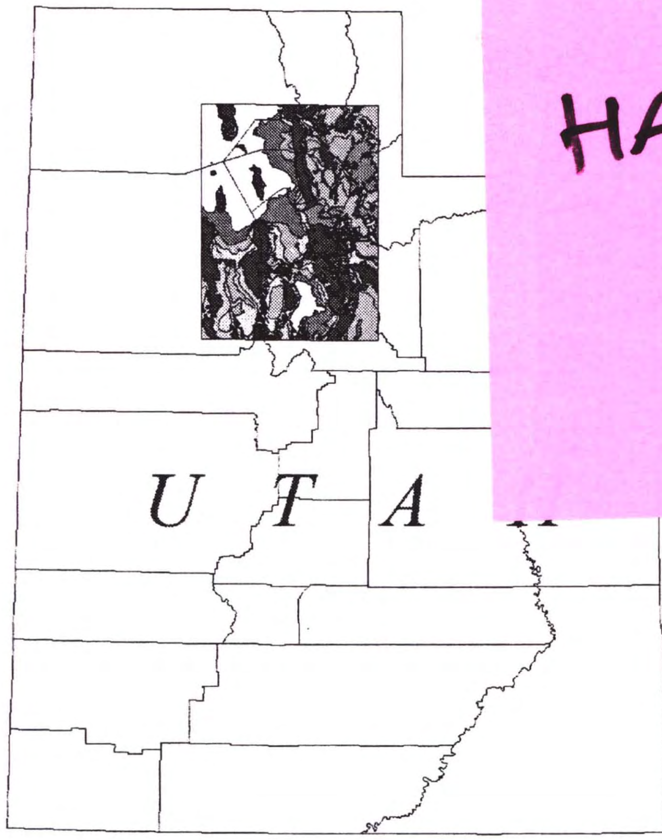
SITE-RESPONSE CHARACTERIZATION FOR IMPLEMENTING *SHAKEMAP* IN NORTHERN UTAH

by

Francis X. Ashland
Utah Geological Survey

HAZARD



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REPORT OF INVESTIGATION 248
UTAH GEOLOGICAL SURVEY
a division of
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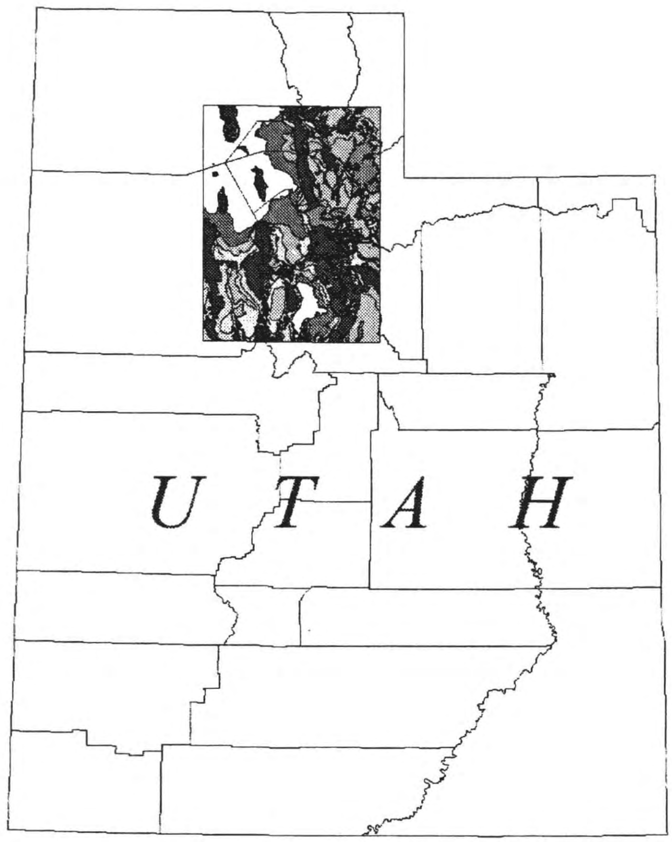

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ABSTRACT

As part of the effort to implement "ShakeMap" in northern Utah, I evaluated surface geology and available shear-wave velocity data to characterize and map the site response of geologic units during earthquake ground shaking. Site-response mapping was performed at two scales: (1) 1:500,000, using a simple geology-based site-response classification for generalized geologic units of northern Utah, and (2) 1:250,000, using a more detailed classification for the Quaternary units of the Wasatch Front urban corridor. Calculated or estimated average shear-wave velocities in the upper 30 meters range from 199 to 2,197 meters/second for the site-response units. I used statistical tests to evaluate the distinctiveness of previously recognized Quaternary site-response units for which shear-wave velocity data exist and grouped three of these units together. I calculated site amplification factors for the new site-response units which provide an estimate for local site response in areas where strong-motion instruments are lacking.

INTRODUCTION

In 2000, the University of Utah Seismograph Stations began implementing a real-time strong-motion data acquisition program in northern Utah. The ability to acquire and process strong-motion data almost instantly will allow for the rapid generation of maps, using "ShakeMap" computer software (Wald and others, 1999), which show instrumental ground motion and shaking intensity following a significant earthquake. Generation of a map showing ground shaking levels during an earthquake in northern Utah requires interpolation between measured ground motions at instrument stations. Frequency- and amplitude-dependent site amplification factors (site corrections of Wald and others [1999]) are needed to characterize local site response in areas that are not instrumented.

Adequate predictions of the average shear-wave velocity in the upper 30 meters (100 ft) (Vs30) are necessary to obtain site amplification factors for geologic units in northern Utah. This report summarizes the results of my site-response characterization of the surface geology in northern Utah. The scope of work included:

(1) evaluation of the available shear-wave velocity data for Quaternary deposits in northern Utah to determine statistically distinct site-response units,

(2) literature review and analysis of shear-wave velocity data for geologic units for which shear-wave velocities are lacking in northern Utah, and

(3) calculation of site amplification factors.

My analysis of shear-wave velocity data and site-response classification of geologic units generally followed the procedures of Park and Elrick (1998). I used the equations of Borcherdt (1994) to calculate frequency- and amplitude-dependent site amplification factors.

SIMPLE SITE-RESPONSE MAP OF NORTHERN UTAH

I grouped the complex surface geology of northern Utah into four simple geology-based site-response units: (Q) Quaternary sediments, (T) Tertiary sedimentary and volcanic rocks, (M) Mesozoic sedimentary rocks, and (P) Paleozoic and older basement rocks and Tertiary intrusive rocks (plate 1). The site-response-unit boundaries are equivalent to the map-unit boundaries from the *Digital Geologic Map of Utah* (Hintze and others, 2000). Each of the site-response units is inferred to have a distinct mean Vs30 and thus have distinct responses during earthquake ground shaking. Of the four units, actual Vs30 data exist only for the Quaternary deposits. I obtained shear-wave velocity data for Quaternary deposits from previous studies (Tinsley and others, 1991; Schuster and Sun, 1993; Ashland and Rollins, 1999) and a few unpublished reports. Table 1 summarizes Vs30 data and site classifications for the simple QTMP map of northern Utah.

Table 1.
Summary of Vs30 for QTMP site-response units.

Unit	Vs30[1] (m/sec)	Stdev[2]	Max (m/sec)	Min (m/sec)	Median (m/sec)	1st Quartile[3] (m/sec)	3rd Quartile[3] (m/sec)	No. Boreholes/ Sites	UBC[4] Soil-Profile Type
Q	234[5]	37%	590	151	215	180	301	101	S_D
T	1023	20%	1245	848	1071	--	--	5	S_B
M	1449	24%	1782	1009	1538	--	--	7	S_B
P[6]	2197	--	--	--	--	--	--	na	S_A

[1]Logarithmic mean. [2]Determined from variance of the log (velocity). [3]Descriptive statistics calculated using statistical software of the Physics Department of the College of Saint Benedict/Saint John's University, Minnesota. [4]UBC equals Uniform Building Code (International Conference of Building Officials, 1997). [5]The applicability of this value outside the limits of Lake Bonneville is uncertain. [6]Includes older basement rocks and Tertiary intrusives. See text for unit abbreviations.

Rock and/or rock-like material (in terms of Vs) was encountered at three sites where surface waves were used to determine shear-wave velocity profiles (Schuster and Sun, 1993) and in several boreholes in which Vs was measured by Tinsley and others (1991) (see also Williams and others, 1993). In one of these boreholes (SLCLAI; Tinsley and others, 1991), a 35-meter interval of probable Mesozoic rock was penetrated in the lower part of the borehole (figure 1) and I calculated both Vs30 and an average Vs gradient. I used the average gradient to calculate a synthetic Vs30 at the remaining sites where less than 30 meters of rock and/or rock-like material was encountered at the bottom of a borehole or Vs profile. At all of these sites, Quaternary sediments overlie the rock and/or rock-like material. Therefore, some uncertainty exists regarding the geology of the rock or rock-like material for which the synthetic Vs30 values were calculated. I used published geologic maps (Davis, 1983; Van Horn and Crittenden, 1987) to estimate the probable simple site-response unit (T, M, or P) of the buried rock at each of these sites. I then compared the calculated synthetic mean Vs30 values to data from the literature for

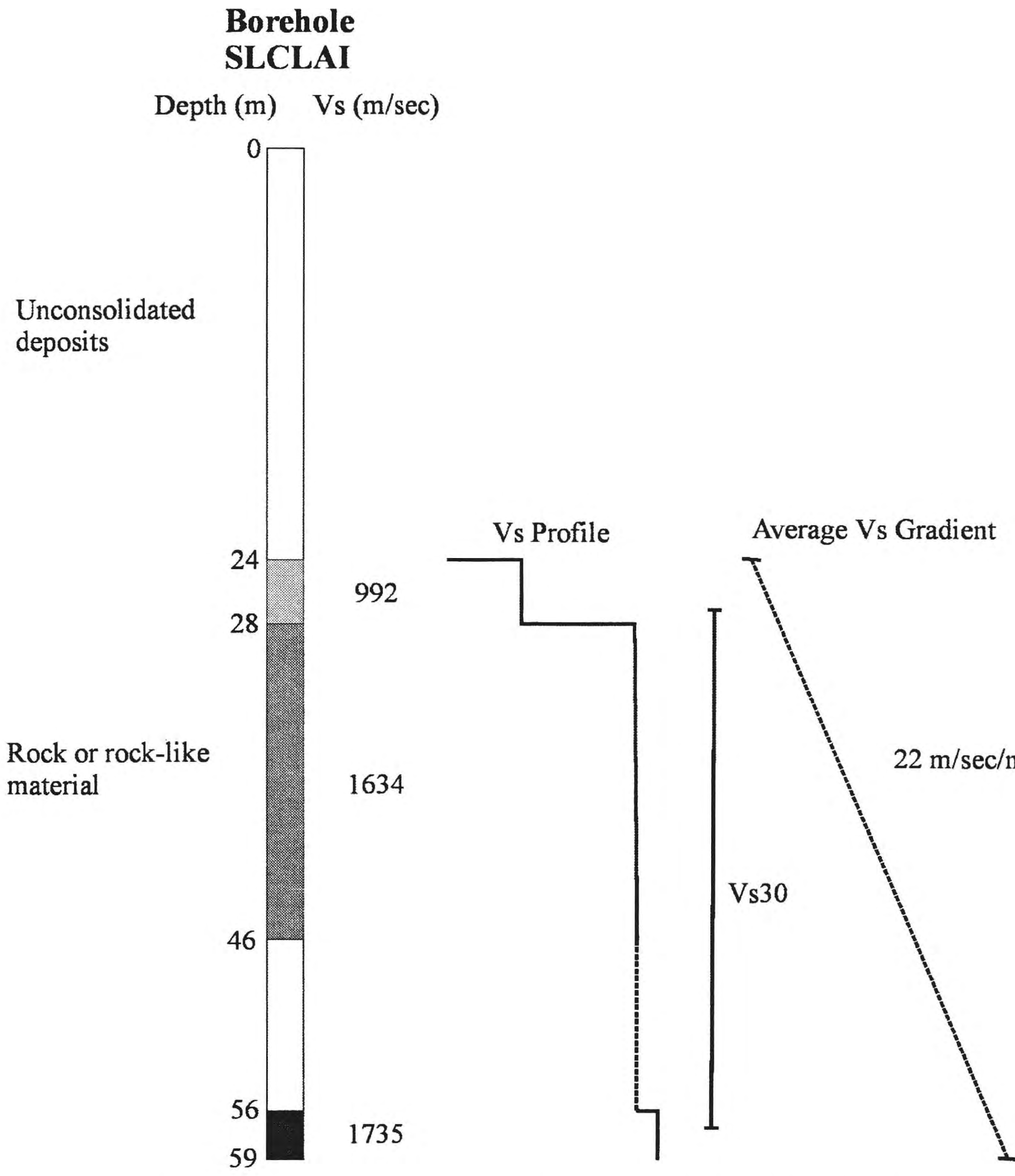

Figure 1. Schematic diagram showing interval in borehole SLCLAI with rock or rock-like material. Rock Vs30 was calculated over a 30-meter-thick interval overlapping the three distinct rock-like layers. Average gradient was determined over the entire interval of rock-like material. Borehole SLCLAI data from Tinsley and others (1991) except between 46 and 56 meters (dashed part of Vs profile) where Vs profile of Adan and Rollins (1993) used.

"similar" rocks (unpublished Utah Geological Survey database).

The synthetic values appeared to be reasonable estimates of Vs30 for Mesozoic rocks. However, the synthetic Vs30 values appeared to be too high for the Tertiary rocks and too low for Paleozoic and older rocks. An empirical correction was used for the Tertiary rocks equivalent to the initial ratio (0.84) of the synthetic Vs30 values for Tertiary and Mesozoic rocks. I believe such a correction is reasonable because of the likelihood that the average Vs gradient of Tertiary rocks in the upper 30 meters differs from the average Vs gradient at the Mesozoic rock site SLCLAI. The likely variation in the amount of consolidation and weathering between Tertiary and older rocks is the basis for this difference. I used Vs data for rock types common to the Paleozoic and older rocks in Utah and upper crustal Vs measurements in northern Utah area (Christensen, 1989) to estimate Vs30. The upper crustal Vs measurement locations of Christensen (1989) included sites near Eureka, Duchesne, and Dugway, Utah and a site near Evanston, Wyoming. Most of the southern part of the present study area is contained within the area defined by these four sites. Table 2 summarizes the Vs data used to estimate Vs30 for the Paleozoic and older rocks.

Table 2.
Summary of shear-wave-velocity data used to estimate Vs30 for Paleozoic[1] rocks.

Rock Type Specific or Regional Vs Data	Logarithmic Mean Vs (m/sec)
Intrusives, carbonates, quartzites, and metamorphic rocks	2427
Northern Utah Vs (Christensen, 1989)	1966
Mean	2197

[1] Includes older basement rocks and Tertiary intrusives.

The number of synthetic Vs30 values in each rock unit (T, M, and P) was insufficient to test whether the differences in Vs30 were statistically distinct; however, statistical tests (*t*-test and Kolmogorov-Smirnov test) were used to compare the composite rock units (TMP) with Quaternary deposits (Q). The test results suggest the differences in these two units are extremely significant.

The calculated site amplification factors for the four simple geology-based site-response units are summarized in table 3. A reference shear-wave velocity of 910 meters/second was used (J.C. Pechmann, written communication, December 27, 2000) to calculate the factors. Note that because the reference velocity is lower than velocities of Tertiary and older rock units, the site amplification factors for these units are below 1.0 for long periods and for short periods where the input rock peak ground accelerations are less than 35 percent *g*.

Table 3.
Site amplification factors for QTMP site-response units.

QTMP Unit/ Period (sec)	Vs30 (m/sec)	IRPGA[1] <15%g	IRPGA[1] 15-25%g	IRPGA[1] 25-35%g	IRPGA[1] >35%g
Quaternary[2] (Q)	234				
0.1-0.5		1.61	1.40	1.15	0.93
0.4-2.0		2.42	2.26	2.05	1.84
Tertiary[2] (T)	1023				
0.1-0.5		0.96	0.97	0.99	1.01
0.4-2.0		0.93	0.93	0.94	0.95
Mesozoic[2] (M)	1449				
0.1-0.5		0.85	0.89	0.95	1.02
0.4-2.0		0.74	0.76	0.78	0.81
Paleozoic[2, 3] (P)	2197				
0.1-0.5		0.73	0.80	0.92	1.05
0.4-2.0		0.56	0.59	0.63	0.67

[1]Input rock peak ground acceleration (IRPGA). [2]Site amplification factors calculated using a reference shear-wave velocity (v_o) of 910 m/sec. [3]Includes older basement rocks and Tertiary intrusives.

DETAILED SITE-RESPONSE MAP OF THE WASATCH FRONT URBAN CORRIDOR

Subdivision of the Quaternary unit (Q) results in better prediction of local shear-wave velocity and site classification. Ashland and Rollins (1999) used the Unified Engineering Geology Mapping (UEGM) System (Keaton and DeGraff, 1996) to group Quaternary surficial geologic units in the Salt Lake Valley having similar geotechnical properties. Ashland and Rollins (1999) subdivided the Quaternary unit into five preliminary site-response units, but recognized the possibility that at least two could be further subdivided. Of these possible seven units, Vs30 data exist for five: lacustrine-alluvial silt and clay (L-Amc); lacustrine silt and clay (Lmc), lacustrine sand (Ls), lacustrine and alluvial gravel (Lg and L-Ag), and alluvial-fan gravel (Ag).

In this study, I added 27 surface geophysical measurements of Vs30 (Schuster and Sun, 1993) to the Ashland and Rollins (1999) Vs30 data set. I calculated Vs30 from Vs profiles obtained by inversion of the fundamental mode dispersion of Rayleigh waves (Schuster and Sun, 1993). Calculating Vs30 in this manner provided the best agreement with Vs30 measurements determined in nearby boreholes at three Salt Lake Valley sites.

As part of this study, I assessed five of the preliminary site-response units identified by Ashland and Rollins (1999) for their statistical distinctiveness. The small number of Vs30 measurements in three of the units allowed for use of only the *t*-test to determine the significance of the difference in the means. The *t*-test results suggest that three of the units (alluvial-fan gravel [Ag], lacustrine sand [Ls], and lacustrine silt and clay [Lmc]) could be combined into a composite unit because they were not distinct from each other. Both the *t*-test and the Kolmogorov-Smirnov test suggest the other two units were distinct from each other and the composite unit. Table 4 summarizes Vs30 for the three distinct Quaternary units. Plate 2 shows the map unit boundaries of the three distinct Quaternary site-response units (Q01 through Q03) in the Wasatch Front urban corridor.

Ashland and Rollins (1999) mapped two other Quaternary site-response units (glacial till and outwash [Gg] and pre-Bonneville alluvial-fan gravels [cAg]) for which Vs30 data are lacking. I used data for glacial deposits (till and outwash) in the Pacific Northwest (Monahan and Levson, 1997; Williams and others, 1997) to estimate Vs30 of glacial deposits in northern Utah. Although the Pacific Northwest glacial deposits include basal lodgement tills formed during continental glaciation which do not occur in Utah, the mean Vs30 of 486 meters/second for these deposits is probably still a reasonable estimate for Utah glacial deposits. In the absence of Vs30 data for deposits similar to the pre-Bonneville alluvial-fan gravels in the literature, a median value of 437 meters/second between the mean Vs30 values for lacustrine gravels and glacial deposits was selected. Plate 2 also shows the map unit boundaries for these two site-response units.

Table 4.
Summary of Vs30 for three distinct Quaternary site-response units.

Site-Response Map Unit	UEGM Unit	Vs30[1] (m/sec)	Stdev[2]	Max (m/sec)	Min (m/sec)	Median (m/sec)	1st Quartile[3] (m/sec)	3rd Quartile[3] (m/sec)	No. Boreholes/ Sites
Q01	L-Amc	199	22%	325	151	188	171	216	68
Q02	Lmc-Ls-Ag composite	301	20%	469	212	303	257	348	23
Q03	Lg and L-Ag	387	29%	590	260	368	322	482	10

[1]Logarithmic mean. [2]Determined from variance of the log (velocity). [3]Descriptive statistics calculated using statistical software of the Physics Department of the College of Saint Benedict/Saint John's University, Minnesota.

The calculated site amplification factors for the Quaternary site-response units are summarized in table 5. I used a reference shear-wave velocity of 910 meters/second (J.C. Pechmann, written communication, December 27, 2000) to calculate the factors. Note that this velocity is considerably less than estimated shear-wave velocities of rock units which may underlie unconsolidated deposits in the study area (see Vs30 values in table 1).

Table 5.
Site amplification factors for Quaternary site-response units.

Site-Response Map Unit	UEGM Unit	Vs30 (m/sec)	Period (sec)	IRPGA[1,2] <15%g	IRPGA[1,2] 15-25%g	IRPGA[1,2] 25-35%g	IRPGA[1,2] >35%g
Q01	L-Amc	199					
			0.1-0.5	1.70	1.46	1.16	0.93
			0.4-2.0	2.69	2.49	2.24	1.98
Q02	Lmc-Ls-Ag composite	301					
			0.1-0.5	1.47	1.32	1.12	0.95
			0.4-2.0	2.05	1.94	1.80	1.65
Q03	Lg and L-Ag	387					
			0.1-0.5	1.35	1.24	1.09	0.96
			0.4-2.0	1.74	1.67	1.57	1.47
Q04	cAg	437					
			0.1-0.5	1.29	1.20	1.08	0.96
			0.4-2.0	1.61	1.55	1.48	1.39
Q05	Gg	486					
			0.1-0.5	1.25	1.17	1.06	0.97
			0.4-2.0	1.50	1.46	1.39	1.33

[1]Input rock peak ground acceleration (IRPGA). [2]Site amplification factors calculated using a reference shear-wave velocity (v_o) of 910 m/sec.

SUMMARY AND CONCLUSIONS

Generation of ShakeMaps requires interpolation between measured ground motions at instrument stations. In areas lacking instruments, frequency- and amplitude-dependent site amplification factors are needed to characterize local site response. In this study, I grouped the surface geology of northern Utah into four simple geology-based site-response units: (Q) Quaternary deposits, (T) Tertiary sedimentary and volcanic rocks, (M) Mesozoic sedimentary rocks, and (P) Paleozoic and older basement rocks and Tertiary intrusive rocks. Mean Vs30 for these units ranges from 234 meters/second (Q) to 2,197 meters/second (P) (table 1). I estimated mean Vs30 for site-response units T and M using synthetic Vs30 extrapolated from Vs measurements at the bottom of Vs profiles in the Salt Lake Valley in which rock and/or rock-like material was encountered. I estimated mean Vs30 for site-response unit P using literature values of Vs for rock types similar to those contained in unit P and from upper crustal Vs measurements in northern Utah. Table 3 summarizes the frequency- and amplitude-dependent site amplification factors for the four site-response units.

I combined Vs30 data for Quaternary deposits from Ashland and Rollins (1999) with Vs30 measurements derived from the Vs profiles of Schuster and Sun (1993) and limited other sources. Using statistical tests, I recognized three statistically distinct Quaternary site-response units: Lg (includes L-Ag), L-Amc, and a composite unit Lmc-Ls-Ag. Mean Vs30 for these units ranges from 199 meters/second (Q01: L-Amc) to 387 meters/second (Q03: Lg and L-Ag) (table 4). I used Vs data from the literature to estimate Vs30 for two other Quaternary site-response units mapped by Ashland and Rollins (1999) for which Vs measurements are lacking. Table 5 summarizes the frequency- and amplitude-dependent site amplification factors for the five Quaternary site-response units.

LIMITATIONS

The mean Vs30 and other values in this report, excluding those for site-response unit Q, are based on limited data and will be updated as new Vs30 data are obtained. Mean Vs30 for site-response unit Q is based on the available Vs30 data from mostly lacustrine deposits in the Salt Lake Valley. Thus, the applicability of the Vs30 value for site-response unit Q to Quaternary deposits outside the limits of Lake Bonneville is uncertain. More data are needed to adequately characterize Vs30 for the majority of the site-response units. Upon retrieval of strong-motion records, ShakeMaps derived using these Vs30 values and station records must be carefully evaluated to determine how accurately the Vs30 values characterize site response and whether revisions to the values are necessary. The site amplification factors in this report are intended only for use in implementing ShakeMap and are not intended for engineering design purposes, although the Vs30 values and site-response maps may be useful for engineering characterization of site response.

ACKNOWLEDGMENTS

This work was supported in part by grants from the Utah Division of Comprehensive Emergency Management and U.S. Geological Survey, and conducted in cooperation with the University of Utah Seismograph Stations (UUSS). Kolmogorov-Smirnov tests were performed using statistical software developed at the Physics Department of the College of Saint Benedict/Saint John's University, Minnesota. The initial digital compilation of plate 1 was completed by Lorraine Nelms (UUSS). Digital compilation of the plates was finalized by Neil Storey and James McBride (UGS). Greg McDonald (UGS) compiled plate 2 and provided a thorough review of calculations and other work performed for this study, but I am ultimately responsible for any errors herein. I appreciate a review of an initial draft of this report by Jim Pechmann and Kristine Pankow (UUSS). Gary Christenson and Michael Hylland (UGS) critically reviewed this report.

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PLATES

ABSTRACT

As part of the effort to implement "ShakeMap" in northern Utah, I evaluated surface geology and available shear-wave velocity data to characterize and map the site response of geologic units during earthquake ground shaking. Site-response mapping was performed at two scales: (1) 1:500,000, using a simple geology-based site-response classification for generalized geologic units of northern Utah, and (2) 1:250,000, using a more detailed classification for the Quaternary units of the Wasatch Front urban corridor. Calculated or estimated average shear-wave velocities in the upper 30 meters range from 199 to 2,197 meters/second for the site-response units. I used statistical tests to evaluate the distinctiveness of previously recognized Quaternary site-response units for which shear-wave velocity data exist and grouped three of these units together. I calculated site amplification factors for the new site-response units which provide an estimate for local site response in areas where strong-motion instruments are lacking.

INTRODUCTION

In 2000, the University of Utah Seismograph Stations began implementing a real-time strong-motion data acquisition program in northern Utah. The ability to acquire and process strong-motion data almost instantly will allow for the rapid generation of maps, using "ShakeMap" computer software (Wald and others, 1999), which show instrumental ground motion and shaking intensity following a significant earthquake. Generation of a map showing ground shaking levels during an earthquake in northern Utah requires interpolation between measured ground motions at instrument stations. Frequency- and amplitude-dependent site amplification factors (site corrections of Wald and others [1999]) are needed to characterize local site response in areas that are not instrumented.

Adequate predictions of the average shear-wave velocity in the upper 30 meters (100 ft) (Vs30) are necessary to obtain site amplification factors for geologic units in northern Utah. This report summarizes the results of my site-response characterization of the surface geology in northern Utah. The scope of work included:

(1) evaluation of the available shear-wave velocity data for Quaternary deposits in northern Utah to determine statistically distinct site-response units,

(2) literature review and analysis of shear-wave velocity data for geologic units for which shear-wave velocities are lacking in northern Utah, and

(3) calculation of site amplification factors.

My analysis of shear-wave velocity data and site-response classification of geologic units generally followed the procedures of Park and Elrick (1998). I used the equations of Borcherdt (1994) to calculate frequency- and amplitude-dependent site amplification factors.

SIMPLE SITE-RESPONSE MAP OF NORTHERN UTAH

I grouped the complex surface geology of northern Utah into four simple geology-based site-response units: (Q) Quaternary sediments, (T) Tertiary sedimentary and volcanic rocks, (M) Mesozoic sedimentary rocks, and (P) Paleozoic and older basement rocks and Tertiary intrusive rocks (plate 1). The site-response-unit boundaries are equivalent to the map-unit boundaries from the *Digital Geologic Map of Utah* (Hintze and others, 2000). Each of the site-response units is inferred to have a distinct mean Vs30 and thus have distinct responses during earthquake ground shaking. Of the four units, actual Vs30 data exist only for the Quaternary deposits. I obtained shear-wave velocity data for Quaternary deposits from previous studies (Tinsley and others, 1991; Schuster and Sun, 1993; Ashland and Rollins, 1999) and a few unpublished reports. Table 1 summarizes Vs30 data and site classifications for the simple QTMP map of northern Utah.

Table 1.
Summary of Vs30 for QTMP site-response units.

Unit	Vs30[1] (m/sec)	Stdev[2]	Max (m/sec)	Min (m/sec)	Median (m/sec)	1st Quartile[3] (m/sec)	3rd Quartile[3] (m/sec)	No. Boreholes/ Sites	UBC[4] Soil-Profile Type
Q	234[5]	37%	590	151	215	180	301	101	S_D
T	1023	20%	1245	848	1071	--	--	5	S_B
M	1449	24%	1782	1009	1538	--	--	7	S_B
P[6]	2197	--	--	--	--	--	--	na	S_A

[1]Logarithmic mean. [2]Determined from variance of the log (velocity). [3]Descriptive statistics calculated using statistical software of the Physics Department of the College of Saint Benedict/Saint John's University, Minnesota. [4]UBC equals Uniform Building Code (International Conference of Building Officials, 1997). [5]The applicability of this value outside the limits of Lake Bonneville is uncertain. [6]Includes older basement rocks and Tertiary intrusives. See text for unit abbreviations.

Rock and/or rock-like material (in terms of Vs) was encountered at three sites where surface waves were used to determine shear-wave velocity profiles (Schuster and Sun, 1993) and in several boreholes in which Vs was measured by Tinsley and others (1991) (see also Williams and others, 1993). In one of these boreholes (SLCLAI; Tinsley and others, 1991), a 35-meter interval of probable Mesozoic rock was penetrated in the lower part of the borehole (figure 1) and I calculated both Vs30 and an average Vs gradient. I used the average gradient to calculate a synthetic Vs30 at the remaining sites where less than 30 meters of rock and/or rock-like material was encountered at the bottom of a borehole or Vs profile. At all of these sites, Quaternary sediments overlie the rock and/or rock-like material. Therefore, some uncertainty exists regarding the geology of the rock or rock-like material for which the synthetic Vs30 values were calculated. I used published geologic maps (Davis, 1983; Van Horn and Crittenden, 1987) to estimate the probable simple site-response unit (T, M, or P) of the buried rock at each of these sites. I then compared the calculated synthetic mean Vs30 values to data from the literature for

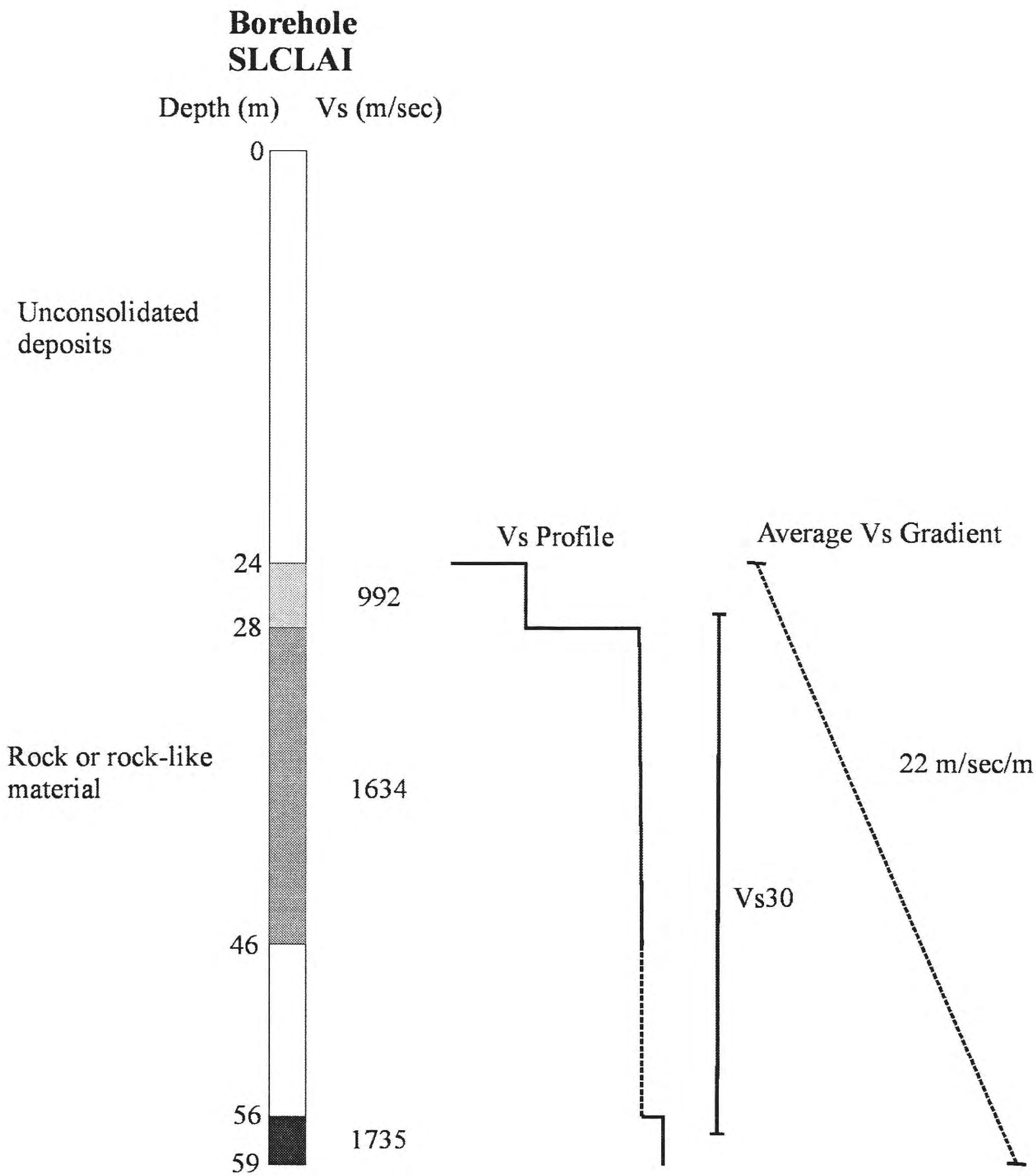

Figure 1. Schematic diagram showing interval in borehole SLCLAI with rock or rock-like material. Rock Vs30 was calculated over a 30-meter-thick interval overlapping the three distinct rock-like layers. Average gradient was determined over the entire interval of rock-like material. Borehole SLCLAI data from Tinsley and others (1991) except between 46 and 56 meters (dashed part of Vs profile) where Vs profile of Adan and Rollins (1993) used.

"similar" rocks (unpublished Utah Geological Survey database).

The synthetic values appeared to be reasonable estimates of Vs30 for Mesozoic rocks. However, the synthetic Vs30 values appeared to be too high for the Tertiary rocks and too low for Paleozoic and older rocks. An empirical correction was used for the Tertiary rocks equivalent to the initial ratio (0.84) of the synthetic Vs30 values for Tertiary and Mesozoic rocks. I believe such a correction is reasonable because of the likelihood that the average Vs gradient of Tertiary rocks in the upper 30 meters differs from the average Vs gradient at the Mesozoic rock site SLCLAI. The likely variation in the amount of consolidation and weathering between Tertiary and older rocks is the basis for this difference. I used Vs data for rock types common to the Paleozoic and older rocks in Utah and upper crustal Vs measurements in northern Utah area (Christensen, 1989) to estimate Vs30. The upper crustal Vs measurement locations of Christensen (1989) included sites near Eureka, Duchesne, and Dugway, Utah and a site near Evanston, Wyoming. Most of the southern part of the present study area is contained within the area defined by these four sites. Table 2 summarizes the Vs data used to estimate Vs30 for the Paleozoic and older rocks.

Table 2.
Summary of shear-wave-velocity data used to estimate Vs30 for Paleozoic[1] rocks.

Rock Type Specific or Regional Vs Data	Logarithmic Mean Vs (m/sec)
Intrusives, carbonates, quartzites, and metamorphic rocks	2427
Northern Utah Vs (Christensen, 1989)	1966
Mean	2197

[1] Includes older basement rocks and Tertiary intrusives.

The number of synthetic Vs30 values in each rock unit (T, M, and P) was insufficient to test whether the differences in Vs30 were statistically distinct; however, statistical tests (t-test and Kolmogorov-Smirnov test) were used to compare the composite rock units (TMP) with Quaternary deposits (Q). The test results suggest the differences in these two units are extremely significant.

The calculated site amplification factors for the four simple geology-based site-response units are summarized in table 3. A reference shear-wave velocity of 910 meters/second was used (J.C. Pechmann, written communication, December 27, 2000) to calculate the factors. Note that because the reference velocity is lower than velocities of Tertiary and older rock units, the site amplification factors for these units are below 1.0 for long periods and for short periods where the input rock peak ground accelerations are less than 35 percent *g*.

Table 3.
Site amplification factors for QTMP site-response units.

QTMP Unit/ Period (sec)	Vs30 (m/sec)	IRPGA[1] <15%g	IRPGA[1] 15-25%g	IRPGA[1] 25-35%g	IRPGA[1] >35%g
Quaternary[2] (Q)	234				
0.1-0.5		1.61	1.40	1.15	0.93
0.4-2.0		2.42	2.26	2.05	1.84
Tertiary[2] (T)	1023				
0.1-0.5		0.96	0.97	0.99	1.01
0.4-2.0		0.93	0.93	0.94	0.95
Mesozoic[2] (M)	1449				
0.1-0.5		0.85	0.89	0.95	1.02
0.4-2.0		0.74	0.76	0.78	0.81
Paleozoic[2, 3] (P)	2197				
0.1-0.5		0.73	0.80	0.92	1.05
0.4-2.0		0.56	0.59	0.63	0.67

[1]Input rock peak ground acceleration (IRPGA). [2]Site amplification factors calculated using a reference shear-wave velocity (v_o) of 910 m/sec. [3]Includes older basement rocks and Tertiary intrusives.

DETAILED SITE-RESPONSE MAP OF THE WASATCH FRONT URBAN CORRIDOR

Subdivision of the Quaternary unit (Q) results in better prediction of local shear-wave velocity and site classification. Ashland and Rollins (1999) used the Unified Engineering Geology Mapping (UEGM) System (Keaton and DeGraff, 1996) to group Quaternary surficial geologic units in the Salt Lake Valley having similar geotechnical properties. Ashland and Rollins (1999) subdivided the Quaternary unit into five preliminary site-response units, but recognized the possibility that at least two could be further subdivided. Of these possible seven units, Vs30 data exist for five: lacustrine-alluvial silt and clay (L-Amc); lacustrine silt and clay (Lmc), lacustrine sand (Ls), lacustrine and alluvial gravel (Lg and L-Ag), and alluvial-fan gravel (Ag).

In this study, I added 27 surface geophysical measurements of Vs30 (Schuster and Sun, 1993) to the Ashland and Rollins (1999) Vs30 data set. I calculated Vs30 from Vs profiles obtained by inversion of the fundamental mode dispersion of Rayleigh waves (Schuster and Sun, 1993). Calculating Vs30 in this manner provided the best agreement with Vs30 measurements determined in nearby boreholes at three Salt Lake Valley sites.

As part of this study, I assessed five of the preliminary site-response units identified by Ashland and Rollins (1999) for their statistical distinctiveness. The small number of Vs30 measurements in three of the units allowed for use of only the *t*-test to determine the significance of the difference in the means. The *t*-test results suggest that three of the units (alluvial-fan gravel [Ag], lacustrine sand [Ls], and lacustrine silt and clay [Lmc]) could be combined into a composite unit because they were not distinct from each other. Both the *t*-test and the Kolmogorov-Smirnov test suggest the other two units were distinct from each other and the composite unit. Table 4 summarizes Vs30 for the three distinct Quaternary units. Plate 2 shows the map unit boundaries of the three distinct Quaternary site-response units (Q01 through Q03) in the Wasatch Front urban corridor.

Ashland and Rollins (1999) mapped two other Quaternary site-response units (glacial till and outwash [Gg] and pre-Bonneville alluvial-fan gravels [cAg]) for which Vs30 data are lacking. I used data for glacial deposits (till and outwash) in the Pacific Northwest (Monahan and Levson, 1997; Williams and others, 1997) to estimate Vs30 of glacial deposits in northern Utah. Although the Pacific Northwest glacial deposits include basal lodgement tills formed during continental glaciation which do not occur in Utah, the mean Vs30 of 486 meters/second for these deposits is probably still a reasonable estimate for Utah glacial deposits. In the absence of Vs30 data for deposits similar to the pre-Bonneville alluvial-fan gravels in the literature, a median value of 437 meters/second between the mean Vs30 values for lacustrine gravels and glacial deposits was selected. Plate 2 also shows the map unit boundaries for these two site-response units.

Table 4.

Summary of Vs30 for three distinct Quaternary site-response units.

Site-Response Map Unit	UEGM Unit	Vs30[1] (m/sec)	Stdev[2]	Max (m/sec)	Min (m/sec)	Median (m/sec)	1st Quartile[3] (m/sec)	3rd Quartile[3] (m/sec)	No. Boreholes/ Sites
Q01	L-Amc	199	22%	325	151	188	171	216	68
Q02	Lmc-Ls-Ag composite	301	20%	469	212	303	257	348	23
Q03	Lg and L-Ag	387	29%	590	260	368	322	482	10

[1]Logarithmic mean. [2]Determined from variance of the log (velocity). [3]Descriptive statistics calculated using statistical software of the Physics Department of the College of Saint Benedict/Saint John's University, Minnesota.

The calculated site amplification factors for the Quaternary site-response units are summarized in table 5. I used a reference shear-wave velocity of 910 meters/second (J.C. Pechmann, written communication, December 27, 2000) to calculate the factors. Note that this velocity is considerably less than estimated shear-wave velocities of rock units which may underlie unconsolidated deposits in the study area (see Vs30 values in table 1).

Table 5.
Site amplification factors for Quaternary site-response units.

Site-Response Map Unit	UEGM Unit	Vs30 (m/sec)	Period (sec)	IRPGA[1,2] <15%g	IRPGA[1,2] 15-25%g	IRPGA[1,2] 25-35%g	IRPGA[1,2] >35%g
Q01	L-Amc	199					
			0.1-0.5	1.70	1.46	1.16	0.93
			0.4-2.0	2.69	2.49	2.24	1.98
Q02	Lmc-Ls-Ag composite	301					
			0.1-0.5	1.47	1.32	1.12	0.95
			0.4-2.0	2.05	1.94	1.80	1.65
Q03	Lg and L-Ag	387					
			0.1-0.5	1.35	1.24	1.09	0.96
			0.4-2.0	1.74	1.67	1.57	1.47
Q04	cAg	437					
			0.1-0.5	1.29	1.20	1.08	0.96
			0.4-2.0	1.61	1.55	1.48	1.39
Q05	Gg	486					
			0.1-0.5	1.25	1.17	1.06	0.97
			0.4-2.0	1.50	1.46	1.39	1.33

[1]Input rock peak ground acceleration (IRPGA). [2]Site amplification factors calculated using a reference shear-wave velocity (v_o) of 910 m/sec.

SUMMARY AND CONCLUSIONS

Generation of ShakeMaps requires interpolation between measured ground motions at instrument stations. In areas lacking instruments, frequency- and amplitude-dependent site amplification factors are needed to characterize local site response. In this study, I grouped the surface geology of northern Utah into four simple geology-based site-response units: (Q) Quaternary deposits, (T) Tertiary sedimentary and volcanic rocks, (M) Mesozoic sedimentary rocks, and (P) Paleozoic and older basement rocks and Tertiary intrusive rocks. Mean Vs30 for these units ranges from 234 meters/second (Q) to 2,197 meters/second (P) (table 1). I estimated mean Vs30 for site-response units T and M using synthetic Vs30 extrapolated from Vs measurements at the bottom of Vs profiles in the Salt Lake Valley in which rock and/or rock-like material was encountered. I estimated mean Vs30 for site-response unit P using literature values of Vs for rock types similar to those contained in unit P and from upper crustal Vs measurements in northern Utah. Table 3 summarizes the frequency- and amplitude-dependent site amplification factors for the four site-response units.

I combined Vs30 data for Quaternary deposits from Ashland and Rollins (1999) with Vs30 measurements derived from the Vs profiles of Schuster and Sun (1993) and limited other sources. Using statistical tests, I recognized three statistically distinct Quaternary site-response units: Lg (includes L-Ag), L-Amc, and a composite unit Lmc-Ls-Ag. Mean Vs30 for these units ranges from 199 meters/second (Q01: L-Amc) to 387 meters/second (Q03: Lg and L-Ag) (table 4). I used Vs data from the literature to estimate Vs30 for two other Quaternary site-response units mapped by Ashland and Rollins (1999) for which Vs measurements are lacking. Table 5 summarizes the frequency- and amplitude-dependent site amplification factors for the five Quaternary site-response units.

LIMITATIONS

The mean Vs30 and other values in this report, excluding those for site-response unit Q, are based on limited data and will be updated as new Vs30 data are obtained. Mean Vs30 for site-response unit Q is based on the available Vs30 data from mostly lacustrine deposits in the Salt Lake Valley. Thus, the applicability of the Vs30 value for site-response unit Q to Quaternary deposits outside the limits of Lake Bonneville is uncertain. More data are needed to adequately characterize Vs30 for the majority of the site-response units. Upon retrieval of strong-motion records, ShakeMaps derived using these Vs30 values and station records must be carefully evaluated to determine how accurately the Vs30 values characterize site response and whether revisions to the values are necessary. The site amplification factors in this report are intended only for use in implementing ShakeMap and are not intended for engineering design purposes, although the Vs30 values and site-response maps may be useful for engineering characterization of site response.

ACKNOWLEDGMENTS

This work was supported in part by grants from the Utah Division of Comprehensive Emergency Management and U.S. Geological Survey, and conducted in cooperation with the University of Utah Seismograph Stations (UUSS). Kolmogorov-Smirnov tests were performed using statistical software developed at the Physics Department of the College of Saint Benedict/Saint John's University, Minnesota. The initial digital compilation of plate 1 was completed by Lorraine Nelms (UUSS). Digital compilation of the plates was finalized by Neil Storey and James McBride (UGS). Greg McDonald (UGS) compiled plate 2 and provided a thorough review of calculations and other work performed for this study, but I am ultimately responsible for any errors herein. I appreciate a review of an initial draft of this report by Jim Pechmann and Kristine Pankow (UUSS). Gary Christenson and Michael Hylland (UGS) critically reviewed this report.

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SITE-RESPONSE CHARACTERIZATION FOR IMPLEMENTING *SHAKEMAP* IN NORTHERN UTAH

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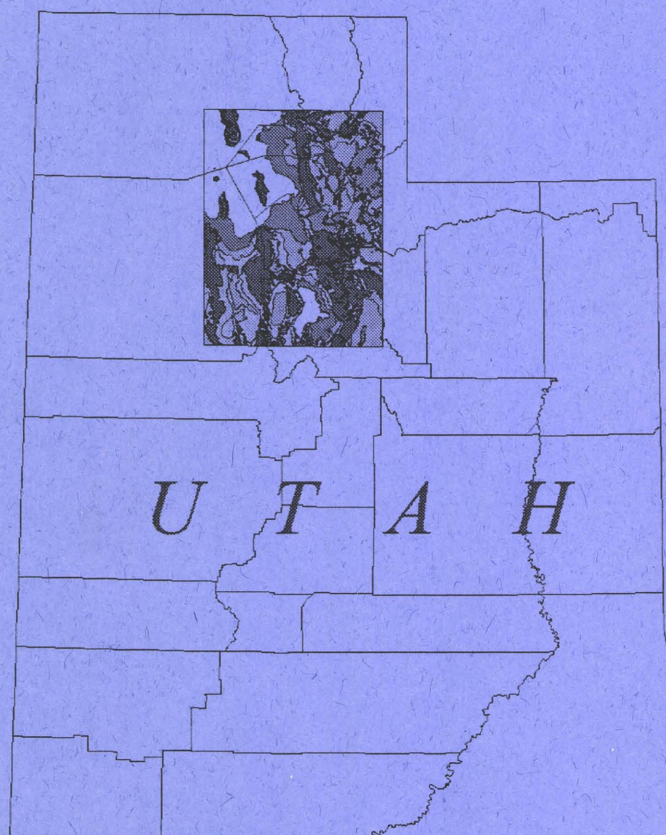

Research supported by the Utah Division of Comprehensive Emergency Management, the University of Utah Seismograph Stations, and the U.S. Geological Survey (USGS), Department of the Interior, under USGS award numbers 1434-HQ-97-GR-03126 and 99HQGR0091. The views and conclusions contained in this document are those of the author and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the U.S. Government and other supporting agencies.

REPORT OF INVESTIGATION 248
UTAH GEOLOGICAL SURVEY
a division of
UTAH DEPARTMENT OF NATURAL RESOURCES

September 2001

UTAH GEOLOGICAL SURVEY