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Neotectonics of the northeastern Basin and Range margin, western USA

by

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with 6 figures

Summary. Eleven backhoe trenches were excavated across six Quaternary fault scarps on the northeastern margin of the Basin and Range extensional tectonic province, western USA. Fifteen Holocene palaeoseismic events can be recognized, bracketed by radiocarbon or thermoluminescence ages. On most faults, the latest rupture event occurred in a relatively short time interval between 2000 yr B.P. and 6000 yr B.P. The period between 6000 yr B.P. and the end of the latest glaciation (ca. 15,000 yr B.P.) was a period of relative tectonic quiescence for the six central faults, but not for the two end faults with higher slip rates (Wasatch and Teton faults). Estimates of future rupture potential for individual faults vary, depending on the presumptive model chosen. If high potential is indicated by large elapsed times compared to average recurrence intervals, then the long end faults of the region (Wasatch and Teton) are most likely to rupture next. If high potential is indicated by late Quaternary slip rates (< 15 ka) lagging behind late Cenozoic slip rates (ca. 15 m.y.), then the central faults (East Cache, Bear Lake, Star Valley) are more likely candidates for future rupture.

Introduction

The neotectonics of the northeastern margin of the Basin and Range extensional tectonic province, western USA, has been studied by palaeoseismic investigations undertaken between 1984 and 1992 on six normal faults. Eleven trenches were excavated during this period, two on the East Cache fault, Utah (Oct. 1985 and April, 1991), two on the eastern Bear Lake fault, Utah (June–July, 1989), two on the western Bear Lake fault, Idaho (Sept.–Oct., 1989), one on the Star Valley fault, Wyoming (May, 1990), three on the Grey's River fault, Wyoming (June–August, 1991), and one on the Rock Creek fault, Wyoming (July, 1991). Previous studies had interpreted trenches on the adjacent Wasatch fault to the southwest (Brigham City Segment; PERSONIUS 1990, 1991) and the Teton fault to the northeast (BYRD & SMITH 1990). By combining these previous results with current data, we reveal the spatial and temporal pattern of palaeoearthquakes in a 330,000 km^2 zone of active extensional tections over the last 15,000 years.

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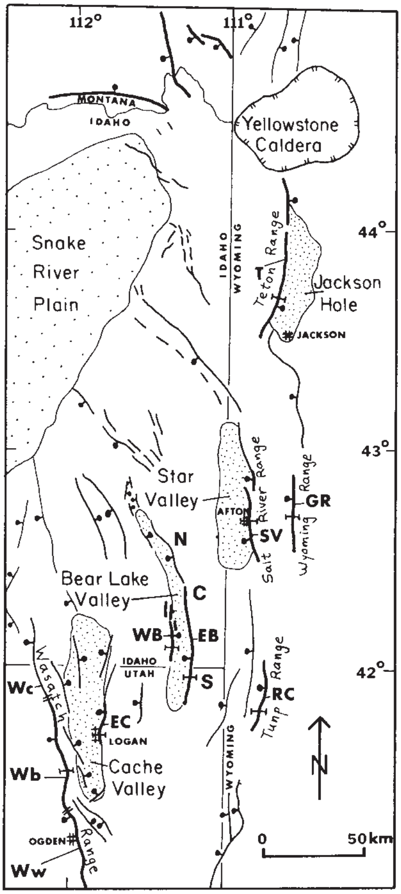

Fig. 1. Location map of the northeastern margin of the Basin and Range province, western USA. Major Neogene basins are shown by fine stipple pattern. Normal faults with Holocene displacement are indicated by heavy solid lines, with ball on the downthrown side. Thinner lines reflect normal faults with late Quaternary, and Quaternary, displacement. Faults described in this study are indicated by bold abbreviations; T – Teton fault, GR – Grey's River fault, SV – Star Valley fault, EB – eastern Bear Lake fault zone, WB – western Bear lake fault zone, EC – East Cache fault zone, RC – Rock Creek fault. The following segments of the Wasatch fault zone are also labelled; Wc – Collinston segment, Wb – Brigham City segment, Ww – Weber segment. Trench sites are shown by lines with crossbars. Figure adapted from PIETY et al. 1986.

Location and Geologic Setting

The northeastern margin of the Basin and Range province is composed of north-trending Neogene normal fault-block mountains and basins. These structures form a northeasterly-trending zone of right-stepping en-échelon horsts, grabens, and tilted blocks between the northern segments of the Wasatch fault zone and the Teton fault (Fig. 1). All faults result from east-west Neogene extension superimposed on the Cretaceous-early Tertiary compressional fold-and-thrust belt (the "Overthrust Belt") of eastern Utah, southeastern Idaho, and western Wyoming (ARMSTRONG 1968). Down-to-the-west normal faulting on the East Cache, eastern Bear Lake and Star Valley faults has created the large, deep (up to 5 km of Neogene fill) basins of Cache Valley, Utah, Bear Lake Valley, Idaho and Utah, and Star Valley, Wyoming, respectively. Linear stream valleys which parallel the Grey's River and Rock Creek faults are incipient tectonic depressions, and suggest that these easternmost extensional faults are in a less evolved state than their western counterparts. The relation of these Neogene structures to the eastward migration of the Yellowstone hot spot has been described by Scott et al. (1985), Anders et al. (1989), Westaway (1990), and Pierce & Morgan (1992).

The fault scarps studied in this investigation displace deposits correlated to the latest glacial and pluvial periods and to Holocene time. The latest Wisconsin ("Pinedale") glaciation in the Rocky Mountains began ca. 32 ka (1 ka = 1000 years B.P.) and reached its maximum extent by a 20–23 ka (Porter et al. 1983). Deglaciation began by 17 ka and mountain valleys were free of ice by 14–15 ka. The oldest alluvial deposits at range fronts, that are offset by fault scarps of the Star Valley, Grey's River, and Rock Creek faults, are correlated to latest glacial deposition. This correlation implies that the faulted alluvium was deposited ca. 15–20 ka. In addition to these late glacial deposits, mid-Holocene alluvial fans and terraces exhibit smaller fault scarps, which were trenched on the Wasatch, Grey's River, and Teton faults. During the latest Pleistocene pluvial lakes also occupied the Bonneville Basin (Gilbert 1890) and the Bear Lake graben. The latest lake cycle (Bonneville lake cycle of Scott et al. 1983) began ca. 32 ka and reached its highstand at 15 ka (the Bonneville shoreline). Shortly thereafter the Bonneville lake fell due to threshold collapse and the Provo shoreline (ca. 13–14 ka) was formed (Currey & Oviatt 1985). The lake then rapidly dessicated after 13 ka, reaching low (modern) levels by 11 ka. Fault scarps on the Wasatch and East Cache fault zones are developed in shoreline and deltaic deposits associated with the Bonneville or Provo shorelines, whereas scarps on the Bear Lake faults are developed in deltas or lake-bottom sediments of slightly younger age (11–12 ka).

Methods

Late Quaternary fault scarps were located by photogeological mapping on aerial photographs of 1 : 15,840 to 1 : 40,000 scale. Potential trench sites were identified and then field-checked, with large-scale geomorphological maps made of the trench site vicinity. Trenches up to 50 m long and 6 m deep were then excavated across the fault scarps with either small rubber-tired backhoes or by large track-mounted excavators.

Trenches were stabilized, cleaned, gridded, and logged following standard palaeoseismic techniques (outlined by McCalpin 1989). Interpretation of individual palaeoseismic events relies heavily on mapping of the colluvial stratigraphy near the fault planes. This "colluvial wedge paradigm" for palaeoseismic interpretation was first proposed by Swan et al. (1980), and elaborated by Hanson & Schwartz (1982) and Schwartz & Coppersmith (1984); reviews of the method for dip-slip faults are provided by McCalpin (1987, 1989).

The East Cache fault

The East Cache fault zone (ECFZ) is the first in a series of northeasterly-stepping faults northeast of the Wasatch fault zone. Although the ECFZ is roughly 90 km long, late Quaternary fault scarps are limited to an 8 km-long reach east of Logan, Utah. The ECFZ was initially trenched in 1985. Based on combined radiocarbon and thermoluminescence dating, McCalpin & Forman (1991) recognized two faulting events in the 1985 trench. The first event, with a vertical displacement of 1.9 m, probably occurred betwen 13 ka and 15.5 ka, soon after the site was subaerially exposed after the recession from the high (Bonneville) shoreline of Lake Bonneville.

The age of the latest event, accompanied by displacements of 0.5–1.3 m in the 1985 trench, was poorly constrained at between 4 ka and 7 ka. To narrow this time interval, a smaller trench was excavated in 1991 across a 1.3 m-high scarp on a latest Pleistocene river terrace. Three concordant radiocarbon ages bracket the latest faulting event at 4 ka (McCalpin in press). The estimated recurrence interval between the two latest events thus range from 9 ka and 11.5 ka, with the elapsed time since the latest event at 4 ka. The relatively small displacements observed in trenches (0.5 -1.8 m per event), and the limited length of fault scarps at the range from (8 km), imply moderate-magnitude palaeoearthquakes (M_s 6.0–7.0).

The Bear Lake faults

The Bear Lake graben is a 80 km-long, 7–14 km-wide, north-trending graben that straddles the Utah-Idaho border (Fig. 1) northeast of Cache Valley. Previous workers (Mansfield 1927, Oriel & Platt 1980, Kaliser 1972, Witkind 1975, Robertson 1978) documented the existence of Quaternary normal faults on both valley margins, informally named the eastern and western Bear Lake faults (Fig. 1).

The Eastern Bear Lake Fault

Seismic data (Evans & Oaks 1990, Evans 1991) show that the eastern Bear Lake fault, at least in its central sections, dips approximately 60–70° west. The normal fault probably merges with a ramp in the Meade Thrust at a depth of 6–7 km, and has a net throw of at least 4.9 km. We divide the fault into three segments, each ca. 20–35 km-long, marked S(outh), C(entral), and N(orth) on Fig. 1. Currently only scarps on the southern segment have been trenched (McCalpin et al. 1990a).

Trenches on the Southern Segment. Two trenches were excavated on the southern segment of the eastern Bear Lake fault across parallel fault scarps 8 m and 14 m high, respectively, that displace late Quaternary deltaic gravels. Fig. 2 shows the log of the south wall of the western trench. Six major stratigraphic units were distinguished, from which three radiocarbon ages were obtained (see Fig. 2). The fault zone in the western trench is complex, including a major west-dipping fault under the scarp center, several near-vertical small-displacement faults that bound toppled blocks, and a vertical to east-dipping shear system under the scarp toe.

Based on stratigraphic superposition, cross-cutting relationships, and sedimentology, the reconstructed sequence of events is as follows. Soil formation on prefaulting deposits (units 1–3) had commenced by 9150±110 yr BP (Fig. 2), when loess began to be deposited on the surface. For the next several thousand (?) years,

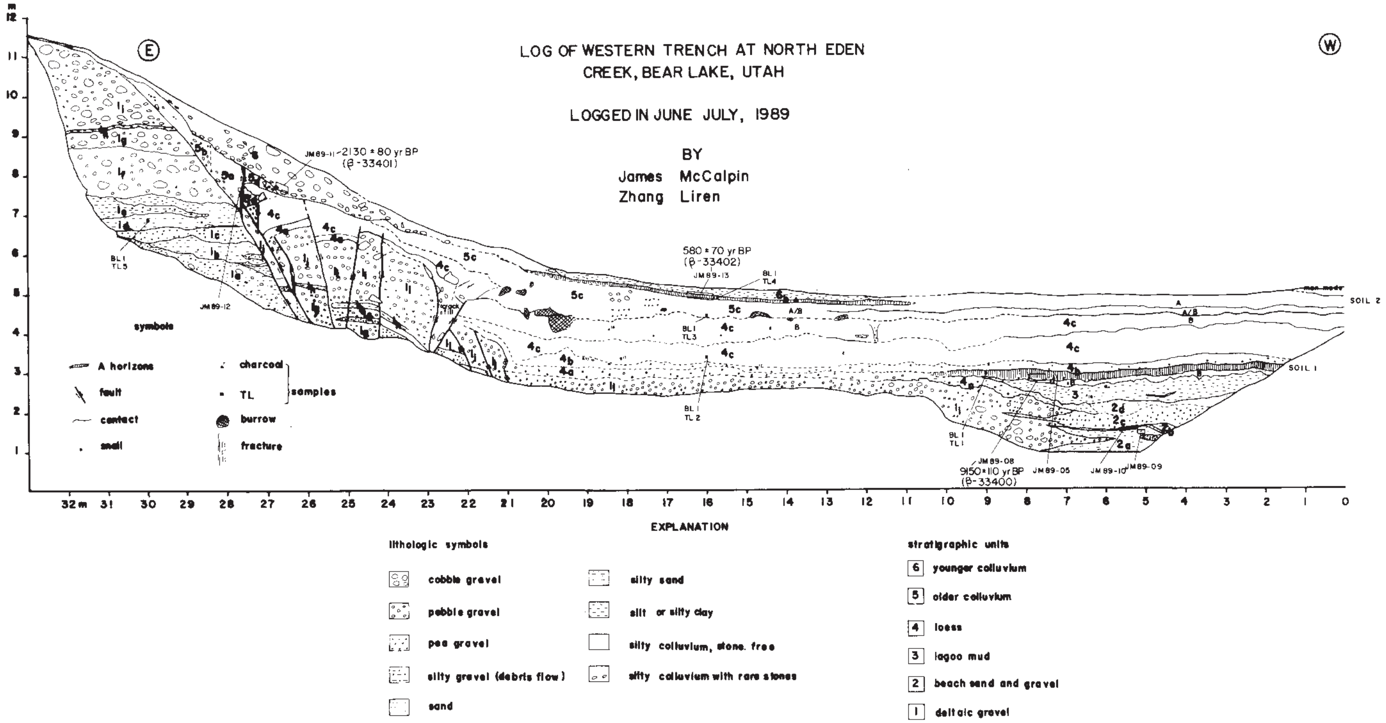

Fig. 2. Log of the western trench on the eastern Bear Lake fault, Utah. The existence of two scarp-derived colluvial wedges (units 5 and 6) indicates two paleoseismic events, the latter of which occurred ca. 2130 ± 80 yr B.P. Locations marked JM89-… and BL1, TL… indicate radiocarbon and thermoluminescence samples, respectively, that are still being analyzed.

loess accumulated to a thickness of 1.5 m. Loess maintains a constant thickness and uniform grain size right up to the fault zone, indicating that no fault scarp existed at the time of its deposition.

After loess deposition, the ground surface stabilized and an A/AB/B soil horizon developed on the loess (on unit 4c). The loess and its soil were offset by an earlier faulting event that produced displacement on both the eastern and western boundary faults. Colluvium shed from scarp free faces (Units 5a, 5b, 5c) is found valleyward of both faults. The age of this earlier faulting event is not well constrained, because the age of unit 4 and its soil are not known. If we assume that deposition of the 1.5 m of loess required at least 1.5 ka, and the development of a soil B horizon required an additional 3 5 ka, then the earlier faulting event must have occurred 4.5 to 6.5 ka after the radiocarbon age of 9150 ± 110 yr BP, or from ca. 2.6 ka to 4.6 ka.

Only a short time separated the earlier from the later faulting events in the western trench. This short time span is indicated by: 1) lack of a well-developed soil on the earlier colluvium near the eastern boundary fault underneath the younger colluvium, and 2) a weak soil A horizon separating the upper part of the older colluvium (unit 5c) from the distal part of the younger colluvial wedge (unit 6). The latest event is closely dated by a radiocarbon age of 2130 ± 80 yr BP (β-33401) from the base of scarp-derived colluvium (unit 6).

Palaeoearthquake recurrence and magnitude: Based on the assumed loess deposition and soil formation rates quoted above, the estimated interval between the two inferred palaeoearthquakes is 0.5 ka to 2.5 ka. In contrast, the time span of tectonic quiescence preceding the earlier event was much greater. Radiocarbon ages from another trench and natural exposures indicate that the upper part of unit 1 was deposited ca. 12.7 ka, thus the 2.6 ka–4.6 ka event is the only event to have occurred in the period 12.7 ka to 2.6–4.6 ka. The resulting minimum recurrence interval between the earlier event seen on this fault strand, and any previous event, is thus 9.1 ka to 10.1 ka.

Palaeoearthquake magnitudes can be estimated based on the net stratigraphic throw of 8.3 m, based on offset of the top of unit 1j. The earlier rupture was clearly responsible for the 3.4 m throw on the western boundary fault, because the overlying colluvium (unit 5c) was not subsequently faulted in the later event. Additional displacement in the earlier event on the eastern boundary fault can be estimated as twice the maximum thickness of colluvium (2 × 1.1 m = 2.2 m), following the method of OSTENAA (1984). If we apply the same method to the maximum 1.3 m thickness of the colluvium shed from the later event on the eastern boundary fault (unit 6), we estimate throw at 2.6 m (2 × 1.3 m). The sum of these throw estimates (3.4 m + 2.2 m + 2.6 m) equals 8.2 m, which is very close to the net throw across all faults of 8.3 m. Thus, it appears that the earlier faulting event (2.6 ka to 4.6 ka?) was accompanied by a net down-to-the-west throw of 5.6 m here, whereas the later event (ca. 2.1 ka) was accompanied by only 2.6 m of throw.

These displacements suggest a minimum M_s of 7.5 ± 0.3 for the earlier palaeoseismic event, and a minimum M_s of 7.3 ± 0.3 for the later palaeoseismic event (BONILLA et al. 1984, all faults data set). A surface rupture that would have broken the entire southern segment of 32 km length implies a $M_s = 7.1 \pm 0.3$ earthquake. For the later event, the displacement-based and length-based magnitude estimates strongly overlap at one sigma, suggesting that the later event was restricted to the

32 km-long southern segment. For the earlier event, the displacement-based magnitude estimate (7.5 ± 0.3) is larger than, and barely overlaps at one sigma, the length-based magnitude estimate (7.1 ± 0.3). Displacements of 5.6 m are typically associated with ruptures with an average length of 68 km (range at one sigma 30 152 km; BONILLA et al. 1984, all faults data set). This apparent discrepancy between displacement-based versus length-based magnitude estimates may simply reflect variation in the empirical (historic) data set. Alternatively, large earthquakes in this tectonic setting may yield larger displacements for a given rupture length than is typical of faults worldwide. This hypothesis is supported by data from the Star Valley, Rock Creek, and Grey's River faults (discussed later), all of which show abnormally large displacements in relation to inferred rupture lengths. A third possibility is that the abnormally large displacement (5.6 m) implies that the earlier event exposed in the western Bear Lake trench had a rupture length greater than 32 km, possibly involving part or all of the central segment (length = 26 km). Holocene faults scarps do extend the full length of the central segment, but have not yet been dated. As DEPOLO et al. (1989) have shown, all historic earthquakes of $M_s > 7$ in the Basin and Range Province have ruptured multiple geometric or structural segments.

The eastern trench on the Bear Lake fault dissected a broad scarp roughly 10 m high and exposed 10 major stratigraphic units (Fig. 3). The eastern trench exhibits three widely-spaced fault zones of different ages. The eastern fault zone (24 m on Fig. 3) is a poorly-defined zone of minor fractures and warping with a net stratigraphic throw of 1.2 m. The central fault zone is a well-defined zone of down-to-the west normal faulting and shear rotation of gravel clasts; stratigraphic throw is 1.9 2.1 m. The western fault zone consists of two discrete faults, the eastern of which has negligible displacement. Throw on the main western fault cannot be measured because unit 1 is not exposed on the downthrown block. Projection of the top of unit 1 q westward, and measurement from that projection to the bottom of the trench, indicates that the net throw on all three fault zones must be at least 14.6 m. Because the eastern and central fault zones account for only 3.1 m to 3.3 m of throw, the western fault zone must account for the remainder, or at least 11.3 to 11.5 m of throw.

Sequence of Events: Unit 1 was deposited as a series of beach and fan-delta gravels, probably in mid-late Pleistocene time. While the trench site was still near lake level, the first faulting event occurred, on the eastern fault zone (throw = 1.2 m). Surface rupture of the soft deltaic sediments opened up a graben into which the active stream channel was diverted. This stream channel deposited the lenticular gravels of unit 2, and cut the channel into which unit 3 colluvium was shed. At some later time, faulting began on the western fault zone. The 11.3–11.5 m of throw must represent at least two faulting events, but the colluvium shed from those events (unit 4 a) is not completely exposed, was partially removed by erosion by unit 5, and is not differentiable into sub-units. After activity ceased on the western fault zone, the scarp free face (as defined by WALLACE 1977) retreated upslope and unit 4 b was deposited unconformably against the degraded free face. By this time the scarp had attained most of its present height (i.e., 12.5–12.7 m of the toal 14.6 m).

Following deposition of unit 4, lake level rose and an active beach began to erode the base of the scarp. This erosion removed much of the distal part of unit 4 (note the oversteepened nature of the unit 4 b/unit 6 contact) and left a 1 m-thick lag gravel

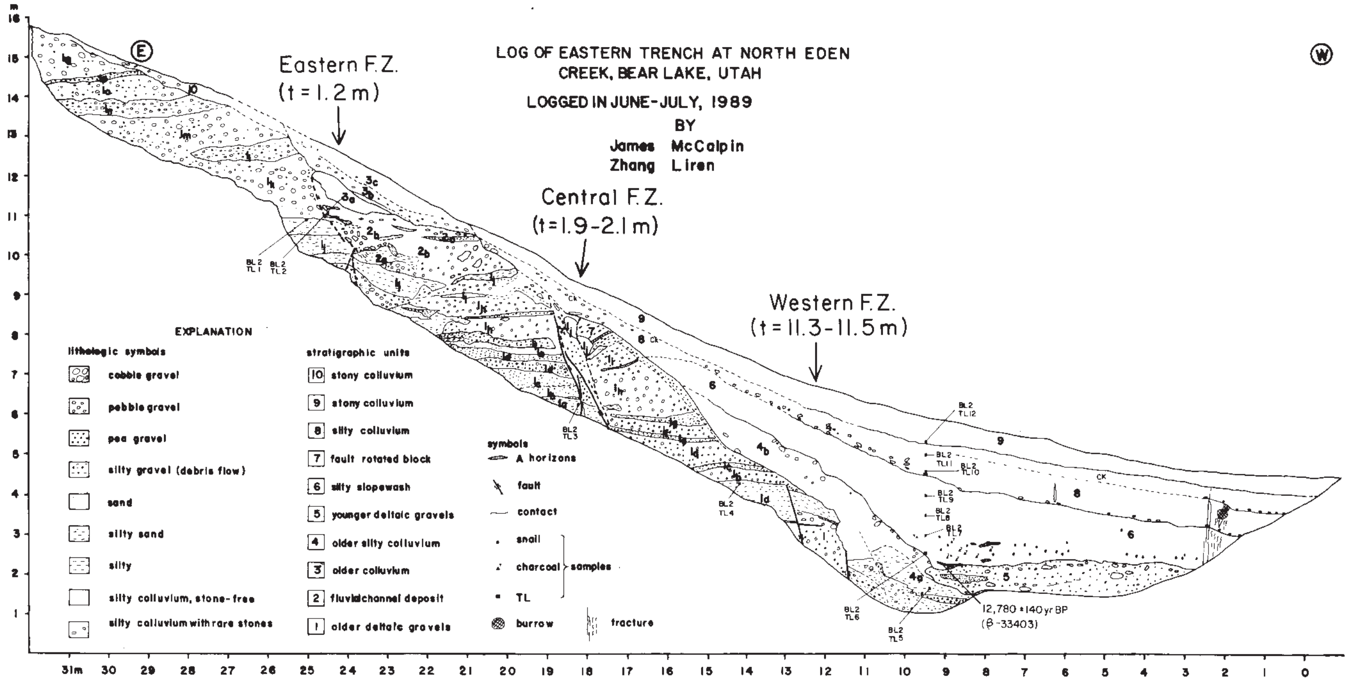

Fig. 3. Log of the eastern trench on the eastern Bear Lake fault, Utah. Three discrete fault zones (Eastern F.Z., Central F.Z., and Western F.Z.) display throws of 1.2–11.5 m. At least 4 palaeoseismic events must be inferred to explain the complex deformation on the three fault zones in this trench; see text for discussion. Locations marked BL2, TL... indicate thermoluminescence samples that are currently being analyzed.

with beach sands and shell fragments (unit 5). Beach and delta deposition at this time are dated at nearby sites at 9.1–12.7 ka. Eventually the lake shoreline receded westward, and the lower scarp face and beach gravels were buried by slopewash colluvium (unit 6). Weak buried soils in the lowest part of unit 6 yield an age of 12,780 ± 140 yr BP (β-33403), which is very similar to a nearby age from loess overlying deltaic gravels (12,700 ± 130 yr BP, β-33404). The stone-free, silty nature of unit 6 suggests it is mainly composed of reworked loess, which was blown onto and above the scarp face, and then retransported downslope to form this 2.5 m-thick wedge. The period of rapid loess deposition responsible for unit 6 may be the same period in which the 1.5 m-thick loess was deposited in the western trench, which is dated as beginning ca. 9.1 ka, and lasted a few ka.

After unit 6 was deposited, a faulting event on the central fault zone created a 1.9–2.1 m-high free face with a basal tension crack. Blocks fell into that tension crack (unit 7), but the bulk of the colluvium was spread down the steep scarp slope below the free face, creating the basal coarse zone of unit 8. As this free face degraded, finer colluvium was deposited as the upper part of unit 8. The exact age of this final faulting event in the eastern trench is unknown, because no datable material was found in the upper part of unit 6, unit 7, or unit 8. Therefore, it is possible that this event in the eastern trench could correlate with either of the two events revealed in the western trench (2.1 ka, and ca. 2.6–4.6 ka). Finally, post-tectonic colluvium covers the modern scarp face (units 9, 10).

Palaeoearthquake recurrence and magnitude: Only the latest event, on the central fault zone, is younger than 12.7 ka; all movements on the eastern and western fault zones are older. Palaeomagnitudes can be estimated for the 1.2 m-displacement event on the eastern fault zone ($M_s = 7.0 \pm 0.3$) and 1.9–2.1 m-displacement event on the central fault zone ($M_s = 7.2 \pm 0.3$) (after BONILLA et al. 1984, all faults data set). These estimates are minima because: 1) displacement at the trench site may not have been the maximum, and 2) contemporaneous displacement may have occurred on parallel fault strands. The 11.3–11.5 m of displacement on the western fault zone cannot be ascribed to a particular number of events, due to partial removal of the colluvial wedge, so magnitude estimates cannot be made. Conceivably 11.5 m of displacement could be created in as few as two large-displacement events, if displacements were on the order of those estimated for the earlier event in the western trench (5.6 m, see preceding section).

The Western Bear Lake Fault

The western side of the Bear Lake graben displays low fault scarps in swamp deposits for a 20 km distance between St. Charles and Ovid, Idaho (Fig. 1). The most prominent of these scarps is 8 m high and was termed the "Bloomington Scarp" by ROBERTSON (1978). The following interpretation of the latest faulting event is taken from MCCALPIN et al. (1990 a). Lacustrine strata at the site were deposited around 11,240 ± 90 yr B.P. At some time between 11 ka and 6.5 ka, a stream eroded through the Bloomington scarp and created the meander scars now west of the fault. The latest faulting event occurred with 1.5–2.0 m net throw, and uplifted the meander channel and floodplain west of the fault; basal radiocarbon ages date the abandonment of the channel at 6530 ± 90 yr B.P. Simultaneously the hanging-wall was downthrown, and the pre-faulting surface soil was buried by swamp silts and clays by 5900 ± 89 yr BP. These two ages suggest that the latest faulting event occurred about 5.9–6.5 ka. After degradation of the scarp and deposition of a thin swamp deposit at its base, the entire scarp was slowly buried by loess, the basal part of which contains organics dating at 1890 ± 70 yr BP.

Palaeoseismic recurrence and magnitude: The 1.5–2.0 m throw exposed in the trench argues for a minimum M_s of 7.1 ± 0.3 (BONILLA et al. 1984). The extent of surface rupture in the latest event is unknown. If rupture extended the complete length of visible surface scarps on the western Bear Lake fault zone (26 km), then a magnitude of 7.0 is indicated. Recurrence interval cannot be calculated with only a single dated palaeoseismic event. However, it appears that in the period 11.2 ka to the present, only one event has occurred at ca. 5.9–6.5 ka. This indicates a minimum recurrence interval of 4.7 to 5.3 ka before the latest event, and a minimum elapsed time of 5.9 to 6.5 ka subsequent to that event.

The Star Valley fault

The Star Valley fault is major west-dipping Neogene normal fault that bounds the eastern side of Star Valley in western Wyoming (Fig. 1). Late Quaternary fault scarps are limited to the southern part of the Star Valley fault (PIETY et al. 1986, 1992, MCCALPIN et al. 1990 b, WARREN & MCCALPIN 1992). According to DIXON (1982) the Star Valley fault is listric and merges into a ramp in the Absaroka Thrust at a depth of 2 km beneath the present valley floor.

Afton trench site. An 11 m-high fault scarp in outwash gravels was trenched in eastern Afton, Wyoming. Trench stratigraphy is shown on Fig. 4. The Afton trench is structurally simple, with almost all displacement occurring on a single fault strand in the eastern part of the trench (Fig. 4).

Based on the trench log, the following sequence of events can be deduced. First, the main aggradation surface of Swift Creek was deposited, probably in late Wisconsin time (ca. 15–20 ka) in response to glacial outwash from its headwaters. Only a short time elapsed between deposition of these gravels (unit 1 in the trench) and the first faulting event, as indicated by the lack of a buried soil atop unit 1 c in the trench. Scarp-derived colluvium was shed off the fault free face (unit 2). The basal part of unit 3 resembles a clast-free, sag pond silt, suggesting that local back-tilting had created a sag at the base of the scarp; note the anomalous eastern dips of units 1 b and 1 c. The tributary alluvial fan (unit 3) was then deposited, and 2 m of predominantly fine-grained fan sediments were deposited against the scarp face. Anomalously large gravel clasts are incorporated in unit 3 near the fault (unit 3 c), showing that the scarp acted as a local source of reworked Swift Creek gravels. A long time span ensued after stabilization of the alluvial fan surface (several ka), as evidenced by the 50 cm-thick textural B horizon and underlying Cca horizon in unit 3.

The second faulting event then occurred, created a large free face, and rapidly shed unit 5. Unit 5 buried the soil atop unit 3 at ca. 8090 yr BP. As deposition rates on the colluvial surface slowed, an organic A horizon developed on unit 5. This soil

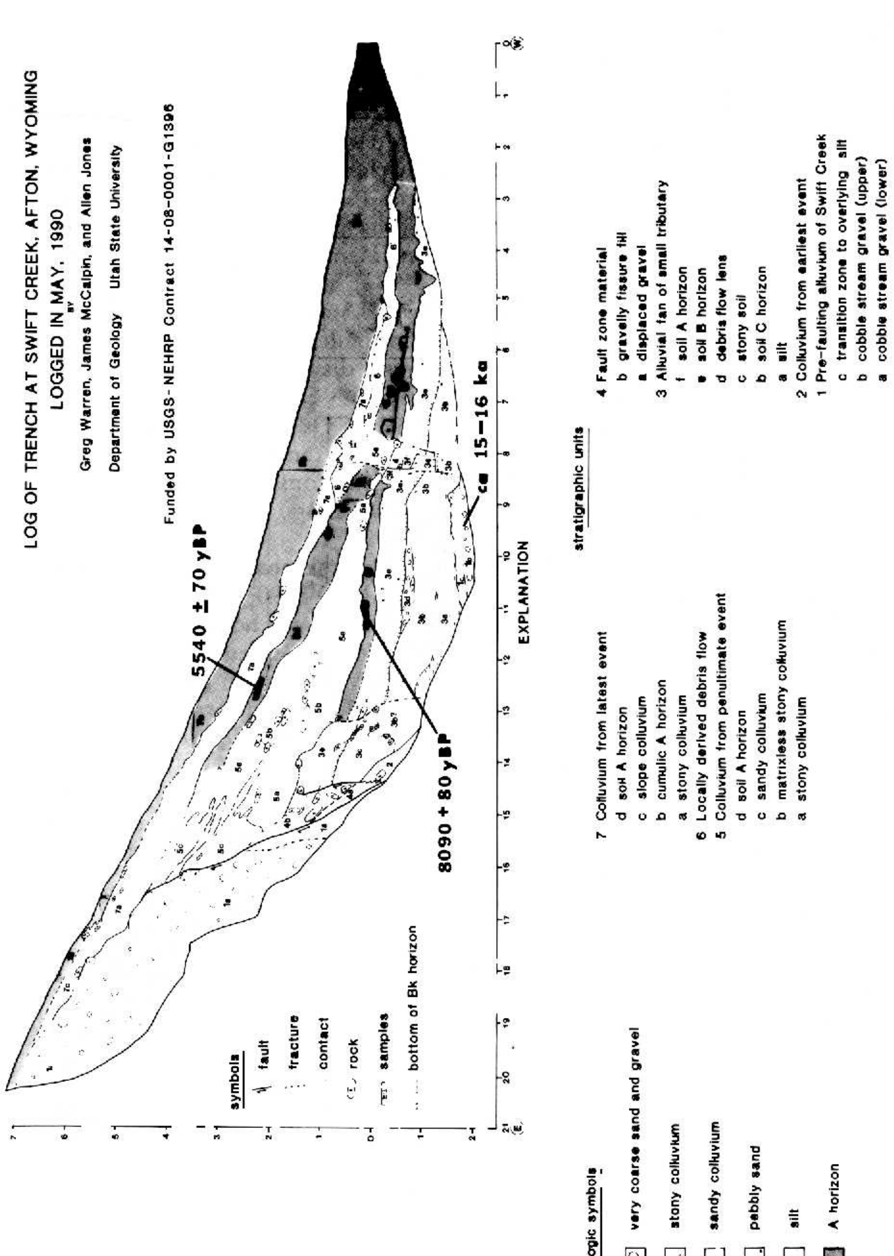

Fig. 4. Log of the Afton trench on the southern segment of the Star Valley fault, Wyoming. Shaded areas show organic-rich soil horizons. Three scarp-derived colluvial wedges (units 2, 5, and 7), along with geomorphological evidence, indicate the trenched scarp was created by three palaeoseismic events.

was buried immediately after the latest event (ca. 5540 yr B.P.) by unit 7, which comprises the scarp-derived colluvium of the latest faulting event.

Palaeoearthquake magnitude and recurrence: Displacement in the earliest faulting event must equal 4 m, the difference between surface offset of the outwash (11 m in three events) and that of a Holocene tributary fan just south of the trench site (7 m in two events). The 7 m of displacement which occurred in the second and third events at the trench site was probably unequally partitioned between those two events. The maximum 2 m thickness of unit 5 colluvium suggests that the causative free face created in the second event may have been twice this height (i.e., 4 m). If so, then the displacement in the latest event would have been only 3 m (7 m minus 4 m), a number which is slightly greater than twice its maximum colluvial thickness (1.2 m for unit 7). According to BONILLA et al. (1984), maximum displacements of 3 m and 4 m occur during earthquakes of M_s 7.3 ± 0.3 and 7.4 ± 0.3, respectively. The length of the southern segment of the Star Valley fault in which Quaternary fault scarps can be identified is only 17 km. In contrast, displacements of 3–4 m are associated with surface rupture lengths which average 51–58 km (range at one sigma = 22–130 km). This discrepancy could be explained if Quaternary fault scarps on the southernmost portion of the northern Star Valley fault (an additional 16 km long) were also created by these three ruptures. However, the combined inferred rupture length of 33 km still barely overlaps (at one sigma) the range indicated by displacement data.

The latest two faulting events at the Afton side are reasonably well constrained by radiocarbon ages on buried soils at 5540 ± 70 yr BP and 8090 ± 80 yr BP. The age of the earliest event is not precisely known, because no organic horizon soil is found beneath the colluvium shed after that event. The lack of a buried soil suggests the time between outwash deposition and initial faulting was less than the 2550 yr span between the latest two events, over which a recognizable soil did form. The estimated age of the earliest event at Afton is thus ca. 0.5–1.5 ka after the end of the Pinedale glaciation (assumed age of unit 1, ca. 16 ka) or ca. 14.0–15.5 ka. The recurrence intervals between the three events thus may range from ca. 5.9–6.4 to 2.5 ka. The elapsed time since the latest event (5.5 ka) is thus similar to the longer estimated recurrence interval, and is roughly twice as long as the shorter interval between the two latest faulting events.

The Grey's River fault

The Grey's River fault (informal name proposed herein) trends north-south for 56 km between the Salt River Range and the Wyoming Range in northwestern Wyoming (Fig. 1). For most of its length it displaces upper Triassic and Jurassic strata down against Permo-Pennsylvanian or lower Triassic strata, with throws estimated by RUBEY (1973) as between 300 m and 1000 m. Structure sections interpreted from seismic reflection data show that the Grey's River fault sharply truncates the upper flat of the Darby Thrust, but then flattens with depth and merges with the master Absaroka/Darby/Prospect decollement at a depth of 8.2 km (WEBEL 1987, Fig. 13). In this respect its structural relations mimic those interpreted for the Star Valley and eastern Bear Lake faults.

Sheep Creek trench site. Three trenches were excavated in a late Wisconsin (15–20 ka?) outwash terrace complex in Sheep Creek, across a 7.5 m-high scarp, a 3.1 m-high scarp, and a 10 m-high scarp-graben pair. Trenches revealed evidence for two palaeoearthquakes, the ages of which were constrained by eight radiocarbon ages (Jones & McCalpin 1992). The latest event was accompanied by a vertical displacement of 5 m and is bracketed between radiocarbon ages of 1910 ± 60 yr B.P. and 2110 ± 60 yr B.P. The earlier event had a displacement of 4.3 m, and occurred ca. 5080–5300 yr B.P.

Palaeoearthquake recurrence and magnitude: Based on displacements of 4.3–5.0 m and surface rupture lengths of 30 km (the extent of Holocene scarps), palaeoearthquake magnitude ranged from M_s 7.1 to 7.5 ± 0.3. If the estimated age of the outwash surface (15–20 ka) is correct, then no faulting events occurred between 15 ka and 5.3 ka, yet two events have occurred since that time, separated by a time span of 3.0–3.4 ka. This irregular recurrence appears to be typical of faults in this region.

The Rock Creek fault

The Rock Creek fault trends north-south for 33 km between two parallel ridges that comprise the Tunp Range, roughly 30 km northwest of Kemmerer, Wyoming (Fig. 1). Total down-to-the-west throw on the Rock Creek fault is 300 to 500 m (Rubey et al. 1975). The position of the Rock Creek fault immediately west of the tip of the Tunp Thrust suggests that it may sole into the thrust at a shallow depth, perhaps utilizing a steep pre-existing ramp, as is interpreted for the Grey's River, Star Valley, and Bear Lake faults (Royse et al. 1975, Dixon 1982). Eastward rotation of Tertiary and Quaternary strata into the Rock Creek fault (Rubey et al. 1975, Plate 2, section C-C′) is compatible with such listric slip.

Surface fault scarps up to 25 m high occur for at least 25 km along the Rock Creek fault. Scarps are most often developed in steep (15°–25°) colluvial slopes at the base of the range front, but lower scarps (6–8 m high) traverse alluvium in tributaries to Rock Creek. The discussion below is summarized from McCalpin & Warren (1992).

Cook Canyon trench site. A 6.4 m-high fault scarp that displaced late Quaternary alluvium was trenched in Cook Canyon, a tributary to Rock Creek. Stratigraphic throw exposed in Quaternary strata in the trench was > 11 m, showing that at least 5 m of Holocene alluvium had been deposited against the fault on the downthrown block. This alluvium was faulted against Wells Formation (Pennsylvanian sandstone) between 3280 ± 70 yr B.P. and 3880 ± 60 yr B.P. Colluvial wedge thickness suggests a 4–5 m displacement during this event. An earlier faulting event of unknown throw occurred before 4470 ± 70 yr B.P., possibly ca. 4800 yr B.P.

Palaeoearthquake magnitude and recurrence: Estimated displacements imply earthquakes of M_s 7.4 to 7.5 ± 0.3 (Bonilla et al. 1984). In contrast, a surface rupture length of 25 km implies considerably smaller earthquakes (M_s 7.0). The discrepancy suggests that the latest rupture (at 3.2–3.8 ka) may have extended beyond 25 km, but ensuing erosion has obscured the small-displacement ends of the rupture. If the estimated age of the penultimate event is correct, then only 1.0 - 1.6 ka separated the two latest events. In contrast, if the faulted alluvium is of late glacial age (15 ka), then no additional events occurred between 15 ka and 4.8 ka. This clustering of events in the mid-late Holocene is very similar to that inferred for the Grey's River fault.

Spatial and temporal trends of palaeoseismicity

The Holocene Pattern

Numerical ages are available for 15 palaeoseismic events within the last 15–20 ka on the northeastern margin of the Basin and Range province (including the Wasatch and Teton faults). The spatial-temporal relation of these events is shown on Fig. 5. Several trends are apparent. First, the recurrence times on the two end faults (Wasatch and Teton) have been much shorter than on the six central faults. Radiocarbon ages document recurrence periods on the Wasatch fault from about 1.1 ka up to 3.5 ka (Machette et al. 1991, 1992). The Teton fault, although it has not experienced a surface rupture in the last 7.1 ka (Byrd & Smith 1990), must have had ca 2–4 ruptures in the period 7.1 ka–15 (?) ka (end of the latest glaciation) to account for large scarps across moraines (Gilbert et al. 1983), implying an average recurrence interval of 3–4 ka. In contrast, recurrence times on the central faults are as long as 11 ka.

Second, recurrence intervals on the central three faults vary by a factor of two or more on each fault, but the range of values is similar for each fault (2.5–6.0 ka). Third, there seems to have been a pulse of seismicity shared by all faults (except the Teton fault) in the period 2–6 ka. Prior to that time a long quiescent period appears on the Grey's River, Star Valley, Bear Lake, and East Cache faults in the period between 8 ka and 12–15 ka.

Several conceptual hypotheses have been formulated to explain how Neogene extensional strain is released through the northeastern Basin and Range. The first theory is that rapid extension on the Wasatch fault, the major eastern boundary fault of Basin and Range, would propagate northeastward. This would result in an general eastward progression of faulting on west-dipping listric faults, or a crustal-scale analog to retrogressive slump failure in a landslide complex. In this scenario, events on the Brigham City segment of the Wasatch fault would be sequentially followed by events on faults farther to the northeast. Fig. 5 shows that this hypothesis is invalid, because the last two (and possibly three) ruptures on the Brigham City segment have not triggered subsequent ruptures on the East Cache fault.

A second, similar, hypothesis is that the Teton fault, lying closer to the Yellowstone hot spot, would act as the high-slip-rate initiator of seismic pulses, spawning rupture sequences that would migrate southwestward with time. Again, Fig. 5 shows that this has not occurred. There have been no ruptures on the Teton fault within the last 7.1 ka, yet in that same time span there have been ruptures on all the other faults.

A third hypothesis is that regional extension is accomplished either on the long end faults, or on the shorter central faults, but at different times. For example, at the northeastern corner of the Basin and Range, the Teton fault must have been slipping

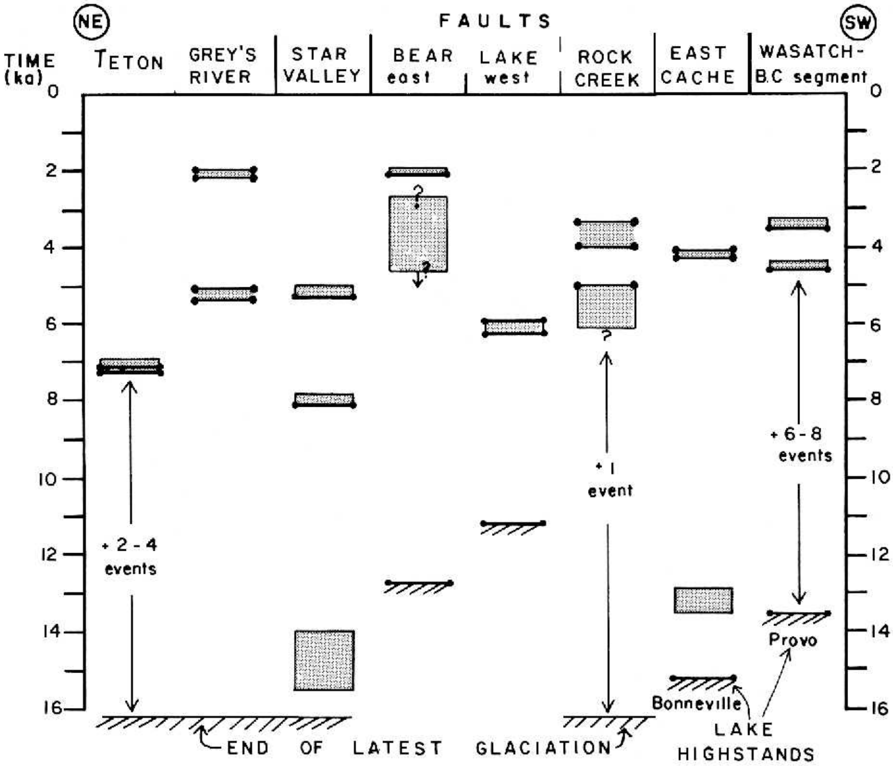

Fig. 5. Distribution of palaeoseismic events in space and time on the northeastern margin of the Basin and Range province. Shaded boxes show inferred time periods for palaeoearthquakes, as bracketed by radiocarbon ages (black dots). Horizontal lines with diagonal hachures at bases of each column indicate the oldest Quaternary stratigraphic unit investigated.

rapidly in the period between 15–20 ka and 7.1 ka, but has locked since 7.1 ka. In contrast, the adjacent Star Valley fault was relatively quiet in the early Holocene, but has had two ruptures since about 8 ka. In this scenario, a period of quiescence on one fault must be accompanied by a period of tectonic activity on the adjacent fault. Based on the above example, these alternating periods of quiescence and activity are ca. 7–8 ka long on each fault.

The fourth hypothesis is that the spatial/temporal pattern shown in Fig. 5 is entirely random. The plausible causative mechanism for such a situation was proposed by Wallace (1989), wherein a thick, prefractured crust is extended from beneath by mantle-scale forces. Because the extensional force is applied uniformly throughout the slab from its base, the exact location and timing of future ruptures is not predictable.

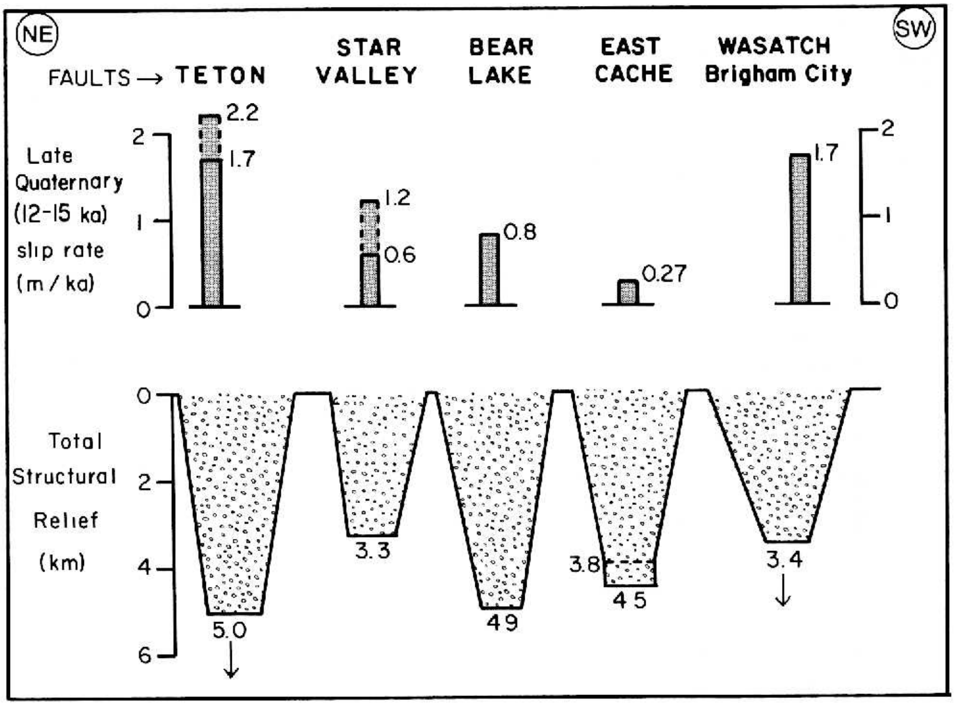

Fig. 6. Comparison of late Quaternary fault slip rates (top row) with total structural relief (bottom row) in the large Neogene grabens on the northeastern margin of the Basin and Range Province. Dashed lines reflect uncertainties in ages of displaced Quaternary surfaces (top row) or in thickness of Neogene graben fill.

The Late Cenozoic Pattern

The late Quaternary slip on studied faults can be compared to the long-term (late Cenozoic) slip rate by looking at total Neogene structural relief in each of the large western grabens (Fig. 6). Total structural relief since the onset of extension (Miocene?) can be estimated based on: 1) maximum depth of Neogene basin fill beneath the valley floor from gravity or seismic data, 2) present height of pre-Cenozoic bedrock above the valley floor on the upthrown block. Fig. 6 shows that total structural relief across the major graben-bounding faults is similar, even though late Quaternary slip rates are high on the end faults and low on the central faults.

This disparity between slip rates in the last 15 ka vs in the last ca. 15 my could result from several factors. First, the long-term slip rates on all faults could be similar, but the "seismic cycle" of some faults may be greater than 15 ka. "Seismic cycle" as conceived herein would encompass alternating periods of tectonic activity, involving several palaeoseismic events within 15 ka or more, alternating with periods of quiescence lasting a similar length. If such cycles have considerably longer periods than 20–30 ka, then the "time window" of the last 15 ka may have caught each fault in a different phase of its cycle.

A second possibility is that the observed short-term slip rates on each fault are typical of their long-term slip rates, but that each fault initiated at a different time. Thus, the low late Quaternary slip rate of the East Cache fault, compared to its large structural relief, would be explained if the East Cache fault began slipping considerably earlier than other faults. This hypothesis is difficult to test because the age of the oldest basin fill in each graben is not known, so the age of graben initiation can only be surmised. In some cases it is unlikely that there is a great age difference between adjacent structures. For example, it is unlikely that the Wasatch fault zone, being a much larger structure than the East Cache fault (400 km vs 80 km), is actually the younger structure. Regional tectonic models proposed by ANDERS et al. (1990) and WEST (1988) suggest an eastward-younging of extensional structures in the Overthrust Belt, which would indicate that the Wasatch fault zone is older than, not younger than, the East Cache fault.

A third possibility is that short-term slip rates on all faults, like long-term slip rates are all similar, and that something has restrained slip on the central faults in the last 15 ka. In this scenario a "slip deficit" has been accumulating on the central faults which must eventually be released by surface-rupturing earthquakes. If this scenario is correct, then the East Cache fault can be identified as the central fault lagging the farthest behind, and the most likely to "catch up" with future slip.

Probable sites of future large earthquakes

There are two ways to assess the likelihood that a particular fault will rupture in the future based on a palaeoseismic record such as shown in Fig. 5. The first is to compare, for each fault, the typical recurence interval with the elapsed time since the latest event. As the elapsed time increases up to and beyond the typical recurrence time, impending slip is suggested. By this criterion, the two most likely faults to slip next are the Teton fault (elapsed time 7.1 ka, typical recurrence 3–4 ka) and the Wasatch fault (elapsed time 3.5 ka, typical recurrence 1.5–2 ka).

The weakness in this method is determining the mean value and standard deviation for recurrence interval, considering that only two or three palaeoseismic events have been dated on each fault. An average recurrence can be estimated by dividing large scarp heights on older geomorphic surfaces, like the 22 m displacement of Provo (13 ka) deltas on the Brigham City segment (PERSONIUS 1991), and assuming a typical displacement per event of 2–3 m. In this example 22 m of offset requires 7 to 11 events; in a period of 13 ka that results in an average recurrence interval of 1.2 to 1.8 ka. However, these numbers may be misleading, if recurrence and slip per event have large variations through time. The palaeoseismic record of the Wasatch fault zone in the last 5–6 ka includes 17 events (MACHETTE et al. 1991, 1992) and shows more irregularity than regularity in recurrence for individual fault segments. Because of the poor statistical nature of recurrence data in this study, a comparison with elapsed time does not carry high confidence for prediction.

The alternative procedure is to compare a fault's late Quaternary slip rate with its long-term slip rate, and look for anomalously low recent slip rates. Using this procedure, the most likely sites for future ruptures are the central faults of the NWTC, especially the East Cache fault. Note that this is just the opposite conclusion to that suggested by the previous procedure. The weak point in this second procedure is that it assumes that short-term slip rates are trying to duplicate the long-term rates, when in fact individual faults may have slowed down or speeded up over periods of tens or hundred of ka. The problem of slip rate variations over the last 15 m.y. is obviously beyond the reach of this paper; however, it must eventually be solved before we can choose which of the above two prediction procedures is more realistic.

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