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A New Look at Landslides of the Vermilion and Echo Cliffs, Northern Arizona

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Key Terms: ***Landslides, Toreva Blocks, Geomorphology, Block Kinematics, Rock Mechanics, Geotechnical Strength Parameters, Slope Stability, Factor of Safety, Erosion, Colorado River, Arizona***

ABSTRACT

The Vermilion and Echo Cliffs form a nearly continuous escarpment more than 160 km long within the Colorado Plateau physiographic province of North America. The cliffs overlie the Marble Platform in northern Arizona and are located along the Colorado River, just upstream of the Grand Canyon. Large rotational block landslides mantle the erosional escarpment along most of its extent. Although these landslides have been noted for over 100 years, their likely origin has never been explained. Landslide failure surfaces appear to be influenced by the Petrified Forest Member of the Triassic Chinle Formation, a shale layer containing smectite clay weathered from volcanic ash. Although landslides are common along the majority of escarpments comprising the Colorado Plateau where the Petrified Forest Member and other shales outcrop, most appear to have been inactive since the early Holocene. Multiple generations of landslides and remnants of previous slides exist up to 3 km from the present cliff face. Multiple working hypotheses explaining these landslides are explored in this article, including past landslides and/or lava dams along the Colorado River within the Grand Canyon, periods of wetter climate with higher groundwater levels, and earthquakes related to nearby faulting and volcanism. Various sliding modes along these cliffs are described along with potential triggering mechanisms. Back-analysis of these landslides has been conducted using mechanical properties of the formations involved as well as varying groundwater levels. Calculated factors of safety for existing slides under present conditions are greater than unity, consistent with their apparent stability.

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INTRODUCTION AND BACKGROUND

The Vermilion and Echo Cliffs form a nearly continuous escarpment overlying the Marble Platform in northern Arizona. This escarpment is mantled with landslides throughout the greater part of its more than 160-km length (see Figure 1). The sequence begins at the southern end of the Echo Cliffs near Cameron, AZ, and continues northward toward Lee's Ferry, AZ, to where it is interrupted by the mouths of the Glen and Paria Canyons. It then continues to the west as the Vermilion Cliffs. The Echo Cliffs reach their maximum height of ∼550 m near Lee's Ferry, but diminish in height to the south. Although intermittent landslides are present along the southern portion of the Echo Cliffs, slides are continuous along the northernmost 24 km, from Bitter Springs to Lee's Ferry. These cliffs are developed along the eroded Echo Cliffs Monocline, which turns to the northwest and crosses the Colorado River at Lee's Ferry, where it gradually diminishes along Paria Canyon. This structural feature allowed for the historic river crossing at this location by placing the resistant Shinarump Bench at river level. The bench is overlain by the erodible Petrified Forest Member of the Chinle Formation, which creates a natural topographic bench, suitable for wagons, horses, and cattle or sheep approaching the Colorado River. Although the crossing is no longer used, it was of significant historical importance since the Colorado River is confined within incised bedrock gorges both up- and downstream of this location for hundreds of kilometers. The Echo Cliffs were named in 1871 during John Wesley Powell's second mapping expedition, while it was being led by his brother-in-law, Almon Thompson. One of the expedition members fired a pistol near Lee's Ferry and allegedly counted 22 echoes. The Vermilion Cliffs were also named by this same party for their brilliant reddish coloration, which the explorers admired on their journey to Kanab, where they spent the winter and spring of 1871–72.

The Echo Cliffs Monocline structurally controls the location of Paria Canyon where the Paria River runs along the eroded axis of the fold. The monocline becomes less pronounced upstream, where Paria Canyon

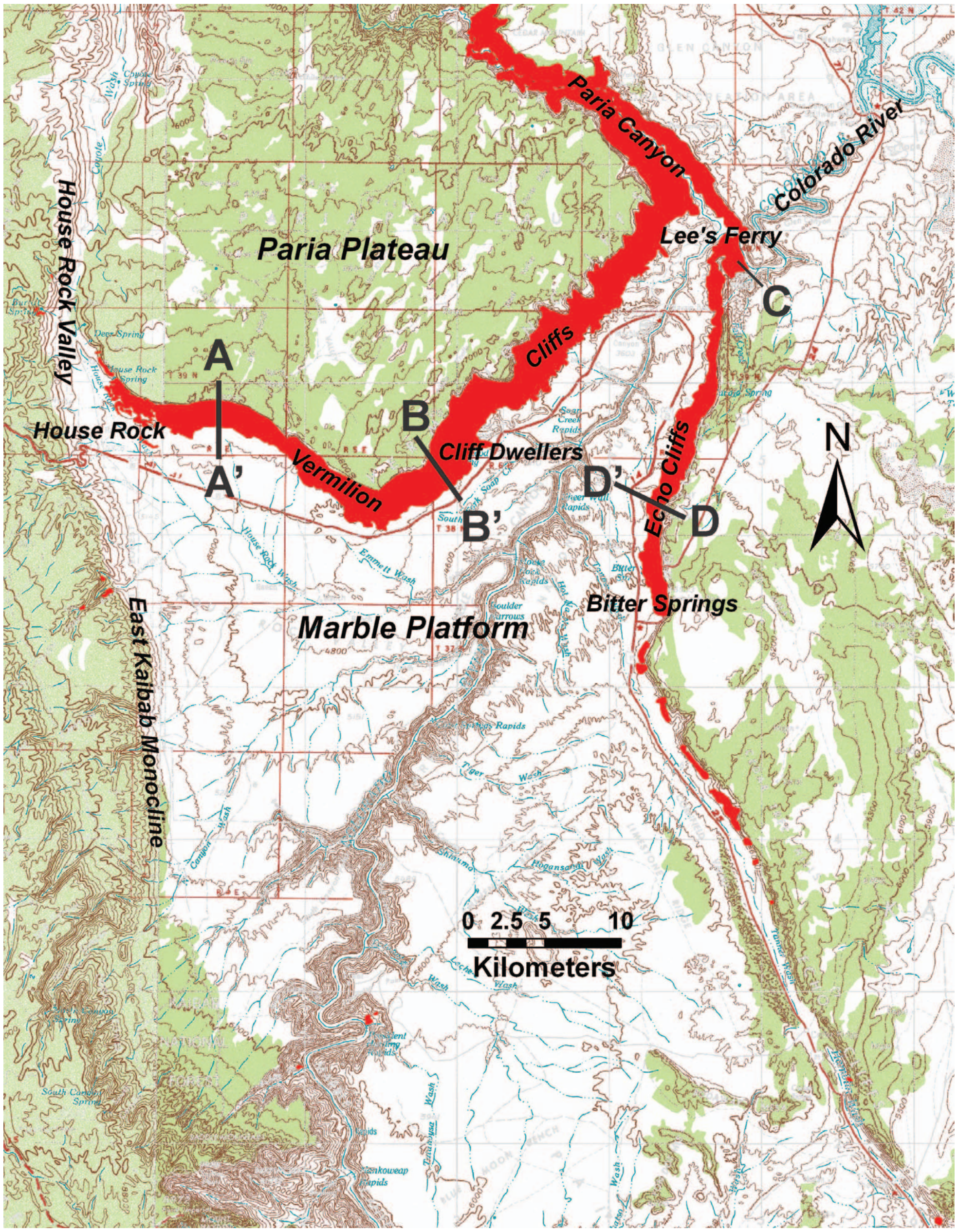

Figure 1. This overview map shows the distribution of landslides throughout the Vermilion and Echo Cliffs escarpments. The location of Figure 8 is shown with line A-A', while Figure 11 is shown with line B-B'. The location of Figure 6a is shown by C. Line D-D' shows the location of Figure 6b.

is deeply incised. The Echo Cliffs transition to the Vermilion Cliffs along the lower portion of Paria Canyon. The lower 12 km of Paria Canyon has incised into the Chinle Formation, allowing the canyon walls to undergo significant retreat due to mass wasting. This regression has allowed this portion of the canyon to form an open amphitheater, in contrast to the narrow slot canyon upstream.

The Vermilion Cliffs separate the Marble Platform from the Paria Plateau (see Figure 1). The cliffs begin at the mouth of Paria Canyon near Lee's Ferry and achieve a maximum height of ~610 m. From Lee's Ferry, they trend southwesterly for 24 km toward a small settlement known as "Cliff Dwellers." Here, the cliffs turn northwest, continuing another 32 km until they turn due north, along the House Rock Valley. The cliffs gradually decrease in height along the East Kaibab Monocline, or "Cockscomb," as it is locally known, decreasing in height to about ~305 m along the southern portion of the House Rock Valley. The

Figure 2. Hummocky landslides mantle much of the Vermilion and Echo Cliffs escarpments. This shows the rotational slumps (Toreva blocks) that typify the western Vermilion Cliffs.

cliffs continue northward and west through southern Utah, although that segment of the cliffs was not examined as a part of this study. The Vermilion Cliffs are continuously mantled with landslides for a distance of approximately 56 km, between the mouth of Paria Canyon and the northern end of House Rock Valley, where they cease to occur. Figure 2 shows an example of rotational slumps along the Vermilion Cliffs near House Rock.

STRATIGRAPHY AND STRUCTURE

The stratigraphic units exposed along the Vermilion and Echo Cliff escarpments include the Navajo, Kayenta, Moenave, Chinle, Moenkopi, and Kaibab Formations, of Jurassic to Permian age. Landsliding in the region generally floors in the Petrified Forest Member of the upper Triassic Chinle Formation. This member is well known for its inclusion of Petrified Wood and development of badlands topography. The Petrified Forest Member comprises shales, siltstones, sandstones, and channel lag gravels deposited in an extensive fluvial system (Dubiel, 1989), making its composition quite variable. The shales/clays in the Petrified Forest Member are derived from ~60 percent volcanic materials, including ash (Riggs et al., 1993), and are rich in smectite clays (Chasteen et al., 2001). Smectites are recognized for their contribution to slope instability because of their low shear strength (Tiwari and Marui, 2005). This member overlies the more resistant Shinarump Member, which forms the basal unit of the Chinle. The Chinle has a thickness of ~130 m throughout the Vermilion and Echo Cliffs area. Figure 3 presents a stratigraphic section of the formations exposed along the Vermilion and Echo Cliffs.

The relatively competent Jurassic age Navajo, Kayenta, and Moenave Formations overlie the Chinle and cap the cliffs. The Jurassic section has a cumulative thickness of ~600 m, although the entire section isn't exposed along the faces of the Vermilion and Echo Cliffs. The resistant Shinarump Member of the Chinle Formation, which comprises cross-bedded channel sands and lag gravels, forms a prominent bench overlying the Triassic Moenkopi Formation. The Moenkopi in the vicinity of Lee's Ferry consists of siltstones, gypsum lenses, sandstone ledges, and minor amounts of limestone. It is easily eroded where the overlying Shinarump Bench has been removed. An undifferentiated member is also present in the vicinity of Lee's Ferry that is usually a slope former (Stewart et al., 1972). The Triassic Moenkopi is extensively composed of red beds. The Shinarump Bench and Moenkopi Formation are pronounced elements forming the base of the escarpment along the eastern Vermilion Cliffs, lower Paria Canyon, and portions of the Echo Cliffs. The Moenkopi overlies the Permian Kaibab Formation, which forms the Marble Platform and the rims of Marble and Grand Canyons downstream.

ECHO CLIFFS MONOCLINE

The Echo Cliffs are structurally controlled by the Echo Cliffs Monocline, a prominent Laramide fold in the western Colorado Plateau. This monocline trends north-south and is upthrown on its western side. The upthrown side of the monocline has been eroded, creating the Echo Cliffs escarpment, which dips to the east at an inclination of 10–30° (Strahler, 1940), creating obsequent bedding (dipping into the slope). The brittle formations comprising the Echo Cliffs appear more intensely jointed than the relatively undeformed strata exposed in the Vermilion Cliffs. This may be due to the extension caused by the monoclinal flexure. The monocline turns to the northwest near Lee's Ferry, where it crosses the Colorado River and trends just north of the axis of Paria Canyon.

VERMILION CLIFFS/PARIA PLATEAU

The Vermilion Cliffs form the southern and western limits of the Paria Plateau, which dips to the northwest (eastern cliffs) and north (western cliffs) at inclinations of 2° to 2.5°. The cliffs gradually decrease in height to the west. The cliffs have a maximum height of around 610 m near Lee's Ferry and diminish to a height of 305 m in House Rock Valley. This is due to a combination of their dip and the increasing elevation of the Marble Platform to the west, approaching the East Kaibab Monocline, a Laramide fold separating the Paria Plateau from the Kaibab Plateau. The

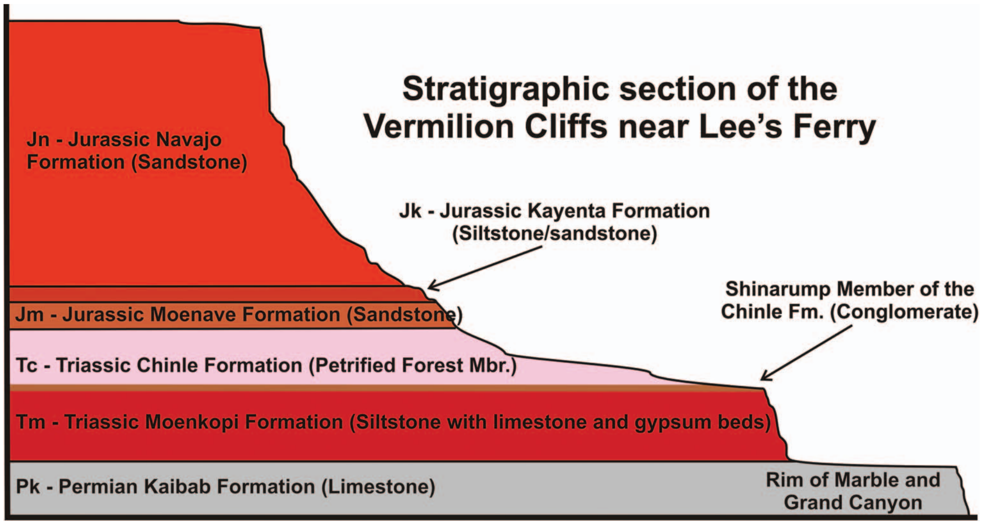

Figure 3. Principal formations comprising the Vermilion Cliffs escarpment near Lee's Ferry. The Shinarump Member of the Chinle Formation forms a prominent bench and armors the less resistant Moenkopi Formation from erosion. The Kaibab, Moenkopi, and Shinarump are not exposed along the western Vermilion Cliffs or southern Echo Cliffs.

Shinarump Bench and Moenkopi Formation are not prominently exposed along the western portion of the cliffs, where headward incision by streams has yet to occur.

DESCRIPTION OF LANDSLIDING

Prior Work in the Area

Davis (1901) appears to have been the first geologist to describe landsliding along the Vermilion and Echo Cliffs. Prior reports by Powell and others make no mention of landslides, although they discuss the Triassic strata exposed in the Vermilion and Echo Cliffs. Davis thought these slides were related to a hiatus and then renewed incision by the Colorado River in the vicinity of Lee's Ferry. He noted two forms of landsliding: coherent rotational slides and disaggregated rock slide-debris avalanches (Hungr et al., 2014), or "sturztroms," which he believed formed when rotational slides broke apart as they cascaded over the Shinarump Bench. His 1901 map (reproduced in Figure 4) shows the occurrence of landslides along both sets of cliffs.

Reich (1937) also identified landsliding along the Vermilion Cliffs, although it doesn't appear that he studied this area in much detail. His 1937 article defines the Toreva block, or rotational bedrock slide, which he named after the type locality near Toreva, AZ (approximately 150 km to the east-southeast). He makes brief mention of their occurrence at several other locations across the southern Colorado Plateau, including the Vermilion Cliffs. He curiously states that Toreva blocks are not present along the Echo Cliffs and are somewhat rare along the Vermilion Cliffs. Prior and subsequent researchers identified numerous rotational bedrock slides along both sets of cliffs.

Strahler (1940) studied the landslides of the Vermilion and Echo Cliffs in greater detail. He made note of both Toreva blocks and disaggregated "rockslides" along both the Vermilion and Echo Cliffs where the cliffs are tallest and the Shinarump Bench is prominent, as noted by Davis (1901). Like Davis, he believed

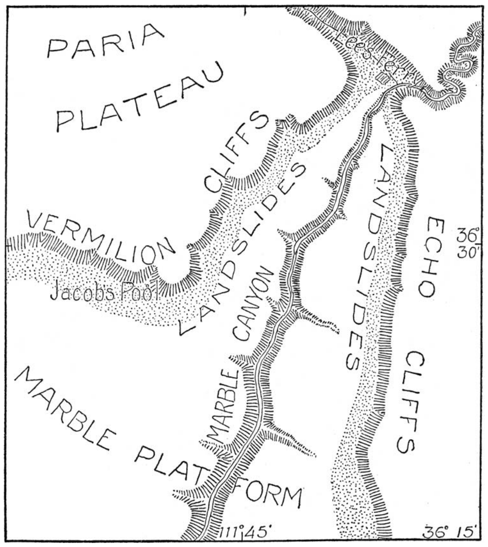

Figure 4. This diagram from Davis (1901) shows the areal extent of the landslides mantling the lower elevations of Vermilion and Echo Cliffs near Lee's Ferry, AZ.

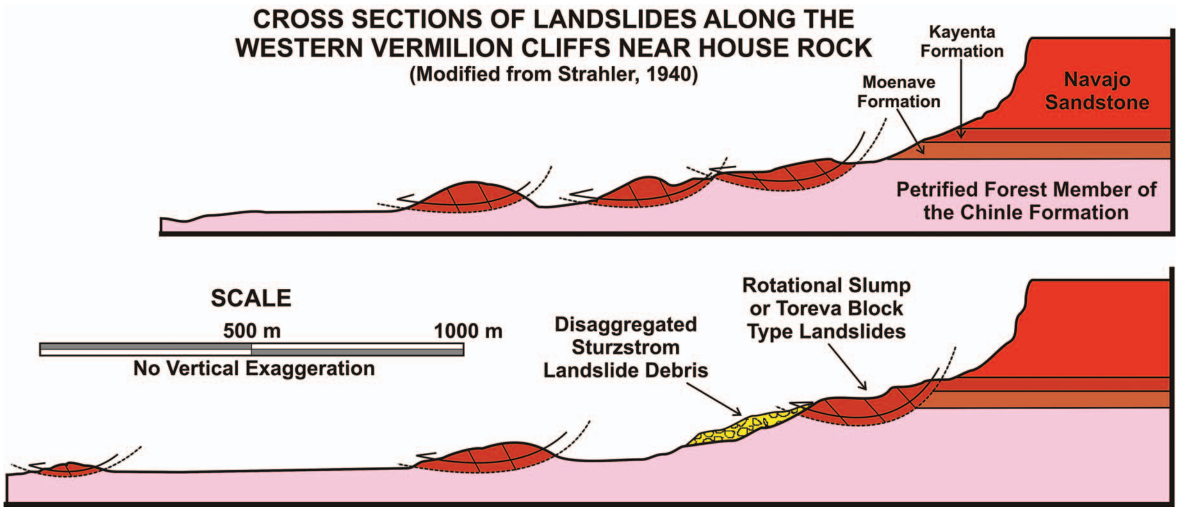

Figure 5. Series of cross sections modified from Strahler (1940) illustrate the retrogressive nature of rotational landslides observed along the western Vermilion Cliffs in the vicinity of House Rock.

that these features formed when Toreva blocks cascaded over the Shinarump Bench and disaggregated.

The upper cliff-forming formations are brittle and regionally jointed, aiding in their disintegration as they cascade over the lower Shinarump Bench. Our research has found similar disaggregated slides in the western Vermilion Cliffs near House Rock. Strahler also identified eroded remnants of Toreva blocks nearly a mile (1.6 km) in front of the escarpment. He also observed that the most recent rotational slides adjacent to the Vermilion Cliffs are only rotated 10–15° and exhibit a rougher and more ragged appearance than those farther from the face of the escarpment, indicative of relative youthfulness (see Figure 5). The younger slides exhibit increasing basal elevations of the failure surfaces, a phenomenon likely caused by the buttressing effect of the pre-existing landslides at the toes of the slopes.

Echo Cliffs

Strata comprising the Echo Cliffs dips to the east, or back into the slope, forming adverse bedding. Such inclinations normally increase stability and reduce the propensity to landsliding. The southern Echo Cliffs exhibit intermittent occurrences of landsliding, likely because the Chinle Formation is not fully exposed along the base of the cliffs. Most of the slope failures are relatively shallow (tens of meters) rotational slumps that appear to have initiated along regional systematic joints. The northernmost portion of the cliffs, running ~24 km from Bitter Springs to Lee's Ferry, is continuously mantled by landslides (see Figure 1). The entire stratigraphic section of the Chinle Formation is exposed in this area. Landslides along this portion of the Echo Cliffs are present as rotational slump blocks and highly disaggregated rockfalls, which appear to have flowed down the slopes, whether or not they cascaded over the Shinarump Bench.

All of the landslides observed along the Echo Cliffs appear to have failed against bedding, with the exception of one major landslide complex on the east side of the Colorado River near Lee's Ferry. Figure 6a presents an overview of this feature from the Spencer Trail, which overlooks Lee's Ferry. This composite landslide translated within the Chinle Formation directly above the Shinarump Member, which is inclined in a ramp-like form toward the Colorado River, where the Echo Cliffs Monocline crosses the channel. This landslide consists of a series of relatively intact blocks covered by a veneer of disaggregated rubble. The complex also includes enormous rock slide-debris avalanches, which may be of partially subaqueous origin. These lobes appear to have flowed down the inclined Shinarump Bench. At least one intermittent drainage has since dissected the parent mass. This slide appears to have deflected the Colorado River slightly to the north, just upstream of Lee's Ferry. A typical cross section of the Echo Cliffs is shown in Figure 6b.

Vermilion Cliffs

Landslides mantling the Vermilion Cliffs exhibit two distinctive styles, as suggested by Davis (1901) and Strahler (1940). The classic rotational slide, or Toreva block–style landslide, is common throughout the western portion of the cliffs (see Figures 2 and 7), while disaggregated, rock slide-debris avalanche de-

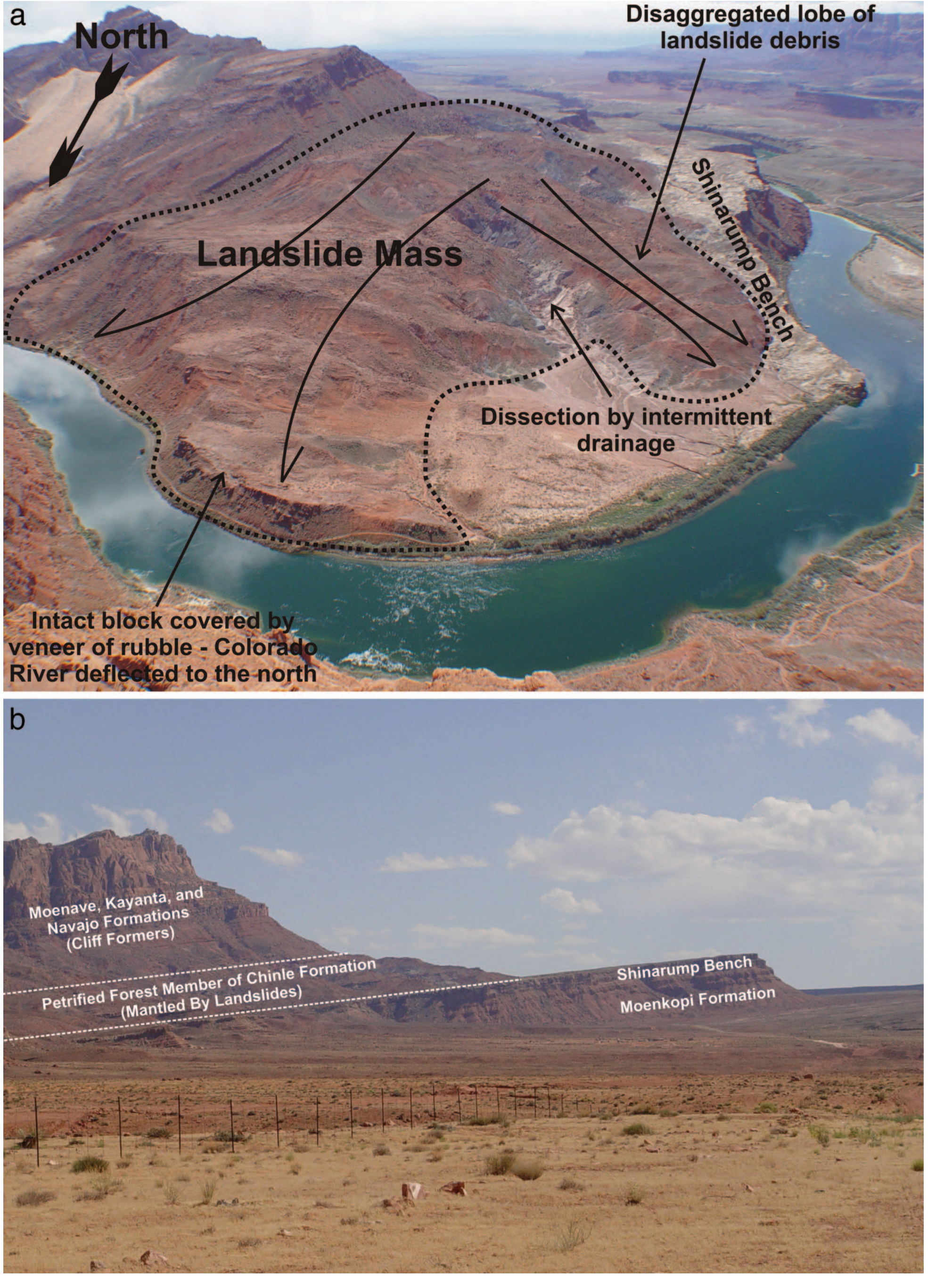

Figure 6. a. Composite landslide mass exposed at the northern end of the Echo Cliffs at Lee's Ferry. These slides appear to floor in the Chinle Formation just above the Shinarump Member, which forms a sloping, resistant platform. b. This view of the Echo Cliffs looking south from Marble Canyon, AZ, illustrates the dipping strata within the Echo Cliffs Monocline. Obsequent dip back into the slope limits the scale of landslides along the Echo Cliffs. The Shinarump Member caps the underlying Moenkopi Formation, creating a sloping, resistant platform.

posits are more numerous in the eastern Vermilion Cliffs, where the escarpment reaches its greatest height. This disaggregation appears to have occurred where rotational slides cascaded over the Shinarump Bench, transitioning to rock slide-debris avalanches capable of flowing long distances (Legros, 2002; Iverson, 2003). These form the distinctive debris lobes shown in Figures 8 through 13 below. All of these debris fans are highly eroded and dissected, suggesting that these features formed some time ago, likely during the late

Figure 7. The rotational slumps of the western Vermilion Cliffs were first described by Davis (1901) and Strahler (1940). Multiple sequences of landslides are present along the escarpment, suggesting a sustained history of cliff retreat via retrogressive mass wasting.

Pleistocene (>14.5 ka). Landsliding ceases where the cliffs turn north along the East Kaibab Monocline, slightly north of House Rock (Figure 1). The cliffs decrease in height along their western limits north of House Rock. There is a lesser degree of incision/headward erosion from Colorado River tributaries, mainly House Rock Wash, and the floor of the House Rock Valley increases in elevation proceeding northward along its axis. The apparent dip of the Paria Plateau also shifts northward. The combination of these factors has led to a condition in which the underlying Chinle Formation has yet to be exposed along this stretch of the cliffs. The combination of a lower overburden stress and a buttressing of the weak Petrified Forest Member of the Chinle Formation has allowed this portion of the cliffs to remain inherently stable.

Disaggregated masses of material are present atop many of the slump blocks in the western Vermilion Cliffs, indicative of rock slide-debris avalanches, described as "sturzstroms" in the literature (Skerner, 1989). These long run-out landslides are influenced by the conservation of momentum (Legros, 2002; Iverson, 2003) and consist of disaggregated debris emanating from the Jurassic section capping the cliffs. These deposits have been dissected by intermittent streams, exposing their contacts with underlying materials, including pre-existing rotational slump blocks. A cross section through one of these features near House Rock is presented in Figure 8, an aerial view in Figure 9, and a ground view in Figure 10. Figure 5 presents an additional cross section through the House Rock area, modified from Strahler (1940).

Rock Slide-Debris Avalanches

Rock slide-debris avalanches are most common where they litter the base of the eastern Vermilion and northern Echo Cliffs, above and below the prominent Shinarump Bench. These physical relationships suggest that different triggers and/or mechanisms of mass wasting might have been operative in this area, closer to the Colorado River. Figure 11 presents a cross section of a slide that disaggregated and flowed over the Shinarump Bench. Figure 12 shows an aerial photo of a disaggregated slide, while Figure 13 shows how these features appear on the ground.

Many of the landslide sequences along the Vermilion and Echo Cliffs appear to be of approximately the same age and morphology, increasing in age with offset from the current escarpment. In the western Vermilion Cliffs near House Rock it appears that at least three major episodes of cliff retreat occurred in distinct groupings. Each sequence of slides appears to be laterally contiguous and of similar age, suggesting that common and/or recurring mechanisms likely played a role in triggering each landslide sequence.

Potential Triggers of Landsliding along the Vermilion and Echo Cliffs

A number of variables appear to have triggered repeated sequences of landsliding along the Vermilion and Echo Cliffs. The likely triggers are described and discussed below. Although landslides are extensive along this escarpment, few, if any, appear to have occurred during the Holocene.Strain Incompatibility and Strain Softening Within the Chinle Formation

The Shinarump conglomerate, which is the basal member of the Chinle Formation, is a stiff sandstone/conglomerate deposited by outwash channels during the Triassic. The member is ∼30 m thick and typically forms a resistant ledge, commonly referred to as the "Shinarump Bench." This bench, along with the underlying Moenkopi Formation, accounts for up to 190 m of the escarpment height and is most prominent in the vicinity of Lee's Ferry. The Shinarump is an anomalously stiff material, as compared to the shaly units lying immediately beneath and above it, and it exhibits strength parameters on par with any of the massive sandstones deposited during the Mesozoic Era in this area (Rogers, 1982). The Shinarump caps several nearby mesas and buttes, with one of the largest being Shinumo Altar. The Petrified Forest and other shale-rich members of the Chinle overlie the Shinarump. These members are considerably less stiff than the Shinarump and are susceptible to strain softening, especially when wetted (Mesri and Shahien, 2003).

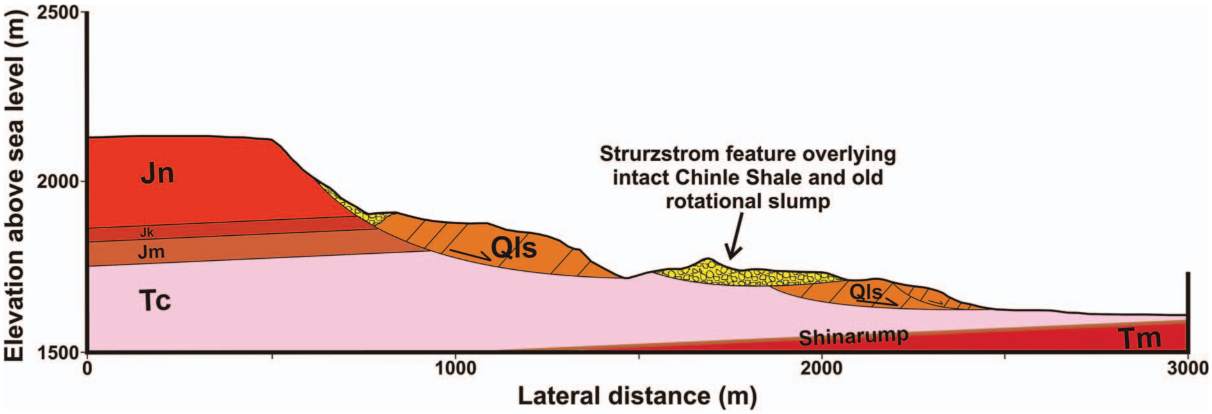

Figure 8. Cross section through the western Vermilion Cliffs reveals multiple sequences of rotational slump blocks with relatively intact bedding. An older rotational block is present beyond the rightmost extent of this cross section, over 3 km from the face of the parent escarpment.

This stiffness contrast between the Shinarump and Petrified Forest Members promotes strain incompatibility at the contact, promoting a disproportionate amount of strain softening at this boundary within the overlying Petrified Forest Member when lateral support is removed by mass movements or erosion. Most of the landslides in this area appear to initiate just above the Shinarump, retrogressing upward through the Petrified Forest Member. Existing slides buttress the lower slopes, forcing succeeding slope failures to occur at higher elevations.

Both Strahler (1940) and Ahnert (1960) observed dilated joints in the Navajo Sandstone capping the Vermilion Cliffs. Joint apertures increase markedly toward the escarpment (see Figure. 14), likely because of creep of the underlying Chinle Formation. The Chinle

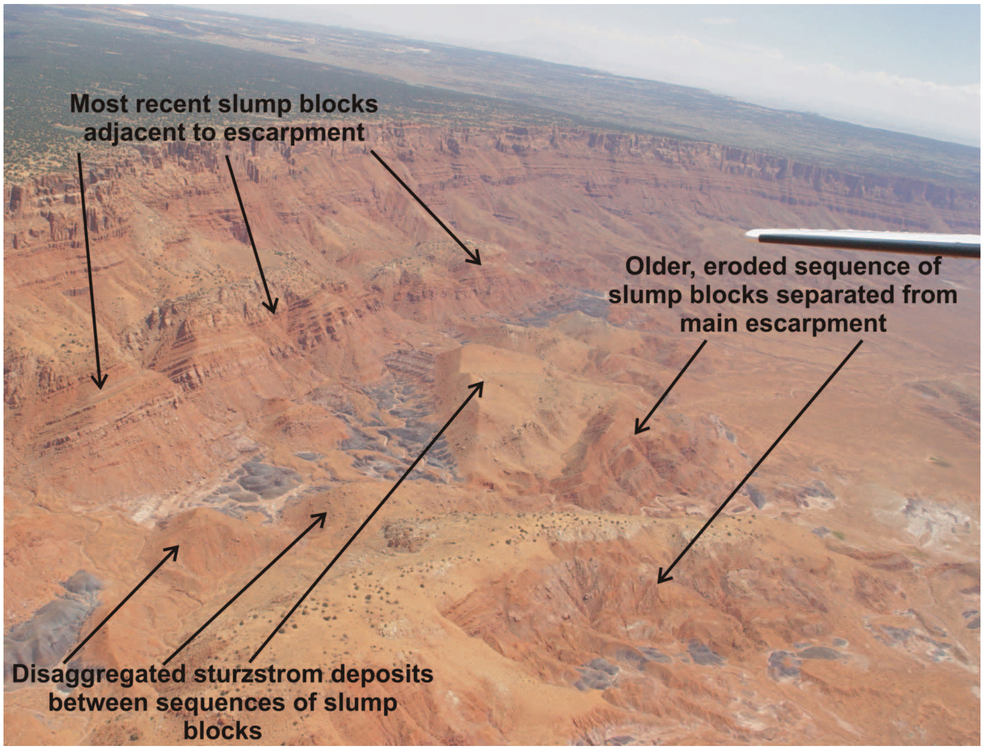

Figure 9. Aerial oblique image of the western Vermilion Cliffs showing three sequences of landsliding, which appear to have occurred in separate episodes. Deposits of highly disaggregated materials, likely emanating from sturzstroms, lie between two sequences of back-rotated slump blocks.

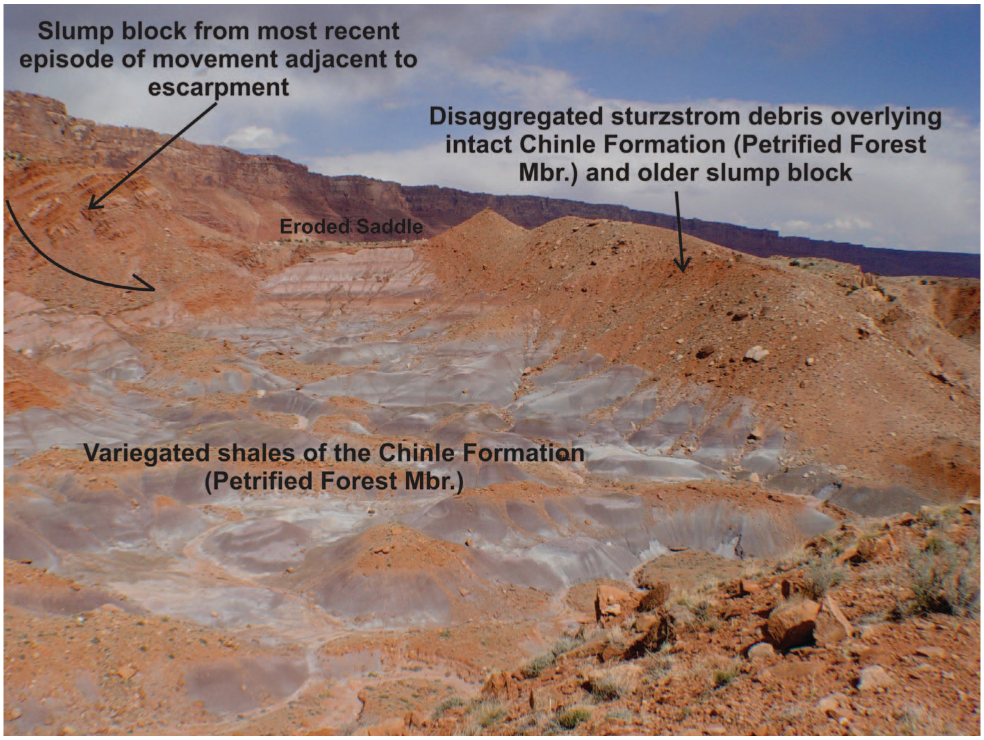

Figure 10. This image, taken in the western Vermilion Cliffs, shows the most recent rotational slump, adjacent to the escarpment, along with sturzstrom debris overlying the variegated shales of the intact Petrified Forest Member of the Chinle Formation. An older slump block is just out of view to the right. The cross section shown in Figure 8 was taken through the eroded saddle seen in the upper third of this image.

shales exhibit high plasticity and strain softening with increasing loss of confinement, often driven by repeated cycles of wetting and drying. Given the static strength parameters exhibited by these units, it would appear that strain softening must necessarily precede any gross landsliding along the Vermilion Cliffs escarpment. Nygard et al. (2006) summarized behaviors of other overconsolidated mudstone formations and found similar losses of shear strength as confining stress is lessened.Seismicity Related to Volcanism and Faulting

The extensive volcanic activity and faulting that have helped shape northern Arizona and New Mexico (Duffield, 1993) may have played an important role in the occurrence of landslides along the Vermilion and Echo Cliffs as well as other locations in the study

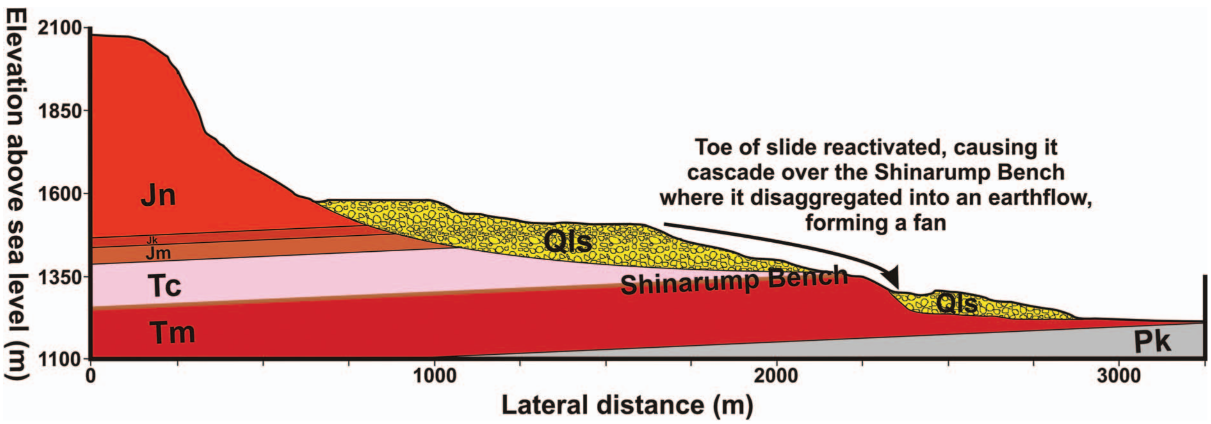

Figure 11. This cross section illustrates the disaggregated nature of the landslides along the eastern Vermilion Cliffs, where landslides have cascaded over the Shinarump Bench.

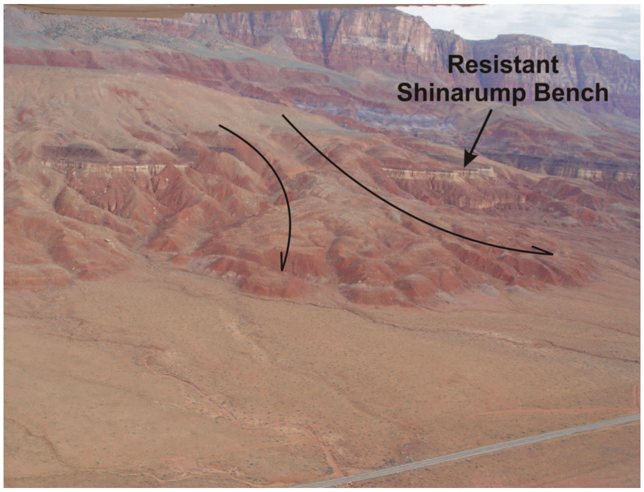

Figure 12. Aerial oblique view of a disaggregated rockslide-debris avalanche (sturzstrom) along the eastern Vermilion Cliffs, where a slide flooring in the Petrified Forest Member of the Chinle Formation appears to have cascaded over the Shinarump Bench. The Shinarump Conglomerate stands out in this image as a resistant buff-colored band intermittently exposed near the base of the escarpment.

Figure 14. Aerial oblique view of the crest of the Vermilion Cliffs showing increasing dilation of regional joints (up to 1.5 m) in the Navajo Sandstone at the precipice of the escarpment. This is likely caused by creep of the softer Chinle beds, lying below the Jurassic section. Strain softening likely precedes landsliding along the escarpment.

area. Movement of magma within the earth's crust often produces long-duration harmonic tremors. Hundreds of eruptions have taken place in the San Francisco Peaks Volcanic Field, with more than 600 cinder cones. This complex lies about 140 km to the south, along with the Uinkaret and Shivwits Volcanic Fields, located ~120 km to the west. Evidence also points to sizable earthquakes triggered by faulting throughout the western margins of the Colorado Plateau.

Figure 13. Disaggregated landslide debris mantling the Vermilion and Echo Cliffs, above and below the prominent Shinarump Bench near Lee's Ferry. These landslides are strikingly different from those observed elsewhere along the Vermilion Cliffs, which are much further from the Colorado River. The clasts are angular and chaotic, without organized structure.

It is possible that earthquakes coincided with wetter periods during the Pleistocene, which, acting together, could be expected to elevate pore water pressures and decrease slope stability. Several factors may have combined to trigger the observed landslides along the base of the cliffs today. The "episodic" nature of the different landslide complexes supports this theory.

Lava Dams in the Western Grand Canyon or a Rockfall/Landslide Downstream

During the Pleistocene (last 1.2 million years), at least 13 lava dams infilled the Colorado River channel in the western Grand Canyon (Hamblin, 1994). These natural dams were short-lived, yet they must have backed water up to Lee's Ferry and beyond. Prospect Lake is the name given by Hamblin (1994) to the highest lava dammed lake, formed by a succession of lava flows that occurred between 1.8 and 0.5 Ma. The highest lava dam appears to have reached a maximum elevation of 1,260 m, about 757 m above the present river level (~35 to ~45 m above the likely channel surface 0.5 Ma). The waters of Hamblin's Prospect Lake would have extended to present-day Moab, UT, and covered Lee's Ferry in ~313 m of water. This would have easily saturated the toes of the eastern Vermilion Cliffs, northern Echo Cliffs, and the mouth of Paria Canyon, shown in Figure 15. The ponding of so much water against these cliffs would have saturated the Chinle Formation within just a few years, hastening loss of cohesion and triggering a successive series of slides

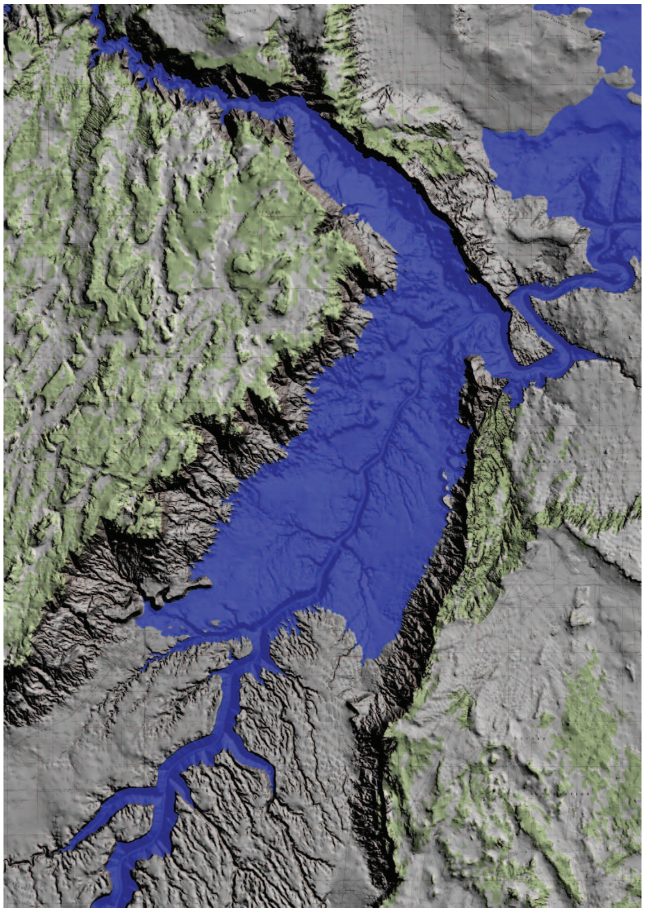

Figure 15. Map showing the extent of Prospect Lake, with a surface elevation of 1,260 m above sea level, overlain on modern-day topography. Lee's Ferry would have been under more than 300 m of water, while the slopes of Paria Canyon, the eastern Vermilion Cliffs, and northern Echo Cliffs would have also been inundated.

through simple strain softening (Trollope, 1969, 1973; Rogers and Pyles, 1980).

The sudden failure of any of the lava dams would have allowed rapid draining of the sizable reservoirs, creating a "rapid drawdown condition" wherein negative pore pressures would develop within the saturated slopes as the reservoir waters evacuated. If any of the lava dams that failed suddenly retained reservoir pools above an elevation of ~1,250 m, their sudden drainage could easily have triggered the massive landslide observed around Lee's Ferry (elevation 947 m). This elevation coincides with the base of the Vermilion and Echo Cliffs near Lee's Ferry, where the Shinarump Bench crosses the Colorado River (Figure 6). The Shinarump Bench creates a resistant platform, allowing landslides from above to cascade over a precipice, promoting their disintegration (Figures 11 and 12).

The disaggregated rock slide-debris avalanches at the bases of the eastern Vermilion and northern Echo Cliffs, above and below the prominent Shinarump Bench (Figures 12 and 13), suggest that different mechanisms of mass wasting were once operative in this area, closer to the Colorado River (Figure 14). The rapid draining of the temporary reservoirs impounded behind the lava dams could have triggered landslides floored in the overconsolidated Chinle shale, which is exposed along the eastern Vermilion and northern Echo Cliff escarpments. The concept of slope failures triggered by rapid drawdown was introduced by Casagrande (1950).

Recent data suggest that incision rates of the Colorado River between Lee's Ferry and the eastern Grand Canyon have varied between 100 and 150 m per million years (Pederson et al., 2002; Karlstrom, 2004; and Karlstrom et al., 2007). Research by Willis and Biek (2001) suggests that incision rates accelerated in the middle to late Quaternary. Polyak et al. (2004) discovered evidence that rates of incision in Marble Canyon near Redwall Cavern (32 mi downstream of Lee's Ferry) have ranged as high as ~550 m/million years during the last 82 ka. If we accept that the age of the Prospect Canyon Lava Dam at its maximum height was ~0.50 Ma and use the above-cited incision rates, the Colorado River was likely between 50 and 75 m higher than it is at present.

Direct shear tests by Rogers and Pyles (1980) demonstrated that overconsolidated shales lose about two-thirds of their intrinsic cohesion upon complete saturation (Figure 4). Such significant strength loss could easily explain the observed failures. This strength loss could also account for repeated episodes of cliff retreat near Lee's Ferry, the formation of the Lee's Ferry re-entrant, and widening of the mouth of Paria Canyon each time a lava dam reservoir breached and drained.

The rounding of Moenkopi slopes in the vicinity of Lee's Ferry and Marble Canyon (Figure 16) resembles shorelines inundated and subsequently exposed in modern reservoirs. The texture of the Moenkopi throughout this area contrasts markedly with other Moenkopi outcrops in the western Colorado Plateau, suggesting that the area was once submerged by a natural lake. The two large rockfall sites within Marble Canyon at Nankoweap Creek and President Harding Rapid may have also played a role in backing up water to Lee's Ferry and beyond. Driftwood logs and fine-grained sediment discovered within Stanton's Cave support the theory that a large lake was once present in this portion of the canyon (Hereford, 1984).

Since landslides along the Vermilion and Echo Cliffs also occur in large numbers, well above the level of any potential prehistoric lakes and throughout the surrounding region, additional components of de-stabilization (or, triggering mechanisms) may have been operative at the time of sliding.

Figure 16. Rounded topography near Lee's Ferry resembles that of modern-day dry lake beds. This shows the smoothed bedding of the Moenkopi outcrops unique to this area.

Wetter Pleistocene Climate

Based on evidence provided by oxygen isotope ratios, pollen abundances, and sediment accumulation, it appears that the climate was cooler and wetter throughout the southern Colorado Plateau during the Wisconsin glaciation (Betancourt, 1984; Cole, 1990; Anderson, 1993; Dryer, 1994; Anderson et al., 2000; Rogers et al., 2004; and Watkins et al., 2007). Based on the references cited above, analysis of sediments throughout the region suggests a higher annual rate of precipitation, possibly by as much as 35–60 percent, and a cooler climate. This precipitation likely arrived in gentle, long-duration events, not via the infrequent torrential downpours common throughout the arid region today. This would have allowed more precipitation to infiltrate the subsurface instead of running off. A cooler climate would also reduce losses to evaporation. Morgenstern and Eigenbrod (1974) described how shales lose shear strength with complete saturation (which can take considerable time). As recently as April 1995, a large paleolandslide partially reactivated, damming the North Fork of the Virgin River within Zion National Park. The previous winter season had been wetter than average, saturating basal shales (Wieczorek and Schuster, 1995).

Permeable Sandstone Overlying Impermeable Shales

The Navajo Sandstone is permeable and systematically jointed, with at least two major sets being nearly vertical (Rogers, 1982; see Figure 14, above). These characteristics allow precipitation falling on the Paria Plateau to easily infiltrate the sandstone and the underlying formations. However, the underlying shales of the Chinle Formation form a relatively impermeable barrier, which would serve to perch groundwater within the cliffs, elevating pore pressures and reducing unit cohesion, both of which hasten slope creep and strain softening.

Both Strahler (1940) and Ahnert (1960) mention the presence of joint planes in the Navajo Formation and have asserted that these structures likely played a role in the channeling of surface water into the subsurface. Ahnert (1960) notes that almost all retreating escarpments mantled by landslide complexes in the Colorado Plateau consist of permeable sandstones underlain by weaker rocks, mainly shales.

Triggers Appear Widespread but Are Not Presently Active

Similar landslide complexes are present throughout the Colorado Plateau, and most appear inactive at the present time. The presence of landslides throughout the entire region suggests that the various triggering mechanisms were once widespread across the entire region.

All of the landslides mantling the Vermilion and Echo Cliffs appear to predate the Holocene (>14.5 ka). Drainage patterns have been re-established, and there are presently no enclosed basins in the headscarp grabens. It appears that such features existed at one time, prior to the renewed incision that likely accompanied the increasingly arid climatic cycle that enveloped in the region during the Holocene. Similar retrogressive landslide complexes mantle other escarpments in the southern Colorado Plateau (Reiche, 1937; Strahler, 1940; Ahnert, 1960; and Radbruch-Hall et al., 1982).

The landslides blanketing the base of the Vermilion and Echo Cliffs exhibit evidence of recurring episodically, suggesting a recurring trigger mechanism in the area. Ahnert (1960) noted what appeared to be groupings of landslides from distinct episodes, based on similar morphologies (weathering, local erosion, and offset from the present escarpment). He assumed the retreat sequences likely occurred during humid glacial cycles of the late Pleistocene. A wetter Pleistocene climate (Anderson and Betancourt, 2000; Huth et al., 2020) and/or seismic activity associated with regional tectonism (Keefer, 1993) and volcanism may have played a role, or may actually been responsible for, the widespread distribution of landslide features throughout this area and the surrounding region.

Analysis and Likely Failure Mechanisms

The authors' detailed reconnaissance mapping of the landslides blanketing the Vermilion Cliffs suggests that the failures floor in thin seams of volcanic ash

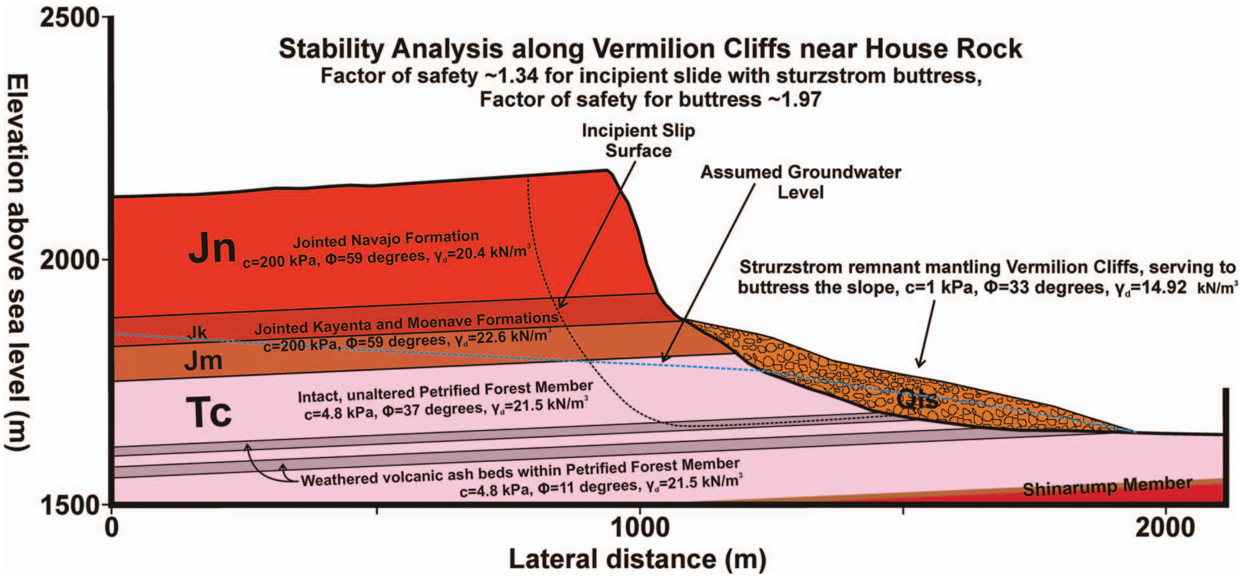

Figure 17. Stratigraphy, mechanical properties, assumed groundwater conditions, and incipient failure surface of a typical landslide along the western Vermilion Cliffs.

within the Petrified Forest Member of the Chinle Formation. The ash appears to have weathered into smectite clays, rich in montmorillonite. X-ray diffraction tests were conducted in the Materials Research Center at the Missouri University of Science and Technology, confirming this assumption. These beds are highly anisotropic and behave like overconsolidated shales, which tend to exhibit significantly lower shear strength parallel to bedding. For this reason, the basal sliding surfaces of most landslides along the Vermilion Cliffs sole along these weaker beds or horizons. The Petrified Forest Member is markedly heterogeneous, comprising old channel sands and volcanic ash, which are laterally variable, even at a localized scale.

Back-analyses of slope stability were conducted using Geo-Slope's Geostudio Slope/W Version 2007, a limit equilibrium package that allows for several different methods of analysis. We employed the Morgenstern and Price (1965) Method because it has been shown to exhibit greater accuracy when applied to any slope, regardless of soil strength parameters or slope geometry (Duncan and Wright, 2005), because of its calculation of interslice forces.

The back-analyses were predicated upon assumed groundwater levels, shown in Figures 17 and 18. The factor of safety for the slope was then held equal to 1.0 for a spectrum of likely groundwater levels, beginning with that assumed to be the highest possible groundwater condition for the paleo-escarpment. Groundwater levels were altered to high, low, and intermediate levels to back-calculate likely combinations of strength parameters. This analysis does not include the influence of Hamblin's (1994) Prospect Lake on groundwater levels. The location analyzed is to the west, near House Rock, above the maximum level of the lake. Table 1 summarizes the various properties, both measured and derived, used in the stability analyses. Ubiquitous vertical joints (without any tensile strength) were employed to model the massive Jurassic age sandstone units, negating the influence of cohesion on the Jurassic section, which comprises the cliff-forming units.

The mobilized cohesion of the Petrified Forest Member was assumed to be a fairly low value, just 4.8 kPa (100 psf). Duncan and Stark (1992) suggest that the use of an assumed cohesion in the back-analysis of the angle of internal friction (phi angle) for slope stability calculations will be self-compensating. This is based upon the fact that other conditions, such as changes in pore water conditions, will change the overall factor of safety in a similar manner when assumed cohesion and friction strength parameters are used. On the other hand, an incorrect assumption for pore water levels can lead to significant over- or underestimation of strength parameters, depending on whether the groundwater level is specified too high or too low within the section being analyzed, respectively. Zero cohesion values are often used for effective stress analyses (Cornforth, 2005), but the authors assumed 4.8 kPa cohesion for this analysis.

Case of Retrogressive Toreva Blocks

An effective friction angle of 37° was used for the initial rupture of the basal slip surface where it cuts across intact beds of the Petrified Forest Member, as

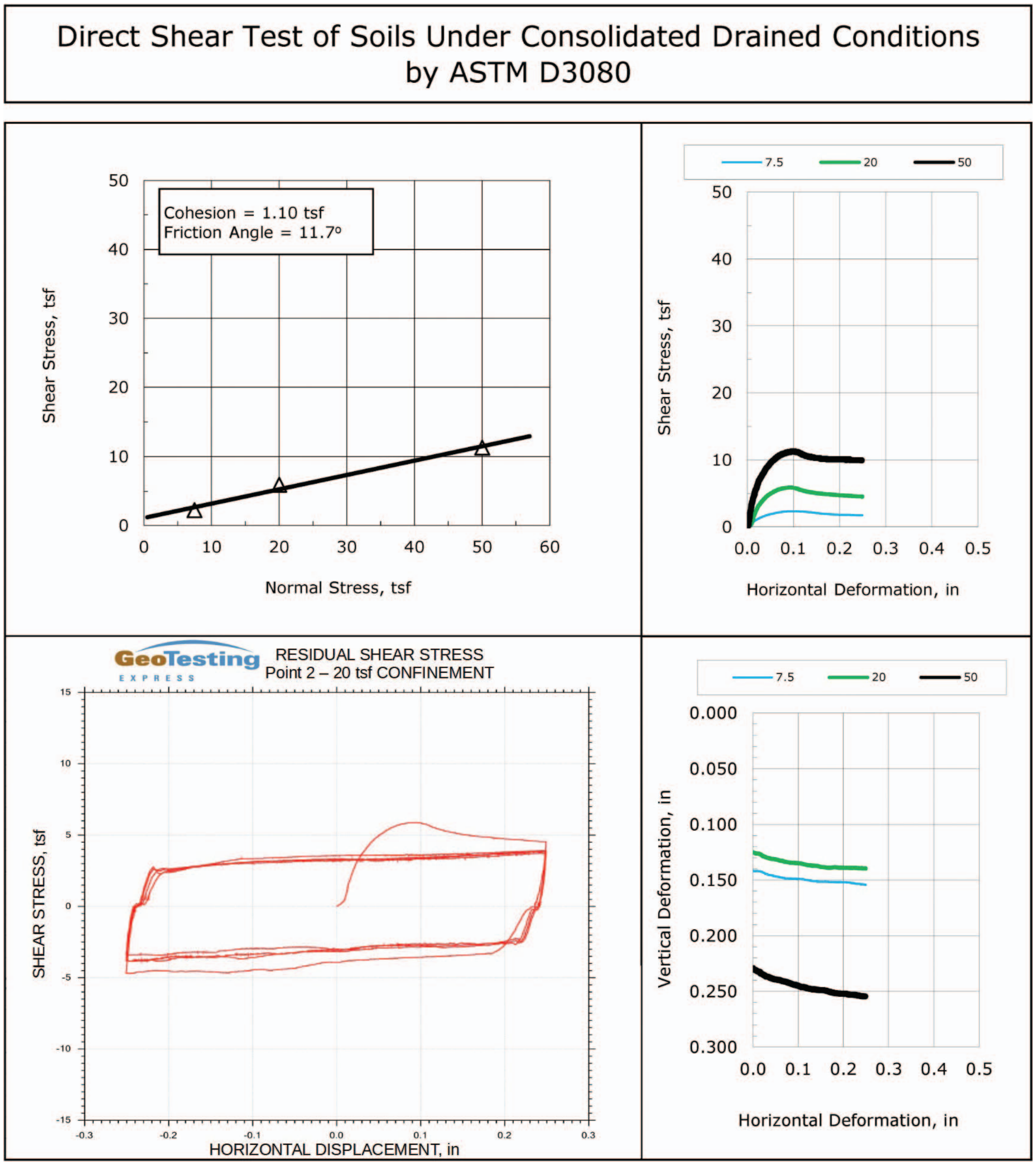

Figure 18. These four plots were generated by GeoTesting Express during direct shear tests (ASTM D3080) under variable confinement of 7.5, 20, and 50 tsf. A phi angle of 11.7° was calculated, and a significant strength loss was noted when sheared to residual strengths, as illustrated in the lower left quadrant.

shown in Figure 17. The weathered volcanic ash beds were assumed to have an effective friction angle of just 11°. A composite value of these materials would be around 22°, so this was assumed to represent the residual shear strength along the slip surface after extensive smearing and mixing, caused by continued translation (movement). This is also shown in Figure 18.

The assumed groundwater levels were then lowered, based upon reasonable assumptions with respect to fracture density, aperture, and geometry observed in outcrops, as well as present-day seepage zones/springs observed along the cliffs. This model assumed a saturated zone slightly above the Chinle beds, with groundwater filling ubiquitous joint elements to a depth not exceeding 20 percent the total height of the joints (shown in Figure 18). This lowering of the likely groundwater profile increased the factor of safety from ~1.0 to ~1.27.

The factor of safety for the pre-existing landslide (Qls) buttresses, independent of the Toreva block,

Table 1. *Factor of safety (FS) for varying phi angles and water levels within low-strength horizon. This table compares conditions and friction (phi) angles derived from parametric back-analyses and laboratory testing. "Transient very high water level" refers to extreme high groundwater conditions that are not expected to persist for long periods of time, possibly ranging from days to months.*

	Water Level FS			
Phi angle (°)	Transient Very High	High	Medium	Low
Extreme high (15.45)	1.000	1.110	1.148	1.236
Extreme low (7.7)	0.812	0.878	0.910	1.000
ADOT (10)	0.866	0.948	0.983	1.071
Geotesting (11.7)	0.909	1.000	1.036	1.120
Back-calculated phi angle (°) at FS = 1.0 for specified water levels	15.450	11.700	10.550	7.700

ADOT = Arizona Department of Transportation.

shown in Figure 17 was found to be around 1.05, close to instability. Such a low factor of safety likely contributed to the numerous reactivations and regression of the escarpment, both of which are apparent by direct observation.

For these analyses, an incipient slide surface was selected from several sliding surfaces observed in the field. Preliminary slope stability analyses showed that this slip surface produced the lowest factor of safety when compared to other alternatives, making it the logical choice for back-analysis.

Case of Sturzstrom Toe Buttress

In order to evaluate the impact of buttressing by previous landslides, we modeled the remnants of a sturzstrom-type landslide, similar to those observed along the western margins of the escarpment (see Figures 9 and 10). The strength parameters of the sturzstrom debris were assumed, based on literature review and experience with analyzing modern sturzstroms in the San Juan Mountains (Rogers and Beckmann, 2003). These analyses suggest the factor of safety for the sturzstrom buttress is about 1.97, while the factor of safety of the incipient landslide mass is ~1.34. We can conclude, therefore, that the slopes buttressed by sturzstrom debris appear to be inherently more stable than those buttressed by rotational slumps because a low-strength basal slip surface is preserved in the former, but is absent in the latter. A sketch of the analysis setup is shown in Figure 17, in which the incipient failure surface is shown by a dashed line.

These analyses revealed the stabilizing effects of confinement on successive sequences of mass movement. The older slides serve to buttress the Petrified Forest Member, which is likely the weakest horizon of the escarpment. The back-analyses suggest that the main escarpment slopes should remain stable (factor of safety > 1.3) until the sturzstrom debris blanketing the Petrified Forest Member is substantially removed, through erosion or re-activation.

Critical Slope Stability Analysis of the Vermilion Cliffs

The Bitter Springs Landslide, named for the nearby community of Bitter Springs, AZ, closed Highway 89 in 2013. This site is where Highway 89 climbs over the Echo Cliffs from its junction with Highway 89A north toward Page, AZ. The landslide destroyed Highway 89, requiring extensive reconstruction, which took 2 years to complete. Analyses conducted by Kleinfelder West, Inc. (McCormick and Richmond, 2014) as part of a geotechnical report prepared for the Arizona Department of Transportation produced a wealth of geotechnical testing information about the Echo Cliffs. These cliffs are the stratagraphic counterpart to the Vermilion Cliffs to the west.

The results of the analysis conducted by Kleinfelder closely correlate with the authors' testing and analysis of similar samples. The authors' samples were recovered at a site along the Vermilion Cliffs near House Rock, AZ, approximately 20 mi (straight line distance) to the west. As with the landslides near House Rock, the Petrified Forest Member of the Chinle Formation appeared to be the controlling weak material in which the Bitter Springs Landslide initiated. Kleinfelder contracted with Cooper Testing Labs of Palo Alto, CA, who conducted torsional ring shear tests (ASTM D7608) on a re-molded sample of the slide plane material.

The authors of this article also conducted a parametric back-analysis using extreme and actual conditions at the site to establish the likely range of strengths. The analysis was conducted using GeoStudio's GeoSlope Slope/W (version 2007) slope stability application. The Morgenstern and Price Method was employed to conduct a limit equilibrium analysis.

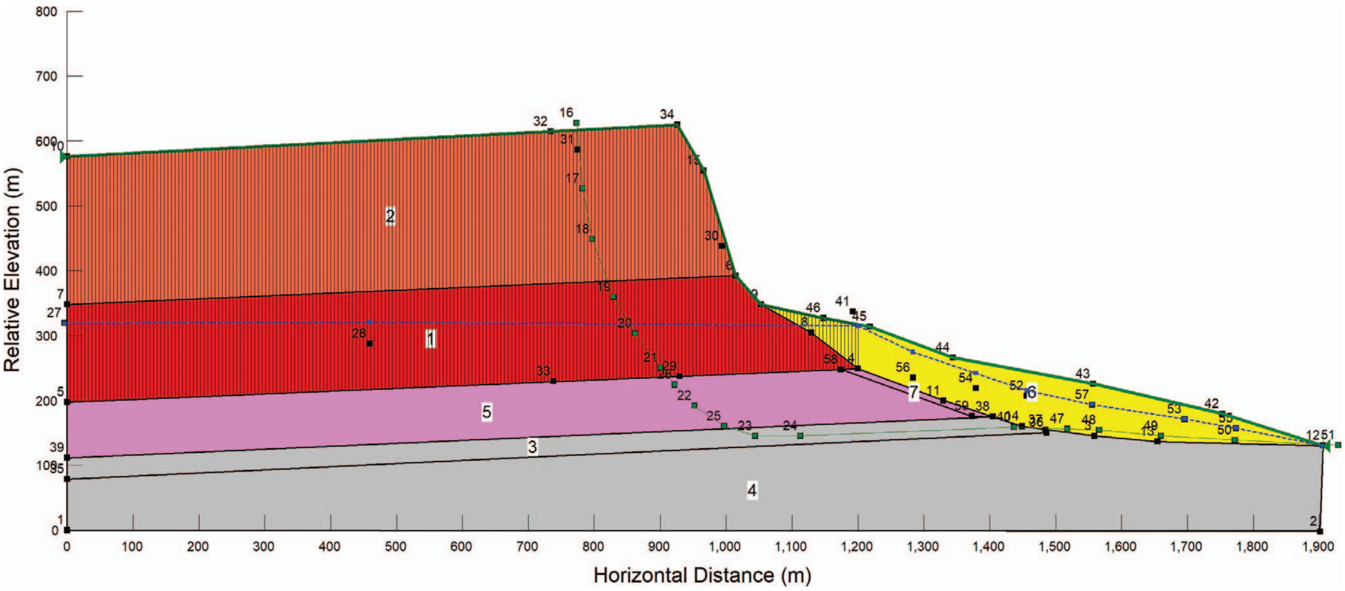

Figure 19. A phi angle of 15.45° was required within the Chinle shales to preclude mass movement of the Toreva block during maximum transient water levels, shown as a dashed blue line.

The main variable in the analysis was the groundwater level, with four conditions set. An extreme high level is illustrated in Figure 19, intended to replicate conditions likely present during the cooler and wetter climate of the Pleistocene. This value provides a maximum shear strength at which the cliffs remain stable. An extreme low level was then set (Figure 20), simulating extended drought periods. Such an analysis provides the lowest likely values by which the cliffs would remain stable under these conditions. A likely groundwater surface for current conditions was also estimated and evaluated (Figure 21). A toe buttress comprising dissected landslide and disaggregated talus materials was included in each analysis. These analyses used actual slope profiles based on topography from the western Vermilion Cliffs near House Rock, where the samples were collected. In this area the Shinarump conglomerate has not been incised to form a bench, as it

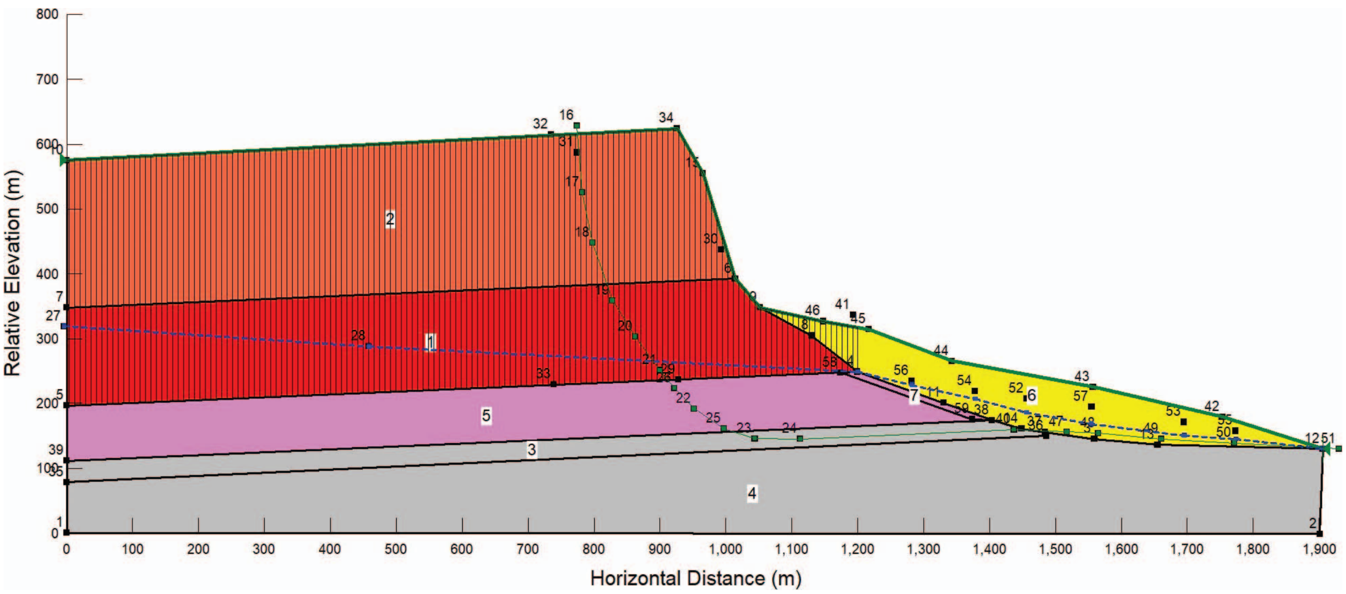

Figure 20. In this back-analysis a phi angle of 7.7° within the Chinle shales was required to maintain stability during periods of extreme low water levels (dashed blue line).

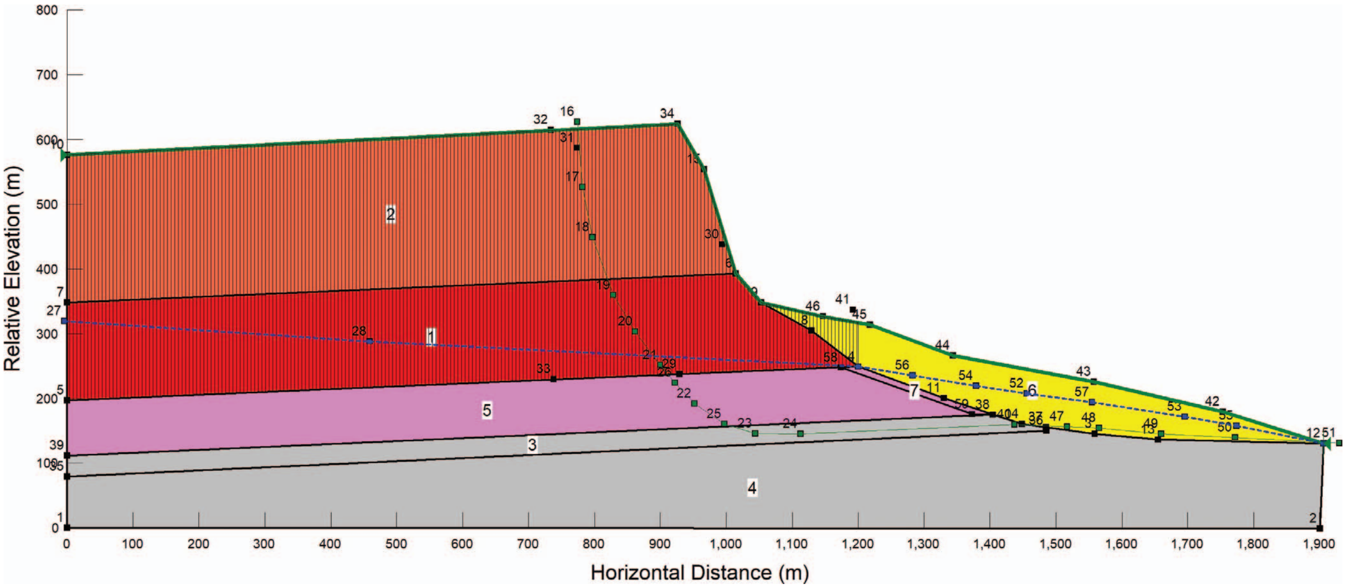

Figure 21. In this analysis a phi angle of 11.7° within the Chinle shales would be required to maintain stability during present-day groundwater conditions.

has to the east, near Bitter Springs. The factor of safety was held at 1.0 for each analysis.

Both the Vermilion and Echo Cliffs exhibit adverse bedding where the strata dip back into the cliffs, opposite of the slope movement. This typically tends to resist failure. The axis of the Echo Cliffs Monocline closely parallels the face of the cliffs, resulting in extensive jointing of the bedrock. The jointing likely negates much of the stabilizing impact caused by the adverse bedding because it facilitates moisture infiltration along the Echo Cliffs. The authors' parametric analyses provided a range of friction (phi) angles from 7.70° to 15.45°, with a likely value of ~10.55°.

Multiple samples of Chinle shale were collected by the authors along the base of the Vermilion Cliffs for analysis. Because of the cost of the testing involved, the samples were initially evaluated using conventional diagnostic tests, such as determining Atterberg limits and X-Ray diffraction. Both tests were conducted at Missouri Science and Technology. Although the samples were physically similar in appearance, the two analyses pinpointed one sample in particular that was the weakest of the collection. This sample was sent off for further testing, as described below.

The authors also contracted with GeoTesting Express of Acton, MA, to conduct three direct shear tests (ASTM D 3080) with a maximum normal force of 4.79 MPa (50 tsf = 100,000 psf) to approximate pre-failure overburden conditions. From these tests, the friction (phi) angle of the material was determined to be 11.7°. The intrinsic cohesion was determined to be approximately 11 MPa (1.1 tsf). A significant loss of strength was also noted during repeated shearing to residual strengths. Mobilized shear strength plots generated by these tests are summarized in Figure 18.

All values from the various tests coincide well, with no more than a 17 percent variance between the key material properties. Table 1 compares the values determined from the parametric back-analyses, as well as the laboratory tests.

CONCLUSIONS

The Vermilion and Echo Cliffs of northern Arizona are mantled by extensive landslide complexes, which have contributed to 3 km or more of scarp regression. These failures are almost exclusively confined to basal translation within the Petrified Forest Member of the Triassic Chinle Formation and have occurred regardless of whether the stratigraphy dips into or away from the direction of movement. Both rotational and disaggregated sturzstrom-type landslides occur along the cliffs, although the sturzstroms are most pronounced where the cliffs reach their maximum height (550–610 m), near Lee's Ferry. Landslides are almost continuous along the escarpment where the Petrified Forest Member of the Chinle Formation is fully exposed. The scale and intensity of landsliding gradually diminish in proportion to exposure of the Petrified Forest Member of the Chinle Formation.

The landslides appear to be relicts of a past climatic regime, during the Pleistocene. They also appear to have occurred in separate, distinct episodes, indicative of recurrent or cyclical environmental triggers.

Paleoecological evidence suggests a significantly wetter climate existed during much of the Pleistocene. Studies of paleovegetation also suggest that Pleistocene rainfall was probably less intense than that afforded by present-day storms and likely extended over a much longer period of time each year, similar to the kind of patterns experienced today in the lower latitudes of Canada (Rogers et al., 2004; Watkins et al., 2007). These sorts of environmental conditions would have allowed a much greater percentage of the precipitation to infiltrate the subsurface. The systematically jointed Jurassic sandstones likely channeled this water into the underlying shales of the Petrified Forest Member, gradually reducing effective shear strength and cohesion through simple saturation and gravity-induced creep under the enormous load of the steep escarpment. Seismicity associated with regional tectonism and volcanism might have played a role as well by temporarily elevating pore pressures in the shale and thereby reducing the effective stress and overall strength of the saturated strata.

Other escarpments mantled by landslides within the Colorado Plateau share similar characteristics, both in terms of the landslides themselves and the formations involved. Occurrences of similar landslides throughout the entire region suggest that the environmental triggers were widespread.

ACKNOWLEDGMENTS

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We would also like to thank Gary T. Torosian, Joseph D. Tomei, and Ethan Maro of GeoTesting Express in Acton, MA, who supervised the shear tests on the Petrified Forest Member of the Chinle Formation. These were performed with normal confining stresses of 8, 20, and 50 tons/ft^2 (100,000 lb/ft^2), These were the highest normal force loads available from any geotechnical lab in the United States. They also performed a five-cycle residual shear test at a normal force of 20 tons/ft^2.

We would also like to thank James J. Lemmon, RG of the Arizona Department of Transportation, for allowing us access to and copies of the geotechnical test data Arizona DOT and their consultants Kleinfelder West developed during their studies of the Bitter Springs Landslide along US Highway 89 in February 2013. This slide was in the Echo Cliffs across the Colorado River from the Vermilion Cliffs in the same stratigraphic units. The slide damage closed the highway for more than two years and cost $25 million to repair. There was an extensive program of geotechnical testing that included ring shear and soil plasticity tests by Cooper Testing Labs in Palo Alto, CA. These data corroborated similar testing we performed as part of our slope stability evaluations of the Vermilion Cliffs.

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