STUDY OF EARTHQUAKE RECURRENCE INTERVALS ON THE WASATCH FAULT, UTAH

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ABSTRACT

No historical earthquakes associated with surface faulting are known to have occurred along the Wasatch fault during at least the past 132 years. However, there is abundant geologic and geomorphic evidence of Late Quaternary faulting along almost the entire length of the 370 kilometer-long fault. Detailed mapping, topographic profiling, and trenching at selected sites along the Wasatch fault provide new data on the recurrence of moderate to large magnitude earthquakes produced by surface faulting during the late Pleistocene and Holocene. During the past 6,000 years, at least three surface faulting events have produced 10 to 11 m of cumulative net vertical tectonic displacement at the Kaysville site. The vertical tectonic displacement per event is between 1.7 and 3.7 m and the interval between the two most recent events was probably more than 500 years and less than 1,000 years. The late Holocene slip rate is 1.7 to 1.8 mm per year and the average recurrence interval at the Kaysville site is probably closer to 1,000 years. During the past 12,000 years at least 6 and possibly 7 surface faulting events have produced 11.5 to 13.5 m of cumulative net vertical tectonic displacement at the Hobble Creek site. The average vertical tectonic displacement per event is between 0.8 and 2.8 m. The Holocene slip rate is 1.1 mm per year and the average recurrence interval is between 1,500 and 2,400 years. A preliminary assessment of data from the Little Cottonwood Canyon site suggests that the Holocene history of surface faulting along this segment of the fault has been similar to the history of the Kaysville and Hobble Creek sites. The displacement data indicate that magnitude 6 1/2 to 7 1/2 earthquakes have occurred repeatedly along these segments of the fault zone. If the recurrence intervals at the Kaysville and Hobble Creek sites are typical of the other segments of the fault zone, the recurrence of moderate to large magnitude earthquakes on the entire Wasatch fault zone may be between 50 and 400 years.

INTRODUCTION

There is abundant geomorphic and geologic evidence that indicates surface faulting earthquakes have occurred repeatedly along the Wasatch fault zone throughout the late Pleistocene and Holocene (Gilbert, 1890; Cluff and others, 1970, 1973, 1974, 1975; Morisowa, 1972). However, no earthquakes associated with surface fault rupture are known to have occurred along the Wasatch fault during historical time (Arabasz and others, 1979; Cook, 1972; Cook and Smith, 1967; Smith and others, 1978). Detailed geologic mapping and subsurface investigations are being conducted at selected sites along the Wasatch fault zone to measure fault displacements in strata that can be dated or correlated with dated units, and to obtain data regarding the amount of displacement per event and the number of faulting events on individual segments along the fault zone.

Investigations have been completed at two sites, the Kaysville and Hobble Creek sites, and are in progress at a third site, the Little Cottonwood site (Figure 1). The results of the completed site investigations are summarized in this report and the progress made at the Little Cottonwood site is described. The data from the Kaysville and Hobble Creek segments of the fault are used to estimate the magnitude and frequency of recurrence of earthquakes associated with surface faulting along the entire 370-kilometer-long Wasatch fault zone.

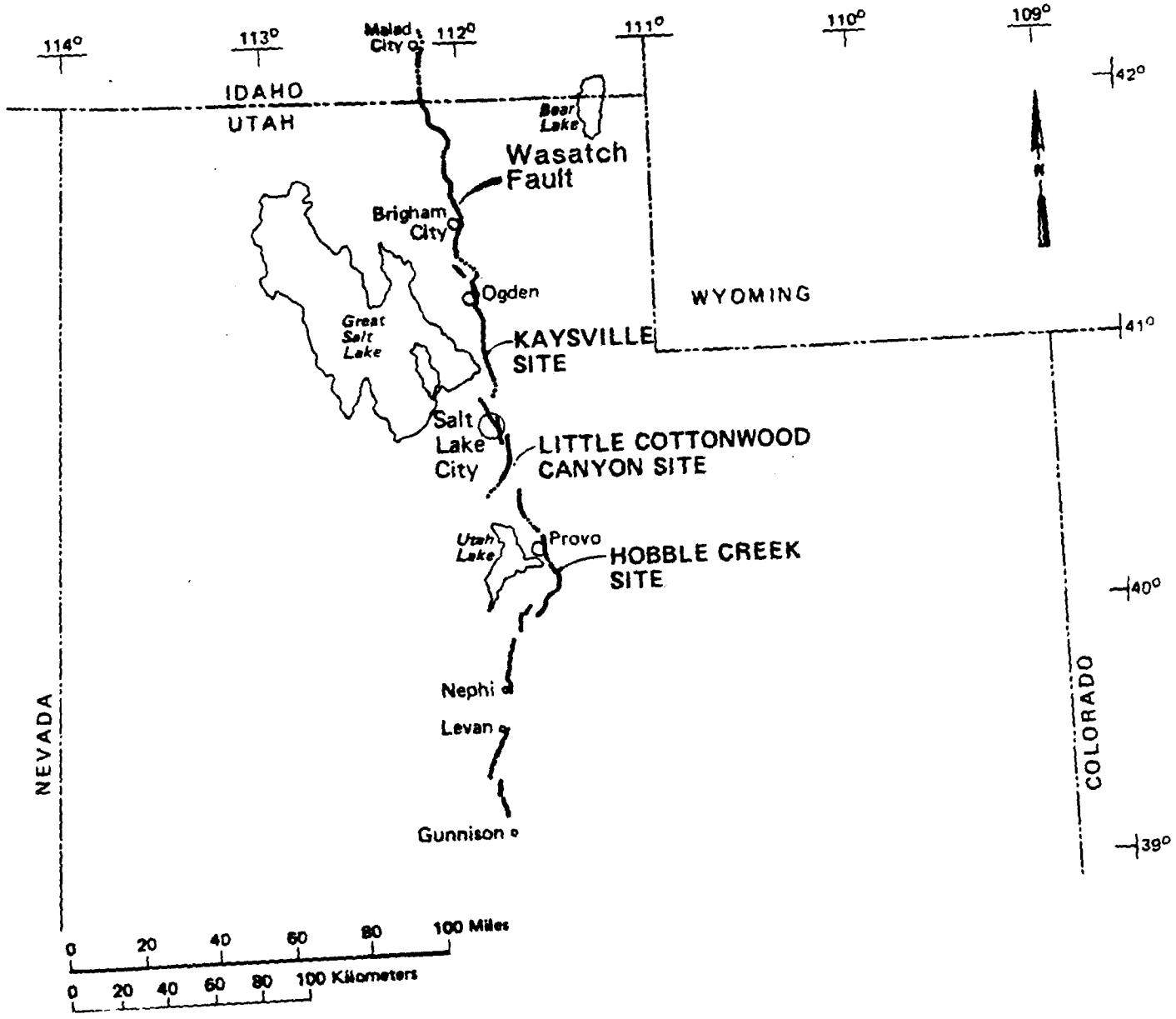


Figure 1 Regional location map

RESULTS OF SITE INVESTIGATIONS

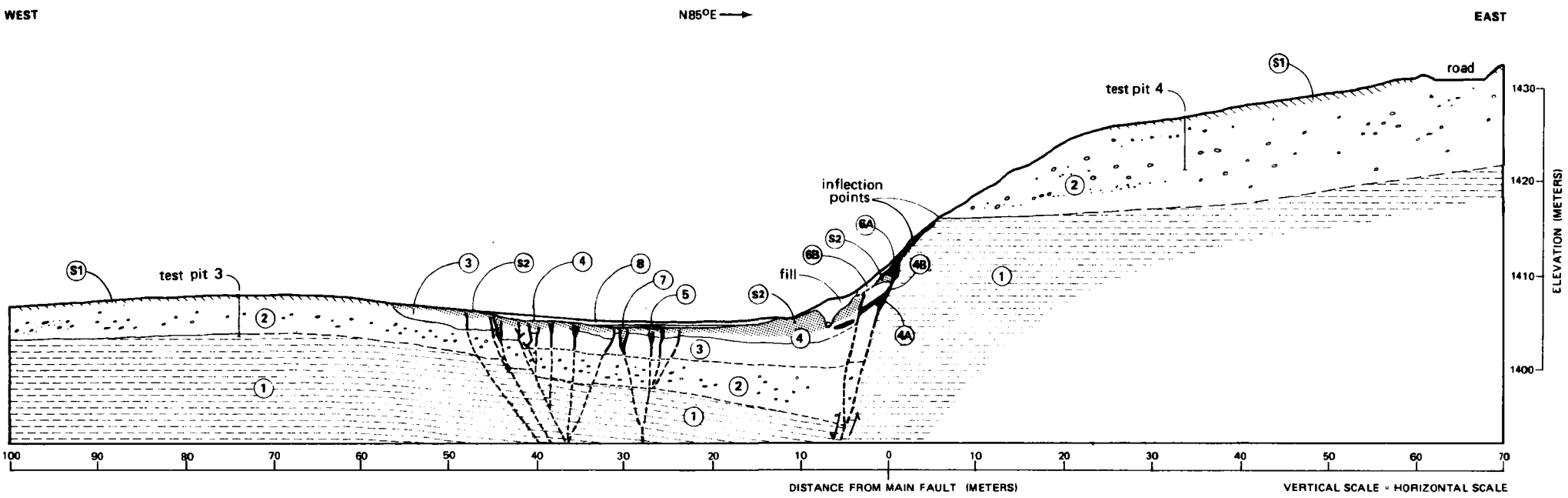
Kaysville Site

During the spring of 1978, detailed geologic mapping and subsurface investigations were completed at the Kaysville site, which is located 30 km north of Salt Lake City (Figure 1). The results of these investigations are described by Cluff and others (1978), Schwartz and others (1979a), and by Swan and others (1978a,b; 1979b,d,e; 1980).

The stratigraphic and structural relations observed at the Kaysville site indicate that a minimum of three surface faulting events have occurred since deposition of a post-Provo alluvial fan that is estimated to be about 6,000 years old. The main fault scarp in the fan deposits is 22 m high. Due to back-tilting and graben formation, the main scarp is approximately twice the true tectonic displacement across the deformed zone. The cumulative net vertical tectonic displacement of the fan surface is 10 to 11 m (Figure 2). The vertical tectonic displacement per event produced during the most recent events is estimated to have been between 1.7 and 3.7 m. The two most recent events postdate deposition of detrital charcoal that yielded a radiocarbon age of 1580 + 150 y.b.p. The interval between these events was probably longer than 500 years and shorter than 1,000 years. The late Holocene slip rate is 1.7 to 1.8 mm per year and the average recurrence interval for surface faulting events at the Kaysville site is probably closer to 1,000 years.

Hobble Creek Site

During the fall of 1978, detailed geologic mapping, topographic profiling, and subsurface investigations were



EXPLANATION

LITHOLOGIC UNITS

OLDER ↓

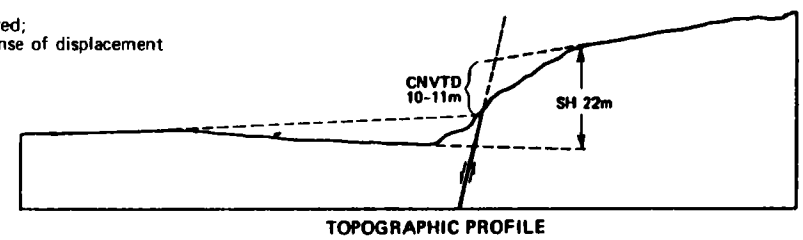
- (8) Historical alluvium / pond deposits
- (7) Pre-Settlement deposit
- (6B) Colluvium / slopewash deposits
- (6A) Colluvium—basal facies
- (5) Pond deposit
- (4) Locally derived sag fill including:
  - (4B) Colluvium
  - (4A) Colluvium—basal facies
- (3) Sag fill derived from north and associated colluvium
- (2) Post-Provo alluvial fan deposits
- (1) Alpine-Bonneville lake deposits (undifferentiated)

SOIL UNITS

- (S1) Relict soil developed on post-Provo alluvial fan deposits
- (S2) Alluviated soil

Lithologic contact; dashed where inferred

Fault; dashed where inferred; arrows indicate relative sense of displacement



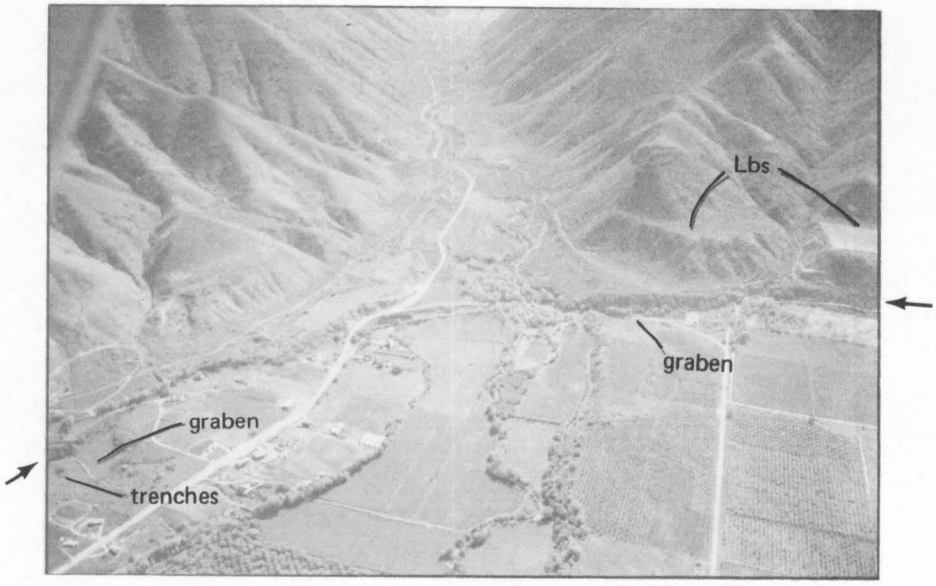
TOPOGRAPHIC PROFILE

Figure 2 Topographic profile and geologic cross section of fault scarp and graben at the Kaysville site. Backtilting and graben formation have incerased the apparent displacement relative to the tectonic displacement; the scarp height (SH on the profile) is approximately two times the cumulative net vertical tectonic displacement (CNVTD) across the deformed zone.

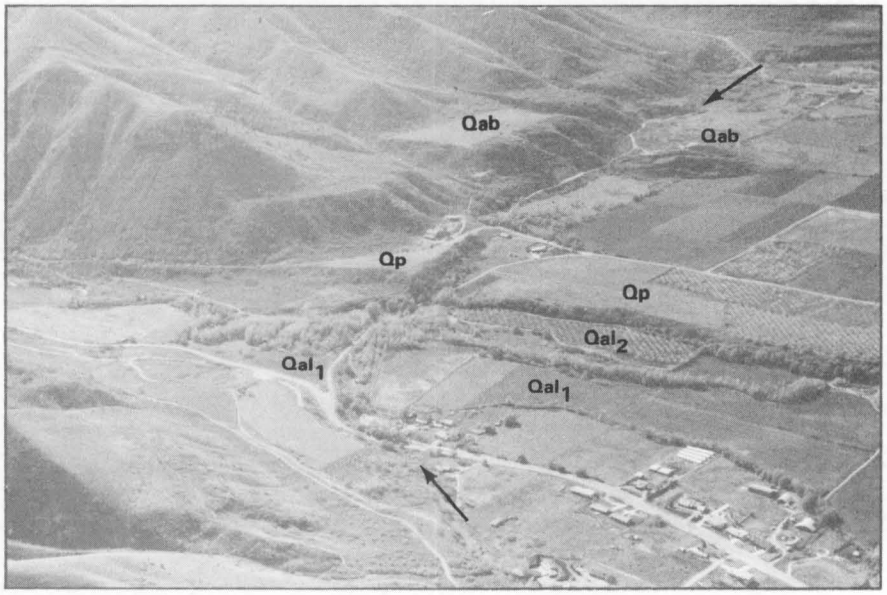
completed at the Hobble Creek site, which is located 46 km southeast of Provo (Figure 1). The results of these investigations are described by Schwartz and others (1979a,b) and by Swan and others (1979a,b,c,e; 1980).

Surface faulting throughout Late Quaternary time at the Hobble Creek site is indicated by the progessively smaller cumulative displacements that are observed in the successively younger datums measured. The vertical heights of the fault scarps in Bonneville-Alpine lake deposits, Provo fan-delta deposits, and post-Provo pre-Utah Lake alluvium are 60 m, 28.5 m, and 12.5 m, respectively (Figures 3 and 4). These heights include the effects of back-tilting and graben formation. The cumulative net vertical tectonic displacements of the Provo terrace and the post-Provo pre-Utah Lake terrace are 11.5 to 13.5 m and 7 to 8.5 m, respectively (Figure 4). Due to erosion and deposition, the cumulative net vertical tectonic displacement of the Alpine-Bonneville deposits are less certain. Estimates of the post Alpine-Bonneville tectonic displacement range from 30 to 50 m; the lower value is probably closer to the actual value.

At least six, and possibly seven, surface faulting events have occurred in post-Provo time (about 12,000 y.b.p.). Three, and possibly four, of these events occurred during early Holocene time and are indicated by pre-middle Holocene strath terraces that are eroded into Provo gravels on the upthrown side of the fault. Three additional events during late Holocene time are indicated by the segmented alluvial fan and the faulted fan deposits observed in the trenches at the mouth of Deadmans Hollow. The average displacement per event associated with these surface faulting events is between 0.8 and 2.8 m and the average recurrence interval between the events is between 1,500 and 2,400 years (Table 1). The actual intervals between successive events may have varied from these mean values. The



(a) View is east towards mouth of Hobble Creek Canyon showing main fault scarp (arrows), grabens, shoreline of Lake Bonneville (Lbs), and trenches.



(b) View is towards the southeast along the main fault scarp (arrows) and shows the progressively lower scraps associated with the successively younger Quarternary deposits. From oldest to youngest, the deposits and related scrap scarp heights are: Alpine-Bonneville lake deposits, (**Qab**), 60 m; Provo fan-delta deposits (**Qp**), 28.5 m; post-Provo-pre-Utah Lake deposits (**Qal_1**), 12.5 m; and the modern flood plain deposits (**Qal_2**), which show no detectable displacement.

Figure 3 - OBLIQUE AERIAL PHOTOGRAPHS OF HOBBLE CREEK SITE

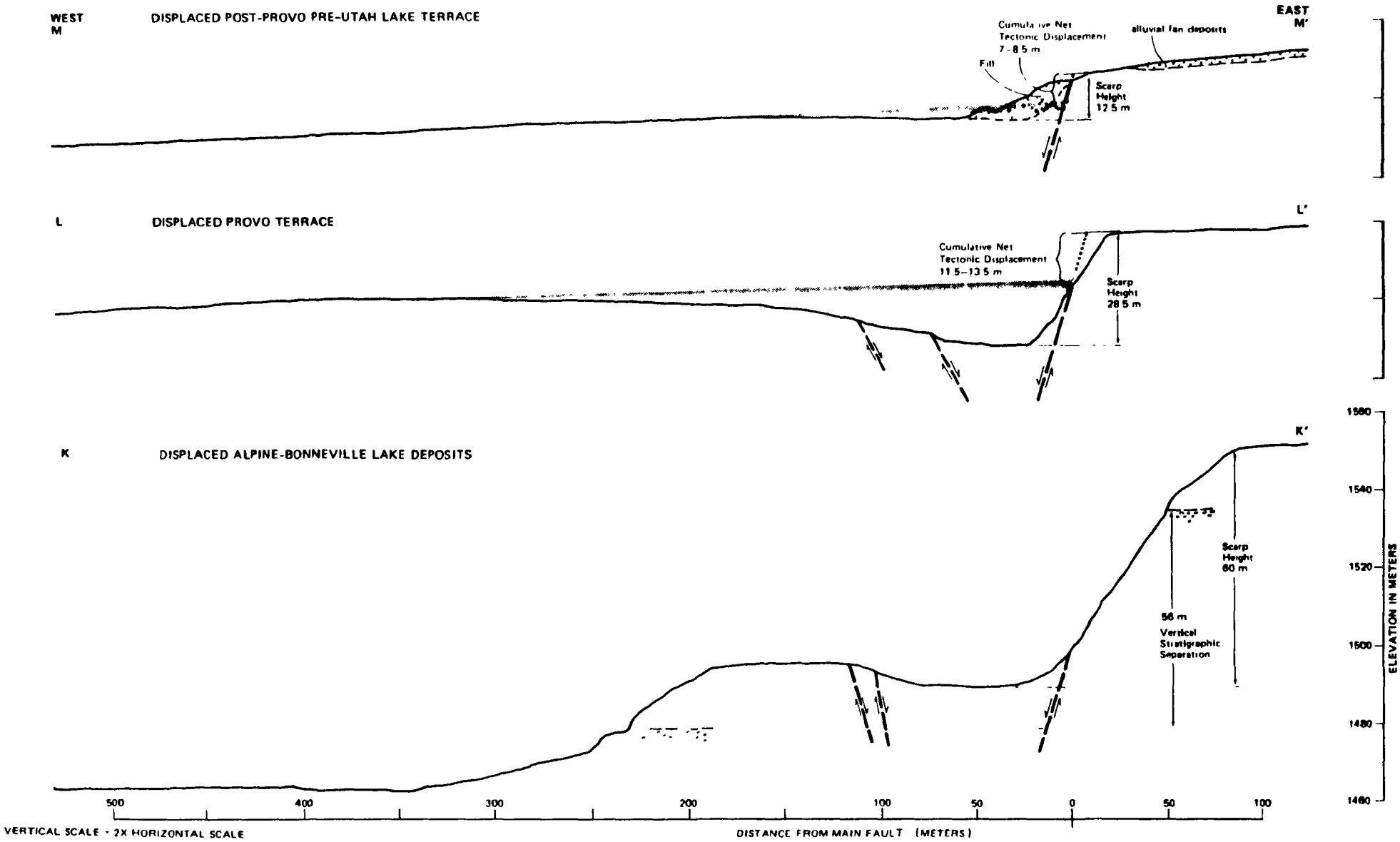


Figure 4 Topographic profiles of fault scarps at the Hobble Creek site showing progressively higher scarps in successively older deposits. Profiles M-M' and L-L' show the relationship between the apparent displacement (scarp height) and the cumulative vertical tectonic displacement (CNVTD) across the deformed zone.

Table 1 Summary of data on fault displacements at the Hobble Creek site

DATUM	APPROXIMATE AGE (yrs. B.P.)	CUMULATIVE VERTICAL TECTONIC DISPLACEMENT POST DATUM (m)	CUMULATIVE VERTICAL TECTONIC DISPLACEMENT DURING INTERVAL (m)	NUMBER OF EVENTS DURING INTERVAL	AVERAGE DISPLACEMENT PER SURFACE FAULTING EVENT (m)	AVERAGE RECURRANCE INTERVAL FOR SURFACE FAULTING EVENTS (yrs.)
ALPINE-BONNEVILLE LAKE DEPOSITS	>15,000 to <35,000	30 – 50	–	–	–	
	–	–	16.5 – 38.5	?	?	
PROVO TERRACE	12,000	11.5 – 13.5	–	–	–	
	–	–	3 – 6.5	3 – 4	0.8 – 2.2	1500 – 2400
MIDDLE HOLOCENE TERRACE	6,000	7 – 8.5	–	–	–	
	–	–	7 – 8.5	3	2.3 – 2.8	
PRESENT FLOOD PLAIN	0	0	–	–	–	

late Pleistocene slip rate was probably between 2 and 6 mm per year. The average Holocene slip rate is 1.1 mm per year.

Little Cottonwood Canyon Site

Soil test pits and trenches were excavated across a main trace of the Wasatch fault and an associated graben near the mouth of Little Cottonwood Canyon during July and August of 1979. The structural and stratigraphic relations observed in these trenches indicate that there have been at least two and possibly three late Holocene surface faulting events that produced 10 to 11 m of vertical displacement on the main fault. This displacement includes the effects of back-tilting and graben formation. Geologic mapping of the Little Cottonwood Canyon site and detailed topographic profiles of displaced geomorphic surfaces will be completed this fall. Although the zone of faulting along this segment of the Wasatch fault contains multiple traces and is more complex than the segments at Kaysville and Hobble Creek, the preliminary data suggest that the history of surface faulting has been similar along these segments of the fault.

MAGNITUDE OF PAST SURFACE FAULTING EARTHQUAKES

When the displacement per event is known, the empirical relation between the logarithm of maximum displacement and earthquake magnitude (Slemmons, 1977) can be used to estimate the size of the past earthquakes. Estimates of the net vertical tectonic displacement for individual surface faulting events at the Kaysville site range from 1.7 to 3.7 m based on the colluvial stratigraphy and structural relationships observed in trenches. According to Slemmons' curve for normal-slip faults, displacements of 1.7 to 3.7 m are

associated with magnitude 7.0 to 7.3 earthquakes. Slemmons' curves, however, are based on the maximum resultant displacement observed during historical surface faulting events, and the reported values include both fault slip (net vertical tectonic displacement) and distortion (exaggerated scarp height due to back-tilting and graben formation). Back-tilting and graben formation may increase the net tectonic displacement by as much as a factor of two along the segment of the Wasatch fault at the Kaysville site. If this factor is taken into account, the displacement for a single event may have been as large as 7.4 m, which gives a magnitude of 7.6 on Slemmons' (1977) curve.

The displacement that occurred during individual surface faulting events at the Hobble Creek site could not be measured directly. Therefore, the average displacement per event for different intervals was calculated by dividing the cumulative tectonic displacement by the number of surface faulting events (Table 1). Values for the average vertical tectonic displacement per event range from 0.8 to 2.8 m per event during the Holocene. Displacements of 0.8 m to 2.8 m produce earthquakes having magnitudes of 6.7 to 7.2 (Slemmons, 1977). As at the Kaysville site, the scarp height at the Hobble Creek site is approximately twice the cumulative net vertical tectonic displacement in the Provo deposits. Considering this factor, the average resultant displacement per event could have been as large as 5.6 m, which gives a magnitude of 7.5 on Slemmons' curve.

Estimates of earthquake magnitude should be based on as many parameters as possible. Average displacement data will not necessarily define the maximum earthquake that has occurred on a fault. More rigorous analysis is required to asess the maximum size earthquake that can occur. Nonetheless, the available data indicate that surface faulting events

associated with earthquakes in the magnitude range of 6 1/2 to 7 1/2 have occurred repeatedly along the fault segments at the Kaysville and Hobble Creek sites.

The available data are insufficient to determine the frequency distribution (b values) of earthquake magnitudes associated with surface faulting events on the individual segments of the fault at Kaysville and Hobble Creek. Therefore, it is not known whether each of these segments is characterized by successive earthquakes having nearly the same magnitude or by successive earthquakes having different magnitudes. For example, do more magnitude 6 1/2 events occur on a given segment than magnitude 7 1/2 events? It is generally observed that smaller earthquakes occur more frequently than larger earthquakes. However, this observation is based on historical and instrumental seismicity records from regions that contain numerous faults, each of which could have its own characteristic magnitude. If surface faulting on an individual fault segment produces an earthquake having a characteristic magnitude or narrow range of magnitudes, it would be incorrect to assume that small magnitude events are more likely to occur on that segment than large magnitude events.

COMPARISON OF SLIP RATES

The average slip rates are different on the two segments of the Wasatch fault where the detailed studies have been completed. The slip rate has also varied with time along the same segment of the fault.

At Kaysville the post mid-Holocene slip rate is 1.7 to 1.8 mm per year and at Hobble Creek the post-Provo rate is 1.1 mm per year. This variation in slip rate between the different segments of the fault may reflect localized perturbations in

the rate of strain released along the fault due to such factors as fault geometry and the nature and relative strengths of the local bedrock. It could also reflect localized variation in the regional stress field.

At the Hobble Creek site the Holocene (post-Provo) slip rate was 1.1 mm per year compared to an estimated 2-6 mm per year for the late Pleistocene. The long-term Late Cenozoic slip rate of 0.4 mm per year, based on fission track dates on apatite collected from different elevations in the Wasatch Mountains between Bountiful and Ogden (Naeser, 1977), is approximately four times slower than the late Holocene slip rate observed in this area at Kaysville. Hamblin (1976) interprets the presence of faceted spurs and uplifted remnants of pediments along the range front to have been produced by repeated episodes of essentially continuous uplift (numerous small faulting events) separated by periods of quiescence. The available geologic evidence suggest there have been both short-term (a few thousand years) and long-term (tens to hundreds of thousands of years) fluctuations in the slip rate along individual segments of the fault zone.

EARTHQUAKE RECURRENCE ON THE WASATCH FAULT ZONE

The recurrence of surface faulting earthquakes along the entire 370-kilometer-long fault zone is a function of the recurrence interval on the individual segments, the temporal and spacial distribution of events on different segments (fault behavior), and, most importantly, on the total number of segments that comprise the fault zone.

Recurrence on Individual Segments. The recurrence of moderate to large magnitude earthquakes associated with surface fault rupture along the segment of the Wasatch fault zone at the

Kaysville site is estimated to be between 500 and 1,000 years, with the longer interval being closer to the average late Holocene value. Similarly, the average recurrence interval for the segment of the fault at the Hobble Creek site is estimated to be between 1,500 and 2,400 years. The recurrence for the Kaysville and Hobble Creek segments of the fault has been presented as average intervals. Except for the two most recent events at Kaysville, the data do not constrain the actual intervals between successive events. Nonetheless, at Hobble Creek three or four events have occurred between 12,000 and 6,000 years ago and three events have occurred during the past 6,000 years. Although the available data do not preclude the possiblility that events could have been clustered during a short interval (e.g., three events in 1,000 years followed by 5,000 years of quiescence), the geological observations suggest that spacing of the six or seven post-Provo events tended to be regular.

In addition to the segments at Kaysville and Hobble Creek, the Wasatch fault zone contains several other segments, and the recurrence intervals on these segments are not known. Variations in the geomorphic expression of fault scarps along these segments suggest that they could have longer and/or shorter recurrence intervals than the segments at Kaysville and Hobble Creek. However, the geomorphic expression may also be a function of the elapsed time since the most recent event, the relative erodibility of the faulted materials, or localized variations in the erosional and depositional processes. Additional data are needed to determine the recurrence on these segments.

Fault Behavior. The relationship between different fault segments will affect the recurrence of surface faulting earthquakes on the entire fault zone. If the individual fault segments behave independently, there will be a random

distribution of surface faulting events. If the segments are interdependent, there may be a clustering of surface faulting events. For example, the occurrence of a large magnitude earthquake along one segment of the fault zone might induce an event (energy release) along other segments of the fault that otherwise would not have slipped until more time had elapsed allowing more stress to build up.

Many statistical models of earthquake behavior assume that large magnitude earthquakes have a uniform distribution with respect to time; this assumption may not be correct in some tectonic environments. For example, a study of the Anatolian fault zone (Ambraseys, 1970) shows that major earthquake sequences associated with surface faulting are separated by periods of quiescence of about 150 years. The earthquake sequence that occurred in Anatolia between 1909 and 1959 was characterized by over 30 events of magnitude 6 or larger; at least 10 of these were associated with right-lateral surface displacements, and in most cases each new rupture either overlapped or began where faulting had ended in the previous event (Ambraseys, 1970).

There are not enough data on past surface faulting events along the various segments of the Wasatch fault to test the dependence or independence of recurrence on the different segments. However, differences in the average Holocene recurrence intervals and slip rate at Kaysville and Hobble Creek suggest that these segments have behaved independently. Also, Hamblin (1976) suggests that the history and patterns of displacement have varied throughout Late Cenozoic time based on differences in the geomorphology along the range front. Although the evidence is not conclusive, the individual segments of the Wasatch fault seem to behave independently. Short-term variations in the behavior of individual fault segments may be a characteristic of long normal-slip faults.

Number of Fault Segments. The greater the number of active segments there are along the fault, the shorter the recurrence interval will be along the entire fault zone. It is difficult to define the number of individual segments. There have been no historical events on the Wasatch fault where the length of surface fault rupture can be measured directly. Also, it is not known whether the same segment ruptures along its entire length during successive events or whether longer and/or shorter lengths can rupture during subsequent earthquakes. This is further complicated by the fact that more than one segment, or parts of more than one segment, may rupture during a single event.

Despite these problems, there are a number of lines of evidence that can be used to estimate the number of segments. Within the Basin and Range province the longest recorded surface ruptures on normal slip faults are 62 km from the magnitude 7 3/4 1915 Pleasant Valley earthquake and 61 km from the magnitude 6.8 1954 Dixie Valley earthquake (Slemmons, 1977). Arabasz and others (1979) report gaps in microearthquake activity approximately 70 km in length along the Wasatch fault. These observations suggest that 60 to 70 km is a reasonable upper limit for the length of an individual fault segment. This suggests there is a minimum of six segments along the 370-km-long Wasatch fault. Worldwide data on surface faulting along normal faults (Slemmons, 1977) shows many earthquakes in the magnitude range of 6 1/2 to 7 1/2 occurring on normal faults that had surface rupture in the 30 to 40 km range. This, coupled with geomorphic variation along the fault, suggests the possibility of up to ten individual segments.

Estimated Recurrence on the Zone. If the recurrence intervals along the Kaysville and Hobble Creek segments of the fault (minimum of 500 years and maximum of 2,400 years per event)

are representative of the recurrence intervals on all of the six to ten segments, and if the segments behave independently, the recurrence interval for the entire zone is one-sixth to one-tenth that of the individual segments, that is, between 50 and 400 years per event. No surface faulting events have occurred along the Wasatch fault zone during at least the past 132 years. This suggests a moderate to large magnitude surface faulting event (magnitude 6 1/2 and 7 1/2) is either due or past due somewhere along the Wasatch fault.

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STUDY OF EARTHQUAKE RECURRENCE INTERVALS ON THE WASATCH FAULT, UTAH

U.S.G.S. Contract No. 14-08-0001-16827

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Summary of Third Semi-Annual Technical Report, October, 1979

INVESTIGATIONS

Detailed geologic studies that include mapping of the Quaternary deposits, topographic profiling of displaced geomorphic surfaces, and trenching have been completed at two locations along the Wasatch fault: the Kaysville site, which is 32 km north of Salt Lake City, and the Hobble Creek site, 28 km southeast of Provo. Investigations at a third site near the mouth of Little Cottonwood Canyon 13 km south of Salt Lake City are currently in progress. Data on the cumulative displacement of late Quaternary deposits, the number of surface faulting events, and the amount of displacement per event have been collected at these sites in order to estimate the magnitude of past surface faulting events and the frequency of recurrence of these events on individual segments of the fault zone and to estimate the recurrence of moderate to large magnitude earthquakes along the entire Wasatach fault.

RESULTS

Site Investigations

Kaysville Site: A minimum of three surface faulting events have produced a cumulative net vertical tectonic displacement of 10 to 11 m of an alluvial fan surface that is approximately 6,000 years old. The vertical tectonic displacements during the two most recent surface faulting events were between 1.7 and 3.7 m per event. The interval between these events was not less than 500 years or more than 1,000 years. The late Holocene slip rate along the segment of the fault at Kaysville was 1.8 mm per year and the average recurrence interval was probably closer to 1,000 years.

Hobble Creek Site: During the past 12,000 years at least six and possibly seven surface faulting events have produced 11.5 to 13.5 m of net vertical tectonic displacement at the Hobble Creek site. The average vertical tectonic displacement per event is

between 0.8 and 2.8 m. The Holocene slip rate is 1.1 mm per year and the average recurrence interval is between 1,500 and 2,400 years.

Little Cottonwood Canyon Site: During the late Holocene at least two and possibly three surface faulting events have produced 10 to 11 m of vertical displacement on a trace of the main fault at the Little Cottonwood Canyon site. This displacement includes the effects of back-tilting and graben formation. Topographic profiles are being measured to assess the cumulative net tectonic displacement across the entire zone. A preliminary evaluation of the data suggests that the Holocene history of surface faulting at the Little Cottonwood site has been similar to the history of faulting at the Kaysville and Hobble Creek sites.

Magnitude of Past Surface Faulting Events

The displacement data from the Kaysville and Hobble Creek sites indicate that earthquakes in the magnitude range of 6 1/2 to 7 1/2 have occurred repeatedly along the fault segments at these sites. These estimates are based primarily on average values of the displacement per event; therefore, they may not necessarily represent the largest earthquake that has occurred on the Wasatch fault.

Earthquake Recurrence on the Wasatch Fault Zone

The recurrence of surface faulting earthquakes along the entire 370-kilometer-long fault zone is a function of the recurrence interval on the individual segments, the temporal and spacial distribution of events on different segments (fault behavior), and on the total number of segments that comprise the fault zone. If the recurrence intervals along the Kaysville and Hobble Creek segments of the fault (minimum of 500 years and maximum of 2,400 years per event) are representative of the recurrence intervals on all of the six to ten segments, and if the segments behave independently, the recurrence interval for the entire zone is one-sixth to one-tenth that of the individual segments, that is, between 50 and 400 years per event. No surface faulting events have occurred along the Wasatch fault zone during at least the past 132 years. This suggests a moderate to large magnitude surface faulting event (magnitude 6 1/2 and 7 1/2) is either due or past due somewhere along the Wasatch fault.

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