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Geologic Setting of the 1884 Bear Lake, Idaho, Earthquake: Rupture in the Hanging Wall of a Basin and Range Normal Fault Revealed by Historical and Geological Analyses

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Abstract Analysis of historical accounts of the ~M 6.3 1884 earthquake in northern Utah reveals that the earthquake had an epicenter near 42.3° N, 111.4° W, approximately 30 km northwest of the event's original location. We use detailed reports of damage to structures and the consequences of ground shaking to define a felt area of approximately 70,000 km^2 and estimate the peak ground accelerations as 100–300 $\mathrm{cm/sec}^2$. Analysis of the geologic structure of the area indicates that the epicentral area is a half-graben bounded on the east by the listric Bear Lake fault and on the west by the steeply dipping West Bear Lake fault. The earthquake epicenter was on the west side of the basin, and we interpret the event to have been the result of slip on the West Bear Lake fault zone at a depth of 4–5 km. This zone consists of steeply dipping antithetic faults in the hanging wall of the East Bear Lake fault. These data suggest that moderate-magnitude earthquakes on antithetic or small-displacement faults pose a significant, if local, seismic hazard in the northeastern Basin and Range province. We also demonstrate the utility of combining geological and historigraphic analyses to examine pre-instrument-era earthquakes.

Online material: Felt reports and town summaries.

Introduction

Geologic and paleoseismologic evidence and recent earthquakes, such as the 1959 Hebgen Lake, 1975 Pocatello Valley, and 1983 Borah Peak earthquakes, highlight the importance of large-magnitude earthquakes in the northern Rocky Mountain region. Fault scarps, trenching studies, and historical seismicity show that the region is subjected to $M > 7.0$ earthquakes due to slip on range-bounding normal faults. Slip of 1–3 m on such faults poses a major risk to inhabited portions of the Basin and Range, and understanding the nature of seismcity is an important task for limiting the amount of earthquake-related damage and loss of life.

Historical seismicity of the area also includes numerous events of M 4–6.5 (Arabasz *et al.*, 1979; University of Utah Seismograph Stations, 2000). In the northern Utah–southeastern Idaho region, the four largest events in the regional catalog are the 1884 Bear Lake event (M 6?; Williams and Tapper, 1953), the 1934 Hansel Valley earthquake (M 6.6; Doser, 1989), the 1962 Cache Valley earthquake (M_b 5.7; Westaway and Smith, 1989), and the 1975 Pocatello Valley earthquake (M_b 6.1; Bache *et al.*, 1980; Arabasz *et al.*, 1981). Most of these earthquakes are interpreted as the result of slip on moderately west-dipping normal faults, which have formed in response to the modern east–west extension of the region (Bjarnasson and Pechman, 1989; Zoback, 1989).

Of these cited earthquakes, the 1884 Bear Lake event is of particular interest in the region. This is the largest earthquake reported for the period 1850–1902 for the Utah region (Arabasz *et al.*, 1979; Martindale, 2001). However, its antiquity precludes seismographic analyses, and the reports of the location, damage, and the number of aftershocks (Williams and Tapper, 1953; Cook and Smith, 1967) indicated that it can provide insight into the nature of ground shaking and damage possible from moderate earthquakes in the region. Williams and Tapper (1953) assigned a maximum Mercalli intensity of VIII to the earthquake based on newspaper reports, and thus, this event could serve as a model for moderate-magnitude events in the more populated regions of the Intermontain Seismic Belt. (ISB)

The 1884 Bear Lake earthquake was assigned a magnitude of 6.3 and was located at 42° N, 111°16′ W (Arabasz *et al.*, 1979) based on interpretations of newspaper accounts and catalogs of the era (Williams and Tapper, 1953; Cook and Smith, 1967), and the proximity to the steep eastern range front of the Bear Lake valley. However, scant data

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existed on the duration, intensity, and location of ground shaking from this event, and thus, these assignments were only approximate. No ground rupture was reported, and the population of the region was sparse at the time of the earthquake.

In this article we summarize the results of a historical analysis of records of the earthquake (Martindale, 2001) and combine these results with a geological and seismological interpretation of the data. We discuss the implications for understanding the seismicity and seismic risks of the ISB. While the region was sparsely populated, historical research of the earthquake (Martindale, 2001) revealed many new details regarding the nature of ground shaking, damage, and earthquake-related effects. Martindale (2001) showed that the habit of writing letters to newspapers, keeping journals, and record-keeping by nineteenth-century settlers of the valley provide rich accounts of events surrounding the earthquake. Such detail is used in this article to construct a Mercalli intensity map for the earthquake and to interpret this map in light of our current understanding of the geology of the area. Rigorous historical analyses such as this and other studies (DuBois and Smith, 1980; Ambraseys and Barazangi, 1989; Spence *et al.*, 1996; Bakun and Wentworth, 1997; Toppozada and Borchardt, 1998) provide valuable seismological information on pre-instrument-era earthquakes.

Geologic Setting of Area

The ISB (Smith and Sbar, 1974; Smith and Arabasz, 1991) is a northeast-trending region of diffuse, moderate seismicity between the Wasatch Fault, Utah, and the Teton Mountains, Wyoming (Fig. 1, inset). The region consists of north-trending valleys bounded on one or both sides by active normal faults (Fig. 1). These normal faults form half or full grabens that have variable thicknesses of Tertiary and Quaternary deposits. The normal faults cut Precambrian through Cretaceous rocks that were thrust eastward during the Cretaceous in the Sevier fold and thrust belt development (Armstrong and Oriel, 1965; Lamerson, 1982; Coogan and Royse, 1990). Large-displacement thrust faults have flat-ramp geometries, and several of the normal faults of the region are interpreted to have reactivated the ramps of the underlying thrust faults (Royse *et al.*, 1975; West, 1992, 1993). The ISB corresponds to the southeastern flank of the Snake River Plain, and seismicity along the ISB may be related to passage of the Yellowstone hot spot (Pierce and Morgan, 1992) as well as to the Basin and Range extension.

The Bear Lake earthquake epicenter was previously assigned to the eastern Bear Lake valley (Arabasz *et al.*, 1979), which is a half-graben in the hanging wall of the Bear Lake normal fault (Coogan and Royse, 1990: Kendrick, 1994). This fault forms a basin up to 3 km deep, and the normal fault appears to reactivate a ramp in the Meade–Laketown thrust systems (Coogan and Royse, 1990; Kendrick, 1994). The basin is highly asymmetric, with the west-dipping Bear Lake fault responsible for the thick basin-fill deposits on the east side of the basin. The major thrusts in the region are the Paris–Willard thrusts on the west side of the valley, which carry Proterozoic and Paleozoic rocks in their hanging walls (Fig. 1), and the Meade–Laketown thrusts, which are exposed on the eastern side of the valley. These thrusts carried Late Proterozic through Mesozoic rocks in their hanging walls. The region lies east of the typical physiographic or geologic description of the Basin and Range province, but regional geophysical analyses (Smith and Sbar, 1974; Eaton *et al.*, 1978; Smith, 1978; Arabasz and Julander, 1986) have shown that crustal stretching extends under the central portion of the Idaho–Wyoming–Utah thrust belt. West (1992) suggested the area east of the Wasatch fault represents an eastward-younging evolutionary sequence of normal faults superimposed on the thrusts.

Methods

This article combines the results of Martindale (2001) with geological analysis (Kendrick, 1994) of the region to determine the likely epicenter location for the earthquake. Martindale (2001) conducted a rigorous historical analysis of the earthquake, which encompassed reviewing newspaper accounts, maps, church archive collections, and personal diaries at 13 archives and libraries in Utah, Idaho, and Wyoming. Beginning with sources dated 10 through 17 November, 11 newspapers with circulation routes in Utah, Wyoming, and Idaho were examined. Historical archives and historical facilities of the Utah State University archives, Utah State Historical Society, University of Utah, the Church of Jesus Christ of Latter-Day Saints (LDS) history department, and LDS archives were examined for any documents that contain references to the earthquake. The LDS Family History Library in Salt Lake City proved to be the best source of historical maps used to present the data. The Wyoming government and Uinta County Museum provided felt reports for Wyoming. Other museums and Internet resources assisted in clarification of pioneer customs and daily tasks mentioned in the reports. These data were plotted on copies of maps of the era (Fig. 2) to correlate with place-names then in use, and these locations were then translated to modern coordinates.

The historigraphic analysis of Martindale (2001) and (Table 1) provides many new data on the earthquake by encompassing a larger time span than previously investigated. Felt reports were correlated to the modified Mercalli intensity scale of Wood and Neumann (1931). Application of the 1931 intensity scale to 1884 reports may introduce some uncertainties due to the differences in the nature of buildings and the type of reporting between the two time periods.

The geologic analysis presented here combines map-scale examination of major structures in the area with subsurface analysis. Subsurface data consist primarily of seismic reflection profiles acquired in the region in the 1970s and 1980s and scant drillhole data from the region. Balanced

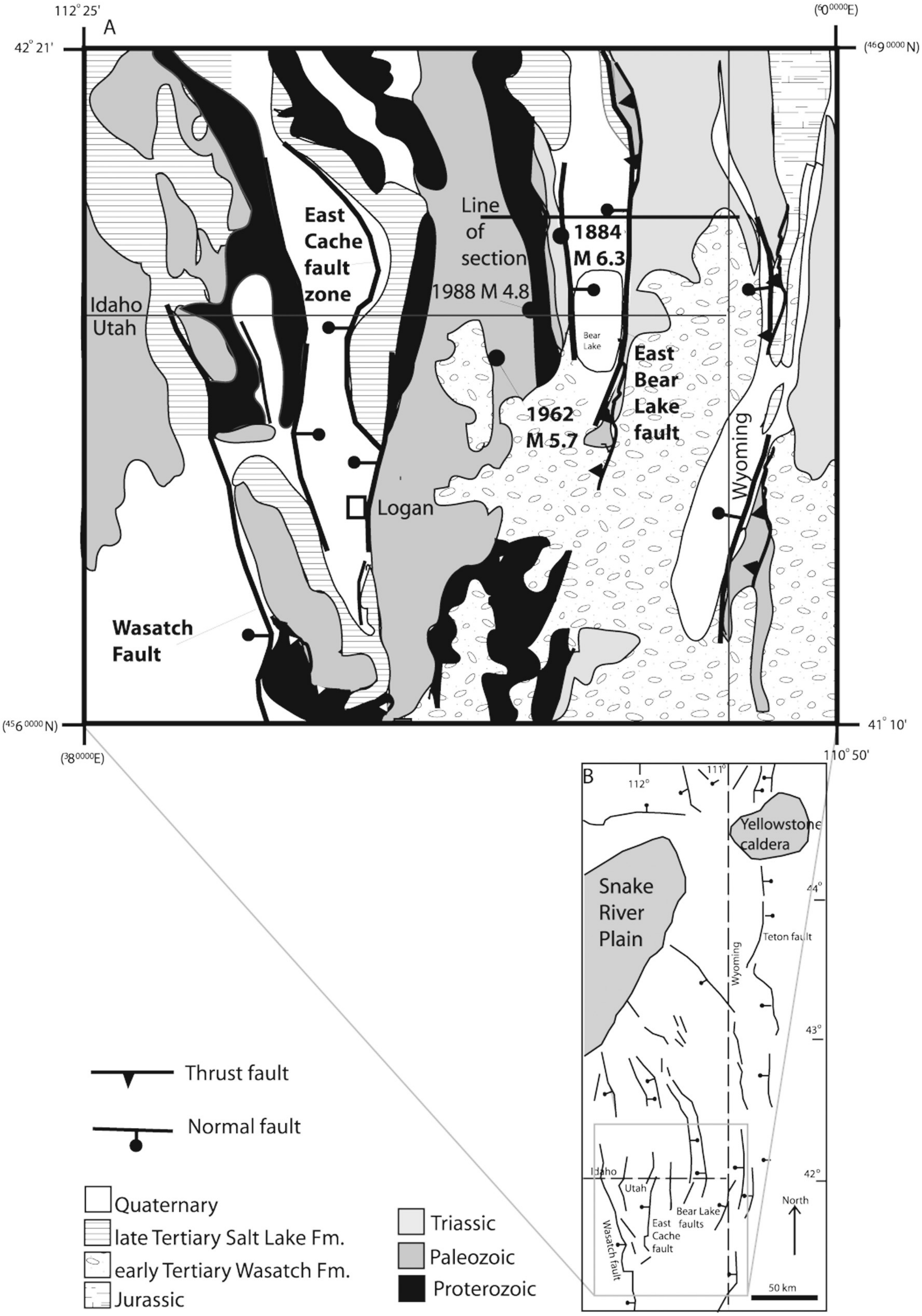

Figure 1. Geologic map of the study area; data are from Oriel and Platt (1980), Dover (1995), and Janecke and Evans (1999). Normal faults bound basins that are superimposed on Sevier folds and thrusts. The inset map shows the location of the study area in the Intermontain Seismic Belt.

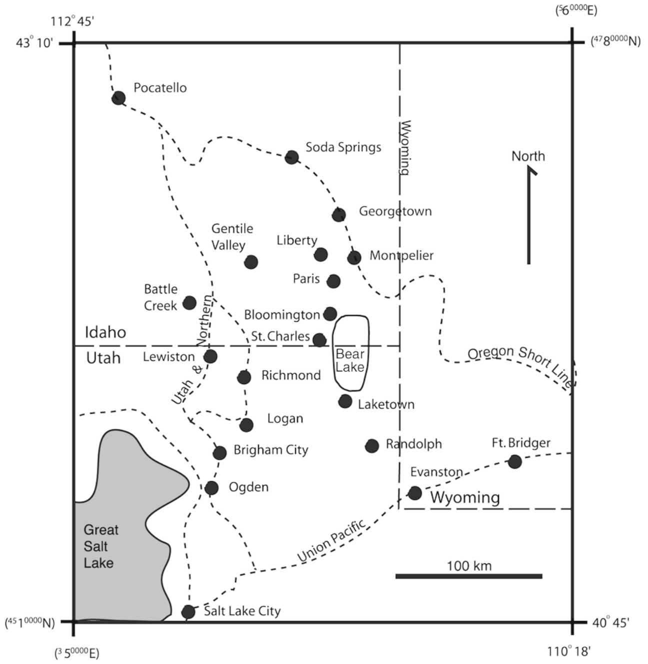

Figure 2. Map of historical place-names used in the study, along with the locations of railroads at the time. These place-names were located on geographic maps of the time and transferred to modern latitude and longitude coordinates for presentation in Table 1.

cross sections (Coogan and Royse, 1990; Kendrick, 1994) depict the subsurface structure based on the constraints of area balanced cross sections. The geology of the area is depicted on the maps of Oriel and Platt (1980) and Dover (1995). Kendrick (1994) compiled all available surface geologic data, drillhole data, and interpreted seismic reflection profiles of the region to interpret the fold and thrust fault geometry and timing of the region. Coogan and Royse (1990) also showed a balanced cross section through the area, and Robertson (1978) examined the near-surface geology and geomorphology of the northern Bear Lake valley. These data form the basis of the geologic interpretation presented in this article.

Summary of Historical Analysis

The Bear Lake earthquake occurred at approximately 1:50 a.m. (local time) on 10 November 1884. Martindale (2001) located seven additional newspaper articles beyond the eight cited by Williams and Tapper (1953) and Cook and Smith (1967) and compiled detailed reports on the nature of damage and felt reports (Table 1). A total of 75 felt reports at 19 sites were recorded over a region in excess of 70,000 km^2 that encompassed the region from Blaine County, Idaho, to Pocatello and Salt Lake City, Utah, and Fort Bridger, Wyoming (Fig. 3). Most of the sites reporting on the earthquake are located on Quaternary and Tertiary basin fill, with many of the town sites associated with sands and gravels of small delta deposits. Thus, while local site effects may affect the nature of the shaking, most of the sites lie on similar unconsolidated deposits. The complete set of felt reports are presented in the electronic supplements. Several representative reports used to compile the Mercalli indicies are presented in the Appendix.

Mercalli magnitude intensity reports indicate intensities from III to VIII; settlers estimated the shaking duration of the event to have ranged from 10 to 30 sec and the direction to depend on the location of the site (Table 1). No reports of liquefaction, sand blows, fissures, or ground displacement were documented. Several reports of water being displaced from irrigation canals were documented, suggestive of a Mercalli intensity of IX or X. However, correlative Mercalli intensity IX or X metrics, such as landslides, ground fissures, collapsed structures, or shifted frame buildings were not reported, and thus we assign a maximum value of VIII, as displacement of water from a canal could be the result of resonance. The number of felt aftershocks ranged from 2 to 21, with the highest number reported for Liberty and Paris, Idaho, northwest of Bear Lake (Figs. 2 and 3). The felt area encompassed Blaine County, Idaho, to Pocatello, Idaho, in the north, Salt Lake City, Utah, in the south, and Fort Bridger, Wyoming, to the east (Figs. 2 and 3). Descriptions of ground shaking include the rocking of a moving train, dislodging and rolling of stacked logs at a sawmill, loud roaring sounds, lights similar to lightening, people thrown from their beds, abundant damage to masonry, and milk spilled from creamer pans. All told, damage was slight due to the low population density and the simple structures in the region. Houses at the time were in the transition from log-style pioneer cabins to wood-frame houses, but there were few differences reported as to the nature of earthquake-related damage. The direction of motion was noted at eight localities. Northwest-to-southeast motion was noted at Liberty and Paris, Idaho, whereas north-to-south or east-to-west motion was noted south of this region.

Martindale (2001) pointed out that many of the recorded felt reports are quite detailed, and the language of the time lends a certain color to the felt reports that must be filtered in order to provide a less biased account. For example, distress and disturbance of females is a common theme, but numerous reports of men being thrown from their beds and being distressed were found when the records are carefully examined. Additional floridity of the descriptions included the interpretation that the event was the revenge of the Earth for a recently held presidential election. The lack of long-term impact of the earthquake may be demonstrated by the fact that most end-of-the-year LDS church reports, presumably written in late December, do not mention the earthquake. Lack of such reporting may also reflect cultural, political, and social norms of the time, where frontier life presented a number of challenges, among them earthquakes, heavy snowstorms, and floods (Martindale, 2001). This shows that historigraphic analyses need to consider the cultural setting in order to determine the actual nature of ground shaking.

Table 1
Summary of Felt Reports

Location	Latitude, Longitude (° ′ N, ° ′ W)	UTM coordinates (Easting, Northing)	Number of Reports	Intensity	Time of First Event	Length of First Event	Direction First Event Felt	Heard Noise Prior	Number of Aftershocks (Nov. 10)	Number of Aftershocks (Nov. 11–13)
Wyoming										
Evanston	41° 15.53′, 110° 57.8′	503072, 4567577	1	–	–	–	–	–	–	–
Fort Bridger	41° 19.2, 110° 21.3′	553985, 4574562	1	III–IV	2:00 AM	5–10 sec	W to E	–	–	–
Utah										
Brigham City	41° 30.63′, 112° 0.96′	415225, 4596015	2	III	1:40 AM (T)	10 sec	N to S	–	–	(1)
Laketown	41° 91.51′, 111° 10.36′	473194, 4630509	3	IV	2:00 AM	10 sec	–	–	–	–
Lewiston	41° 49.52′, 111° 51.98′	428048, 4630822	1	IV	About 2 AM	–	–	–	–	–
Logan	41° 44.13′, 111° 50.08′	430582, 4620927	4	IV	Before 2 AM	Few minutes	–	–	2	(1)
Ogden	41° 13.31′, 111° 58.25′	418622, 4563930	4	IV	–	–	Follow Mts	–	–	–
Randolph	41° 39.97′, 111° 11.03′	484691, 4612742	1	III–IV	–	–	–	–	–	–
Richmond	41° 55.36′, 111° 48.76′	432606, 4641521		IV–VII	1:55 AM	–	–	Yes	–	–
Salt Lake	40° 46.32′, 111° 53.33′	424982, 4513869	4	IV	1:55/2 AM	30 sec 10–15 sec	E to W N to S	Yes	–	–
Idaho										
Battle Creek/ (Franklin)	42° 7.78′, 111° 59.96′	417393, 4664745	1	IV–V	–	–	–	–	–	–
Blaine/Little Wood Valley	43° 25′, 114° 5′	736125, 4811219	1	IV	–	–	–	–	(Several)	–
Bloomington	42° 11.53′, 111° 24.08′	466857, 4671280	3	IV	1:58 AM	–	E to W	Yes	2 (in AM)	–
Gentile Valley	42° 24.62′, 111° 44.15′	439450, 4695677	5	V	After 1:30 AM	–	N to S	Yes	3–5	1 − Wed (AM)
Georgetown		467301, 4702462	7	V	2 AM	12–15 sec/ (1–7 min)	–	Yes	3	–
Liberty	43° 10.12′, 112° 33.28′	473617, 4780799	10	VI–VII	1:52 AM	–	NW to SE	Yes	21 (in AM)	2 + (Tue PM)
Montpelier	42° 19.3, 111° 17.92′	475394, 4685618	5	IV	1:56/7 AM	10–15 sec	–	Yes	2 (in AM)	–
Paris	42° 13.62′, 111° 24.05′	460043, 4675171	19	VII–X	1:50/1:53 AM	30 + sec	NW to SE	Yes	6 (in AM)	2 − Tue (AM) 3 Wed (−) 2 − Thur (AM)
Pocatello	42° 52.28′, 112° 26.68′	381991, 4747360	1	IV	–	–	–	–	–	–
St. Charles	42° 6.8′, 111° 23.36′	467803, 4662516	1	IV	1:55 AM	30 sec	N to S	–	–	–
Soda Springs	42° 39.23′, 111° 36.02′	450796, 4722640	1	IV	–	–	–	–	–	–

Analysis also revealed regions of no felt reports, which constrains the size of the felt area. The Provo and Park City newspapers failed to mention the earthquake, and reports from LDS church archives show that the earthquake was felt only as far south as approximately 40°45′ (approximately equivalent to the street Sixth South in Salt Lake City). The absence of reliable newspaper records in western Wyoming and western Utah preclude definitive determination of the eastern and western margins of the felt area.

The general shape and size of the felt area reflects the location and size of the earthquake along with basin geometry and basin-fill deposits. The data are also biased by the distribution of the settlements at the time, local site effects, and the nature of reporting. For example, a single intensity VII report in Evanston, Wyoming, over 80 km from the inferred epicentral area, may be the result of the report coming from a telegraph operator who was at work when the event occurred and reporting the event in near real-time. Likewise, people made the VII report in Richmond, Utah, on a train, whereas most of the reports from settlers were made by people who were awakened by the event.

The only multiple reports of intensity VII or greater shaking come from Liberty and Paris, Idaho. Intensities fall off steeply with distance from these towns, and this area also had the largest number of aftershocks. The northwest-trending felt area in the valley, with local maxima in the Liberty–Paris, Idaho, area may be strongly influenced by the concentration of settlements in the Bear Lake valley and the limited number of settlements to the east in the Bear Lake plateau or west of the valley in the Bear River Range.

Macroseismic Analysis

The historical data presented in Table 1 and Figure 3 can in principle be inverted to infer the magnitudes and approximate locations of historic earthquakes (Bakun and Wentworth, 1997). However, such an analysis in this case did not yield a physically plausible solution, due perhaps to the distribution of the felt reports or the apparent site effects at significant distances from the epicenter (W. H. Bakun, personal comm., 2000).

Based on the data presented in Figure 3, we estimate that the earthquake epicenter in the region of 42.3° N, 111.40° W, near the town of Paris, Idaho. We reassign the

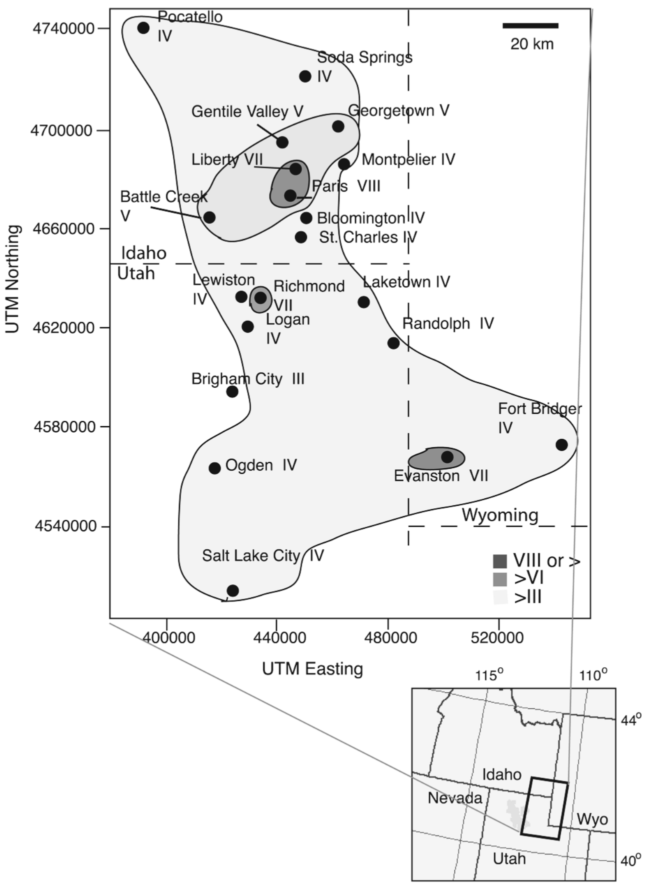

Figure 3. Summary of the Mercalli felt reports for the 1884 event. Numbers next to the intensities indicate the number of independent reports. Arrows show the direction of motion reported at different localities; shaded regions encompass all sites above the Mercalli felt index shown and do not represent any contouring.

location due to the number and detail of felt reports examined by Martindale (2001) and the nature of the ground shaking necessary to produce these felt reports, as opposed to the lack of such reports in Laketown, Utah, which is the location of the previously assigned epicenter (Arabasz *et al.*, 1979). Most of the settlements reporting damage or earthquake-related shaking were of similar size to Paris, and thus we take the fewer reports in other villages to be a true indicator of a reduced amount of shaking. Of particular note is the report of logs being displaced and rolling at a sawmill in Paris and the number of reports of milk spilled from creamer pans. The latter reports are a robust measure of shaking, as all households at the time used a standard set of pans to separate the cream from milk, and such damage, while not critical to a structure, would likely be inconvenient enough to have been reported where it occurred. Other reports that constrain the epicenter location are the reports of cracks in masonry, displaced furniture, and the stopping of pendulum-style clocks.

Determination of the size of the entire felt area is made difficult by the lack of felt reports east of the epicenter, due to sparse population and the lack of continuous newspaper coverage in the region. The felt area encompassed by Salt Lake City on the southwest, Fort Bridger to the east, and Pocatello to the north yields a felt area of at least 70,000 km^2. The felt area was likely elliptical rather than rectangular, but we cannot accurately constrain the axes of the ellipse with our data. Incorporation of the felt report in Blaine, Idaho, north of the Snake River Plain, increases the felt area to 210,000 km^2.

We can estimate the peak ground acceleration and the magnitude of the earthquake using a variety of empirical relationships between Mercalli intensity, magnitude, acceleration, and depth. Interpretations of magnitude and acceleration in the Utah catalog (Arabasz *et al.*, 1979; University of Utah Seismograph Stations, 2000) used the Gutenberg–Richter (1956) relationship of

$$\log(a) = I/3 - 0.5 \qquad (1)$$

and

$$M = 1 + 0.66 I_o, \qquad (2)$$

where a = peak ground acceleration (cm/sec^2), I = Mercalli intensity, M = magnitude, and I_o = maximum intensity. This yields a magnitude of ~6.3 (see Arabasz *et al.*, 1979). Qamar and Stickney (1983) examined the relationship between felt areas and magnitudes for earthquakes in Montana, some of which include Basin and Range events. Applying their correlation to the 1884 event would imply that the Bear Lake earthquake had a magnitude of 5.5–6.1. Thus, we suggest that the 1884 Bear Lake magnitude was 5.5–6.3.

Determining the depth to an earthquake based on the size of the area of a specific intensity is an empirical problem (Bath, 1973). Brumbaugh (2002) examined 24 earthquakes in the western United States for which there was an accurate magnitude and depth determination and felt area report and found the following relationship:

$$I_o = 2.8\log\left[\left(\frac{\left(\frac{2.79A_v}{\pi}\right) + h^2}{h^2}\right)\right] + 2 - \frac{6}{1.2h} + \frac{(6 - I_o)}{6}, \qquad (3)$$

where A_v is the area of the region with intensity V or greater, h is the depth to the earthquake, and I_0 is the maximum intensity. Using 1900 km^2 for the value of A_v for the Bear Lake earthquake yields a focal depth of 4–5 km (Fig. 4). We show later that this agrees well with the geologic interpretation of the structure of the basin.

Murphy and O'Brien (1977) reviewed a variety of methods of estimating ground accelerations from Mercalli intensity values (their figure 5). For the nine methods they reviewed, peak ground accelerations for a Mercalli intensity

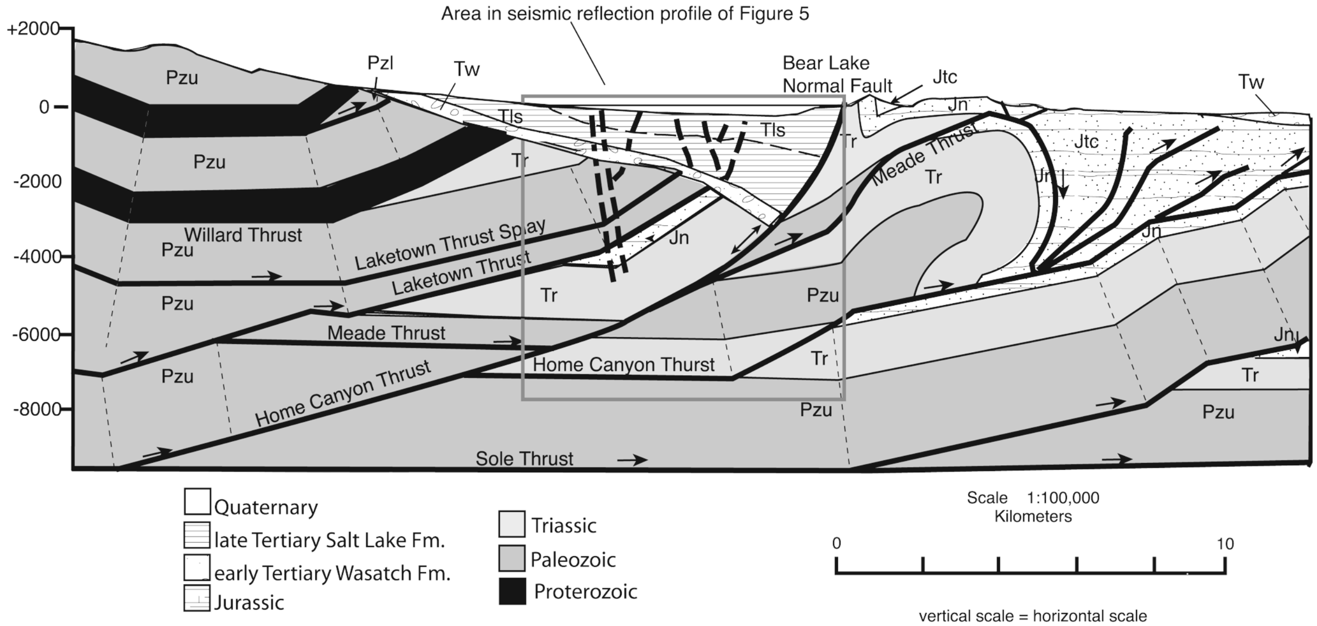

Figure 4. Balanced east–west cross section of the area north of Bear Lake (see Fig. 1 for location). The cross section is based on surface geology, some drillhole data, and industry-acquired seismic data. Reflection data were migrated using sonic velocities recorded in drillholes of the area. The East Bear Lake fault soles into a ramp of the Home Canyon thrust, which has a dip of $\sim 30°$ west in our interpretation. Steep east-dipping normal faults interpreted by Evans (1991) in the hanging wall of the East Bear Lake fault are shown schematically. These faults are interpreted based on the presence of disrupted reflectors in seismic profiles. East tilts of the Tertiary basin-fill deposits, and internal structure of the basin, indicate that the East Bear Lake fault has been the dominant fault in the region in late Tertiary time.

VIII varies from 100 to 1000 cm/sec^2; however, seven of the nine methods limit the peak accelerations to 100–300 cm/sec^2. Using the method of Gutenberg and Richter (1956), the peak ground acceleration for the Bear Lake earthquake was $\sim$140 cm/sec^2. Murphy and O'Brien (1977) suggested that

$$\log (a_{\mathrm{h}}) = 0.25I + 0.25, \tag{4}$$

where a_{h} = peak horizontal ground acceleration, which yields a peak horizontal acceleration of 178 cm/sec^2. Using spectral response models, Atkinson and Sonley (2000) gave a result of 258 ± 198 cm/sec^2 for an M 6.3 event. Thus, the range of peak ground accelerations for the Bear Lake event are in the range of 100–300 cm/sec^2.

The closest recent analog to the Bear Lake event is the 1994 Draney Peak earthquake (M_{w} 5.9) (Schuster and Murphy, 1996; Brumbaugh, 2001). The Draney Peak event had a similar felt area, with a relatively restricted region of intensities of VII and a similar structural setting in the hanging wall of a listric normal fault, as described later.

Geologic Interpretation of the Earthquake

The geologic structure of the epicentral region was examined by Kendrick (1994) and shown in a cross section in Coogan and Royse (1990). Our interpretations are based on unpublished seismic reflection data provided to and interpreted by J. P. Evans and R. Q. Oaks, Jr. (personal comm., 1989, 1990), surface geologic mapping, some deep drillhole data, and construction of balanced cross sections of the region (Fig. 4). Here we summarize this work in order to decipher the fault(s) responsible for the 1884 Bear Lake earthquake. Seismic reflection profiles for the northern Bear Lake valley were primarily data provided by Exxon, who allowed us to make line tracings and interpret stacked, migrated profiles.

The geology of the study area is characterized by contractional structures formed during the development of the Cretaceous Sevier fold and thrust belt (Armstrong and Oriel, 1965; Dixon, 1982). Tertiary extension of the easternmost Basin and Range is related to the location of ramps in the underlying thrusts (Royse *et al.*, 1975; Arabasz and Julander, 1986; West, 1993) and perhaps to the passage of the Yellowstone hot spot (Pierce and Morgan, 1992). The Paris and Willard thrusts lie west of the Bear Lake valley and transported broadly folded Late Proterozoic to early Paleozoic rocks eastward. Kendrick (1994) followed the interpretation of Coogan and Royse (1990) to suggest that the Laketown, Meade, and Home Canyon thrusts east of the Bear Lake valley belong to a distinct thrust sheet that transported Pa-

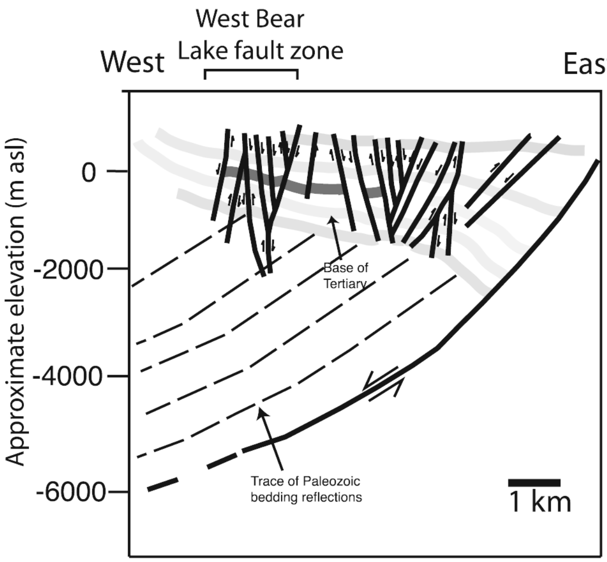

Figure 5. Interpretation of a part of a reflection seismic profile acquired across the northern end of Bear Lake. Line tracing of the prominent reflections, interpreted to be due to units in the basin, is shown, as is the location of the East Bear Lake fault and the faults in the hanging wall. The original data were in two-way travel time. This section is an approximate depth migrated section using the following velocities: Tertiary rocks above the Wasatch Formation = 6000–8000 ft/sec; Wasatch Formation = 10,000 ft/sec; Mesozoic and upper Paleozoic rocks = 15,000 ft/sec above 1-sec two-way travel time, 17,000 ft/sec below 1-sec two-way travel time; middle and lower Paleozoic rocks = 16,000 ft/sec above 0.5-sec two-way travel time, 19,000 below 0.5-sec two-way travel time. Velocities were taken from sonic logs from the well, drilled 8 km north of the section through the northern Bear Lake valley.

leozoic and Mesozoic rocks eastward and resulted in a large anticline in the hanging wall of the Home Canyon thrust (Fig. 5). The Paris, Willard, and Laketown thrusts are all flat to shallowly dipping in the area, whereas the Meade and Home Canyon thrusts are interpreted to have flat-ramp geometries under and east of the Bear Lake (Fig. 4).

The dominant normal fault in the area is the East Bear Lake fault, which is a listric normal fault that soles into the Home Canyon thrust (Fig. 4). Kendrick (1994) and Coogan and Royce (1990) interpreted the Bear Lake fault to cut out the Meade thrust, leaving a tip of the thrust in the footwall of the normal fault. This geometry is similar to that documented by West (1992), which he ascribed to the intermediate amount of extension in the region. The Bear Lake normal fault has 3.8–3.9 km of slip as measured on the cutoffs on the Meade thrust. The Bear Lake fault has a large radius of curvature, dipping 70° at the surface, and gradually reaching a dip of 20° at a depth of 6 km below sea level (Fig. 4). Coogan and Royse (1990) have shown the fault to dip 65° at the surface, and at a depth of 5.8 km below sea level, the fault makes a sharp bend and becomes flat.

Neither Kendrick (1994) nor Coogan and Royse (1990) gave details of deformation or sedimentary structures in the hanging wall of Bear Lake fault. Evans (1991) used proprietary seismic data acquired along the north shore of Bear Lake to examine details of the structure of the hanging wall. Here, numerous small-displacement steeply dipping normal faults were interpreted to cut reflectors that represent the Paleozoic and Proterozoic rocks in the hanging wall of the Bear Lake normal fault (Fig. 5). These small offset faults (throws of ~50–150 m) represent extensional strain in the hanging wall of the normal fault. These faults may penetrate to depths of 6–8 km, where they likely merge with the East Bear Lake fault. A dense set of these faults lies along the western margin of the Bear Lake basin, coincident with the inferred epicentral region for the 1884 event.

No surface ruptures were reported for the 1884 earthquake, but Robertson (1978) recognized fault scarps on both sides of the valley, including an 8-m-high scarp on the west side of the Bear Lake valley (Fig. 6; see also Hecker, 1993). McCalpin (1993, 2003) trenched both the East and West Bear Lake faults and found that *M* >7 earthquakes occurred on the faults 2.1 ka and 5.9–6.5 ka, respectively. The traces of these faults are 6–15 km north of the location of the interpreted seismic section of Figure 5, and thus the West Bear Lake fault zone may be a set of steeply dipping synthetic faults.

There are two candidates for the source of the 1884 earthquake that are compatible with an epicenter defined by the macroseismic data and the geology of the area: (1) the shallowly dipping part of the East Bear Lake fault at depths of 8–10 km and (2) the West Bear Lake fault zone at depths of 5–7 km. These two possibilities raise important issues regarding seismicity in the northeastern Basin and Range province. We briefly discuss these three interpretations in light of recent work on seismicity of extending regions, including the study area.

Seismicity on shallowly dipping normal faults has been the source of much discussion in the past 10 years (Wernicke, 1995). Shallowly dipping normal faults are thought to be unfavorably oriented relative to the nominal state of stress for such regions (e.g., Jackson and White, 1989). Field and seismological evidence indicate that low-angle faults may be seismogenic in some regions (Doser, 1987; Abers, 1991; Wernicke, 1995; Reitbrock *et al.*, 1996; Axen *et al.*, 1999; Sorel, 2000). However, the geological and geophysical record for the northeastern Basin and Range province strongly points to the fact that the large, basin-bounding normal faults produce *M* 7+ events and smaller events tend to occur off the main faults (Arabasz and Julander, 1986; Bjarnsson and Pechmann, 1989; Doser, 1989). In addition, the likely depth to the earthquake focus described earlier likely precludes slip on the East Bear Lake fault.

Slip on the West Bear Lake fault zone thus seem to be the most likely interpretation for the 1884 event. Doser (1989) suggested that small to intermediate earthquakes in the Basin and Range province nucleate on secondary faults,

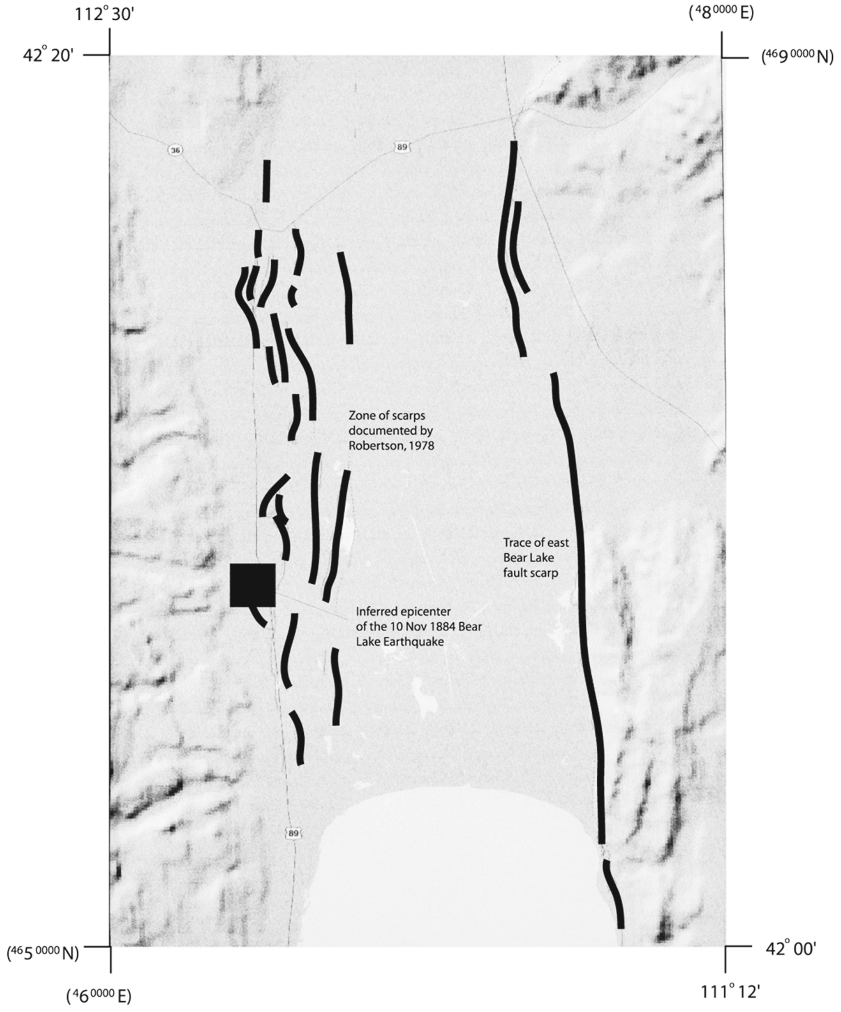

Figure 6. Digital elevation model of the area north of the Bear Lake, with the surface trace of faults interpreted by Robertson (1978) and J. P. McCalpin. Both the West and East Bear Lake faults have produced surface ruptures in the past 10,000 years due to slip from $M \geq 7$ earthquakes (McCalpin, 1993). Scarps up to 8 m high are reported for the West Bear Lake fault (Robertson, 1978; Mccalpin, 2003) indicate that these faults have the potential for ground-rupturing earthquakes.

and the large-magnitude events produce the range-bounding structures that characterize the region. Such an interpretation is consistent with the paleoseismology of the region (McCalpin, 1993, 2003), the 1994 Draney Peak earthquake (Schuster and Murphy, 1996; Brumbaugh, 2001), and the M 4.8 event that occurred in the Bear Lake valley in 1989 (Pechmann *et al.*, 1992). Over time periods of several thousand years, slip on listric normal faults may trigger later, smaller events (Ofoegbu and Ferrill, 1998), generating seismicity across the basin. If the 1884 event occurred on the West Bear Lake fault, this would indicate that some Basin and Range normal faults are capable of producing large events and an occasional moderate-magnitude event that could produce local ground shaking and damage.

The data presented here, along with the work of Arabasz and Julander (1986), West (1992), and McCalpin (1993, 2003), can be combined to suggest a seismotectonic model for the region. To the west, the Cache Valley is bounded on both sides by active normal faults with prominent Quaternary fault scarps (McCalpin, 1993; Black *et al.*, 2000). The East Cache fault is broadly curved to planar, has up to 5.4 km of dip slip, and cuts contractional structures in its footwall (Evans and Oaks, 1996). The faults that make up the West Cache fault system appear to be planar (Evans and Oaks, 1996) and exhibit evidence for recent ground-rupturing earthquakes (Black *et al.*, 2000). The Bear Lake valley is the next extensional basin to the east, and here the East Bear Lake fault clearly soles into the underlying thrust. The fault that likely produces large ($M > 6.5$) seismicity and controls the structure of the basin lies on the east side, whereas the West Bear Lake fault exhibits evidence for past seismic slip that ruptures the ground surface (Robertson, 1978; McCalpin, 1993). However, the fault zone as imaged by seismic reflection data indicates that the fault on the west side has slip on the orders of hundreds of meters, and the 1884 earthquake shows that moderate-magnitude seismicity occurs here. The Bear Lake basin thus may be in an intermediate stage of development (see West, 1992) in which an asymmetric basin is in its early stages of developing a normal fault on the west side of the basin.

Conclusions

We use the results of historical analysis of felt reports of the 10 November 1884 earthquake to determine that its epicenter was in the area of 42.3° N, 111.40° W, with a magnitude of approximately 6.0–6.3. The depth of the focus was likely to have been 4–7 km, and there was no surface rupture associated with the event. This relocation is based on the number and intensity of felt reports discovered through a thorough analysis of regional newspaper accounts and descriptions in journals of local citizens. We combine the historical analysis with the geologic interpretation of the area to show the fault likely occurred by slip on a steeply east-dipping fault in the hanging wall of the East Bear Lake fault. This work documents the potential effects of moderate-sized earthquakes due to slip along faults within basins of the Basin and Range province.

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Appendix

Examples of Accounts of the 1884 Bear Lake, Idaho, Earthquake

These are transcribed directly from the source. We have preserved misspellings, late nineteenth-century grammar, and other aspects of the language not commonly used today. (Ⓔ Felt reports and town summaries are available online at the SSA Web site.)

Deseret Evening News, 13 November 1884

Paris Points Earthquake Incidents and Other Jottings

Brother Richard G. Lambert, of this office, who is traveling through the "north countree" in the interests of the NEWS, sends us a few interesting fragments picked up in Paris, Bear Lake County, Idaho. He begins with last Monday's earthquake of which we have already heard something.

Says he: "This quiet town was startled this morning at ten minuets to two o'clock by an earthquake, the shock lasted at least half a minute. It was quite severe, causing ornaments to be thrown from shelves and a rattling among dishes. It was preceded by a rumbling sound resembling, as mush as anything, a runaway team with a heavy wagon, or a heavy train or cars. It cracked the walls of houses and the first shock was followed by four lighter ones.

The town was throughly startled, some thinking that the end had come. One young man who drives a team, imagining it was running away, awoke calling out "Whoa! Whoa!"

In the office of Wolley Bros., a heavy clock was thrown from the top of a safe to the floor and broken. Sundry articles were cast from the shelves in their store.

The shock seemingly passed from north-west to south-east, and was felt at Evanston and north of here along the Oregon Short Line. At Soda Springs and Pocatello the shock was heavy and was felt at other places as well."

The Bear Lake Democrat, 14 November 1884

Earthquake!! Bear Lake Receives a Good Shaking Up and Causes a Little Damage

About ten minutes to 2 o'clock, last Monday morning, the people of Paris were awakened from their peaceful slumbers by a most tremendous shock of earthquake, which lasted fully 30 seconds at the least. To give here the different versions of the shock, as recited by those who experienced it, would take up more space than we can devote. But the following is about as true and faithful a report of it as we can give: About 11 minutes to 2 o'clock or a few seconds before the first and most terrific shock was felt,—a roar as of a rushing wind was heard approaching from the northwest, and as it came nearer resembled the report of heavy cannonading. Striking the houses it took hold of them as toys, rocking them to and fro as a person would rock a cradle. People were aroused from their sleep in dread and fear, and for the moment hardly realized what it was!

When the truth flashed across their minds many of the frail sex swooned with fright, others were prostrated with sickness, and nearly all say that they never experienced anything so much like seasickness before. Several had their arms, legs, or other portions of their body entirely paralized with electricity. Although the shock was not fatal, so far as we have learned, it had done considerable damage. Clocks were stopped, some being thrown from their places and smashed; crockeryware of all descriptions were thrown from shelves and tables and broken; milk was upset out of pans; books, papers, etc., were strewn around the house in horrid confusion; chimneys fell to the ground; plaster cracked and dropped; wood work from stables loosened and fell; the water in several ditches was upset, while new channels were formed; people in bed were literally uncovered; pictures were thrown from the walls; hanging lamps swayed to and fro as though done by the hand; bedsteads rocked like small cradles; and all this confusion, accompanied by the bellowing of cattle, barking of dogs, bleating of sheep, neighing of horses and crowing of roosters, made the scene a perfect picture of terrible bewilderment. In fact we cannot begin to give a faint idea of the fearful affair.

Several other shocks followed, but none to equal the one just mentioned . . .

We herewith give reports as received from the various settlements:

Liberty

I send you to-day an account of some of the pranks of the "but cut" of an earth quake, which introduced itself to the citizens of this burg rather unceremoniously last night. The shaking up or the shaking down, commenced at 1:52 a.m., standard time. Twenty one shocks followed at intervals, the last occurring at 10:25 a.m. They seemed to come from the north west, passing to the south east. The casualties are not serious, although some persons were somewhat frightened, two or three woman fainting from fear. . . .

Plastering was shaken out of log houses, and chimneys were thrown down. David King had just completed his new house and was ready to move in, but Monday morning found it so badly damaged by the earthquake that he found it necessary to re plaster it, and re-build the chimneys, as the latter were broken off at the roof. At Liberty saw mill the people were greatly disturbed by logs rolling down the hill side from the mill yard, which is situated on quite a steep side hill above the houses. There was almost a constant rumbling noise as of distant thunder or cannonading, and it did not seem to be very far off some of the time either. Cattle bellowed, dogs barked, turkeys gobbled, cocks crewed, and general confusion reigned throughout the night. Some experienced a sea sickness. The air seemed full of electricity. Tuesday night, at 8 or 10 o'clock, more shocks were felt, being sufficiently strong to shake the houses and wake the people.

Bloomington

On the morning of the 10th inst, at about two minutes to 2 o'clock, the first of three shocks of earthquake was felt in Bloomington. Different parties describe it very differently. My own experience is, that a rumbling noise like that of a slow railroad train, was accompanied by six or eight sharp jerks, north and south; which made the castor bedstead strike the south wall near it three or four times, followed in five or ten minutes by a light shake, and another very light shock about 5 o'clock. Several parties in Bloomington think the rolling motion was from east to west, and several saw a bright glow in the sky, going from west to east. One lady, who resides in an old log house, thought the building was falling, and told her husband she always told him it would. A young married couple ran to the next house, leaving the baby in bed.

St. Charles

On the morning of the 10th isnt., at St. Charles, at 1:55, my house had the motion as if on wheels, moving north and south, in sailor's parlance, the house lurched forward. The motion lasted for about thirty seconds. The sky was clear, excepting a slight haze around the moon. The thermometer at that time was 19 above zero. This is the second shock of an earthquake that I have felt in my life time, the first when a boy in Scotland.

Georgetown

This place got a lively shaking up last night; or rather this morning, somewhere near two o'clock. Things danced around in a lively manner, frightening many of the female portion, as well as some of the opposite sex out of their wits. Nearly all the clocks in town were stopped, milk thrown out of the pans all over the cupboard, and articles that were on shelves and bureaus were thrown into the middle of the floor. No particular damage was sustained, with the exception that dishes were thrown from cupboards and broken.

There were four distinct shocks, the first being the most severe and of the longest duration. The length of the shock is variously estimated at from twelve or fourteen seconds, to from one to seven minutes. I think perhaps fourteen or fifteen seconds would be nearly right. I was wide awake when it all happened. At first I heard a rumbling noise, which I took for the cars on the O.S.L. R.R., at some distance, it kept getting louder and louder until I thought it was crossing the railroad bridge just below Georgetown, when all at once the house began shaking like "Sam Hill." That is all I know about the row.

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