THE MARCH 16, 1992 M_L 4.2 WESTERN TRAVERSE MOUNTAINS EARTHQUAKE, SALT LAKE COUNTY, UTAH

compiled by

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PREFACE

Two agencies in Utah share the principal responsibility for the study of and scientific response to earthquakes in the state. The University of Utah Seismograph Stations operates the seismic monitoring network and determines the earthquake's location, magnitude, and focal mechanism. The Utah Geological Survey evaluates geologic effects through field reconnaissance immediately following the earthquake. In addition, the Utah Division of Comprehensive Emergency Management helps coordinate the emergency response and, for damaging earthquakes, documents losses. Following each "significant" earthquake in Utah for which geologic and seismologic studies are undertaken, the Utah Geological Survey will publish a summary report. This is the first such report.

The report is a compilation of papers regarding the March 16, 1992 M_L 4.2 Western Traverse Mountains earthquake in the southern Salt Lake Valley. In the first paper, Christenson and Olig give an overview of the earthquake and summarize some of the more detailed information in papers that follow. Next, Pechmann discusses the focal mechanism and seismotectonic aspects of the earthquake. Olig and Mulvey report on investigations after the earthquake for geologic effects, and Harty discusses in more detail the evidence for possible earthquake-induced liquefaction at one locality. Individual papers have been formatted with some minor editing for inclusion in this report. An accelerograph record from a site at the north end of the Oquirrh Mountains was provided by Kennecott Utah Copper and is included in the appendix.

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OVERVIEW

by

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At 7:42 a.m. on Monday, March 16, 1992, Salt Lake and northern Utah Valleys were shaken by a M_L (local magnitude) 4.2 earthquake. It was reported felt from Kaysville in Davis County to Orem in northern Utah Valley, and from Brighton in the Wasatch Range to Tooele, west of the Oquirrh Mountains (Susan J. Nava and Jim Tingey, verbal communications, March 31, 1992), an area of about 2,000 square miles (5,200 km^2). Shaking was strongest in the southern Salt Lake Valley in Bluffdale, Riverton, Draper, and Sandy.

The epicenter was located in the Traverse Mountains near Camp Williams (figure 1). Early reports from the U.S. Geological Survey's worldwide seismic network indicated a local magnitude of 4.8, but later reports from the University of Utah Seismograph Stations' (UUSS) network downgraded the magnitude to M_L 4.2. The UUSS calculated a focal depth of 12.5 kilometers (7.8 mi) (see Pechman, this report).

Ten seismometers had been deployed in the Salt Lake Valley in the fall of 1991 under a 2-year National Science Foundation grant directed by James Pechmann and Gerard Schuster at the University of Utah to investigate low-strain (weak) earthquake ground motion in the valley. Records from these instruments have been retrieved and are now being analyzed, and may yield information regarding ground motions in the valley. Unfortunately, many of the records are clipped (off-scale) because the instruments were not intended to record ground motions as large as those that occurred. Conversely, the level of ground shaking was too small to trigger any of the U.S. Geological Survey strong-motion instruments in the valley.

A preliminary focal mechanism determined by the UUSS indicates normal slip on either a northwest striking plane dipping 38 ± 4 degrees west or a north-striking plane dipping 56 ± 2 degrees east (see Pechmann, this report). There are no mapped Quaternary faults in the immediate epicentral area. However, given the focal mechanism and focal depth, it is possible the earthquake was on the west-dipping Wasatch fault. If so, it is near the boundary between the Salt Lake City and Provo segments of the fault. The west-dipping nodal plane of the focal mechanism is consistent with the geometry of the Wasatch fault zone segment boundary at this location.

The earthquake was generally too small to generate any significant geologic effects other than local rock falls and stream-bank caving. Utah Geological Survey (UGS) teams were dispatched to the epicentral area within a few hours of the earthquake to search for possible geologic effects. The Traverse Mountains were combed for rock falls, landslides, and ground cracks, and the Jordan River and other areas of shallow ground water were searched for evidence of liquefaction. Nothing was found, as might be expected (see Olig and Mulvey, this report), but a later investigation by Harty (this report) of a reservoir on the Jordan River at about 9400 South (16 kilometers [10 mi] north of the epicenter) that was drained the morning of the earthquake turned up possible evidence of liquefaction in freshly exposed reservoir sediments. Many small holes, some surrounded by cones of sediment, were found in the organic, silty, bottom sediment. Possible origins of these features include earthquake-induced liquefaction, expulsion of trapped gases, and de-watering of sediment following rapid draining of the reservoir. The investigation concluded that a combination of these processes, including liquefaction, probably formed the features.

Most felt reports were of rattling dishes, swaying of hanging objects, and rocking motions. Shaking was of very short duration, and in many cases was felt as a single jolt. Although a comprehensive study of damage to manmade structures by the earthquake was not undertaken, reports indicate that damages were slight. No structural damage to buildings was reported, but ground shaking locally cracked foundations, brick walls, sidewalks, and patios, and dislodged bricks from a chimney. Significant non-structural damage to a curtain wall and window system was reported in a modern three-story building in Sandy (Larry Reavely, Reavely and Associates, verbal communication, August 27, 1992). The front steps of Jordan High in Sandy settled about an inch (2.5 cm), and minor step-cracks in brick were noted at West Jordan High in West Jordan (Brian Hazlem, Jordan School District, verbal communication, August 31, 1992). At least two older unreinforced masonry homes in Riverton experienced foundation cracks, some an inch (2.5 cm) or more wide, which extended upward into step-cracks in brick (Brian Mitchell, verbal communication, August 27, 1992). Cracks were also reported in concrete floors at the Utah Army National Guard Building in Draper (see Olig and Mulvey, this report).

WF-W: Wasatch fault-Weber segment
WF-S: Wasatch fault-Salt Lake segment
WF-P: Wasatch fault-Provo segment
WF-N: Wasatch fault-Nephi segment
EGSL: East Great Salt Lake fault zone
WV: West Valley fault zone
NO: Northern Oquirrh fault zone
UL: Utah Lake faults

Figure 1. Location of the M_L 4.2 March 16, 1992 earthquake (from the University of Utah Seismograph Stations) and faults with evidence for displacement during the last 30,000 years (from UGS compilation in preparation by Suzanne Hecker).

FOCAL MECHANISM AND SEISMOTECTONIC SETTING

by

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Figure 2 shows a focal mechanism for the M_L (local magnitude) 4.2 earthquake which occurred on March 16, 1992, at 14:42 UTC (Universal Coordinated Time; 7:42 a.m. MST) in the Western Traverse Mountains south of Salt Lake City, Utah. I determined this focal mechanism from data recorded on the University of Utah regional seismic network, using velocity models and procedures described in Bjarnason and Pechmann (1989). The focal mechanism shows dominantly normal faulting on a fault dipping moderately to the southwest (strike = 138° ± 10°, dip = 38° ± 4°, rake = -115° ± 6°) or to the east (strike = 349° ± 2°, dip = 56° ± 2°, rake = -71° ± 8°). The signs for the rake angles follow the convention of Aki and Richards (1980, p. 106). Aftershock locations cannot be used to distinguish which of these two nodal planes is the fault plane, because as of this writing (August 12, 1992) there has been only one locatable aftershock––an M_c (coda magnitude) 1.2 event that occurred 41 minutes after the main shock.

Figure 2. Focal mechanism for the M_L 4.2 Western Traverse Mountains earthquake of March 16, 1992. P-wave first motions are plotted on a lower hemisphere equal area projection, with compressions shown as solid circles and dilatations as open circles. Smaller circles indicate readings of lower confidence. The triangles show slip vectors and P and T axes.

The hypocenter used to determine the focal mechanism is at 40° 28.02' N., 112° 2.88' W., and 12.5 kilometers (7.8 mi) depth (measured from a datum which is 1.5 kilometers [0.9 mi]) above sea level). A rough estimate of the uncertainty in this hypocenter is 1.5 kilometers (0.9 mi) in all directions. This estimate is based on the standard horizontal and vertical errors calculated by the location program HYPOINVERSE, which are 0.6 and 0.5 kilometers (0.4 and 0.3 mi), respectively. Multiplying these standard errors by 2.4 gives estimates of the 95 percent confidence limits on the location (Klein, 1978) of 1.4 kilometers (0.9 mi) horizontal and 1.2 kilometers (0.7 mi) vertical, which I rounded upward. The 1.5 kilometer (0.9 mi) error estimate is larger than the maximum horizontal (1 kilometer [0.6 mi]) and vertical (0.8 kilometers [0.5 mi]) shifts in location that result from varying the distance weighting applied to the arrival time data and using or not using the pick from station BBUT. BBUT is located on alluvium 31 kilometers (19 mi) north of the epicenter and has a large (0.64 sec) positive travel-time residual, most likely due to the slow velocity of the underlying alluvium. Changes in hypocentral location of 1.5 kilometers (0.9 mi) have only a negligible effect on the nodal plane orientations.

Figure 3 is a map of the Salt Lake Valley region showing the location of the Western Traverse Mountains earthquake (represented by the focal mechanism diagram, which is centered on the epicenter) relative to surface traces of Holocene faults (solid and dashed lines), and seismicity from July 1962 through March 1992 (circles). The epicenter of this earthquake is at the western edge of a prominent ENE-WSW-trending band of seismicity, where small earthquakes have occurred episodically since at least 1971. This band of seismicity appears to coincide with the boundary between the Salt Lake City segment of the Wasatch fault to the north and the Provo segment to the south (see, for example, Machette and others, 1991). This segment boundary is located at a major bend in the surface trace of the fault, termed the Traverse salient by Machette and others (1991).

Unfortunately, the three-dimensional distribution of hypocenters in the ENE-WSW-trending band of seismicity west of the Traverse salient cannot be determined with the available data. Only 19 of the earthquakes in this band have locations which met the usual minimum requirement for good focal depth constraint: one recording station at an epicentral distance less than or equal to the focal depth or 5 kilometers (3 mi), whichever is larger (see, for example, Arabasz and others, 1992). The focal depths for all but one of these 19 earthquakes fall between the surface and the 12.5-kilometer (7.8-mi) depth of the Western Traverse Mountains earthquake. Although the shallowest of these earthquakes are located at the eastern end of the band, this apparent shallowing of focal depths appears to be an artifact of the station distribution and the sorting criteria.

Could the Western Traverse Mountains earthquake have occurred on the Wasatch fault? The answer is yes, given the information at hand. To illustrate this possibility, I have projected the SW-dipping nodal plane of the focal mechanism upward and plotted its intersection with the surface as a solid line on the map in figure 3. The length of the line is arbitrary. The hachured lines parallel to the projection line show the error bars on the projection for depth variations of ±1.5 kilometers (0.9 mi) and dip variations of ±4°. Note that the surface projection of the SW-dipping nodal plane lies within one kilometer (0.6 mi) of the surface trace of the Wasatch fault at the western edge of the Traverse salient, where the local strike of the fault is similar to the NW strike of the nodal plane. Yonkee and Bruhn (1991) have constructed a subsurface model of the Wasatch fault zone in the vicinity of this salient by downward projection of fault orientations measured at the surface (figure 4). In their model, the Wasatch fault forms an approximately cylindrical surface at the salient with an axis that plunges 25° towards azimuth 240°. (This fault surface disappears beneath the Traverse Mountains block at depth on figure 4.) The downward projection of the NW-trending section of the fault bend (section S4 on figure 4) along this axis comes within 7 kilometers (4 mi) of the hypocenter of the earthquake––reasonably close considering the uncertainties in the hypocentral location and in the downward projection of the fault surfaces. Therefore, it is possible that the Western Traverse Mountains earthquake occurred on the Wasatch fault at the Traverse salient. But it is equally possible that this earthquake occurred on a small unrecognized fault or a buried fault with no clear surface expression, as do most of the small- and

Figure 3. Seismicity map of the Salt Lake Valley showing epicenters of earthquakes located by the University of Utah from July 1962, when the University's regional seismic network began operating, through March 1992. The epicenter of the Western Traverse Mountains earthquake is indicated by the miniature version of the focal mechanism diagram from figure 2. The solid straight line marks the surface projection of the SW-dipping nodal plane of this focal mechanism, and the hachured lines parallel to it show the error bars on this projection (see text). The dashed box outlines epicenters of probable mining blasts which have not yet been removed from the earthquake catalog. The other solid and dashed lines are the surface traces of Holocene faults, taken from maps by Cluff and others (1970), Davis (1983a, b), Keaton and others (1987).

Figure 4. Perspective view of a model of the subsurface geometry of the Wasatch fault zone in the vicinity of the Traverse salient, reproduced with permission from Yonkee and Bruhn (1991). The fault surfaces are approximated by planar sections, which are identified by the labels given in the inset. The thick contour with an elevation of 1500 meters (4921 ft) corresponds approximately to the surface traces of the faults. The numbers indicate the estimated dips of the fault sections and the arrows indicate generalized slip directions.

moderate-sized earthquakes in Utah (Arabasz and others, 1992).

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GEOLOGIC EFFECTS

by

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INTRODUCTION

An M_L 4.2 earthquake occurred at 7:42 a.m. (MST) on March 16, 1992 near Camp Williams, Salt Lake County (figure 5). This is a report of our investigation for physical geologic effects associated with the earthquake. On March 16, one Utah Geological Survey (UGS) team (W.E. Mulvey and Bill Black) searched the Traverse Mountains in the Camp Williams area for rock falls and other effects while a second team (Susan Olig and Bea Mayes) investigated the banks of the Jordan River for liquefaction features and slope failures (figure 5).

The earthquake was too small to generate significant geologic effects, except perhaps for rock falls or bank caving near the epicenter, and neither team found any geologic effects that could be attributed to the earthquake. Olig and Mayes observed new cracks in the Utah National Guard building in Draper. In a separate investigation on March 17, 18, and 19, Kimm Harty investigated a reservoir at about 9400 South along the Jordan River, which had been drained after the earthquake, and found possible evidence for liquefaction (see Harty, this report).

TRAVERSE MOUNTAINS

The investigation included a driving and walking reconnaissance of the Traverse Mountains to the east, south, and north of the epicenter, looking for evidence of surface fault rupture and other ground cracks, rock fall, and landsliding (figure 5). We also examined streams, springs, and seeps for turbidity, to see if the earthquake disturbed the local ground-water system. Much of the reconnaissance was on Camp Williams, and we were accompanied by Captain Ronald Haskell and Sergeant First Class Doug Mooneyham of the Utah National Guard.

Vegetation in the area consists of oak brush-maple, and sagebrush-grassland communities. Terrain is mountainous, with steep hillslopes and narrow drainages. Bedrock is Pennsylvanian-Permian sandstone and limestone (Oquirrh Formation), and Tertiary volcanic rocks (Hintze, 1980). Quaternary deposits consist of alluvium along stream drainages, and colluvium on slopes. Soils are thin over weathered bedrock. Outcrops are few, and consist of Paleozoic sandstone and limestone.

We concentrated our investigations in the area south of the epicenter, in the vicinity of Beef Hollow and Tickville Springs. Throughout this area there was no evidence for surface fault rupture, ground cracks, or landslides caused by the earthquake. Outcrops had talus slopes below them, making it difficult to identify fresh rock-fall debris. We examined numerous outcrops and found no evidence for rock falls.

Streams, springs, and seeps were checked for water clarity. Streams in Beef Hollow were turbid, but the cause was runoff from graded roads paralleling the drainage. Tickville Spring, approximately one mile south of the epicenter, was clear. We checked a small earth dam approximately one mile below the spring for damage and found none. Sloughing of stream banks was observed in the Tickville Spring drainage. This is the only evidence we observed that could represent geologic effects possibly caused by the earthquake, but it

Figure 5. Location Map

could also be attributed to normal erosional processes.

We viewed the north side of the Traverse Range, driving up Rose Canyon and side roads leading to drainages north of the epicenter. In these areas no evidence for surface fault rupture, landslides, or rock falls were observed. Streams, springs, and seeps were clear. Mine dumps at the Kennecott Bingham Canyon operation just north of Rose Canyon also appeared undisturbed by the earthquake.

JORDAN RIVER

The investigation included reconnaissance of the banks of the Jordan River from Bluffdale south to Camp Williams (figure 5). The banks along this section of the river are well vegetated with willow, sage, and grasses. Slopes along the banks are moderate to steep, with cliffs over 100 feet (30 m) high at Jordan Narrows. The river cuts through a semi-consolidated conglomerate at Jordan Narrows and gravel deposits are common along the river channel. We did not observe any sand boils, cracks, fissures, fresh scarps, or any feature related to liquefaction. We did observe some sloughing along steeper banks, but this is most likely due to ongoing erosion. It is possible that the earthquake triggered very small movements of material in these areas, but there is no conclusive evidence of earthquake-induced slope failure in the vicinity.

UTAH NATIONAL GUARD BUILDING

The Utah National Guard building is a one- to two-story concrete building located at 12953 Minute Man Drive in Draper. The site is flat and underlain by fine-grained Lake Bonneville deposits (Personius and Scott, 1990). We met with Major Paul D. Harrell and various maintenance personnel who gave us a tour of the facility on March 16, 1992.

Two types of damage were observed: cracks along expansion joints in the concrete walls, and shear cracks in a second-story concrete floor. The cracks along expansion joints were observed throughout the building and varied in width from less than 1/16th inch to more than 1/8th inch (1 to 3 mm). Patching of old cracks had recently been completed and maintenance personnel were certain that these new cracks formed during the earthquake.

The shear cracks were extending out from the corners of openings in the floor for columns. The cracks varied in width from less than 1/16th inch to nearly 1/8th inch (1 to 3 mm). Maintenance personnel were certain that the cracks formed during the earthquake because the area is swept daily and small pieces of loose concrete were visible along the cracks. No other damage was observed.

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POSSIBLE LIQUEFACTION AT THE 9400 SOUTH DAM AND RESERVOIR, SALT LAKE COUNTY, UTAH.

by

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On March 17th, 1992, John Hollenhorst (KSL-TV) called the Utah Geological Survey and reported seeing numerous small holes in sediment exposed in the recently drained 9400 South reservoir (figure 6). I examined these features on March 18th and 19th, in an effort to determine if they may have been caused by liquefaction during a magnitude 4.2 earthquake that occurred in the Traverse Mountains on March 16th, 1992.

Modern sediments exposed after water was released from the reservoir on the morning of March 16, 1992, the day of the earthquake, were covered with numerous small holes averaging about 1 centimeter (0.4 in) in diameter. I observed these holes on nearly every surface that had been submerged before the water release. No holes were found downstream of the dam, nor upstream of the farthest extent of the reservoir (about 10000 South Street) (figure 6). In addition, holes were limited to generally flat, recently exposed point and channel bars; no holes were observed on the river-bank slopes. The density of holes was variable, with relatively few holes on some bars, and many on others. Hole density seemed the least on bars nearest the dam, and greatest on bars in the upper reaches of the reservoir. Some holes were rimmed with a small cone of sediment, indicating the upward movement of sediment through the holes (figure 7). There appeared to be more sediment cones around holes in the upper reaches of the reservoir than in the lower reaches.

On March 19th, I examined these holes more closely to determine if they may have been caused by liquefaction during the earthquake. Sediment ejected from the holes appeared to be the organic-rich, fine-grained sediment forming the surface of all newly exposed features. In cross-section, the holes appeared shallow, with the deepest of the four I excavated extending vertically only about 5 centimeters (2 in) below the surface. Sectioning holes in the saturated, black sediment caused smearing and closure, thus some holes may extend deeper than 5 centimeters (2 in). However, the holes did not appear to extend below the layer of saturated organic sediment. I examined the sediment using a microscope (50X magnification) and classified it in accordance with the visual/manual procedures outlined in ASTM Standard D-2487-83. The sediment is a clayey silt (ML) and contains a small amount (<5 percent) of fine sand.

To reach some of the holes for sampling, sectioning, and photographing, I stood on a plywood board placed over the organic-rich sediments. On one occasion, loading caused by stepping on the board forced water and sediment out of the existing holes, indicating the organic sediments were still saturated and that the holes may have formed by extrusion of water and sediment from below.

Possible explanations for the formation of the holes and sediment cones surrounding the holes include: 1) crayfish (or some other animal/insect) burrowing, 2) gas bubbles, 3) de-watering of the sediments, 4) earthquake-induced liquefaction, and 5) a combination of processes. These possibilities are each discussed below.

To obtain information on crayfish and other burrowing creatures (possibility 1), I spoke to Dr. Chris Luecke, a limnologist in the Department of Biology, and to Dr. Todd Crowel, College of Natural Resources, Utah State University. Both Dr. Crowel, who has conducted extensive research on crayfish, and Dr. Luecke discounted the animal/insect-burrowing theories based on my descriptions of the holes and sediment conditions. The main reasons given to discount the burrowing theory include:

Figure 6. Location map.

Figure 7. Photograph of holes with rims of sediment (average hole diameter is approximately 1 centimeter [0. 4 in]).

- **Anoxic sediment conditions**. Crayfish and most other burrowing creatures (for example, clams) are not adapted to living in de-oxygenated sediments.
- **Hole Size**. Crayfish typically leave burrow holes about the size of a quarter (2.5 centimeters [1 in]). The holes averaged about 1 centimeter (0.4 in) in diameter, but many smaller holes were observed. The 1-centimeter (0.4-in) holes are too large to have been made by chironmid (fly) larvae, a burrowing insect adapted to living in anoxic sediments.
- **Hole geometry**. Crayfish burrow horizontally as well as vertically, but no horizontal tunnels were observed in the near subsurface.
- **Type of sediment**. Crayfish usually burrow into firm clays that maintain tunnel shape. The sectioned holes in the low-strength sediments closed quickly.
- **Cone texture and symmetry**. Crayfish excavate sediment with their back legs, piling it asymmetrically around the holes. The observed cones were smooth and nearly symmetrical.
- **Lack of physical evidence**. Crayfish usually leave behind molts; crayfish and other burrowing creatures may leave tracks. No molts, bodies, or tracks other than from birds and small mammals were observed around the holes or on the exposed bars I examined.

The possibility that gas bubbles formed the holes cannot be dismissed (possibility 2). A strong fetid odor permeated the area upstream of the dam, indicating the presence of hydrogen sulfide (H_2S) gas. In addition, the exposed bottom sediments were rich in iron sulfide, which contributes to the black color of anoxic sediments. Dissolved H_2S most likely existed in the waters at the bottom of the reservoir, and in interstitial water within the bottom sediments. Saturation of dissolved gases, including H_2S, varies with temperature, salinity, and pressure. Removal of the reservoir waters above the anoxic, H_2S-rich sediment resulted in a decrease in the hydrostatic pressure in the water-saturated bottom sediments. This decrease in pressure may have caused the formation of H_2S gas bubbles within the sediments, which then rose to the surface, forming the holes. That the holes were not observed to extend below about 5 centimeters (2 in) may be due to structural collapse shortly after their formation. Although this scenario well explains the formation of the holes, it does not adequately explain the sediment cones surrounding some of the holes. Rising gas bubbles may be capable of deforming sediments around the perimeters of the holes, but the sediment cones were clearly depositional, not deformational features, and rising bubbles likely do not carry or expel much sediment. Thus, the formation of gas bubbles cannot fully explain the origin of the sediment-rimmed holes.

De-watering of the sediments upon removal of the reservoir waters (possibility 3) may explain the formation of the holes and cones. As the water table drops (in this case as a result of release of reservoir waters), ground water usually migrates downward and/or laterally down gradient. However, if ground water becomes confined and cannot drain freely, the weight of the overlying de-watering sediment may force upward flow, particularly if open flow paths (cracks, holes) are present. If the holes were formed by rising gas bubbles, loading pressures from the weight of the draining sediment may have been sufficient to partially de-water the sediment through the existing holes, creating the sediment cones. R.C. Rasely (U.S. Soil Conservation Service, oral communication, April 1992) has observed similar sediment-rimmed holes in de-oxygenated bottom sediments of partially drained reservoirs in Indiana. He attributed the formation of those holes to de-watering processes.

The possibility that the holes and cones were formed by liquefaction during earthquake ground shaking (possibility 4) also cannot be discounted. "Sand boils," "mud volcanoes," and "blow holes" have been observed after numerous moderate to large earthquakes throughout the world. Evidence suggests that the sediments in the reservoir were likely highly susceptible to liquefaction. Prior to the opening of the dam on March 16, 1992, the reservoir had been accumulating sediment since the dam's last opening in the late summer of 1991 (Al Pendleton, North Jordan Canal Company, verbal communication, March, 1992). These recent sediments contained much silt, were loose and saturated, and thus susceptible to liquefaction. Although liquefaction is not commonly reported in earthquakes smaller than magnitude 5, I believe it is possible that these susceptible sediments liquefied and formed the small boils during the magnitude 4.2 earthquake, whose epicenter was only 16 kilometers (10 mi) southwest of the reservoir.

The formation of the holes and sediment cones is probably related to a combination of processes (possibility 5). A plausible explanation is that draining of the reservoir created gas bubbles that formed the holes, which then served as conduits for water and sediment expulsion from liquefaction, de-watering, or a combination of the two processes. The amount of upward force needed to expel material through pre-existing holes by de-watering or liquefaction would be less than that required to create new holes. Furthermore, stepping on the plywood board did not create any new holes; water and sediment exited only through existing holes. Release of reservoir waters commenced at approximately 7:30 a.m.; the earthquake occurred 12 minutes later, at 7:42 a.m. According to Al Pendleton, draining of the reservoir lasted about two hours. At the time of the earthquake, only those sediments in the upper reaches of the reservoir would have been exposed. This may explain why there appeared to be more sediment cones on bars in the upper reaches of the reservoir; the cones were less likely to remain preserved submerged in water.

As previously mentioned, some of the exposed sediments, particularly those closest to the dam, showed evidence of cracking and slumping. I observed most of the cracks and shallow slope failures in the recently exposed bars immediately adjacent to the river channel. Although these features were likely caused by changes in pore-water pressures in the sediments resulting from draw-down of the reservoir, liquefaction may also have contributed to the formation of these features.

APPENDIX

ACCELEROGRAPH RECORD

An accelerograph (Kinemetrics SSA-1) record was collected by Kennecott Utah Copper at a site near Deadman's Cave at the northern end of the Oquirrh Mountains 30 kilometers (18.6 mi) from the epicenter (figure A1). Preliminary time histories and response spectra, derived using Kinemetrics software, are shown in figures A2 and A3, respectively. The site is on bedrock, and recorded a maximum horizontal acceleration of 2.26 centimeters/second^2 (0.0023 g) on the east-west component of the accelerograph (figure A2). The maximum acceleration on the north-south component (not plotted) was 1.46 centimeters/second^2 (0.0015 g).

The Utah Geological Survey has not evaluated these records, and we present them here to make the data available, courtesy of Kennecott Utah Copper. Because the records are preliminary, we caution users that further processing, with explanation of apparent irregularities in the latter part of the record, may be advisable.

Figure A1. Location of strong-motion instrument triggered by the March 16, 1992 Western Traverse Mountains earthquake.

Figure A2. Acceleration, velocity, and displacement time-histories for the east-west component.

Figure A3. Response spectra for the east-west component.