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Structural Setting of Seismicity in Northern Utah

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Project Summary

Seismic-reflection profiles, drill-hole data and a new geologic map have been used to examine the distribution and form of normal faults and fault-related basins east of the Wasatch fault. These data place constraints on models for the evolution of extension in the eastern Basin-and-Range Province and help determine the possible sources of seismicity in the area. The major fault zones from west to east are: 1) the West and East Cache, 2) the Temple Ridge, 3) the West and East Bear Lake, and 4) the Crawford faults. Geologic map data and subsurface seismic-reflection profiles from northern Utah show that numerous normal faults are responsible for the extension of the region. In addition to slip on major faults of the area, small-displacement normal faults with little or no surface expression exist in the Bear River Range and may be responsible for small to moderate earthquakes in the range. Some of small and large-displacement normal faults in the region may be related to ramps in Sevier thrust faults, whereas others do not have a clear relationship to pre-existing structures of any age.

The East Cache normal fault zone and the Cache Valley basin exhibit several changes along strike. The Cache Valley basin is bounded on its west side by a steeply dipping West Cache fault zone, which dies out towards the southern end of the valley. At the southern end of the basin faults of the East Cache fault zone dip 65° to 70° near the surface and 50° at depth, and have 7.6 to 8.1 km of net slip. A narrow basin of east-dipping strata lies west of the fault zone. In the central portion of the Cache Valley the East Cache fault has 4.5 to 6.4 km net slip, and the basin is bounded by the East and West Cache faults. The subsurface data suggest that the West Cache fault became active later than the East Cache fault. Slip on the East Cache fault decreases to 2.5 km at the northern end of the basin. In the northern part of the Cache Valley Basin, west of the East Cache fault, the basin is a broad, shallow structure filled with Tertiary sediments. Average slip rates calculated over the past 10 million years for the East Cache fault zone are 0.15 mm/yr along the northern part and 0.8 mm/yr along the southern part. Slip along the central part of the West Cache fault has resulted in westward tilting of the youngest Tertiary sediments to form a doubly-tilted basin. To the north along the western edge of the valley, numerous normal faults bound several blocks of Tertiary and Paleozoic rocks, but slip on these faults appears to be modest.

The Temple Ridge fault zone, near the center of the Bear River Range, likewise exhibits along-strike variation in map expression and net slip. On its central segment, the fault has up to 750 m of post-Wasatch Formation throw along one major fault and two smaller faults that dip 70° to 85° west near the surface. Southward, offset is on many faults of moderate throw in a stair-stepped arrangement. Most of these faults also dip 70° to 85° west at the surface, and cumulative throw is at least 325 m. In order for the Temple Ridge fault to have been responsible for the 1962 M_L 5.7 Cache Valley earthquake, as suggested by Westaway and Smith (1989), the fault would have to flatten to ~45° dip at a depth of about 10 km in the Bear River Range.

The East Bear Lake fault zone in southeastern Idaho is a listric normal fault which appears to sole into the underlying Meade thrust. At the southernmost part studied, just north of Bear Lake, the fault dips 65° to 70° west near the surface, and flattens to 30° dip at a depth of 6 km. It has a net Tertiary slip of 4.0 km. Tertiary strata in the hanging-wall of the fault form the east-dipping limb of an asymmetric, east-verging rollover anticline cut by numerous antithetic normal faults with small displacement. Ten kilometers to the north the basin is a nearly symmetrical graben bounded on both sides by the East and West Bear Lake normal faults, and Tertiary strata have gentle eastward dips across nearly the entire width of the graben. Small normal faults dipping steeply east and west have been interpreted above the ramp in the Meade thrust. Either these steep faults or reactivation of the Meade thrust with normal-fault offset could have been responsible for the 1988 Bear Lake earthquake.

The Crawford normal fault is a listric fault which merges with the Crawford thrust at depth. Net slip along the fault is 1.5 to 1. 9 km, and a small prism of sediment fills a basin above the fault west of the surface trace of the normal fault.

Introduction

The region east of the Wasatch fault zone in northern Utah is characterized by small to moderately sized back valleys which formed by slip along north-striking normal faults (Gilbert, 1928; see Figure 1). The area is characterized by relatively small magnitude but frequent seismicity whose structural setting is poorly documented. Four earthquakes of magnitude 4.0 or greater have been recorded in the region (Figure 1 and Table 1) and a fifth has been inferred by Arabasz and others (1978) to have occurred in the Bear Lake area. The 1962 M_L 5.7 Cache Valley event is the largest instrumentally recorded event in the area. There is no consensus as to the form or location of the fault responsible for the earthquake (see Westphal and Lange, 1966 and Smith and Sbar, 1974 versus Westaway and Smith, 1989). Focal-mechanisms for the event suggest that the earthquake occurred by slip on a west-dipping or an east-dipping fault at a depth of 10 ± 3 to 12 km ± 3 km. Nodal planes for the preferred focal mechanism for the 1988 M_L 4.8 Bear Lake event both strike north-south, and are either nearly horizontal or nearly vertical (Pechmann, written comm., 1989). The foci of most of the instrumentally-located seismicity in the area are located within the Bear River Range and in regions of no known surface faults. The recorded seismicity of the region is at odds with the geologic evidence for large magnitude seismicity along the large-displacement, range-bounding faults in the region, including the East Cache and the East Bear Lake faults (McCalpin, 1989; McCalpin et al., 1990). The available geologic evidence indicates that large events rupture along the range-bounding normal faults, whereas contemporary seismicity documents rupture in a much more diffuse setting.

Table 1. Summary of earthquakes in northern Utah with magnitude 4.0 and greater. See Plate 1 and Figure 1 for location of epicenters.

Date	Magnitude (M_L)	Location (Lat. and Long.)	References
8-30-62	5.7	41° 55' ± 3' N, 111° 44' ±3' W	Westphal and Lange, 1966
			Smith and Sbar, 1974
		41° 54' N, 111° 48' W	Smith and Lehman, 1978
		41° 55' ± 3' N, 111° 44' ± 3' W	Westaway and Smith, 1989
10-18-64	4.1	41° 53.55' N, 111° 43.77' W	Richins, 1978
3-17-66	4.6	41° 39.66' N, 111° 33.63' W	Richins, 1978
11-19-88	4.8	41° 59.89' N, 111° 27.86' W	Pechmann, written comm., 1988
1884	6?	Bear Lake	Arabasz et al., 1978

This study examines in detail the setting of earthquakes from a structural geology point of view. I have assembled geologic and geophysical data to more accurately constrain the form and locations of faults at depth and to evaluate the influence of the pre-existing Sevier fold- and thrust-belt structures on the location and form of the extensional structures in the region. This work also documents the along-strike variations of faults and hanging-wall basins, and demonstrates the changes in structural style from the Wasatch fault eastward to the Utah-Wyoming border.

Methods of Investigation

The original goal of this project was to provide the Utah Geological and Mineral Survey with one regional geologic cross section and a strip map associated with this cross section to assess the structural setting of faults responsible for the seismicity in the region, and to specifically address the setting of the 1988 Bear Lake event. However, the wealth of data provided us by petroleum exploration companies, combined with new geologic mapping of the area related to other U. G. M. S. - supported studies, allowed us to revise and expand the scope of the study. The present work consists of five east-west regional geologic cross sections between 111^{o} and 112^{o} west longitude, several smaller cross sections across Cache Valley, Bear Lake Valley, and Crawford Valley, and a new preliminary 1:100,000 geologic map of the entire Logan and eastern part of the Tremonton 30'x60' quadrangles (Plate 1). This geologic map largely supersedes Dover (1985) in that it incorporates much new mapping published since 1985 (Plate 2), and mapping in the region which will be published in the next year (Evans et al., in prep., Oaks, in prep.).

Geologic map data were combined with seismic-reflection profiles acquired across the area (Figure 3) to draw regional and local-scale cross sections. The seismic-reflection profiles were acquired by five petroleum exploration companies in the 1970's and 1980's, range in quality from excellent to poor, and consist of both migrated and unmigrated sections. The reflection profiles were provided for our use in company offices, and we were able to make tracings of all usable data. Oil-field maps and drill-hole data were also provided for all of Cache and Rich counties. The data acquired in the Cache Valley were part of an Amoco exploration project for hydrocarbons in Tertiary basin-fill deposits in northern Utah (Patton and Lent, 1977), and the data are of good to excellent quality. This enables us to tightly constrain the form of faults in the area and the history of the Cache Valley basin. Data across the Bear River Range is of marginal quality, whereas the data from the Bear Lake Valley and Bear Lake Plateau are very good. The total data set consists of 160 km (100 mi) of seismic-reflection profiles in the Cache Valley and 195 km (120 mi) of profiles from Bear Lake Valley and the Bear Lake Plateau. Several cross sections were drawn across the Bear Lake Plateau in order to determine the regional setting of the normal faults. However, for much of the area east of Bear Lake I rely on the recent work of J. Coogan at the University of Wyoming (see Coogan and Royse, 1990).

The cross sections for the Bear Lake area were drawn to coincide with the results of his work to the east.

The seismic-reflection profiles from the Cache Valley were fully processed and migrated; most of the remaining lines were not migrated from time to depth sections. We have "hand" migrated the sections using ranges of velocities for the rocks of the region. These velocities come from velocity profiles for several drill holes and from recommendations of several exploration geophysicists familiar with the area (Table 2). Two-way travel times to key reflectors were converted to depth using the velocities in Table 2. True dips were calculated from the apparent dips where the reflection profiles were at angles to the section lines. A limited number of drill holes in the study area provide depth to formation tops and were used to check our migrations. While this hand migration is an admittedly crude method when compared to more sophisticated seismic modeling techniques, it has provided robust results for the determination of fault geometries and hanging-wall basin structure.

The cross sections emphasize the setting and form of normal faults and the hanging-wall basins which formed above the normal faults. The sections are not regionally balanced, as the Sevier fold and thrust belt telescopes a broad shelf to slope to deep-water section of Paleozoic rocks which exhibit a wide variation in thicknesses from the Utah-Wyoming border to the Wellsville Mountains (Coogan and Royse, 1990; Royse, 1990). In addition, cross-section balancing is made more difficult by the presence of eastward-thinning Proterozoic metasedimentary rocks in the Willard and Paris thrust sheets, wherein the location of the zero thickness line and variations of thicknesses from east to west are unknown. These cross sections thus represent our best estimates of the forms of the normal faults in the region, the shapes and histories of the hanging-wall basins, and the relationships among the locations of normal faults and the structures within the Sevier fold and thrust belt.

Table 2. Velocities used to migrate seismic-reflection profiles

rocks and	velocities(ft/sec)
Tertiary rocks above Wasatch Fm.	6000 - 8000
Tertiary Wasatch Fm.	10,000
Mesozoic and younger Paleozoic rocks	15,000 above 1 sec of two-way travel time
	17,000 below 1 sec of two way travel time
Middle and lower Paleozoic rocks	16,000 above 0.5 sec of two-way travel time
	19,000 below 0.5 sec of two-way travel time

I. Cache Valley

General Statement

The six east-west cross sections (Plates 3 and 4) and the north-south sections (Figures 4 and 6) correspond closely to the locations of seismic-reflection profiles provided by Amoco Production Company. The sections are based on the geology on either side of the basin and on the seismic-reflection profiles. The data for the Cache Valley basin will be discussed from the southern end of the valley to the north. Previous published work on the basin include Williams (1948, 1958) who suggested that the basin was broad and flat-bottomed, Peterson and Oriel (1970), and Mabey (1985,1987) who used gravity data to document a complex basin with several structural highs and lows, and Zoback (1983) who examined the region as part of a larger regional study. Zoback (1983) suggested that there is at least one east-west-trending gravity saddle in the central part of the basin which may correspond to a segment boundary of the East Cache fault system.

The southernmost part of the Cache Valley basin (Plate 3 A) is a narrow, deep basin bounded on the east side by the East Cache Fault zone. In the central and northern parts of the valley (Plates 3 B - 3 C and Plates 4 A-4C), the basin widens, Tertiary sediment thicknesses decrease, and both the East and West Cache fault systems bound the basin. The northern three cross sections across the valley (Plates 4 A - 4 C) show that total slip along range-bounding faults is distributed along a series of normal faults and net slip along these faults decreases. A series of shallowly to moderately dipping normal faults are located in the Bear River and Malad Ranges (Plate 4). Critical constraints on the depth of key reflectors and on the depth of Tertiary rocks are provided by the Amoco Lynn Reese drill hole (T 12 N, R 1 E, NWSW sec. 17; TD 8159 ft). Clem and Brown (1985) and Brummer (1990) reported a depth to the top of the Wasatch Formation of 7,395 ft, and a depth to the top of the Ordovician Swan Peak Formation of 7,750 ft (Plate 4 A). The drill hole encountered 335 m of Quaternary sediments and nearly 1900 m of Tertiary rocks.

The cross sections clearly demonstrate the changes in fault geometry, basin form, and slip rates along the East Cache fault zone. The data show that the basin is a deep trough above a single listric normal fault at its southern end, is fairly deep and bounded by two active normal faults along the central segment, and is shallow and bounded by several normal fault zones with much less slip in the northern segment.

Southern and Central Cache Valley Basin

The southern end of the Tertiary Cache Valley is a deep, asymmetrical sag basin (nomenclature of Anderson et al., 1983) bounded on the east by two strands of the East Cache fault (Plate 3 A). Tertiary sedimentary rocks and sediments dip approximately 25° east, and there is no evidence from either map data or reflection profiles that there is a fault of any appreciable displacement along the western part of the basin. Reflections from the seismic profile which I interpret to be due to the Tertiary basin-fill deposits have uniform dips of 20° to 25° east towards the East Cache fault system, and the strata appear to be unfaulted across the basin. Total slip along the East Cache fault system is 7.6 to 8.1 km (~25,000 to 26,500 ft) based on the offset of the interpreted base of the Tertiary sedimentary rocks. The base of the Tertiary rocks as shown in Plate 3 A is at a maximum depth of 3 km (10,000 ') below the surface. Taking dip of the fault into account, this suggests a roughly equal partitioning between footwall uplift and hanging wall subsidence. The estimate of slip along the East Cache fault has an unmeasurable error, as there are no footwall cutoffs in the Tertiary rocks. A footwall cutoff in this and subsequent cross sections is estimated by projecting the nearest outcrop of Tertiary Wasatch Formation in the Bear River Range (Dover, 1985) updip westward approximately 4 km (2.5 miles) from the east. The amount of slip on each of the two strands of the East Cache fault system cannot be determined, as the seismic-reflection data are poor in this area. The location of the surface trace of the western splay of the fault zone combined with the eastern-most location of Tertiary reflectors at depth constrain the dip of the fault to approximately 70° near the surface. Preservation of hanging-wall cutoff angles in deeper portions of the Tertiary section indicate that the fault flattens slightly at depth to a dip of approximately 50° at approximately 3050 m (~10,000 ft) below sea level.

Cross section 3A is the only cross section across the southern segment of the East Cache fault system (segments of the East Cache fault after McCalpin, 1989). It appears that this segment of the fault has acted as a single master fault along the east side of the basin for the entire history of the basin. The average cumulative slip rate for this segment of the fault, assuming 8 km of net slip, if slip began ~10 million years ago, is 0.8 mm/ year (0.8 m/1000 yr), and 0.47 mm/yr if slip began 17 million years ago. Onset of Basin and Range extension along the East Cache fault in the area is poorly constrained, as the age of the Salt Lake Formation, which presumably is largely a basin-filling sequence that was deposited in extensional basins, is itself poorly constrained. Williams (1964) suggested a Miocene age for the base of the Salt Lake Formation. The 10 million year date used here for the duration of extension is used throughout for comparison purposes only. Slip rates based on a 17 million year initiation of extension on the Wasatch fault (Parry and Bruhn, 1987) are also calculated to give a reasonable range of slip rates on the faults in the study area.

Geologic maps of the southern end of the Cache Valley (Blau, 1975; Crittenden and Sorensen, 1985) show that the East Cache fault terminates abruptly at the James Peak fault (Nelson and Sullivan, 1987) and suggest that displacement along the East Cache fault must decrease abruptly to the south. A migrated seismic section oriented north-south at the southern end of the basin (Figure 4) indicates that the base of the Tertiary rocks dips northward. In the southernmost portion of the Cache Valley basin the Tertiary rocks appear to thicken northward. The slightly listric form of the base of the Tertiary rocks may be due to: 1) a northward listric form of the normal fault, so that the East Cache fault is listric both northward and westward, 2) paleotopography on the older rocks, or 3) a northward dip of the Willard thrust sheet.

Cross section 3B is approximately 6 km (4 miles) north of the section 3A and crosses the central segment of the East Cache fault. The data suggest that the Tertiary basin-fill deposits are approximately 2750 m (9022') thick and dip gently east. The basin at this point is bounded on the east and the west by the East and West Cache faults, respectively. The easternmost continuous reflector in the Tertiary rocks and the surface trace of the East Cache fault yields a near-surface dip of 68^{o}, which flattens to a dip of 50^{o} to 55^{o} at a depth of approximately 3175 m (10500'). Net slip along the East Cache fault is approximately 5.0 km and the throw is 4.4 km, calculated with the method described above. The overall slip rates (for 17 and 10 million year periods) are 0.29 to 0.5 mm/yr for this portion of the East Cache fault. The data do not allow an interpretation of the form of the West Cache fault at depth, but projection of the reflectors representing the base of the Tertiary rocks to the West Cache fault suggest a minimum of 914 m (3000 ft) of net slip along the fault. Another high-angle normal fault which cuts the Mississippian and Pennsylvanian rocks is present within the Wellsville Range (Beus, 1958).

Peterson and Oriel (1970) used gravity data to interpret the southern part of the basin to be a southward-deepening trough from Logan to near Paradise. This present work (Figures 4 and 6) confirms that interpretation, and there may be as much as 3 km of Tertiary basin-fill in the southernmost part of the basin. Cook et al. (1989) showed a slightly different interpretation of the gravity data in Cache Valley in which the deepest part of the gravity low is southwest of Logan, and a deep trough extends to the south from this gravity low towards the southern end of the valley. Either data, when combined with the seismic reflection profiles, indicate that the southern Cache basin is filled with as much as 3 km (10,000') of Tertiary sedimentary rocks. Thickness of the Tertiary rocks decreases both north and south of the southern Cache Valley basin.

The changes from south to north in fault distribution and related basin shape are clearly demonstrated in the cross section which begins west of the city of Logan (Plate 3 C). This section shows the full development of a "doubly-tilted" graben in the central segment of the East Cache fault system. The quality of the reflection data is very good, and enables us to determine with some confidence the history of the basin. Reflectors which I interpret to be the lower parts of the Tertiary rocks and underlying lower Paleozoic rocks dip gently eastward, whereas the reflectors representing the upper Tertiary section dip gently westward to yield 10^{o} to 15^{o} angular discordance between the lower and upper parts of the Tertiary section. I interpret this angular discordance to be due to a two-stage basin development in this region (Figure 5). Early slip along the East Cache fault resulted in east-dipping sediments and eastward rotation of underlying Paleozoic rocks. Later slip along the West Cache fault then resulted in "back rotation" of the basin-fill deposits and the Paleozoic rocks, yielding anomalously shallow dips of the older rocks (relative to dips of rocks exposed in the Wellsville

Mountains directly to the west) and a westward dip of the younger Tertiary rocks. Geologic mapping in the region suggests that both the West Cache and East Cache faults have been active in the Holocene (McCalpin, 1989; Oviatt, 1986 a).

The dips of the East and West Cache faults cannot be tightly constrained due to the location of the seismic section. The eastern end of the seismic-reflection line is 5.25 km (~3.25 miles) west of the range front where Quaternary fault scarps of the East Cache fault are exposed (McCalpin, 1989). East-dipping reflectors at the eastern edge of the reflection profile are not disrupted by faults, and thus the East Cache fault must dip at least 45^{o} west at this latitude. Net slip along the East Cache fault zone is 5485 to 6400 m (18,000 to 21,000 ft) , for a steep 70^{o} fault and a 45^{o} fault, respectively. Cumulative slip rate for a steep fault along the central segment of the East Cache fault zone, is 0.32 to 0.54 mm/year. Dip and form of the West Cache fault likewise cannot be accurately determined. Net slip is on the order of 600 to 1200 m (approximately 2000 to 4000 ft).

The three cross sections from the central and southern segments of the valley show that the basin changes form from north to south from a doubly-tilted graben to a deeper sag basin above a single, west-dipping, slightly listric normal fault. The central segment of the valley has extended by slip along the West and East Cache faults, whereas to the south slip appears to be concentrated on the East Cache fault. The East Cache fault zone appears to have a relatively consistent orientation. Maps of the southwestern part of the Cache Valley (Williams, 1958 and Plate 1) show few normal-fault traces in the area, which suggests that the West Cache fault dies out or breaks up into a series of poorly exposed splays southward.

Northern Cache Valley Basin

Cross section 4 A shows that the basin is bounded on the east side by the East Cache fault zone (Plate 4A), which dips approximately 70^{o} west. Net slip on the fault is about 4.5 km (~14,700 ft) which gives a 17 m.y. to 10 m.y. slip rate of 0.26 to 0.45 mm/yr, respectively. The East Cache fault at this latitude splays into several strands northward; the eastern splay appears to die out northward into Proterozoic and Cambrian rocks of the Bear River Range (see Plate 1), whereas the western splay appears to increase in displacement northward, and exhibits evidence for the most recent slip (McCalpin, 1989). The East Cache fault zone also cuts a shallowly-dipping normal fault with 3 km of slip which places Tertiary conglomerates on Cambrian quartzites (Plate 4 A and 4 B). Brummer (1990) interpreted this shallowly dipping fault as either pre-Basin and Range normal fault or a tectonically-driven gravity slide which slid into the newly formed Cache basin.

Net slip calculated from the cumulative sedimentation rates of the basin-filling sedimentary rocks (Plate 4 A) gives a cumulative slip rate of 0.21 mm/year for the Quaternary sediments and 0.22 mm/yr for the Tertiary rocks, which is roughly half the rate calculated for the East Cache fault zone. This suggests that as is the case to the south, slip along the East Cache fault is partitioned into roughly equal amounts of footwall uplift and hanging wall subsidence. Shallowly-dipping faults along the western margin of the range may also contribute an unknown amount to the total fault slip in this area.

The bounding faults on the western side of the basin are not clearly shown by the seismic data due to poor quality data. Two faults with unknown amounts of displacement bound a small horst block which to the north forms the Little Mountain topographic feature on the west side of the valley, and small-displacment normal faults offset rocks of the southern Malad Range (Oviatt, 1986 b).

North-south profiles which intersect the Lynn Reese drill hole and continue along the entire length of the basin allows us to tie reflectors to the top of the Wasatch Formation (or oldest Tertiary gravels of Oviatt, 1986 a,b). These data confirm the southward deepening of the basin by approximately 450 to 610 m (1500 to 2000 ft) from the Lynn Reese drill hole to the southern end of the basin (Figure 6).

The two northern cross sections across the Cache Valley (Sections 4 B and C) show that the basin is shallow and quite broad in this region. The quality of the reflection profiles which form the basis of the northern cross sections is much poorer than to the south, which limits our ability to determine the depth of the Tertiary rocks. I have interpreted a relatively continuous and strong reflector which correlates with known base of Tertiary reflectors in profiles from the south to be the base of the Tertiary section. If the picks are correct, the data suggest that the Tertiary rocks are about 1270 m thick (4160 ft) in the central part of the basin. The East Cache fault zone splits into two splays with net slip of 3.6 km in the section 4 B and 2.7 km in section 4 C along the Utah-Idaho border. These values yield cumulative slip rates of 0.27 mm/yr to 0.36 mm/yr for an assumed age of 10 million years for the initiation of extension, and a rate of 0.16 to 0.21 mm/yr if faulting began 17 million years ago.

Summary of Cache Valley data

Cumulative average slip rates for the East Cache fault and the Morgan fault, and footwall uplift rate data from the Wasatch fault are summarized in Table 3. Slip rates for the three faults exhibit a wide degree of variability. Slip rates for the Wasatch fault would likely be higher than reported uplift rates (see Table 3) as net slip is the sum of the footwall uplift and basin subsidence. If the slip rate along the Wasatch Fault is roughly twice the uplift rate calculated for the Wasatch fault near Ogden, then the southern East Cache and Ogden segment of the Wasatch fault have comparable slip rates. However, there is significant discrepancy between the Morgan fault, which lies south of the East Cache fault, and the southern East Cache fault. These data also exhibit discrepancies between average rates calculated for the Miocene to present and the Holocene slip rates for the East Cache fault zone. Holocene slip rates on the East Cache fault zone are 0.009 mm/yr over the past 150,000 years and 0.28 mm/yr for the past 15,000 years (McCalpin, 1989).

These data can provide some clues to evaluating the seismic risks for the Cache Valley, but only by revealing possible locations of faults and suggesting possible locations of earthquake foci. Because of the nature of the data, I cannot provide estimates of recurrence intervals nor can I

Table 3. Net slip and long-term average slip rates on the East Cache, Morgan, and Wasatch faults, Utah. See text for details of calculated slip rates.

Segment and fault	**Net Slip of fault (km)**	**Long-term average slip rate (mm/year)** (number in parenthnses is net slip used in rate calculation)	**Reference**
		<u>17 Ma</u> - <u>10 Ma</u>	
Southern East Cache	7.6 - 8.1	0.47 - 0.8 (8 km)	this study
Central East Cache	5.0 - 6.4	0.29 - 0.54 (5.4 km)	this study
Northern East Cache[1]	4.5	0.27 - 0.45 (4. 5 km)	this study
Northern East Cache[2]	2.7 - 3.6	0.16 - 0.36 (3.6 km)	this study
Ogden Segment, Wasatch[3]		0. 4	Naeser et al., 1983
Salt Lake City segment, Wasatch[4]		0.67	Parry and Bruhn, 1986
Morgan fault[5]	~1.0	0.03 - 0.2[a] 0.03 - 0.15[b]	Sullivan and Nelson, 1987

1- southern end of the northern segment

2 - northern end of the northern segment

3 - uplift rate of footwall of the Wasatch fault, based on fission track dates. Rate calculated for the last 10 m.y.

4 - uplift rate of footwall of the Wasatch fault for the past 17 m. y., based on K-Ar age of hydrothermal sericite in fault-related rocks

5a - Slip rate calculated for 5 ma to 35 ma range, based on inferred thickness of Huntsville conglomerates in Morgan Valley

5b - Slip rate calcuated for 1 ma to 5 ma range, based on rotation of Late Cenozoic erosion surface determine the amounts of slip for any given seismic event. The data do show that if rupture along the major faults in the area were to nucleate at depths of 10-15 km common for the Basin and Range (Smith and Bruhn, 1984), the foci would be located as much as 10 km from the eastern margin of the valley. In addition, the data suggest that there is considerable risk for slip along either the West or East Cache faults in the central segment of the basin, with both hypothetical foci located under the basin.

Bear River Range and Bear Lake Valley

General Statement

Structural interpretation of extension within the Bear River Range and the area west of Bear Lake is critical to understanding the recent seismicity of the area. The 1962 M_L 5.7 earthquake in the area, normally referred to as the Cache Valley event (Westaway and Smith, 1989) has been ascribed to slip on either an east-dipping fault within the range, based on aftershock data (Westphal and Lange, 1966; Smith and Sbar, 1974) or on a planar 40^o west-dipping Temple Ridge fault (Westaway and Smith, 1989). The preferred focal mechanism of the 1988 M_L 4.8 Bear Lake earthquake supports slip on a nearly vertical fault or on a very shallowly west-dipping fault (Figure 7). Two other small events also have epicenters under the Bear River Range (Figure 2). These data point to some complexities in the distribution of faults responsible for small to moderate-sized earthquakes in the region. The reflection profiles acquired across the range and made available to us are low quality, and show little structure. However, these data can be used with excellent data acquired across the north end of Bear Lake and with surface geological data to constrain the form of faults within the range.

Temple Ridge Fault

The Temple Ridge fault is a north-south-striking normal fault which forms a narrow half-graben near the center of the Bear River Range (Plate 1). At its northern and southern ends of the Temple Ridge fault zone consist of several poorly exposed splays. The central segment of the Temple Ridge fault is approximately 20 km (12.4 mi) long, consists of a single strand (Dover, 1985) or closely spaced strands (R. Q. Oaks, written comm., 1990), and slip along the central part of the fault has generated a degraded fault scarp which forms a topographic escarpment along the eastern edge of the graben. Slip on the fault appears to decrease southward, where the fault dies out into a series of splays each of which has little displacement (R. Q. Oaks, Jr., unpublished mapping). Mapping of the Tertiary Wasatch Formation and related rocks in the range to the west and east of the fault (Oaks, 1989) shows that the fault has approximately 750 m of displacement, and the fault dip is 75^o to 80^o to the west (Evans and Oaks, 1990). To the north the Temple Ridge fault may splay into two strands (Plate 1), one of which juxtaposes Ordovician rocks in the hanging-wall against Cambrian rocks in the footwall, and the second of which cuts Ordovician rocks (Dover, 1985).

The poor quality of seismic data from the area does not help resolve the form of the Temple Ridge fault. One profile vaguely suggests that the fault may flatten and join the shallowly west - dipping Meade thrust at a depth of 8 km (16,670 ft), but this interpretation is speculative. In order for the Temple Ridge fault to have been responsible for the 1962 Cache Valley earthquake as proposed by Westaway and Smith (1989), the fault must have the form shown in Plate 4 A, where the fault flattens to a 43^{o} dip as prescribed by the focal mechanism of Westaway and Smith (1989). This does not prove or preclude the Temple Ridge fault from being responsible for the 1962 event; however, from the available data, slip on an east-dipping fault which is not exposed at the surface, or has yet to be recognized by geologic mapping, is also possible.

Bear Lake Faults

Excellent quality seismic data acquired in two lines across the Bear Lake valley and into the Bear Lake Plateau and the eastern Bear River Range reveal the detail and complexity of the Bear Lake basin. The data may also provide a possible solution to the question of the fault responsible for the 1988 earthquake. The two seismic lines were acquired 13 and 24 km (~8 and 15 miles) north of the epicenter of the 1988 earthquake. Due to along-strike variability in the structures of the basins in this area, data projected along-strike must be interpreted conservatively. The reflection profiles, drill hole data and map patterns of the area provide a reasonable solution to the problem of what fault(s) were responsible for the 1988 earthquake, but we cannot prove it with existing data.

The southern reflection profile was acquired along the north shore of Bear Lake and into the ranges on either side of the lake. The data show that the Bear Lake normal fault zone is a listric normal fault which likely soles into the Meade thrust at depth (Plate 4 C and Figure 8). The fault has 4 km (13,000 ft) of net slip as determined from the offset of the base of the Tertiary Wasatch Formation, and dips 55^{o} near the surface. The fault appears to be a single fault and flattens to a dip of 28^{o} at a depth of about 6 km (20,000 ft). This interpretation of the reflection data suggests that the fault merges with the Meade thrust at depth, or at least becomes parallel to west-dipping sedimentary rocks in the hanging-wall of the thrust. A similar geometry has been documented to the north and east in the Sevier fold and thrust belt of Wyoming (Royse et al., 1975). Slip rates on the Bear Lake fault at this location are 0.4 mm/yr if extension began about 10 million years ago and about 0.25 mm/yr if extension began 17 million years ago.

The sedimentary basin which formed in response to slip on the Bear Lake normal fault zone is an asymmetric triangular prism 2.5 km (8200 ft) deep at the deepest part of the basin, slightly west of the surface trace of the fault (Figure 8). Tertiary rocks in this basin exhibit a roll-over or growth sedimentation pattern, with beds dipping steeply eastward toward the fault at the base of the section and exhibiting shallower eastward dips upsection. The Tertiary rocks are cut by numerous small-displacement, steeply east-dipping faults that have produced horsts and graben in the sedimentary section below approximately 750 m depth. Reflectors which represent the Tertiary sedimentary rocks above the Wasatch Formation have a thin lowermost sequence, followed by a thicker sequence which onlaps eastward to give a growth sequence adjacent to the East Bear Lake fault.

The western end of the reflection profile extends into the Bear River Range and reveals structures within and beneath the Paris and Willard thrust sheets. Of greatest interest are a number of steeply dipping faults which offset reflectors that represent Mesozoic and Paleozoic rocks in the hanging-wall of the Meade thrust sheet and which also offset reflectors that mark the base of the Paris and Willard thrust sheets (Plate 4 C). These faults are nearly vertical or dip steeply to the west or east, and do not appear to have had large displacements along them. These steeply dipping faults are present at depths of 6 to 11 km, and may be similar to the fault responsible for the 1988 Bear Lake earthquake. The origin of these faults is enigmatic - possibly they formed initially as steeply dipping backthrusts in the Meade thrust sheet during Sevier folding and thrusting and subsequently have been reactivated by modern extension. Conversely, these faults could mark the initiation of steeply-dipping faults forming along the western margin of the Bear River Valley.

The auxiliary plane of the preferred focal-mechanism solution for the 1988 Bear Lake earthquake indicates that slip could have occurred along a shallowly dipping fault or a steeply dipping fault (Figure 7). The reflection data indicate that the Meade thrust may dip 10^{o} to 15^{o} westward in this area. Although it is possible that reactivation of the Meade thrust could have resulted in the 1988 earthquake, slip along the steeply dipping normal faults is the preferred solution.

The northern cross section across the Bear Lake valley, 9 km farther to the north, displays significant variability in the form of the basin along its strike. The East Bear Lake fault zone is again a listric normal fault which may sole into the Meade thrust (Figure 9). Slip on the fault is approximately 1.7 km (5500 ft). In this interpretation, the main fault dips 65^{o} near the surface and flattens to 25^{o} at depth. The fault zone is more complex than to the south, with shallow and steeply west-dipping footwall fault splays and steeply east-dipping faults in the hanging wall of the East Bear Lake fault. I interpret the strand with the largest amount of slip in the reflection profile to be the main range-bounding fault that has exhibited Holocene activity (McCalpin et al., 1990). In both cross sections, the East Bear Lake fault cuts off the leading edge of the Meade thrust, leaving a small wedge of Mesozoic rocks east of the Bear Lake fault zone. This structure is similar to the listric normal-fault geometries of the Star Valley-Grand Valley normal fault system to the northeast in the Sevier fold and thrust belt (Royse et al., 1975 ; Royse, 1983). Slip rates for the East Bear Lake fault at this section are 0.17 mm/yr for a 10 million year onset of extension and 0.10 mm/yr for a 17 Ma onset.

An alternative interpretation for the East Bear Lake fault zone which is permitted by the data is shown in Figure 10. In this scenario, the East Bear Lake normal fault zone cuts the Meade thrust and continues at depth with a dip of approximately 40^{o}. This interpretation yields approximately the same amount of net slip as shown in Fig. 9, and also results in the front portion of the Meade thrust being cut off in the footwall of the normal fault zone. The quality of the reflection data from the deeper parts of the footwall of the East Bear Lake fault exhibits significant velocity pull-ups and makes this region difficult to interpret. This alternative interpretation does not conform to the most common model of normal faults in the thrust belt (e. g., Royse et al., 1975), but these data cannot preclude this interpretation.

The basin at this point is a nearly symmetrical graben filled with virtually horizontal Tertiary sedimentary rocks which exhibit several internal onlap and offlap relationships which suggest periods of tectonic activity interspersed with periods of relative quiescence. Deformation within the sedimentary rocks is restricted to two peculiar west-directed thrusts with offset reflectors which represent the Tertiary Wasatch Formation and several small displacement antithetic normal faults which cut the Tertiary rocks. These thrusts may be contraction structures in the hanging-wall of the listric, down-to-the west East Bear Lake fault.

The seismic-reflection data indicate that basin-filling deposits are nearly flat-lying across the basin and dip east along the west side of basin. Based on reflection data, it is not clear if a fault exists the western margin of the basin, and if it exists, how deep the fault penetrates. However, one must exist in order to account for the abrupt change in dip in the sedimentary rocks (Figure 9) and for the surface ruptures interpreted along the western edge of the Bear Lake valley (McCalpin et al., 1990). Reflectors at depths greater than 4 km do not appear offset on the western margin of the basin, and thus the West Bear Lake fault may cut Tertiary and Mesozoic rocks and sole into an underlying thrust. If the basin is bounded on the west side by a listric West Bear Lake fault zone, the fault likely bifurcates into several strands near the surface, and one of these strands is responsible for Holocene surface rupture (McCalpin et al.,1990).

The profiles shown in Figures 8 - 10 demonstrate the northward changes of the Bear Lake graben from an asymmetric, east-tilted half-graben with a growth sequence in the hanging-wall sedimentary rocks in the central part of Bear Lake valley to a broad, flat-bottomed graben bounded on both sides by normal faults in the north. Along-strike variation is also shown by shallow seismic studies conducted across Bear Lake (Skeen, 1975). This study showed that sediments in the upper 0.3 second in two-way travel time comprise a small triangular prism at the southern end of the lake, gradually thicken and broaden in the central part of the lake, and are thin at the northern end of the lake.

Crawford Normal Fault

The Crawford normal fault lies along the western edge of the Crawford Mountains (Plate 3 C and Figure 11). This fault zone forms a prominent, steep scarp along the western edge of the range which is accentuated in part by steeply west-dipping rocks in the footwall of the fault zone (Chamberlain, 1980). Quaternary movement on the normal fault zone has been inferred by Gibbons and Dickey

(1983). One reflection profile acquired across the northern end of the Bear River Valley west of the Crawford Mountains shows that the Crawford thrust is a listric normal fault zone which soles into the Crawford thrust at a depth of about 4 km (13,000 ft). The dip of the fault zone near the surface is 55^{o} and it decreases downward to ~ 17^{o}. The basin which formed above the fault zone contains a small, triangular wedge of Tertiary sediments which are cut by synthetic and antithetic normal faults with small displacement. Total slip along the Crawford fault zone is 1.5 to 1.9 km (4900 to 6250 ft).

Discussion

Setting of Seismicity

The data and interpretations presented above help to infer the forms and location of faults which may be responsible for future earthquakes. Earthquakes may occur along the main range-bounding faults and along faults distributed through the Bear River Range. Investigations of Holocene paleoearthquakes (Swan et al.,1983; McCalpin, 1989; McCalpin et al., 1990) show that earthquakes of magnitude (M_L) 7.0 or greater have probably occurred on the major range-bounding East Cache, East Bear Lake, and Crawford faults, and surface-rupturing events have also occurred along the West Cache and West Bear Lake faults. Slip along the East Cache fault zone may occur along the entire length of the fault zone (McCalpin, 1989), and the fault's shape suggests that future earthquakes would nucleate under the Cache Valley or the Wellsville Mountains on a fault zone which dips at least 45^{o} to 55^{o}. The West Cache fault zone also appears to pose some risk of slip along the central and northern parts of the Cache Valley, and, although the form of the fault zone at depth is less well constrained, it seems likely that the nucleation region lies under the Cache Valley.

The Bear Lake faults appear to have slip potential in a different setting. In one interpretation of the East Bear Lake fault, the sharply listric form of the East Bear Lake fault zone would place the foci under the eastern Bear River Range for nucleation of earthquakes at depths common in the Basin and Range province. If the fault does not have a sharply listric form (Figure 9), earthquakes might nucleate under the western edge of Bear Lake valley. Potential for slip on the West Bear Lake fault zone is more difficult to determine, as the form of the fault is poorly constrained. The East Bear Lake fault cuts latest Tertiary sediments along much of its length, and Quaternary fault scarps are visible from the central part of Bear Lake to Montpelier, Idaho. Thus, slip on the East Bear Lake fault zone could occur on its length from near Laketown, Utah, to north of Montpelier, Idaho.

In addition to the obvious seismic potential of the large faults, smaller faults may be responsible for much of the seismicity within the Bear River Range in a way similar to that described by Arabasz and Julander (1986, their Figure 18) for central Utah. Steeply east-dipping to vertical faults visible in seismic-reflection lines north of Bear Lake lie in the Meade thrust sheet. The southward continuation of these faults, or faults similar to them, may have been responsible for the 1988 Bear Lake earthquake. The alternative candidate is a very shallow fault which is very nearly parallel to bedding in the vicinity of the Meade thrust.

The existence of concealed steep normal faults in the Meade thrust sheet provides some evidence for earthquakes to rupture within the thrust sheets throughout the Bear River Range. Faults with displacements less than 1 km may also lie in the Paris and Willard thrust sheets (e. g., the Temple Ridge fault zone), and slip along these faults would result in earthquakes with shallow foci. Earthquakes within the Bear River Range of M_L 4.0 to M_L 6.0 may nucleate along most of these faults whereas larger earthquakes nucleate along the range-bounding faults.

These data and interpretations of northern Utah, combined with the work of Richins et al. (1983) and Arabasz and Julander (1986) show that Basin and Range extension and contemporary seismicity is superimposed on early compressional structures. These data display a more complex picture of the structure of the region than is discussed by Westaway and Smith (1989) or Westaway (1989, see Figure 12).

Implications for growth of basins and the easternmost Basin and Range

The data show a wide range of variability within and between the basins. In the Cache Valley basin, net slip is greatest near the southern end of the basin, where a single listric normal fault zone bounds the east side of the basin. Net slip along the East Cache fault zone decreases northward and the basin is bounded by faults on both sides, with a doubly-tilted basin giving way to a wide, shallow graben to the north. The Bear Lake Valley basin shows the same trends, although the southern part of the basin has seen the least extension. The southern part of the basin is a tilted half-graben which changes to the north to a wide fault zone-bounded basin. The opposed tilting of the Cache Valley basin is an unexpected result, and points out that "simple" basins in the northeastern Basin and Range province may hold surprises in their subsurface form and evolution. Tilting to the east, followed by tilting to the west due to slip on antithetic faults has been documented by Axen (1986) in southern Nevada, and it seems likely that other basins in the Basin and Range may have similar complex histories.

The distribution of the rocks of the Salt Lake Formation on the edges of the basin and in the footwalls of the basin-bounding faults suggests that the central and northern Cache Valley basin likely started out as a broad depression into which the oldest beds of the Tertiary Salt Lake Formation were deposited. Over time the basin narrowed with the development of the basin-bounding faults, which gives the present outcrop pattern of Tertiary Salt Lake Formation rocks. A corollary to this model has been suggested by R. Q. Oaks, Jr. (written comm., 1990). Early in the Tertiary history of the area, closed basins may have formed by faulting, but the inability to drain the basin caused Tertiary sediments to lap onto the mountain front and over the bounding faults. As faulting continued, the depocenter became narrower and the early onlap sediments were preserved in the footwalls of the faults.

If the largest amount of slip or structural relief in the basin is a function of structural maturity and not a difference in slip rate, then the southern Cache Valley basin is the oldest part of the basin. The lack of a western normal fault zone makes it distinct from that part of the basin to the north, and suggests that different parts of the basin evolved differently. The single, west-dipping listric East Cache fault zone system appears to have controlled the form of the basin during its entire history. An alternative interpretation is that the thickness of Tertiary sedimentary rocks in the southern part of the basin could reflect a compound two-stage basin development, with an early Eocene-Oligocene basin filled with Norwood Tuff or equivalent rocks as seen in Morgan and Ogden valleys (Hopkins, 1982; Crittenden and Sorensen, 1985). Renewed extension which began in Middle Miocene time would then be superimposed on the earlier basin to form the deep trough seen today.

The East Bear Lake and Crawford normal faults probably are listric normal faults which sole into thrusts along or near ramps in the thrusts, which agrees with a model first outlined by Royse and others (1975) in the Hoback Basin and the Star Valley of Wyoming. The relationship between the East Cache fault zone and Sevier fold and thrust belt structures is more obscure. The most reasonable subsurface interpretations of the normal faults at the southern end of the basin suggest that the East Cache fault zone cuts a flat portion of the Willard thrust (Plate 3 A). East-vergent overturned folds and small-displacment thrusts along the western edge of the range (Williams, 1948; Galloway, 1970; Dover, 1983, 1985) show that the East Cache fault zone cuts contractional structures at a much higher structural level. These structures could reflect a thrust at depth which is dropped down along the East Cache fault zone (Williams, 1948). These data support, but cannot prove, a model for early localization of the East Cache fault zone along a Sevier thrust fault zone and subsequent stranding of a part of the thrust sheet in the footwall of the normal fault zone.

The largest amount of slip in the Bear Lake basin is along the East Bear Lake fault zone at the northern end of Bear Lake. If this region represents the oldest part of the basin, the displacement pattern, inferred from the thickness of sediments in the basin, suggests that the Bear Lake basin has grown from the center of the basin southward. The older portion of the basin is a graben bounded by two normal faults, or is a deep half-graben bounded by the East Bear Lake fault zone. It appears that the East Bear Lake fault zone is responsible for the basin shape along the length of the lake, and slip along the fault zone decreases to the south.

Table 4. Net slip along normal faults in northern Utah and western Wyoming.

Fault	slip on fault (km)	reference
East Cache south	5.4 - 8.1	this study
East Cache north	2.7 - 4.5	this study
Bear Lake	1.9 - 4.0	this study
Crawford south	1.9	this study
Crawford north	0.5 - 1.0	Evans and Oaks, 1990
Morgan Valley	6.8	Hopkins, 1982
Grand Valley-Star Valley	5.5	Coogan and Royse, 1990

Extension across the entire area may be relatively constant if one considers the combined slip on the East Cache and Bear Lake fault systems (Table 4). At the southern end of the Cache Valley basin, net horizontal displacement is approximately 4 to 5 km, and there are few normal faults to the east to accommodate more extension. As extension decreases northward across the Cache Valley basin, extension across the Bear Lake fault zone system increases. Along the northernmost cross section, horizontal displacement across the Cache Valley basin is approximately 1 to 1. 5 km, and due east, horizontal displacement across the Bear Lake fault zone is 2.5 to 3.0 km.

The shapes of the normal faults and the hanging-wall basins may support West's (1988) model for the evolution of extension across the region. If the Wasatch fault zone represents the most mature normal fault zone in the region, progressively younger faults may lie to the east. The East Cache fault zone does not now appear to be related to an underlying thrust fault zone, but contractional structures in the footwall of the East Cache fault zone allow for early slip along the East Cache fault to have been related to a pre-existing thrust which was subsequently cut out by additional slip on the normal fault. The East Cache fault zone is also a steeply dipping fault zone to significant depths. To the east, slip along the East Bear Lake and Crawford faults is less than along the Wasatch or the East Cache fault zones. Several of the eastern faults are listric, and appear to sole into underlying thrusts. West (1988) suggested that these listric normal faults reflect an early stage of extension superimposed on the Sevier fold and thrust belt. Over time, the normal faults may abandon the listric form and become steeply dipping faults. This process would preserve part of the thrust sheet in the footwall of the normal fault zone and a listric normal fault zone in the hanging-wall. Although the former is seen in the area, we have no conclusive evidence for the latter. It is also possible that not all of the normal faults are listric faults which sole into an underlying thrust. The Bear Lake fault and the East Cache fault can easily be interpreted as cutting the nearest normal faults and maintaining a relatively steep dip (> 40^o to 45^o) to depths in excess of 6 km.

The data presented here show that the normal faults and extensional basins east of the Wasatch fault zone are rather complex structures, with significant amounts of down-dip and along-strike variability in fault zone shape, and that hanging-wall basins likewise exhibit a wide degree of variability along and across the basin axis.

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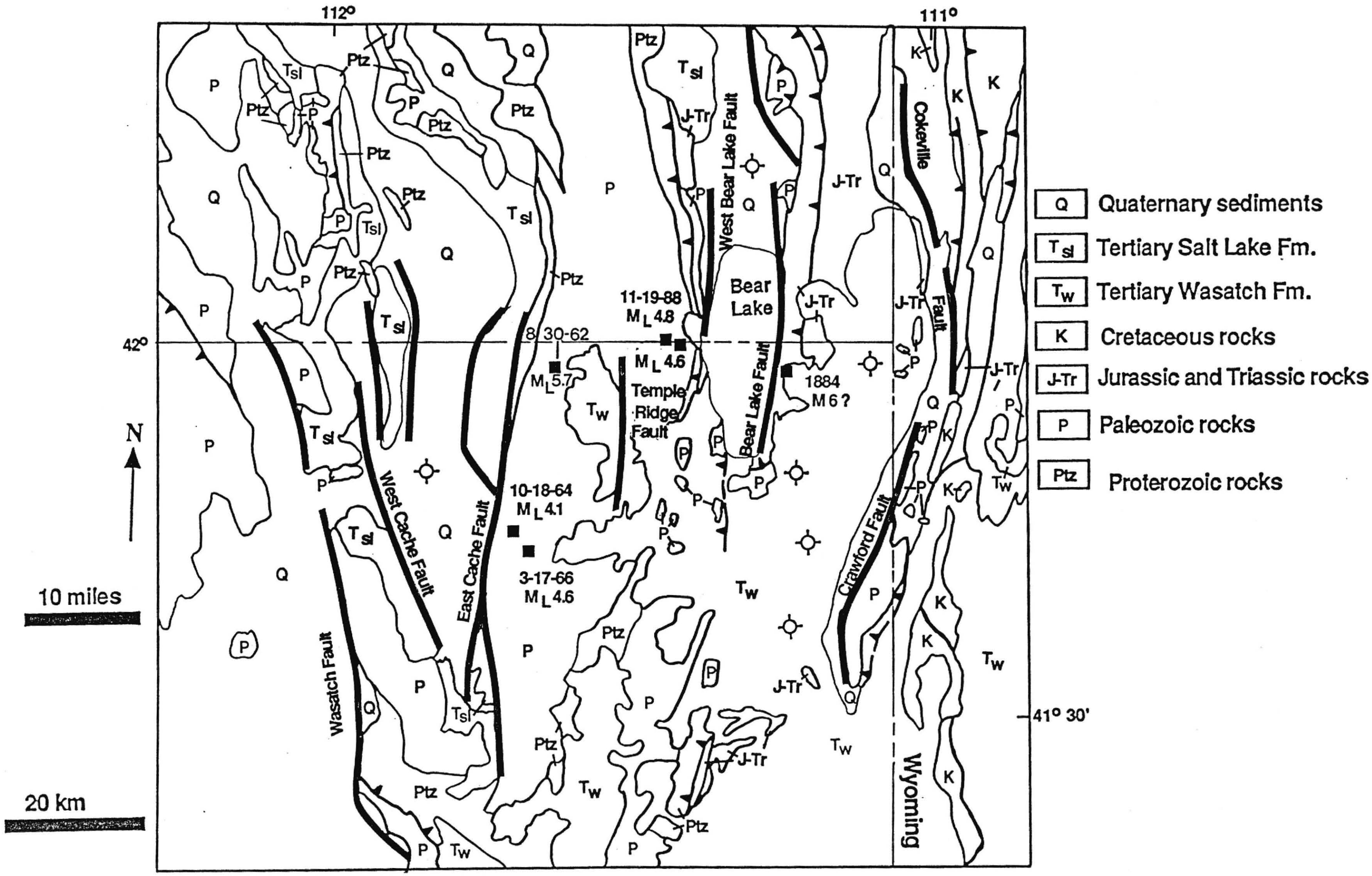


Figure 1. Generalized geologic map of the study area. The major normal faults are indicated along with locations of epicenters of earthquakes in the area. Drill hole symbols show locations of important drill holes used in construction of cross sections across the area. Data for drill holes shown on relavant plates.

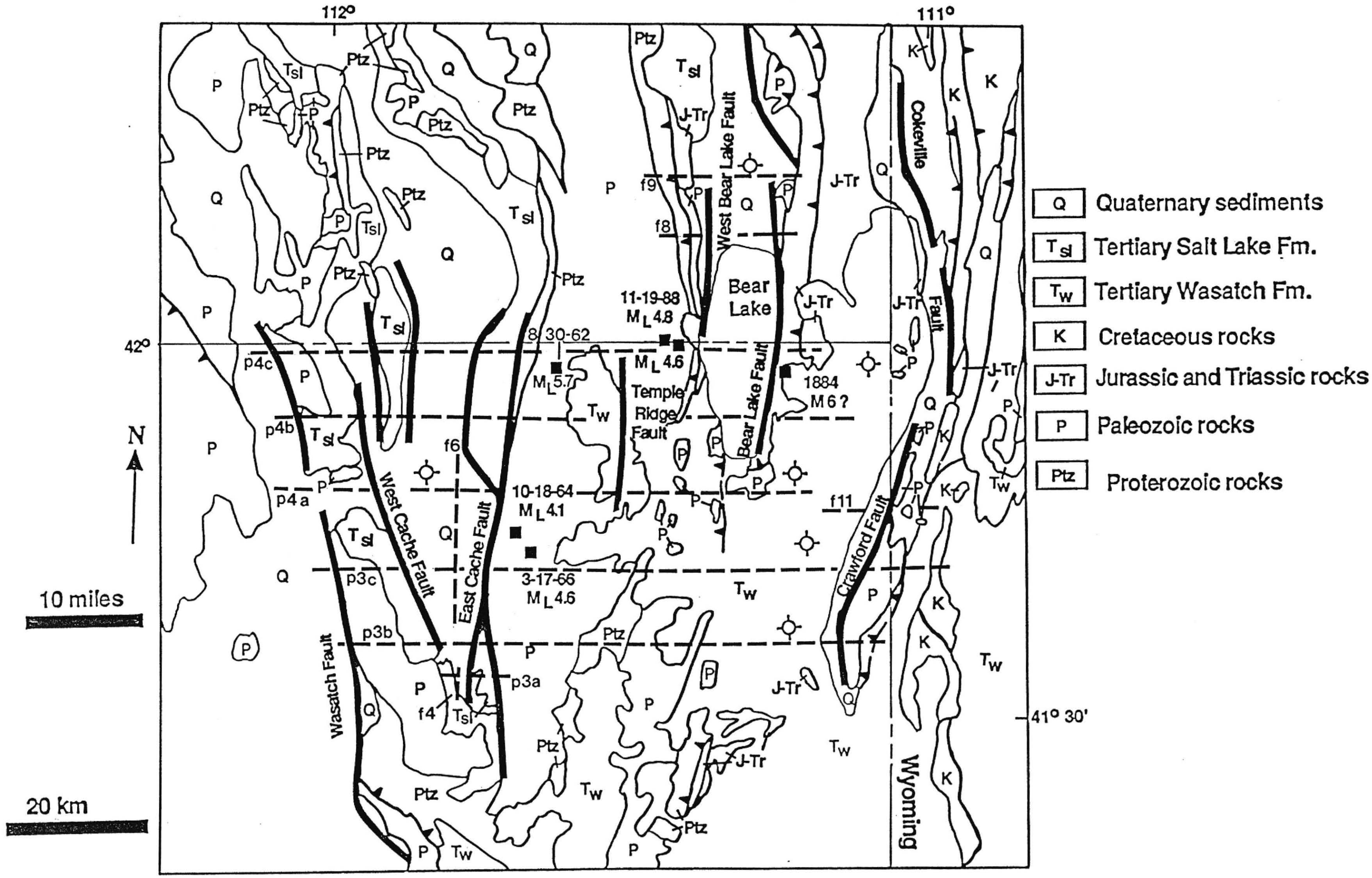


Figure 2. Generalized geologic map of the study area showing the locations of cross sections discussed in text. The numbers next to lines indicate figure number: P refers to Plates, F refers to Figures in text. Dashed lines correspond to the location of cross section lines.

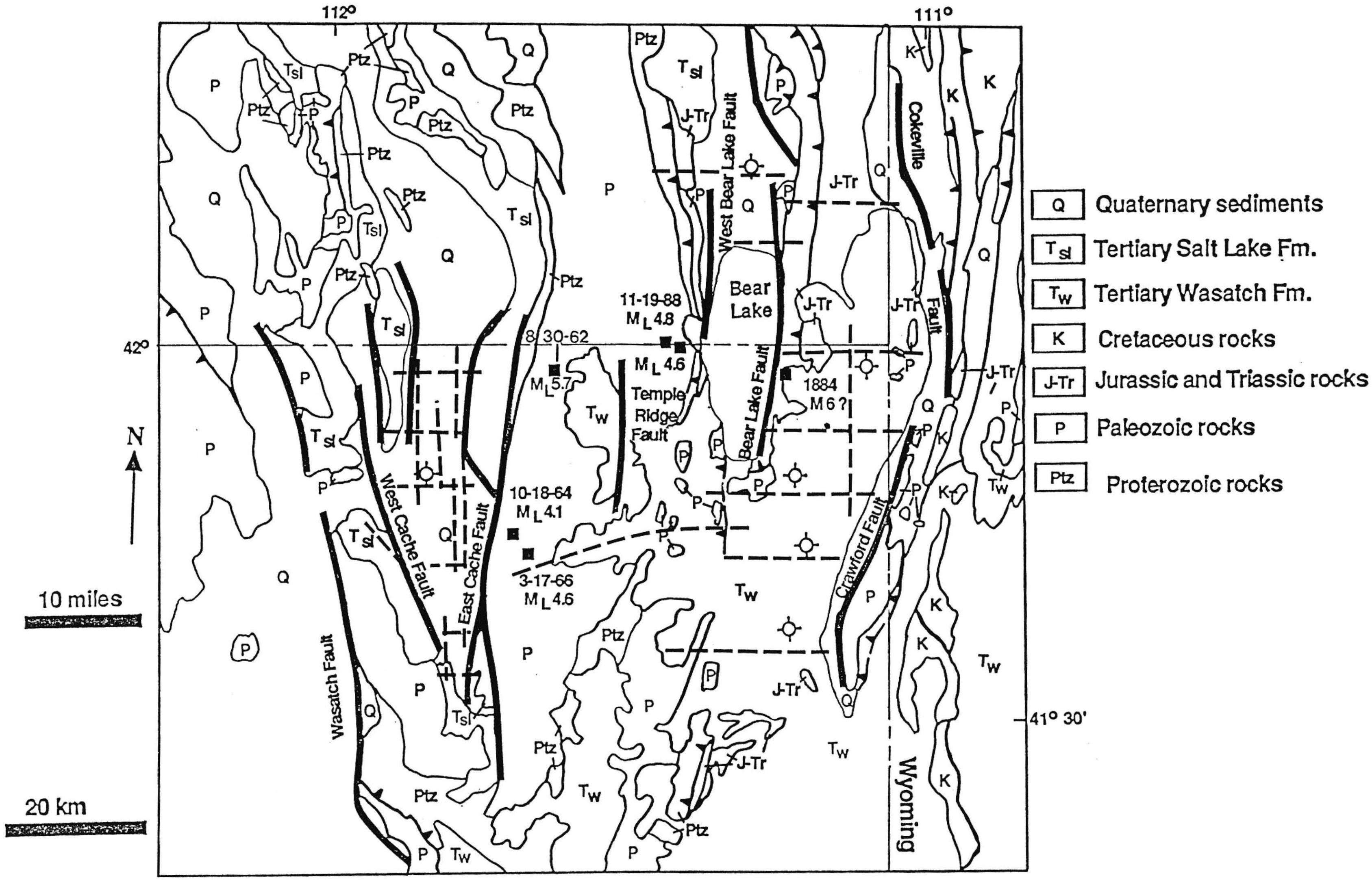


Figure 3. Generalized geologic map of the study area showing the locations of seismic-reflection profiles used in this study. Dashed lines indicate the approximate locations of the profiles.

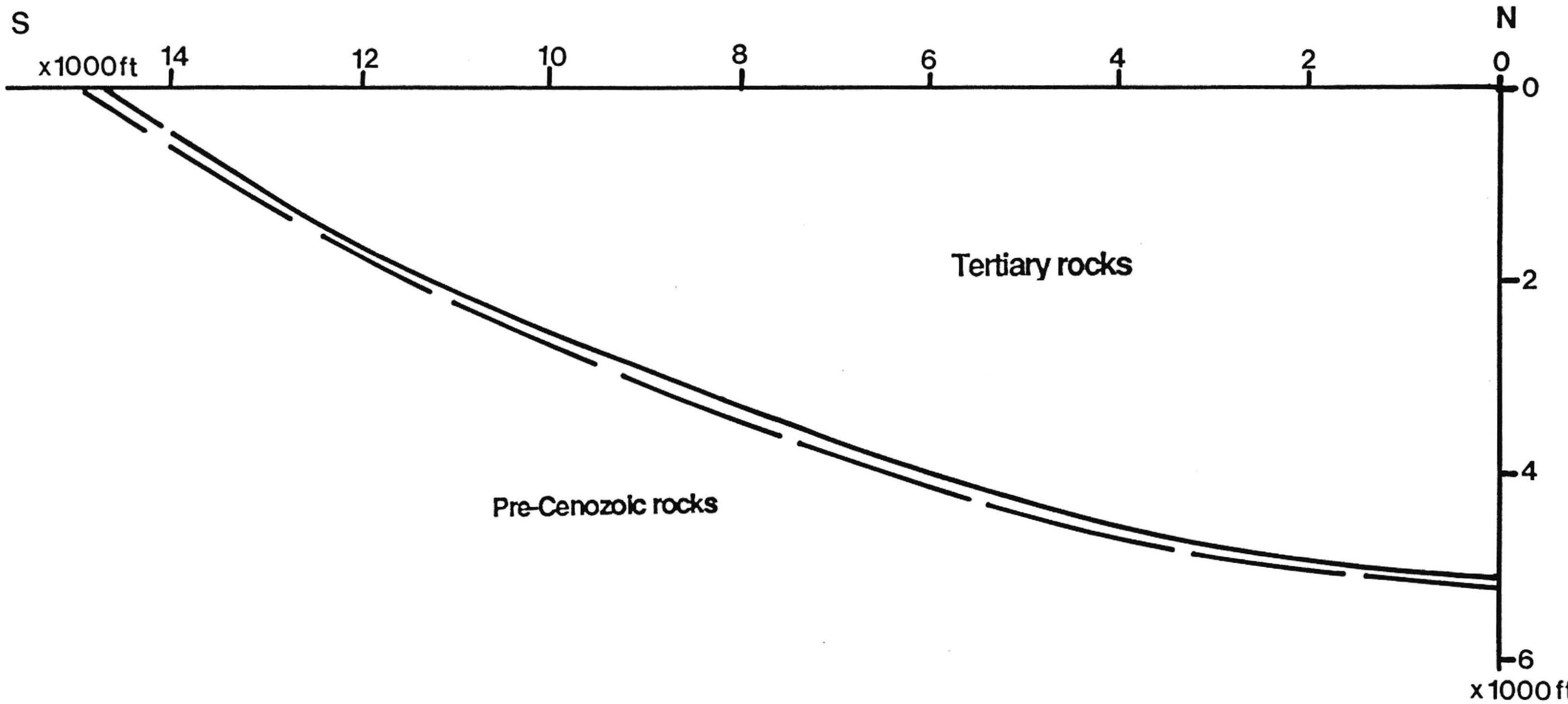


Figure 4. North-south migrated seismic section along the southern edge of the Cache basin. Curved solid and dashed lines represent the possible base of the Tertiary rocks in the basin. No reflectors above or below the base of the Tertiary were visible to constrain the structures. Listric form of these reflectors may mimic a listric form of the normal fault under the rocks, may represent paleotopography cut into Proterozoic and Paleozoic bedrock, or may follow a northward slope of the Willard thrust.

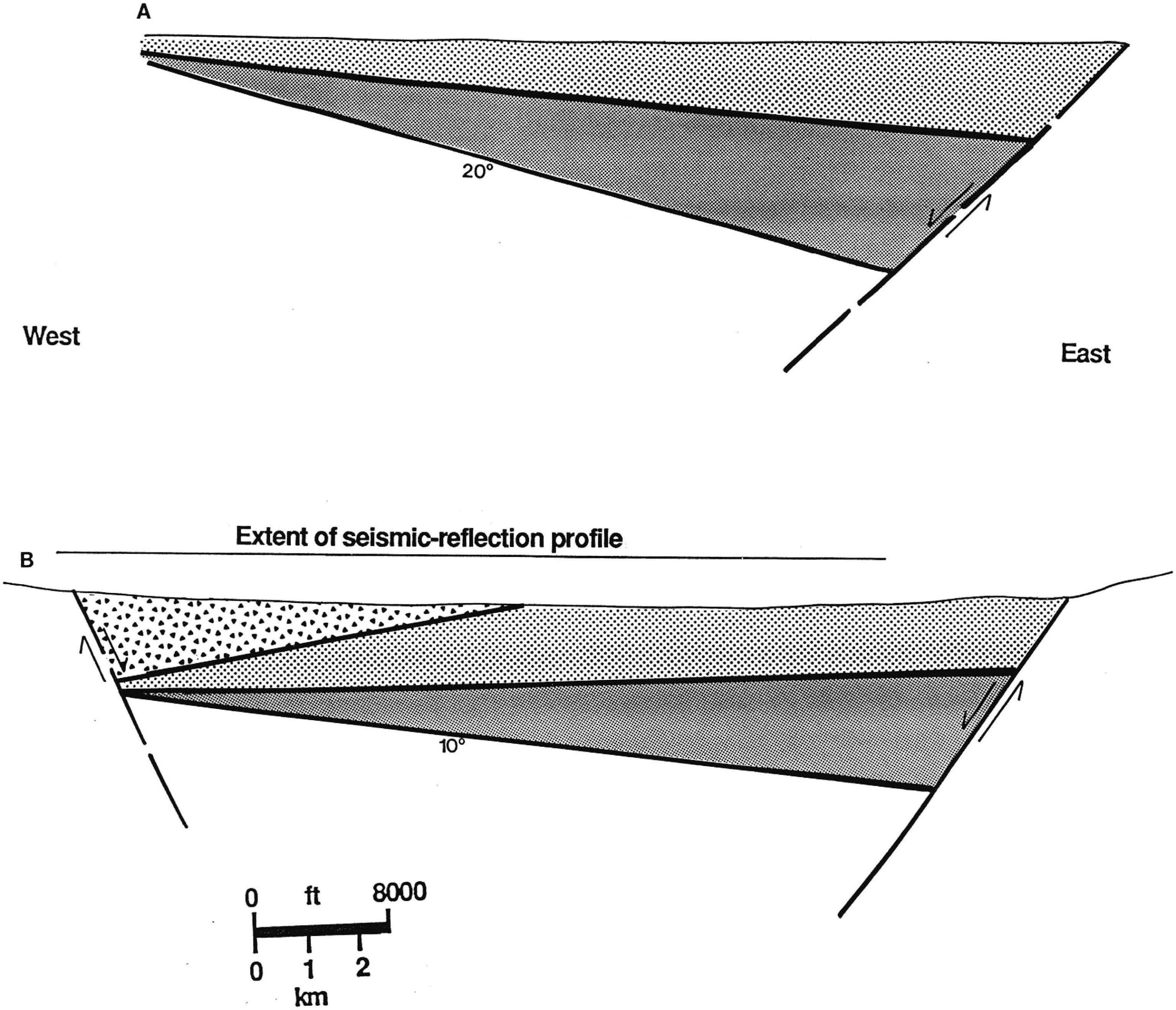


Figure 5. Schematic cross section of the double-tilting of the rocks in the central Cache basin due to slip on opposing normal faults.

A) Early slip along the East Cache fault is resposible for the eastward dips of the Paleozoic rocks and the older Tertiary rocks which fill the basin as the fault grows.

B) Later in the history of the basin, the West Cache fault becomes active and results in westward tilting of all strata in the basin. The youngest rocks of the basin become west-dipping and the older strata dip to the east, but less than before the slip on the West Cache fault.

Youngest sediments deposited during slip on West Cache fault

Older Tertiary rocks

Younger Tertiary rocks deposited during slip on East Cache fault

Paleozoic rocks

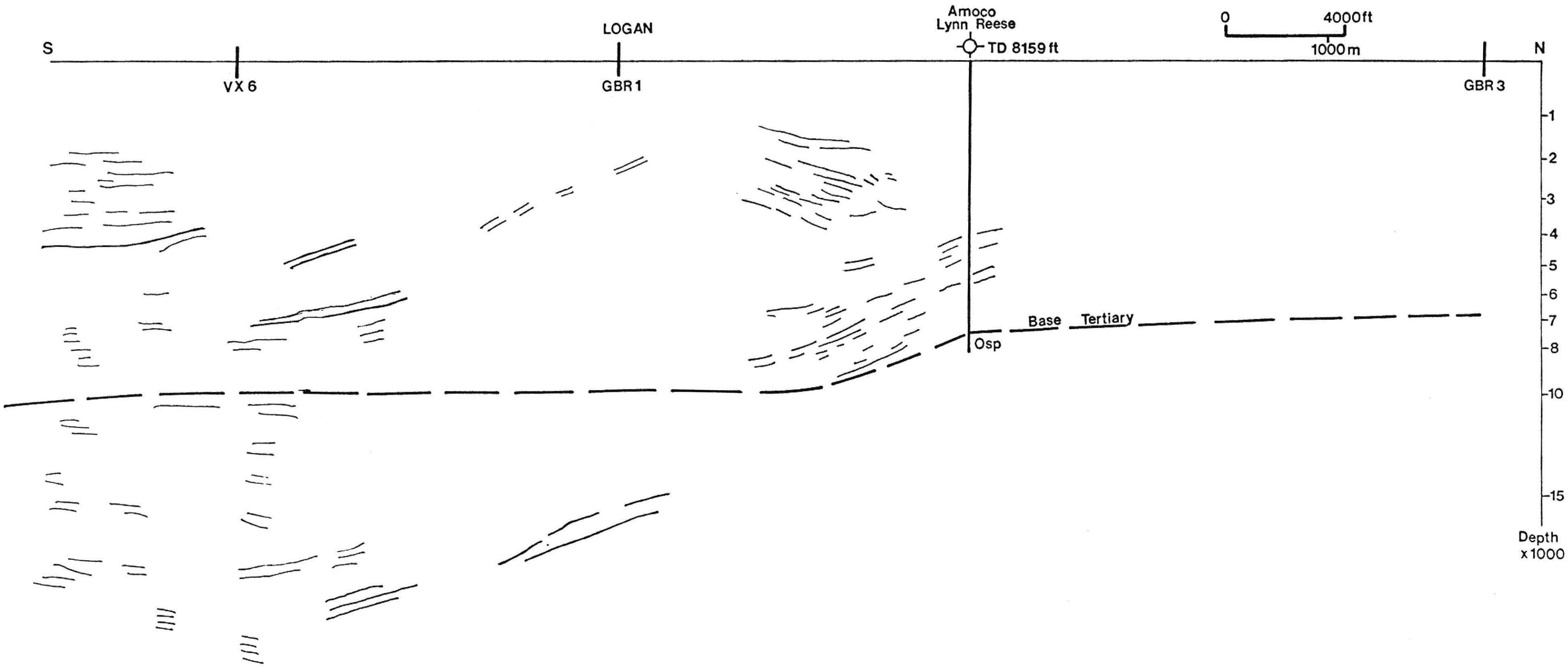


Figure 6. North-south migrated section of the central Cache basin showing the southward deepening of the basin. Lightest lines are reflectors interpreted from the data. The Tertiary basin fill deposits are 1500 to 2000 ft thicker to the south. Reflectors beneath the base of the Tertiary sedimentary rocks may indicate a lateral ramp in the thrust structures and suggest that the form of thrust-related structures influence the along-strike shape of the basin. Heavy dashes at the top of figure show the location of east-west seismic reflection profiles.

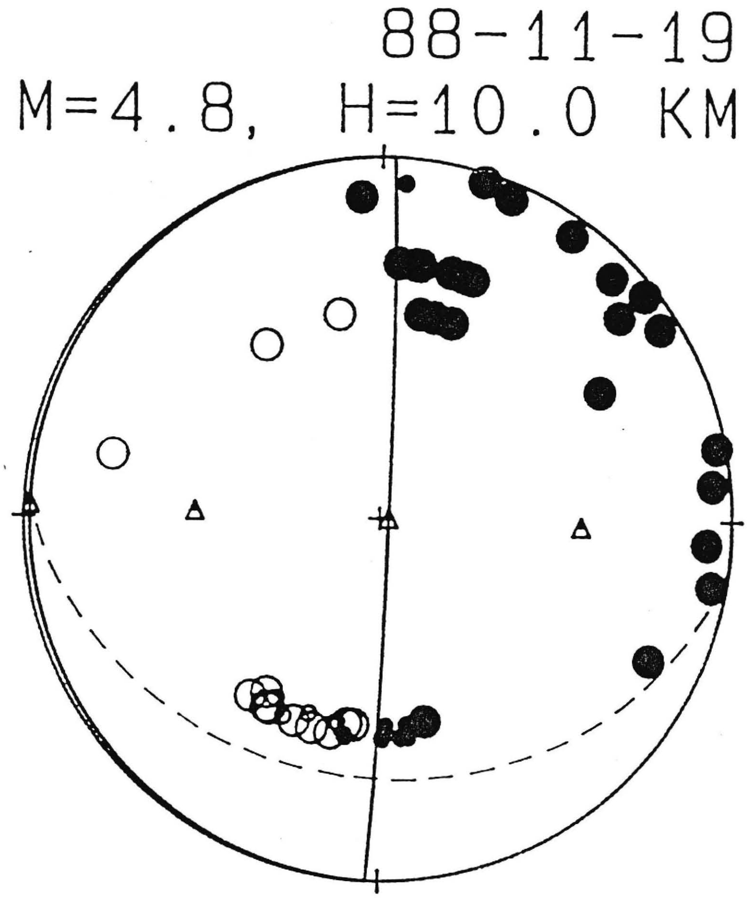
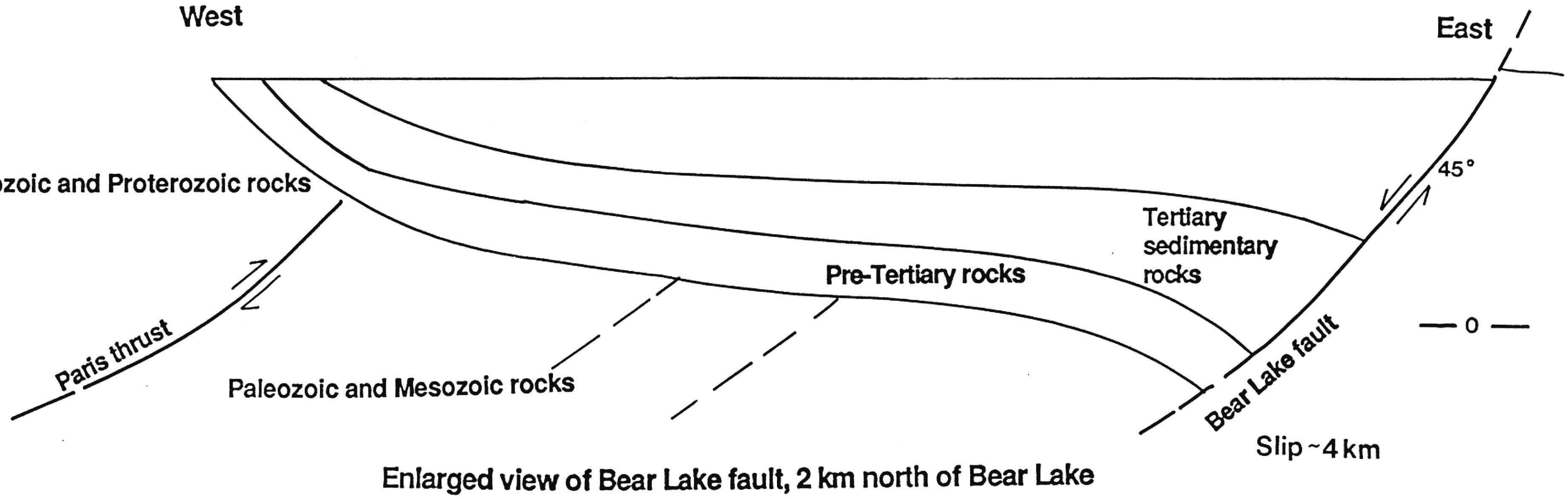


Figure 7. Focal mechanism solution for the 1988 Bear Lake earthquake (M_L 4.8), provided by J. Pechmann of the University of Utah Seismographic Stations. Preferred focal mechanism based on seismological considerations yields either a steeply dipping nodal plane or a very shallowly dipping nodal plane, both of which strike nearly north-south. Preferred nodal planes shown by solid line great circles on a lower-hemisphere equal-area projection. Solid circles represent compressional P-wave first motions; open circles represent dilations.



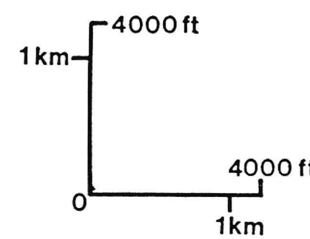


Figure 8. Enlarged view of the Bear Lake basin along a section line approximately 2 km north of the lake in southern Idaho. The migrated section shows that Tertiary rocks dip eastward toward the East Bear Lake fault and form a growth sequence in the basin. Antithetic faults have small displacement which does not show up at this scale.

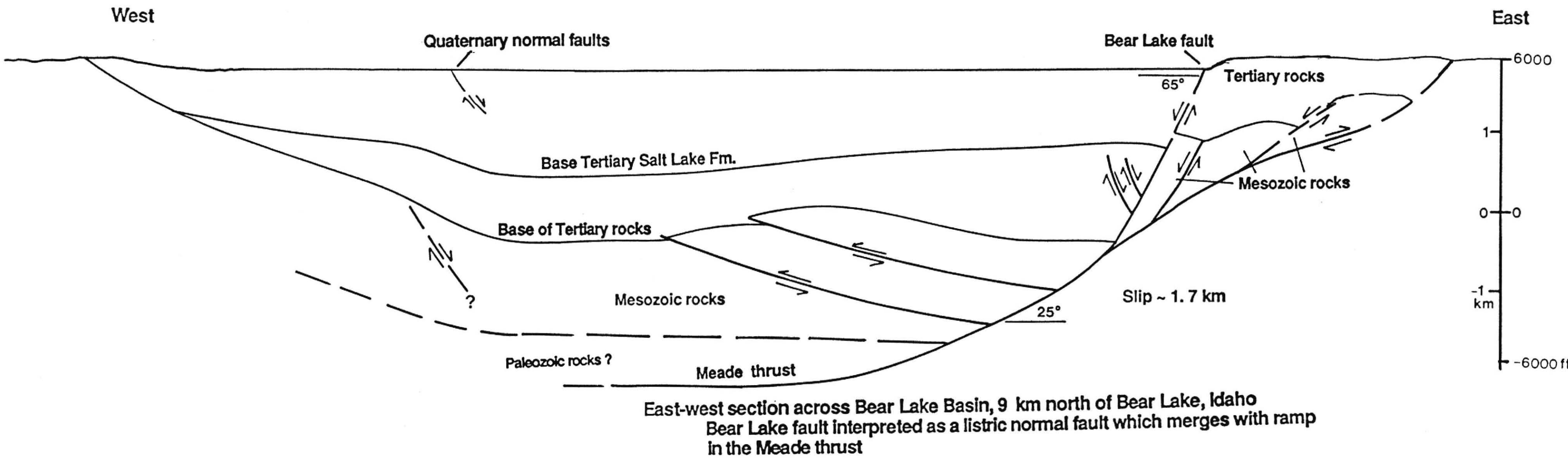


Figure 9. East-west cross section across the Bear Lake basin 9 km north of Bear Lake in southern Idaho. The basin at this location is a broad, flat-bottomed basin with a nearly symmetrical shape. The eastern edge of the basin is bounded by the East Bear Lake fault, which may sole into the Meade thrust. No distinct fault is apparent on the western edge of the basin, but the existence of the fault is suggested by the change in dip of the Tertiary sedimentary rocks. West-directed thrusts may have formed during development of the East Bear Lake fault, or may be back thrusts in the Meade thrust sheet which have been cut off by the East Bear Lake fault.

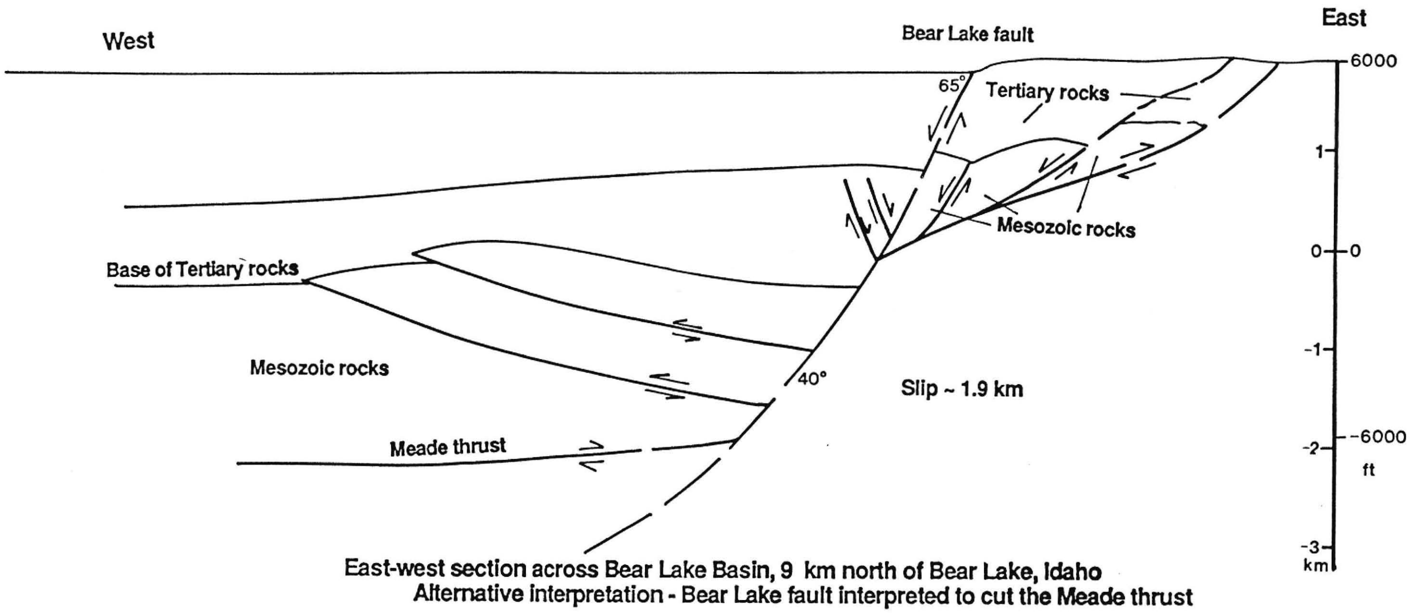


Figure 10. East-west cross section across the Bear Lake basin 9 km north of Bear Lake in southern Idaho showing an alternative interpretation of the East Bear Lake fault. The normal fault may cut the Meade thrust rather than sole into the thrust. Both interpretations yield approximately the same amount of slip on the normal fault.

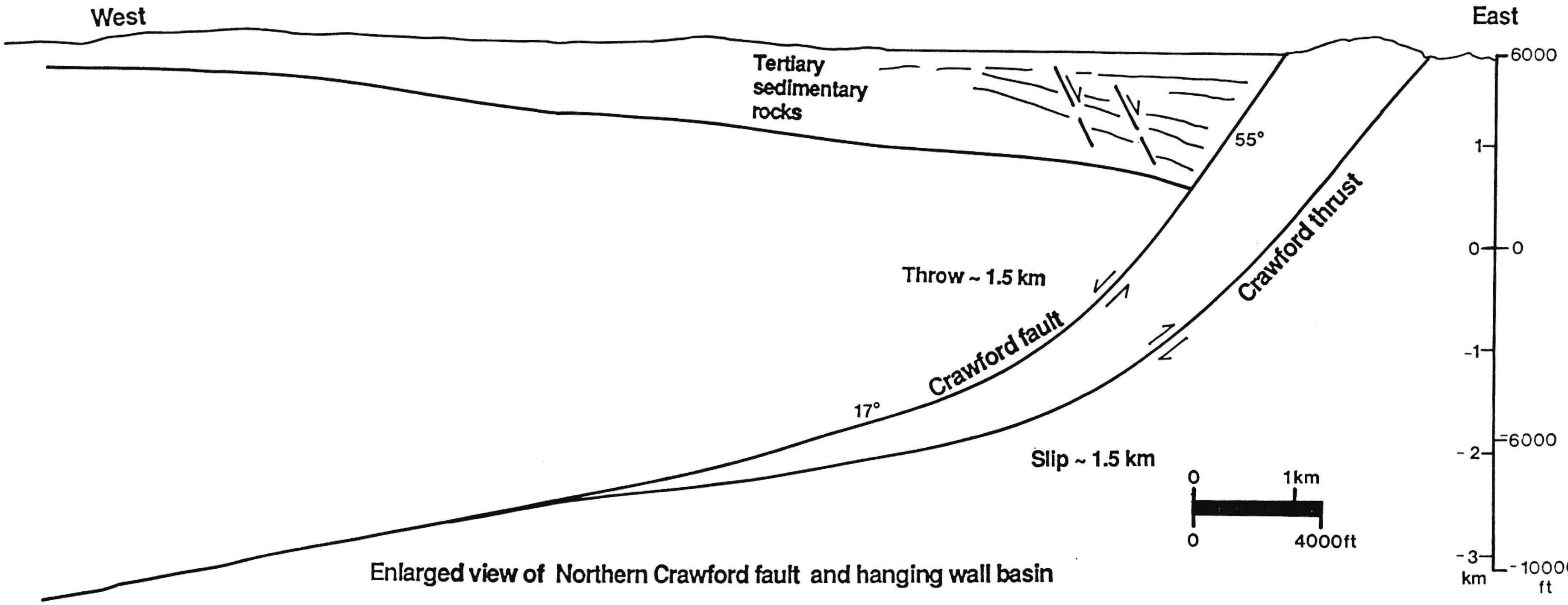


Figure 11. East-west cross section of the Crawford normal fault. The normal fault clearly soles into the Crawford thrust. Tertiary sedimentary rocks are cut by small-displacement antithetic normal faults which do not appear to cut underlying Paleozoic rocks.

East-west cross section of northern Utah, from Westaway, 1989 (Geology, p. 779-783]

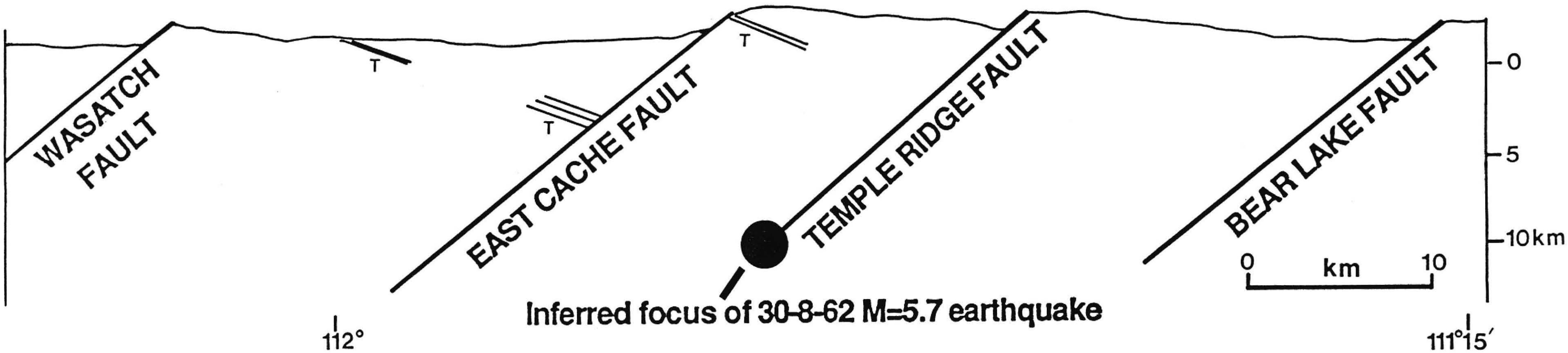


Figure 12. East-west cross section of northern Utah as presented by Westaway (1989). Westaway and Smith (1989) suggested that the 1962 Cache Valley earthquake nucleated on the Temple Ridge fault, and that the faults across the region are planar and dip between 40° and 50°. T indicates the base of the Tertiary rocks in the mountain ranges. Compare with the geologic map and cross sections (Plates 1, 3 and 4) for locations of Tertiary rocks and the forms of the faults. Approximately 10 km of slip is inferred on the East Cache fault.