeast-striking fault is marked by triangular facets and a vegetation lineament along the trace of the fault. Paleozoic sedimentary rocks form an escarpment in the footwall of the fault and mid-Tertiary volcanic rocks that are tilted about 20° into the fault form a syncline in the hanging wall (Baker, 1976; Young, 1978). Triangular facets as much as 400 m high are preserved in the Paleozoic rocks along a 12-km-long segment at the southern end of the Little Diamond Creek fault. A prominent air-photo lineament is also present at the base of the triangular facets. The triangular facets and the lineament on the trace of the fault are characteristic of late Quaternary faults identified elsewhere in the back valleys of the Wasatch Mountains.

Reconnaissance geologic investigations for this study have provided no direct evidence of the age of most recent displacement on the Little Diamond Creek fault. Low-sun-angle overflights and our review of aerial photos at scales of 1:58,000 and 1:15,400 revealed no scarps in unconsolidated deposits associated with the fault; however, they also showed that there were no areas along the fault where scarps might be expected to have been preserved for more than a few thousand years. The most promising location for evaluating the age of most recent displacement on this fault is in the canyon where Little Diamond Creek crosses the fault (fig. 3). The canyon is as much as 200 m deep on the hanging wall exposing the Uinta Formation and the overlying mid-Tertiary Wanrhodes volcanics. Within the canyon alluvial deposits are preserved across the trace of the fault. These deposits have been incised only about 1 m by the creek and have a weakly developed soil profile indicating they are of Holocene age. On the interfluves between the canyons that dissect the escarpment of the Little Diamond Creek fault, colluvial deposits, probably of late Quaternary age, are draped across the trace of the fault at the base of the escarpment. No scarps are preserved in these deposits, but investigations of the Morgan fault in the northern Wasatch Mountains (Sullivan and others, 1986) showed that small scarps (<1 m) at or near the base of a similar bedrock escarpment were removed in less than 10 ka. Trench investigations may have provided useful information about the age of most recent displacement on the fault, but deep incision of the hanging wall deposits precludes backhoe access to suitable trench sites.

The presence of deformed mid-Cenozoic rocks and the triangular facets preserved on the footwall escarpment suggest that the late Quaternary displacement history of the Little Diamond Creek fault is similar to that of the Morgan and Strawberry faults where trenches exposed displaced late Quaternary deposits (Sullivan and others, 1986; Nelson and VanArsdale, 1986).

The trench stratigraphy indicated that surface displacements of a meter or less had occurred on the Morgan fault (Sullivan and others, 1986, chap. 4.2). The Little Diamond Creek fault, as well as other faults discussed in Sullivan and others (1986), share common characteristics with the Morgan fault; therefore, we conclude that late Quaternary surface displacements of a meter or less have probably also occurred on a 12-km-long segment of the Little Diamond Creek fault.

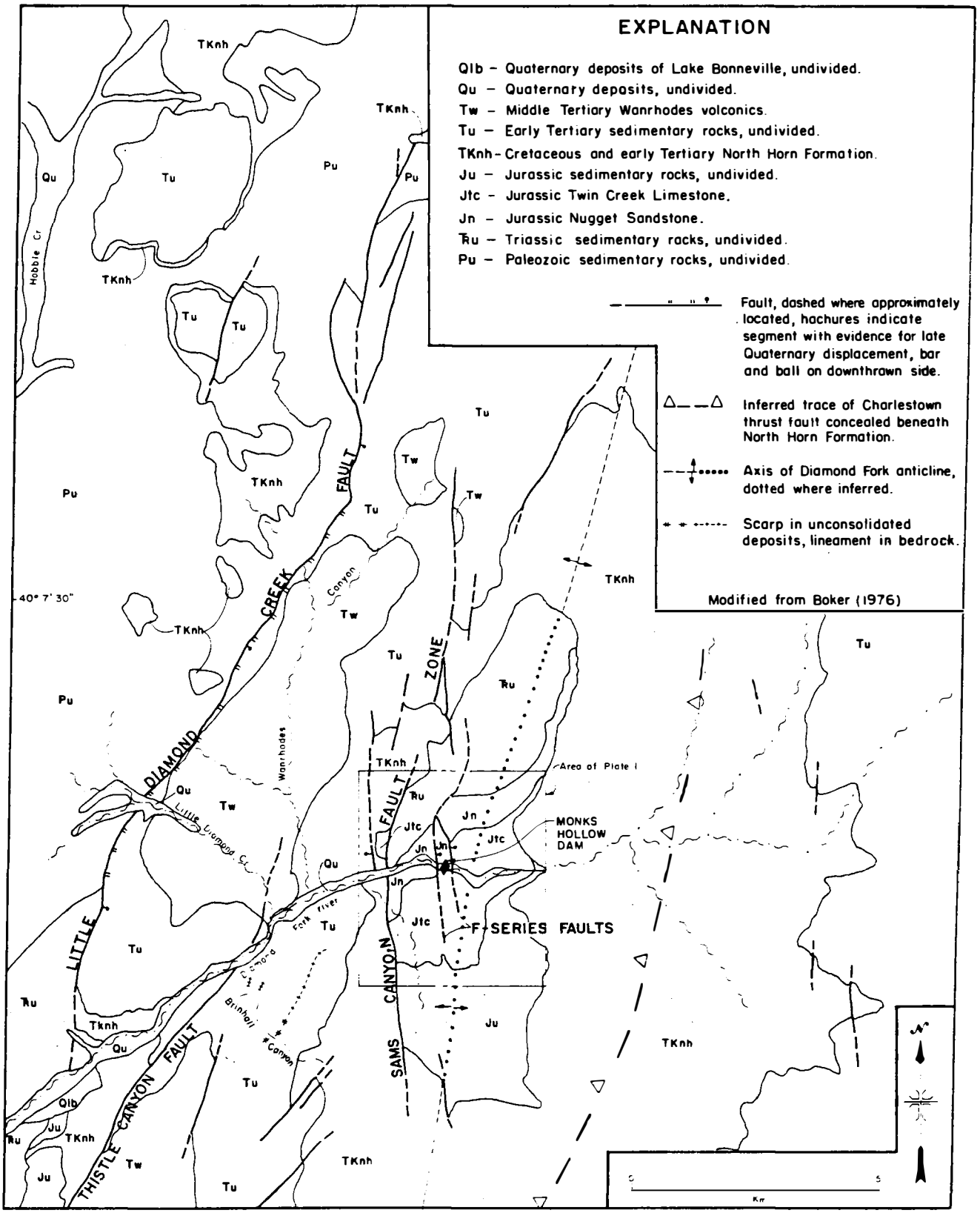


Figure 3 - Faults and generalized geology of a portion of the southern Wasatch Mountains. Southern portion of the Little Diamond Creek fault is considered as potential seismic source for Monks Hollow Damsite (♦). The area of Plate 1 is also shown.

2.1.3 Strawberry fault

Evidence from trenching of multiple fault scarps in alluvial fan deposits and bedrock near the north end of the Strawberry normal fault (fig. 2) and from coring of alluvial sediments near the south end of the fault indicate that late Quaternary surface displacements in the range 1 to 2 m have occurred on the Strawberry fault (Nelson and VanArsdale, 1986). The late Quaternary slip rate on the Strawberry fault is in the range of 0.03 to 0.17 mm/yr. which is similar to the slip rates for other late Quaternary faults in the back valleys of the Wasatch Mountains (Sullivan and others, 1986). The north-trending Strawberry fault bounds the east side of Strawberry valley about 25 km east of Monks Hollow, where it forms a single 28 km-long, west-facing bedrock escarpment, 100 to 230 m high in the Eocene Uinta Formation. While discrete triangular facets are not evident, the steep slope and oversteepened base of the escarpment suggest recent surface displacements. Royse (1983) has suggested that the fault is related to the underlying Strawberry Thrust fault, that is exposed north of Strawberry Valley (Astin, 1977).

2.1.4 Round Valley

The preservation of triangular facets and the linearity and steepness of escarpments in the Pennsylvanian quartzite on the margins of Round Valley suggest that late Quaternary surface displacements have occurred on faults in the valley (Sullivan and others, 1986). Round Valley is 12-km-long, 6-km-wide basin that it is located 30 km north of Monks Hollow and 2 km south of Heber Valley (fig. 2). Review of aerial photography revealed no fault scarps in unconsolidated deposits along the margins of the valley; however, three, 0.5-1-km-long, northwest-trending vegetation lineaments were observed on the fans along the southwest margin. The lineaments trend discontinuously across the middle portion of two fans parallel to the mountain front in the northwestern part of the valley. A trench excavated across one of the lineaments south of the Main Creek inlet of Deer Creek Reservoir showed no evidence of faulting, but a sequence of interbedded debris flow and loess-slopewash units is cut by a fan stream channel (Sullivan and others, 1986, their fig 6.2).

2.1.5 Wasatch Plateau

Trenches across scarps in late Pleistocene deposits described by Foley and others (1986) provide documentation of late Quaternary displacements on 30-to 70-km-long segments of faults in the Joes Valley graben (fig. 2) on the Wasatch Plateau. Six backhoe trenches were excavated across fault scarps associated with three faults in the graben. Stratigraphic data from these trenches, in addition to scarp heights measured in upper Pleistocene deposits, were used to estimate apparent vertical surface displacements of <1 to >5 m, and average recurrence intervals for surface displacements of 10 to 20 ka (Foley and others, 1986). Three other major fault zones on the Wasatch Plateau exhibit characteristics associated with late Quaternary surface faulting: the Pleasant Valley, Snow Lake, and Gooseberry fault zones (Foley and others, 1986).

2.2 Seismicity

Monks Hollow Dam is located within the Intermountain seismic belt (ISB), a

100-km-wide zone of contemporary seismicity on the eastern margin of the Basin and Range. Centered approximately on the Wasatch fault in central Utah, the ISB is considered to have the highest level of earthquake risk in the United States outside of California and Nevada (Arabasz and Smith, 1979). Commonly observed features of earthquake occurrence within the ISB have been described by Smith and Sbar (1974), Smith (1978) and Arabasz and Smith (1981). Among these features are: 1) diffuse seismicity which shows only general correlation with locations exhibiting late Quaternary surface faulting; 2) an apparent lack of correlation between small to moderate-magnitude earthquakes and mapped faults; 3) shallow focal depths (less than 15 to 20 km); 4) sporadic occurrence of earthquakes both spatially and temporally; and 5) a persistent pattern of normal faulting indicating predominantly east-west extension (Sullivan and others, 1986).

Eight historical earthquakes of M 6 or greater have occurred in Utah (fig. 4). The largest of these events is the 1934 M 6.6 Hansel Valley earthquake, the only earthquake in Utah to have been accompanied by documented surface faulting (Shenon, 1936). Aftershock studies of recent moderate-magnitude earthquakes including the 1962 Cache Valley earthquake of M 5.7, the 1972 Heber earthquake of M 4.3, and the 1975 Pocatello Valley earthquake of M 6.0 have indicated that these events occurred at depths of 8-12 km on faults that can not be identified at the surface. These observations suggest that seismic slip manifested as background seismicity is occurring on moderate to high-angle segments of blind faults that have no surface expression (Arabasz and Smith, 1981; Arabasz and Julander, 1986). These observations form the basis for considering a random earthquake as a seismic source for Monks Hollow Damsite.

On figure 1 two principal clusters of activity are discernable. South of Utah Lake a diffuse pattern of microseismicity occurs in Goshen Valley including earthquakes of magnitude 3.5 and 4.4. Fault plane solutions for seismicity in Goshen Valley all indicate normal faulting on possible fault planes striking northeast to northwest, but the tectonic significance of the activity has not been determined (McKee and Arabasz, 1982). Another cluster of activity east of Scofield Dam is related to coal mining activity. A number of earthquakes with magnitudes less than 3 occur within 15 km of Monks Hollow Damsite (fig. 1). This background activity appears unrelated to the faults identified in the vicinity of the damsite.

Reservoir-induced seismicity (RIS)--the occurrence of earthquakes as a result of impoundment of reservoirs-- has been generally acknowledged to have occurred at a number of sites around the world. The most destructive induced event was the 1967 M 6.5 Koyna, India event. The probability of occurrence of RIS increases greatly with reservoir depths greater than 92 m and volumes greater than 1,000 000 acre-ft (Baecher and Keeney, 1982). The presence of favorably oriented faults, and the magnitude and orientation of the crustal stress field are also important factors.

In order to assess the potential for RIS in the back valleys of the Wasatch Mountains the historical record of earthquakes (1850 to 1986) in the back valleys was analyzed (Sullivan and others, 1986, Appendix B) to determine if RIS had occurred at any of the 13 existing USBR reservoirs in the area. These dams, constructed between 1913 and 1973, have structural heights that range from 22 to 81 m. A statistical analysis of the seasonal frequency

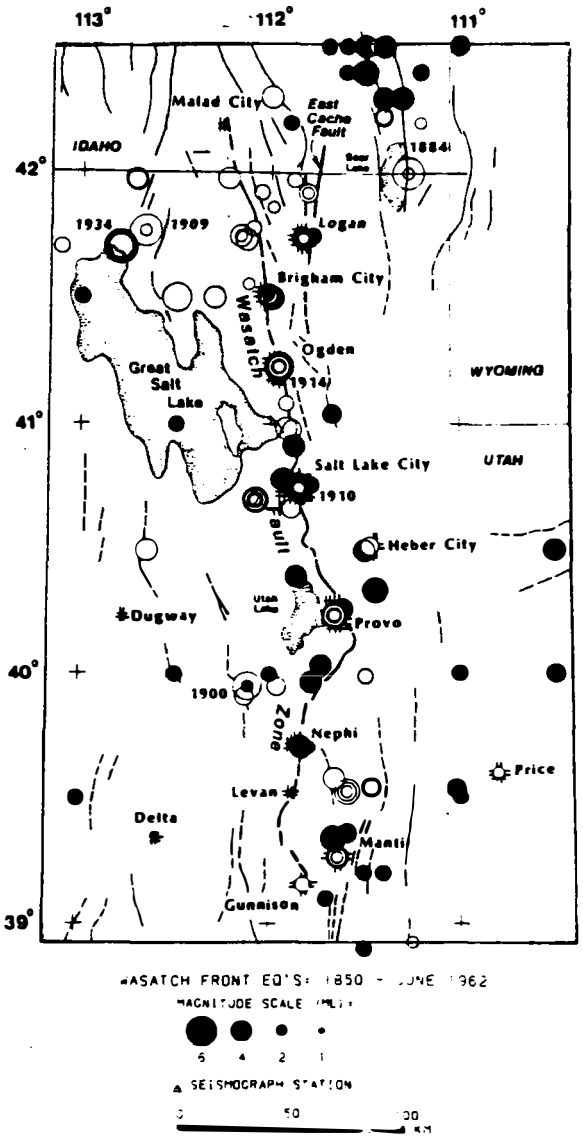


Figure 4 - Epicenter map of north-central Utah, 1850 to June 1962. Locations of 1850 to 1949 earthquakes shown as open circles, those for 1950 to 1962 as solid circles. Young faults shown for reference. Significant events labelled by year. From Arabasz and others (1980).

indicated that no seasonal increase in the rate of earthquake occurrence had occurred at any of the 13 USBR existing dams in the region; histograms of earthquake occurrence over time do not indicate increased seismic activity upon the initial filling of any of the existing USBR reservoirs. This evidence suggests that the potential for RIS may be low. However, a number of factors suggest that RIS could occur at Monks Hollow Dam. The structural height of Monks Hollow Dam (103 m) exceeds the empirical criteria of 92 m, although the reservoir volume is small. Crustal stress directions determined from hydrofracture studies on drill holes in the area (Haimson, 1981; Zoback, 1981) indicate that north-trending normal faults (F-series faults) below the deepest portion of the reservoir are favorably oriented for stress release. The magnitude of the principal stresses determined from the hydrofracture studies indicate a potential for induced earthquakes (Haimson, 1981; Zoback, 1981).

3. FAULTS IN THE VICINITY OF MONKS HOLLOW DAMSITE

Geologic studies have shown that no late Quaternary displacement has occurred on north-trending normal faults mapped in the vicinity of the damsite. Terrace profiles--reconstructed from Quaternary terrace remnants preserved along the Diamond Fork that have been correlated on the basis of height above the river and soil profile development--indicate that there has been no discernible surface displacement on the Sams Canyon fault zone, 2 km downstream of the dam, or the F-series faults, at the damsite, in at least the last 130 to 150 ka and 350 ka, respectively.

Quaternary deposits and landforms mapped along the Diamond Fork between Monks Hollow and the confluence of the Diamond Fork and Spanish Fork Rivers include alluvium in fans and terraces, colluvium on hillslopes, landslide deposits on the north side of the river near the right abutment of the proposed dam, and deposits of Lake Bonneville that are present in terraces at the western edge of the study area (fig. 3 and pl. 1). At several localities terrace remnants occur on or near projections of faults mapped in the bedrock. The age of these terraces is important to reconstructing the Quaternary displacement history of the faults in this area.

3.1 Quaternary terraces on the Diamond Fork

Reconstructed terrace profiles that slope parallel to the Diamond Fork channel project across faults mapped in the vicinity of the damsite indicating that displacements greater than the resolution of the profile measurements (1.5 m) or the projections (5 m) have not occurred since deposition of the terrace remnants. Remnants of nine alluvial surfaces are preserved along the sides of the Diamond Fork Valley over a distance of 13 km between its confluence with the Monks Hollow drainage on the east and the Spanish Fork River on the west. Using a computer-assisted photogrammetric mapping system (PG-2 plotter), these terraces were mapped on aerial photographs at a scale of 1:15,840 and on a U.S. Geological Survey topographic map at a scale of 1:24,000 (Billies Mtn. Quadrangle). Longitudinal terrace profiles that reconstruct past positions and gradients of the Diamond Fork were then prepared using this quadrangle as a base (fig. 5). The terrace remnants were correlated on the basis of their height above the modern Diamond Fork floodplain, the extent of dissection of their surfaces, and, where exposures were either available or excavated, the relative degree of soil development on their surfaces. Using the PG-2 plotter, the elevations of the terraces could be measured with an accuracy of about +/- 1.5 m. The characteristics of these terraces are summarized in table 2.

Numerical age data for the Quaternary terrace deposits on the Diamond Fork are available from two sources: (1) amino acid ratios of gastropod shells found in alluvial deposits in the right abutment area of the proposed dam and (2) a correlation of terraces at the western edge of the study area with lake levels of Lake Bonneville that have been numerically dated elsewhere (Scott and others, 1983). Additional chronological information was obtained by relative age dating of terraces using soil profile characteristics (tables 3 and 4).

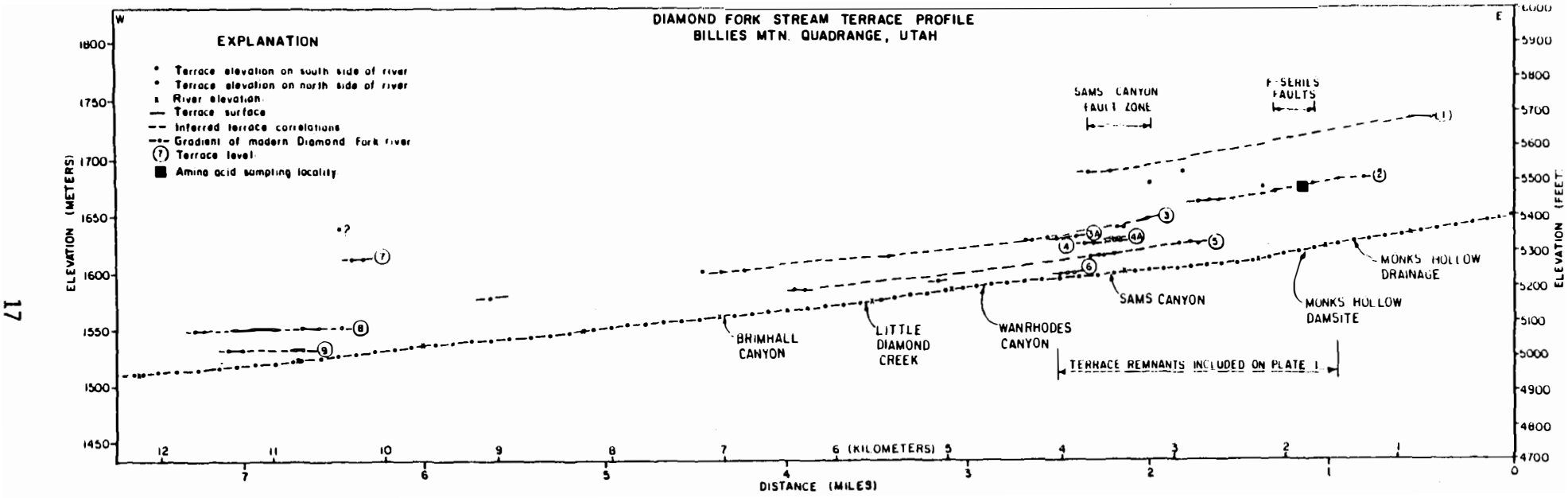


Figure 5 - Longitudinal profile of stream terraces on the lower Diamond Fork River.

Table 2 - Quaternary terraces on the Diamond Fork River and tributaries near Monks Hollow Damsite

TERRACE	HEIGHT above modern base level (m)	ESTIMATED AGE (ka)	RELATIVE AGE GROUP*	SOIL PROFILE NUMBER	DESCRIPTION
Qt9	9-15 (el. 1532 m)	13-16			terrace on south side of Diamond Fork River inferred to be deposits of Lake Bonneville
Qt8	24-33 (el. 1548 m)	13-16			terrace on south side of Diamond Fork River inferred to be deposits of Lake Bonneville
Qt7	83	>250			One remnant on north side of Diamond Fork River
Qt6	5	15-18			1 remnant on south side Diamond Fork River
Qt5	16	15-18			6 remnants on north side Diamond Fork River
Qt4,4A	26-29	>150 - >350	2	DF-3,5	2 remnants on south side Diamond Fork River
Qt3,3A	36-39	>150 - >350	2	DF-1,2,4	8 remnants on north and south sides of Diamond Fork River
Qt2	55	>350	2	DF-6	5 remnants on north and south sides of Diamond Fork River; amino acid ratios for snails in trench 2 suggest a mid-Pleistocene (>250 ka) age for this terrace
Qt1	87	>(350 - 730)			3 remnants on both north and south sides of the Diamond Fork River
Qt	variable	variable			Terrace remnants not included in terrace profile study
QTt	> 90	>730			Terraces > 90 m above base level, undifferentiated

* Relative age groups assigned based on the comparison of soil profile development with soils described in Sullivan and others (1986).

Table 3: Selected horizon properties of soil profiles described in the Diamond Fork drainage, Utah

Profile	Horizon	Depth (cm)	Parent Material	Munsell color (dry)	Texture	--- % clasts >2 mm --- pebbles	cobbles	boulders	Carb. stage /1	% CO_3 /2	% O.M./3	% sand /4	% silt /4	% clay /4
DF-1	Bt1	0-7	fluvial gravels	5YR 4/7	c	20	5	0	-	0.6	1.1	36.7	19.4	43.9
	Bt2	7-18	fluvial gravels	5YR 4/7	c	20	5	0	-	1.5	1.0	41.4	18.1	40.5
	Bk1	18-59	fluvial gravels	7.5YR 6/5	scl	40	20	10	I+	23.6	0.6	57.7	14.6	27.7
	Bk2	59-93	fluvial gravels	7.5YR 6/4	sl	40	20	10	II	23.2	0.4	66.6	13.7	19.7
	Bk3	93-145	fluvial gravels	7.5YR 6/5	sl	40	20	10	II+	20.8	0.4	68.4	13.2	18.4
	C	145-190	fluvial gravels	7.5YR 6/0	ls	50	20	10	-	0.4	0.6	80.6	11.7	7.7
DF-2	A1	0-7	colluvium	7.5YR 5/3	sl	5	0	0	-	16.8	0.4	66.1	14.4	19.5
	A2	7-25	colluvium	7.5YR 5/3	sl	5	5	10	-	0.3	1.2	77.7	12.5	9.8
	B	25-40	colluvium	7.5YR 4/5	sl	5	5	0	-	0.3	0.9	63.4	20.2	16.4
	2Bt1	40-95	fluvial gravels	5YR 4/7	scl	40	10	0	-	0.4	0.9	46.2	20.3	33.5
	2Bt2	95-123	fluvial gravels	5YR 4/7	scl	40	20	10	-	0.7	0.8	47.0	22.4	30.6
	2BC	123-154	fluvial gravels	7.5YR 5.5/5	scl	40	20	25	I-	6.6	0.9	55.5	18.0	26.5
DF-3	A1	0-8	colluvium	10YR 5/3	sil	5	0	0	-	0.6	4.9	28.8	54.3	16.9
	A2	8-20	colluvium	10YR 5/3	sil	5	0	0	-	0.4	2.2	28.1	52.9	19.0
	A3	20-47	colluvium	10YR 5/3	sil	5	0	0	-	0.2	1.4	27.6	51.6	20.8
	2Bt1	47-61	colluvium	7.5YR 5/4	cl	15	5	5	-	0.2	1.1	29.8	39.5	30.7
	3Bt2	61-87	fluvial gravels	5YR 4/4	cl	25	15	20	-	0.3	0.7	43.0	27.3	29.7
	3Bt3	87-148	fluvial gravels	5YR 4/7	scl	40	10	25	-	0.4	0.6	47.7	25.8	26.5
	3Bt4	148-170	fluvial gravels	5YR 4/7	scl	40	10	25	-	5.4	0.8	45.3	24.5	30.2
DF-4	A1	0-10	colluvium	10YR 5/2.5	sil	5	0	0	-	0.1	3.7	30.5	51.8	17.7
	A2	10-46	colluvium	10YR 5/2.5	sil	5	0	0	-	0.7	3.1	30.9	52.0	17.1
	B	46-58	colluvium	7.5YR 4/3.5	l	5	5	0	-	0.4	1.4	29.7	46.7	23.6
	2Bt1	58-75	colluvium	7.5YR 4.5/6	cl	15	0	0	-	0.4	0.8	41.7	25.6	32.7
	3Bt2	75-118	fluvial gravels	5YR 3/4	c	20	20	10	-	0.6	1.0	39.1	16.9	44.0
	3Bt3	118-147	fluvial gravels	5YR 3/4	c	20	20	20	I-	0.7	0.9	35.9	17.6	46.5
	3BC	147-191	fluvial gravels	5YR 4/6	sl	20	20	20	I	15.4	0.6	61.7	19.1	19.2
DF-5	A1	0-6	colluvium	7.5YR 4/3	l	5	0	0	-	n.d.	n.d.	n.d.	n.d.	n.d.
	A2	6-25	colluvium	7.5YR 4/3	l	5	0	0	-	n.d.	n.d.	n.d.	n.d.	n.d.
	2Bt1	25-38	colluvium	5YR 4/5	sc	15	0	0	-	n.d.	n.d.	n.d.	n.d.	n.d.
	3Bt2	38-58	colluvium	5YR 4/5	c	10	0	0	-	n.d.	n.d.	n.d.	n.d.	n.d.
	3Bt3	58-72	colluvium	5YR 4/3	c	10	0	0	-	n.d.	n.d.	n.d.	n.d.	n.d.
	3Bk1	72-114	fluvial gravels	7.5YR 5/4	scl	75	0	0	II	n.d.	n.d.	n.d.	n.d.	n.d.
	4Bk	114-145	fluvial gravels	7.5YR 5/5	scl	50	15	0	II	n.d.	n.d.	n.d.	n.d.	n.d.
DF-6	A	0-22	alluvium	7.5YR 4/3	cl	15	5	0	-	0.4	2.5	36.4	38.8	24.8
	B	22-30	alluvium	7.5YR 4/4	cl	10	5	0	-	0.3	2.2	28.2	35.5	36.3
	2Bt1	30-42	lacustrine	5YR 5/6	c	15	15	0	-	0.3	1.4	35.8	23.4	40.8
	2Bt2	42-70	lacustrine	5YR 5/8	sc	15	20	0	-	0.2	0.9	45.4	16.1	38.5
	3Bt3	70-95	alluvium	5YR 5/8	sl	0	0	0	-	0.2	0.5	54.2	28.6	17.2
	3Bk	95-140	alluvium	5YR 7/6	sl	0	0	0	II	19.0	0.5	57.5	31.9	10.6

/1 Minimum stage of carbonate development in the profile, terminology of Gile and others (1966) and Bachman and Machette (1977).
/2 Percent $CaCO_3$ by dilution with sulfuric acid and titration with sodium hydroxide using methods of Soltanpour and Workman (1981).
/3 Percent organic matter by wet titration using methods of Soltanpour and Workman (1981).
/4 Grain size data are given in percent by weight of the less than 2 mm fraction: sand (>50um), silt (2-50um), clay (<2um).
Sand fractions by dry sieve with prior removal of organic matter and $CaCO_3$. Silt fractions by pipette with prior removal of organic matter and $CaCO_3$.

Table 4: Laboratory analyses and soil development indices for selected* soils in the Diamond Fork canyon.

Profile	Cs 1/ (g/cm2)	Secondary clay 1/ (g/cm2)	Harden indices 2/ Rubification	Arid	Nonarid	All Properties
DF-1	14.50	13.23	0.1515	0.1158	0.1197	0.1570
DF-2	2.11	16.48	0.1815	0.2549	0.3115	0.2992
DF-3	0.38	12.65	0.1697	0.2498	0.3085	0.3441
DF-4	4.80	28.26	0.1174	0.2955	0.3338	0.3576
DF-5	n.d.	n.d.	0.2882	0.2768	0.2600	0.1790
DF-6	26.76	14.04	0.4561	0.1103	0.1743	0.1941

1/ Secondary carbonate (Cs) and secondary clay values using methods of Machette (1978, 1985) and Nelson and Taylor (1985).
2/ Numbers are weighted means of horizon indices following the methods of Harden (1982) and Harden and Taylor (1983) and modified by Nelson and Taylor (1985).
* Laboratory data not available for profiles DF-5 and DF-6.

A comprehensive study using soil relative age dating in the back valleys of Utah is presented in Sullivan and others (1986) and the methodology employed in that study is also used here. Numerical ages are estimated for the Diamond Fork soils by comparing characteristics such as the amount of secondary clay and carbonate and selected soil development indices with those in the back valleys because they are within the same general region and can be assumed to have similar rates of soil formation. The techniques for quantifying these indices are those of Harden (1982), Harden and Taylor (1983) and Nelson and Taylor (1985).

Remnants of six terrace levels in the vicinity of the Sams Canyon fault zone, 1.4 km downstream from the damsite, and in the vicinity of the F-series faults at the damsite, were studied in detail (pl. 1 and fig. 5). The lowest terrace (Qt6) consists of a small isolated 300-m-long remnant about 5 m above the modern floodplain on the south side of the Diamond Fork between Sams Canyon and Wanrhodes Canyon. The next terrace (Qt5), 16 m high, is more extensive, consisting of 6 remnants located between the damsite and Brimhall Canyon. The elevation of these two terrace levels above the present Diamond Fork is comparable to terrace levels about 6.5 km downstream (Qt8 and Qt7) inferred to be Lake Bonneville deposits with an estimated age of 13-16 ka.

Terrace levels 4 and 4A (Qt4 and Qt4A) are two remnants on the south side of the river, 26 and 29 m, respectively, above base level. Soil profiles DF-5 (Qt4) and DF-3 (Qt4A) were described on these surfaces. The parent materials in these profiles consist of a veneer of colluvium less than 50 cm thick composed of reworked loess and slopewash overlying about 10-50 cm of hillslope colluvium with fluvial gravels at the base. The soils have argillic horizons 50 cm to >1 m thick (it extends to the base of the excavation in DF-3 at a depth of 170 cm) with 5YR hues (table 3). The estimated amount of secondary clay in profile DF-3 (table 4) is greater than that for soils elsewhere in the back valleys of the Wasatch Mountains that are considered to be 130-150 kyrs old (Sullivan and others, 1986) suggesting that Qt4 is at least this old.

Terrace level 3 (Qt3) is about 10 m above level 4 on the south side of the Diamond Fork valley, 36 m above the river. Level 3A, on the north side, is 39 m above the river channel. Soil profile DF-1 is located in a gravel quarry on the 3A surface and two soil profiles, DF-2 and DF-4, were described in excavated pits on terrace level 3. The parent materials in these soil pits are similar to those on terrace levels 4 and 4A: fluvial gravels overlain by colluvium from the nearby hillslopes and a surface layer of finer grained colluvium that probably has a significant loess component. The upper horizons in profile DF-1 have been stripped by bulldozer activity, so it appears less developed than the other profiles and the soil development indices reflect this. All three soils are strongly developed with thick (80-90 cm) reddish (5YR) argillic horizons and stage I and II carbonate (table 3).

Terrace level 2 (Qt2) consists of 4 remnants, one of which is present about 100 m upstream of the proposed right abutment of the dam. These small remnants are about 55 m above the present channel of the Diamond Fork. On the right abutment of the proposed dam, alluvial sediments consisting of very gravelly fine sand overlain by stratified fine sands occur at the same elevation above the river as Qt2 (pl. 1). Slump blocks of overbank deposits

that occur within the gravels contain shells that are older than 350 ka by amino acid racemization (discussed in sec. 3.2.1). The sediments containing the shells are correlated with the second terrace level (Qt2). One hundred meters to the east is a terrace remnant of Qt2 where soil pit DF-6 is located (pl. 1). The pit exposes well sorted overbank alluvium and very well sorted lacustrine deposits overlain by a thin layer of active slope colluvium with a 65 cm thick reddish (5YR) argillic horizon and stage I+ carbonate. The profile characteristics (table 4) are similar to those of soil profiles elsewhere in the back valleys that have estimated ages of at least 130-150 ka.

Terrace level 1 (Qt1) consists of 3 isolated remnants about 87 m above the Diamond Fork. Several higher surface remnants (QTt) are included on plate 1 that are inferred to be as old as early Quaternary (>730 ka) or Tertiary (>2 Ma) because they are more than 90 m above the present river. Also included on plate 1 are undifferentiated terrace surfaces mapped as Qt that were not included in the terrace profile study and have not been correlated with the numbered sequence.

The only numerical age for the deposits of the Diamond Fork terrace sequence is estimated from amino acid ratios of shells found in a trench on the right abutment of the proposed dam (sec. 3.2.1). The alluvial deposits containing the shells are correlated with the second terrace level (Qt2). The 6 soil profiles described on the Diamond Fork terraces can be compared with soils in the back valleys of Utah that have been assigned to relative age groups on the basis of soil characteristics (Sullivan and others, 1986). The soils on Qt4 and Qt3 have soil development indices (table 4) similar to RAG 2 soils in the back valleys that are inferred to be >150,000 years old. Comparing both the height above base level and the degree of soil development with terraces along the Weber River described by Sullivan and others (1986) suggests that Diamond Fork terraces above 36 m (Qt3, Qt2, Qt1) are at least mid-Quaternary (150-730 ka) in age.

Although no soil profiles were described on terrace levels 5 and 6, their height above base level relative to terrace level 4 indicates that they are considerably younger and we infer a correlation with Pinedale (15-18 ka) terraces on the upper Weber River (Sullivan and others, 1986). Terrace level 5 may be graded to the higher of the two Lake Bonneville shorelines represented by terrace level 8 (pl. 1), and this correlation would support the Pinedale age of the terrace.

3.2 Faulting in the vicinity of Monks Hollow Damsite

A 500-m-wide zone of north-trending normal faults displace the Jurassic Nugget Sandstone and the Twin Creek Formation near the crest of the Diamond Fork anticline in the vicinity of the damsite. Detailed mapping of the region surrounding the damsite at a scale of 1" = 400' (pl. 1) for this study has delineated Mesozoic and upper Tertiary sedimentary rocks displaced by the faults. Mapping of the dam abutments has defined 8 north-trending faults referred to as the F-series faults (USBR, 1986). The faults are exposed in the canyon along the Diamond Fork and have been identified in drill holes in the dam foundation and abutments.

3.2.1 F-series faults at Monks Hollow Damsite

The F-series faults are not considered a potential source for large-magnitude earthquakes because geologic evidence shows that no late Quaternary surface displacements have occurred on the faults: the faults do not share geomorphic and structural characteristics of other late Quaternary faults in the region, and the faults do not disrupt profiles reconstructed from terrace remnants with an estimated age of 130 to 150 ka. Late Quaternary faults identified in the back valleys, such as the Little Diamond Creek fault about 6 km west of the dam, have common characteristics including: stratigraphic displacements of more than 300 m; triangular facets at the bases of bedrock escarpments, sometimes with associated vegetation lineaments; and mid- Tertiary and younger deposits in the hanging wall. In contrast, displacements on the F-series faults are all less than 82 m, no scarps are present in the colluvial deposits on the northern projection of the faults in Wignal Flat, and north of the damsite the sense of displacement of the faults in the Twin Creek Formation is opposite to that of the topographic slope (pl. 1).

The F-series faults are normal faults with apparent vertical displacements ranging from <3 m to 82 m in the Twin Creek Formation (USBR, 1986). The F1 fault, exposed about 400 m west of the proposed dam, has displacement of about 82 m (275 ft), estimated in the Twin Creek Formation on the south side of the river (pl. 1). This fault is concealed by colluvium on the north side of the river but has been inferred to offset the contact between the Nugget Sandstone and the underlying Ankareh Formation about one km north of the dam (pl .1). The remaining faults to the east have displacements varying from 1.5 m (5 ft) to > 50 m (170 ft). These faults can be traced in drill holes across the river to trench exposures on the north side of the river near the abutment of the dam (USBR, 1986). The faults are inferred to merge with the F1 fault to the north.

One of the F-series faults, the F5 fault, with apparent vertical offset of at least 50 m (170 ft) in the Twin Creek Formation, is mapped near the right abutment of the proposed dam. The F5 fault is exposed in three bulldozer trenches as a 10-ft-wide zone of fault gouge and breccia between the hard, competent Nugget Sandstone in the footwall and the fractured and intensely weathered Twin Creek Formation in the hanging wall (fig. 6). The log of a portion of one of these trenches is shown in figure 7. In this trench the F5 fault strikes N24^{o}W and dips 76° NE. Gravelly alluvium and overlying colluvium extend across the F5 fault (figs. 6 and 7). Detailed trench mapping shows that a thin bed of fine sand within the alluvium extends across the F5 fault zone between stations 0 and 60 showing that there has been no surface displacement on the fault (with a resolution of a few cm) since the deposition of the alluvium.

The age of these alluvial deposits is estimated from amino acid ratios of samples of the gastropod Oreohelix cf. cooperi preserved in a slump block incorporated within the alluvium (station 125 on fig. 7). The average amino acid ratio from six preparations is 0.393 +/0.035. Using kinetic models of amino acid racemization and temperature histories discussed in Sullivan and others (1986), this ratio yields a minimum age for the sample of 350 ka; therefore, this alluvial terrace remnant was deposited >350 ka. Based on the detailed mapping and the estimated age of the deposit, we conclude that no surface displacements have occurred on the F5 fault in at least the last

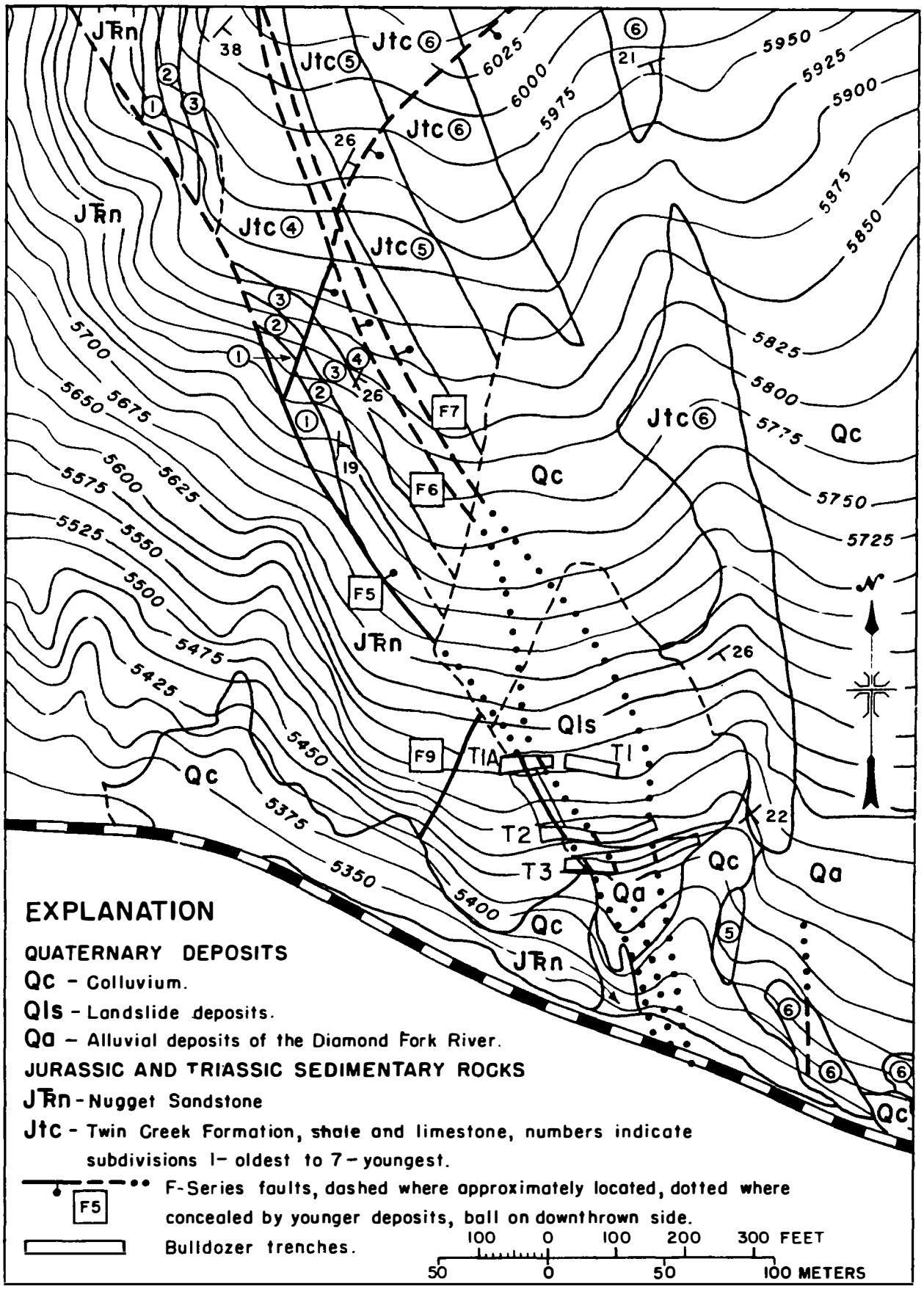
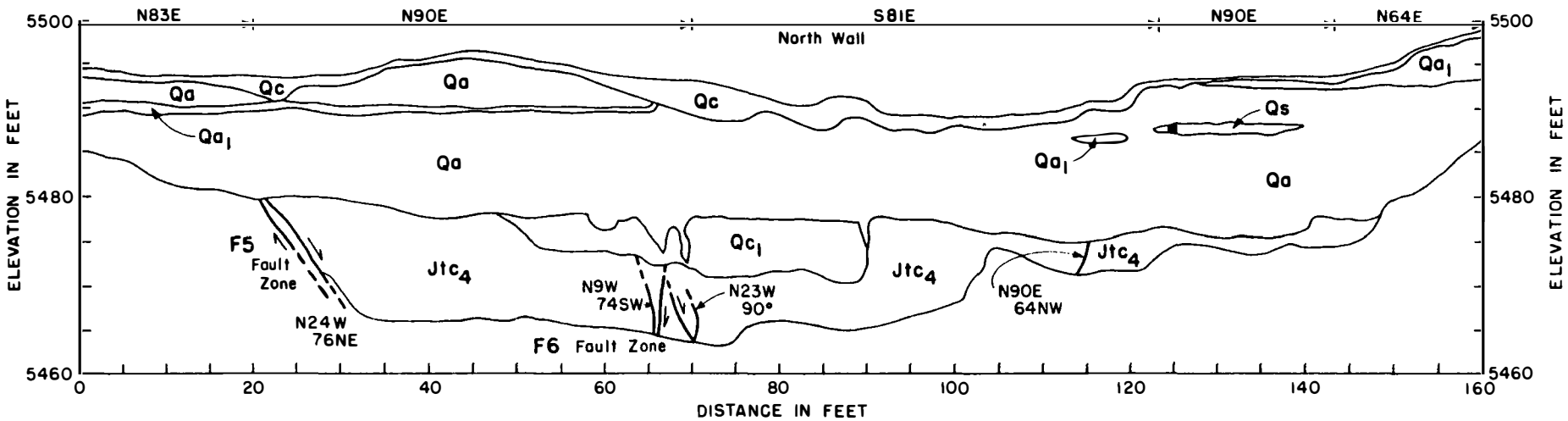


FIGURE 6 – Geologic map of the north abutment of the proposed Monks Hollow Dam. Mapping slightly modified from site geology maps prepared by the Bonneville Construction office, Provo, Utah.



EXPLANATION

QUATERNARY DEPOSITS

Qc - Surface colluvium (HOLOCENE), light brown, unconsolidated clayey gravel containing angular clasts of limestone and shale locally derived from the Twin Creek Formation.

Qs - Slump block (MID-QUATERNARY), older colluvium and overbank deposits within the alluvium containing gastropods with an amino-acid age estimate of >250 ka.

Qc_1 - Older colluvium (MID-QUATERNARY OR OLDER), dark brown, well-indurated clayey gravel with angular clasts of limestone and shale from the Twin Creek Formation.

Qa - Alluvium deposited by the Diamond Fork River (MID-QUATERNARY), rounded and subrounded clasts of quartzite, limestone, siltstone, and sandstone in matrix of fine sand.

Qa_1 - Alluvium (MID-QUATERNARY), overbank deposits of the Diamond Fork River, loose, crossbedded, laminated, fine sand

JURASSIC AND TRIASSIC SEDIMENTARY ROCKS

Jtc_4 Twin Creek Formation, unit 4.

JTRn Nugget sandstone.

——— — — Faults, dashed where approximately located.

■ Amino-acid sampling locality.

FIGURE 7 - Log of Trench 2 on the north abutment of Monks Hollow Dam.

350 000 yrs.

3.2.2 Sams Canyon fault zone

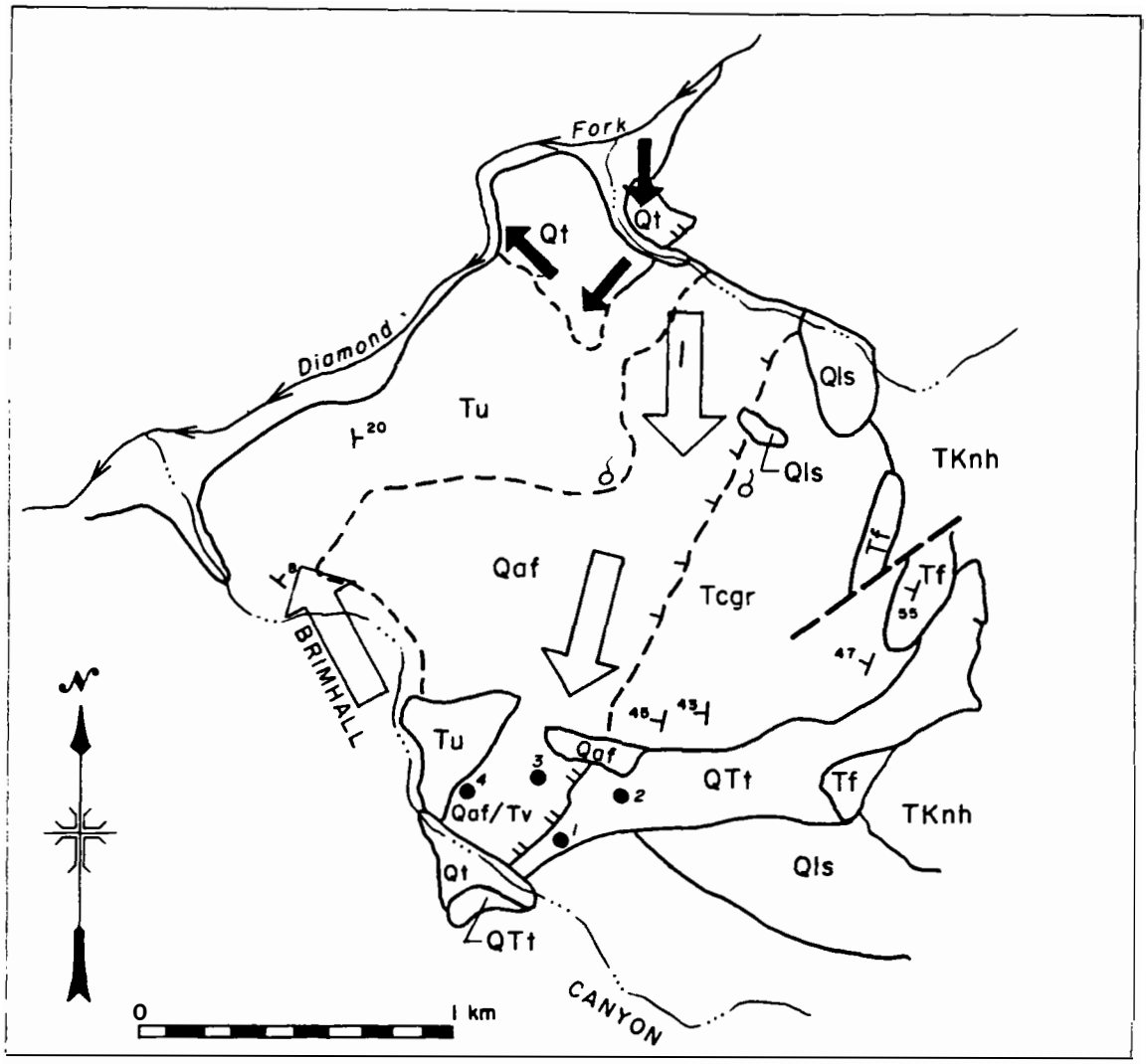
The north-trending zone of normal faults 2 km west of Monks Hollow Damsite called the Sams Canyon fault zone is not considered a potential source for large-magnitude earthquakes because geologic evidence shows that no late Quaternary surface displacements have occurred on the faults: the faults do not share geomorphic and structural characteristics of other late Quaternary faults in the region, and the faults do not disrupt profiles reconstructed from terrace remnants with an estimated age of 130 to 150 ka. On plate 1, near the point of maximum displacement of more than 300 m (1000 m) in Tertiary rocks (Young, 1978), an eroded escarpment less than 30 m high in the North Horn Formation marks the inferred position of the fault (Young, 1978). Generally no escarpment is associated with the fault and, locally on plate 1, mapping has shown that the trace of the fault coincides with a bedrock fault-line escarpment. Along this escarpment the hanging wall of the fault is at higher elevation than the footwall. This geomorphic relationship strongly suggests that no Quaternary displacements have occurred on the fault.

At the junction of Sams Canyon and the Diamond Fork, the principal trace of the Sams Canyon fault juxtaposes Jurassic sedimentary rocks in the footwall on the east and the late Cretaceous and early Tertiary North Horn Formation in the hanging wall to the west (pl. 1). North of the Diamond Fork, the fault is well-exposed as a sheared zone of near-vertical beds. South of the Diamond Fork, the trace of the fault is constrained by outcrops to a corridor about 150 m (500 ft) wide. In the same area terrace remnants of three different ages are preserved (pl. 1, fig. 5). Careful mapping and correlation of the remnants using soil profile development and relative elevation shows that remnants of Level 3 with estimated ages of 130 to 150 ka are not displaced across the Sams Canyon fault zone.

3.2.3 Brimhall canyon scarps

Low-sun-angle overflights and a review of aerial photography revealed no scarps in unconsolidated deposits associated with the mapped faults in the region. However, a northeast-trending scarp about 700 m long and 15 m high is present in unconsolidated alluvial deposits along Brimhall Creek about 1.5 km upstream from its confluence with the Diamond Fork (fig. 8). The alluvial deposits form a gravel terrace in a tributary to Brimhall Canyon that extends upstream of the scarp about 2 km. The terrace that has been incised 15 - 20 m by Brimhall Canyon and remnants in tributaries that have been incised a similar amount are locally preserved elsewhere on the Billies Mountain Quad (Young, 1978). The scarp trends about perpendicular to Brimhall Canyon and nearly parallel to the Sams Canyon fault zone which is mapped more than a km to the east (fig. 3). A poorly-defined break in the topographic slope extends about 3 km north on the projection of the scarp suggests the possibility that the scarp may be fault-related. In order to assess the feasibility of conclusively determining the origin of the scarp by trenching, four power auger holes were drilled both above and below the scarp (fig. 8).

The auger holes show that the scarp has formed in unconsolidated, poorly stratified, debris-flow deposits 5.5 m or more thick. The samples taken



EXPLANATION

Qaf — Quaternary alluvial fan deposits

Qls — Quaternary landslide deposits

Qt — Quaternary terrace deposits

QTt — Quaternary or Tertiary terrace deposits

Tv — Mid-Tertiary volcanic rocks

Tu — Tertiary - Uinta Formation

Tcgr — Tertiary - Colton / Green River Formations undivided

Tf — Tertiary - Flagstaff Limestone

TKnh — Tertiary and Cretaceous North Horn Formation

Scarp in unconsolidated deposits

Lineament

Inferred Fault

Springs

Auger holes

Figure 8 - Geologic map of the Brimhall Canyon area. Mapping suggests scarps in terrace deposits have an erosional origin. Large and small arrows indicate former courses of the Diamond Fork River discussed in the text.

during the augering were described and crude logs were developed for each of the holes. In each of the holes unconsolidated, interbedded, red and reddish-brown silty clay and gravelly clay were found to depths of 5.5 m to 7.6 m. The contacts between the interbeds are gradational; no distinct stratigraphic units were discernable. Only one of the auger holes, BC-3 located just below the scarp, encountered bedrock. At a depth of about 5.9 m (19.5 ft) bright red clay with visible biotite flakes and friable igneous clasts was encountered. This is interpreted to be the mid-Tertiary volcanic rocks mapped by Baker (1976) and Young (1978) in the vicinity. Argillic B-horizons about 0.5 m thick were present in the upper one meter of each of the holes but no detailed soil profiles on the surfaces were described. The auger holes provided no conclusive evidence bearing on the origin of the scarps. The lack of distinctive stratigraphic contacts suggested that faults, if present, would have been difficult to discern in a trench.

The distribution and relative elevations of the gravel deposits and the landforms between the scarps and the Diamond Fork on figure 8 suggest an erosional origin for the scarps. Gravels forming a terrace remnant 38 m above the Diamond Fork channel are mapped in the northern part of figure 8. This remnant is correlated with other remnants at similar elevations that form terrace level Qt3 (fig. 5) which has an estimated age of >150 to >350 ka (table 2). The steeply west-dipping, unconformable contact between the horizontally-bedded gravels and the southeast-dipping sandstone and shale units of the Uinta Formation is well-exposed near the Diamond Fork on figure 8. Units within the Uinta Formation can be traced below the gravels showing that the northeast-trending scarp on the eastern contact of these gravels resulted from erosion by the Diamond Fork prior to deposition of the gravels (small solid arrows on fig. 8). We suggest that the scarp at Brimhall Canyon had a similar origin. The base of the scarp in Brimhall Canyon is at an elevation of about 1680 m (5600 ft), about 61 m above and parallel to the channel of the Diamond Fork. The scarp appears to have been cut by the Diamond Fork when it was flowing in a channel east of the modern channel (large open arrows on fig. 8). The short length of the scarp, its concave trend, and the lack of an associated mapped fault also suggest that the scarps formed as a result of erosion.

Previous mapping of this area (Baker, 1976; Young, 1978) together with additional mapping for this study suggest that the lineament north of the scarp (fig. 8) follows a stratigraphic contact rather than a fault. Bedrock units strike nearly parallel to the scarp and the lineament. East of the lineament the Flagstaff Limestone and the overlying Colton-Green River Formations strike north-northeast parallel to the lineament, and dip 45° to 55° to the west-northwest, forming a series of west-facing hogbacks (fig. 8). West of the scarps the Uinta Formation dips to the northeast and southeast outlining the limbs of the syncline (fig. 8). The volcanics encountered in the auger hole below the scarp are interpreted as being preserved in a syncline with its axis oriented approximately northeast. The position of the lineament appears to correspond with the contact between the volcanics and the underlying, less resistant Tertiary sedimentary rocks.

Although the investigations of the Brimhall Canyon scarps and lineament have not conclusively established their mode of origin, the available evidence suggests the scarps were cut by the Diamond Fork and that the lineament on the northern projection of the scarps is stratigraphic contact and not a

fault. Even if these features are interpreted as part of the Sams Canyon fault zone, our investigations along the Diamond Fork have shown that the main trace of the Sams Canyon fault zone does not displace alluvial deposits with an estimated age of 150 to >350 ka. Therefore, we do not consider these features to be a potential seismic source.

3.2.4 Charleston Thrust

Allocthonous rocks in the upper plate of the Charleston thrust fault (fig. 3) are overlapped on the east by late Cretaceous and Tertiary sedimentary rocks (Baker, 1976) indicating that there has been no displacement on the fault in the vicinity of Monks Hollow Damsite since that time; therefore, the fault is not considered a potential source for large-magnitude earthquakes. The Charleston Thrust is the lowermost of a sequence of at least six imbricate stacked thrust faults identified south of the Uinta reentrant (Morris, 1983; Tooker, 1983). The Charleston Thrust was first recognized by Baker (1947; Baker and others, 1949) southwest of Heber Valley. In this location the thrust places sedimentary rocks of Precambrian through Permian age over sedimentary rocks of Permian through Jurassic age along a west-dipping, low-angle thrust fault with an estimated tens of kilometers of late Cretaceous eastward displacement. The lower plate paraautocthonous sequence of east-dipping Pennsylvanian Weber Quartzite and overlying Triassic and Jurassic sedimentary rocks are exposed to the north in the Uinta reentrant (Beutner, 1977).

Folded Mesozoic and Paleozoic sedimentary rocks in the upper plate of the Charleston Thrust are exposed along the Diamond Fork and at Monks Hollow Damsite (Baker, 1976). The damsite is located on the east limb of the Diamond Fork anticline, a north-trending fold in the upper plate of the Charleston Thrust that involves both Mesozoic and early Tertiary sedimentary rocks (fig. 3 and pl. 1). The Mesozoic rocks dip 30° - 60° and the overlying late Cretaceous to early Tertiary Price River Formation dips 10° - 30° (Baker, 1976), indicating that displacement on the Charleston Thrust and related folding in the upper plate have been episodic.

3.3 Pre-Quaternary stratigraphy

In this section we provide a brief summary of the Pre-Quaternary stratigraphy (pl. 1, fig. 6, and table 1). For detailed descriptions of the rock units and measured sections see Baker (1976) and Young (1978). Permian marine sedimentary rocks including the Oquirrh Formation, the Kirkman Limestone, the Diamond Creek sandstone, and the Park City Formation in the upper plate of the Charleston thrust fault are exposed west of the Little Diamond Creek fault (fig. 3). Triassic and Jurassic, predominantly marine, sedimentary rocks including the Thaynes Formation, Ankareh Shale, Nugget Sandstone, Twin Creek Limestone, Entrada Sandstone, Curtis Formation, Summerville Formation, and Morrison Formation are exposed in the Diamond Fork anticline in the vicinity of Monks Hollow Damsite.

Late Cretaceous and early Tertiary alluvial and lacustrine deposits unconformably overlie Jurassic and older sedimentary rocks. These rocks are mapped as the Price River Formation by Baker (1976). Within the Billies Mountain Quadrangle, Young (1978) has subdivided these conglomerates into the Cretaceous conglomerate and a Cretaceous and Paleocene upper and middle Red

Narrows conglomerate. On the Geologic Map of Utah (Hintze, 1980) and in existing USBR reports these rocks are shown as the North Horn Formation and that usage is retained in this report. These conglomerates are overlain by the Eocene Flagstaff Limestone, shales of the Colton and Green River Formations, and the shales and sandstones of the Uinta Formation.

Tilted volcanic rocks overlie the early Tertiary sedimentary rocks east of the Little Diamond Creek fault (fig. 3). These rocks include tuffs and bedded conglomerates referred to as the Wanrhodes volcanics by Baker (1976). They are inferred to be of Oligocene or Miocene age, although they have not been directly dated. Young (1978) considers most of the volcanic rocks north of the Diamond Fork to be the equivalent of the Tibble Formation (Baker and Crittenden, 1961) and suggests that the volcanic breccias south of the Diamond Fork are somewhat younger. He also maps Tertiary terraces and pediment gravels, although the deposits have not been dated.

Table 5 - Pre-Quaternary stratigraphic units in the vicinity of Monks Hollow damsite (fig. 3 and pl. 1)

MAP UNIT	AGE	FORMATION (UNIT)	DESCRIPTION
Tw	Oligocene?	Wanrhodes Volcanics	light grey, friable tuff with interbedded conglomerate
Tu	Eocene	Uinta Formation	interbedded red and grey shale, sandstone and conglomerate
Tcg	Eocene	Green River Formation	mostly light grey to green marlstone
Tf	Eocene	Flagstaff Limestone	grey to light red, ledge-forming freshwater limestone
TKnh	Paleocene - Late Cretaceous	North Horn Formation	massive, grey to red, coarse conglomerate; includes Price River formation of Baker (1976) and Red Narrows Conglomerate of Young (1978)
Jm	Jurassic	Morrison Formation	greyish green to lavender shale
Ju	Jurassic	Summerville Formation	red orange mudstone, shale, and sandstone
Ju	Jurassic	Curtis Formation	greyish green sandy shale and sandstone
Je	Jurassic	Entrada Sandstone	light brown siltstone and sandstone
Jtc	Jurassic	Twin Creek Formation	grey to yellowish grey shale and limestone, lower limestones divided into 7 units at Monks Hollow damsite after Young (1978) and USBR (in prep.)
		Jtc:7	silty micrite, red silty shales and light grey oolitic limestone, brownish grey, laminated to thinly bedded
		Jtc:6	greenish-grey micrite, thin to medium bedded, forms prominent cliff, approximately 120-140 ft thick
		Jtc:5	predominantly collapsed micrite breccia and oolitic limestone, medium to thickly bedded, red silty shale at the base (unit 5a), 45-60 ft thick
		Jtc:4	predominantly grey silty micrite, thin to medium bedded with laminated shale, 25-30 ft of shale at the base (unit 4a), 285-300 ft thick
		Jtc:3	predominantly greyish brown micrite, laminated to thinly bedded, includes intensely weathered 1 to 4 ft thick red clay at the base (unit 3a), 45-50 ft thick
		Jtc:2	greyish brown oolitic limestone with minor siltstone, 35-45 ft thick
		Jtc:1	predominantly light grey siltstone with some shale, very thin to thinly bedded, includes 3-5 ft red shale at the top, 50-65 ft thick
JTRn	Jurassic - Triassic	Nugget Sandstone	light grey to orange-brown and red, crossbedded, medium-grained eolian sandstone
TRu	Triassic	Ankareh Formation	interbedded bright red shale and red, silty sandstone
TRu	Triassic	Thaynes Formation	brown-weathering limestone
TRu	Triassic	Woodside Shale	red shale
Pu	Permian	Park City Formation	grey limestone with chert with some siltstone and sandstone
Pu	Permian	Diamond Creek Sandstone	light grey and white sandstone
Pu	Permian	Kirkman Limestone	grey and black limestone
Pu	Permian	Oquirrh Formation	grey, tan-weathering sandstone

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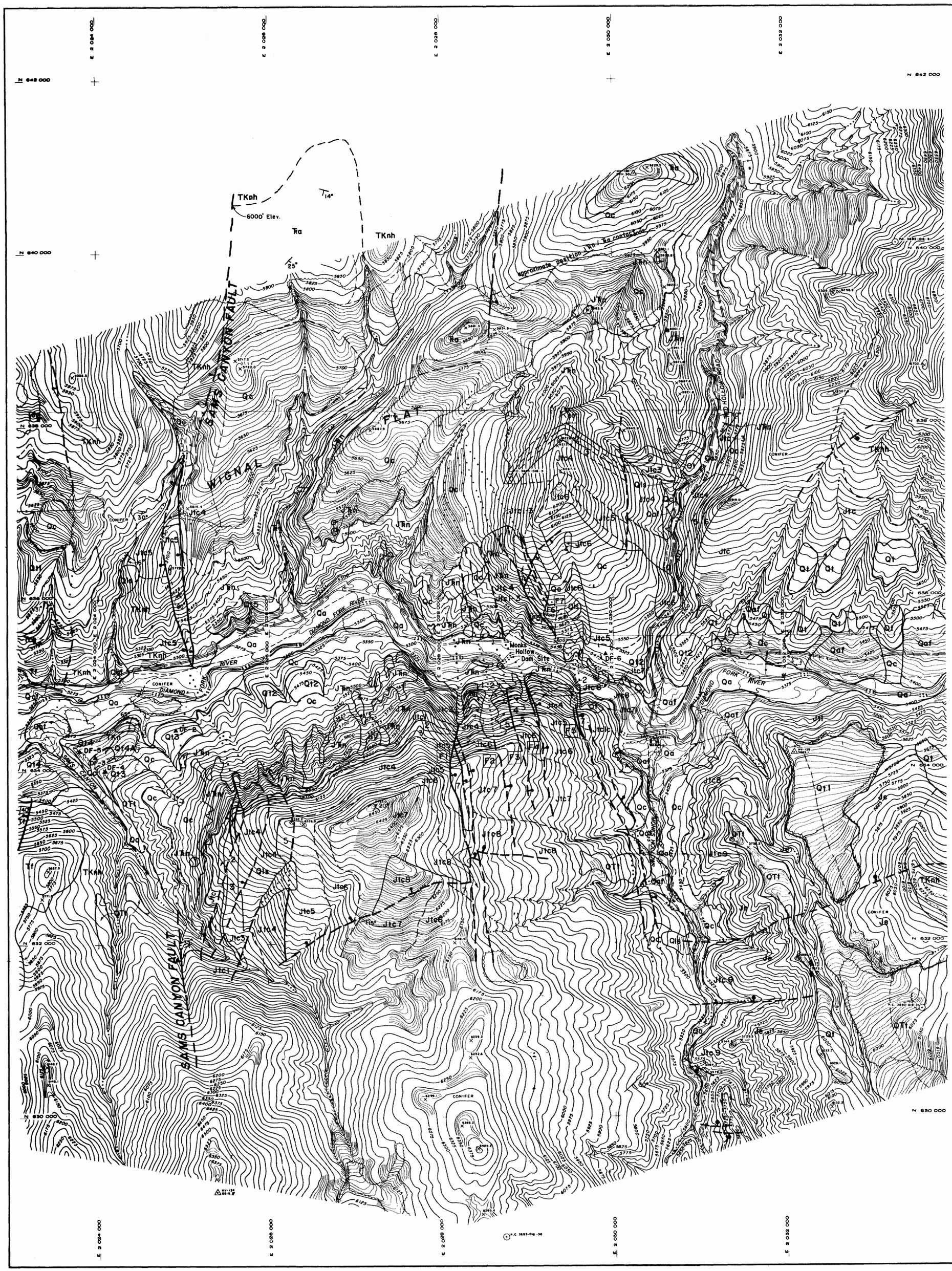

EXPLANATION

Quaternary deposits and landforms

Qa –	alluvium in modern drainages
Qaf –	alluvial fan
Qc –	colluvium on hillslopes
Qls –	landslide deposits
Qt 1-6 –	alluvial terrace remnants of the Diamond Fork River
Qt –	alluvial terrace remnants in Diamond Fork tributaries
QTt –	Quaternary–Tertiary terrace remnants

UNCONFORMITY

Tertiary deposits

Tcg –	Colton / Green River Formations
Tf –	Flagstaff Formation
TKnh –	North Horn Formation

UNCONFORMITY

Jurassic sedimentary rocks

Je –	Entrada Formation
Jtc –	Twin Creek Formation, units 1-7 (see table 1)
JTRn –	Nugget Sandstone

Triassic sedimentary rocks

TRa	Ankareh Formation

Geologic contacts, dashed where approximately located

Faults, dashed where approximately located, dotted where concealed by younger deposits, ball on downthrown side

Strike and dip location

▲ DF-4 Soil pit location

SCALE OF FEET: 0, 500, 1000, 1500, 2000

SCALE OF METERS: 0, 200, 400, 600

MONKS HOLLOW DAMSITE
SEISMOTECTONIC STUDY

GEOLOGIC MAP OF MONKS HOLLOW

PLATE 1