Paradise from Cataclysm: Zion Canyon's Sentinel Landslide

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M. Milligan, R.F. Biek, P. Inkenbrandt, and P. Nielsen, editors

Cover Image: *Looking up Zion Canyon from Mt. Spry. During Sentinel Lake's time, water would have stretched up the canyon farther than can be seen in this photograph. Photo credit Sarah Meiser.*

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Utah Geosites showcases some of Utah's spectacular geology, both little-known localities and sites seen by visitors to Utah's many national and state parks and monuments. The geosites reflect the interests of the many volunteers who wrote to share some of their favorite geologic sites. The list is eclectic and far from complete, and we hope that additional geosites will be added in the coming years. The Utah Geological Survey also maintains a list of geosites https://geology.utah.gov/apps/geosights/index.htm.

We thank the many authors for their geosite contributions, Utah Geological Association members who make annual UGA publications possible, and the American Association of Petroleum Geologists—Rocky Mountain Section Foundation for a generous grant for desktop publishing of these geosite papers.

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Presidents Message

I have had the pleasure of working with many different geologists from all around the world. As I have traveled around Utah for work and pleasure, many times I have observed vehicles parked alongside the road with many people climbing around an outcrop or walking up a trail in a canyon. Whether these people are from Utah or from another state or country, they all are quick to mention to me how wonderful our geology is here in Utah.

Utah is at the junction of several different geological provinces. We have the Basin and Range to the west and the Central Utah Hingeline and Thrust Belt down the middle. The Uinta Mountains have outcrops of some of the oldest sedimentary rock in Utah. Utah also has its share of young cinder cones and basaltic lava flows, and ancient laccoliths, stratovolcanoes, and plutonic rocks. The general public comes to Utah to experience our wonderful scenic geology throughout our state and national parks. Driving between our national and state parks is a breathtaking experience.

The "Utah Geosites" has been a great undertaking by many people. I wanted to involve as many people as we could in preparing this guidebook. We have had great response from authors that visit or work here in the state. Several authors have more than one site that they consider unique and want to share with the rest of us. I wanted to make the guidebook usable by geologists wanting to see outcrops and to the informed general public. The articles are well written and the editorial work on this guidebook has been top quality.

I would like to personally thank Mark Milligan, Bob Biek, and Paul Inkenbrandt for their editorial work on this guidebook. This guidebook could not have happened without their support. I would like to thank Jenny Erickson for doing the great desktop publishing and the many authors and reviewers that helped prepare the articles. Your work has been outstanding and will certainly showcase the many great places and geology of Utah. Last, but not least, Thank you to the American Association of Petroleum Geologists, Rocky Mountain Section Foundation for their financial support for this publication.

Guidebook 48 will hopefully be a dynamic document with the potential to add additional "geosites" in the future. I hope more authors will volunteer articles on their favorite sites. I would like to fill the map with locations so that a person or family looking at the map or articles will see a great location to read about and visit. Enjoy Guidebook 48 and enjoy the geology of Utah.

Peter J. Nielsen
2019 UGA President

LOCATION INFORMATION

GPS location (NAD83): 12S 325840E 4123026N
Suggested driving directions: Park at the Springdale entrance and board the Zion National Park shuttle bus. Disembark at Stop 4, Court of the Patriarchs.
Physical location description: From the shuttle stop, follow the path west to the Sand Bench trailhead, then proceed approximately 250 feet (approximately 75 m) to the bridge crossing the North Fork Virgin River to the GPS coordinates given above.

INTRODUCTION

Zion Canyon hosts millions of visitors each year, yet few are aware of the massive prehistoric landslide that played an important role in shaping the iconic landscape. South of the Sand Bench trailhead and bridge, a large hill encroaches on the canyon bottom around which the North Fork Virgin River flows (figure 1). North of the bridge, Zion Canyon's flat bottom stretches into the distance. The hill is part of an enormous rock avalanche deposit known as the Sentinel slide that is nearly 2 miles (3.2 km) long and more than 650 feet (200 m) thick. After failure, the Sentinel rock avalanche dammed the North Fork Virgin River creating a lake (known as Sentinel Lake) which persisted for approximately 700 years (Grater, 1945; Hamilton, 1976; Castleton and others, 2016). Over the course of the lake's lifetime, sediment settled at the bottom of the lake to create thick deposits of mud, clay, and sand. Sediment eventually filled in the canyon bottom behind the landslide dam, and the lake ceased to exist. These sediment layers are still visible today and are responsible for the remarkably flat floor of upper Zion Canyon (Grater, 1945; Hamilton, 2014; Castleton and others, 2016).

A rock avalanche is a variety of landslide, primarily composed of rock, with a volume greater than approximately 1 million cubic yards [10^6 m^3] and speed greater than 16 feet per second [5 m/sec] (Hungr and others, 2014)—here we will use the terms rock avalanche, landslide, and slide interchangeably to describe the event.

GEOLOGIC SETTING

Like many national parks in southern Utah and northern Arizona, Zion National Park (Zion) represents a slice of The Grand Staircase—"layer cake" geology with relatively horizontal sedimentary rock formations stacked neatly atop one another (figure 2) ascending northward from the Grand Canyon. The formations represent a variety of depositional environments as described by Biek and others (2010) and references therein.

In Zion Canyon, the uppermost visible formation capping many of the high cliffs is the Middle Jurassic (approximately 173-170 million years old) Temple Cap Formation, which consists of three members in the park: reddish-brown mudstone of the lower (Sinawava) and upper (Esplin Point) Members, separated by a cliff of sandstone of the middle (White Throne) Member, collectively representing shallow-marine to coastal-dune environments (Doelling and others, 2013).

Below the Temple Cap we find the formation responsible for Zion's famous cliffs—the Navajo Sandstone (the Navajo). The Navajo was deposited about 185-180 million years ago during the Early Jurassic Period in an expansive desert similar to the modern Sahara. Quartz sand grains were deposited in a vast sand dune field known as an erg. Sand deposited on the lee sides of massive dunes created steeply dipping beds that are preserved as the inclined layers (i.e., crossbeds) that zig-zag across cliff walls. The Navajo averages 2000 feet (600 m) thick within the park.

The slope-forming Kayenta Formation (the Kayenta) is found below the Navajo. It is an Early Jurassic formation (195-180 million years ago) comprised of alternating layers of thin sandstones and mudstones. The Kayenta was deposited in a fluvial floodplain environment where sands came to rest along river beds while muds accumulated in the adjacent floodplains. The Early Jurassic to Late Triassic (approximately 205–195 million years ago) Moenave

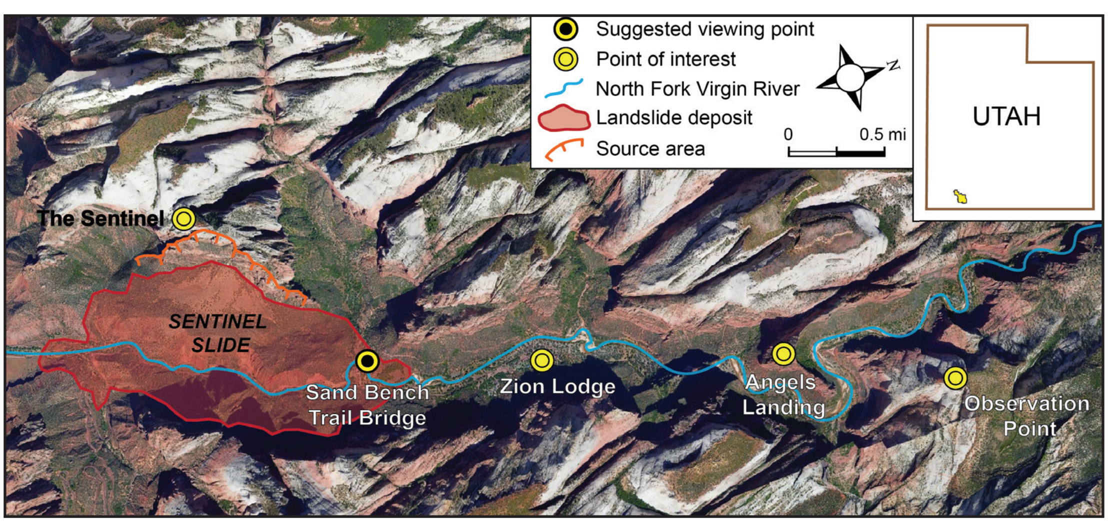

Figure 1: Location map of Zion Canyon in Zion National Park. Imagery from Google Earth Landsat/Copernicus (2016).

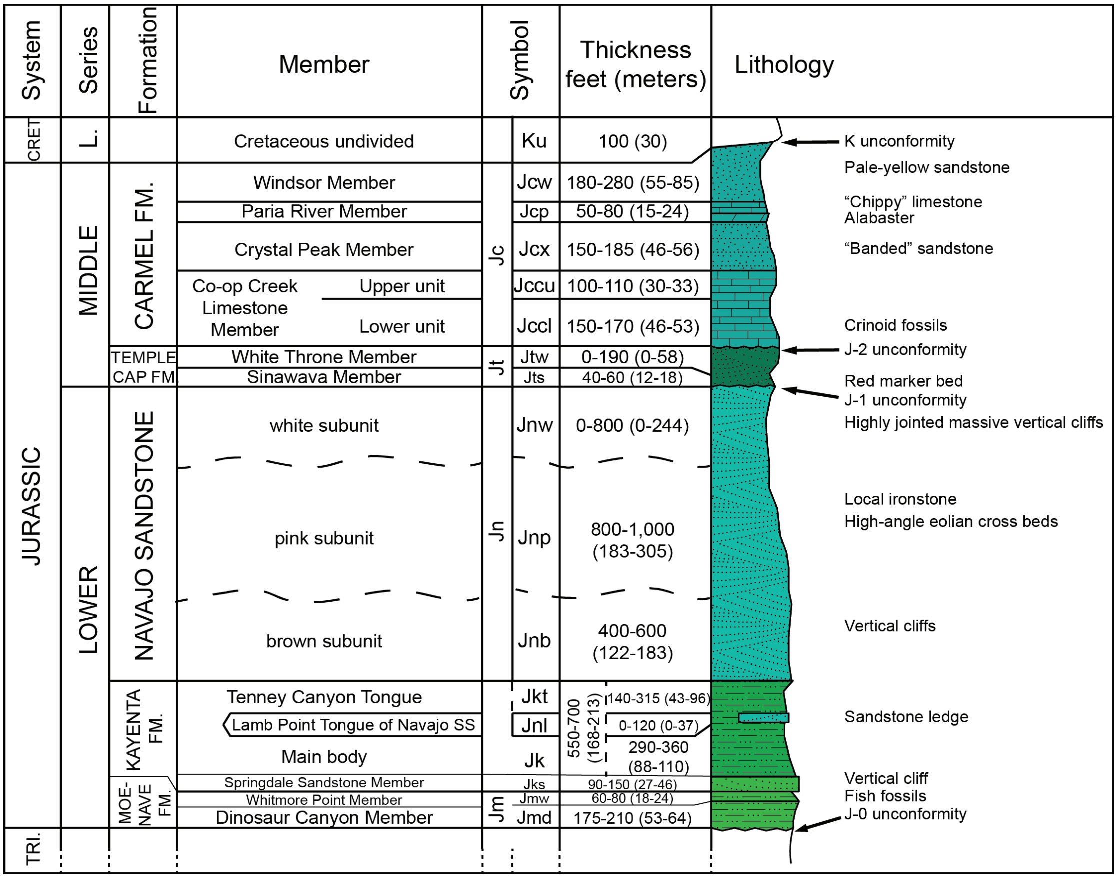

Figure 2: Stratigraphy of Zion National Park. Modified from Biek and others (2010).

Formation (the Moenave) sits below the Kayenta. The Moenave contains sandstone, siltstone, mudstone, and limestone amassed in a complex system of rivers, floodplains, and lakes. The lowermost Kayenta and the Moenave did not fail in the Sentinel slide as evidenced by intact outcrops of the Springdale Sandstone (the basal subdivision of the Kayenta Formation) below the rock-avalanche deposit (figures 2 and 3) (Doelling and others, 2002; Castleton and others, 2016).

Zion stands on the western edge of the Colorado Plateau, on a relatively stable fault block bordered to the east by the Sevier fault and to the west by the Hurricane fault (Grater, 1945; Rogers and others, 2004; Biek and others, 2010). Continued tectonic uplift across the Hurricane fault, along with its counterpart, fluvial erosion, are responsible for the deep incision of Zion's canyons (Grater, 1945). Miles upstream from the Sand Bench trailhead, the North Fork Virgin River begins cutting through the Navajo Sandstone in the section of Zion known as the Narrows. Flowing water exploits pre-existing joints produced during uplift, gradually widening them (Rogers and others, 2004). Farther downstream near the Sentinel, the Virgin River has cut through the entirety of the Navajo and into the underlying Kayenta and Moenave formations. As the North Fork Virgin River erodes the relatively weak Kayenta and Moenave, it undermines the overlying Navajo cliffs causing rockfall and other landslides as part of the canyon widening process.

The Deposit

The volume of the Sentinel slide deposit was originally approximately 375 million cubic yards (286 million m^3) (Castleton and others, 2016), which is enough to cover all of New York City's Central Park with 275 feet (84 m) of debris. It has a maximum thickness of 656 feet (200 m) and stretches approximately 2 miles (3.2 km) along Zion Canyon (Castleton and others, 2016). Approximately 45% of the original deposit has been removed by the Virgin River creating the steep and narrow gorge adjacent to the slide.

Rock-avalanche deposits are often known for their hummocky (i.e., irregular surface comprised of small mounds) appearance. The Sentinel slide's surface has significant topography, which hinders views of the entire deposit from the canyon bottom. A short hike along the Sand Bench trail reveals the magnitude of local relief atop the slide. The uneven surface can be attributed to the irregularity of the slide sediments themselves, which range from house-sized boulders to sand and silt, as well as the slide's failure mechanics (Paguican and others, 2014). The topography has been subdued since emplacement of the deposit due to erosion of boulders and deposition of sand (both locally derived from weathering and from aeolian [i.e., wind-driven] deposition) across the deposit's surface.

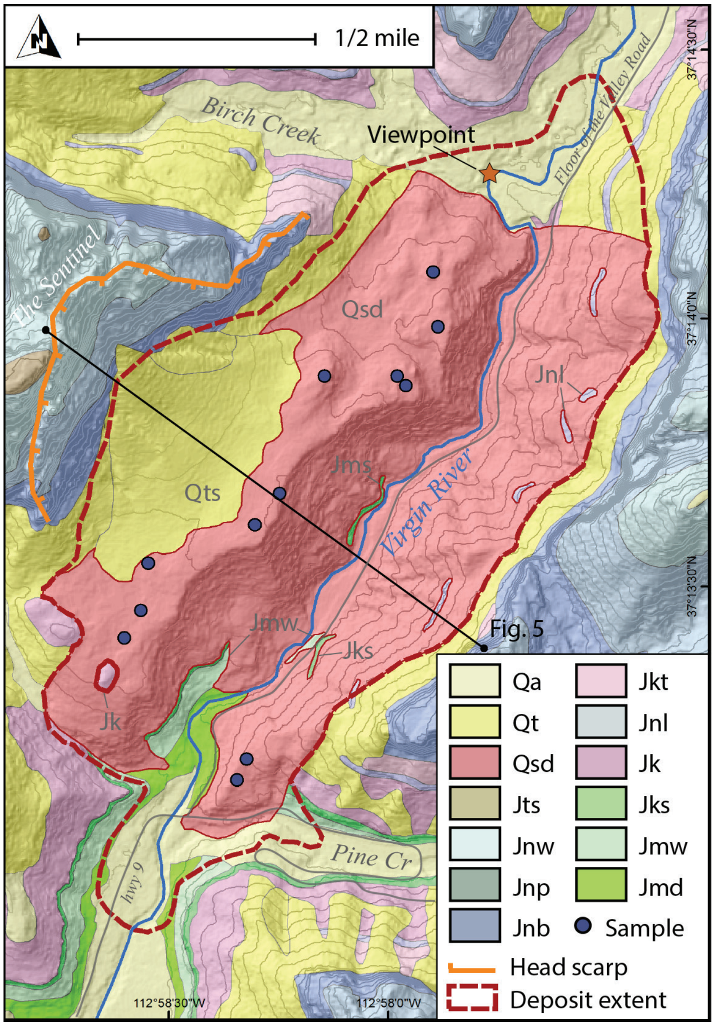

Figure 3: *Geologic map of the Sentinel slide and surrounding area. Modified from Castleton and others (2016) after Doelling and others (2002). Map units are defined in figure 2. Orange star is the bridge viewpoint. Blue circles are sample locations from cosmogenic exposure age dating (Castleton and others, 2016). The head scarp refers to the intact, upper limit of the surface which ruptured during the landslide. Contour interval is 100 feet (30 m). See figure 5 for cross section.*

Figure 4: *Nearly intact but deformed and tilted blocks of the Kayenta Formation near the base of the Sentinel slide deposit. Trees are approximately 30 feet (9 m) tall for scale.*

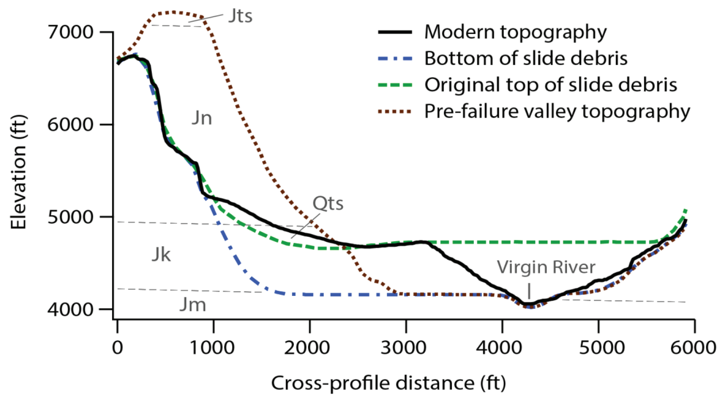

Figure 5: *Rock-avalanche deposit cross profile; geological units as in figure 3. See figure 3 for cross section location. Modified from Castleton and others (2016).*

The Sentinel slide's composition reflects the geology of the surrounding cliffs. Rock-avalanche deposits commonly preserve the stratigraphy (i.e., the ordered layers of rock) of the source area (Hewitt, 2009). Since the Navajo overlies the Kayenta in the cliffsides, we expect the Navajo to overly the Kayenta in the deposit and indeed, this relationship is observed. Note that while the upper Temple Cap was likely also involved in the rock avalanche, its relative proportion is small and its sandstone blocks can be difficult to distinguish from the Navajo.

A short walk southwest along the park road offers a view into the internal structure of the landslide deposit revealed by river incision. Here the upper deposit contains highly fractured, angular blocks of predominantly Navajo Sandstone of differing sizes – from enormous boulders to sand. It is the sand-size particles which lend their name to the trail, Sand Bench, that traverses the slide. Below the highly fractured, densely-compact and jumbled blocks of Navajo, large slabs of maroon and white beds of the Kayenta Formation are visible (figure 4). These blocks of Kayenta underwent significant movement but appear less fractured and disrupted than the overlying Navajo. This difference may be due to the displacement experienced by the respective blocks. The Navajo's vertical cliffs extend much higher above the river than the underlying Kayenta, therefore the Navajo blocks fell farther and likely experienced greater disruptive energy. Additionally, the interbedded, mud-rich Kayenta is more deformable than the massive Navajo sandstone which is brittle and tends to break into angular blocks.

The Failure

A 2016 study by Castleton and her colleagues recounts a detailed description of the Sentinel slide, including a numerical landslide runout model. To model the slide, they reconstructed the pre-rock avalanche topography including the source area and the original canyon bottom. They then employed a landslide runout model to simulate the failure (figure 5). Their results showed that the rock avalanche traveled at a maximum velocity of approximately 200 mph (90 m/s), crossed Zion Canyon in less than 20 seconds, and then spread laterally up and down the canyon. The model indicated that the failure (i.e., initial detachment to final deposit emplacement) had a total duration of just over 1 minute.

The Age

Age estimates for the Sentinel slide were previously derived from radiocarbon (^{14}C) samples from Sentinel Lake sediments (Hamilton, 1976, 2014; Doelling and others, 2002). Castleton and others (2016) later directly dated the landslide deposit itself using a method known as *cosmogenic isotope surface exposure dating*. This method can be used to determine the age of exposure for features at the earth's surface, such as glacial moraines and landslides (Ivy-Ochs, 1996; Gosse and Phillips, 2001; Ivy-Ochs and Kober, 2008). Cosmic and solar rays constantly bombard Earth's surface with energetic particles. These particles interact with the atomic nuclei of elements within minerals, resulting in the creation of rare secondary, or cosmogenic, isotopes within the mineral and rock. The production of certain cosmogenic isotopes in specific minerals (such as ^{10}Be in quartz) occurs at a relatively well-known rate. By measuring the concentration of these cosmogenic isotopes in a sample from the landslide's surface, we can calculate how long a rock has been exposed to cosmogenic bombardment and therefore when the landslide occurred (Ivy-Ochs, 1996; Gosse and Phillips, 2001; Ivy-Ochs and Kober, 2008). Castleton and others (2016) sampled 12 boulders atop the Sentinel slide for dating (figure 3). The resulting mean age of the Sentinel slide was found to be 4800 ± 400 years old.

Sentinel Lake

The Sentinel slide immediately dammed the North Fork Virgin River, causing the canyon behind the deposit to slowly fill with water. Based on modern flow rates measured at the North Fork Virgin River and reconstructions of the deposit's original topography, it likely would have taken 5 to 10 years for the water to fill the canyon and begin to overtop the rock-avalanche dam (Castleton and others, 2016). As the lake overtopped the dam, water rapidly eroded the loose upper portions, but the rushing cascade did not incise entirely through the deposit. The lake outlet stabilized, establishing Sentinel Lake, which persisted until it filled with sediment several hundred years later (figure 6) (Hamilton, 2014; Castleton and others, 2016). Using modern East Fork Virgin River sediment yield measurements as a proxy for prehistoric North Fork conditions (Andrews, 2000; Castleton and others, 2016), Sentinel Lake likely occupied Zion Canyon for approximately 700 years from 4800 to 4100 years ago. The lake was 4.4 miles (7 km) long at maximum and covered an area of 1.1 square miles (2.85 km^2). The water level would have been approximately 175 feet (53 m) above the current ground surface at the Sand Bench trailhead viewpoint. The thick accumulation of sediment deposited in Sentinel Lake partly fills what might otherwise be a steep and narrow canyon, to create a gentle and inviting landscape.

Just as river erosion reveals the internal stratigraphy of the rock avalanche, it has also incised into the muds and clays deposited in Sentinel Lake. Exposures of yellow, tan, and gray layers of fine sediment can commonly be found along river cut banks (figure 7). Aquatic snail shells and uninterrupted clay beds indicate that Sentinel Lake was likely deep and long lasting, while overlying sand deposits indicate river deposition after the lake had filled with sediment (Hamilton 1976, 2014). Currently the North Fork Virgin River lies approximately 80 feet (approximately 24 m) below the elevation of the highest lake-bed deposits, revealing the extent of erosion into what was once a higher and broader valley floor several thousand years ago (Castleton and others, 2016).

Other Vantage Points

The enormity of the Sentinel slide is difficult to appreciate from a single viewpoint. Hiking the Sand Bench trail up and across the deposit allows better appreciation of its immense size; from a variety of viewpoints hikers can see clues to its original width across the valley and imagine The Sentinel rock wall before and during failure (figure 8). Walking southwest down the park road towards the Canyon Junction shuttle stop provides a sense of the deposit's length and height and reveals outcrops of its internal structure including large blocks of the Kayenta Formation involved in the slide (figure 4). Farther upcanyon, views from the Kayenta trail highlight

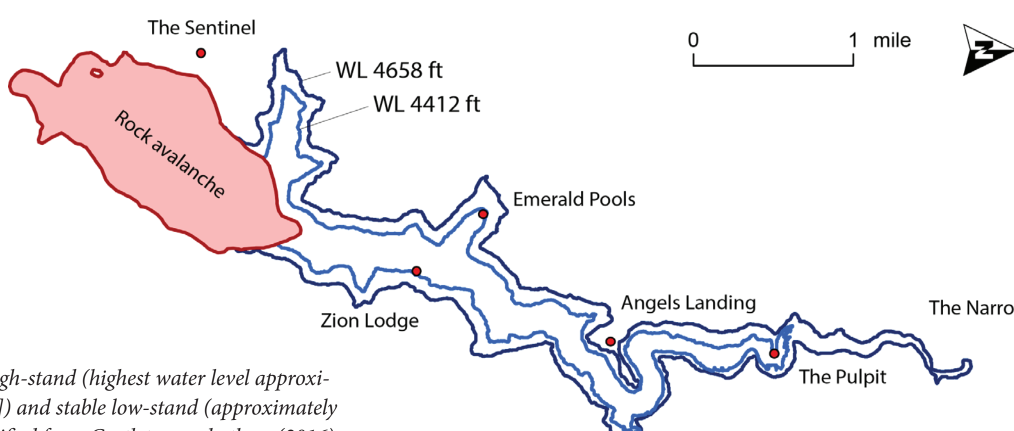

Figure 6: Sentinel Lake high-stand (highest water level approximately 4659 feet [1420 m]) and stable low-stand (approximately 4413 feet [1345 m]). Modified from Castleton and others (2016).

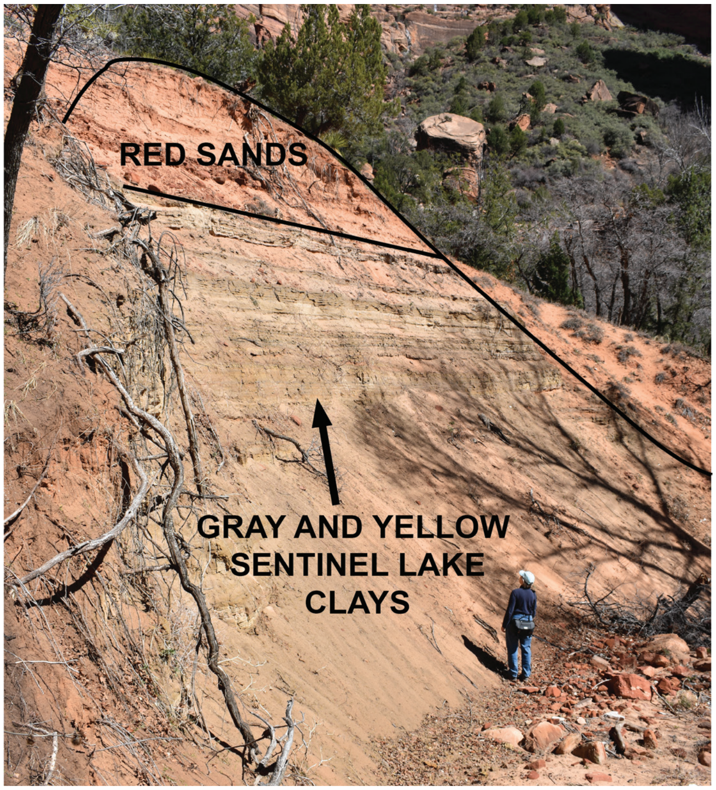

Figure 7: *A large outcrop of Sentinel Lake deposits near Zion Lodge. Gray and yellow lake-bottom clay layers are capped by red sandy layers emplaced near the end of the lake's life once it filled with sediment.*

Figure 8: *View from the Sand Bench trail looking down the incised rock-avalanche deposit to the North Fork Virgin River and the park road below.*

Figure 9: *Modern Zion Canyon's flat valley floor. Photo taken looking down canyon from the Kayenta trail.*

the flatness of the canyon floor where Sentinel Lake once stood (figure 9). In this same area, exploration along the banks of the Virgin River and its tributaries locally reveals excellent exposures of yellow and gray lake deposits. Lastly, a hike up Angels Landing or Observation Point gives views of the overall valley shape and provides the optimal opportunity to imagine what Zion Canyon would have looked like filled with several hundred feet of water.

Landslide-Dammed Valleys Throughout Zion National Park

While the Sentinel slide is the largest landslide dam in the park, evidence exists for 10 other hypothesized landslide-dammed canyons across Zion (figure 11) (Hamilton, 1976, 2014; Biek and others, 2010). In the northern Kolob Canyons section of Zion, Hop Valley shares many similarities to Zion Canyon: Hop Valley has a rock-avalanche deposit at its mouth and a flat valley floor caused by sediment accumulation behind the slide blockage. However, unlike Zion Canyon with its mud and clay lake deposits, Hop Valley is filled with vast amounts of sand. This is likely due to differences in water influx and Hop Valley's much smaller drainage basin that taps mostly sandstone bedrock. Whereas Zion Canyon hosts the large North Fork Virgin River, Hop Valley holds a relatively small stream which only reaches the larger La Verkin Creek during floods. The smaller stream flow has also better preserved the rock avalanche deposit. Hop Valley's rock avalanche is older than the Sentinel slide (Stanczyk, *in prep.*), yet the deposit is significantly less incised, and it will take much longer for floods in the small catchment to cut through the remaining debris.

In addition to these ancient slide deposits, landslides have dammed several canyons in Zion in recent history. In the 1970's a small rockfall occurred in Mystery Canyon (a minor tributary near The Narrows; figure 8) (Hamilton, 1976, 2014). The rockfall created a natural dam which holds a seasonal pond and impounds sediment. In 1990, a larger landslide blocked Middle Fork Taylor Creek in the Kolob Canyons section of the park, creating a small lake which rose for 3 years (Lund and others, 2010). In March 1993 water overtopped the dam, resulting in an outburst flood that reached all the way to Interstate 15 where it collided with several cars (Lund and others, 2010). Luckily, no injuries resulted, but this recent example emphasizes the continued hazard that landslides bring to this popular national park.

Figure 10: Looking up Zion Canyon from Mt. Spry. During Sentinel Lake's time, water would have stretched up the canyon farther than can be seen in this photograph. Photo credit Sarah Meiser.

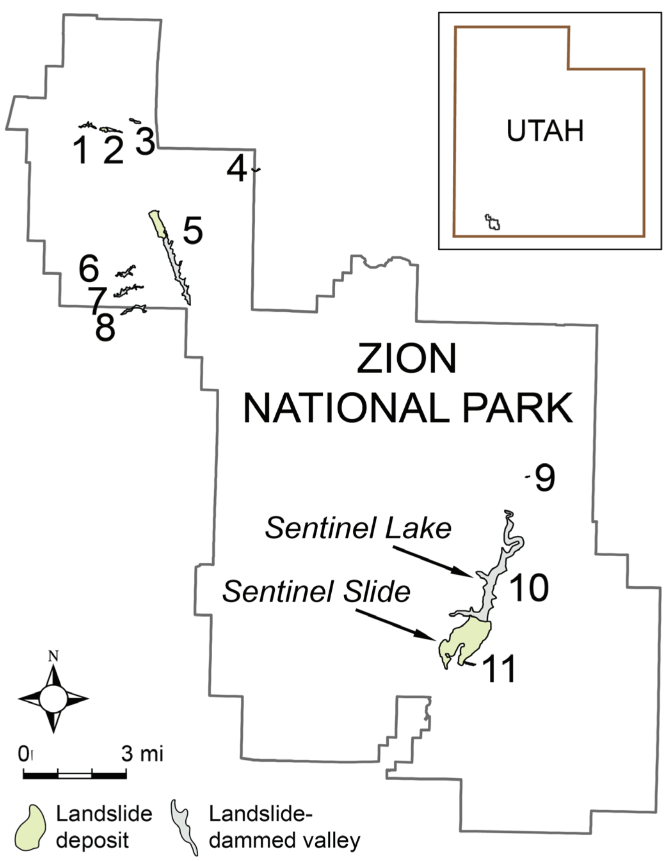

Figure 11: Other landslide-dammed valleys in Zion National Park. (1) Paria Pond, (2) Beatty Slide and Pond, (3) Middle Fork Taylor Creek Slide, (4) Potamogeton Lake, (5) Hop Valley Slide and landslide-dammed valley, (6) Currant Creek (pond), (7) Cane Creek (pond), (8) Smith Creek (pond), (9) Mystery Canyon Slide and pond, (10) Sentinel Slide and Sentinel Lake, (11) Pine Creek valley (pond). Modified from Hamilton (2014).

In Zion's steep, high-relief topography, landslides have played and will continue to play an important role in eroding and widening canyons. While running water drives the consistent incision of bedrock, landslides ranging from small-scale rockfalls to enormous rock avalanches like the Sentinel slide account for abrupt changes in canyon topography, sometimes with long-lasting impact. Geological studies highlight the variety of landslides in Zion and historical records provide much needed context to evaluate the hazard they pose (Lund and others, 2010). However, further work is needed to characterize and date ancient prehistoric landslides, especially those of large magnitude. Once robust catalogs and timing information are available, trends may become apparent in landslide location and/or timing, indicating important factors contributing to triggering such as climate change and ancient earthquakes. For now, recognizing the dramatic impact that the Sentinel slide has had on the geomorphology (and ecology) of Zion Canyon highlights both the hazard and possibility for constructive transformation brought on by large-magnitude rock avalanches in this desert paradise.

ACKNOWLEDGEMENTS

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