Harty, Lowe   GEOLOGIC EVALUATION AND HAZARD POTENTIAL OF LIQUEFACTION-INDUCED LANDSLIDES, WASATCH FRONT, UTAH   UGS SS104

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by

Kimm M. Harty and Mike Lowe

SPECIAL STUDY 104
UTAH GEOLOGICAL SURVEY
a division of
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Cover photograph of south view of the Harrisburg trench, by K.M. Harty

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GEOLOGIC EVALUATION AND HAZARD POTENTIAL OF LIQUEFACTION-INDUCED LANDSLIDES ALONG THE WASATCH FRONT, UTAH

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ABSTRACT

Much of the Wasatch Front of northern Utah is underlain by saturated sandy sediments that are prone to liquefaction during moderate and large earthquakes. Precluding development in these high-liquefaction-potential zones is impractical because they are areally extensive and urbanized in many areas, and because liquefaction is not generally a life-threatening hazard. However, large, earthquake-induced slope failures initiated by liquefaction can present a hazard to life as well as property. Thirteen liquefaction-induced landslides have been identified along the Wasatch Front by previous researchers, but development has proceeded in these areas with little consideration of the hazards from these landslides. This is partly because little evidence was available to indicate that the slope failures have reactivated during earthquakes, and because the modern hazard potential of these features had not been evaluated.

We conducted geologic investigations of the 13 late Pleistocene/Holocene features along the Wasatch Front. Most were identified as liquefaction-induced, lateral-spread landslides by previous investigators. The goal of the investigation was to assess the hazard these features pose by determining if they are indeed liquefaction-induced landslides, and determining their potential for movement during future earthquakes. Methods used to investigate the features included detailed surficial-geologic and geomorphic mapping of the landslides and surrounding deposits, and evaluation of stratigraphy in excavations and exposures on the landslides.

Geomorphic evidence suggests that the six features mapped as lateral spreads in Box Elder County are predominantly rotational slides into Lake Bonneville that were possibly earthquake-induced. However, the morphology of the deposits, and the fact that they formed in gravel deposits on steep slopes, suggest that liquefaction was probably not a contributing factor to these failures. Geomorphic and subsurface evidence suggests that the features in Utah County may have formed by a process other than landsliding, and may be related to differential subsidence or other conditions caused by a fluctuating shallow water table or spring discharge. We observed evidence of late Holocene earthquake-induced liquefaction in a trench in Harrisville on the North Ogden landslide complex. Geomorphic mapping indicates that this feature has had multiple periods of movement under several failure modes. Geomorphic mapping and radiocarbon dating of the Farmington Siding landslide complex supports work done by previous researchers that showed this feature consists of multiple liquefaction-induced failures, and has moved in the late Holocene. Geomorphic mapping of the seven features outside Box Elder County indicates that most formed in Holocene time (East Ogden, Farmington Siding, North Salt Lake, West Kaysville, and Beer Creek), although some (Springville-Spanish Fork and possibly North Ogden) may have initiated movement in the late Pleistocene.

The hazard potential of the features varies because of differences in failure mechanism and uncertainty in their origin. Whereas the hazard potential of some failures, such as the North Ogden and Farmington Siding landslide complexes, likely remains high in certain areas, that of others, such as the East Ogden landslide, has decreased due to significant changes in hydrologic conditions. Multiple failures, and possibly recurrent landsliding have occurred within the boundaries of the North Ogden, East Ogden, and Farmington Siding failures. The potential for future movement of these landslides needs to be considered by local governments during land-use evaluations prior to development. Several features were examined on a reconnaissance level, with no subsurface investigation. These features require further detailed study to understand their hazard potential.

INTRODUCTION AND PURPOSE

Approximately 1.7 million people live along the Wasatch Front, many in areas with a high liquefaction potential, and many within the borders of 13 previously mapped, prehistoric, liquefaction-induced landslides. Little is currently known about the hazard potential of these earthquake-induced features. Engineering studies conducted along the Wasatch Front in the 1980s (Anderson and others, 1982, 1986a, 1986b, 1990; Bay, 1987; Mabey and Youd, 1989) have identified areas with a high liquefaction potential during earthquakes. These areas are underlain by saturated sandy sediments and are widespread in the low-lying parts of Wasatch Front valleys (figure 1). To preclude development in these high-liquefaction-potential zones is impractical because they are areally extensive, and many are already devel-

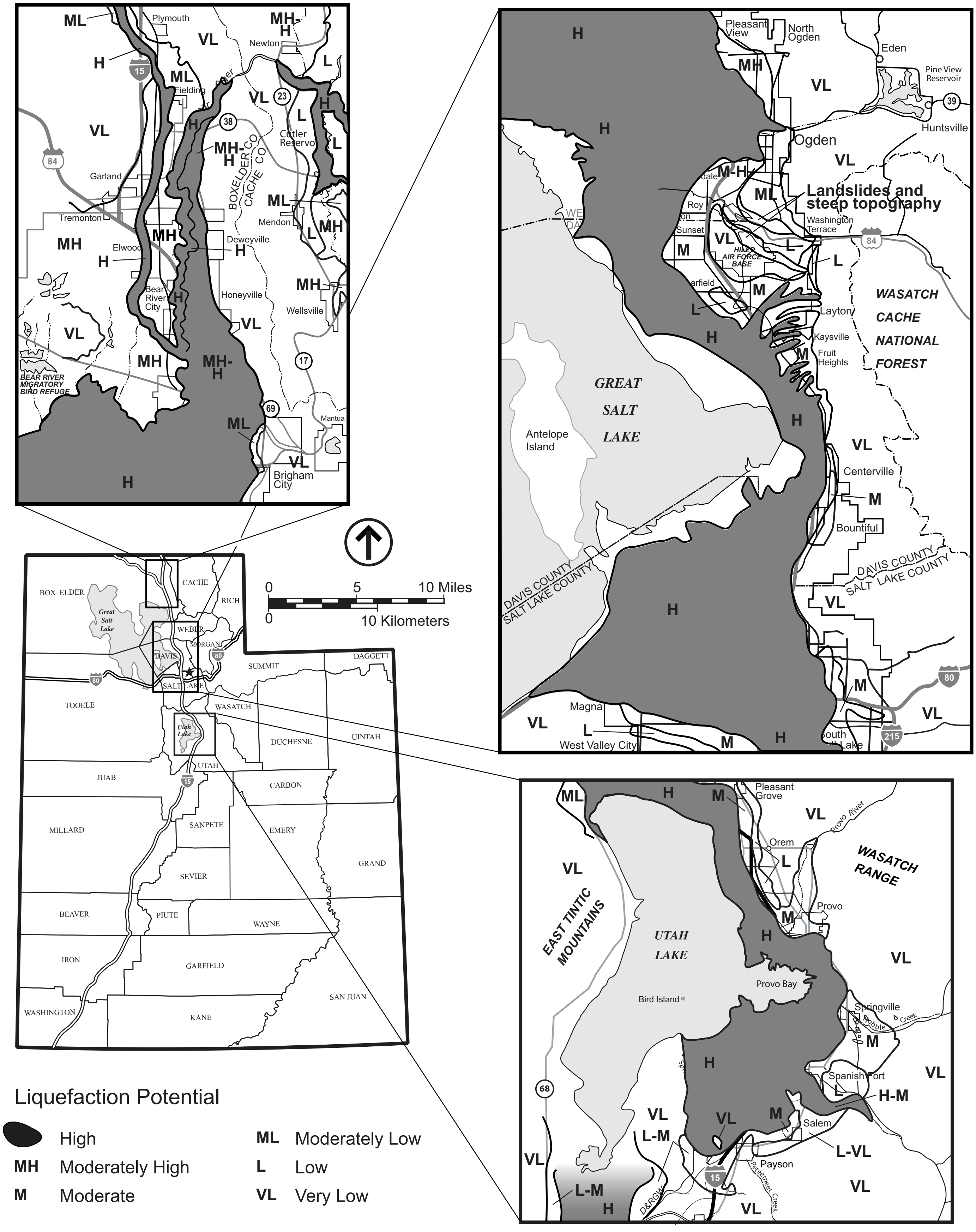


Figure 1. Liquefaction potential of portions of the Wasatch Front (modified from Anderson and others, 1982, 1986a, 1986b, 1990).

oped (figure 1). In addition, liquefaction is not generally a life-threatening hazard. However, large, liquefaction-induced slope failures accompanying earthquakes may present a greater hazard to life and property, and thus require careful consideration prior to development.

Thirteen liquefaction-induced landslides were identified along the Wasatch Front during the 1970s-1990s (figure 2). Large-magnitude surface-faulting earthquakes on the Wasatch fault were considered by previous workers to be the most likely cause of these failures. Urbanization covers some of these suspected liquefaction-induced failures; others are largely undeveloped at present. With continued population growth along the Wasatch Front, the likelihood increases that development will continue or begin in these areas. Our study, designed to conduct further evaluation of the potential hazard, can help government officials and others to make informed decisions when development is proposed in these areas.

The reader should note that a fourteenth possible liquefaction-induced landslide has been identified in a number of building excavations in downtown Salt Lake City (Osmond and others, 1965; Dames and Moore, 1977; Van Horn, 1982; Kleinfelder, Inc., 1999; Korbay and McCormick, 1999). Because this area is heavily urbanized and inaccessible for surface and subsurface investigations, the feature was not included in this study.

The purpose of this study is to evaluate the potential for future movement of the landslides during earthquakes to determine the hazard these features may pose. Goals of the study were to: (1) determine when landslide movement occurred, (2) determine the failure mode (lateral spread versus flow failure), (3) determine if recurrent movement has occurred, (4) correlate, where possible, through radiocarbon dating, the timing of landslide movement(s) with the paleoseismic record from fault studies along the Wasatch Front, and (5) assess the current hazard from liquefaction-induced landslides along the Wasatch Front. Once the study was underway, it became evident that not all 13 landslides were liquefaction induced, or even landslides at all. Thus, an additional goal of the study became determining which of the 13 mapped landslides were liquefaction induced, which were not liquefaction induced, and which were formed by other processes.

GEOLOGIC CHARACTERISTICS OF LIQUEFACTION-INDUCED GROUND FAILURE

Liquefaction is the transformation of a loose granular material from a solid state to a liquefied state due to increased pore-water pressures (Youd, 1973); these increased pressures are caused by earthquake ground shaking. The potential for earthquake-induced liquefaction depends mainly on soil and ground-water conditions, severity and duration of ground shaking, and proximity to the earthquake epicenter. Liquefaction occurs in areas of shallow ground water (generally less than 9 meters [30 ft] deep) and loose sandy soils. An earthquake of magnitude 5 is considered the minimum needed to cause liquefaction and liquefaction-induced landslides (Kuribayashi and Tatsuoka, 1975, 1977; Youd, 1977; Keefer, 1984).

Earthquake-induced liquefaction may cause four principal ground-failure types: (1) loss of bearing strength (bearing-capacity failure) on relatively flat ground, (2) ground oscillation where the ground slope is less than 0.1 percent, (3) lateral-spread landslides where slopes range between 0.1 and 5.0 percent, or (4) flow failures where slopes exceed 5.0 percent (figure 3) (Youd, 1978, 1984; National Research Council, 1985; Bartlett and Youd, 1992). The eruption of sand and water onto the ground surface (sand blows) may accompany these failure types (figure 3).

Liquefaction produces a significant decrease in the shear strength of a soil, causing it to lose bearing strength. If a flat-lying layer at the surface liquefies, little effect is preserved at the surface. However, structures atop the liquefied layer may tip or settle. Similarly, a thin layer at depth could liquefy without producing ground displacement or evidence of liquefaction at the ground surface. Ground oscillation occurs where non-liquefiable soils are present above a liquefied layer, and where the ground surface lacks free faces and is too flat to allow lateral displacement by gravity. During ground oscillation, liquefaction at depth disrupts overlying sediments, producing blocks that collide and jostle (Youd, 1984; National Research Council, 1985). Ground settlement occurs where liquefied sediment moves laterally or is extruded in sand blows, allowing overlying blocks to sink (figure 3). The surface expression of sand blows and ground cracks formed by ground oscillation would not likely be preserved long in the geologic record because erosion or burial of these low-relief features would occur more quickly than that of scarps and fissures formed by other types of liquefaction-induced ground failure. Subsurface geologic evidence of ground oscillation would include disrupted bedding in liquefied layers, and cracks that may contain injected sand. Cracks may exhibit offsets from differential settlement.

Lateral spreads consist of blocks of sediment displaced laterally downslope, usually toward a free face, during liquefaction of a subsurface layer (figure 3)(Youd, 1973, 1984; Tinsley and others, 1985). Lateral displacements may amount to several meters, perhaps tens of meters if soil conditions are especially favorable for liquefaction and if earthquake ground shaking is of sufficient duration (Youd, 1984; National Research Council, 1985; Tinsley and others, 1985). Downslope movement of the blocks can form a main scarp along the upslope margin of the failure. Over time, erosion and deposition fill fissures and subdue scarps and other topographic features created by lateral spreads.

Because movement by lateral spreading consists of shifting of sheared-off but intact blocks, pre-existing bedding within blocks usually is preserved, although beds may be tilted or contorted. If not depleted by forming sand dikes and blows, the liquefied layer may be unstratified, and possibly contain sediment from adjacent confining units. Sand dikes may emanate from the liquefied layer. Logs of trenches excavated into a lateral spread in gravelly alluvium that moved about 2.6 to 3.3 feet (0.8-1.0 m) during the 1983 Borah Peak, Idaho earthquake (M_S 7.3) show numerous offsets, grabens, and displaced and mixed sediments. However, the geologic units overlying the liquefied layer are still horizontally traceable in trenches (Andrus and Youd, 1987).

Flow failures are composed chiefly of liquefied sediment or, like lateral spreads, blocks of intact material suspended in a liquefied layer. Because they initiate on steeper slopes,

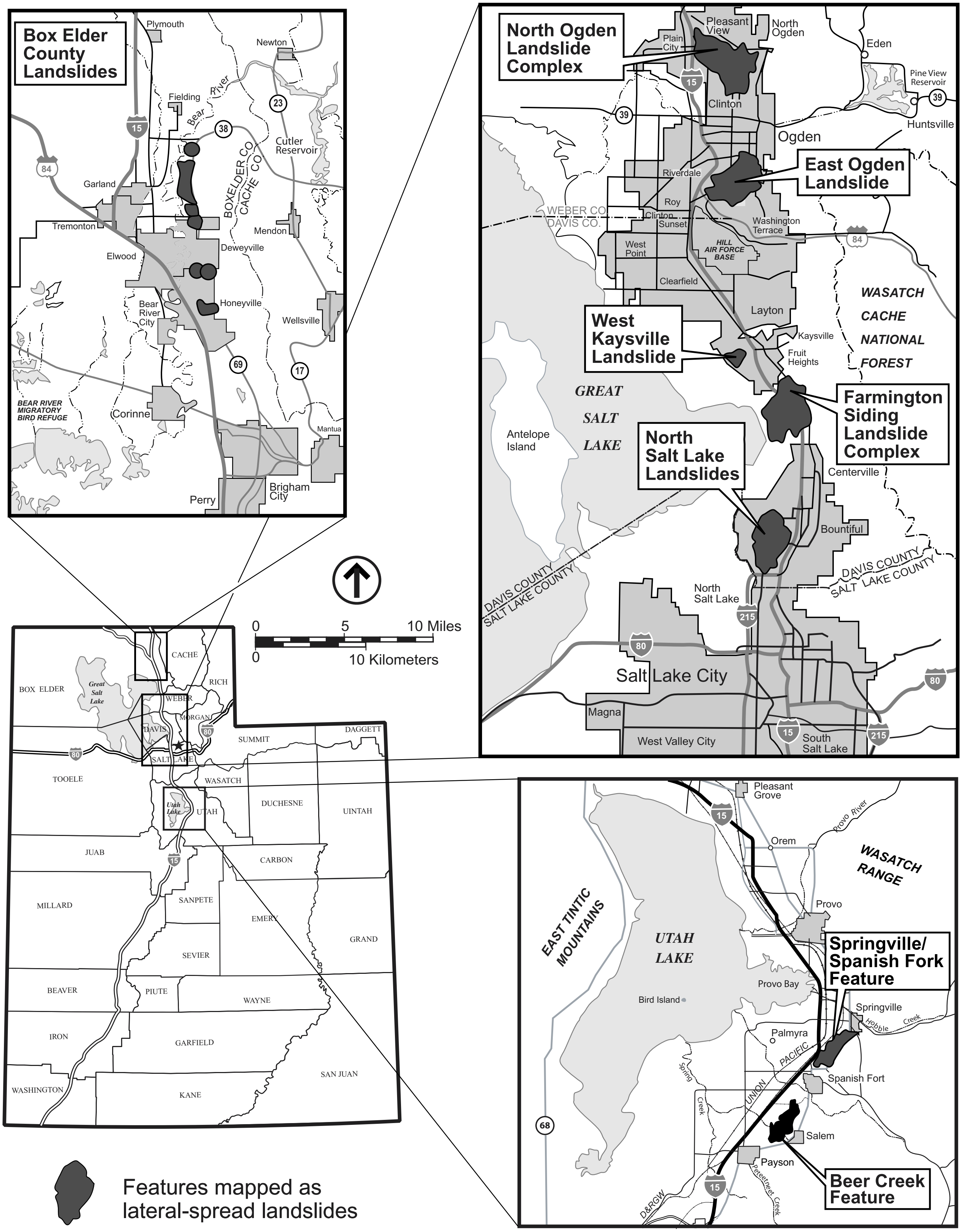


Figure 2. *Previously mapped lateral-spread landslides along the Wasatch Front (modified from Harty, 1991).*

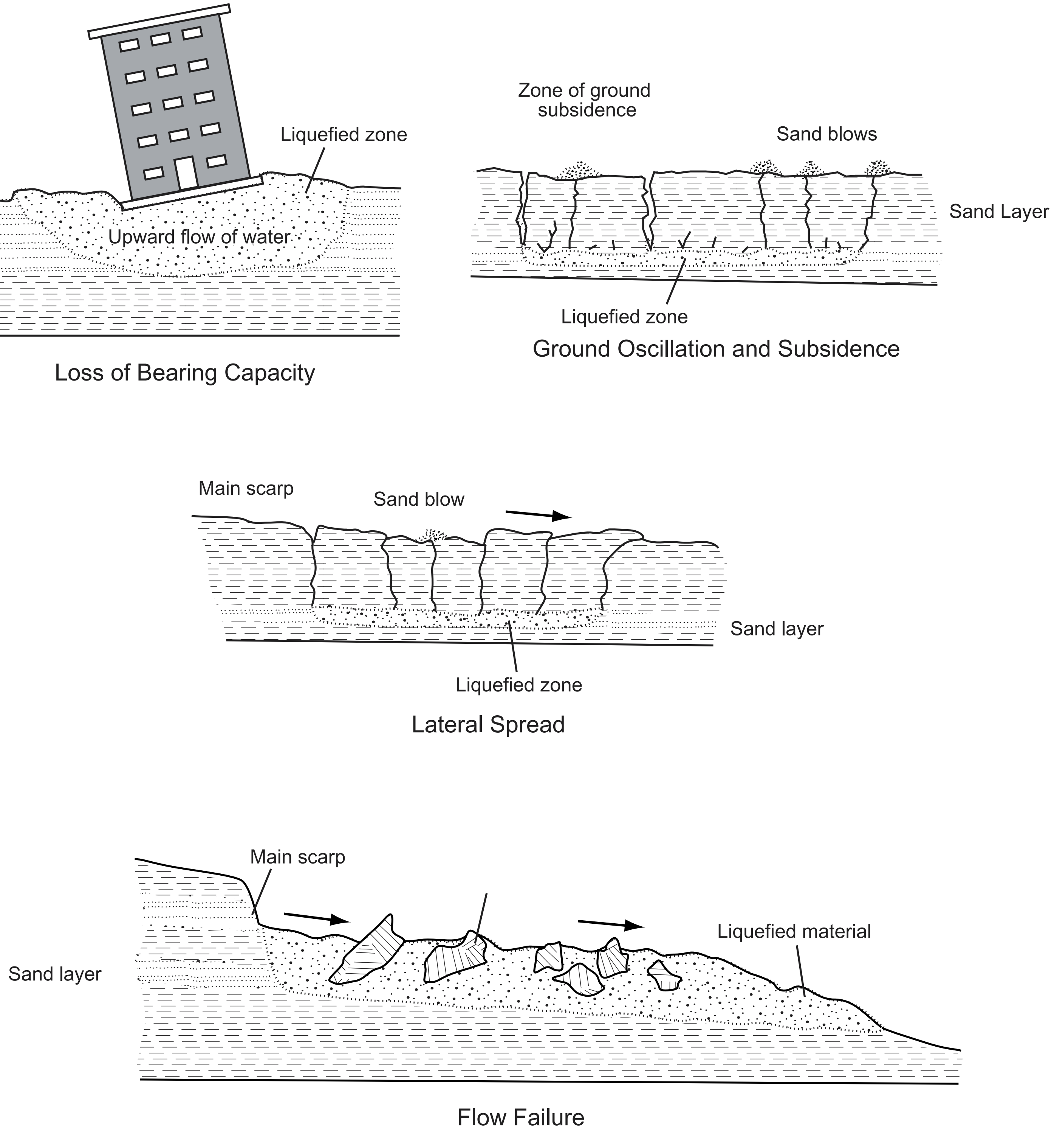


Figure 3. *Four principal types of liquefaction-induced ground failure; arrows indicate direction of ground movement (modified from Youd, 1984).*

flow failures usually travel farther than lateral spreads, and are the most catastrophic type of ground failure caused by liquefaction (Youd, 1978; Tinsley and others, 1985). They typically travel tens of meters, but under favorable conditions can displace materials by tens of kilometers at velocities of tens of kilometers per hour (Youd, 1984; Tinsley and others, 1985). The internal structure of flow-failure deposits is generally more disrupted than that of lateral spreads, and usually displays more sediment mixing and contortion of bedding. Internal faults and shear planes, common in lateral spreads, may be entirely absent within the more fluid parts of flow failures.

STUDY METHODS

To determine if the features mapped by previous investigators are liquefaction-induced lateral-spread landslides, we interpreted 1:10,000-, 1:20,000-, and 1:40,000-scale aerial photographs and used field mapping to produce 1:24,000-scale surficial-geologic and geomorphic maps of the features and surrounding Quaternary deposits. Geomorphic features identified included landslide-generated main and minor scarps, transverse ridges and cracks, depressions, and hummocks. We also mapped lacustrine shorelines and fluvial terraces. Estimates of the relative ages of movements within landslide complexes are based on degree of dissection/erosion of the deposit, relationships with lacustrine shorelines of Great Salt Lake and Lake Bonneville, for which detailed lake-level chronologies have been developed (Scott and others, 1983; Currey and Oviatt, 1985; and Murchison, 1989), and radiocarbon dating. The explanation for all the geologic/geomorphic map units and symbols is in appendix A. We used aerial photos to identify potential trench sites, test pits, and auger holes.

Although time constraints prohibited full-scale trenching of all the features, on many we were able to excavate shallow trenches and test pits, supplemented with auger holes, across selected main and minor scarps, toe areas, hummocks, and depressions. We mapped the stratigraphy exposed in the walls of the trenches at a scale of 1:20 where contorted or disturbed sediments were present, and at 1:40 where sediments were undisturbed. Brief descriptions of geologic units in trenches are included in the text and on the trench logs; detailed descriptions are in appendix B. We evaluated sand-filled fissures and other features observed in the subsurface using concepts developed by Obermeier and others (1990) to determine if they were induced by liquefaction or by soft-sediment deformation.

For some features, radiocarbon dating of organic material from soil A horizons provided estimates of the timing of landsliding. Radiocarbon age estimates were converted to calendric ages using the Radiocarbon Calibration Program 1987 Revision 2.0 (Stuiver and Reimer, 1986). In 2002, we ran the radiocarbon age estimates again using the updated Calib Radiocarbon Calibration Program, HTML version 4.3 of Stuiver and others (2002). Selecting the calendar-calibrated results with the highest relative area under the probability distribution, the updated program gave virtually the same age estimates as the 1987 program. Therefore, we report the age estimates obtained during our initial run using the 1987 program (Stuiver and Reimer, 1986). Calendric age estimates were rounded to the nearest decade and we report them with one-sigma error limits. Because soil A horizons contain decomposed organic matter that accumulates in the soil profile with time, a mean residence time (MRT) of carbon must be subtracted from the laboratory radiocarbon ages to reduce the chance of overestimating ages. Following methods outlined by Machette and others (1992), we subtracted 300 years from laboratory radiocarbon ages for samples taken near the top of soil profiles prior to converting the radiocarbon age estimates to calendric ages. Laboratory radiocarbon ages from samples taken at the base of soil profiles were not corrected for MRT because these age estimates are believed to approximate the time when the soil began forming.

We report measurements in metric units with English units in parentheses, except where elevations were taken directly from topographic maps printed in English units. In those cases, elevations are given in English units with metric equivalents in parentheses. All township, range, and section locations reference the Salt Lake Base Line and Meridian. Soil unit descriptions are reported according to ASTM Standard D-2487-83 Unified Soil Classification System (visual-manual procedure).

Field work was conducted during 1991-92 and a final technical report (Harty and others, 1993) was prepared and submitted to the U.S. Geological Survey (USGS), who supported this work. This report is modified from that final technical report. Since submittal of Harty and others (1993), little follow-up work has been done on the topic of liquefaction-induced landslides in Utah. An exception, however, is the Farmington Siding landslide complex, for which the Utah Geological Survey has since completed additional studies on timing, causes, and extent of movement (Lowe and Harty, 1993; Hylland and others, 1995; Lowe and others, 1995; Hylland and Lowe, 1998; and Hylland, 1999). The reader is referred to these studies for the most recent findings, which build upon those presented here.

SETTING AND GEOLOGY

The 13 features mapped by previous investigators as lateral-spread landslides along the Wasatch Front are in the Wasatch Front Valleys Section of the Basin and Range physiographic province (Stokes, 1977). The Wasatch Front Valleys Section consists of a series of north-south-trending structural troughs that have accumulated great thicknesses of sediment since the advent of basin-and-range normal faulting approximately 15 million years ago (Hintze, 1993). The Wasatch Range and the west-dipping Wasatch fault zone bound the troughs to the east. Sediments filling the troughs are predominantly alluvial, lacustrine, and deltaic. Geophysical data indicate that these sediments are up to 4 kilometers (2.5 mi) thick in some areas (Mabey, 1992).

The Wasatch Front (Valleys Section) is in the Lake Bonneville hydrologic basin, a closed basin dominated by evaporation. The basin has been an area of internal drainage for much of the past 15 million years, and lakes of varying sizes likely existed in the area during all or most of that time (Currey and others, 1984). The last deep-lake cycle in the basin, the Bonneville lake cycle, is the lacustrine period of most concern for this study, as much of the surface geology in the

Wasatch Front consists of Lake Bonneville sediment. At its largest extent, this lake had a maximum depth of at least 305 meters (1,000 ft) and covered an area of about 50,000 square kilometers (20,000 mi^2) (Currey and others, 1984). Lake Bonneville occupied the basin in the late Pleistocene, from about 28,000 to 12,000 yr B.P. (Oviatt and others, 1992).

Major shorelines associated with the transgressive (Stansbury and Bonneville shorelines) and regressive (Provo and Gilbert shorelines) phases of the Bonneville lake cycle provide a means of relative dating in the Lake Bonneville basin, as do the principal shorelines of the modern-day remnant of Lake Bonneville, Great Salt Lake (Currey, 1990; Oviatt and others, 1992; Oviatt, 1997). Figure 4 shows a time-elevation hydrograph of Lake Bonneville and early Great Salt Lake; table 1 provides data on ages and elevations of the four principal shorelines.

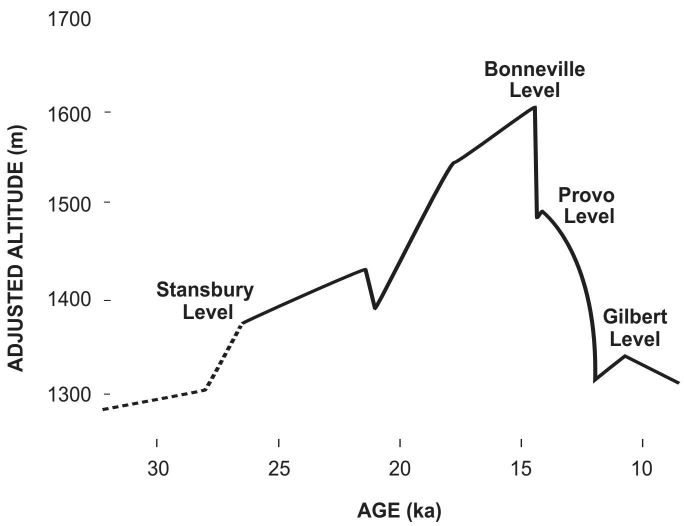


Figure 4. *Hydrograph of Lake Bonneville and Great Salt Lake, 32,000 - ~10,000 years ago (modified from Oviatt and others, 1992; Oviatt, 1997).*

Table 1. *Age (radiocarbon years B.P.) and elevation estimates for the principal shorelines of the Bonneville lake cycle (after Currey, D.R., unpublished data, and Oviatt and others, 1990, 1992; Oviatt, 1997).*

Shoreline	Phase	Elevation (m)[1]	Age Estimate (10^3 years ago)
Stansbury	transgressive	1,347-1,378	between 21 and 20
Bonneville	transgressive	1,552-1,626	~15-14.5
Provo	regressive	1,444-1,503	~14.5-14
Gilbert	regressive	1,311-1,293	~10.9-10.3

[1] *Shoreline elevations are reported as ranges because the amount of post-Lake Bonneville isostatic rebound is geographically variable.*

The Wasatch Front is in the Intermountain seismic belt (ISB), an active earthquake zone that extends from northwestern Montana, through Utah, to northwestern Arizona and southern Nevada (Smith and Sbar, 1974; Smith and Arabasz, 1991). Numerous earthquakes have occurred within the ISB in historical time. Most of these cannot be attributed to known active faults, although many faults thought capable of generating earthquakes are present in the ISB. The Wasatch fault zone trends north-south along the Wasatch Front, and is pertinent to this study because of its recency of movement, potential for generating large earthquakes (magnitude 7.0-7.5) (Schwartz and Coppersmith, 1984; Machette and others, 1991), and proximity to the features we investigated. The Wasatch fault consists of as many as 10 discrete segments of varying lengths (figure 5) that probably rupture independently of one another. These segments generally control the location and length of expected surface rupture, and place physical constraints on the maximum magnitudes of potential earthquakes (Schwartz and Coppersmith, 1984; Machette and others, 1991). Figure 6 summarizes the timing of past surface-faulting earthquakes on the more active central segments of the Wasatch fault zone.

BOX ELDER COUNTY LANDSLIDES

Previous Work

Six lateral-spread landslides were mapped in Box Elder County by Oviatt (1986a, 1986b) and Personius (1990) (figure 2). Most of these landslides occurred about 12,000-13,000 yr B.P. in Lake Bonneville gravels, when the lake was at an elevation of 1,353 meters (4,440 ft) and receding (Oviatt, 1986a, 1986b; Personius, 1990). Evidence cited by Oviatt (1986a, 1986b) and Personius (1990) for the timing of landsliding is Lake Bonneville sediments covering, and shorelines etched onto, most of the landslides at and below 1,353 meters (4,440 feet) elevation. Both Oviatt (1986a, 1986b) and Personius (1990) theorized that these landslides formed simultaneously during a single earthquake. No field evidence for liquefaction was identified by these researchers (C.G. Oviatt, Kansas State University, verbal communication, April 1992; S.F. Personius, U.S. Geological Survey, verbal communication, April 1992), but Personius (1990) reported observing contorted bedding and unstratified deposits. Harty and Lowe (1999) investigated the Madsen Spur landslide, one of the six Box Elder County landslides mapped by previous researchers as a lateral-spread landslide, and concluded that this landslide was likely not triggered by liquefaction.

Geology and Geomorphology

We do not present geologic or geomorphic maps of the Box Elder County landslides because our field work, aerial-photo mapping, and subsequent discussions with C.G. Oviatt and S.F. Personius lead us to conclude that liquefaction was not necessary to account for the landslides. Furthermore, we believe that these landslides are not lateral spreads according to the definition presented by Youd (1978, 1984). Some of the landslides show morphology characteristic of rotational landslides including back-tilted blocks and minor scarps

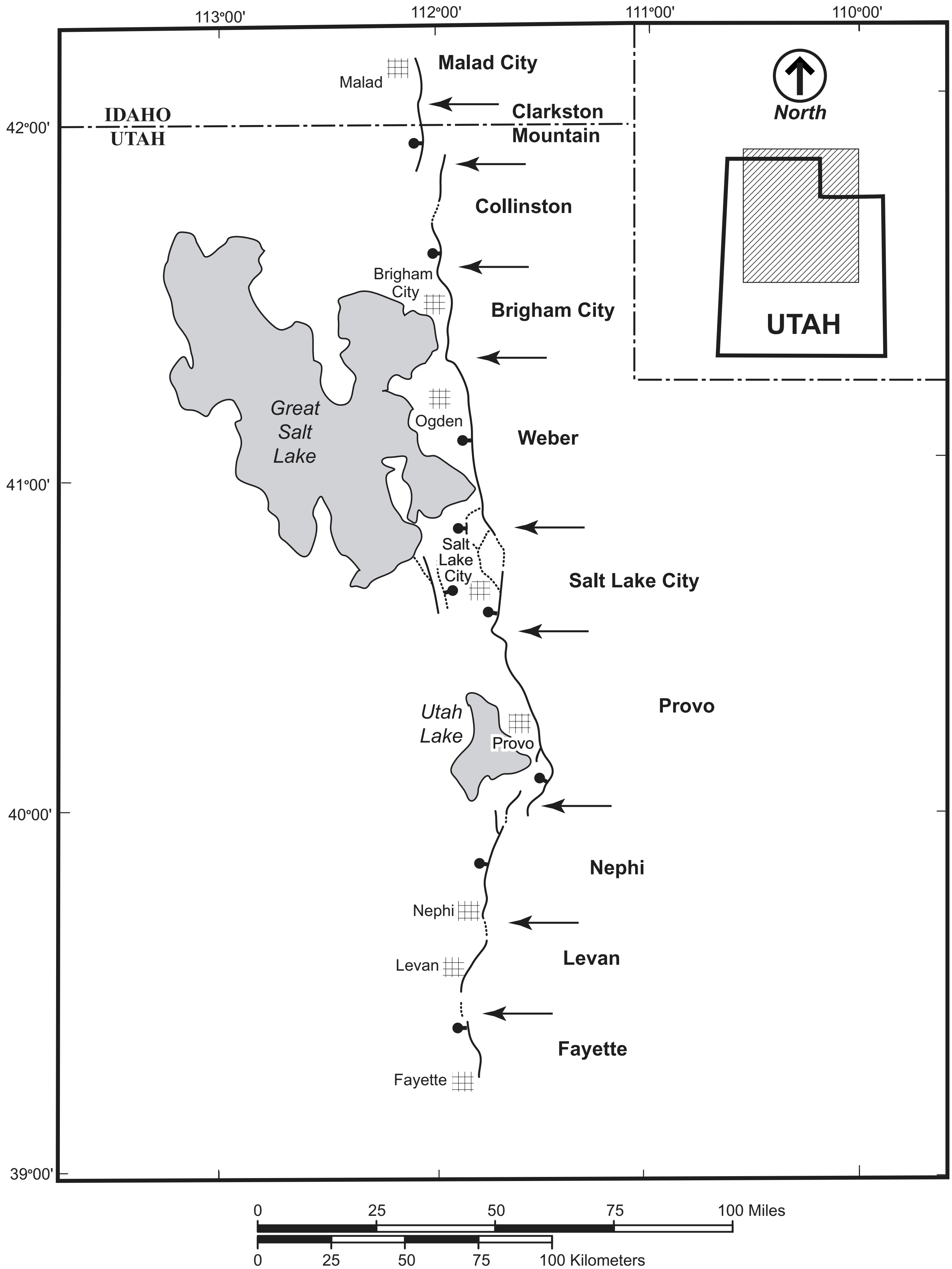
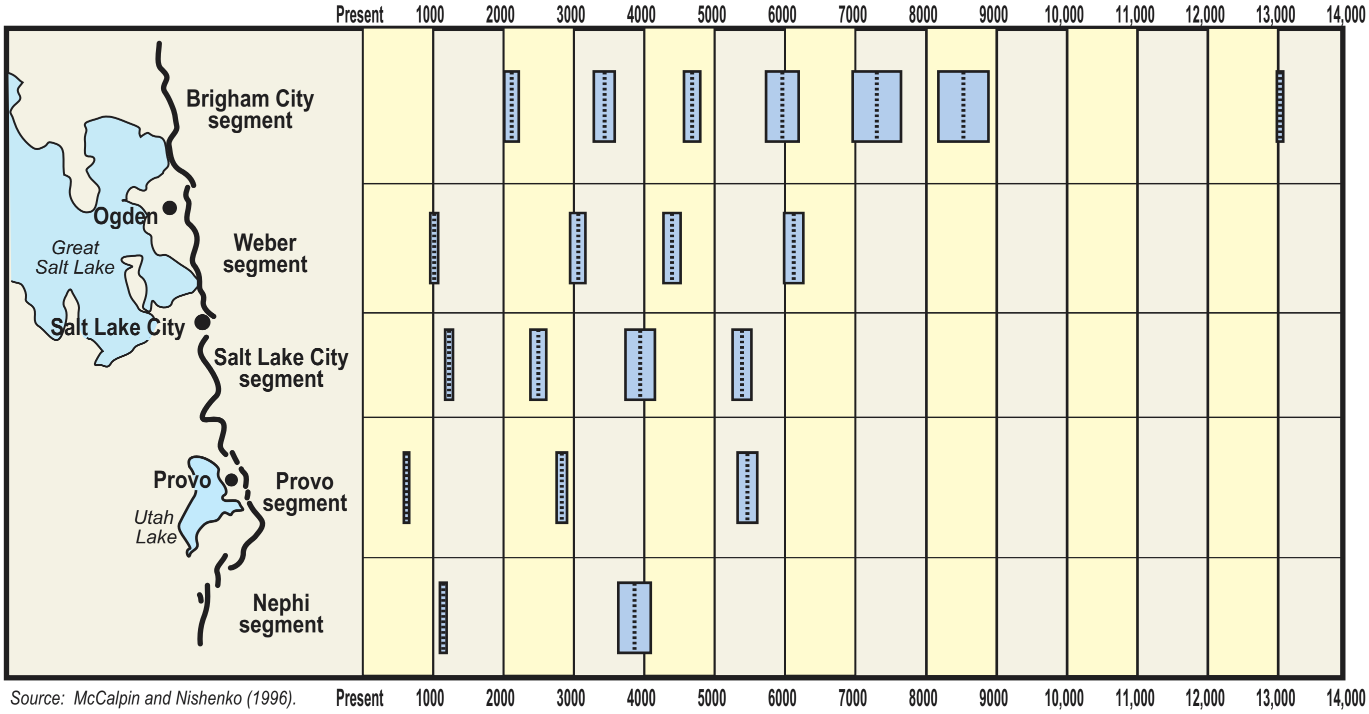


Figure 5. Wasatch fault zone segments (modified from Machette and others, 1992).



Segment	Event	Limiting Ages cal years B.P. No.	Limiting Ages cal years B.P. Mean ±2σ	Weighted Inter-event Time, Mean ±2σ, cal year
Brigham City	Z	4	2125±104	1309±176
	Y	3	3434±142	1240±220
	X	3	4674±108	1296±294
	*W	1	5970±242	1330±426
	*V	1	7300±350	1218±488
	*U	2	8518±340	4492±412
	*T	1	13,010	mean =1282 ±138
Weber	Z	6	1016±62	2048±130
	Y	3	3064±114	1339±108
	X	4	4403±122	1729±188
	*W	3	6132±144	mean =1782 ±102
Salt Lake City	Z	9	1230±62	1269±152
	Y	3	2499±138	1442±258
	X	2	3940±216	1440±256
	W	4	5381±136	mean =1441 ±182
Provo	Z	10	618 ±30	2224±78
	Y	5	2842±72	2639±168
	X	2	5481±152	mean =2297±70
Nephi	Z	7	1148±68	2716±248
	Y	5	3864±238	mean =2716±248

* These earthquakes predate 5.6 ka and are not used in the modeling.

Figure 6. *Wasatch fault zone paleoseismicity, limiting numerical ages, and surface-faulting earthquake recurrence intervals for the five central segments. Earthquake chronologies from McCalpin and Nishenko (1996). Well-constrained pre-6000 yr B.P. earthquake chronologies for the Weber, Salt Lake City, Provo, and Nephi segments are not available.*

(Harty and Lowe, 1999). All of the landslides occurred on slopes considerably steeper than 5 percent, and many of the landslide deposits "spread" into Lake Bonneville. We could find no evidence of liquefaction in any exposures in the landslide deposits, but preservation of such features in gravel would be unlikely. In a number of places, we observed unstratified to weakly stratified gravel mounds resting on Lake Bonneville sediments; we interpret the mounds to be landslide deposits that were reworked by lake currents.

Results and Hazard Potential

We concur that the six Box Elder County features are landslides, and that most of them occurred when Lake Bonneville was at approximately 1,353 meters (1,440 ft) elevation. However, the landslides could have been initiated by: (1) earthquake ground shaking without liquefaction, (2) a sudden, partial draw-down of the lake, or (3) a period of above-average precipitation. We cannot discount the possibility that liquefaction may have occurred in the gravel deposits saturated by Lake Bonneville, but the morphology of these landslides and steepness of slopes on which they formed are such that they could have initiated without liquefaction. Most of the landslides are now well above the water table, and the possibility of their reactivation by earthquake-induced liquefaction is low.

NORTH OGDEN LANDSLIDE COMPLEX

Previous Work

First identified as a possible lateral-spread landslide by Miller (1980), the North Ogden landslide complex covers approximately 25 square kilometers (9.7 mi^2) in northern Weber County, mostly southwest of the city of North Ogden (figure 2). Miller (1980) mapped the boundaries of the landslide based on aerial-photo interpretation and field reconnaissance, and described contorted and disturbed bedding in fine-grained Lake Bonneville sediments in a subdivision excavation and in a brick plant pit in the town of Harrisville (plate 1). He gave a broad age estimate of "Holocene and Pleistocene" for the North Ogden landslide. U.S. Geological Survey personnel mapped the northern (Personius, 1990) and the eastern (Nelson and Personius, 1990) parts of the landslide, using predominantly aerial photographs (A.R. Nelson, U.S. Geological Survey, verbal communication, April 1992). Few details about the landslide are given in these reports, but Nelson and Personius (1990) reported observing an area of contorted Lake Bonneville sediments. They assigned a "Holocene to middle Pleistocene" age to the landslide. Preliminary results from the present study of the North Ogden landslide complex were published earlier by Harty and Lowe (1992, 1995).

Geology and Geomorphology

Our geologic and geomorphic mapping of the North Ogden landslide was done using aerial photos (1952, 1:10,000 scale, and 1978, 1:40,000 scale) and field checking. In addition, we excavated and logged two trenches, and obtained radiocarbon age estimates from organic-rich sediments in one of the trenches.

Geologic and geomorphic evidence shows that the North Ogden landslide is a complex landslide that contains a number of smaller failures that have likely undergone recurrent movement. The landslide complex is mainly surrounded by Lake Bonneville and post-Lake Bonneville deposits ranging in age from late Pleistocene to late Holocene (plate 1). Alluvial fans cover much of the landslide's crown and head area, but the main scarps are sharp and clearly visible from the ground and on aerial photos. Age estimates of these alluvial fans are grouped into two categories: late Holocene, and late Pleistocene to late Holocene (Nelson and Personius, 1990; Personius, 1990). This indicates that initial movement of the North Ogden landslide complex could have occurred in the late Pleistocene.

Young alluvium (Qal_1) covers a large portion of the landslide complex, and shallow, Holocene-age drainages have eroded the original landslide topography. About 60 percent of the area forming the landslide complex is flat (< 5 percent slope); the remaining 40 percent of the complex has steeper slopes, primarily in the main scarp areas in the northeast and southern parts of the landslide complex. A 1.8-kilometer-long (1.1 mi) undeformed segment of the Gilbert shoreline of Lake Bonneville is just west of the toe area of the landslide (plate 1); however, meandering streams have eroded most of the Gilbert shoreline in the landslide vicinity. The shoreline and the landslide are not coincident in position; thus either (1) landslide movement occurred after about 10,000 yr B.P. and stopped short of the shoreline, or (2) the landslide in this area formed prior to about 10,000 yr B.P. As we identified no Lake Bonneville shorelines on the landslide, the first scenario is the most plausible.

Other geologic evidence supports the idea that movement on the North Ogden landslide has occurred in post-Lake Bonneville time. Main scarps along the landslide's northeastern perimeter, and the landslide's right-lateral margin southwest of the town of Pleasant View, are in Lake Bonneville sediments (plate 1). In the latter area, disturbance of recessional lake gravels (Qlg_3) down to at least 1,308 meters (4,290 ft) elevation indicates that the northern part of the North Ogden landslide moved sometime after about 12,000 yr B.P., when Lake Bonneville receded past this elevation (figure 4; Oviatt and others, 1992).

Geomorphic features of the North Ogden landslide suggest a history of complex movement, including both flowing and sliding. Landslide features include arcuate main scarps, minor scarps within the body of the landslde, depressions, hummocks, and transverse lineaments that may represent cracks, flow lines, or eroded pressure ridges (plate 1). Hummocks, depressions, cracks, and ridges are typical of rotational and translational landslide morphology; arcuate main scarps typically form after a flow failure (Rib and Liang, 1978). Many landslides classified as lateral-spread failures contain surface features characteristic of both slides and flows (Rib and Liang, 1978), and the North Ogden landslide complex appears to be a representative example.

The southwestern margin of the landslide has been eroded in places by the Weber River and smaller streams that have created an erosional escarpment along this portion of the landslide (plate 1). Based on observed differences in the relative ages of alluvial deposits and fluvial features (for example, meander scars and oxbows) along and near the escarpment, we believe that different parts of the escarpment probably formed at different times in the Holocene. The height of the escarpment varies, but averages about 3 to 4.5 meters (10-15 ft) in the Harrisville area (plate 1). Near the town of Farr West, part of the landslide drapes over the escarpment. In Harrisville, the escarpment has eroded into the landslide. The relationship between the landslide toe and fluvial escarpment is unclear in the Harrisville Heights area.

The southeastern part of the North Ogden landslide complex may be an area of multiple failures where portions of the landslide likely moved at different times. In this area, the landslide complex appears to consist of at least two separate, smaller failures (plate 1). Geomorphic features within this part of the landslide complex that suggest multiple failures include: (1) an escarpment that may represent a lateral margin between two landslides, (2) a set of sub-parallel, arcuate escarpments that probably define the toe area of one of the landslides, (3) lineaments that are normal to the direction of movement on one of the landslides, and (4) a scarp (N1/2 section 4, T. 6 N., R. 1 W.) that may be the main scarp of the northern of the two landslides (plate 1).

The arcuate scarps that define the northern and northeastern margins of the landslide complex also seem to indicate movement of discrete, small failures rather than a single, large landslide. Two springs, the "Cold Springs" in section 34, T. 7 N., R. 1 W., and an unnamed spring in section 30, T. 7 N., R. 1 W. (plate 1), respectively discharge from within and just downslope of amphitheaters formed by the landslide. These springs, like others associated with landslides, may be the cause of localized landslide movement in these areas. Although erosion and urbanization have obscured surface evidence, additional parts of the North Ogden landslide complex may also consist of discrete failures.

Lomond View Park Trench

A trench was excavated across the main scarp of the North Ogden landslide complex about 0.5 kilometers (0.3 mi) northwest of the city of North Ogden (NE1/4 section 29, T. 7 N., R. 1 W.) (plate 1). The trench was about 17 meters (56 ft) long and averaged about 3.5 meters (11.5 ft) deep. We excavated the trench into an arcuate scarp that forms an amphitheater containing Lomond View Park (figure 7). The purpose of excavating this trench was to locate and possibly date a colluvial wedge (formed by erosion and deposition off the free face of the scarp) in an attempt to estimate the age of landslide movement. Trenching of earthquake fault scarps along the Wasatch Front has commonly exposed colluvial wedges that contained datable organic material, and we hoped that a similar wedge would be found in this trench. However, we found no colluvial wedge, landslide deposit, or organic material in the trench at Lomond View Park. The trench revealed undisturbed, horizontally bedded Lake Bonneville sediments (including potentially liquefiable sands) in the crown area of the landslide (plate 2). The main scarp consisted of an eroded free face buried by an alluvial fan (Qaf_1) (plate 2). Based on trench stratigraphy and the morphology of the scarp in this area, we believe that the landslide moved as a liquefaction-induced flow failure, leaving the arcuate scarp as it vacated the area. This mode of failure likely formed most if not all of the main scarps of the landslide complex.

Figure 7. *Northwest view of the main scarp of the North Ogden landslide complex as seen from Lomond View Park.*

Harrisville Trench

The Harrisville trench was excavated across a large hummock on the distal portion of the North Ogden landslide complex (plate 1, figure 8). The trench was 21 meters (69 ft) long and averaged about 2.5 meters (8.2 ft) deep. We excavated the trench at this location to observe the relationship between the hummock and surrounding material; we assumed the hummock was formed by the landslide, and had hoped to find disturbed sediments and possibly buried, organic-rich sediments on which to obtain radiocarbon age estimates. The log of the Harrisville trench (plate 3) shows the subsurface stratigraphy to be complex, containing buried soil A horizons, blocks of soil, blocks of sediment with contorted bedding, and sand-filled fractures diagnostic of earthquake-induced liquefaction.

Stratigraphy and Timing of Events

To determine the ages of deposits in the trench, we obtained four standard radiocarbon age estimates from bulk samples of three buried soil A horizons, and from the base of the modern soil A horizon (plate 3). The three age estimates (HT-1 through 3) from the buried soils were within 830 years of one another, and we believe that they represent the same soil (S1, plate 3, figure 9). Because of the uncertainty as to which of the three age estimates is the most accurate, we averaged them, and use the value 7,860 ± 240 cal yr B.P. as the best approximation for the age of the S1 soil.

The oldest unit in the trench, unit 1, is an unstratified lacustrine clay deposited in a deep-water environment by Lake Bonneville sometime after 26,000 yr B.P. This unit forms the core of the hummock across which the trench was excavated, and is exposed in the northern end of the trench (plate 3). Because unit 1 is unstratified, we are uncertain as to whether the hummock was formed by landsliding, or whether

Figure 8. *South (downslope) view of the Harrisville trench excavated on the flank of a hummock.*

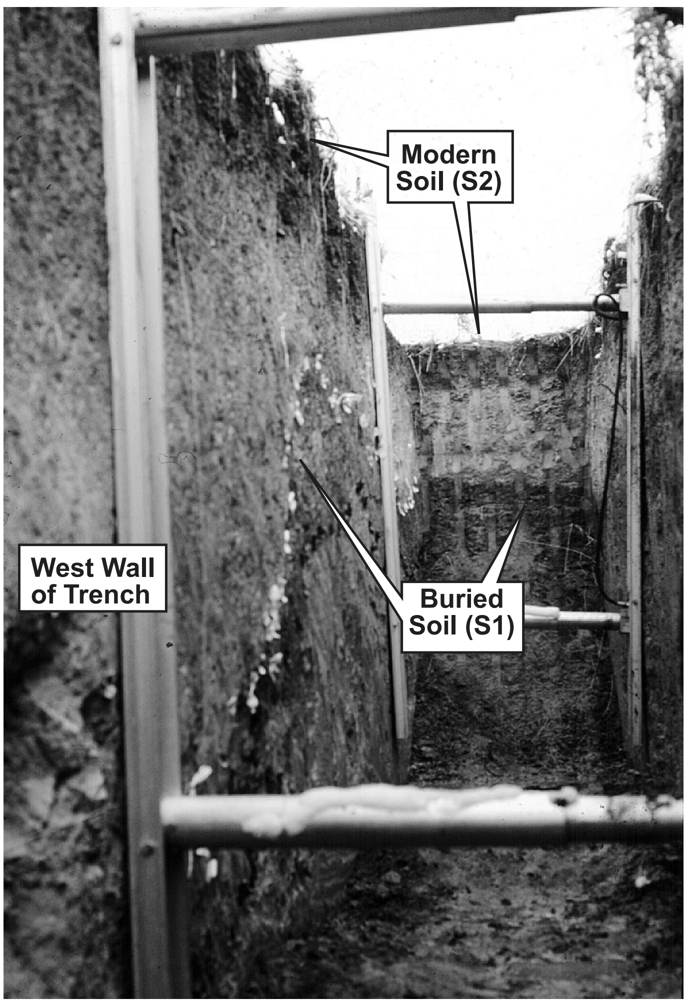


Figure 9. *Modern (S2) and buried (S1) soil units in Harrisville trench.*

it represents a stationary remnant around which landsliding has occurred. The age estimate of 7,860 cal yr B.P. obtained from soil S1 developed on unit 1 indicates that the hummock formed prior to this time. The irregular contact with S1 and the small detached blocks of S1 soil in unit 1 (at about station 16.5 on the trench log) suggest that unit 1 was disturbed sometime after 7,860 cal yr B.P.

In the southern end of the trench, unit 2 has characteristics of a mud flow. The deposit is an unstratified clay containing subangular to subrounded gravel, and cobbles up to 10 centimeters (4 in) in diameter (figure 10). Mud flows and debris flows characteristically originate in steep canyons or mountain hillslopes, and may reach canyon mouths and deposit material on alluvial fans. However, this deposit is 3 kilometers (1.9 mi) from the base of the nearest mountain, and 2 kilometers (1.2 mi) from the most distal part of the closest mountain-front alluvial fan. We believe unit 2 is the distal part of a liquefaction-induced flow failure derived from farther upslope on the North Ogden landslide, rather than a mud flow that originated in the mountains. The closest mapped landslide scarp is about 1.6 kilometers (1 mi) upslope from the Harrisville trench (plate 1), and we believe unit 2 was derived from this area. Soil S1 formed directly on unit 2 and radiocarbon dating of this soil indicates that the flow failure was deposited about 7,860 cal yr B.P.

Unit 3 is loess deposited sometime after 7,860 cal yr B.P. Remnants of this eroded unit lie atop soil S1 on both units 1 and 2, and were incorporated into unit 5 (plate 3). Unit 4 is a mostly unstratified, fluvial or possibly eolian (dune) medium-grained sand found at the base of the hummock. It was deposited after 7,860 cal yr B.P., and likely after loess unit 3. The upper part of unit 4 contains clay, probably by illuviation from overlying unit 5. A thin band of manganese oxide(?) in unit 4 possibly indicates a former ground-water level. The contact of unit 4 with unit 5 is irregular, and at station 13-13.5 on the trench log (plate 3), unit 4 has intruded upward into unit 5 (figure 11), probably during deposition of unit 5. We observed deformed bedding within the intruded material. A block of soil S1 mixed with unit 4 is at the base of the trench at about station 12-12.5. Soil S1 was also identified just below the base of the trench in a 2-meter-deep (6.6 ft) core augered at about station 11.4 on the trench log (plate 3), indicating that soil S1 is likely continuous beneath the trench.

Unit 5 is an unstratified clay containing subangular to rounded gravel averaging 1 to 2 centimeters (0.4-0.8 in) in diameter (figure 12). Like unit 2, unit 5 also appears to be a liquefaction-induced flow-failure deposit. Although we do not know the areal extent of the deposit, we identified it in a 2-meter-deep (6.6 ft) core extracted from a large topographic depression about 200 meters (660 ft) east-northeast of the

Figure 10. *Harrisville trench flow-failure deposit (unit 2) containing subangular to subrounded gravel and cobbles.*

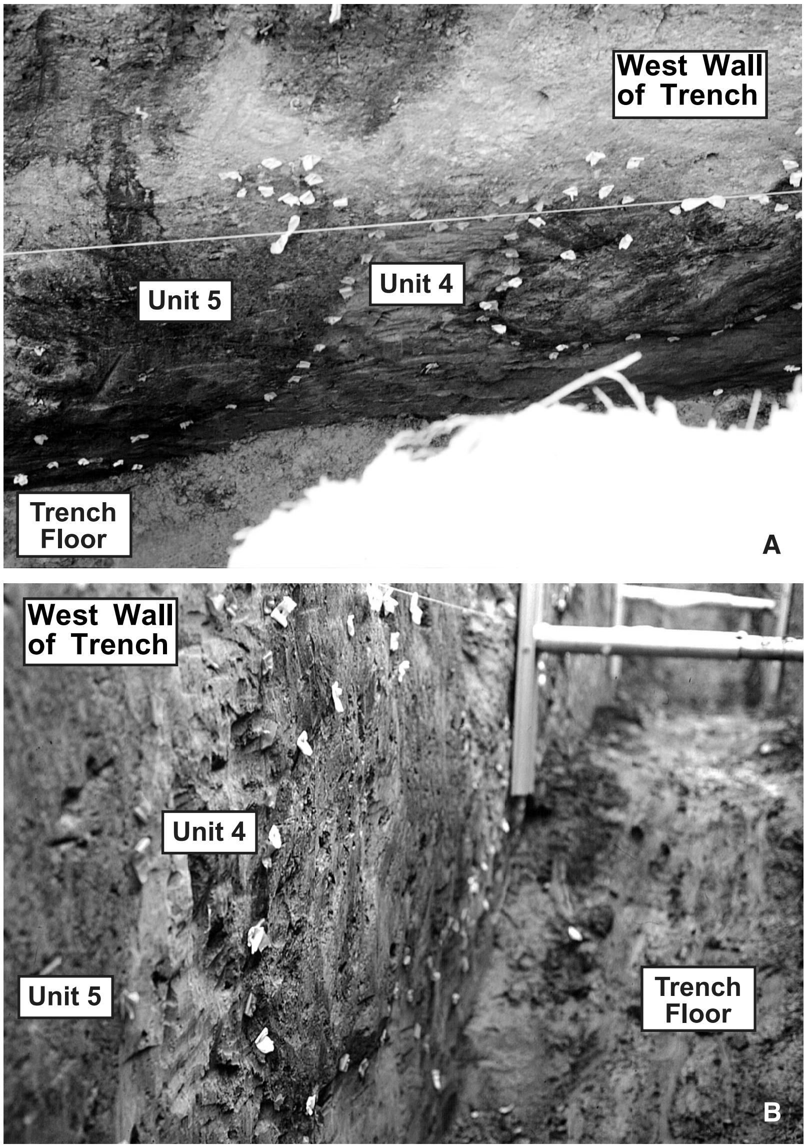


Figure 11. *Harrisville trench sand (unit 4) extruded upward into unit 5. (A) View from ground surface looking down into trench west wall. Distance between white ribbons on string line is 1 meter. (B) View of west wall from trench floor.*

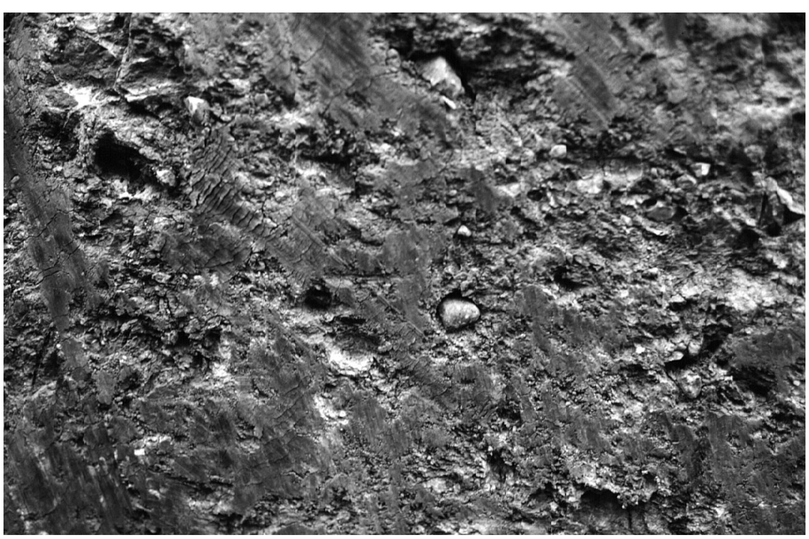


Figure 12. *Harrisville trench flow-failure deposit (unit 5). Rounded clast in center of photo is about 4 centimeters (1.6 in) long.*

Harrisville trench (plate 1). A radiocarbon age estimate obtained at the base of the modern soil (S2) that developed directly on unit 5 indicates that this flow failure occurred just before 3,390 ± 230 cal yr B.P. The flow failure caused significant disturbance to the ground surface, as it ripped up and incorporated blocks of soil from unit S1 and other near-surface sediment (figure 13). Sediment blocks 5a and 5b (plate 3) contain deformed bedding and are of lacustrine origin. These blocks, and a package of jumbled alluvial sediments (unit 5c), did not originate from any units identified in the trench. However, as seen at station 6 in the trench (figure 14, plate 3), the flow failure detached and incorporated in an overturned position both loess and soil from unit 3 and soil S1, respectively. Also at station 6, unit 5d is an unstratified clay that contains a disseminated soil A horizon, giving the material a brown to dark-brown color. This unit may be a block of soil S1, possibly mixed with other sediment entrained in the flow failure.

Flow-failure units 2 and 5 both contain sand-filled fractures (unit 6) diagnostic of injection during earthquake-induced liquefaction (figure 15). The fractures are commonly less than 1 centimeter (0.4 in) wide, and many are only a few millimeters or less in width. The fractures contain unstratified, poorly graded fine sand. We could not find the source of this sand in the trench, nor in a core sample obtained from below the trench floor. As many of the injection features do not stem from the base of the trench, the source of the sand is likely at depth and lateral to the trench.

We found the sand-injection features only in units 2 (eastern [unlogged] side of trench) and 5. We believe that the injection features probably formed during one earthquake, and that injections likely penetrate intervening units S1 and 3 elsewhere in the subsurface. Injections of fine sand into unit 4 would likely disperse because of the lack of cohesiveness of unit 4 sand and its inability to maintain open fractures. No injection features extend into the modern soil (S2), but this does not preclude the possibility that the modern soil was present or forming when the liquefaction event occurred. None of the fractures is closer to the base of the modern soil than about 0.4 meters (1.3 ft), and perhaps the fracture network naturally dissipated at about this height above the source material.

If all sand-injection features observed in the trench formed during the same earthquake, this event occurred sometime after 3,390 cal yr B.P., when flow-failure unit 5 was deposited. Supporting evidence for a late- rather than early-Holocene age for the sand-injection event is seen in the trench stratigraphy. Since the formation of soil S1 about 7,860 cal yr B.P., time is needed for at least three depositional events (units 3, 4, and 5) prior to the liquefaction event that formed the sand injections.

The Harrisville trench shows evidence of at least three liquefaction events (two flow failures and subsequent sand injections), but more may be represented in the trench. If the hummock (unit 1) originated as a liquefaction-induced flow failure, then possibly

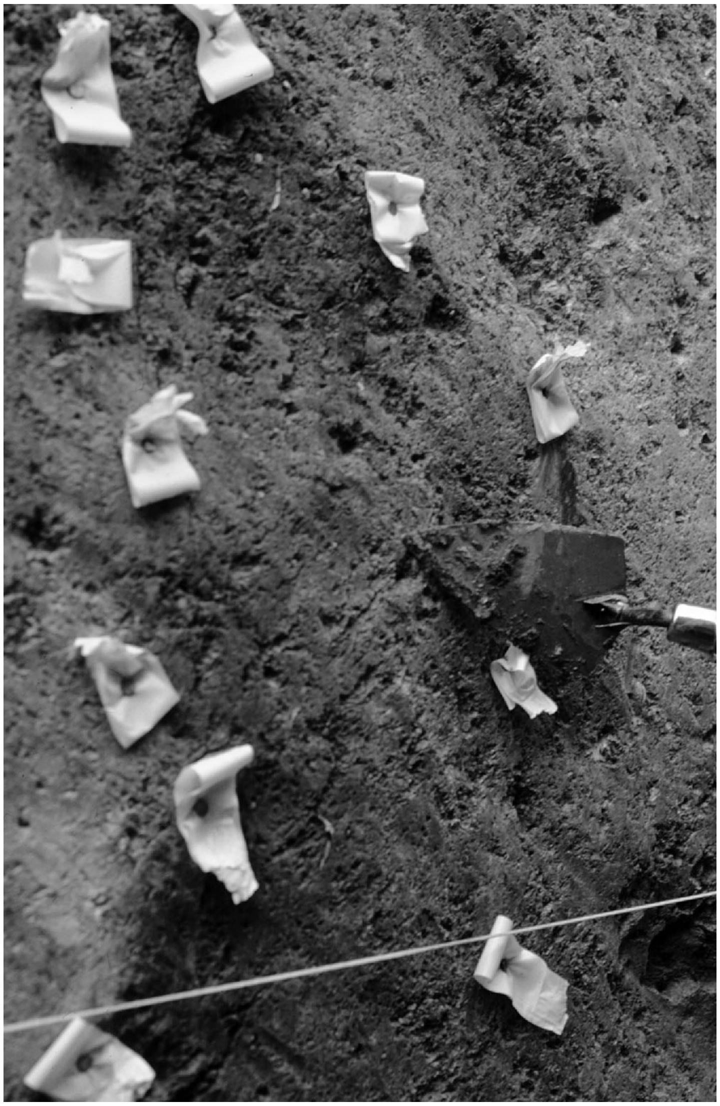


Figure 13. Block of buried soil (unit S1) incorporated into flow-failure deposit (unit 5). See Harrisville trench log (plate 3, meter-mark 14) for location.

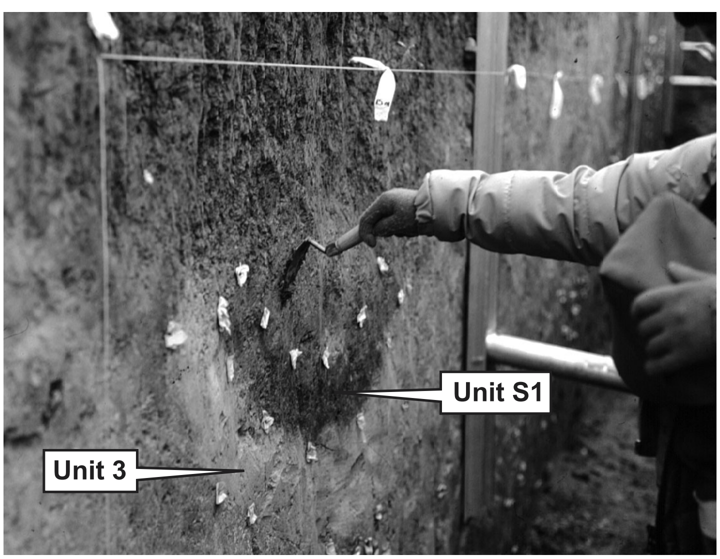


Figure 14. Block of loess (unit 3) and paleosol (unit S1) detached from an upslope area and incorporated into flow-failure deposit (unit 5). See Harrisbille trench log (plate 3, meter-mark 6) for location.

Figure 15. Sand-filled cracks (light-colored material at left and at point of trowel) in flow-failure (unit 5) along the west wall of the Harrisville trench (station 12 on plate 3).

four liquefaction events occurred during the Holocene; one (or two) prior to 7,860 cal yr B.P. (units 1 and 2), and two (units 5 and 6) after this time. Also, the possibility remains that the sand injections formed during more than one liquefaction event.

Paleoseismic Implications

Paleoseismic trenching studies on the Weber segment of the Wasatch fault (east of Ogden and in Kaysville) showed evidence of four large surface-faulting earthquakes within the past 6,100 years (Forman and others, 1991; McCalpin and others, 1994; McCalpin and Nishenko, 1996). Age estimates of these events are based on average mean residence time (AMRT) radiocarbon and thermoluminescence dates. From re-evaluated radiocarbon age estimates from trenches east of Ogden and in the Kaysville area, McCalpin and Nishenko (1996) estimated the age of the most recent event (MRE) on the Weber segment as about 1,016 cal yr B.P, the penultimate event about 3,064 cal yr B.P., the antepenultimate event about 4,403 cal yr B.P., and a prior event about 6,132 cal yr B.P. (figure 6). McCalpin and others (1994) suggested two or three additional surface-faulting earthquakes on the Weber segment that occurred sometime after about 13,000 years B.P., but before the fourth most recent event. None of these events could be dated.

A comparison of paleoseismic data from fault trenches on the Weber and Brigham City segments of the Wasatch fault (McCalpin and Nishenko, 1996; figure 6) with data obtained from the Harrisville trench reveals a variety of possible correlations. Because the Harrisville trench flow-failure unit 5, dated at just before 3,390 cal yr B.P., is penetrated by sand-injection features, the liquefaction event that produced the injection features probably occurred during the MRE on the Weber segment (about 1,016 cal yr B.P). Alternatively, the event could also have been triggered during the MRE on the adjacent Brigham City fault segment (about 2,125 cal yr B.P.). In fact, it is possible that both of these large earthquakes could have caused the injected sand in the Harrisville trench. Alternatively, none of these events, but a smaller, non-surface-faulting event could have initiated liquefaction.

In part because the potential for liquefaction and liquefaction-induced slope failure increases with severity and duration of ground shaking, and because the severity of ground shaking increases with proximity to the earthquake for any given earthquake event, and because the North Ogden landslide complex is close to the northern end of the Weber segment of the Wasatch fault, we believe that the liquefaction events observed in the Harrisville trench were initiated by large earthquakes on the Weber or directly adjacent northern segment (Brigham City) of the fault. Under this assumption, we propose the following paleoseismic-liquefaction scenario.

The formation of the hummock (unit 1) and deposition of flow-failure unit 2 occurred in post-Lake Bonneville time, but prior to about 7,860 cal yr B.P. Flow-failure unit 2 may correlate with one of the two or three large earthquakes suggested by McCalpin and others (1994) and McCalpin and Niskenko (1996) as having occurred on the Weber segment of the Wasatch fault between about 6,100 to 13,000 years B.P. Because soil S1 formed directly on the flow failure, this earthquake occurred during the early Holocene, shortly before 7,860 cal yr B.P. It is interesting to note that, presuming this earthquake occurred on the Weber segment of the Wasatch fault, it would represent the fifth most recent event on the segment, and would have occurred about 1,728 years before the fourth most recent event on the segment; the mean recurrence interval on this segment for the last four large earthquakes as derived by McCalpin and Nishenko (1996) is 1,782 years. The one-sigma error limits of the flow-failure event only marginally overlap the refined, two-sigma error limits of the two closest large earthquakes on the Brigham City segment of the Wasatch fault (figure 6); thus we believe that this flow-failure was indeed triggered by a large earthquake on the Weber segment.

The unit 5 flow failure initiated in mid-Holocene time, about 3,390 cal yr B.P., likely during the antepenultimate event on the Weber (about 3,064 cal yr B.P.) or Brigham City (about 3,434 cal yr B.P.) segment of the Wasatch fault.

As previously noted, the liquefaction event that formed the sand injections observed in the Harrisville trench probably occurred in the late Holocene, most likely during the MRE on either the Weber or Brigham City segment.

Results

We found no definitive evidence in the Harrisville trench that the landslide complex in the Harrisville area has moved within the past 7,860 years. The sand-filled fractures and the manganese-precipitate (?) layer showed no shear planes or minor offsets, although the latter showed minor deformation probably unrelated to earthquake-induced liquefaction. However, movement could have occurred in the form of an intact block during flow failure or lateral spreading, or tilting of blocks during ground oscillation. The site has experienced a number of depositional events related to flow failure. Due to the lack of bedding in unit 1, we are uncertain as to how the hummock was initially formed. However, like unit 2, it may have been created during a liquefaction-induced landslide that occurred about 7,860 cal yr B.P. The unit 5 flow failure occurred about 3,390 cal yr B.P. At least one liquefaction event formed the sand injections, sometime after 3,390 cal yr B.P.

Geomorphic and geologic evidence and trench excavations indicate that the North Ogden landslide is a liquefaction-induced complex landslide that has moved by flow failure and lateral spreading. Morphology of the main scarp of the landslide, supported by observations from the trench at Lomond View Park, suggest that this part moved by means of flow failure. Two flow-failure deposits identified in the trench at Harrisville also support this hypothesis. However, a large part of the landslide complex (60 percent) lies on almost flat valley-bottom ground (slopes < 5 percent), where movement by lateral spreading was a probable failure mode. The presence of a number of relict minor scarps on the flat-lying body of the landslide complex also point to movement by lateral spreading. Thus, geomorphic evidence shows that the North Ogden landslide complex has moved under different failure modes.

The landslide may have initially moved as a large single mass during an earthquake, and an undetermined number of smaller movements occurred later, perhaps at different times. Geologic and geomorphic mapping and data from the Harrisville trench indicate that the North Ogden landslide complex initiated sometime in the early Holocene or late Pleistocene; parts of the landslide may have moved a number of times – perhaps three or four – during the Holocene, and at least one liquefaction event occurred in the late Holocene.

Hazard Potential

In part because this study indicates that the North Ogden landslide complex has moved several times during the Holocene, we believe the potential exists for additional liquefaction events and further movement by lateral spreading and/or flow failure during future moderate to large earthquakes. Geologic and hydrologic conditions conducive to liquefaction, including sandy sediments and ground water within 9.1 meters (30 ft) of the surface, currently exist in the landslide area. Most of the landslide complex is classified as "high to moderate" liquefaction potential (Anderson and others, 1990). Slopes between 0.1 and 5.0 percent are prevalent on the landslide; therefore, we cannot rule out future movement by lateral spreading. Post-Lake Bonneville stream erosion along a large segment of the landslide toe area has formed a free face toward which future movement by lateral spreading could be accommodated. Also, recurrent, liquefaction-induced flow failures and retreat of the main scarp of the landslide are also possible. Many areas near the main scarp are developed and therefore receive excess water from lawn and crop irrigation. Furthermore, springs discharging from the two amphitheaters in the northern and northeastern parts of the landslide also indicate where flow failures off the main scarp could be expected in the future.

EAST OGDEN LANDSLIDE

Previous Work

The East Ogden landslide covers approximately 10 square kilometers (4 mi^2) in central Weber County, mostly in Ogden City (figure 2 and plate 4). It was first identified by Pashley and Wiggins (1972), who observed faults, tilted beds, folds, and sand injections in a series of deep utility trenches on the Weber State University campus and attributed them to a large translational landslide that had moved laterally westward from the mountain front. They mapped 373 faults in bedded Lake Bonneville deposits within a 440-meter-long (1,443 ft) portion of a trench, and also observed folds that were overturned to the northwest (Lowe and others, 1992).

Woodward-Clyde Consultants (1985) examined faults exposed in the foundation excavation for the Allied Health Sciences Building on the Weber State University campus (plate 4). The faults are truncated by Provo-level nearshore sediments deposited about 14,000 to 14,500 yr B.P. Woodward-Clyde Consultants (1985) contended that the faults are probably not of tectonic origin because the Wasatch fault has experienced a number of surface-faulting earthquakes since Provo time, and further movement on these pre-Provo-age faults has not occurred. They suggested that the faults may represent seismically induced sliding and lateral spreading, or gravity-induced subaqueous sliding of saturated sediments (Woodward-Clyde Consultants, 1985).

Nelson and Personius (1990) mapped the scarp associated with the faults studied by Woodward-Clyde Consultants (1985) as the main scarp of the East Ogden lateral-spread landslide. They mapped two separate lateral-spread landslides west of the Wasatch fault zone between the Ogden and Weber River Provo-level deltas, and concluded that the younger lateral-spread landslide, underlying the Weber State University campus and southern Ogden City (plate 4), postdates the Provo shoreline. Nelson and Personius (1990) observed that the southern, older lateral-spread landslide is cut by the Provo shoreline; consists of more subdued, rounded, and hummocky topography; and probably predates the Bonneville shoreline.

Geology and Geomorphology

Geologic and geomorphic mapping of the East Ogden landslide (plate 4) was done through aerial-photo interpretation (1937, 1:20,000 scale; 1952, 1:10,000 scale; 1978, 1:40,000 scale; and 1985, 1:24,000 scale) and field checking. The area underlain by the East Ogden landslide is almost completely urbanized. Much of it was already developed by the time of the earliest (1937) aerial photos. No trenches were excavated on the landslide.

The East Ogden landslide is on the delta constructed jointly by the Weber and Ogden Rivers when Lake Bonneville stood at the Provo level, and during the early stages of regression from that level. The landslide is bordered by Lake Bonneville and post-Lake Bonneville deposits ranging in age from late Pleistocene to late Holocene. Streams from the Wasatch Range have incised the main scarps of the landslide, but the scarps are sharp and clearly visible. In the northeastern part of the landslide, streams have deposited alluvial fans (Qaf_1) on the head of the landslide (plate 4). Streams have also deposited thin layers of alluvium (Qal_1) at several other locations on the landslide surface.

In two places the landslide truncates a regressional shoreline of Lake Bonneville at an elevation of about 4,600 feet (1,402 m) (plate 4), indicating that the failure occurred sometime after about 13,000 to 13,500 yr B.P. The East Ogden landslide ranges in elevation from about 4,760 feet (1,451 m) in the northern part and in the vicinity of Weber State University, to about 4,480 feet (1,366 m) near South Ogden (plate 4). The location of the landslide toe is unclear; a linear topographic feature at 4,480 feet (1,365 m) elevation may be a lake shoreline rather than the toe of the landslide. If so, the landslide occurred sometime prior to 13,000 to 12,500 yr B.P. A regressional shoreline is visible at this elevation on the delta surface to the north of the landslide.

Geomorphic features of the East Ogden landslide include minor scarps with a variety of orientations, horst-and-graben structures, closed depressions, hummocks, transverse lineaments, and relatively linear as well as arcuate main scarps (plate 4). These features suggest a complex landslide containing flow failures, lateral spreading, and translational and rotational slides. The arcuate shape of the main scarp in the northern part of the landslide suggests movement by flow failure. Part of the landslide may have moved west off the delta surface down the Waterfall Canyon Creek drainage; if so, failure occurred after stream incision but prior to deposition of Weber River alluvium at the western end of this creek, where landslide deposits may have existed. Hummocks, depressions, and horst-and-graben structures in the central and southern portions of the landslide were likely produced by sliding of cohesive material.

Southeast of Weber State University, deposits are primarily lacustrine sands containing silt and clay beds, deposited mainly during the highstand of Lake Bonneville. However, Nelson and Personius (1990) mapped this area as a lateral-spread landslide of pre-Bonneville-shoreline age. Many west-facing scarps are in these Bonneville sand deposits, and although some of the scarps are tectonic faults, others are of landslide origin, possibly related to periodic, localized sliding rather than liquefaction-induced lateral spreading. Most of these scarps are short in length and discontinuous, but a scarp about 12 meters (39 ft) above the Provo shoreline is fairly continuous for about 1.6 kilometers (1 mi) (plate 4). The Provo shoreline cuts the western margin of these deposits. We identified no evidence of liquefaction in these Bonneville sand deposits, and map this feature as Bonneville nearshore sand deposits containing landslide scarps (plate 4).

Results

Geomorphic and geologic evidence, and observations of sand dikes in the subsurface by Pashley and Wiggins (1972), indicate that the East Ogden landslide is a liquefaction-induced complex landslide that failed by means of both flow failure and lateral spreading. A truncated recessional shoreline with an elevation of about 4,600 feet (1,402 m) indicates that movement on the landslide occurred sometime after about 13,000 to 13,500 yr B.P. Faults that do not offset recessional-shoreline deposits on the face of the main scarp were observed in a building foundation excavation on the Weber State University campus (Woodward-Clyde Consultants, 1985), possibly indicating that subaqueous landsliding also occurred sometime prior to 14,000 yr B.P.

The feature mapped as an older landslide by Nelson and Personius (1990) southeast of the Weber State University campus we interpret as Lake Bonneville transgressive-phase lacustrine sand (Qls_4) containing localized landslides. We believe that liquefaction was not necessarily involved. All of the landslides and scarps are of post-Lake Bonneville age. If the feature is a lateral spread as suggested by Nelson and Personius (1990), then initial movement occurred prior to the Provo stillstand (about 14,500 yr B.P.), because an undisturbed Provo shoreline crosses the feature.

Hazard Potential

Geologic evidence indicates that liquefaction-induced landsliding has occurred at least once, and perhaps twice in the eastern Ogden City area in post-Bonneville shoreline time (since about 15,000 yr B.P.). At the time of the movement(s), the area may have been submerged beneath Lake Bonneville or close to the lake's shoreline, where ground-water levels were much shallower than they are today. Ground-water levels in eastern Ogden are generally deeper than 9.1 meters (30 ft) (Bedinger and others, 1983), and Anderson and others (1990) map the current liquefaction potential of the area as moderate to low. Due mainly to a relatively deep water table, the potential for recurrent movement of large, liquefaction-induced landslides is low. However, localized areas of shallow, perched ground water and sandy sediments susceptible to liquefaction are common in the eastern Ogden City area, and slopes are commonly greater than 0.1 percent, so smaller liquefaction-induced landslides could occur in the area during future earthquakes.

WEST KAYSVILLE LANDSLIDE

Previous Work

The West Kaysville landslide was first mapped as a lateral spread by Miller (1980), and covers an area of about 2.6 square kilometers (1 mi^2) (figure 2). Miller (1980) described 1- to 9- meter-high (3-30 ft) knobs and mounds as the principal landforms associated with the feature. Anderson and others (1982) mapped the Gilbert shoreline across the West Kaysville landslide, indicating that it formed more than 10,000-11,000 years ago.

Geology and Geomorphology

Geologic and geomorphic mapping of the West Kaysville landslide (plate 5) was accomplished through interpretation of aerial photos (1937, 1:20,000 scale; 1952, 1:10,000 scale; 1978, 1:40,000 scale; and 1985, 1:24,000 scale) and field checking. No trenches were excavated.

The West Kaysville landslide is in an area underlain by fine-grained deposits of Lake Bonneville and Great Salt Lake (Qlf_1, Qlf_2, and Qlf_3) (plate 5). Along its northwestern and southeastern margins, the landslide is covered by older Holocene alluvial fans (Qaf_2) of the Kays Creek and Holmes Creek drainages. Marshes (Qsm_1) occupy the southwestern part of the landslide.

Recessional shorelines of the Bonneville lake cycle, including the Gilbert shoreline at about 4,240 feet (1,290 m) elevation, are buried by the older Holocene alluvial fans and are truncated by the landslide (plate 5). A Great Salt Lake shoreline at about 4,210 feet (1,280 m) elevation cuts the landslide and the alluvial fans. In historical time, Great Salt Lake has reached this elevation twice, in the 1870s and mid-1980s (U.S. Geological Survey records).

Other geomorphic features associated with the West Kaysville landslide include a northwest-southeast-trending main scarp; shallow, closed depressions; and a few flat-topped, elongate, northeast-southwest-trending hummocks (plate 5). The scarp is about 1 meter (3.3 ft) or less high. The northern end of the scarp may be, at least in part, fluvial in origin. The closed depressions are less than 1 meter (3.3 ft) deep and are most common near the scarp and along the southern margin of the landslide. These depressions are also found within the boundaries of the older Holocene alluvial fans, indicating that either the alluvial-fan deposits are very thin or the depressions are recent and not of landslide origin. The hummocks, presumably the mounds discussed by Miller (1980), are only in the marsh area.

Results

We believe that the West Kaysville landslide is a lateral-spread landslide, based on the presence of a discernible main scarp, and the truncated Gilbert and other recessional shorelines of the Bonneville lake cycle that were disrupted by landslide movement. Movement occurred after the Gilbert stillstand about 10,000 yr B.P.

Hazard Potential

The West Kaysville landslide is underlain by sandy sediments and shallow ground water, and is in a high-liquefaction-potential zone where the ground slope is between 0.5 and 5.0 percent (Anderson and others, 1982). The West Kaysville landslide could experience movement during future earthquakes and the most likely failure mode is lateral spreading.

FARMINGTON SIDING LANDSLIDE COMPLEX

Authors' note: Results presented in this section are based on field work and radiocarbon dating done in 1991-92. Since then, the UGS has performed additional work on this landslide complex. For additional details on this landslide, the reader is referred to Hylland and others (1995), Lowe and others (1995), Hylland and Lowe (1998), and Hylland (1999).

Previous Work

The Farmington Siding landslide complex covers an area of approximately 19.5 square kilometers (7.5 mi^2) (figure 2), and was first identified and mapped by Van Horn (1975). He described geomorphic features, including longitudinal ridges and undrained depressions on the surface of the landslides, and exposures of internal structures such as landslide faults (shear zones), folded beds, and injected sand. Van Horn (1975, p. 83) noted that near the main scarp along the northwestern margin of the landslide complex, "the ridges are subparallel to the main scarp and are long and high," but "farther out on the landslides the ridges become lower and shorter until, at the outermost end of the landslide, they are only small unoriented hummocks." He recognized two different ages of landslides in the complex, based in part on differences in soil development on the landslide deposits. The younger landslide disrupts the Gilbert shoreline, which he thought formed 2,000 to 5,000 years ago based on soil development. The relationship between the older landslide and the Gilbert shoreline was unknown to Van Horn (1975), but he assigned an age of 2,000 years or less to the younger landslide and 2,000 to 5,000 years to the older landslide.

Miller (1980) also mapped two landslides of different age in the Farmington Siding landslide complex, and his map also indicates the younger landslide truncates the Gilbert shoreline. He did not map the Gilbert shoreline either across or adjacent to the southern margin of the older landslide.

Miller and others (1981) drilled two test holes on the Farmington Siding landslide complex. In one hole, drilled through the top of a hummock, bedding inclined 12 degrees was encountered between about 1.5 to 2.25 meters (4.9-7.4 ft) deep, and contorted laminae were identified at a depth of about 6.3 meters (21.7 ft). In another hole drilled at the base of the same hummock, intensely contorted bedding was encountered between about 1.25 to 2 meters (4.1-6.6 ft), and high- and low-angle fractures or faults were found at a depth of about 3 meters (9.8 ft).

Anderson and others (1982) also mapped two landslides of two ages in the Farmington Siding landslide complex. The younger landslide disrupts the Gilbert shoreline, which Anderson and others (1982) mapped as crossing the older landslide.

Nelson and Personius (1990) mapped the Farmington Siding landslide complex as three separate slope failures, and noted (p. 13) that the younger, northern landslide "clearly postdates the Gilbert shoreline." They did not map the Gilbert shoreline across the two "older" landslides but indicated that these failures are also of Holocene age.

The toe area of the northern, younger Farmington Siding landslide may have been encountered during a drilling project in Farmington Bay to test foundation conditions for a proposed water-storage reservoir (figure 16) (Everitt, 1991). Inclined and deformed bedding in lacustrine sediments, attributed to landsliding, were encountered in drill holes to a maximum of about 21.3 meters (70 ft) below the bottom of the bay. Lateral margins of the offshore landslide deposit as determined by drilling correspond well with those of the onshore younger Farmington Siding landslide (figure 16) (Everitt, 1991). An organic clay layer overlying the landslide deposit in Farmington Bay yielded a radiocarbon age estimate of 2,930 ± 70 yr B.P. (Everitt, 1991). This age is similar to those obtained for the penultimate surface-faulting earthquake on the Weber segment of the Wasatch fault zone (Nelson, 1988; Forman and others, 1991; McCalpin and others, 1994.

Building upon data presented in Harty and others (1993), Hylland and Lowe (1998) used relative and absolute (radiocarbon) dating of trench soils to conclude that parts of the Farmington Siding landslide have moved at least three, and possibly four, times since about 14,500 14C yr B.P. Their data indicate that liquefaction-induced landsliding is triggered by large-magnitude earthquakes on the Weber segment of the Wasatch fault that are temporally coincident with Great Salt Lake highstands and associated high ground-water levels.

Geology and Geomorphology

Geologic and geomorphic mapping of the Farmington Siding landslide complex (plate 6) was accomplished through aerial-photo interpretation (1952, 1:10,000; 1978, 1:40,000; and 1985, 1:24,000 scale) and field checking. Three trenches were excavated. We logged only two because one trench collapsed due to shallow ground water. We obtained four radiocarbon age estimates from organic-rich sediments in the two logged trenches.

The Farmington Siding landslide complex and surrounding geologic units consist primarily of fine-grained deposits (Qlf_3 and Qls_3) of Lake Bonneville and Great Salt Lake (plate 6). Post-Lake Bonneville alluvial-fan and debris-flow deposits bury the landslide complex in places along its eastern margin (plate 6). Streams flowing from the Wasatch Range have dissected the main scarp of the landslide, but it is still sharp and clearly visible. Marshes occupy much of the surface of the landslide complex, particularly at lower elevations near Great Salt Lake (plate 6).

We subdivide the Farmington Siding landslide complex into two landslides based on relationships to recessional shorelines of Lake Bonneville and Great Salt Lake and on geomorphic expression. The Gilbert shoreline is clearly visible in the southern part of the landslide complex, indicating that movement in this area took place more than about 10,000 yr B.P. and apparently has not recurred since (plate 6). The northern part of the landslide complex has disrupted the Gilbert shoreline (plate 6), indicating that the most recent movement occurred sometime after about 10,000 yr B.P. The only shorelines preserved on the northern landslide are at an elevation of about 4,215 feet (1,285 m) (plate 6). Great Salt Lake reached or exceeded this level at least twice during prehistoric time: once about 2,000 years ago when the lake reached about 1,286.6 meters (4,221 ft) in elevation, and once during the 1600s, when the lake reached about 1,285.3 meters (4,217 ft) in elevation (Murchison, 1989).

Other geomorphic features associated with the Farmington Siding landslide complex include main and minor scarps, closed depressions, hummocks, and transverse lineaments (plate 6). The main scarps of the northern part of the northern landslide are relatively linear. Elsewhere, the main scarps of the northern and southern landslides consist of a series of arcuate scarps. Although present over most of the surface of the landslide complex, hummocks and closed depressions are more common on the northern landslide. Hummocks are most prevalent in the head regions of the landslide complex, and closed depressions are most common in the middle and distal parts. The hummocks, some of which may be landslide blocks bounded by degraded minor scarps, are elongate and parallel to the main scarp in the northwestern part of the northern landslide, but orientation becomes more random with increasing distance from the head. Transverse lineaments are visible predominantly in the distal portion of the northern landslide, and are particularly common near the margin between the northern and southern landslides (plate 6).

Farmington Siding Trench

An approximately 15-meter-long (50 ft) trench (FST) was excavated in the NW1/4 section 23, T. 3 N., R. 1 W., near

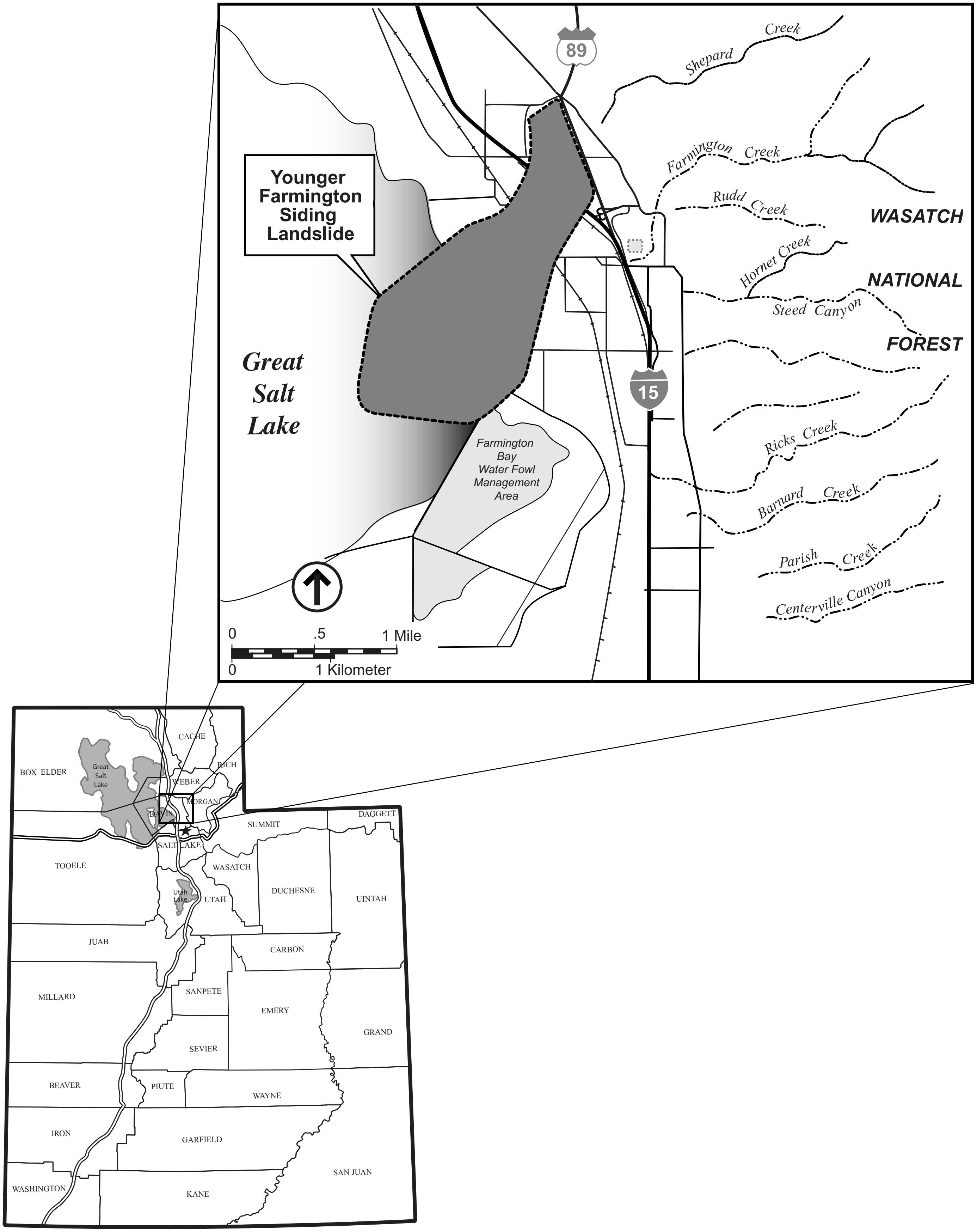


***Figure 16**. Extent of the younger Farmington Siding landslide in Farmington Bay of Great Salt Lake (modified from Everitt, 1991).*

Farmington Siding (plate 6). The trench extended from the crest of one hummock to the crest of another through the low area between the hummocks. We encountered shallow ground water and the trench walls collapsed. Before the collapse, however, we briefly inspected the stratigraphy of the easternmost hummock. The sediments were bedded fine-grained Lake Bonneville silts with lesser amounts of sand and clay. Beds dipping at low angles to the northeast (upslope) suggest that the hummocks were likely formed by landsliding.

North Farmington Junction Trenches

Two trenches were excavated in the SE1/4 section 11, T. 3 N., R. 1 W., near North Farmington Junction (plate 6). The North Farmington Junction eastern and western trenches (respectively NFJET and NFJWT) were excavated on and perpendicular to the northern flank of an east-west-trending, wedge-shaped hummock at the head of the northern landslide (plate 6, figure 17). We believe that the hummock is a landslide block that detached from the main scarp about 0.24 kilometers (0.15 mi) northwest of the trench site. We excavated the trenches at this location to observe the relationship between the hummock and surrounding material; we assumed that the hummock was formed by the landslide, and expected to find disturbed sediments and possibly buried, organic-rich sediments or colluvial wedges. The trenches were each about 11 meters (36 ft) long and averaged about 2 meters (6.6 ft) deep (plates 7 and 8). The stratigraphy consisted of unstratified lacustrine sand, sandy colluvium, and, in the NFJET, an alluvial-fan deposit (plates 7 and 8). We observed stratification in lacustrine sands in exposures in the central part of the hummock (between the trenches) as well as in the main scarp of the landslide. Pre-existing stratification in the lacustrine sands exposed in the trenches was likely destroyed by liquefaction and landsliding. The NFJET contained a soil, atop unstratified sand (landslide) deposits, that was buried by an alluvial fan (figure 18, plates 6 and 7). The soil block in the NFJWT (plate 8) was probably incorporated into the lacustrine sand unit during landsliding.

Stratigraphy and Timing of Events

The oldest unit in both trenches is unit 1, which consists of unstratified fine to very fine sand containing some silt and clay. We observed similar, but well-stratified lacustrine sediment within the hummock in the area between the trenches. Because unit 1 is unstratified and is similar in color and composition to bedded lacustrine sediments in the hummock, we believe it is landslide material derived from the hummock.

Unit 2 in the NFJET consists of silty clay with sand, and contains well-rounded gravel. We believe this unit is also a lacustrine deposit in which stratification has been destroyed by landsliding. This unit is highly mottled due to a fluctuating water table.

Unit 2a in the NFJWT consists of unstratified fine sand containing ironstone concretions, small soil blocks, and animal burrows. We interpret this unit to be a landslide deposit derived from lacustrine sand. We presume that the soil blocks incorporated into this unit (plate 8) originated from a soil forming in the landslide area prior to movement of the landslide. A radiocarbon age estimate from one of the larger blocks (NFJWT-1) indicates that landsliding occurred sometime after 4,530 ± 300 cal yr B.P. However, because we do not know where within the soil profile the block originated, this age estimate may represent a maximum age for landsliding, particularly if the block came from the base of a soil A horizon.

Units 2b/S1 in the NFJWT and 3/S1 in the NFJET consist of unstratified fine sand (NFJWT) or silty-clayey fine sand (NFJET) containing soil blocks and animal burrows. Both units include organic material from a soil A horizon that has imparted a dark color to the sand units (plates 7 and 8; appendix B). For this reason, we dually classified these units as soils. We also interpret these soils to be landslide deposits derived from lacustrine sediments. Soil from the top of unit 3/S1 beneath the alluvial-fan deposit (unit 5) in the NFJET provided an age estimate (NFJET-2) of 2,730 ± 370 cal yr B.P., indicating landsliding occurred just prior to this time. Soil S1 thickens to the north in both trenches.

Unit 3 in the NFJWT and unit 4 in the NFJET consist of unstratified fine sand containing silt and/or clay and abundant burrows. These units are colluvial wedges derived from landslide and lacustrine sediments on the hummock. Neither of these colluvial wedges contained datable material.

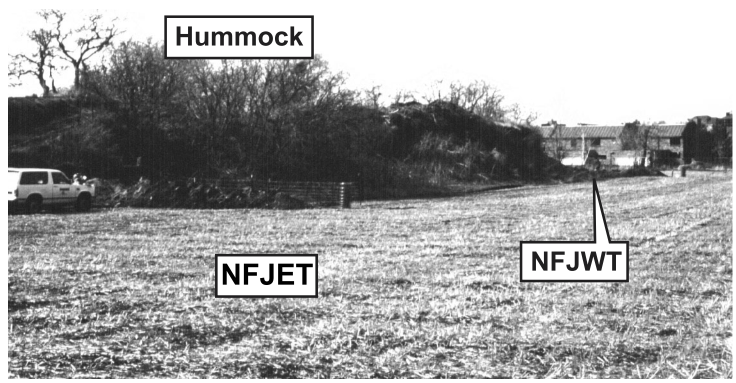


Figure 17. Southwest view of an east-west-trending hummock in the Farmington Siding landslide complex. The spoil pile and fence roll of the North Farmington Junction east trench (NFJET) is visible in the left center of the photograph. Those of the North Farmington west trench (NFJWT) are visible in the right center of the photograph.

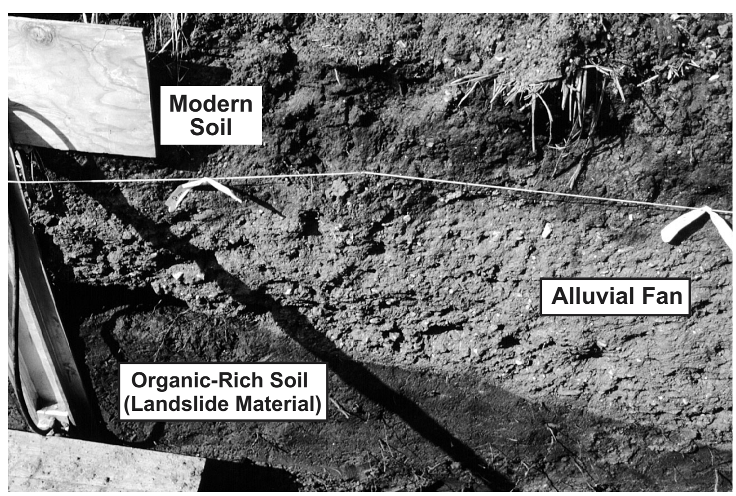


Figure 18. *West wall of the North Farmingtion Junction east trench (NFJET) between stations 8 and 9 on plate 7. The light-colored alluvial-fan deposit overlies organic-rich sand (landslide material). Note the sharp contact between these two units. The uppermost dark unit (above the string) is the modern soil which formed on the alluvial fan.*

Unit 5 in the NFJET consists of gravelly sandy clay deposited in an alluvial fan from a drainage northeast of the trench site (plate 6). Age estimates from soil S1 (NFJET-2) below the alluvial fan, and soil S2 (NFJET-3) above the fan, indicate that the landslide deposit was buried by alluvial-fan sediments sometime between 2,730 ± 370 and 1,990 ± 150 cal yr B.P. (figure 18, plate 7).

Unit S2 in both trenches is the A horizon of the modern soil. Radiocarbon age estimates (NFJET-1 and NFJET-3) indicate that this soil began forming at least 1,540 ± 160 to 1,990 ± 150 cal yr B.P.

Paleoseismic Implications

As discussed under the subheading "Paleoseismic Implications" in the North Ogden landslide section of this report, trench studies on the Weber segment of the Wasatch fault show evidence of four large surface-faulting earthquakes in the past 6,100 years B.P. (Forman and others, 1991; McCalpin and others, 1994; McCalpin and Nishenko, 1996). A comparison of age estimates from these studies with age estimates obtained from the North Farmington Junction trenches reveals a variety of possible correlations. The younger, northern part of the Farmington Siding landslide complex could have formed during: (1) the penultimate event on the Weber segment about 3,064 cal yr B.P. (McCalpin and Nishenko, 1996), (2) the antepenultimate event on the Weber segment which occurred about 4,403 cal yr B.P. (McCalpin and Nishenko, 1996), (3) a surface-faulting earthquake associated with another fault or different segment of the Wasatch fault, or (4) a smaller, non-surface-faulting event in the immediate area. In part because the potential for liquefaction and liquefaction-induced slope failure increases with severity and duration of ground shaking, and because the severity of ground shaking increases with proximity to the earthquake for any given earthquake event, we believe that the large landslides that comprise the Farmington Siding landslide complex occurred during surface-faulting earthquakes on the Weber segment of the Wasatch fault. In addition, the age estimates obtained from the two trenches on the younger, northern part of the landslide most closely match the penultimate or antepenultimate events on the Weber segment of the fault rather than events on the adjacent Brigham City or Salt Lake City segments.

Radiocarbon age estimates from the North Farmington Junction trenches indicate that the northern landslide formed before 2,730 ± 370 cal yr B.P., but after 4,530 ± 300 cal yr B.P. Because the older date could be much older than the landslide movement, we believe the northern landslide formed closer to the younger date, probably sometime before about 2,730 years ago, and likely during the penultimate event on the Weber segment of the Wasatch fault.

Results

Geomorphic and geologic evidence indicate that the Farmington Siding landslides are complex landslides that failed by both flow failure and lateral spreading. The arcuate main scarps and unstratified, disturbed lacustrine sediments near the main scarp suggest movement by flow failure. The preservation of transverse lineaments (shears, pressure ridges?) and hummocks with bedding intact but dipping upslope on the body of the landslide complex may indicate movement by more brittle lateral spreading.

The Farmington Siding landslide complex consists of at least two landslides of different ages. The southern landslide is in Provo- and post-Provo-age lake sediments, and thus formed sometime after about 14,500 yr B.P. A largely undisturbed Gilbert shoreline crosses this landslide, so movement of the southern landslide occurred between about 10,000 and 14,500 yr B.P. The fewer and more subdued geomorphic features on this landslide also show that it is appreciably older than the northern landslide. However, the possibility exists that the southern landslide could have experienced minor movement in post-Gilbert time.

Geomorphic features on the northern landslide appear more youthful than any other we looked at during this study, suggesting a relatively recent age for landslide movement. The radiocarbon age of 2,930 ± 70 yr B.P. obtained as a minimum age estimate for the northern landslide by Everitt (1991) supports the geomorphic evidence, as well as the radiocarbon age estimate of about or just prior to 2,730 ± 370 cal yr B.P. we obtained from the North Farmington Junction trenches. Our best estimate of the age of most recent movement on the northern landslide is late Holocene time, during the penultimate surface-faulting earthquake on the Weber segment of the Wasatch fault.

Hazard Potential

The eastern part of the Farmington Siding landslide complex is urbanized, whereas the western part, especially near Great Salt Lake, is rural. Both the northern and southern landslides are in areas of high-liquefaction potential (Anderson and others, 1982). Sandy sediments and shallow ground water in the region are conducive to the recurrence of liquefaction during future earthquakes.

Liquefaction-induced landsliding has occurred at least twice in the area since 14,500 yr B.P.; the latest movement occurred as recently as late Holocene. Geomorphic evidence shows that both flow failures and lateral spreading have been generated within the landslide complex. In the future, flow failures are most likely to form along the more populated crown of the landslide complex. Ground-water data compiled by Anderson and others (1982) show that although the water table deepens to the east, it is within 9.1 meters (30 ft) of the surface in most areas upslope from the main scarps, where flow failures would likely initiate. Lateral spreading and bearing-capacity failures are the failure modes most likely to occur in the middle and distal parts of the landslide complex, where the average ground slope is less than 5 percent.

Because the southern landslide has not moved appreciably (if at all) during the Holocene, we consider the potential for recurrent movement of this landslide to be lower than that of the northern landslide.

NORTH SALT LAKE LANDSLIDES

Previous Work

Two landslides west of Bountiful in southern Davis County were identified as possible lateral spreads and mapped by Van Horn (1982). Together, they cover a combined area of 14.0 square kilometers (5.4 mi^2) and Van Horn (1982) labeled them as "younger" and "older" landslides. Their identification was based on analysis of 1937 aerial photos that "... show a hummocky surface, which has been leveled by grading. The younger [northern] deposit appears to truncate the older [southern] deposit" (Van Horn, 1982, map text). He mapped the entire "older" landslide and the southern part of the "younger" landslide, and reported observing no exposures of the deposits.

Following Van Horn (1982), Personius and Scott (1992) mapped the southern landslide and the southern part of the northern landslide, and Nelson and Personius (1990) mapped the eastern parts of both landslides. Both of these maps depict the landslides as lateral spreads. Nelson and Personius (1990, map text) reported mapping the boundary between the younger and older lateral spreads based on a difference "in vegetation and degree of preservation of hummocky topography." Van Horn (1982) estimated the age of the features as Quaternary; Nelson and Personius (1990) reported that both features formed less than 10,500 yr B.P., based on an observation that landslide deposits partly cover the Gilbert shoreline.

Anderson and others (1982) excavated three test pits into the features. Two test pits on the "younger" feature showed minor offsets of marker beds of 1-2 centimeters (0.4-0.8 in); no disturbed bedding was observed in the test pit on the "older" feature. Anderson and others (1982) surmised that the general lack of disturbed bedding may indicate that either ground failure did not occur at some test-pit sites, or the pits were excavated into a block of material that moved as a cohesive unit.

Robison and others (1991) excavated a trench and drilled boreholes just east of the "older" feature and found evidence of shearing that may represent landsliding. In addition, anecdotal reports from local consultants indicate contorted bedding and injected sand in utility-corridor trenches excavated on the features.

Geology and Geomorphology

Geologic and geomorphic mapping of the North Salt Lake features was done using aerial photos (1952, 1:10,000 and 1980, 1:40,000 scale) and field checking. In addition, we cleared and logged the walls of a land drain that crosses both features.

Due to a lack of distinct boundaries, on plate 9 we depict a composite of those mapped by Anderson and others (1982), Van Horn (1982), Nelson and Personius (1990), and Personius and Scott (1992). Fine-grained Lake Bonneville sediments (Qlf_1, Qlf_2, and Qlf_3) predominate in the area of the features. Thin sheets of eolian sand and sand dunes (not mapped) locally cover the lake deposits. The modern and an older flood plain (respectively Qal_1 and Qal_2) of the Jordan River abut lake sediments along the western margins of the mapped features. The well-developed Gilbert shoreline and a number of other well-preserved recessional shorelines are present on or near the features (plate 9).

We cannot confirm that the features are landslides. However, based on our surficial geologic mapping (time constraints did not allow us to trench these features), and geologic evidence uncovered by other researchers, we believe these features are liquefaction-induced landslides, likely lateral spreads but possibly flow failures. Their boundaries and surficial geomorphic features are indistinct, both in the field and on aerial photos. The landslides contain only a few hummocks, but numerous depressions. However, most of the depressions have distinct borders, appear fresh, and contain actively growing phreatophytes (figure 19). The depressions are incongruous with the otherwise smooth, subdued surface of the landslides, and are probably related to ground water rather than landsliding. Many of the depressions are near the base of the Gilbert shoreline (plate 9) and are likely remnants of depression springs that once discharged in that area.

Aerial photos reveal that the Gilbert shoreline is not deformed or offset across the landslides; only two small late Holocene rotational landslides and a number of stream channels have eroded the shoreline. Previous workers mapped the main scarp of the "younger" landslide to the east of the Gilbert shoreline (Anderson and others, 1982; Nelson and Personius, 1990; Personius and Scott, 1992) (plate 9). Anderson and others (1982) do not show the Gilbert shoreline crossing the landslide, suggesting that the landslide truncates and thus postdates the approximately 10,000 yr B.P. shoreline. Nelson and Personius (1990) and Personius and Scott (1992) dashed the Gilbert shoreline through the "younger" landslide and believe that both landslides partly cover the Gilbert shoreline. They suggested that the landslides are younger than the Gilbert shoreline. We show a mostly uneroded Gilbert shoreline across both landslides (plate 9); we could not identify sediments draped over the shoreline or other disruption of the shoreline by landsliding. For this reason, we believe that the landslides formed in pre-Gilbert time. Additional evidence for a pre-Gilbert age for the landslides is provided by other recessional shorelines in the area. As shown on plate 9, a number of unbroken, fairly linear shorelines cross the northern part of the "younger" landslide and adjacent "non-landslide" terrain. However, at the scale of our mapping, small lateral offsets of shorelines may not be detectable, so this evidence is supportive but not conclusive. The lack of surface expression (for example, hummocks, lateral margins) on these landslides also suggests

Figure 19. *Vegetated, circular depression on the North Salt Lake northern landslide.*

they are old. Robison and others (1991) excavated a west-oriented trench and drilled four boreholes across the Gilbert shoreline just east of the "older" landslide in the northern half of section 2, T 1 N., R 1 W. (plate 9). They found a series of shallow shear planes of non-tectonic origin indicative of either lateral spreading or rotational sliding of the Gilbert shoreline (Robison and others, 1991). The presence of undeformed, approximately 10,500 yr B.P. beach sands of the Gilbert shoreline overlying the shears shows that the shears formed prior to the formation of the Gilbert shoreline. Although Robison and others (1991) were uncertain as to the exact origin of the shears, they provided supporting evidence that landsliding has not occurred in this area in Holocene time.

A 2-square-kilometer (0.77 mi^2) area within the northern part of the "younger" landslide (sections 22, 23, and 27, T.2 N., R.1 W., plate 9) contains subdued hummocky topography and a number of lineaments that could represent filled-in ground cracks or flow lines (possibly remnant pressure ridges). This area appears to have experienced liquefaction-induced landsliding since the initial movement of the larger lateral spread landslide. Further investigation is required to confirm the timing of movement.

A down-to-the-west escarpment upslope from the North Salt Lake landslides is visible on 1952 aerial photos but has been largely obscured by recent development and was unmapped by previous researchers. As mapped on plate 9, this roughly northeast-southwest-trending escarpment generally parallels the existing slope and recessional shorelines. The escarpment trends along an elevation of about 4,295 feet (1,309 m), and we traced it on aerial photos for about 3.8 kilometers (2.4 mi) before it is truncated to the south by an alluvial fan in the city of North Salt Lake, and obscured by roads and oil refineries to the north near Woods Cross Siding (plate 9). In a number of places, depressions (sag ponds?) lie at the base of this escarpment. At present, we are uncertain whether this feature is a shoreline, fault scarp, or landslide scarp, although we believe it is most likely the main scarp area of the landslides. Additional field work would be required to confirm its origin.

Approximately 1.1 kilometers (0.7 mi) east of the "younger" landslide, in the W1/2 section 30, T.2 N., R. 1 E., is an area of hummocks and depressions visible on 1952 aerial photographs, but now obliterated by development (plate 9). This area probably moved as a landslide, possibly a liquefaction-induced landslide, but further subsurface investigation would be required to confirm this.

Land-Drain Excavations

A 0.8-kilometer-long (0.5 mi), roughly north-south-trending land drain crosses both the "older" and "younger" landslides mainly in the E1/2 section 35, T. 2 N., R. 1 W. (plate 9). We cleared and logged the western side of the drain, on the "younger" landslide (site A, plate 9), and the eastern side of the drain on the "older" landslide (site B, plate 9). Plate 10 shows stratigraphic logs of the excavations. In both excavations, we encountered just under 2.5 meters (8.2 ft) of lacustrine sediments below fill used to construct the levees of the drain (plate 10). The excavations revealed only unstratified clay units (plate 10). We found no evidence of deformed sediments, but the lack of bedding makes it difficult to preclude the possibility that deformation occurred. No significant differences in unit lithologies were observed between excavations on the "younger" versus "older" landslides.

Results

Boreholes and test pits on and near the landslides (Anderson and others, 1982; Robison and others, 1991) have not confirmed the presence of liquefaction-induced landslides, but show evidence of subsurface deformation that may be related to liquefaction-induced landsliding. Verbal reports from consultants of deformed bedding and sand-injection features, and our observations of subdued hummocky topography, lineaments, and a possible main landslide scarp, suggest that these features are likely liquefaction-induced landslides, probably lateral spreads. No toe or lateral margins of landslides are distinguishable on aerial photos, and only a scarp along the eastern edge of the "younger" landslide is partly discernable. Our mapping shows the landslides contain late-Holocene depressions and alluvial channels, and degraded and discontinuous Lake Bonneville and Great Salt Lake shorelines. These geomorphic features suggest to us that no major liquefaction-induced landsliding has occurred within the past 10,000 years, based on a general lack of distinct landslide features and the presence of a largely undisrupted and continuous Gilbert shoreline crossing the northern, "younger" landslide. However, a 2-square-kilometer (0.77 mi^2) area in the northern part of the “younger” landslide may have moved since the initial movement of the larger, main landslides.

Hazard Potential

Anderson and others (1982) have confirmed the presence of liquefiable sediments in the area of the landslides. Ground water is extremely shallow, thus the potential for liquefaction is high (Anderson and others, 1982). Although we have not found evidence of movement of these landslides within the past 10,000 yr B.P., we believe the possibility still exists for recurrent movement of these landslides, or of portions of these landslides, during earthquake ground shaking. The presence of shallow ground water over most of the area, and the landslides’ proximity to the Jordan River, which provides a free face for landslide movement, enhance the potential for recurrent movement of these landslides.

SPRINGVILLE/SPANISH FORK FEATURE

Previous Work

The Springville/Spanish Fork feature (figure 2) was first mapped as a possible lateral spread by Miller (1982) at 1:100,000 scale. He identified the feature as a lateral spread based on aerial-photo interpretation and field reconnaissance. Although he did not present geologic evidence of liquefaction-induced landsliding, Miller (1982, p. 11) surmised, based on geomorphic appearance, that the northeastern part of the feature probably moved by flow failure, possibly subaqueously. He reported that this landslide and the Beer Creek landslide to the south exhibit grabens, ridges parallel to the main scarps, undrained depressions between ridges, and hummocks with low relief (< 1 meter [3.3 ft] high). Miller offered no specific age of formation for this feature other than the broad range of "Holocene to upper Pleistocene." The Springville/Spanish Fork feature was also mapped by Machette (1989) at 1:50,000 scale. He refined the mapping done by Miller, but presented no new information on the nature or age of the feature. As mapped by Machette (1989), the feature covers about 3.6 square kilometers (1.4 mi^2).

Geology and Geomorphology

Geologic and geomorphic mapping of the Springville/Spanish Fork feature was done using aerial photos (1952, 1:10,000 and 1987, 1:40,000 scale) and field checking. In addition, three trenches were excavated and logged. Because we are uncertain that the feature is actually a liquefaction-induced landslide, the boundary of the feature shown in plate 11 is mainly that of Machette (1989).

The Springville/Spanish Fork feature is near the western margin of the Provo-age delta (Qd_3) that was deposited in Lake Bonneville by the Spanish Fork River (plate 11). The feature consists of fine-grained Lake Bonneville sediments (Qlf_3) and contains a number of marsh/swamp areas (Qsm_1) (plate 11). Many of these areas, particularly in the southeastern part of the feature, are fed by springs or seeps from the base of the delta. Swamps in the W1/2 section 8, T. 8 S., R. 3 E., are fed by spring-fed drainages that converge near the margin of the feature (plate 11). Between the swamp-filled channels, and to the south (SW1/4 section 8, T. 8 S., R. 3 E.) and northeast (N1/2 section 8, T. 8 S., R. 3 E.) of this region, are flat-topped erosional remnants of fine-grained lacustrine sediments between about 4,440 and 4,550 feet (1,383.8 - 1,386.8 m) elevation. The northern part of a landfill (Qf1) is on one of these remnants (plate 11).

We observed a few isolated hummocks on the feature, but they may be erosional remnants. In addition, we mapped a few small depressions mainly on the distal parts of the feature. Two lineaments trend southwest-northeast across parts of the Springville/Spanish Fork feature and they appear to be regressive shorelines of Lake Bonneville (plate 11). Neither of these shorelines was mapped by previous researchers. The shorelines have been eroded in many places and are difficult to identify in the field, but show up clearly on 1:10,000-scale aerial photos. The easternmost shoreline is at approximately 4,570 feet (1,393.0 m) elevation, and is traceable on aerial photos for about 2.4 kilometers (1.5 mi). The other shoreline is at about 4,545 feet (1,385.3 m) elevation, and is traceable for 1.5 kilometers (0.9 mi) beginning just north of Spanish Fork (plate 11). The flat, isolated remnants discussed previously are at about the same elevation as this shoreline, and the western margins of the remnants may correspond to this Lake Bonneville shoreline. We map a 0.85-kilometer-long (0.52 mi) portion of what we believe to be a trace of the westernmost shoreline along one of these remnants in the N1/2 section 8, T. 8 S., R. 3 E. (plate 11). Both shorelines cross areas on and off the feature, but neither appears to be deformed or offset by landslide movement. If the feature is a landslide, the shorelines indicate that it formed sometime prior to about 13,000 yr B.P., before post-Provo-age Lake Bonneville had regressed to the elevation of these shorelines.

Trench SP-1

Trench SP-1 was excavated in one of the isolated flat-topped lacustrine remnants (SW1/4SW1/4 section 8, T. 8 S., R. 3 E.) (plate 11). We chose to trench a remnant to avoid encountering shallow ground water, and to look for evidence of deformed bedding. The trench was approximately 7 meters (30 ft) long by about 2.5 meters (8.2 ft) deep, and showed no evidence of liquefaction or sediment deformation associated with landsliding. The trench walls showed massive lacustrine clay with interbedded small lenses of fine sand (plate 12).

Trench SP-2

Trench SP-2 (SE1/4 section 8, T. 8 S., R. 3 E.) was excavated into the easternmost regressive shoreline of Lake Bonneville (plate 11). In this area, the shoreline appears as a gentle, northwest-facing escarpment (plate 11), and the trench was placed near the crest of the slope. The trench was approximately 8 meters (26 ft) long by about 3 meters (9.8 ft) deep, and showed no evidence of liquefaction or soil deformation. The trench contained predominantly finely laminated lacustrine-clay units; a thin, continuous red-clay bed showed no deformation (plate 13). We believe the gravel layer (unit 3, plate 13) lying atop the clay units was deposited in a nearshore lake environment, associated with development of the shoreline in this area. The gravel is poorly graded and rounded to subrounded, which is consistent with a lacustrine shoreline environment.

Trench SP-3

Trench SP-3 (NW1/4 section 8, T. 8 S., R. 3 E.) was excavated on a gentle escarpment on the distal part of the Springville/Spanish Fork feature (figure 20, plate 11). As discussed earlier, the escarpment may be a remnant of the westernmost shoreline. The trench was 8 meters (26.2 ft) long by 2.75 meters (9.0 ft) deep at its deepest point (plate 14). It showed no direct evidence of liquefaction, but displayed one unit of lacustrine clay that contained two continuous red-clay marker beds that showed minor faulting and tilting characteristic of brittle deformation (plate 14). Offsets were generally on the order of a few centimeters and numerous; the longest unfaulted portion of either red-clay bed was only a little over 1 meter (3.3 ft) (plate 14).

We believe that the deformation in trench SP-3 formed in one of two ways. In the first scenario, an unidentified sediment unit beneath the trench liquefied during an earthquake and the clay unit above experienced ground oscillation resulting in the offsets seen in the trench. Movement by lateral spreading could have occurred here, but because the sheared red clay beds are only slightly dislocated, the area exposed in the trench would have moved as a relatively in-place block. Alternatively, minor sliding unrelated to earthquake-induced liquefaction may have occurred along the escarpment, fracturing the clay beds. However, as with the lateral-spread hypothesis, the area exposed in the trench would have moved as an intact slide block. Deformation likely occurred sometime after Lake Bonneville regressed from this area about 13,000 yr B.P., but no datable material was found in the trench to further constrain the timing of deformation.

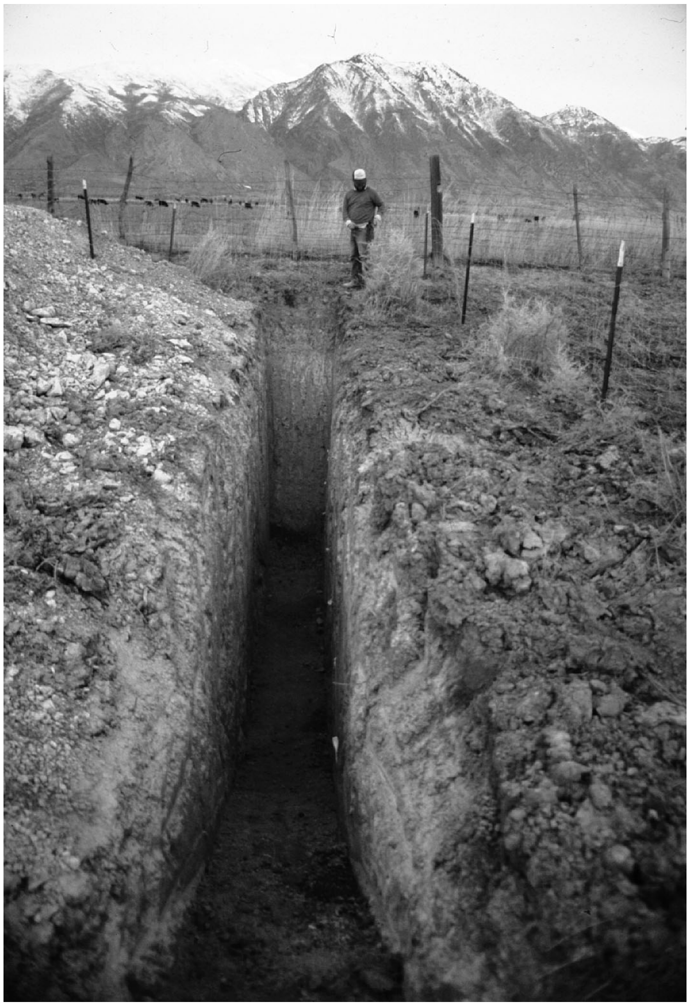


Figure 20. *Springville/Spanish Fork feature, trench SP-3 excavated across a gentle escarpment (recessional shoreline of Lake Bonneville). See text for further description.*

Results

Geologic evidence is equivocal as to whether earthquake-induced liquefaction occurred in the area. However, the deformation observed in trench SP-3 indicates that liquefaction may have caused at least in-place ground oscillation at this location. Such disturbance, now undetectable at the surface, could have occurred subsequent to the formation of the recessional shorelines about 13,000 yr B.P. However, significant lateral spreading or flow failure in the area after about 13,000 yr B.P. is unlikely because: (1) the two recessional shorelines are not appreciably (if at all) offset or deformed, and (2) no flow-failure deposits were found in the trenches. Bedding in the trenches indicates negligible amounts of lateral movement. Flow failure or lateral spreading could have occurred prior to the formation of the shorelines, perhaps subaqueously as suggested by Miller (1982), but we found no evidence for such an event.

Localized liquefaction could have occurred within the boundaries of the Springville/Spanish Fork feature, but as a whole, it could also have formed by processes other than liquefaction-induced landsliding. The main scarp of the feature, including the arcuate shape of the scarp at both its northeastern and southeastern ends, may be related to spring sapping along the margin of the delta. The main scarp is sharpest and steepest in the southeastern corner of the feature, where marshes lie at the base of the slope. The subsurface contact between the fine-grained Lake Bonneville sediments (Qlf_3) and the overlying coarser grained delta (Qd_3) may be an area of perched ground water that feeds the springs and marshes on the feature. Shallow perched ground water may have, and may still be, contributing to slope weakness in this area.

Hazard Potential

The area covered by the Springville/Spanish Fork feature is in a zone of high liquefaction potential (Anderson and others, 1986a). No subsurface soil data were collected on the feature, but liquefiable sediments were identified within 9.1 meters (30 feet) of the surface in nearby boreholes (Anderson and others, 1986a). In addition, ground water is near or at the ground surface over most of the area. Despite inconclusive evidence that the feature as a whole was liquefaction-induced, geologic and hydrologic conditions are favorable for liquefaction and liquefaction-induced landsliding. Similar to portions of the main scarp of the North Ogden landslide complex, hydrologic conditions along the eastern margin of the feature are favorable for flow failures and eastward retreat of the main scarp. In addition, the possibility that future earthquakes could produce ground oscillation or movement by lateral spreading cannot be ruled out.

BEER CREEK FEATURE

Previous Work

The Beer Creek feature was first identified and mapped as a queried lateral-spread landslide by Miller (1982). The feature covers an area of approximately 6 square kilometers (2.3 mi^2) (figure 2). Miller (1982) described geomorphic features such as remnants of ridges parallel to the main scarp, undrained or poorly drained depressions, and low mounds or hummocks on the surface of the landslide, and internal structures such as locally disturbed and contorted bedding in exposures on the landslide. He also described an amphitheater that forms the northern part of the main scarp of the landslide, and hypothesized that it may have formed by flow failure (possibly subaqueous), lateral spreading, or dewatering of the scarp following failure. He assigned an age range of Holocene to upper Pleistocene to the feature. Machette (1989) also mapped the Beer Creek feature (1:50,000 scale). He removed the query and refined the surficial-geologic mapping, but provided no new information on the nature or timing of formation of the feature.

Geology and Geomorphology

Geologic and geomorphic mapping of the Beer Creek feature (plate 15) was done using aerial-photo interpretation (1952, 1:10,000 scale, and 1987 and 1988, 1:40,000 scale) and field checking. One trench was excavated and logged. Because we are uncertain that the feature is actually a liquefaction-induced landslide, the boundary shown in plate 15 is mainly that of Machette (1989).

The Beer Creek feature is near the western margin of a Provo-age delta of Lake Bonneville. The feature is in Lake Bonneville and post-Lake Bonneville deposits ranging in age from late Pleistocene to late Holocene (plate 15). Alluvial fans (Qaf_1) cover the feature at two locations, and marshes (Qsm_1) are common on the feature's surface (plate 15).

Geomorphic features include main and minor scarps and closed depressions (plate 15). In the northeastern part of the feature, the main scarp is high and sharp. It is especially linear in the northern part along a 1.5-kilometer (0.93 mi) segment where it follows the western margin of a lacustrine-gravel deposit (Qlg_3) (plate 15). To the north, the main scarp forms an amphitheater. To the south, the scarp is low and indistinct. We identified two escarpments (possibly minor scarps) in the southern part of the feature. The closed depressions are generally less than 1 meter (3.3 ft) deep and are most common near the main scarp in the southwestern part of the feature (plate 15). Upslope and east of the feature, in sections 10 and 11, T. 9 S., R. 2 E., we identified a number of what appear to be circular depressions (unmapped) on the 1952, 1:10,000-scale aerial photos. These features have since been filled in and obscured by agricultural activity in the area.

Beer Creek Trench

The water table is shallow or at the surface over most of the feature. We placed a trench across a linear portion of the main scarp about 1.6 kilometers (1.0 mi) north of Salem in the NE1/4 section 2, T. 9 S., R. 2 E. (figure 21, plate 15). The trench was about 12 meters (40 ft) long by about 2 meters (6.5 ft) deep. The scarp at the Beer Creek trench site consists of sand and clay deposits of lacustrine origin that are overlain mainly by lacustrine gravel and colluvium (figure 22). The purpose of this trench was to locate and possibly date a colluvial wedge that may have formed at the base of the scarp following landslide movement. We found no dat-

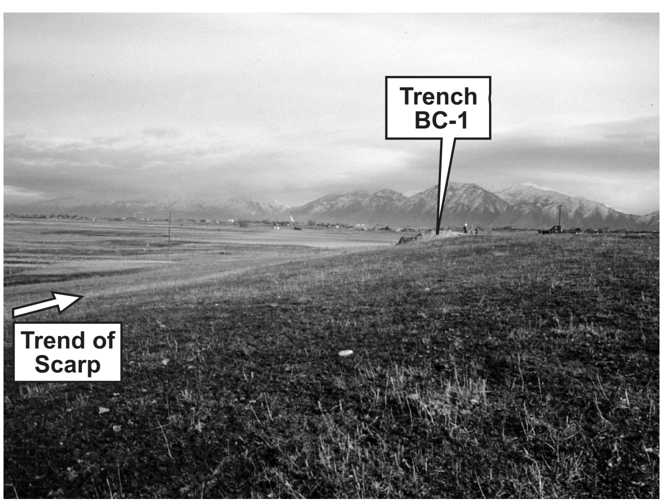


Figure 21. North view of the Beer Creek feature main scarp(?). Trench (BC-1) in center of photo. Darker, flat area in right lower half of photo is a Provo-level delta deposit formed in Lake Bonneville.

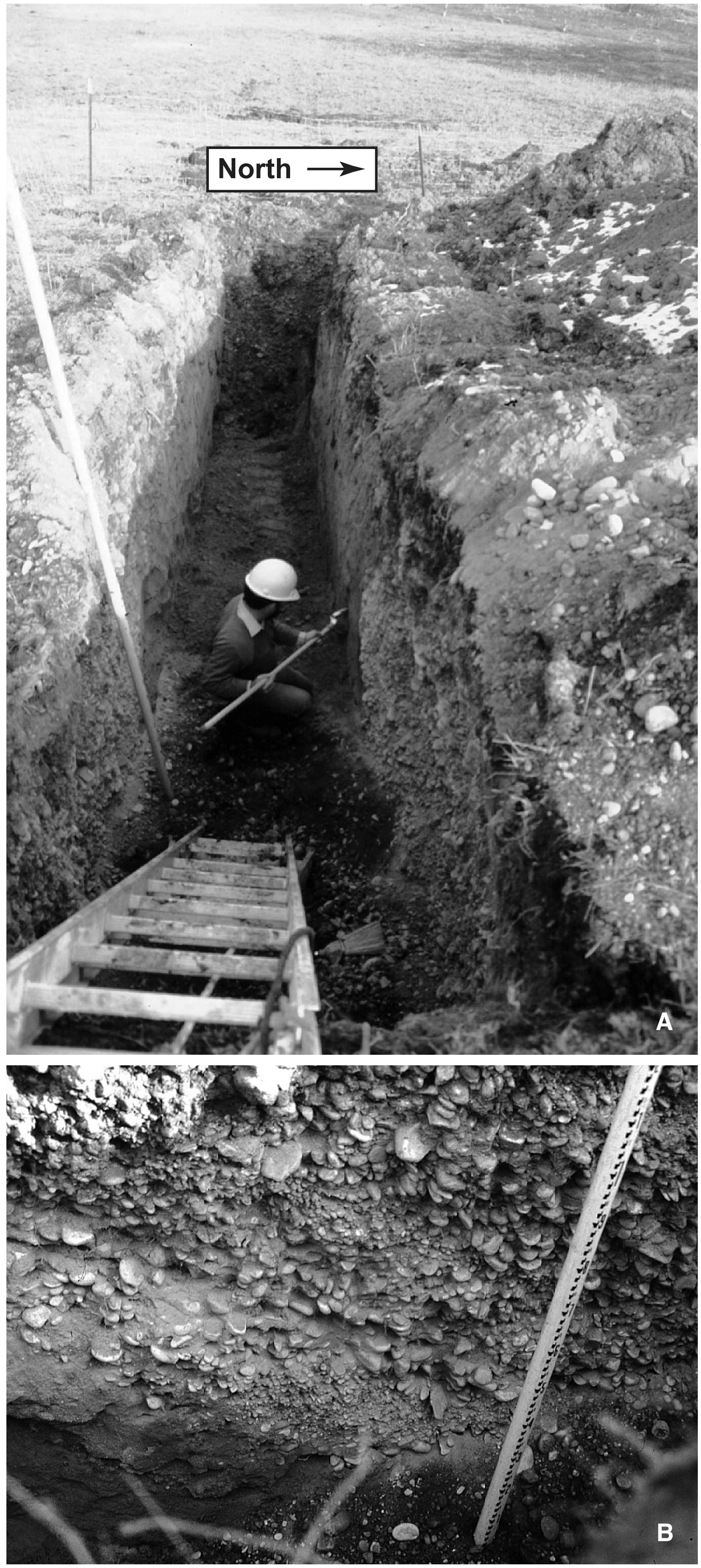


Figure 22. Trench BC-1 excavated into the main scarp(?) of the Beer Creek feature. (A) Geologist clears north wall of trench, exposing contact between lacustrine clay (distal part of trench) and lacustrine gravel (unit 4a, plate 16) in foreground wall of trench. (B) Closer view of lacustrine gravel (unit 4a) on south wall of trench.

able material nor a colluvial wedge, but uncovered evidence of a rotational slide in the main scarp. This smaller failure caused the back-tilting observed in sediments in the eastern part of the trench (plate 16). Because the rotational slide did not significantly alter the linearity of the main scarp, we believe that the slide could have formed before the scarp reached its present position (see discussion below). Although we uncovered complex, deformed stratigraphy in this trench, it did not provide information on the age or genesis of the scarp or feature.

Results

We found no conclusive evidence that the Beer Creek feature is a landslide. The main scarp, however, could be of landslide origin. We examined the main scarp where ephemeral streams have eroded through it, and found no evidence that the scarp is tectonic in origin. Undeformed sediments observed in these stream-cut exposures indicate that the deformed bedding observed in the trench is localized. The base of the scarp consists mainly of fine-grained lacustrine deposits; therefore, if the feature was created by shoreline erosion, few or no nearshore sediments were deposited.

Although the following hypothesis does not preclude the possibility that the scarp was initiated by earthquake-induced landsliding, a non-tectonic process could have formed the distinct scarp in the northeastern part of the feature. Only where the scarp abuts the lacustrine-gravel deposit (Qlg_3) is the scarp so high, sharp, and linear (plate 15). The linearity of the scarp could be related to its encountering, through headward erosion perhaps due to spring sapping, the relatively resistant lake gravels. Unlike the extreme northern part of the scarp, which may be eroding into fine-grained lake sediments and forming the arcuate scarps, the lake gravels to the south may inhibit the formation of such scarps. A lack of significant amounts of gravel on the surface of the feature downslope of the Beer Creek trench site seems to support the hypothesis that the scarp has experienced headward retreat through non-gravelly material that halted, or at least slowed considerably, upon encountering the gravel deposit.

Because of its indistinct surface expression, we are uncertain that the main scarp in the southeastern part of the feature is actually a landslide scarp. It could be a degraded lacustrine shoreline, but further study would be required to confirm this. We identified no hummocks on the feature, and the depressions, which appear to be present both on and off the feature, may be the result of a fluctuating, shallow water table and/or spring discharge rather than landsliding.

Hazard Potential

The Beer Creek feature is located in an area that is currently rural, but the cities of Spanish Fork, Salem, and Payson are near its periphery. Because of shallow ground water and sandy sediments, the feature is in an area of high liquefaction potential (Anderson and others, 1986a). Although we are uncertain that the feature is a landslide, liquefaction could occur in this area during future earthquakes. Ground slope in the vicinity of the Beer Creek feature is between 0.1 and 5 percent. Therefore, the most likely failure mode is by lateral spreading on the body of the feature, and flow failure along the main scarp in the northeastern part of the feature.

SUMMARY AND CONCLUSIONS

Study results are summarized in table 2. Based on geomorphic expression and documented presence of liquefaction features, we are confident that the North Ogden, East Ogden, West Kaysville, Farmington Siding, and North Salt Lake landslides are liquefaction-induced landslides. As noted earlier, we do not believe the Box Elder County landslides were liquefaction-induced, although geomorphic evidence indicates that they were initiated by earthquake ground shaking when Lake Bonneville was at about 1,353 meters (1,440 ft) elevation and adjacent to the initiation points of the landslides. We are less certain that the Springville/Spanish Fork and Beer Creek features are liquefaction-induced landslides (table 2). We did not find conclusive evidence for liquefaction, but a liquefaction-induced origin cannot be discounted. The presence of certain geomorphic features such as distinct scarps, and the features' presence in areas of high liquefaction potential leave open the possibility that these features could be liquefaction-induced flow failures.

With the exception of the Box Elder County landslides, only the North Ogden, East Ogden, and Farmington Siding landslides contain an appreciable number of hummocks (table 2). The degree of preservation of these hummocks can in part be related to the relative age of movement on the landslides. Having the most youthful geomorphic features, the northern part of the Farmington Siding landslide complex has moved more recently than all the other features we investigated (~ 2,730 cal yr B.P., table 2). Also showing relatively youthful hummocks, scarps, and internal flow lines, the North Ogden landslide complex is the only other landslide we investigated that shows clear evidence of later Holocene movement (≤ ~ 3,390 cal yr B.P., table 2).

Although the East Ogden landslide contains hummocks, this feature does not show evidence of Holocene movement. Preservation of these features is probably due to its location higher up in the bench area of the valley. The landslides located in the flatter valley areas are nearer Great Salt Lake and stream channels, which over time obscure geomorphic features through both erosional and depositional processes. This may account for the lack of many hummocks or other geomorphic features on the West Kaysville landslide, which shows evidence of movement in Holocene time; its proximity to fluctuating water bodies and shallow ground water may enhance the rate by which such features erode, relative to those in areas that are above these water sources. Virtually all of the landslides we looked at showing no youthful geomorphic features show evidence of movement in the latest Pleistocene rather than the Holocene (table 2).

The North Ogden, West Kaysville, Farmington Siding, and North Salt Lake landslides are in areas of shallow ground water and liquefiable sediments and may experience recurrent movement in future earthquakes. Because ground water is deep in the East Ogden area, the potential for recurrent liquefaction-induced landsliding on this landslide is low. The Springville/Spanish Fork and Beer Creek features are both at least partly in areas of shallow ground water and high liquefaction potential. These features should be considered as potential hazards until further detailed studies to evaluate the hazard potential are completed.

Both of the two features we rate with a possible chance of being liquefaction-induced landslides (table 2) appear to have moved at least in part by flow failure, leaving behind distinct and generally high main scarps. It is these scarps that likely prompted previous researchers to identify the features as possible liquefaction-induced landslides. Because of the distinct scarps, paleo-flow failures are more easily identified than paleo-lateral spreads that rarely have a high, distinct scarp. Therefore, more lateral spreads may exist along the Wasatch Front than have yet been identified. These lateral spreads may be identifiable only through subsurface investigation.

RECOMMENDATIONS FOR FURTHER WORK

The work undertaken during this study allowed for brief examination of many features. More detailed investigation of individual features and landslides is the next step to gain a better understanding of their failure history and hazard potential. For those whose genesis is uncertain, additional subsurface investigation is needed to identify possible rupture surfaces, liquefied or disturbed sediment, or contacts between undisturbed land and landslide deposits. Subsurface investigations may help define lateral margins of the features, most of which are obscure at best. Datable material will likely be difficult to find in excavations on many of these features. Those close to Great Salt Lake (West Kaysville, North Salt Lake) and those where trenches revealed only mostly undisturbed Lake Bonneville sediments (Springville/Spanish Fork, Beer Creek) hold the least potential for yielding material suitable for radiocarbon dating.

Further study of the Farmington Siding landslide by Hylland and Lowe (1998) has refined both the timing history of that landslide, and the failure environment, which gives us a better understanding of the hazard potential of that landslide complex. Our knowledge of the East Ogden and North Ogden landslides would also benefit from similar additional investigation, particularly of the latter landslide complex, which is one that should receive high priority for follow-up investigation. It covers a large area in a rapidly growing part of the Wasatch Front, where buildable land is still relatively plentiful. Based on ground-water levels, subsurface soil type, and the presence of springs at the base of flow-failure scarps, this area may still be under threat from liquefaction-induced landsliding during regional earthquakes. To better determine the hazard potential, further work on this landslide complex could focus on: (1) confirming modes of failure on different parts of the complex; (2) refining the landslide's boundaries and those of smaller, internal landslides; and (3) obtaining more absolute age estimates to refine the timing of recurrent movement on different parts of the landslide. This work could also help to refine the relationship among known local earthquakes, movements on the nearby Farmington Siding landslide complex, and movements on the North Ogden landslide; we suspect that these two landslide complexes may have experienced simultaneous movement during earthquakes on the Weber segment of the Wasatch fault, but additional work is needed to confirm this. These tasks could be accomplished by placing more trenches on the various smaller landslides that make up the North Ogden landslide com-

Table 2. *Summary of results.*

Landslide/Feature	Is it a liquefaction-induced landslide?	Failure modes likely involved	Geomorphic features present			Estimated time of formation, latest movement, or latest liquefaction event		Relative potential for future liquefaction-induced landsliding	
			Scarps	Hum-mocks	Depres-sion				
Box Elder County landslides (six)	no	Not applicable	X	X		12,000-13,000 yr B.P.		low	
North Ogden landslide complex	yes	Flow failure, lateral spread, ground oscillation	X	X	X	≤~3,390 cal yr B.P.		high	
East Ogden landslide	yes	Flow failure, lateral spread	X	X		<13,000-13,500 yr B.P.		low	
West Kaysville landslide	yes	Lateral spread	X	X	X	<10,000 yr B.P.		high	
Farmington Siding landslide complex	yes	Flow failure, lateral spread	X	X	X	northern: ~2,730 cal yr B.P.	southern: <14,500, >10,000 yr B.P.	northern: high	southern: moderate
North Salt Lake landslide	yes	Flow failure, lateral spread	X		X	>10,000 yr B.P.		moderate - high	
Springville/Spanish Fork feature	possibly	Flow failure, ground oscillation	X		X	>13,000 yr B.P.		high	
Beer Creek feature	possibly	Flow failure	X		X	<14,500 yr B.P.		high	

plex, and by employing a systematic, shallow drilling program geared toward identifying the nature, extent, and source of individual flow failures and liquefied layers.

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APPENDIX A

DESCRIPTIONS OF GEOLOGIC MAP UNITS AND SYMBOLS

Geologic Map Units

Younger Holocene (less than 10,000 years old and younger than older Holocene units of the same type on the map).

Qal_1 Stream alluvium. Moderately sorted, clast-supported gravel and cobbles, gravelly sand, and silty sand deposited in channels and on flood plains. Generally, fluvial processes are periodically active.

Qaf_1 Alluvial-fan deposits. Moderately to poorly sorted, clast- and matrix-supported gravel and cobbles (but locally boulders), sand, and silt deposited by streams and debris flows in active alluvial fans.

Qf_1 Artificial fill.

Qlf_1 Fine-grained lacustrine deposits. Mainly interbedded silt, clay, and fine sand, possibly containing salt, deposited in Great Salt Lake.

Qms_1 Landslide deposits. Masses of rock and/or soil that moved due to gravity as rotational or translational slides; includes complex landslides.

Qml_1 Lateral-spread landslide deposits. Masses of soil that moved during earthquakes by liquefaction-induced lateral spreading.

Qmf_1 Debris-flow deposits. Clast- and matrix-supported boulders, cobbles, and gravel. Matrix is predominantly sand and silt with lesser amounts of clay. Deposits may form debris-flow levees.

Qsm_1 Marsh deposits associated with springs. Predominantly organic silt, clay, and fine sand, but may contain peat deposits.

Older Holocene (less than 10,000 years old and older than younger Holocene units of the same type on the map).

Qal_2 Stream alluvium. Moderately sorted, clast-supported cobbles, gravel, gravelly sand, and silty sand deposited in channels and on flood plains. Generally, fluvial processes are no longer active.

Qat_2 Stream-terrace alluvium. Moderately sorted, clast-supported cobble, gravel, and gravelly sand deposits graded to base levels below the Gilbert shoreline, but above modern flood-plain levels.

Qaf_2 Alluvial-fan deposits. Moderately to poorly sorted, clast- and matrix-supported gravel (including cobbles and locally boulders), sand, and silt deposited by streams and debris flows in alluvial fans that are generally no longer active.

Qlf_2 Fine-grained lacustrine deposits. Mainly interbedded clay, silt, and fine sand, possibly containing salt, deposited in Great Salt Lake.

Qms_2 Landslide deposits. Masses of rock and/or soil that moved due to gravity as rotational or translational slides; includes complex landslides.

Qml_2 Lateral-spread landslide deposits. Masses of soil that moved during earthquakes by liquefaction-induced lateral spreading.

Qmq_2 Liquefaction-induced landslide deposits. Masses of soil forming complex landslides that moved during earthquakes, probably as both flow failures and lateral spreads.

Qsm_2 Marsh deposits associated with springs. Predominantly organic silt, clay, and fine sand, but may contain peat deposits.

Lake Bonneville Regressive Phase to early Great Salt Lake (between about 14,500 and 10,000 yr B.P.).

Qal_3 Stream alluvium. Moderately sorted, clast-supported cobbles, gravel, and gravely sand deposited in channels and on flood plains. Fluvial processes are no longer active.

Qat_3 Stream-terrace alluvium. Moderately sorted, clast-supported cobble, gravel, and gravelly sand deposits graded to base levels above or at the Gilbert shoreline.

Qaf_3 Alluvial-fan deposits. Moderately to poorly sorted, clast- and matrix-supported gravel and cobbles (but locally boulders), sand, and silt deposited by streams and debris flows in alluvial fans that are no longer active.

Qd_3 Deltaic deposits. Mainly clast-supported cobbles and gravel underlain by interbedded sand, silty sand, and gravelly sand deposited by streams into Lake Bonneville at or below the Provo shoreline. Includes sand, silt, and clay bottomset beds.

Qlg_3 Lacustrine gravel. Mainly interbedded gravel, gravelly sand, and sand deposited in high-energy lacustrine environments, generally beach and nearshore.

Qls_3 Lacustrine sand. Mainly interbedded sand, silty sand, and gravelly sand deposited in moderate-energy lacustrine environments, generally nearshore.

Qlf_3 Fine-grained lacustrine deposits. Mainly interbedded silt, clay, and fine sand deposited in low-energy lacustrine environments, generally offshore and commonly deep-lake.

Qms_3 Landslide deposits. Masses of rock and/or soil that moved due to gravity as rotational or translational slides; includes complex landslides.

Qmq_3 Liquefaction-induced landslide deposits. Masses of soil forming complex landslides that moved during earthquakes, probably as both flow failures and lateral spreads.

Lake Bonneville Transgressive Phase (between about 28,000 and 14,500 yr B.P.).

Qaf_4 Alluvial-fan deposits. Moderately to poorly sorted, clast- and matrix-supported gravel and cobbles (but locally boulders), sand, and silt deposited by streams and debris flows in alluvial fans that are no longer active.

Qd_4 Deltaic deposits. Mainly interbedded sand, silty sand, and gravelly sand deposited by streams into Lake Bonneville at the Bonneville shoreline. Includes sand, silt, and clay bottomset beds.

Qlg_4 Lacustrine gravel. Mainly interbedded gravel, gravelly sand, and sand deposited in high-energy lacustrine environments, generally beach and nearshore.

Qls_4 Lacustrine sand. Mainly interbedded sand, silty sand, and gravelly sand deposited in moderate-energy lacustrine environments, generally nearshore. These deposits commonly form bars and spits.

Qlf_4 Fine-grained lacustrine deposits. Mainly interbedded clay, silt, and fine sand deposited in low-energy lacustrine environments, generally offshore. These sediments may form bottomset beds in deltas.

Qms_4 Landslide deposits. Masses of rock and/or soil that moved due to gravity as rotational or translational slides; includes complex landslides.

Qmq_4 Liquefaction-induced landslide deposits. Masses of soil forming complex landslides that moved during earthquakes, probably as both flow failures and lateral spreads.

Units Undivided By Age (Holocene and latest Pleistocene).

Qac Alluvium and colluvium, undivided. Alluvium having a large colluvial component. Boulders, cobbles, gravel, sand, and silt deposited on hillslopes or in low-order ephemeral stream channels.

Qmc Colluvium. Boulders, cobbles, gravel, sand, silt, and clay deposited predominantly by processes associated with rock fall, slope wash, and creep; includes minor talus deposits.

Qmt Talus. Boulder and cobble accumulations on steep slopes or at the base of slopes or cliffs.

Pre-Lake Bonneville (older than about 28,000 years).

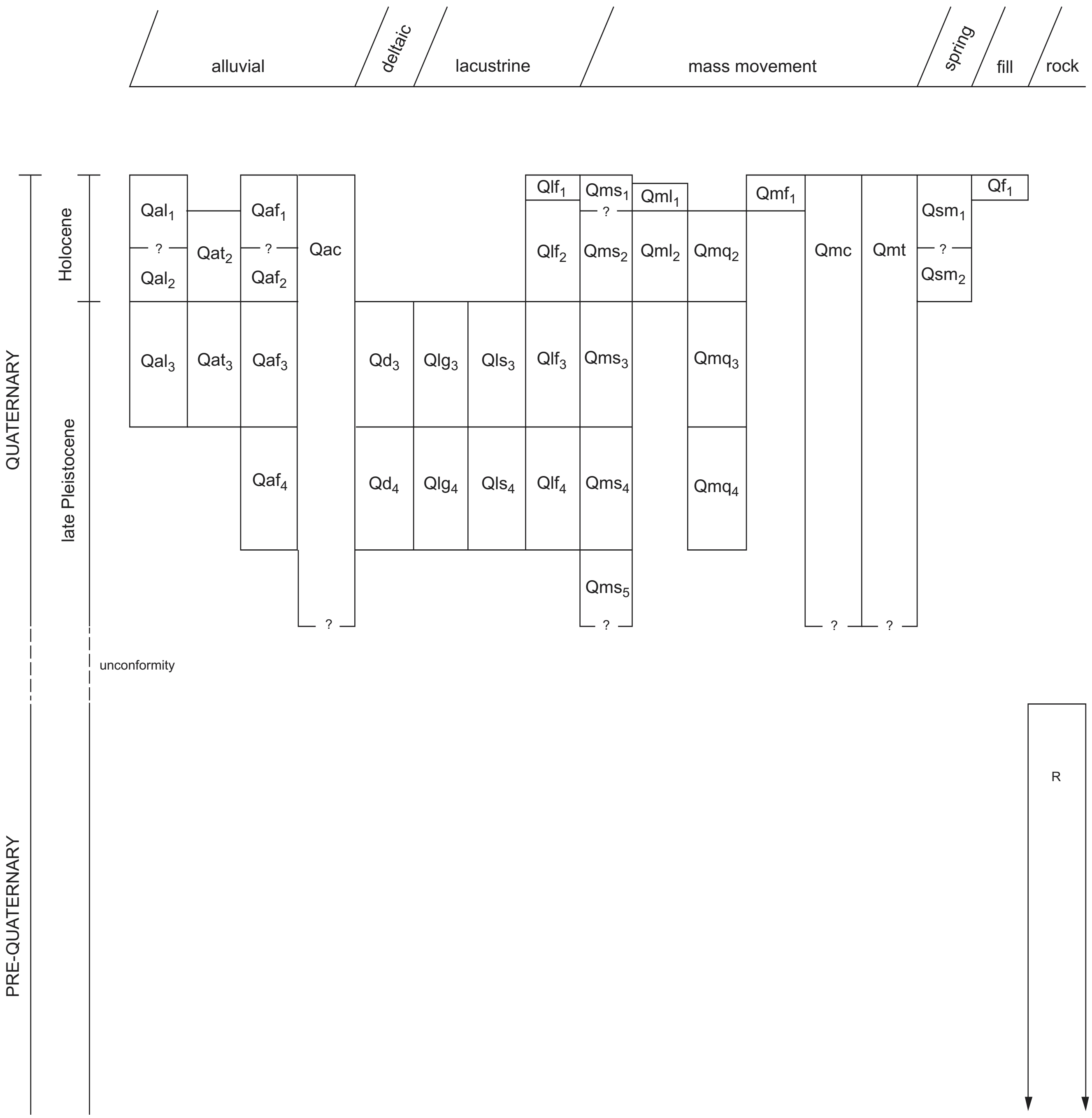
Qms_5 Landslide deposits. Masses of rock and/or soil that moved due to gravity as rotational or translational slides; includes complex landslides.

R Bedrock.

MAP SYMBOLS

	Contact - dashed where aproximately located, dotted where concealed. Includes boundaries between individual landslides.
	Lineament - linear feature of uncertain origin
	Hummock or hill
	Depression
	Zone of closely spaced hummocks and depressions
	Trench site
A * B *	Land-drain excavation site (plate 9)
Qx/Qy	Thin unit x over unit y
Qml_2?	Query indicates origin of unit uncertain
Escarpments	(hachures point downscarp)
	Normal fault - dashed where location inferred, dotted where concealed; bar and ball on downthrown side.
	Landslide scarp - dashed where approximately located
	Fluvial escarpment - dashed where approximately located
	Escarpment of uncertain origin
Shorelines	(mapped at base of scarp)
B B	Bonneville shoreline of Bonneville lake cycle
y y	Other transgressive shorelines of Bonneville lake cycle
P P	Provo shoreline of Bonneville lake cycle
G G	Gilbert shoreline of Bonneville lake cycle
x x	Other regressive shorelines of Bonneville lake cycle and Great Salt Lake

CORRELATION OF MAP UNITS



APPENDIX B

TRENCH AND EXCAVATION GEOLOGIC UNIT DESCRIPTIONS

NORTH OGDEN LANDSLIDE COMPLEX

Harrisville Trench

Unit 1 Lacustrine; lean clay (CL); 10 YR 6/6 - brownish yellow; dry; unstratified; roots; mottled; well-developed iron staining, concentrated toward top; disseminated nodules of $CaCO_3$ in top 0.18 m of unit, effervesces vigorously with HCl; no $CaCO_3$ visible in lower unit, effervesces moderately; well-developed blocky structure; contains blocks of unit S1.

Unit 2 Flow failure; lean clay (CL); 7.5 YR 7/2 - pinkish gray; dry; unstratified; roots; disseminated iron staining; disseminated $CaCO_3$; effervesces vigorously; weak blocky structure; contains subangular to rounded gravel (average dimension 1-2 cm) and few cobbles (largest 10 cm); unit contains sand-filled fractures (sand injections).

Unit 3 Loess; Logged at station 20: silty clay/clayey silt (CL/ML); 10 YR 7/3 - very pale brown; dry; unstratified; roots; disseminated $CaCO_3$ within lower 7.5 cm of unit, effervesces vigorously; blocky structure within lower 12 cm of unit. At station 15.5: silt with clay (ML); 10 YR 6/4 - light yellowish brown; unstratified, effervesces moderately. At station 6: silty clay (CL); 10 YR 6/4 - light yellowish brown; dry; unstratified; incorporated into unit 5. At station 2.5: clayey silt/silty clay (CL/ML); 10 YR 6/4 - light yellowish brown; dry; unstratified; forms a small lens (eroded remnant) on unit S1.

Unit 4 Fluvial or eolian; well-graded sand with clay, and clayey sand (SW and SC); color varies from 10 YR 4/3 - dark brown to 10 YR 4/4 - dark yellowish brown; moist; locally interfingered, mixed with, and intruded into unit 5 above; locally stratified, bedding highly deformed where intruded into unit 5 between stations 13 and 14; localized iron staining; no visible $CaCO_3$ but effervesces moderately; structureless; contains a soil block and grussified gravel (station 12-12.5); contains a thin (1 cm thick), darkened horizon associated with a clay band - possibly a manganese stain where the clay layer created an impermeable boundary in the sand.

Unit 5 Flow failure; clay (CL/CH); 10 YR 7/4 - very pale brown; dry; unstratified; roots; disseminated iron staining; disseminated $CaCO_3$ more concentrated at top of unit, effervesces vigorously, lower portion effervesces moderately; contains localized areas of disseminated manganese staining(?); locally weakly stratified; weak blocky structure; contains matrix-supported subangular to rounded gravel (average dimensions 1-2 cm, mostly quartzite, limestone, and schist), and sparse cobbles (largest 10 cm, quartzite, limestone, and schist); numerous sand-filled fractures (sand injections); isolated blocks of soil; contorted blocks of sediment, some of which are stratified; grades laterally (north) to a silty clay (CL), 10 YR 6/4 - light yellowish brown, with less gravel.

Unit 5a Stratified blocks in unit 5, lacustrine(?); lean clay (CL) with laminations of fine sand with silt (SM); clay is 10 YR 4/6 - dark yellowish brown; sand is 10 YR 6/3 - pale brown; bedding deformed; most beds in block at station 14 dip 51 degrees; sand laminations in block at station 14 coarsen upward and toward the south (station 13); beds in block at station 15 dip 90 degrees; sparse rounded gravel with a concentration of gravel clasts near the center of the block at station 14.

Unit 5b Stratified block in unit 5, lacustrine(?); lean clay (CL) interbedded with silty sand (SM); sand and clay beds up to 2 cm thick; clay beds are 10 YR 4/6 - dark yellowish brown and 10 YR 4/3 - brown to dark brown; sand beds are 10 YR 6/3 - pale brown; bedding highly deformed; sparse rounded gravel.

Unit 5c Block of channel fill in unit 5, alluvium; mixture of material ranging from fine sand to cobbles (largest 13 cm); lens of stratified fine gravel (average diameter 0.5-1.0 cm, largest 1.5 cm); gravel matrix is clay, probably a secondary accumulation; matrix color is 10 YR 6/4 - light yellowish brown; lower portion of channel contains fluvial sand injected with fine sand, color ranges from 10 YR 6/4 - light yellowish brown to 10 YR 6/1 - light gray to gray.

Unit 5d Colluvium; mixed with soil A horizon; (soil block); lean clay (CL); 10 YR 4/3 - brown to dark brown; dry; unstratified, roots; contains gravel; no visible $CaCO_3$, effervesces moderately; blocky structure.

Unit 6 Sand injections into units 2 and 5; poorly graded fine sand (SP); 2.5 YR 6/2 - light brownish gray; unstratified; locally contains small blocks (< 1 cm) of unit 5.

Unit S1 Soil, A horizon on unit 1: lean clay (CL); 10 YR 2/1 - black at top lightens with depth to 10 YR 4/2 - dark grayish brown; dry; unstratified; roots; disseminated iron staining in fractures; disseminated $CaCO_3$ throughout, concentration greatest at base, top effervesces moderately, base effervesces vigorously; blocky structure; one 2.5-cm rounded gravel clast found in unit.
Soil, A horizon on unit 2: lean clay (CL); 10 YR 4/2 - dark grayish brown; dry; unstratified; roots; no visible $CaCO_3$; effervesces moderately; contains subangular to rounded pebbles; well-developed structure.
Soil, A horizon in unit 5: silty clay (CL); 10 YR 4/1 - dark gray.

Unit S2 Soil, modern A horizon on unit 5; lean/fat clay (CL/CH); 10 YR 4/4 - dark yellowish brown; moist; unstratified; roots; contains gravel.

FARMINGTON SIDING LANDSLIDE COMPLEX

North Farmington Junction East Trench (NFJET)

Unit 1 Landslide deposits derived from lacustrine sediment; silty, very fine sand (SM); 10 YR 7/3 - very pale brown; dry; loose; unstratified; well sorted; numerous burrows; $CaCO_3$ at top of unit; effervesces vigorously.

Unit 2 Landslide deposits derived from lacustrine sediment; silty clay/clayey silt with sand (CL/ML); 10 YR 6/3 - pale brown; moist; unstratified; mottled; contains some fine (0.5 cm) well-rounded gravel; effervesces weakly.

Unit 3/S1 Landslide deposits derived from lacustrine sediment 3/S1 mixed with soil A horizon; at station 2.5: silty clayey fine sand (SC/SM); 10 YR 4/4 - dark yellowish brown; moist; unstratified; contains soil blocks, numerous burrows; some mottles; effervesces moderately; grades laterally northward into unit S1; at station 6.5: sandy clay (CL); 10 YR 3/2 - very dark grayish brown; moist; unstratified; some mottles; effervesces moderately.

Unit 4 Colluvium; clayey silty very fine sand (SM/SC); 10 YR 6/4 - light yellowish brown; moist; unstratified; contains numerous burrows; effervesces vigorously.

Unit 5 Alluvial-fan deposit; gravelly sandy clay (SC); 10 YR 4/3 - brown to dark brown; moist; poorly stratified; matrix-supported; largest rock clast 6 x 4 x 2.5 cm; gravel clasts subangular to subrounded; matrix effervesces weakly.

Unit S2 Soil A horizon; sandy clay with gravel (CL); 10 YR 2/2 - very dark brown; moist; unstratified; tilled toward northern end of trench; gravel clasts subangular to subrounded, up to 2 cm diameter; effervesces vigorously.

North Farmington Junction West Trench (NFJWT)

Unit 1 Landslide deposits derived from lacustrine sediment; fine sand with clay (SP); 10 YR 8/3 - very pale brown; dry; unstratified; poorly graded; effervesces vigorously; numerous burrows.

Unit 2a Landslide deposits derived from lacustrine sediment; fine sand (SP); 2.5 YR 6/4 - light yellowish brown; moist; unstratified; poorly graded; contains abundant ironstone concretions in lower portion; contains soil blocks, burrows, round lenses of light and dark sand; no effervescence, but top 25 cm of unit near southern end of trench contains disseminated $CaCO_3$.

Unit 2b/S1 Landslide deposits derived from lacustrine sediment; 2b/S1 fine sand (SP); same as unit 2a - grades upward into unit S1. Color grades laterally from 2.5 YR 6/4 (light yellowish brown) at stations 5-6 to 10 YR 3/3 (dark brown) at station 8, to 10 YR 2/2 (very dark brown) at station 10; moist; unstratified, poorly graded; contains soil blocks; some mottles; effervesces weakly.

Unit 3 Colluvium; fine sand with clay (SP); 10 YR 6/4 - light yellowish brown; moist; unstratified; effervesces vigorously.

Unit S2 Soil A horizon; sandy clay (CL); 10 YR 2/2 - very dark brown; moist; unstratified; contains rounded gravel up to 2 cm diameter; effervesces vigorously.

NORTH SALT LAKE LANDSLIDES

Land Drain Excavation, Log A

Unit 1 Lacustrine; sandy clay (CL); gray; massive; wet; abundant muscovite flakes; iron staining; gray mottles (gley).

Unit 2 Lacustrine; clay with fine sand and silt (CL); gray; massive; moist to wet; disseminated $CaCO_3$.

Unit 3 Lacustrine; clay with fine sand and silt (CL); tan/pale brown; massive; dry to moist; iron staining; abundant $CaCO_3$ nodules up to 5 cm; numerous $CaCO_3$ filaments in matrix.

Unit 4 Fill; clay with fine sand and silt (CL); light gray; massive, hard; dry.

Unit 5 Fill (imported topsoil); dark brown.

Land Drain Excavation, Log B

Unit 1 Lacustrine; clay with fine sand and silt (CL); tan/pale brown; massive; dry to wet; iron staining; gley.

Unit 2 Lacustrine; lean clay (CL); very light gray; massive; dry; indurated; heavily impregnated with $CaCO_3$ nodules.

Unit 3 Fill; clay with fine silt and sand (CL); light gray; massive; hard; may be derived primarily from unit 2.

Unit 4 Fill (imported topsoil); dark brown.

SPRINGVILLE/SPANISH FORK FEATURE

Trench SP-1

Unit 1 Lacustrine; sandy clay (CL); 7.5 YR 6/4 - light brown; bedded (stratified); contains a thin continuous clay layer, 5 YR 5/4 - reddish brown; discontinuous laminae of very fine sand, 2.5 Y 7/2 - light gray; lenses of very fine gray sand, 10 YR 6/2 - light brownish gray; stratigraphy shows horizontal bedding but individual laminae display minor undulations and minor offsets up to 2 cm.

Unit S1 Soil A horizon on unit 1; sandy clay (CL); 5 YR 4/4 - reddish brown; lower 10 cm of unit contains disseminated $CaCO_3$.

Trench SP-2

Unit 1 Lacustrine; silty clay (CL); 10 YR 6/4 - light yellowish brown; stratified; finely laminated; horizontal bedding; contains thin discontinuous clay layers (0.75 cm thick); disseminated iron staining; undisturbed.

Unit 2 Lacustrine; sandy clay (CL); 10 YR 6/4 - light yellowish brown; stratified; contains thin, continuous red clay layer; few rounded to subrounded gravel clasts, average diameter 1 cm, largest 3 cm; localized $CaCO_3$ nodules; iron staining; undisturbed.

Unit 3 Lacustrine; clayey gravel with cobbles (GC); 10 YR 5/4 - yellowish brown; poorly graded; unstratified; average gravel size 4 cm; largest cobble 10 cm; subrounded to rounded; matrix contains disseminated $CaCO_3$; matrix may be by illuviation from overlying unit.

Unit 4 Lacustrine; clayey silt/silty clay (ML/CL); 10 YR 4/4 -dark yellowish brown; unstratified; contains some gravel possibly tilled up from underlying unit; average gravel size 5 cm; disseminated $CaCO_3$.

Unit S1 Soil A horizon on unit 4; silty clay (CL); 10 YR 4/2 - dark grayish brown; unstratified; contains some subrounded to rounded gravel at base of lower contact, possibly tilled up from below.

Trench SP-3

Unit 1 Lacustrine; lean clay with silt (CL); 10 YR 7/3 - very pale brown; weakly stratified except where marker beds are visible; contains some gravel, well-rounded, average size 1 cm, largest 3 cm; disseminated iron staining throughout unit; northern end of trench (from station 0 to 2.5) contains a zone (maximum width 40 cm) of disseminated nodules of $CaCO_3$ at top of unit that extends into basal area of unit S1; effervesces vigorously; contains continuous and discontinuous thin clay layers (widths between 2-4 mm), 5 YR 6/6 - reddish yellow; continuous clay layers are faulted and tilted.

Unit S1 Soil A horizon on unit 1; lean clay with silt (CL); 10 YR 3/3 - dark brown; contains few well-rounded gravel clasts, average size 1 cm, largest 3 cm; nodules of disseminated $CaCO_3$ at base of unit at northern end of trench; well-developed soil structure; effervesces vigorously.

BEER CREEK FEATURE

Beer Creek Trench

Unit 1 Lacustrine; clayey silty sand (SC/SM); 10 YR 5/6 - yellowish brown; dry to moist; bedded, mostly fine sand with clay laminae (CL); well stratified; poorly graded; contains few well-rounded gravel clasts of 3-cm average size, 5-cm largest size; effervesces vigorously; clay layers are of two colors, 10 YR 6/4 - light yellowish brown and 5 YR 5/8 - yellowish red; clay layers are both continuous and discontinuous, average 1 cm thick (thickest is 2 cm), and are back-tilted and faulted.

Unit 2 Lacustrine; silty clay with fine sand (CL); 10 YR 5/6 -yellowish brown; moist; bedded, mostly silty clay with clay laminae (CL); stratified; contains few rounded gravel clasts, 1-cm average size, 2-cm largest size; effervesces vigorously; some clay beds are 5 YR 6/4 - light reddish brown; clay layers are both continuous and discontinuous; thickest clay bed is 2 cm; faulted and tilted; may be a fining-upward sequence of unit 1.

Unit 3 Lacustrine; well-graded sand (SW); grades from 2.5 Y 5/4 - light olive brown at base to 2.5 Y 6/4 - light yellowish brown at top; stratified; fines upward from mostly medium to mostly fine sand; effervesces moderately; contains a few isolated areas of iron staining; back-tilted with dips of 39 degrees to the east.

Unit 4a Lacustrine; gravel with silt and sand, series of poorly graded (gap-graded) gravel and cobble layers (GP); stratified; clast supported; matrix is 10 YR 6/4 - light yellowish brown; gravel and cobbles are well rounded; imbricated; average size 4 cm, largest size 12 cm; effervesces vigorously; $CaCO_3$ rinds on bottom of many cobbles; beds back-tilted and increase in dip from west to east 34 to 46 degrees.

Unit 4b Lacustrine; gravel with silt and sand, series of poorly graded (gap-graded) gravel layers (GP); stratified; clast supported; matrix is 10 YR 6/4 - light yellowish brown; gravel is well rounded; imbricated; average size 1.5 cm; largest 7.5 cm; $CaCO_3$ rinds on bottom of many gravel clasts; effervesces vigorously; some beds are back-tilted with a greatest dip in trench 46 degrees; some beds tilt downslope with dips ranging from 8-16 degrees; unit lies conformably over unit 3, represents a fining-upward depositional sequence of unit 3.

Unit 5 Scarp-derived colluvium; gravelly sandy silt (ML); 10 YR 6/4 - light yellowish brown; unstratified; matrix supported; gravel is rounded to well rounded; largest gravel size is 6 cm; average gravel diameter is 3 cm; thin $CaCO_3$ rind on one side of one gravel clast; effervesces vigorously; may be derived from units 4a or 4b with matrix from unit 6 above.

Unit 6 Colluvium/slope wash; clayey silt/silty clay with gravel and cobbles (ML/CL); 10 YR 6/4 - light yellowish brown; unstratified; moist; gravel is rounded to well rounded, average size 5 cm; largest cobble is 9 cm; $CaCO_3$ on underside of gravel; few $CaCO_3$ nodules in matrix; effervesces vigorously; derived from units 2 and 4b.

Unit 7 Colluvium/slope wash; clayey silty gravel with sand (GC/GM); poorly stratified; matrix supported; 10 YR 5/4 - yellowish brown; well-graded throughout; clast size ranges from fine gravel to cobbles; effervesces vigorously; gravel and cobble content decreases slightly in downslope direction; derived from erosion of units 4a and 4b.

Unit S1 Soil A horizon on units 6 and 7; clayey silty gravel with sand (GC/GM); poorly stratified; matrix supported; 10 YR 5/2 - grayish brown; effervesces vigorously; $CaCO_3$ on bottom of some cobbles; well-graded throughout; clast size ranges from fine gravel to cobbles; gravel and cobble content decreases slightly in downslope direction.

SS-104
Plate 1

GEOLOGIC MAP OF THE NORTH OGDEN LANDSLIDE COMPLEX, WEBER COUNTY, UTAH

Mapped by Kimm M. Harty and Mike Lowe

1991 - 1992

See figure 2 in text for location of study area
See appendix A for descriptions of map units and symbols

Base map from Plain City and North Ogden USGS
7 1/2' topographic quadrangles

SKETCH OF SOUTH WALL OF LOMOND VIEW PARK TRENCH, NORTH OGDEN, UTAH

Mapped by Kimm M. Harty and Mike Lowe, 1991

Refer to plate 1 for trench location

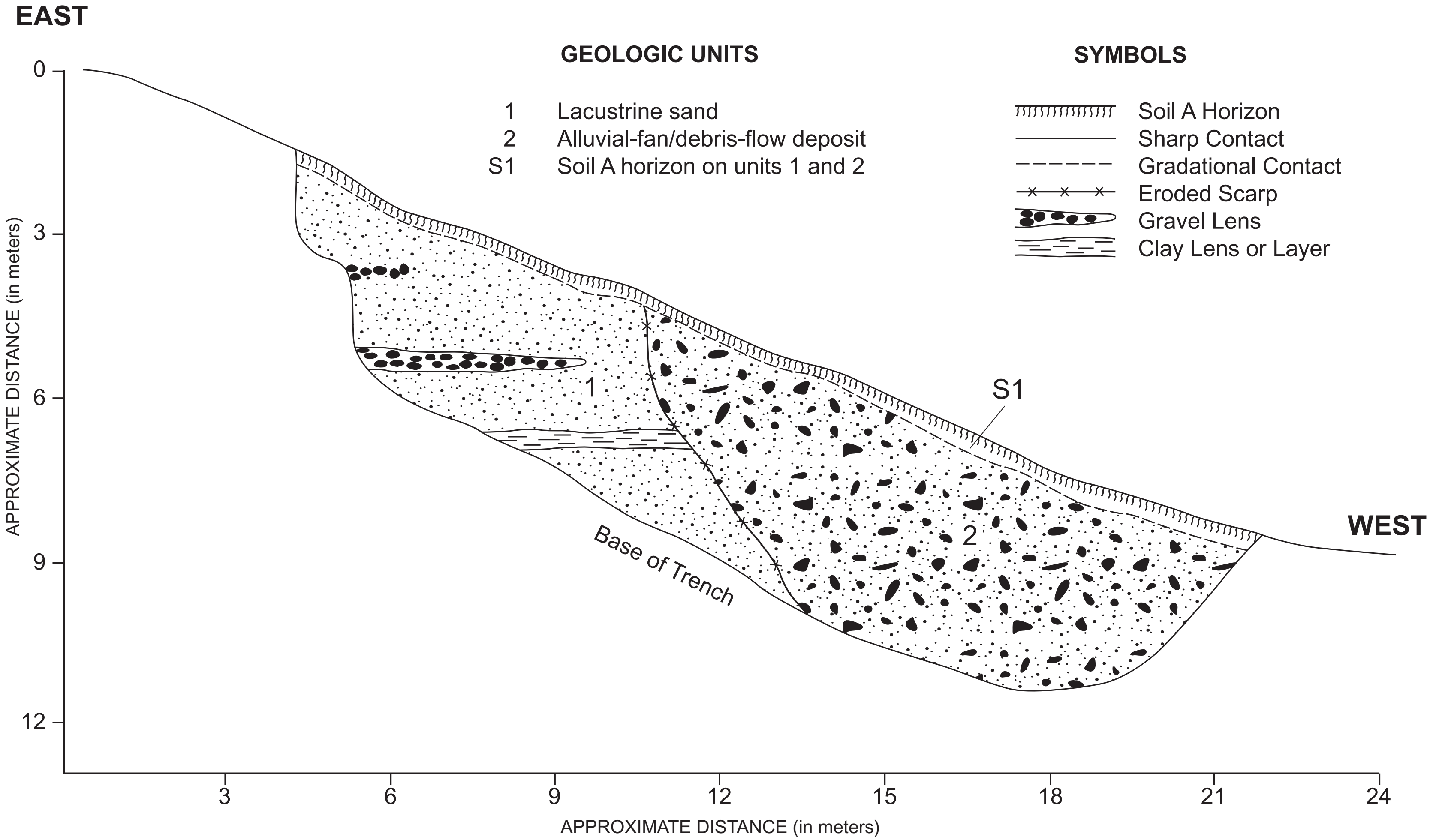


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Plate 3

WEST WALL OF HARRISVILLE TRENCH, NORTH OGDEN LANDSLIDE COMPLEX, WEBER COUNTY, UTAH

Mapped by Kimm M. Harty and Mike Lowe, 1991

Refer to plate 1 for trench location

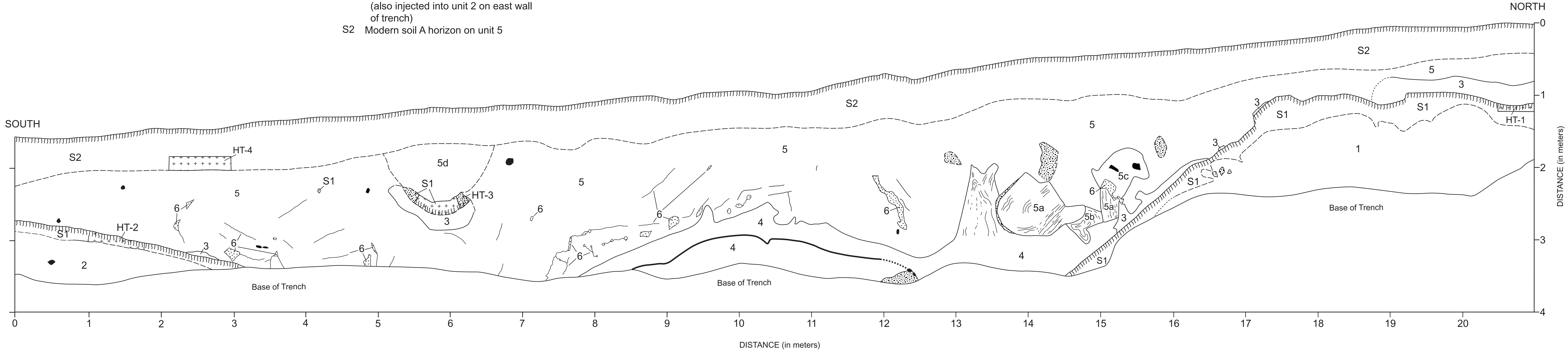
Planimetric base constructed on a 1 m X 1 m grid using horizontal level lines

GEOLOGIC UNITS
(See appendix B in text for complete unit descriptions)

1 Lacustrine clay (landslide block ?)
S1 Soil A horizon on units 1 and 2
2 Flow-failure deposit
3 Loess
4 Fluvial sand
5 Flow-failure deposit
  5a blocks in unit 5
  5b blocks in unit 5
  5c channel fill in unit 5
  5d block in unit 5
6 Sand injections into unit 5
  (also injected into unit 2 on east wall of trench)
S2 Modern soil A horizon on unit 5

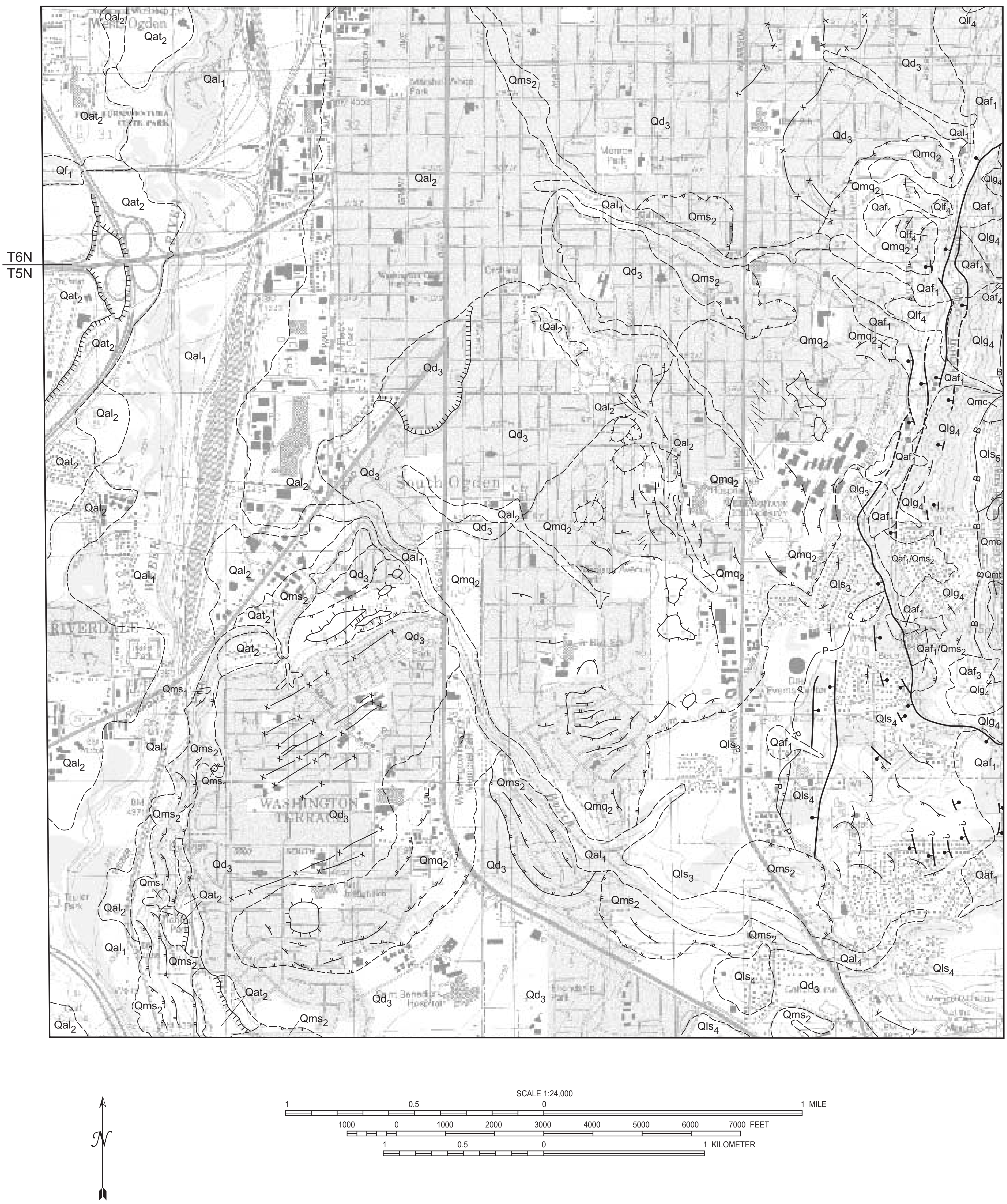
SYMBOLS

Soil A Horizon
Sharp Contact
Gradational Contact
Indistinct Contact
Soil Block
Isolated Cobble
Sand-Filled Fractures
Bedding (diagrammatic)
Zone of Manganese Oxide (?) Staining in Unit 4
AMRT Age Estimate from Standard ^{14}C Date on Bulk Soil Sample (Calendar Calibrated)
HT-1 8370 ±240 yr B.P.
HT-2 7550 ±170 yr B.P.
HT-3 7670 ±240 yr B.P.
HT-4 3390 ±230 yr B.P.



SS-104
Plate 4

R1W



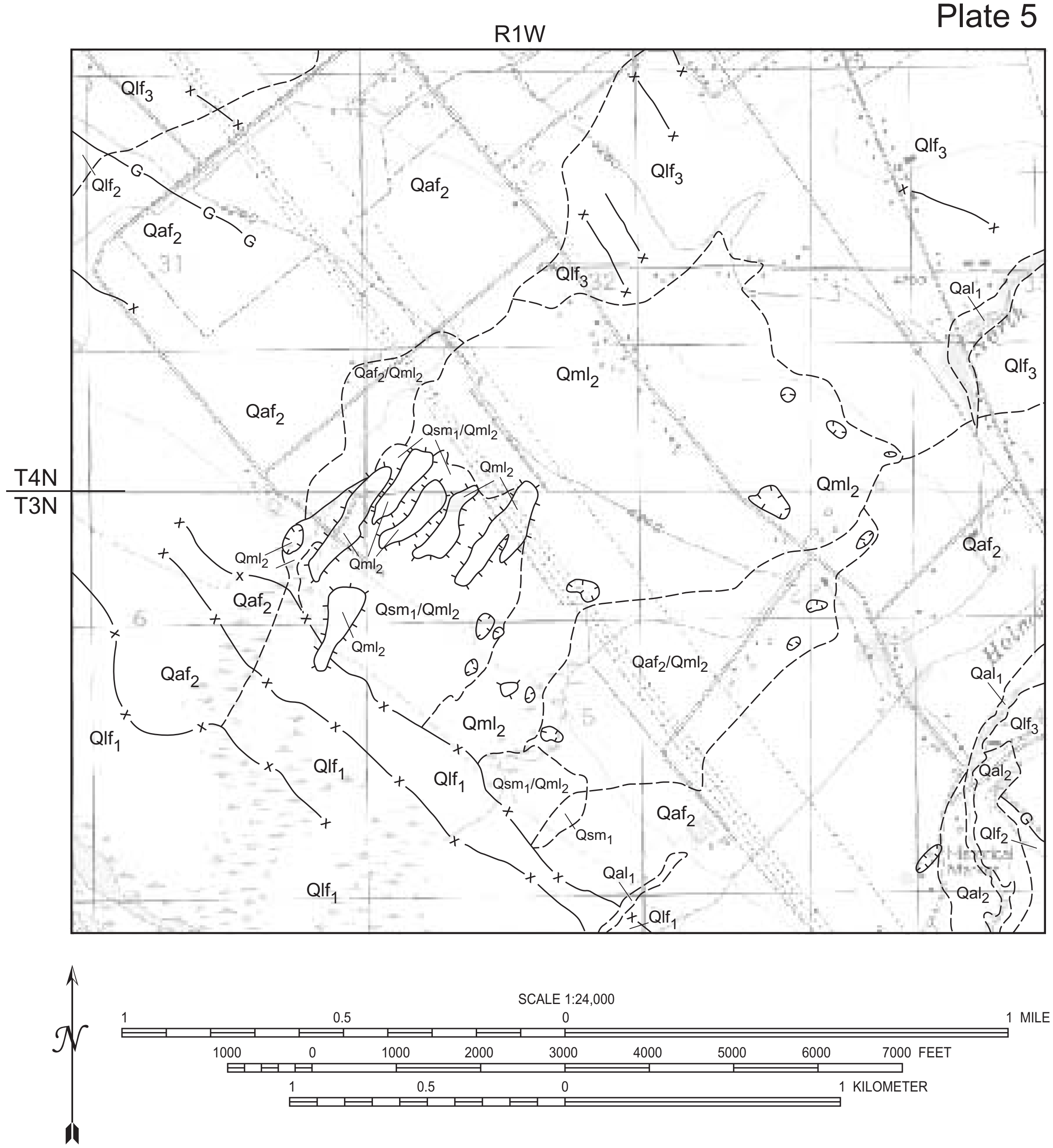
GEOLOGIC MAP OF THE EAST OGDEN LANDSLIDE, WEBER COUNTY, UTAH

Mapped by Mike Lowe and Kimm M. Harty

1992

See figure 2 in text for location of study area
See appendix A for descriptions of map units and symbols

Base map from Ogden USGS
7 1/2' topographic quadrangle



GEOLOGIC MAP OF THE WEST KAYSVILLE LANDSLIDE, DAVIS COUNTY, UTAH

Mapped by Mike Lowe and Kimm M. Harty
1992

See figure 2 in text for location of study area
See appendix A for descriptions of map units and symbols

Base map from Kaysville USGS
7 1/2' topographic quadrangle

GEOLOGIC MAP OF THE FARMINGTON SIDING LANDSLIDE COMPLEX, DAVIS COUNTY, UTAH

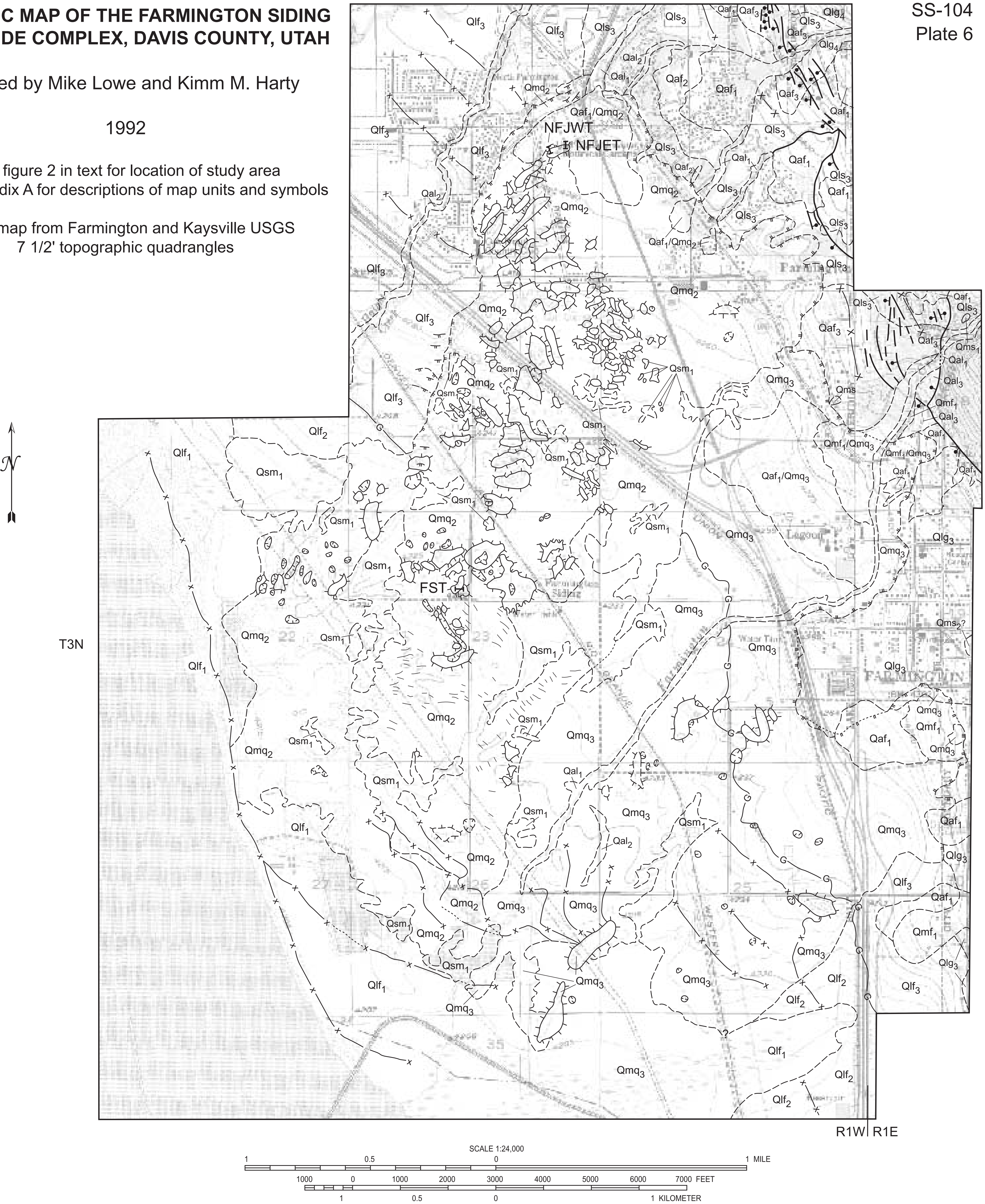
SS-104
Plate 6

Mapped by Mike Lowe and Kimm M. Harty

1992

See figure 2 in text for location of study area
See appendix A for descriptions of map units and symbols

Base map from Farmington and Kaysville USGS
7 1/2' topographic quadrangles



SS-104
Plate 7

WEST WALL OF THE NORTH FARMINGTON JUNCTION EAST TRENCH (NFJET), FARMINGTON, UTAH

Mapped by Kimm M. Harty and Mike Lowe, 1992

Refer to plate 6 for trench location

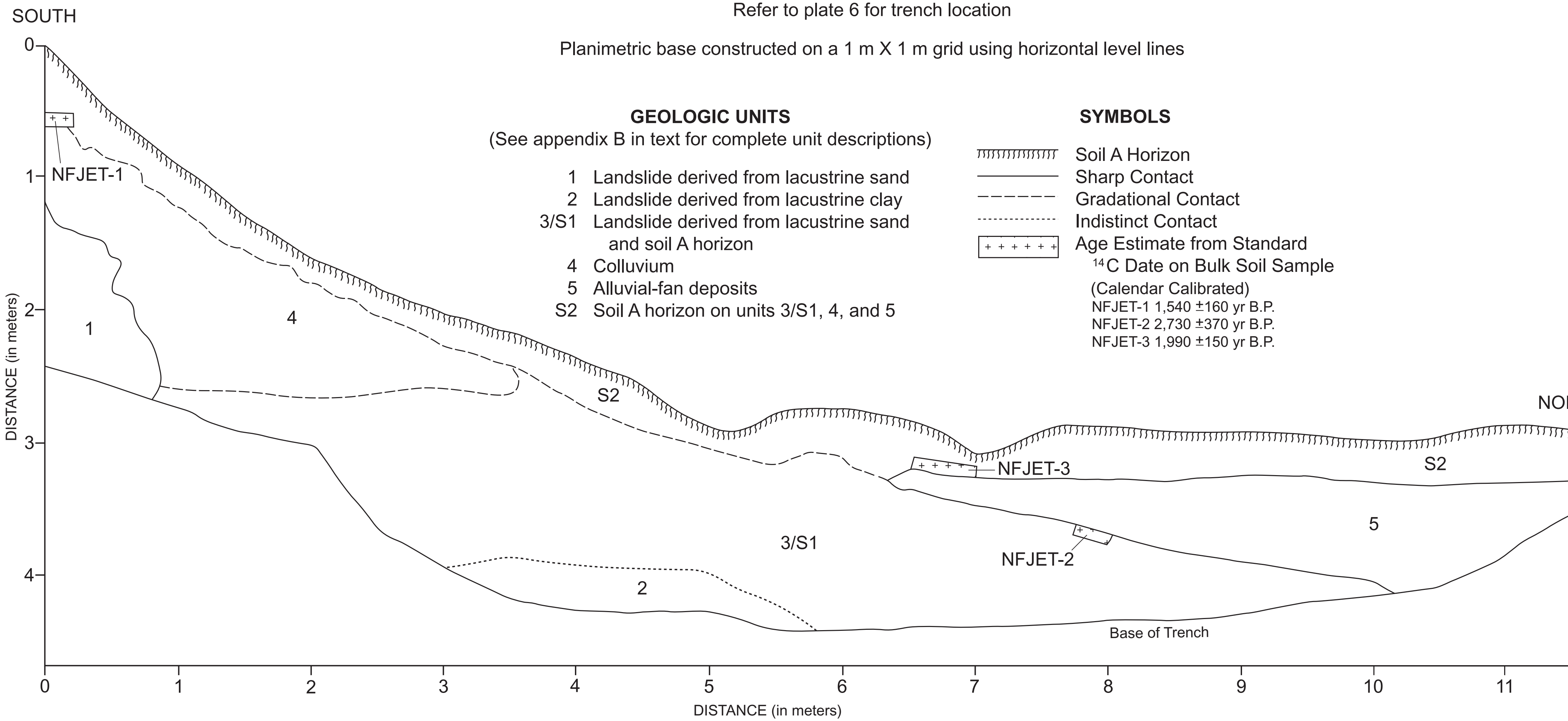
Planimetric base constructed on a 1 m X 1 m grid using horizontal level lines

GEOLOGIC UNITS
(See appendix B in text for complete unit descriptions)

1 Landslide derived from lacustrine sand
2 Landslide derived from lacustrine clay
3/S1 Landslide derived from lacustrine sand and soil A horizon
4 Colluvium
5 Alluvial-fan deposits
S2 Soil A horizon on units 3/S1, 4, and 5

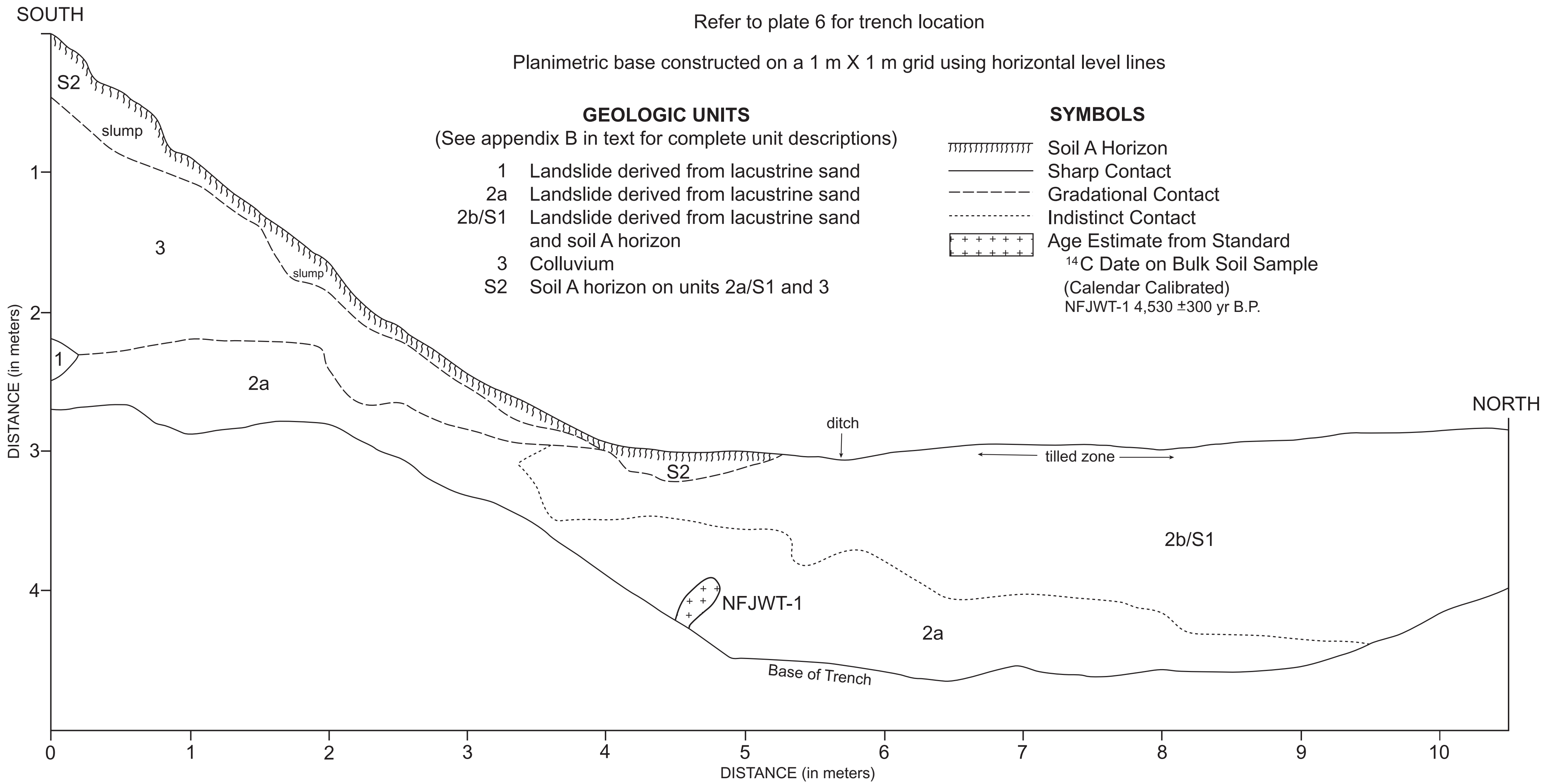
SYMBOLS

Soil A Horizon
Sharp Contact
Gradational Contact
Indistinct Contact
Age Estimate from Standard ^{14}C Date on Bulk Soil Sample (Calendar Calibrated)
NFJET-1 1,540 ±160 yr B.P.
NFJET-2 2,730 ±370 yr B.P.
NFJET-3 1,990 ±150 yr B.P.



WEST WALL OF THE NORTH FARMINGTON JUNCTION WEST TRENCH (NFJWT), FARMINGTON, UTAH

Mapped by Kimm M. Harty and Mike Lowe, 1992



GEOLOGIC MAP OF THE NORTH SALT LAKE LANDSLIDES, DAVIS COUNTY, UTAH

Mapped by Kimm M. Harty and Mike Lowe
1992

See figure 2 in text for location of study area
See appendix A for descriptions of map units and symbols

Trench from Robison and others (1991)

Landslide boundaries (Qmq_3) modified from Anderson and others (1982), Van Horn (1982), Nelson and Personius (1990), and Personius and Scott (1990)

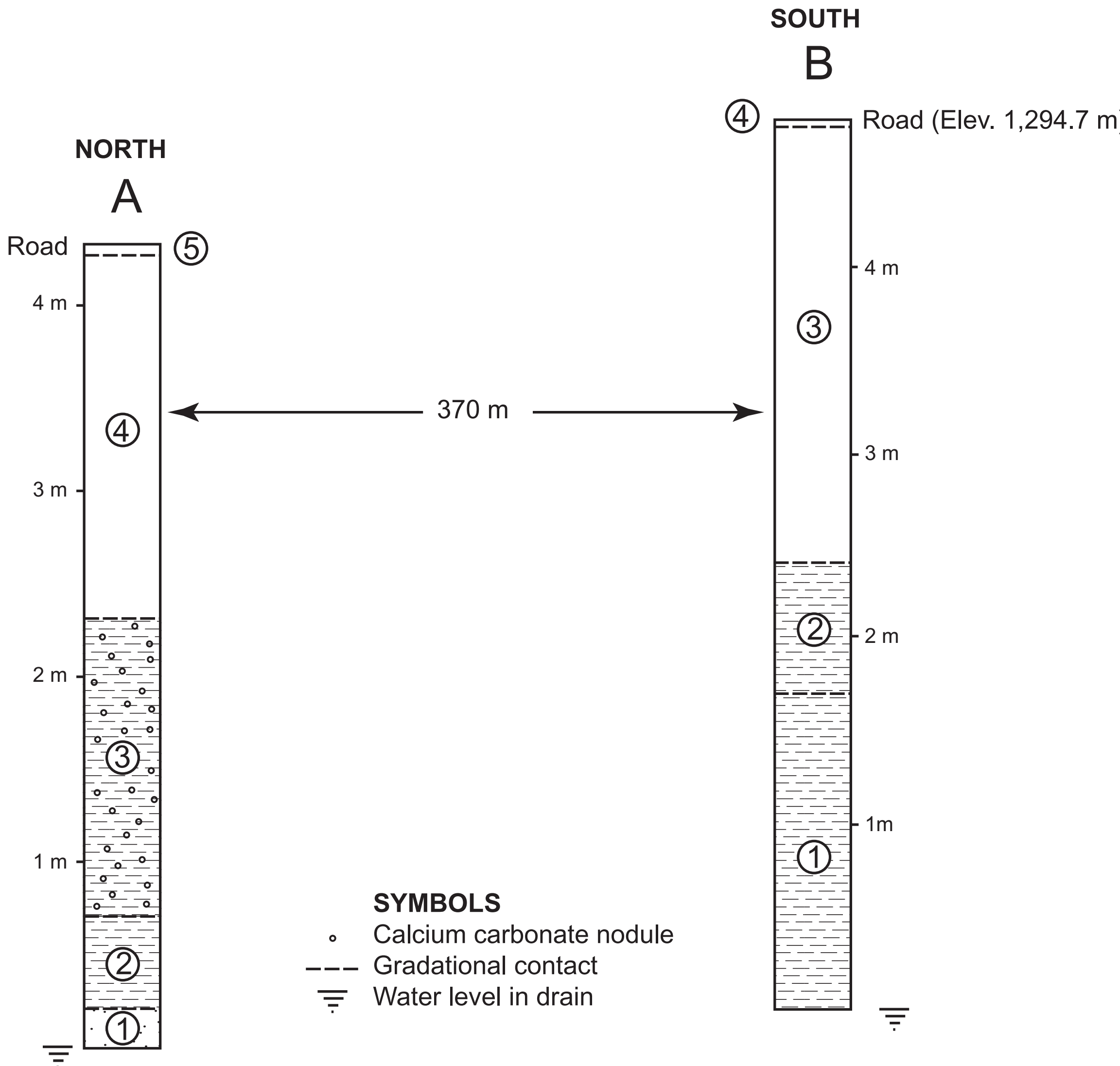
Base map from Salt Lake City North and Farmington USGS 7 1/2' topographic quadrangles

STRATIGRAPHIC LOGS OF LAND-DRAIN SITES, NORTH SALT LAKE LANDSLIDES, DAVIS COUNTY, UTAH

SS-104
Plate 10

Mapped by Kimm M. Harty and Janine L. Jarva, 1991

Refer to plate 9 for land-drain locations



GEOLOGIC UNITS

(See appendix B in text for complete unit descriptions)

Site A

1 Lacustrine sandy clay
2 Lacustrine clay with fine sand and silt
3 Lacustrine clay with fine sand and silt
4 Fill - clay with fine sand and silt
5 Topsoil

Site B

1 Lacustrine clay with fine sand and silt
2 Lacustrine clay
3 Fill - clay with fine sand and silt
4 Topsoil

GEOLOGIC MAP OF THE SPRINGVILLE/SPANISH FORK FEATURE, UTAH COUNTY, UTAH

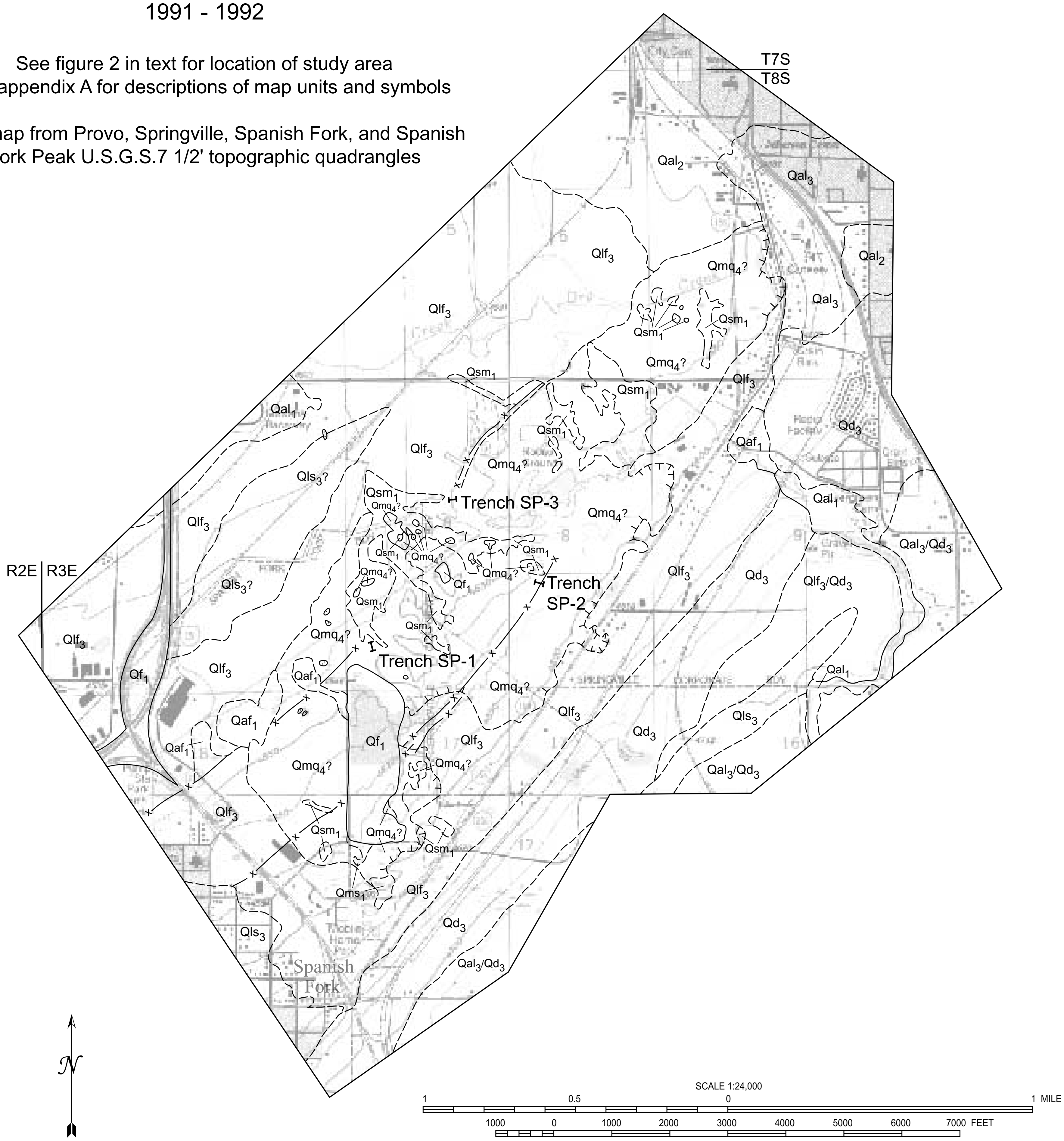
SS-104
Plate 11

Mapped by Kimm M. Harty and Mike Lowe

1991 - 1992

See figure 2 in text for location of study area
See appendix A for descriptions of map units and symbols

Base map from Provo, Springville, Spanish Fork, and Spanish Fork Peak U.S.G.S.7 1/2' topographic quadrangles



NORTHEAST WALL OF TRENCH SP-1, SPANISH FORK, UTAH

Mapped by Kimm M. Harty and Mike Lowe, 1991

SS-104
Plate 12

Refer to plate 11 for trench location

Planimetric base constructed on a 1 m X 1 m grid using horizontal level lines

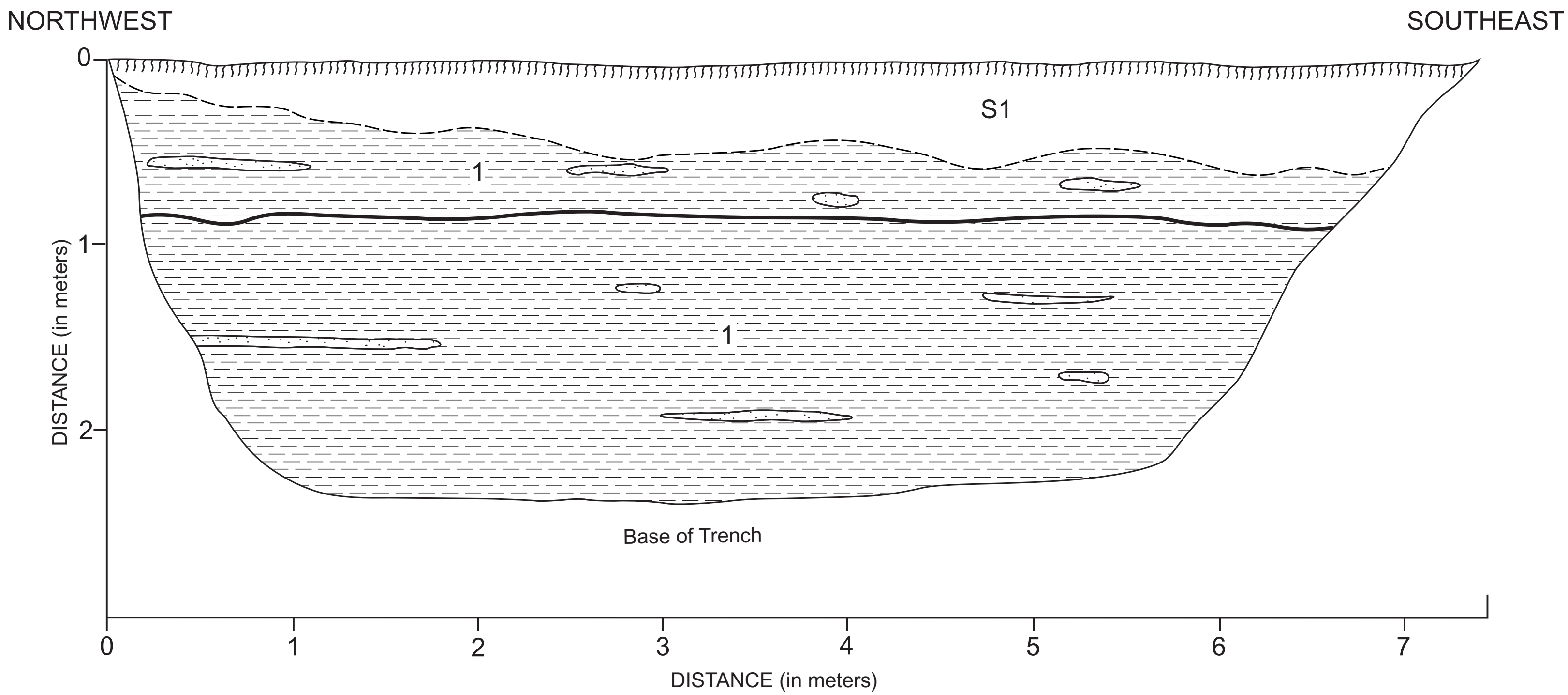
GEOLOGIC UNITS

(See appendix B in text for complete unit descriptions)

1 Lacustrine clay
S1 Soil A horizon on unit 1

SYMBOLS

Soil A Horizon
Sharp Contact
Gradational Contact
Red Clay Bed
Pod of Fine Sand



NORTHEAST WALL OF TRENCH SP-2, SPRINGVILLE, UTAH

Mapped by Kimm M. Harty and Mike Lowe, 1991

Refer to plate 11 for trench location

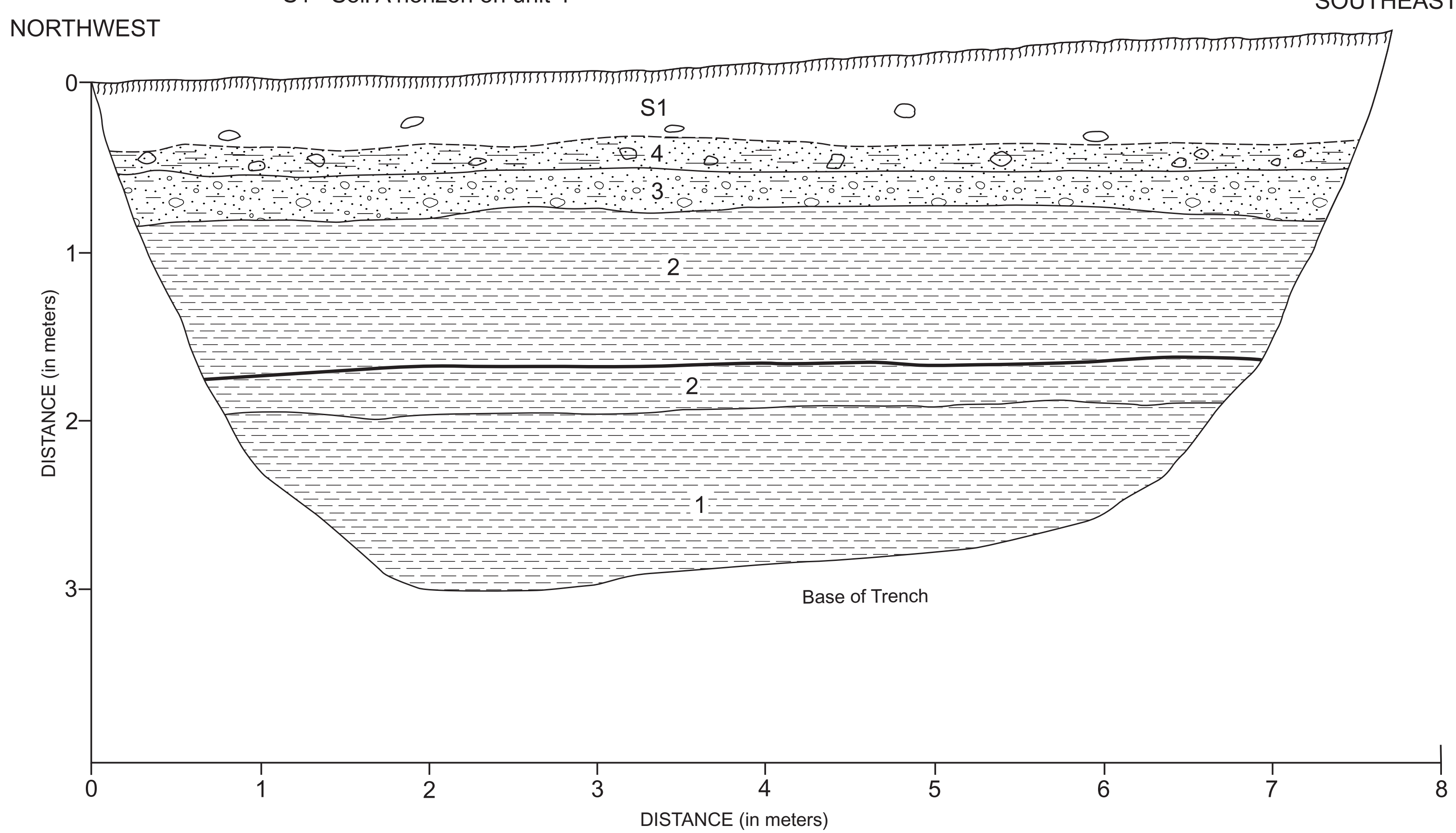
Planimetric base constructed on a 1 m X 1 m grid using horizontal level lines

GEOLOGIC UNITS
(See appendix B in text for complete unit descriptions)

1 Lacustrine clay
2 Lacustrine clay
3 Lacustrine gravel
4 Lacustrine silt and clay
S1 Soil A horizon on unit 4

SYMBOLS

Soil A Horizon
Sharp Contact
Gradational Contact
Red Clay Bed
Rock



NORTHWEST WALL OF TRENCH SP-3, SPRINGVILLE, UTAH

Mapped by Kimm M. Harty and Mike Lowe, 1991

SS-104
Plate 14

Refer to plate 11 for trench location

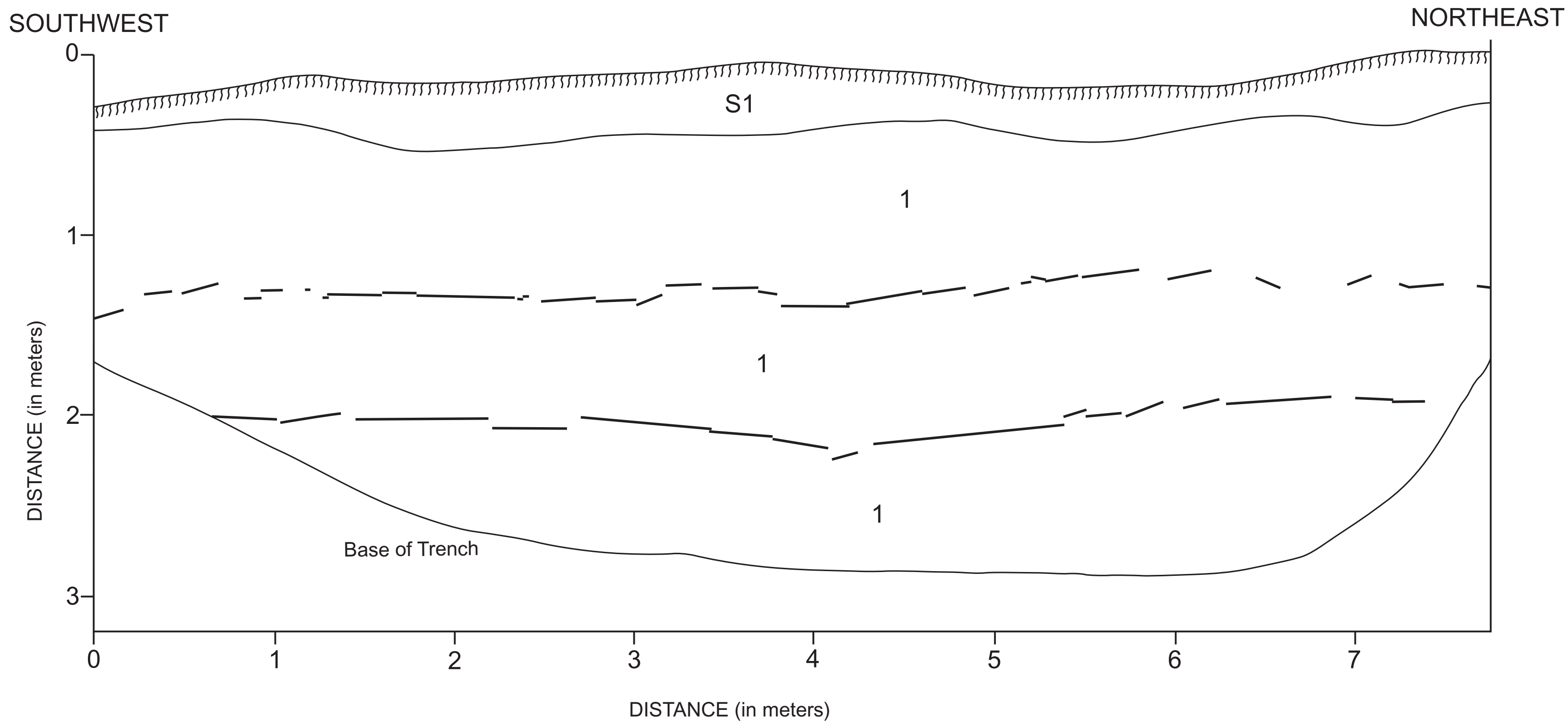
Planimetric base constructed on a 1 m X 1 m grid using horizontal level lines

GEOLOGIC UNITS
(See appendix B in text for complete unit descriptions)

1 Lacustrine clay
S1 Soil A horizon on unit 1

SYMBOLS

Soil A Horizon
Sharp Contact
Red Clay Beds



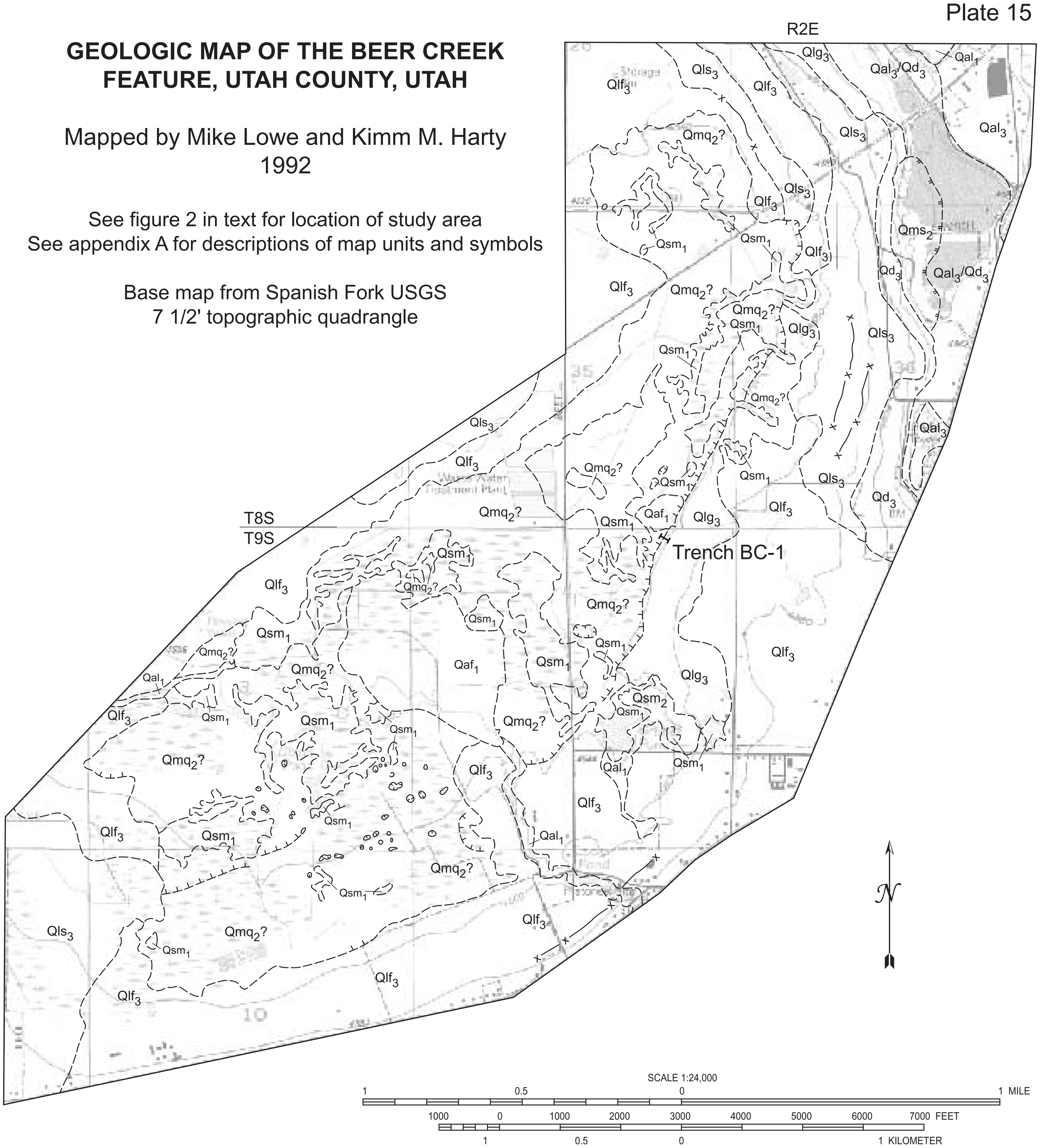
SS-104
Plate 15

GEOLOGIC MAP OF THE BEER CREEK FEATURE, UTAH COUNTY, UTAH

Mapped by Mike Lowe and Kimm M. Harty
1992

See figure 2 in text for location of study area
See appendix A for descriptions of map units and symbols

Base map from Spanish Fork USGS
7 1/2' topographic quadrangle



NORTH WALL OF BEER CREEK TRENCH (BC-1), SALEM, UTAH

Mapped by Kimm M. Harty and Mike Lowe, 1991

Refer to plate 15 for trench location

Planimetric base constructed on a 1 m X 1 m grid using horizontal level lines

GEOLOGIC UNITS

(See appendix B in text for complete unit descriptions)

- 1 Lacustrine sand
- 2 Lacustrine clay
- 3 Lacustrine sand
- 4a Lacustrine gravel
- 4b Lacustrine gravel
- 5 Scarp-derived colluvium
- 6 Colluvium/slope-wash derived from units 2 and 4b
- 7 Colluvium/slope-wash derived from units 4a and 4b
- S1 Soil A horizon on units 6 and 7

SYMBOLS

- Soil A Horizon
- Sharp Contact
- Gradational Contact
- Shear Plane
- Clay Beds in Units 1 and 2