Figure 1. The Wasatch fault lies at the foot of the snow-capped Wasatch Mountains. Downtown Salt Lake City, Utah, with the state capitol building, is visible in the foreground. The city is built on the downdropped hanging wall of the Wasatch fault. Attribution: Photo by Andrew Smith, Wikimedia Commons.

The Wasatch Fault: Geoheritage that Informs Society About Seismic Risk

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At 7:09 a.m. on 18 March 2020, a magnitude Mw = 5.7 earthquake shook Salt Lake City, Utah. The Magna earthquake (so designated because its epicenter lay near the western suburb of Magna) was the largest to occur since monitoring began on the Wasatch fault. Fortunately, few injuries occurred, but this moderate-sized earthquake caused $150 million in damage. Experiencing seismic shaking of the normally static surface is always disconcerting, but the timing of the Magna earthquake, just days after many area schools and businesses had shut down in response to the coronavirus 2019 (COVID-19) pandemic, compounded residents' already heightened anxiety. One manifestation of that anxiety was the proliferation on social media of rumors that a monster, magnitude M = 9 earthquake would strike in the coming hours (Pankow et al., 2021).

Geoscientists at the University of Utah Seismograph Stations (UUSS), which spearheads seismic monitoring of the fault, faced the urgent challenge of simultaneously allaying unfounded fears (for example, communicating that the Wasatch fault is incapable of generating an M = 9 earth-

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quake), helping to inform the public of the area's very real seismic risk, and explaining the large scientific uncertainty inherent in earthquake forecasting. They quickly swung into action—On the day of the earthquake, they participated in a virtual press conference, gave 16 media interviews, and issued social media posts to combat misinformation. They have continued to use the Magna earthquake as an opportunity to educate the public through (1) tweets sent to their much-expanded post-earthquake social media following, (2) by creating earthquake education YouTube videos, and (3) adding a Magna Earthquake Frequently Asked Questions (FAQ) page and tips for how to prepare for a major earthquake to their Web site (Pankow et al., 2021).

GEOHERITAGE EXPLAINS THE PRESENT AND INFORMS THE FUTURE

Not all geoheritage sites are formally designated, but they can be recognized by their importance to humanity. For example, geological and geophysical studies of the Wasatch fault "advance our knowledge of natural hazards" and "demonstrate the relevance and importance of geology to society," two geoheritage hallmarks (GSA, 2022). The activities of UUSS, the Utah Geological Survey, and other scientific organizations in response to the Magna earthquake sequence carry on the long tradition of scientific advancement and public education about the hazard posed by the Wasatch fault that began with G.K. Gilbert's pioneering fault mapping and the 1883 letter he sent to the Salt Lake Tribune newspaper warning the population of the fault's dangers (Gilbert, 1884).

Today, nearly 3 million people live along the Wasatch front, the interface between the Wasatch Mountains and the urbanized valleys at their feet, separated by the Wasatch fault (Fig. 1). They face a serious and often underappreciated seismic risk (Pankow et al., 2015) from the very feature on which movement has raised the metropolis' impressive mountain backdrop and formed the well-watered valleys that have sustained people here for thousands of years.

A MIGHTY FAULT AT THE EDGE OF THE BASIN AND RANGE

The 370-km-long Wasatch fault forms the eastern boundary of the 700-km-wide Basin and Range Province (DuRoss et al., 2016). The interface between each range and basin in the province is marked by a normal fault, which accommodates extension as the province's crust is stretched. Each basin formed when a block of crust on the fault's hanging wall (the block resting on the inclined fault plane) dropped down relative to the adjacent mountain range (on the fault footwall) during repeated earthquakes (Fig. 2). The Wasatch fault exemplifies this regional configuration, but bigger: It is one of the world's longest normal faults, and its slip rate is higher than that of most other Basin and Range faults. The fault consists of 10 segments, with the

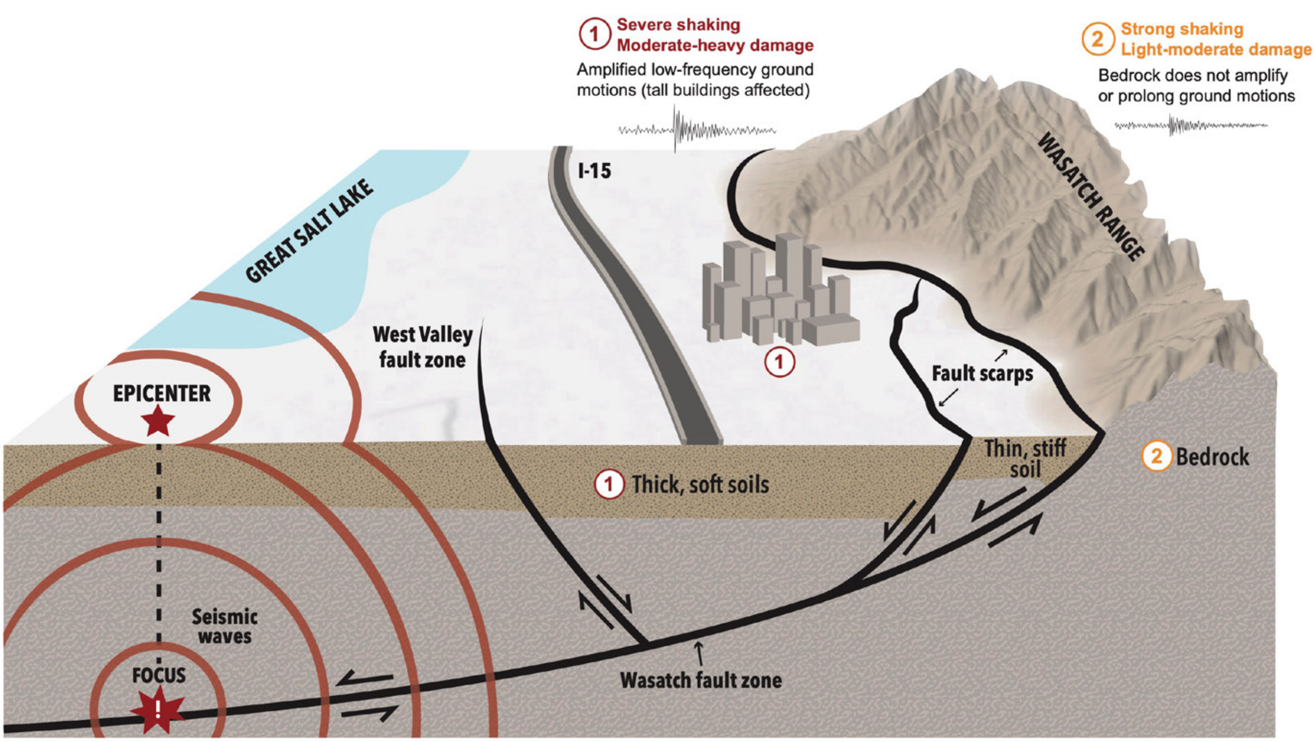


Figure 2. Cross-sectional view of the Wasatch normal fault. The fault's two strands lie at or near the foot of the Wasatch Mountains. The block of rock resting atop the fault (the hanging wall, on the left side of each fault strand) moves down relative to the footwall (right side) block during each earthquake. Notice how the fault dips below Salt Lake City (depicted by the buildings near the number 1 on the diagram). That means the epicenter for the next "Big One" will be in the valley, subjecting the population to considerable shaking. That is illustrated by the marked location of the Magna earthquake epicenter (the point on Earth's surface directly above the focus, the spot where the rupture began). Shaking in Salt Lake City will be further compounded because the city is built on loose sediment that amplifies ground motion. This diagram depicts the Wasatch fault as a listric fault, with a downward-shallowing dip angle, but recent research has called that specific geometry into question (see text). Attribution: Utah Geological Survey.

five central segments, each 35–59 km long, being the most seismically active (Fig. 3; DuRoss et al., 2016).

The best estimates of the Wasatch fault's lifespan and total displacement come from the southern portion of the Salt Lake City segment, near the mouth of Little Cottonwood Canyon, home of the famous Alta and Snowbird ski resorts. Thermochronology and fluid inclusion studies here indicate this section of the fault has accommodated an impressive ~11 km of total vertical displacement over its ~12–17 m.y. lifespan, with a long-term average slip rate of ~0.7–0.8 mm/yr (Parry and Bruhn, 1987; Ehlers et al., 2003; Armstrong et al., 2003). Although slip-rate data are sparser for the other segments, studies averaging rates over both short (10^4–10^5 yr; Machette et al., 1992; Stock et al., 2009) and long (~5 m.y.; Armstrong et al., 2004) time scales suggest that slip rates are slower, 0.2–0.4 mm/yr, on them.

HAS LAKE BONNEVILLE MODULATED WASATCH FAULT SLIP?

G.K. Gilbert is renowned for his shoreline reconstructions of Pleistocene Lake Bonneville and the prescient inferences he made about crustal isostasy based on their elevations (Gilbert, 1890). Lake Bonneville, which was a much larger version of today's Great Salt Lake, gradually filled between ca. 30 and 17 ka in response to increased precipitation during the last glacial cycle, reaching a maximum depth of ~270 m, at which time it covered ~40% of Utah. The lake drained catastrophically sometime between 17.6 and 17.0 ka, reaching its present, shallow depth by ca. 13 ka (Oviatt, 2020).

Gilbert noted that almost all the lake's weight was concentrated on the Wasatch fault's hanging wall (Fig. 2) and speculated that this added weight might promote fault slip when the lake was full, with activity decreasing after the lake drained (Gilbert, 1890, p. 357). One-hundred years later, Machette et al. (1992) documented the opposite trend: 2–3 times faster slip rates (0.5–1.5 mm/yr) during the last 15 k.y. compared to 0.1–0.3 mm/yr recorded since 200–150 ka (see Machette et al., 1992, their fig. 21). The authors extolled Gilbert's astute observation and hypothesized that he had the cause right but the effect backward: The weight of Lake Bonneville increased the normal force acting on the Wasatch fault, thereby inhibiting slip; the slip rate increased after the lake drained at 15 ka, which reduced the normal force.

Analysis of a 307-m-long sediment core collected on the shore of the Great Salt Lake revealed that Lake Bonneville was just the most recent of four large lakes that filled northwestern Utah since 780 ka. Predecessor lakes filled the basin during earlier phases of especially extensive Northern Hemisphere glaciation at ca. 620 ka, 417 ± 55 ka, and ca. 150 ka (Oviatt et al., 1999). A recent study concluded that fault slip decreased at the zenith of each lake (Smith et al., 2024), consistent with the hypothesis proposed by Machette et al. (1992). On a much shorter time scale, the study by Young et al. (2021) on changes in microseismicity in and around the Great Salt Lake between 1987 and 2020 further supports this idea. Those authors found that earthquakes occur 20% more often during dry periods than during wet periods. That finding is not encouraging given that drought and water diversions in recent years have shrunk the volume of the Great Salt Lake to half its historic average volume (Siegler, 2024).

THE WASATCH FAULT'S UNCERTAIN GEOMETRY

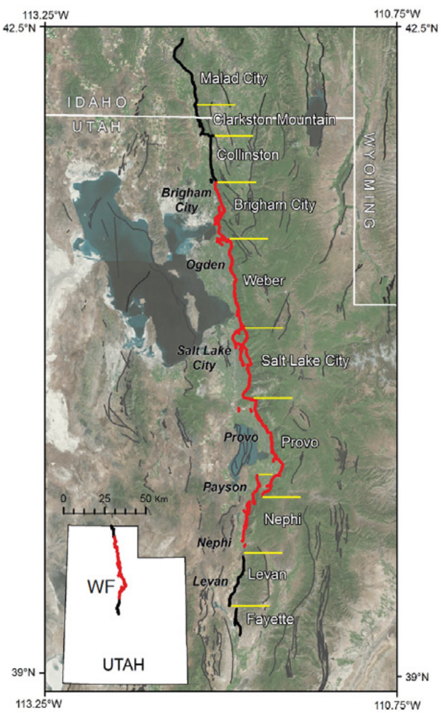
The Wasatch front harbors significant seismic hazard, highlighted by the fact that at least 22 large, surface-rupturing earthquakes have occurred along the Wasatch fault in the last 6000 yr (Fig. 3), averaging about one every 300 yr (DuRoss et al., 2016). Combine that history with the fact that it is home to 80% of Utah's population, and it is easy to see why experts conclude that earthquakes pose the greatest natural threat to Utah's people, built environment, and economy (Pankow et al., 2015).

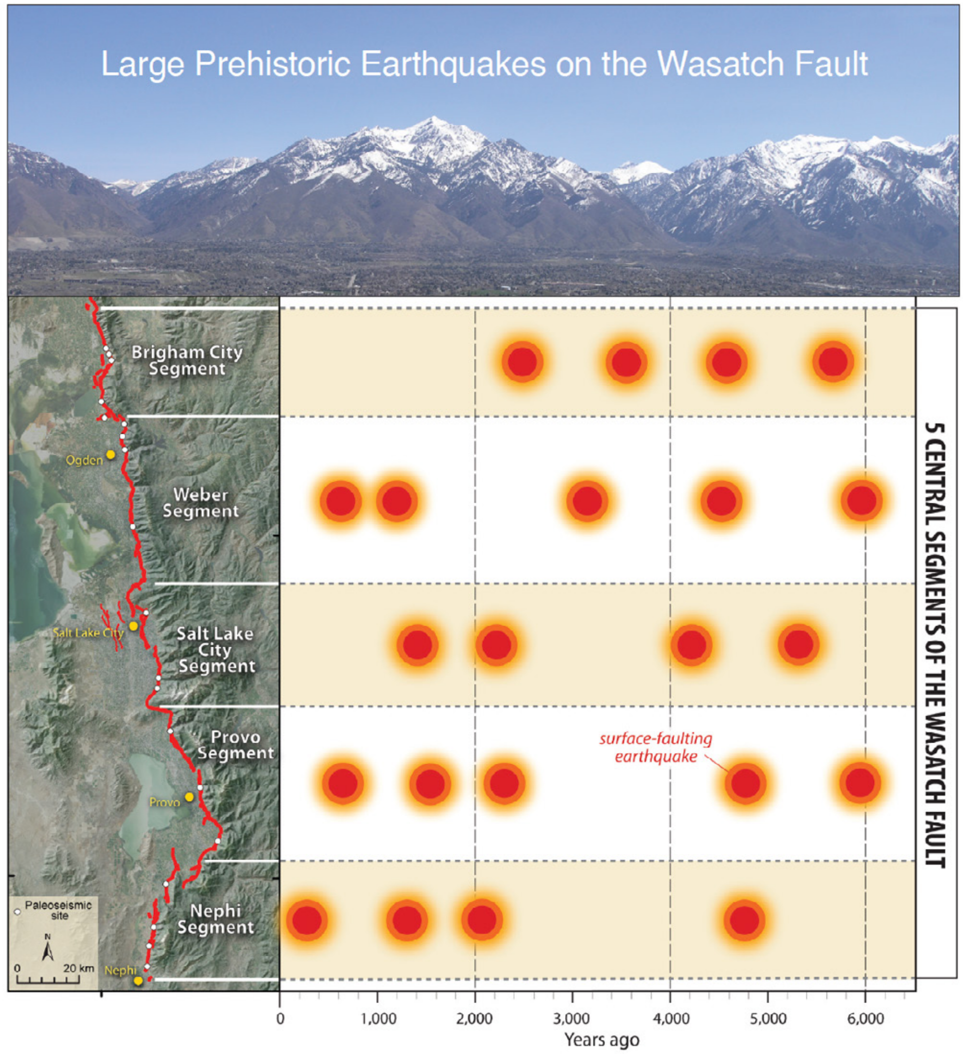
Multiple modeling studies have assessed the hazard, but as Kristine Pankow, UUSS's associate director, points out, despite over 140 yr of research, we remain unsure which values to select for several key parameters that affect the model results, with the fault dip being perhaps the most important. That is because the fault's westward dip (Gilbert, 1928) places it beneath the populated valleys at depth, so most Utahans live, quite literally, atop the fault (Fig. 2). Earthquakes originate at depth, so the epicenter (the spot on Earth's surface directly above the rupture point), where seismic shaking is typically most violent, will be in the middle of the city, not on its fringes. The epicenter of the Magna quake, west of downtown Salt Lake City, illustrates this point. A shallower earthquake will generate more ground shaking than a comparable but deeper quake, so the depth of the fault at the initial rupture point matters.

Two different fault geometries have historically been assumed in hazard models: one in which a planar Wasatch fault dips 40°–70° beneath the western valleys, and another in which it is "listric," curving to shallower dip angles at depth (Fig. 2 depicts this latter geometry). Rock mechanics theory and earthquake focal mechanisms are cited as evidence for the steeper dip, whereas geodetic data and seismic reflection profiles better fit the listric model (Wells et al., 2024). If the steep, planar fault model is correct, then the seismic hazard, while still considerable, is lower than if the fault is listric, because the latter implies that the fault lies at a much shallower depth, where future earthquakes are likely to nucleate.

The UUSS seismologists recognized the unprecedented opportunity the Magna earthquake and its aftershocks presented to better constrain the fault geometry. Within one week after the main shock, they had added five temporary telemetered seismometers and 180 self-recording, three-component geophones to the already extensive seismic network they operated. Deployment of those additional stations allowed them to record over 5000 aftershocks down to M = 0.4 with unprecedented depth resolution (Pankow et al., 2021). The surprising result was that the Wasatch fault geometry is complicated and appears to be neither clearly steep nor listric, but rather could be a low-angle normal fault dipping ~25°, like the detachment faults that bound metamorphic core complexes elsewhere in the Basin and Range (Wells et al., 2024).

Figure 3. Map of the Wasatch fault, showing all 10 fault segments. The five central segments, from Brigham City to Nephi, are the most seismically active. Each red dot shows major earthquake (~M = 7) occurrence during the last 6000 yr, as recorded by offset of well-dated geologic layers. Note that no major earthquake has struck the Salt Lake City segment in ~1400 yr. Attribution: Utah Geological Survey.





WHAT TO EXPECT WHEN THE "BIG ONE" STRIKES

If the latest conclusion about the Magna earthquake sequence, i.e., that it indicates a shallowly dipping Wasatch fault, is correct (Wells et al., 2024), then that means the seismic hazard is even higher than previously estimated—and the previous estimate was grim enough. A 2015 study used Federal Emergency Management Agency (FEMA) modeling software to simulate the impact of a M = 7 earthquake that ruptures the entire Salt Lake segment. The study estimated there will be 2000–2500 deaths and 7400–9300 injuries severe enough to require hospitalization. There were only 3200 hospital beds in the Salt Lake area in 2015, and the scenario projected that almost all area hospitals would sustain damage, meaning some of those beds likely would not be available during the emergency (Pankow et al., 2015).

Beyond the human suffering, the economic toll would devastate Utah's economy. Short-term economic losses were projected at >$33 billion, representing a large fraction of Utah's 2013 gross domestic product (GDP) of $131 billion. There are more than 147,000 unreinforced masonry buildings, the type most vulnerable to seismic shaking, on the Wasatch front (20% of all structures, with most being residences), and 7800 of those are projected to collapse. That will place an overwhelming demand on search-and-rescue operations in the short term, and in the recovery phase, it will require safety inspections of >300,000 buildings. To accomplish that task in a reasonable (30 day) time frame would require 2400 building inspectors (Pankow et al., 2015). The list of both short- and long-term challenges Utah will face in the aftermath of the "Big One" goes on and on.

The report concludes that Utah is not prepared for the major earthquake that, while no geoscientist can predict its exact timing, all agree is inevitable. The Salt Lake City segment's last surface-rupturing event occurred ~1400 yr ago (Fig. 3), and its recurrence interval is 1300–1500 yr (Pankow et al., 2015). Geoscientists have learned a great deal about the fault's history and have repeatedly warned of its hazard in the more than 140 yr since G.K. Gilbert first mapped it. Unfortunately, everything we have learned has only reinforced the chilling warning Gilbert communicated to the local newspaper in 1883 (Gilbert, 1884, p. 52): "Continuous as are the fault scarps at the base of the Wasatch, there is one place where they are conspicuously absent, and that place is close to this city", going on to say, "It is useless to ask when this disaster will occur . . . by the time experience has taught us this, Salt Lake City will have been shaken down . . . ." The

Wasatch fault is a geoheritage site that harbors the clues geoscientists read to warn residents about the valley's unstable seismic future—a monument to the importance of geology for society.

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