Austin S.A., E.W. Holroyd III, T.F. Folks, and N. Loper. 2023. Shoreline transgressive terraces: Tufa-encrusted landforms indicate rapid filling and failure of Hopi Lake, western Bidahochi Basin, northeastern Arizona. In J.H. Whitmore (editor), *Proceedings of the Ninth International Conference on Creationism*, pp. 346-362. Cedarville, Ohio: Cedarville University International Conference on Creationism.

SHORELINE TRANSGRESSIVE TERRACES: TUFA-ENCRUSTED LANDFORMS INDICATE RAPID FILLING AND FAILURE OF HOPI LAKE, WESTERN BIDAHOCHI BASIN, NORTHEASTERN ARIZONA

Steven A. Austin, Cedarville University, 251 N. Main St., Cedarville, Ohio 45314, mudflowman@comcast.net
Edmond W. Holroyd III, Carmel Consulting, Arvada, Colorado, eholroyd@juno.com
Thomas F. Folks, St. George, Utah, nigelt1@msn.com
Nate Loper, Canyon Ministries, 2727 W Rte 66, Flagstaff, Arizona 86001, nate@canyonministries.org

ABSTRACT

For more than 160 years geologists have been pondering the notion that a lake once occupied a large part of Bidahochi Basin in the Painted Desert of northeastern Arizona and western New Mexico. Could the 300-kilometer-long Hopi Lake have spilled over the Kaibab Upwarp to erode Grand Canyon? A composite satellite image of a 25-square-kilometer tract from Coconino County adjacent to Buffalo Range Road in Wagon Box Draw displays terracelike landforms within the structural ramp of Kaibab Formation. Landforms are terraces expressed upon gentle slopes as low as 0.02 (rise over run 1:50) within the uppermost limestone beds of the Harrisburg Member of the Kaibab Formation at elevation of ~1750 m (5740 ft). A typical 20-meter-wide, steplike terrace has a thin, centimeter-thick, light yellow-brown, porous carbonate encrustation we term "tufa." The transgressive Lake Bonneville depositional terrace model of Chen and Maloof (2017) is applied to the limestone dip slope at Wagon Box Draw. As the wave-dominant shoreline rises over the dip slope, our model specifies how the terrace is first eroded into thin-bedded limestone and, later, is deposited with residual gravel. Lastly, because of continued quick transgression, the shoreline depositional terrace is accreted with a thin crust of tufa. We consider and dispute four alternates to our shoreline transgressive terrace model (landform outcrop pattern caused by level strata, spacing caused by bedrock joints, dunelike or boudinage structural expression in limestone bed, and soil solifluction with gravity compaction). We interpret these Wagon Box Draw shoreline terraces to have been carved within the limestone slope as Hopi Lake rose to fill Bidahochi Basin. We believe that filling of Bidahochi Basin was accelerated by breaching of another big lake upstream in Utah. Top-down overflow of higher basins promoted quick filling of Bidahochi Basin, initiated catastrophic spillover of Kaibab Upwarp, began rapid drainage of Hopi Lake, and resulted in catastrophic erosion of Grand Canyon.

KEYWORDS

Shoreline landforms, erosional terrace, depositional terrace, transgression, tufa, Hopi Lake, Bidahochi Basin, Lake Bonneville, Grand Canyon.

INTRODUCTION

Bidahochi Basin is an elongate, 300-kilometer-long structural depression in the Painted Desert region of northeastern Arizona (Figure 1). Today, that basin is occupied by the Little Colorado River directly east of Grand Canyon. For more than 160 years geologists have been pondering the notion that a lake once occupied a large part of Bidahochi Basin. During an expedition to the Southwest in 1858, John Newberry, the first geologist to explore Grand Canyon, proposed that an enormous lake was responsible for spillover erosion along the course of the modern Colorado River (Newberry 1861). The noteworthy and enduring legacy of Newberry's original hypothesis among both creationist and evolutionist geologists has recently been recounted (Austin et al. 2020). Newberry's hypothesis is tectonic process created a 300-kilometer elongate depression in Northeastern Arizona that was older than the Colorado River. That depression was recognized as the "synclinal trough or basin" during Newberry's 1858 explorations where at Hopi Buttes he measured the thickness of fine carbonate cemented sandstone, siltstone and claystone that he believed to be Miocene lake deposits. Newberry (1861, pp. 19, 20) described his lake spillover hypothesis:

> Doubtless in earlier times it [Colorado River] filled these basins to the brim . . . its accumulated waters, pouring over the lowest points in the barriers which opposed their progress towards the sea, have cut them down from summit to base, forming that remarkable series of deep and narrow canyons . . . leaving open areas . . . which were once lakes and afterwards fertile valleys – arid and sterile wastes."

Later generations of geologists took up the task of defining and naming features that John Newberry first recognized. That 300-kilometer-long tectonic depression has recently been named "Bidahochi Basin" (Dallegge et al. 2003; He and Kapp 2021). Newberry's fine-grained clastic deposits in the Hopi Buttes were assigned to the Mio-Pliocene Bidahochi Formation (Reagan 1924). The putative Pliocene paleolake that filled the topographic depression was named "Hopi Lake" by Howel Williams as he was describing the volcanic strata of Hopi Buttes (Williams 1936). Some geologists started calling that paleolake "Lake Bidahochi" (Meek and Douglass 2001), but Williams' name "Hopi Lake" has priority. Creationist geologists have engendered their own legacy concerning spilling lakes. During the last 50 years the consensus creationist explanation has been that the 300-kilometer-long Hopi Lake spilled over the Kaibab Upwarp to erode Grand Canyon (Austin et al., 2020).

What was the elevation of the paleolake? A likely elevation of the paleolake is 1860 meters (6100 feet) as recognized from tufa deposits just east of Grand Canyon and similar tufa near St. Johns, Arizona (Scarborough et al., 1998; Scarborough 2001; Austin et al., 2020). Current models of 1860-meter lake level assume post-lake tectonic tilting of Kaibab Plateau (Austin et al., 2020). A higher elevation of the putative paleolake, without plateau tilting, was suggested by Douglass et al. (2020).

The Bidahochi Basin terrain model (Figure 1) depicts a stage in filling when the paleolake was at elevation 1770 meters (5800 feet) as terraces formed at Wagon Box Draw. We believe the lake continued to rise to ~1860 meters (~6100 feet). Figure 1 shows the eastern Grand Canyon and Kaibab Upwarp in the upper left. Eastward of Grand Canyon is Echo Cliffs Monocline crossing Marble Canyon at Lees Ferry, Arizona. On the horizon in the top middle of Figure 1 is the upper Colorado River basin in Utah and Colorado. In the upper right of Figure 1 is the Defiance Upwarp forming the highlands on the eastern end of Bidahochi Basin. Mogollon Rim is the highland in the foreground marking the southwestern edge of the Colorado Plateau.

Through the years three geologic evidences have been offered by spillover advocates indicating the Bidahochi Basin was a depression filled by a lake. First, sedimentary deposits in the upper half of the Bidahochi Formation, along with an ecosystem of lake fossils, argue strongly for the paleolake (Douglass et al. 2020). Second, near 1770 meters elevation, there is no tectonic confinement within the middle of Bidahochi Basin allowing western extension and filling with water against the Kaibab Upwarp (Scarborough, 1989; Holm, 2001; Dallegge et al. 2003; He and Kapp, 2021). Third, widely distributed shoreline tufa deposits above 1860 meters elevation make the paleolake credible (Harris et al., 1998; Scarborough, 2001; Austin et al, 2020). A fourth geologic evidence for the lake might be offered in terracelike landforms at the shore. However, no publication yet concerns Hopi Lake shoreline terraces. The present authors here seek to explore this possible shoreline evidence.

Before proposing a search for shoreline terraces of Hopi Lake, we must ask if our motives for such a search are geologically reasonable. Slopes along the shoreline of putative Hopi Lake just below 1860 meters (6100 feet) elevation are typically 0.02 (topographic "rise" divided by horizontal "run," sometimes depicted as 1:50). Slope expressed as 0.02 (rise over run) is equivalent to slope angle 1.1 degree (the arctangent of 0.02). Ice Age Lake Bonneville has the most intensely studied Pleistocene shorelines (Gilbert 1890, Chen and Maloof 2017, Oviatt 2020). If the comparison of Ice Age Lake Bonneville to Hopi Lake is proper, then shoreline terraces of ancient glacial Lake Bonneville should be evident on slopes of 0.02 or less. However, Lake Bonneville shorelines are typically found on slopes averaging 0.1 (rise over run 1:10), equivalent to 5.7 degrees. We have been searching Bonneville slopes of 0.02 (rise over run), equivalent to 1 degree for shoreline erosional terraces, but we have not found good examples. The expression of former Lake Bonneville shorelines on different slopes is perhaps best illustrated at Brown Knoll, a volcanic lava-dome complex in the southern basin of Lake Bonneville, Utah (lat./long., +38.722, -113.350). Figure 2 is the oblique profile aerial photograph of the western dome at Brown Knoll that was completely transgressed by filling to the highest level of Lake Bonneville. Brown Knoll West displays excellent transgressive shoreline terraces on slopes of 0.1 (6 degrees) near the base of the volcanic dome structure. However, at slopes of 0.02 (1 degree) at the top of the western dome, shoreline terraces do not occur. The same conclusion could be made about

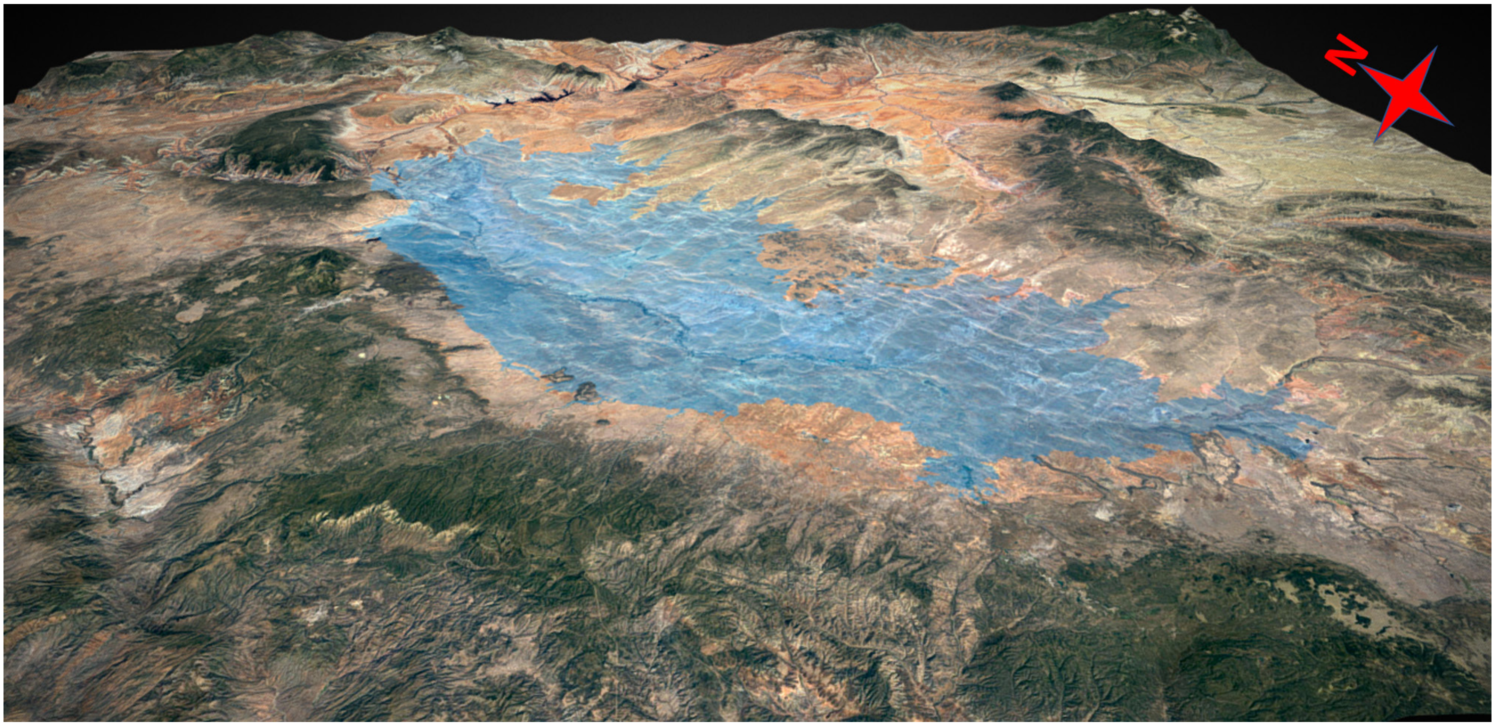

Figure 1. Bidahochi Basin oblique terrain model overlooking northeastern Arizona and western New Mexico, including simulated 300-kilometer-long Hopi Lake rising through elevation 1770 meters (5,800 feet). Rendered by Nate Loper as a 3D terrain model using Blender software and posted on 3D hosting platform Sketchfab (Loper, 2022a).

Figure 2. Lava dome structure of western Brown Knoll, Utah. The high-level filling of Pleistocene Lake Bonneville completely transgressed the volcano producing transgressive shoreline depositional terraces visible on slopes of 0.1 (rise over run 1:10). Oblique aerial photo by Dan Slyter.

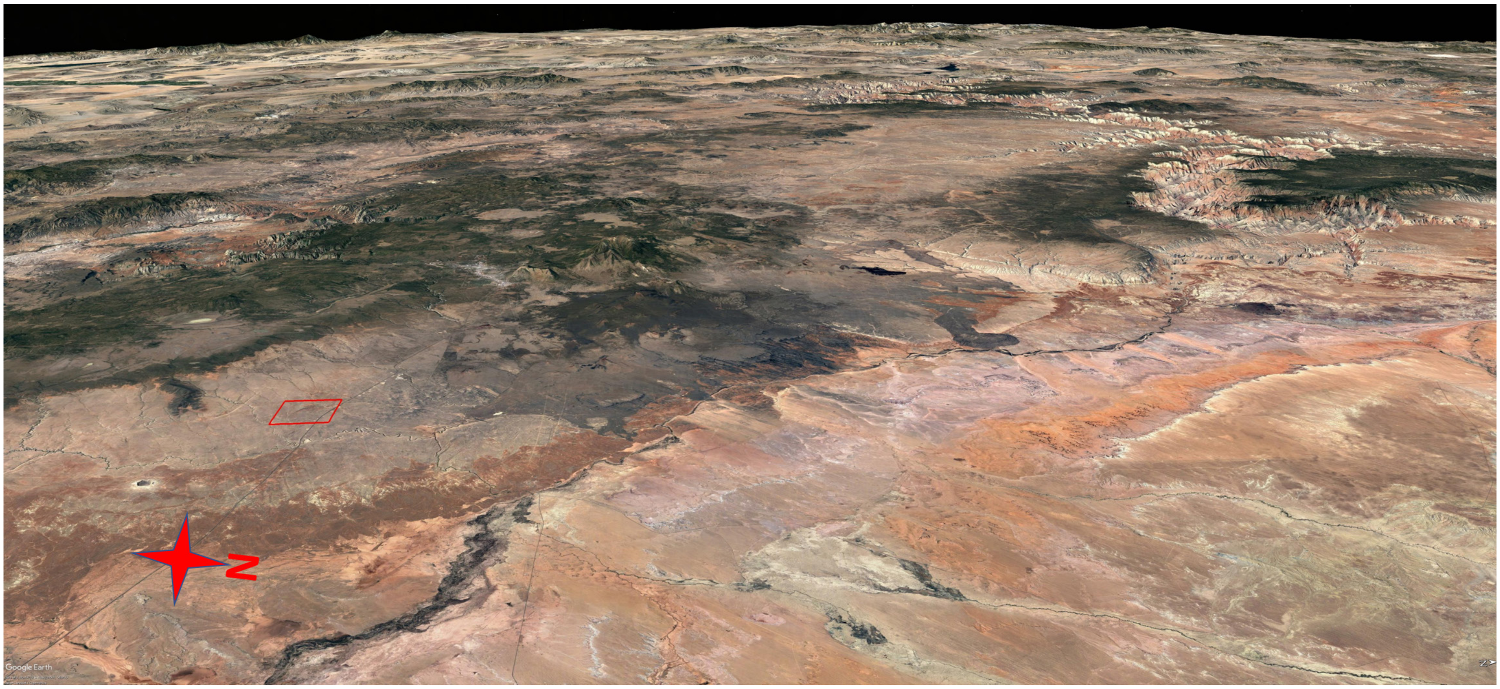

Figure 3. Oblique and very wide image of western Bidahochi Basin. Meteor Crater is in lower left and Grand Canyon is in upper right. Red square is 25-square-kilometer Wagon Box Draw landform study area.

the primary eastern dome at Brown Knoll. We continue our yet-to-be-successful search for low-angle Lake Bonneville shorelines elsewhere in Utah. After our initial survey of shoreline terraces on Bonneville low slopes, we find ourselves asking if we would expect to find shoreline evidence on bedrock slopes of 0.02 around the shore of ancient Hopi Lake. Our conclusion from our survey at Lake Bonneville is special conditions would be necessary for preservation of terraces on bedrock slopes of 0.02 (1 degree) or less. In this paper we propose and test the hypothesis that transgressive depositional terraces can be produced on limestone dip slopes as low as 0.02 if certain bedrock conditions are present (dip slope exposure with thinner heterogeneous limestone beds).

LANDFORM STUDY AREA AND METHODOLOGY

Our attention was focused on observation of certain landforms on low slopes in the southwestern margin of Bidahochi Basin at elevations

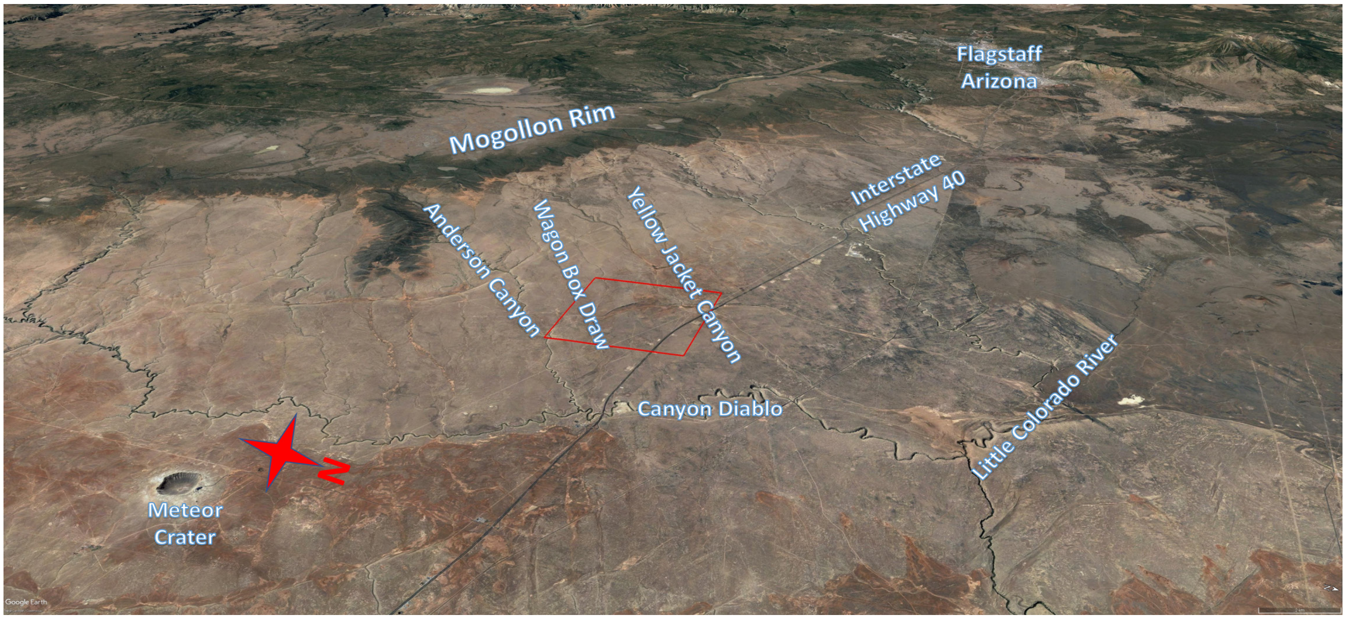

Figure 4. Oblique image of western Bidahochi Basin showing the location of the 25-square-kilometer Wagon Box Draw landform study area (red square). Wagon Box Draw is a tributary to Canyon Diablo, which is tributary to Little Colorado River.

Figure 5. Terracelike landforms are very abundant on Nate's Hill on north side of Wagon Box Draw. Here the hill is viewed in the upslope direction looking northwest. Hill is terminated on the right side by the fault scarp and graben structure parallel to Buffalo Range Road. Oblique aerial still photo clipped from Loper (2022b).

approaching 1860 meters. These landforms occur just south of Interstate Highway 40 at the Buffalo Range Road exit (Arizona I-40, exit 225) about 45 kilometers east of Flagstaff, Arizona. Figures 3 and 4 show the geographic context of what we call "Wagon Box Draw Landform Tract." The area of interest is 18 kilometers west-northwest of Meteor Crater, Arizona. In this region, most land is administrated by the Hopi, and the tract is used primarily as cattle rangeland. We discovered, upon viewing satellite imagery, a complex of terracelike landforms at 1740 meters (5,700 feet) elevation in the drainage called Wagon Box Draw, an example of which is shown in Figure 5. Early in our study we obtained low-altitude, oblique aerial movie footage of this location we call "Nate's Hill." Landform aerial overflight video was edited and posted so we could invite specialists to give us their opinions (Loper, 2022b).

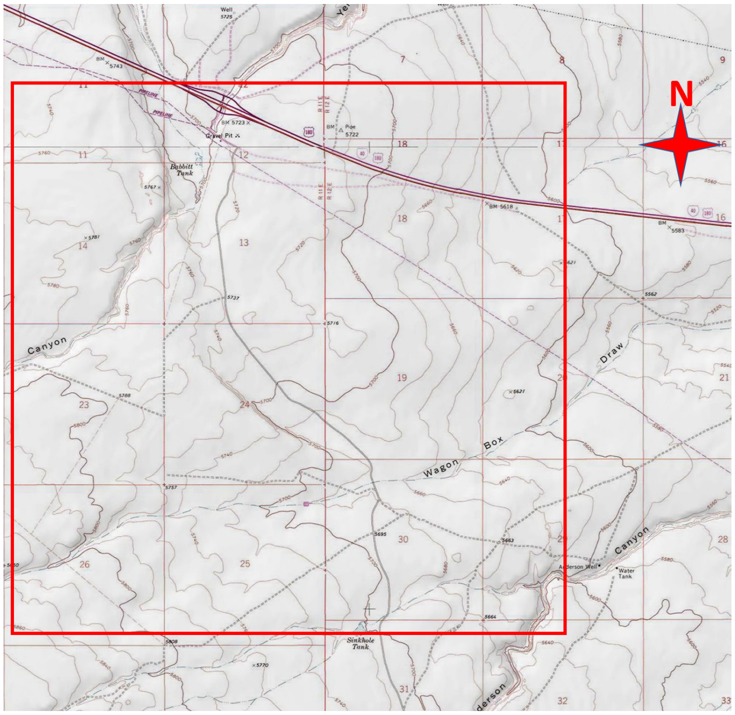

Figure 6. Portion of Anderson Canyon 1:24,000 USGS topographic map of the 25-square-kilometer Wagon Box Draw study area (large red square). The contour interval is 20 feet. Section boundaries (inset red grid) are one-mile squares.

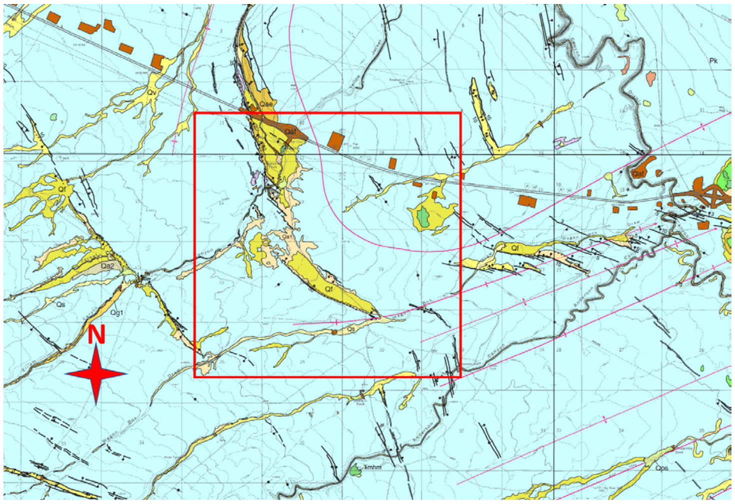

Figure 7. Geologic map of the Wagon Box Draw study area (large red square is 5 kilometers on each side). Light blue is Kaibab Formation. Green is Moenkopi Formation. Repeating square grid pattern contains 1-mile-wide section boundaries. Geologic base map is after Billingsley et al., 2013.

We recognized a 25-square-kilometer area of interest (Figures 6 and 7). Figure 6 is the portion of the Anderson Canyon USGS 1:24,000 scale topographic map. Figure 7 is the published USGS Flagstaff 30' x 60' geological quadrangle map of Billingsley et al. (2013). We used the map and report of Billingsley et al. (2013) as our introductory framework for bedrock structure and stratigraphy. We greatly expanded our understanding of bedrock structure through field study at the landform tract.

Next, we assembled satellite imagery from Google Earth to form a half-meter-resolution composite, vertical image collectively composed of about 100 million pixels. Upon the composite, high-resolution image, we overlayed a two-meter contour interval map from the USGS digital elevation model (DEM). The 25-square-kilometer composite landform tract image with overlain contour lines is rendered in lower resolution in Figure 8. Our attention became focused on 13 "landform fields" within Figure 8. Those 13 "landform fields" are numbered in Figure 8, and we selected four fields for the most detailed study. Each of these four fields is depicted as an added figure. Figure 9 is field 2 which we call "Interstate Highway Arch." Figure 10 is field 4 which we call "Chevron Hill." Figure 11 is field 7 which we call "Nate's Hill." Figure 12 is field 8 which we call "Graben Hill."

Finally, and most important for methodological discussion, we studied the landforms in the field. We observed the stratigraphy of the outcropping Harrisburg Member at the top of the Kaibab Formation, and related the landforms to the faults and folds that form the bedrock ramp structure of the southern margin of the Colorado Plateau just north of the Mogollon Rim.

OBSERVATIONS—STRUCTURE AND STRATIGRAPHY

Figure 7 is the relevant portion of the geologic map of Billingsley et al. (2013) showing the 25-square-kilometer research area. It displays the limestone ramp of Kaibab Formation that descends from southwest to northeast, away from the Mogollon Rim and through the landform tract. The ramp dips northeastward with slope 0.01(rise over run 1:100) and primarily exposes the uppermost beds of the Harrisburg Member of the Kaibab Formation (light blue in Figure 7). Two secondary geologic structures occur on the ramp. The first is gentle, northeast-trending, plunging anticlines and synclines. The plunging anticline axis runs northward through "Interstate Highway Arch" (field 2). That feature has limestone strata dipping westward on the west side of the hill and eastward on the east side of the hill. The northern side of Wagon Box Draw is a consequence of a very gentle plunging syncline, and the limestone outcrop called "Nate's Hill" (field 7). The north side of Wagon Box Draw at "Nate's Hill" is the limestone northern limb (dip slope) of the gently plunging syncline. The slope of "Nate's Hill" is 0.02 (rise over run 1:50) and is a two-component system (0.01 + 0.01 = 0.02) being composed of the ramp's slope (0.01) added to the anticline's slope (0.01). The second structure superimposed on the ramp is a suite of northwest-trending graben structures expressed at northwest-trending listric normal faults. Strata of Moenkopi Formation (green in Figure 7) and Quaternary-Pliocene gravels (yellow in Figure 7) are frequently depressed within these grabens.

The stratigraphy within the primary ramp is best displayed in Figure 13 just 3.7 kilometers northeast of the landform research tract (just off the northeast corner of Figure 7). There deep erosion

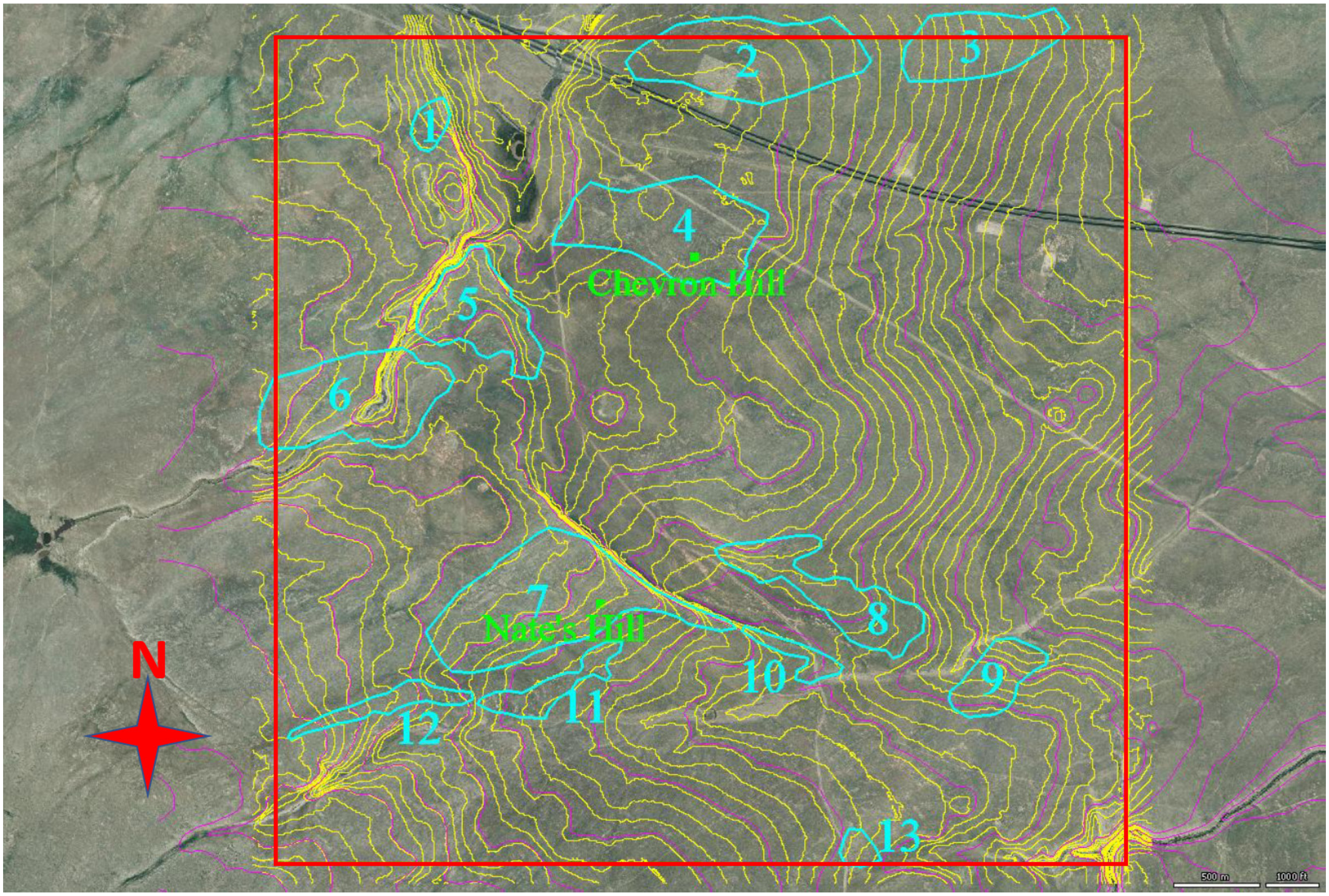

Figure 8. Composite image of the 25-square-kilometer Wagon Box Draw landform study area. Thirteen landform fields were selected for detailed research. Purple lines are 20-foot contours from the 1:24,000 Anderson Quadrangle map. Yellow lines are 2-m contours generated from the USGS DEM.

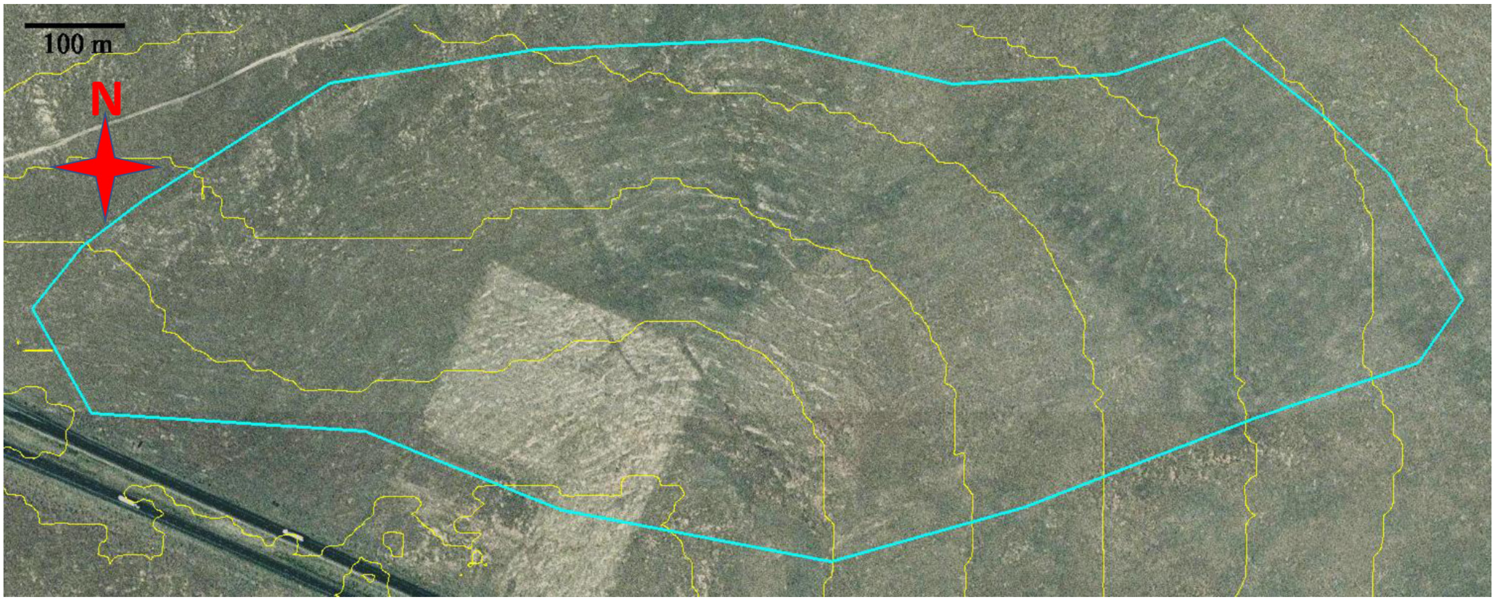

Figure 9. "Interstate Highway Arch" is our name for landform field 2. This field contains a northward-plunging anticline. Terrace gravel at the surface above Kaibab Formation Harrisburg Member limestone was quarried from the large borrow pit by Interstate Highway engineers. Yellow lines are 2-meter contours.

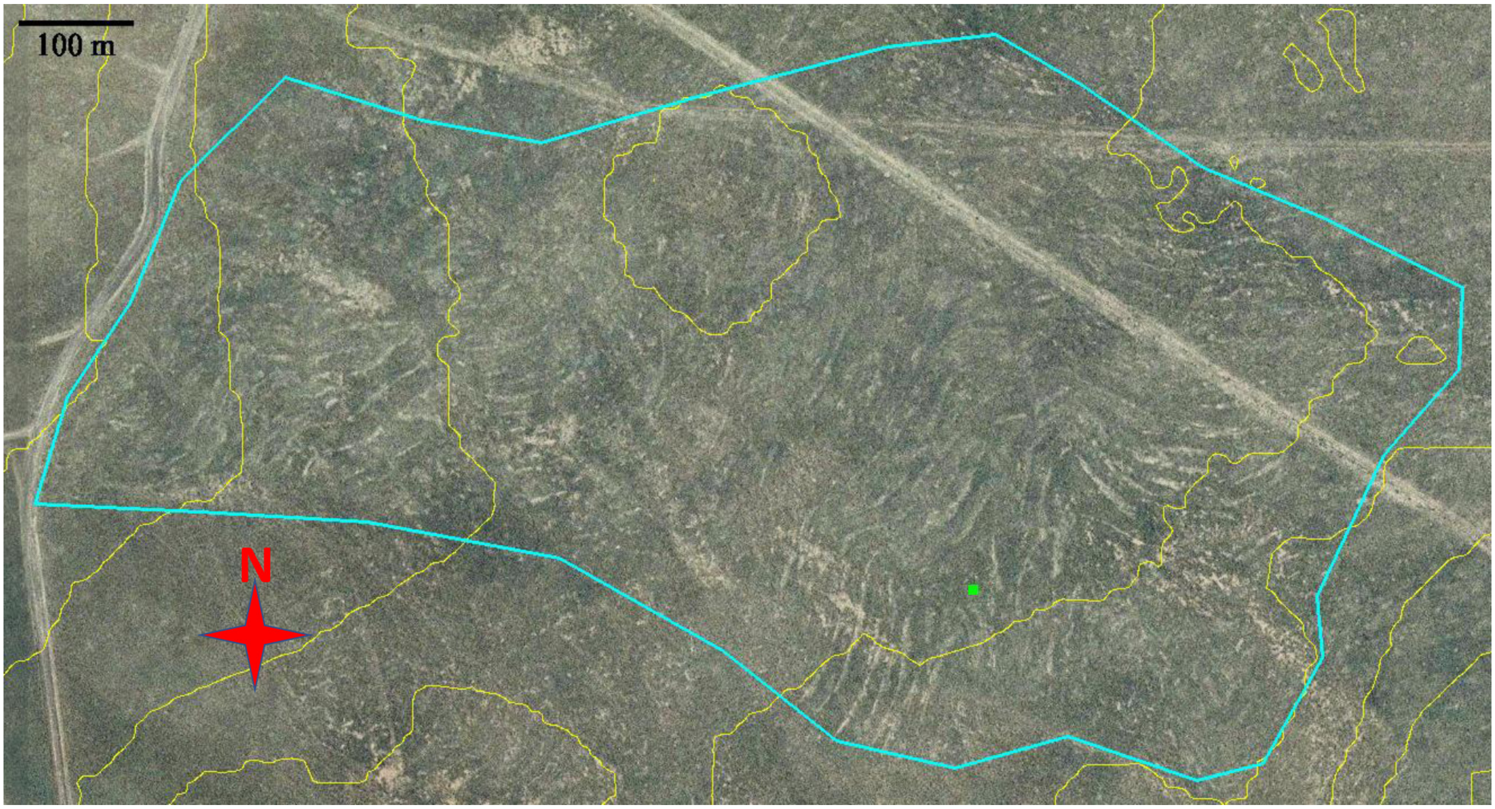

Figure 10. "Chevron Hill" is our name for landform field 4. Yellow lines are 2-meter contours from DEM.

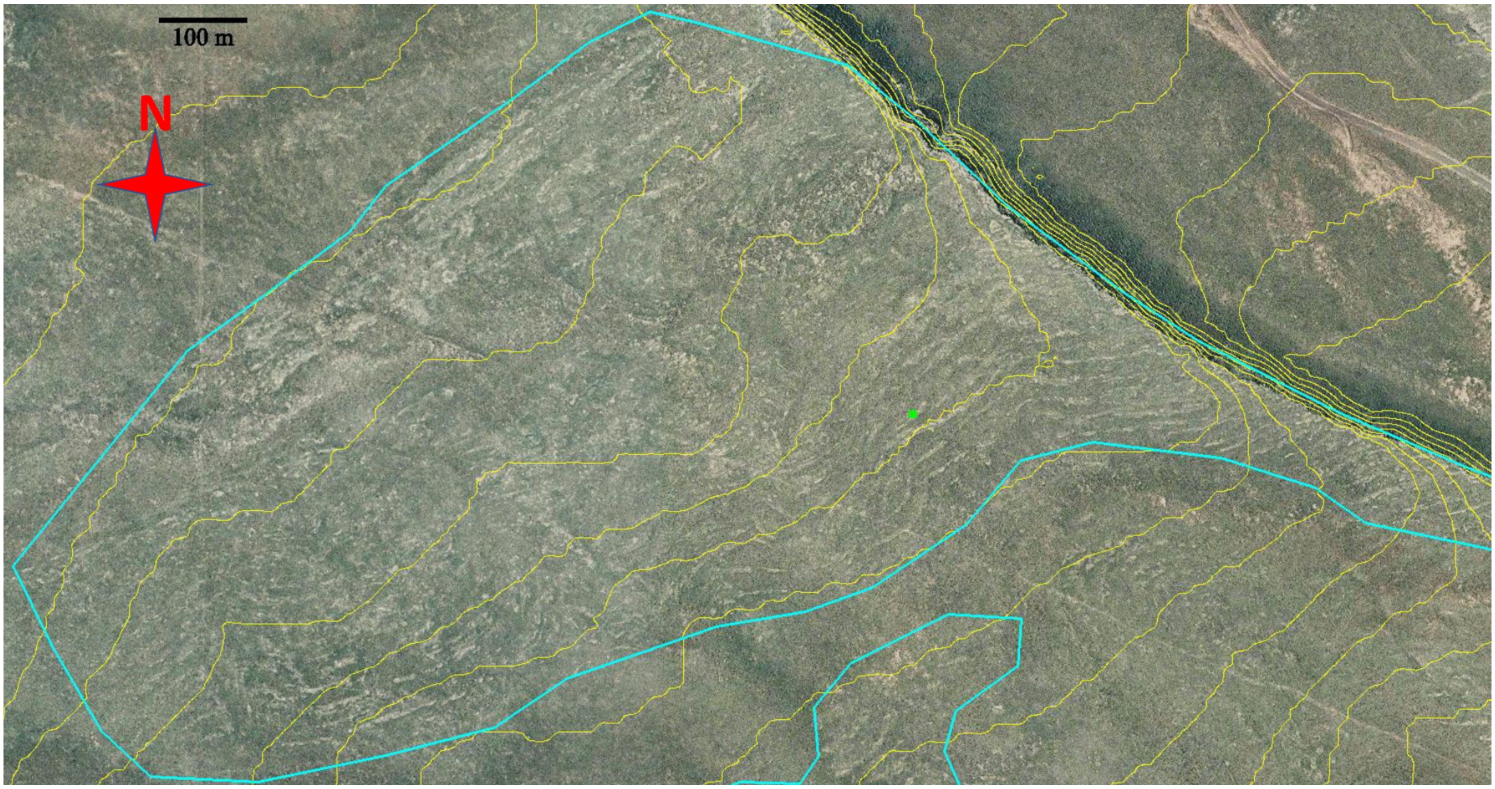

Figure 11. "Nate's Hill" is our name for landform field 7. The structure of Nate's Hill is a limestone dip slope exposing the upper thin beds of the Harrisburg Member dipping southeast. Terrace landforms follow yellow 2-meter contours except in the southwest and northeast of this field where listric normal faults displace the Harrisburg Member. Deformations near faults is consistent with normal drag folds near the faults. Overflight video of this terrain is provided in Loper (2022b).

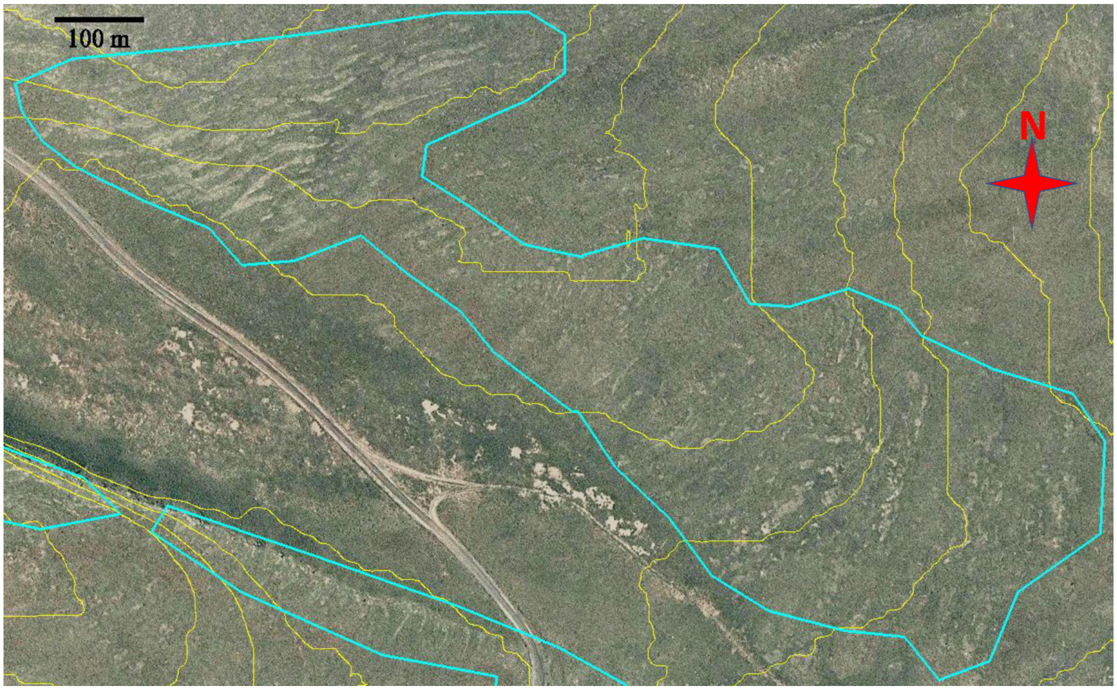

Figure 12. "Graben Hill" is our name for landform field 8. Graben structure runs through middle left along Buffalo Range Road. Drag of faults appears to cause terrace landforms to deviate from horizontal. Yellow lines are 2-meter contours.

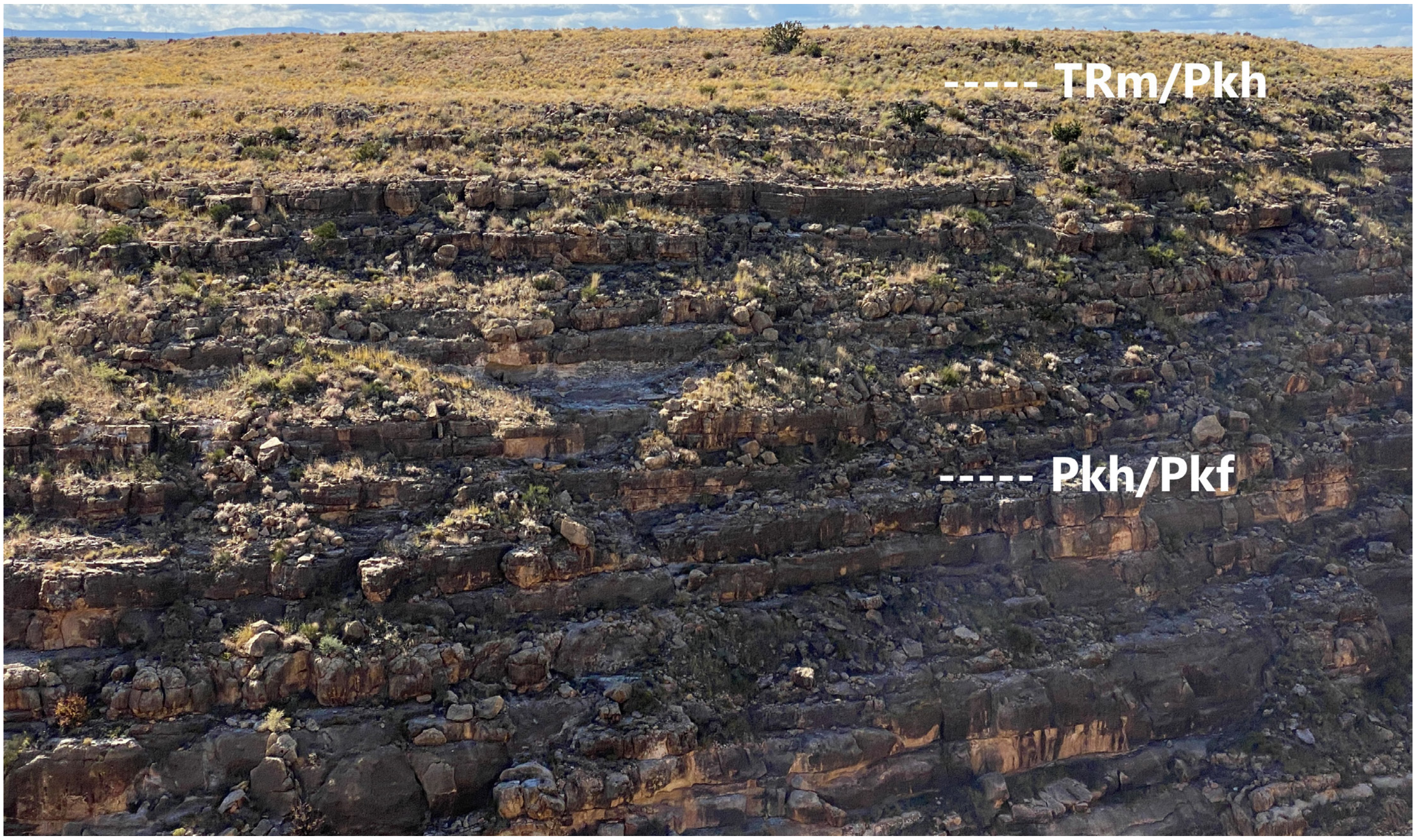

Figure 13. The uppermost limestone strata of the Kaibab Formation, including the complete 23-meter-thick Harrisburg Member, are excellently exposed in the western wall of Canyon Diablo. This canyon wall exposure is near the railroad bridge over the canyon just 3.7 kilometers northeast of the northeastern corner of the Wagon Box Draw landform study area. Contact "TRm/Pkh" is friable siltstone of lowest Moenkopi Formation overlying more resistant thin-bedded limestone of the Harrisburg Member at the top of the Kaibab Formation. Contact "Pkh/Pkf" is thin-bedded, somewhat resistant, limestone strata of Harrisburg Member overlying thicker-bedded, more resistant limestone of the Fossil Mountain Member. Scale is provided by three-meter-diameter lone tree at the skyline along the mesa at the top of the canyon wall. Photo by Nate Loper.

within Diablo Canyon has exposed the full, 23-meter-thick strata sequence within the Harrisburg Member of the uppermost Kaibab Formation. The Harrisburg Member is slope-forming brownish-gray to reddish-gray interbedded, thin-bedded limestone, sandstone, and siltstone. That Figure 13 displays the complete 23 meters thickness of the Harrisburg Member is confirmed in Diablo Canyon by contact with the overlying Moenkopi Formation (reddish and brownish friable siltstone, sandstone and mudstone) which usually weathers and crumbles markedly to form the ramp's surface at the top of Harrisburg Member. Also, within Diablo Canyon, is the cliff outcrop of the underlying Fossil Mountain Member of the Kaibab Formation (light-gray cherty, thick-bedded limestone that is extremely resistant to erosion). Within and around the structural ramp of the Wagon Box Draw research tract, Billingsley et al. (2013) mapped several small erosional outliers of Moenkopi Formation sitting on Harrisburg Member. Thus, we conclude that the ramp is expressed with the beds of the upper Harrisburg Member. We identified informally the uppermost six meters of Harrisburg Member in Figure 13 (slope forming, thin-bedded limestone, with thin bedded sandy and silty limestone) as the "platform carbonate unit" that we regard as marker beds that can be recognized widely on the ramp's surface. An excellent exposure of these ramp limestone strata has been created by Interstate Highway roadbuilders who quarried surficial gravel from the rectangular borrow pit on the north side of Highway 40 at "Interstate Highway Arch" (Figure 9). Here the landform terrace erosional surface and its overlying terrace deposit has been quarried.

That the dip slope of the "platform carbonate unit" is the bedrock host for the linear, terracelike landforms on Nate's Hill is demonstrated, we believe conclusively, by geometric analysis of oblique photography. Figure 14 is a compelling oblique image of Nate's Hill looking westward. Linear landforms on the southern slope of Nate's Hill are seen extending eastward to the scarp of the prominent listric normal fault where the limestone strata of the "platform carbonate unit" are displayed in the scarp beneath the linear landforms. Obviously, the landforms in Figure 14 are inscribed on the dip slope of limestone. In the field we were impressed by the horizontality of the linear landforms. Through one-kilometer distance across Nate's Hill we were able to follow a linear landform ridge that appears to vary in elevation by less than one meter. We observed this extraordinary horizontality on Figure 11's DEM overlay and on the outcrop in the field using the level bubble on a Brunton compass. Even more remarkable, however, is how the landforms deviate from horizontality at both east and west ends of Nate's Hill. Notice on Figure 11 how the landforms turn down slope as the listric normal faults are approached on both the east and west ends of Nate's Hill. These deviations from horizontality, we believe, are caused by drag on the faults. Figure 12 even shows the effect of fault drag on the landforms on the opposite side of the large graben at what we call Graben Hill. Overall, the Buffalo Range Road graben offsets landforms vertically by 15 meters, down on the eastern side. These observations of deviations from horizontality persuade us, by their cross-cutting relationship, that nearly level terracelike landforms on the dip slope are older than the normal faults that produced the graben. Thus, we understand the Bidahochi Basin has been deepened tectonically by listric faulting since the time that Hopi Lake formed.

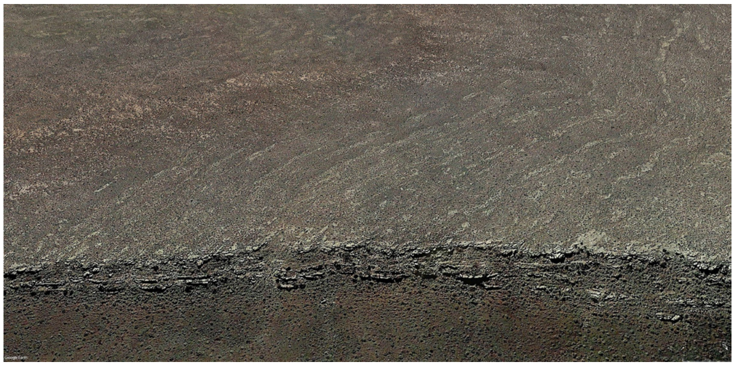

Figure 14. Oblique aerial view of Nate's Hill looking west over the fault scarp. Terrace landforms typically have 20-meter spacing. This oblique view, we believe, makes a compelling case for the successive terraces being inscribed on the dip slope exposing a single, thinner limestone bed at the top of the Harrisburg Member. This view disputes the notion that the successive landforms on the slope are outcrop expressions of a series of thinner limestone beds.

OBSERVATIONS—OVERALL APPEARANCE OF LANDFORMS

Landforms were studied in the field to obtain a better appreciation of relationships to bedrock stratigraphy and structure. Oblique aerial video (Loper, 2022b) shows linear landforms on Nate's Hill that typically light-brown ridges of rock separate darker brown depressions with sandy soil and xerophytic plants. Of the rangeland plants, bushes on the flats are the most visible from the aerial video. Bushes typically are half-meter diameter, so that scale indicates that light-brown ridges of rock are typically spaced 20 (+/- 5) meters. When walking in the upslope direction across the sandy low areas, one first encounters the linear rocky ridge with a noteworthy steeper, inclined rocky surface element that we call the "face" of the landform. Sometimes the "face" shows evidence of concave upward curvature and the strike the limestone. Upslope from the "face" is a convex rock surface with the highpoint being the crest of the landform. We call this convex rock surface the "berm" of the landform. In the upslope direction, the "berm" passes into the adjacent "flat" usually expressed as gravel or sand. The overall height of the sloping "face" and the upslope convex "berm" is typically 0.4 (+/- 0.2) meter. The width of the rocky mound over the ground surface is usually less than 5 meters. These rocky mounds do not display soil and, therefore,

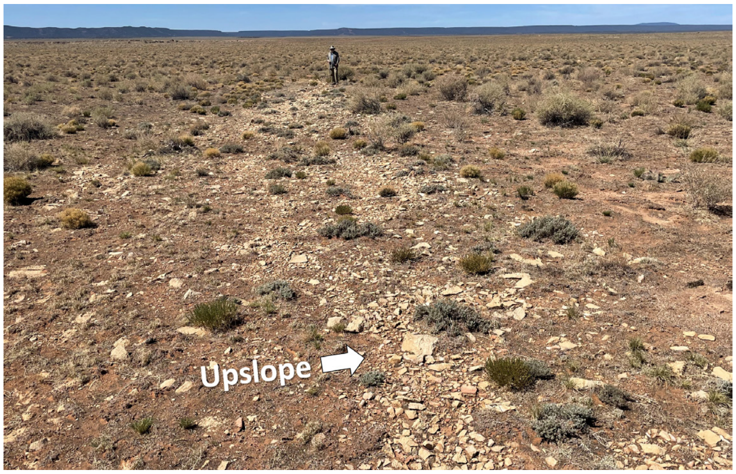

Figure 15. Chevron Hill displays the Harrisburg Member outcrop ridge (berm and face) landform that divides two flat terrace landforms. The entire limestone outcrop is encrusted with thinly laminated, cool-water carbonate ("tufa"). We saw (1) abundant bladelike limestone clasts, (2) positioning of bladelike clasts on the downslope side of an outcropping bedrock ridge, and (3) encrustation with calcareous tufa. We noted the similarity to Lake Bonneville tufa and Lake Bonneville transgressive shoreline terraces (Chen and Maloof 2017) and we asked, "Is this a beach deposit?"

Figure 16. Gray, very hard, Harrisburg Limestone cobble is thinly encrusted with friable, laminated, yellow-brown, porous tufa.

Figure 17. Cross-sectional view of the encrusted Harrisburg Limestone surface. Tufa shows internal lamination parallel to the limestone surface and displays internally pillarlike calcite structures with abundant porosity.

do not promote growth of bushes, the prominent desert plant, on these rocky mounds. Contrast this with soil-covered surface of the "flat" that has darker color and distinctive texture caused by bushes and aeolian volcanic deposition. These contrasting colors and textures accentuate the linearity of landforms seen, especially, in the oblique fly-over in the aerial video (Loper, 2022b). Slopes are poorly appreciated on aerial video because video hardly ever shows the horizon. Field observations allow us to state that landforms are expressed upon gentle slopes of 0.02 to 0.08 (rise over run 1:50 to 1:12).

Before addressing details in the different elements of these landforms, we must recognize and describe the carbonate coating that frequently covers Harrisburg Member limestone, especially near the tops of hills. The carbonate-rock coating is widespread with the landforms, but it is not universal. Figures 15 to 18 help characterize this carbonate coating. Figure 15 shows the widespread distribution of the carbonate-encrusted Harrisburg Member near the top of Chevron Hill. The limestone exposure is almost completely encrusted with yellowish-brown, spongy carbonate. As is typical of these outcrops, the coating conforms to angular and broken corners of limestone boulders and cobbles. Figure 16 shows a larger cobble encrusted with typical, yellowish-brown, spongy carbonate. The yellowish-brown coating in Figure 16 is thin where the surface of the cobble is broken exposing gray Harrisburg Limestone that is the substrate for the coating. The background in Figure 16 accentuates the story: the cobble was moved from the rocky ridge to the adjacent flat to contrast its color with the darker, reddish-brown soil in the flat. Figure 17 displays a typical cross-sectional view of the encrusting coating which possesses pillarlike botryoidal columns and faintly laminated structure within an open spongy texture. Figure 17 shows the encrustation in its common 2 centimeters thickness. We examined the encrustation with hand lens and microscope. Figure 18 shows the encrustation by a "flashlight microscope" inserted into the open spongy texture. Figure 18 displays the encrustation dominated by silt-size calcite crystals that express botryoidal masses that have grown into a hole between pillars.

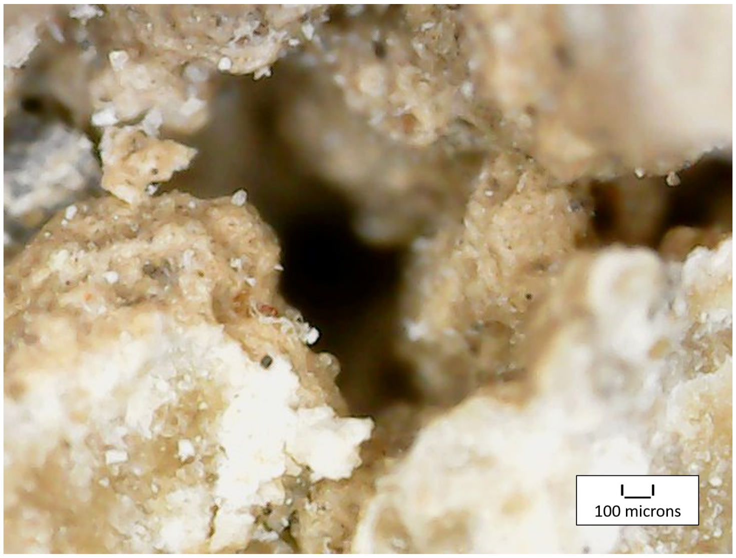

Figure 18. Flashlight microscope view of encrustation on limestone surface. The open structure of pillars, with abundant holes between, displays botryoidal masses composed of silt-size calcite bound together by microcrystalline calcite. These types of carbonate structures form in modern shallow lake shorelines, at normal surface temperature, where microbial films coat surfaces creating a sticky and alkaline microenvironment, inducing trapping of silt-size particles, and cementation with microcrystalline calcite. This thin encrustation, we propose, should be called tufa.

What name should we assign to this laminated carbonate encrusting rock? One can visualize calcite crystals being precipitated while immersed in fresh water, at Earth's normal surface temperature, beneath an alkaline organic slime layer that temporarily covered the rock surface (Ford and Pedley, 1996; Pedley et al., 2008). Our visualized calcite precipitation process differs markedly from the present desert slope, near the top of a dry hill, where we find the carbonate encrustation today! The encrustation is surficial, not associated with joints or faulting. No evidence was found for hydrothermal process. The encrustation does not compel us to imagine a thermal spring deposit (travertine) as we have studied at Yellowstone. Furthermore, this surficial feature is unlike a cave deposit (speleothem). The spongy encrustation reminds us of the rock called "tufa" that we have seen along the high shoreline of Ice Age Lake Bonneville (Hart et al., 2004; Nelson et al., 2005; Felton et al., 2006). We have found the rock we call calcareous tufa to be a widespread encrustation throughout Wagon Box Draw on gentle slopes where the terrace landforms appear. It even occurs on hilltop locations in Wagon Box Draw. It resembles the Bonneville "capping tufa" of Felton et al. (2006).

OBSERVATIONS—LANDFORMS IN DETAIL

As we already have described, Wagon Box Draw landforms are linear and ridgelike being composed of three elements: "berm," "face" and "flat." The berm contains the crest line of exposed limestone that is the high point of the structure with the line of the berm crest expressing nearly horizontal orientation. It is a convex-upward, subtle ridgelike landform. Beneath the widespread yellow-brown encrustation of calcareous tufa, the berm is composed of resistant gray limestone of the upper Harrisburg Member. Where bedrock limestone is exposed within the berm, it is sometimes evident that strike and dip of the limestone is approximately concordant with the overall slope. The surface of the berm is often strewn with platy or bladelike clasts of Harrisburg Member limestone with a deficiency of rollable, spindlelike limestone clasts. The concentration of platy clasts, together with the presence of tufa, remind us of shorelines terraces we have inspected at Lake Bonneville and Salt Lake in Utah and at Salton Sea in California.

The face is the most steeply dipping landform surface within the Wagon Box Draw landform field. The face is the dipping plucked limestone surface always just downslope of the berm. In other places the flat is loose gravel without tufa coating. Often, especially where tufa encrustation is missing, the face appears to be an erosional scarp where the strike of the scarp surface approximately parallels the strike of the Harrisburg Member limestone bedding. As one looks down the strike of the erosional scarp, that scarp appears to be the uppermost part of a concave-upward surface that is mostly buried by the adjacent flat. From this viewing angle, one can appreciate that the face is exposing information on the strike and dip of Harrisburg Member limestone strata. This viewing angle sometimes allows one to appreciate that the landform is inscribed laterally by erosion on the dip slope of the bedrock beneath.

An unusual viewpoint effect occurs when one stands on the face of the landform and looks directly downslope. The face of the next landform downslope is invisible, because its exposed surface is directed downslope. What one sees looking downslope is the next berm (which conceals the next face below) whose topography appears indistinct because that berm is being observed from a low angle from above. Therefore, the downslope viewpoint shows just sediment-filled terraces with rather indistinct berms whose topography is not accentuated. Color contrast is the most noteworthy downslope property. That viewpoint effect can be contrasted with

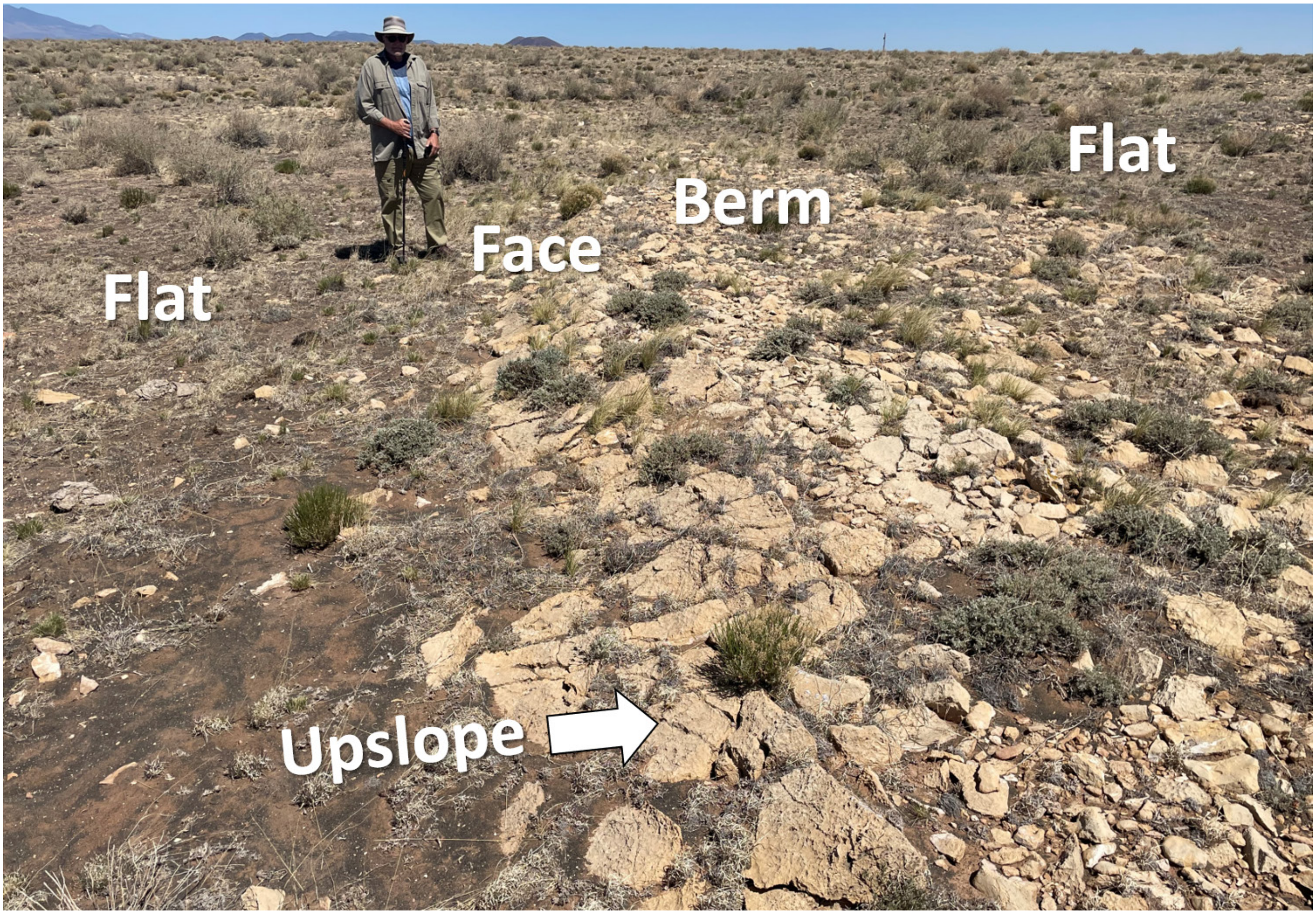

Figure 19. Field view of steplike terraces near the top of Chevron Hill. Landform terminology is applied. The slope is almost completely coated with thin, yellow-brown tufa encrustation.

the view upslope where the face landforms are obviously displayed.

The flat is the nearly horizontal soil surface just downslope of the face. Sometimes a very thin calcite crust ("tufa") remains accreted to the face element of the landform. The berm and face expose light-beige-colored limestone, whereas the flat is covered by darker reddish-brown aeolian soil with short xerophytic shrubs. Hand lens observation of the soil of the flat reveals abundant fine volcanic shards reminding us of the volcanics of San Francisco Peaks. Aeolian sorting, not direct air fall, appears to be the dominant process impacting the upper surface of the flat. There is pronounced color and texture contrast between the rocky, often tufa-covered, face and adjacent soil-covered flat. Landform lineation is impressive on high-resolution satellite photos and low-altitude aerial photos because of the color and texture contrast. That texture and color contrast can be obscured if tufa-covered limestone clasts are strewn over the surface of the flat. Rarely, cross sectional views of the flat show coarse gravel overlying an erosional terrace underlying the flat. That gravel fill is likely a significant volume of the flat as can be seen from the borrow-pit excavation of the flat by Interstate Highway construction engineers (Figure 9).

Typical spacing between berms is 20 m (+/- 5) over the ground. Height of the landform between adjacent berms averages 0.4 (+/- 0.2) meter. Figure 19 is a typical view of landforms occurring in steplike terraces ascending the limestone slope. These three landform elements can be deflected by topographic irregularities as if a shoreline of a lake rose over the curved surface of limestone forming coves and points.

INTERPRETATION -- DIP SLOPE DEPOSITIONAL TERRACE MODEL

The word "shoreline" can be defined as a narrow erosional and depositional zone formed where the earth's exposed surface meets a body of water. The terrace, composed of a front slope (the "riser") and a flatter elongate step (the "tread"), is the familiar shoreline landform (Bates and Jackson, 1984). Shorelines can be described as belonging to one of two types dominated by either erosion or deposition. Most familiar are high relief erosional shorelines that make classic impact on human perception. There are also less impressive low relief depositional shorelines. Further characterization recognizes the time sequence of shoreline landforms produced whether regression or transgression. Thus, shorelines can be classified into four types (inspired by Helland-Hansen and Martinsen, 1996):

1. High-relief erosional shorelines.
    a. Regressive erosional terrace.
    b. Transgressive erosional terrace.
2. Low-relief depositional shorelines.
    a. Regressive depositional terrace.
    b. Transgressive depositional terrace.

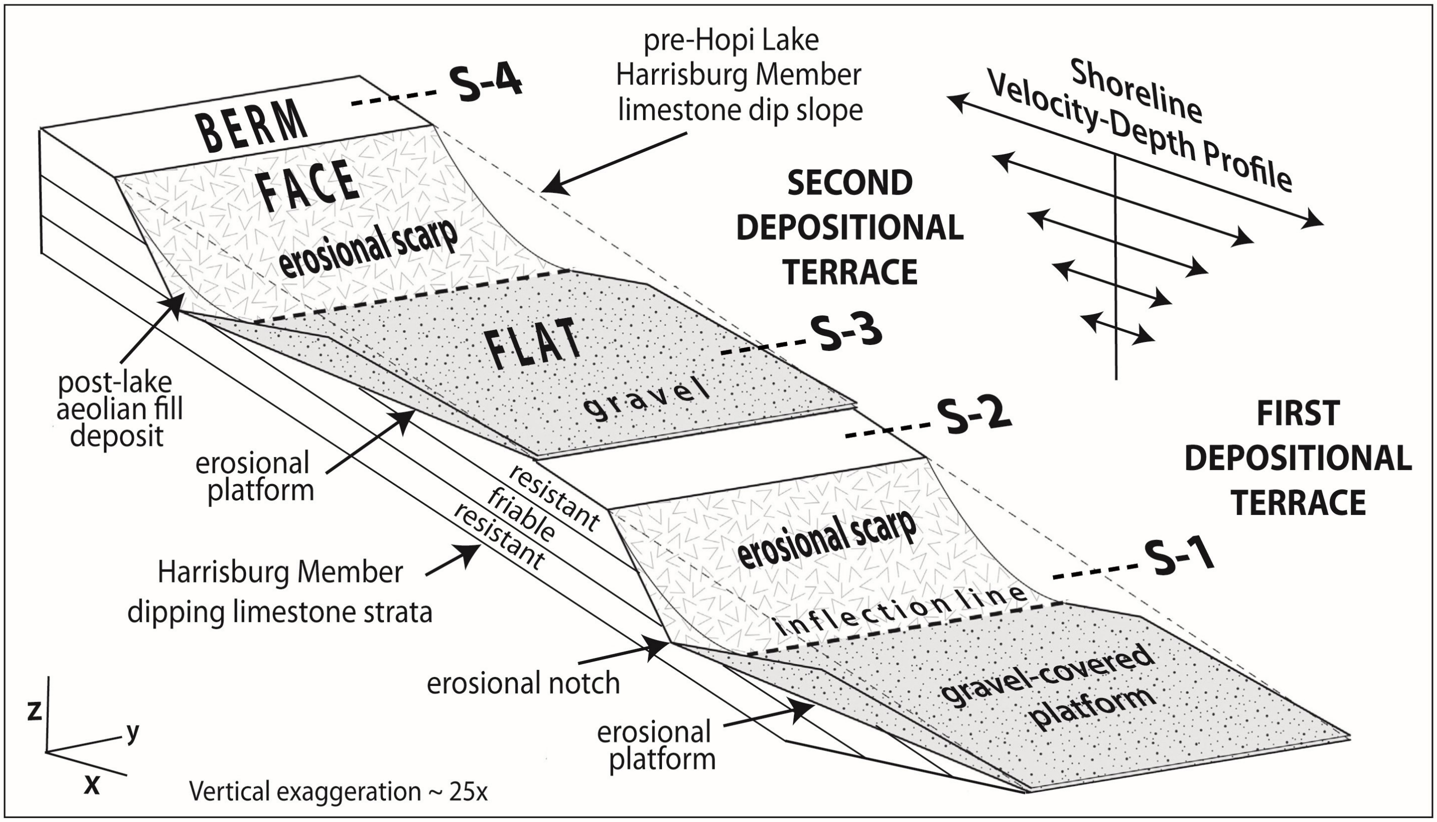

Figure 20. The "transgressive depositional terrace" model for Hopi Lake shoreline landforms. The high Lake Bonneville shoreline model of Chen and Maloof (2017) is applied to the Wagon Box Draw terraces of Hopi Lake. Here we depict two successive terraces have been inscribed by rising water on a limestone dip slope possessing resistant and friable beds. These two terraces are about 40 meters wide through the slope but only 0.5 meter high. Shorelines S-1, S-2, S-3, and S-4 mark succeeding water levels during the rapid lake transgression over the limestone slope. Transgression causes milling of the limestone surface and leaves behind subsequent erosional and depositional landforms. Note block diagram employs extreme vertical exaggeration (>25 times actual) to bring landscape elements into horizontal proximity.

Among the geomorphologists who have so marvelously documented the highest shorelines of Lake Bonneville during the last 130 years, the consensus is that these highest Bonneville shorelines are "transgressive depositional terraces" (Chen and Maloof, 2017; Oviatt and Jewell, 2016). These most intensively studied Bonneville terraces are typically imprinted on slopes of 0.1 (rise over run 1:10), but we are unaware of reported examples for slopes of 0.02 (rise over run 1:50). These high Bonneville shorelines are widely recognized to be *transgressive* because they culminate with the highest shoreline and the catastrophic flood and rapid regression of the lake by over 100 meters.

Figure 20 is our adaptation of the "transgressive depositional terrace" model of Chen and Maloof (2017) to the lower slopes of Hopi Lake within Bidahochi Basin. Observations of Bonneville high shorelines allowed Chen and Maloof (2017) to derive their model of a "transgressive depositional terrace" assuming a steep and steady slope over uniform bedrock. Our adaptation of their model assumes a low-sloping surface with a dip slope having alternating resistant and friable beds of thin-bedded Harrisburg Limestone. Chen and Maloof need little vertical exaggeration in their Bonneville terrace model. We used "extreme vertical exaggeration" of at least 25 times vertical in Figure 20 to display the Hopi shoreline terrace on a perspective block diagram.

Water waves are widely appreciated to have declining water velocity (and shear stress on bedrock surfaces) with increasing depth. Recreational snorkel divers and SCUBA divers are experienced with this fact. Declining velocity with depth is caused by the circular motion of molecules within the water surface wave that die out with depth. Figure 20 (upper right) displays our model of the velocity-depth profile as water waves impact the shore parallel to the limestone dip slope.

Figure 20 shows the initial lake shoreline level (S-1) where shallow water waves with higher velocity and shear stress have already begun to bevel a new surface called the "terrace erosional platform" into the "resistant" limestone dip slope. The down-slope side of "terrace erosional platform" begins to accumulate coarse gravel in the lower right as the platform continues to be eroded by waves. The erosion process occurs fastest at the "notch" on the growing platform as the "friable" limestone bed within the dip slope is intersected. Even though the water becomes deeper with time, the erosional terrace continues to extend shoreward forming the "notch" into the dip slope with erosion of the underlying "friable" limestone bed.

In Figure 20 at lake level S-2, the level of the lake has risen enough to reach a critical system threshold. At the increased water depth at the "notch," there is no longer enough shear stress to erode the "resistant" limestone underlying the "friable" layer. Therefore, the "erosional platform" stops being eroded, and the erosive power of waves is expended on the "erosional scarp" above the "notch." That "erosional scarp" is a concave-upward surface where water waves pluck the limestone substrate. The debris plucked is accumulated downslope of the "inflection line" where a convex-upward mound of coarse gravel builds up. The threshold at lake level S-2 causes the excavated "erosional platform" (sculpted at S-1) to be overlain by the "gravel-covered platform" (deposited at S-2).

In Figure 20 after lake level S-2, the lake continues to rise even more reaching another critical system threshold. At S-3 there is no longer enough shear stress within the deeper water to pluck limestone from the "erosional scarp." Instead, deeper water allows gravel to be deposited over the "notch" and "erosional scarp." The newer, elevated water level at S-3 is, again, on the upper surface of the "resistant" limestone dip slope. The erosive power of shallow waves is, again, able to start forming another "erosional platform." This process initiates the formation of the next "transgressive depositional terrace." While the second depositional terrace is forming, the first depositional terrace's erosional scarp receives silt and sand which fills most of the concavity. Then, on shallow, quiet, sunlit, cool, off-shore beveled limestone when the lake level has risen above S-4, lacustrine microbial carbonate encrustation form "tufa." The second depositional terrace block diagram (top of Figure 20) displays the structure after Hopi Lake has drained and after soil has occupied the new landform. The final condition of the terrace landform (top of Figure 20) shows the "berm," "face," and "flat" as we describe them in the field.

DISCUSSION

We interpret these Wagon Box Draw landforms to be old shoreline depositional terraces carved within the limestone dip slope as Hopi Lake rose to fill Bidahochi Basin. Could other explanations be offered instead of shoreline erosion and deposition on terraces? Here we note four processes that could be alternates to shoreline erosion and we respond briefly. The four alternate processes are: (1) pattern from multiple flat-lying strata eroding differentially within the slope, (2) pattern from erosion of strata that possess strong joint expression, (3) pattern from erosion of hummocky bedforms, dunes or boudinage within the Harrisburg Limestone, and (4) pattern of terrace-like steps caused by surficial gravity deformation through soil creep or solifluction. A compelling case can be made that Nate's Hill is a dip slope, not an outcrop erosion pattern of numerous, *level* and successive strata (see Figure 14). The dip slope is expressing just a few strata at its surface, not multiple successive strata. Landforms on the dip slope are not controlled by vertical limestone joints, because landform alignments deviate greatly from steady northwestward joint orientation on and around Nate's Hill. Could hummocky, dunelike or boudinage bedding structure within the limestone cause regularly spaced ridges (resembling terraces) to be expressed on the dip slope? We have not found hummocks in the uppermost Harrisburg Member with 20-meter spacing. Figure 13 shows remarkable planar beds, not hummocks, within the upper Harrisburg. Reflect upon the improbability that crests of *ancient* limestone hummocks, dunes or boudins would follow *present* topographic contour. Coarse gravel deposits on bedrock terraces would hardly be regarded as susceptible to soil creep and solifluction.

Remarkably, linear landforms strongly parallel the 2-meter topographic contour overlay except where the limestone is deformed by drag adjacent to faults. We observed a berm structure that could be traced one kilometer along the limestone dip slope of Nate's Hill, yet the berm's elevation appears to vary by less than a meter. The limestone dip slope at Nate's Hill is terminated on its northeastern edge by the graben structure hosting Buffalo Range Road, with the associated landforms northeast of the graben having 15-meter lower elevation compared to the southwestern side. Thus, these landforms correspond marvelously with the bedrock structural geology and dip slope stratigraphy. These observations support shoreline terraces.

Critics of Hopi Lake often ask why shorelines have *not* been found at Hopi Lake. Michael Oard (2010, 2016, 2021) described successions of erosional benches that he understands to be shoreline terraces associated with steep slopes adjacent to glacial Lake Bonneville. Oard shows transgressive shoreline terraces for Lake Bonneville's highstand in Utah. These glacial lake terraces are imprinted on slopes steeper than 0.1 (rise over run steeper than 1:10). The Bonneville example of Oard include transgressive shoreline terraces as defined by Chen and Maloof (2017) along the tectonically active Wasatch

Front where slopes are often steeper than 0.1 (rise over run). Oard frequently makes the comparison of Lake Bonneville with Hopi Lake, saying that Hopi Lake has "no evidence for the lakes," "no lake-bottom sediments," "no tufa" and "no shorelines" (Oard 2010, 2016, 2021). Similarly, Tim Clarey dismisses Hopi Lake which he regards as one of those "fictional lakes that some creation geologists propose emptied in a catastrophic manner to carve Grand Canyon but are based on little if any geological evidence" (Clarey 2018). The way that Hopi Lake critics argue seems to imply that they are extremely familiar with Bidahochi Basin landforms. That allows them to toss out freely universal negatives, statements we believe are unworthy of good science publications.

Michael Oard (2021) makes a lengthy argument claiming "no tufa" at Hopi Lake as described in Austin et al. (2020). Oard discusses tufa, travertine and speleothems, then concludes, "So, tufa, or the interpretation of tufa, is not necessarily a positive indicator of a shoreline.…" (Oard, 2021, p. 217). Algal-secreted, laminated, cool-water carbonate coatings ("tufa") are a very prominent feature along the high shorelines of Lake Bonneville (Felton et al., 2006; Vennin et al., 2018). Because Oard believes in shorelines of Pleistocene Lake Bonneville and modern Great Salt Lake, he should tell us why Bonneville and Salt Lake tufa "…is not necessarily a positive indicator of a shoreline" at these lakes. Notice, Oard can elaborately convolute the definition of "tufa," but we have in modern times witnessed deposition of an analogous cool-water, calcareous encrustation at the shore of the modern Great Salt Lake! Just because *terminology* can be controversial, that does not require *interpretations* to be (Cappezzuoli et al., 2013).

What was the final volume of the paleolake? If the basin structure that impounded the lake is older than the lake, then Bidahochi Basin's structure can be used to estimate the volume of the 300-kilometer-long paleolake. Because tufa deposits indicate that the final filling of Bidahochi Basin was to present elevation of 1860 meters (6100 feet), the present topographic depression could have filled with approximately 4700 cubic kilometers (1130 cubic miles) of water. We estimated paleolake volume from topographic cross-sections of the basin. However, our topographic-basin estimate of Hopi Lake is almost certainly an underestimate as illustrated by better-studied Pleistocene Lake Bonneville in the Great Basin of Utah, Nevada and Idaho. O'Connor (1993, 2016) estimated the volume of the Lake Bonneville Flood into the Snake River to be 4750 cubic kilometers from analysis of Great Basin topography. O'Connor (1993) assumed,

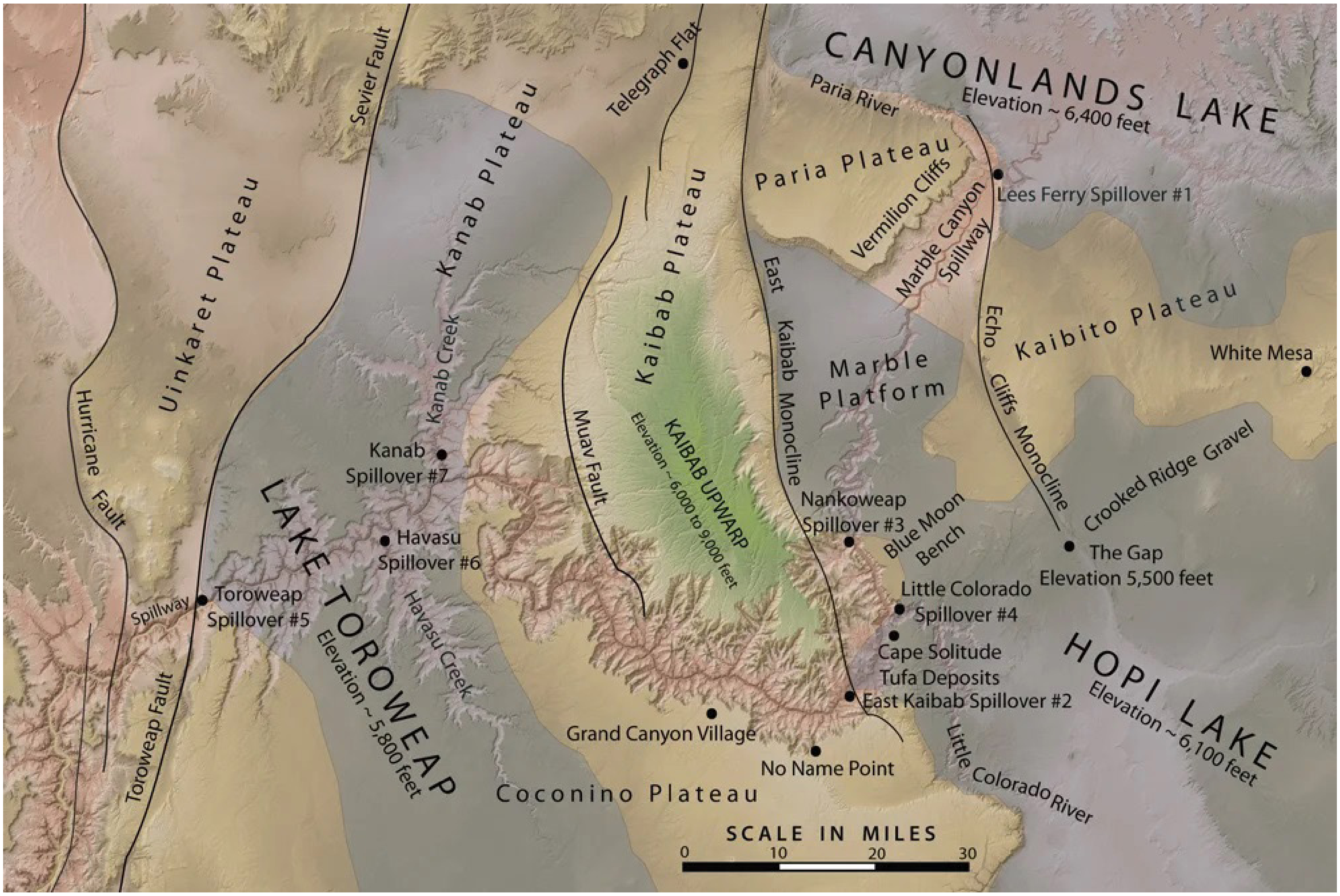

Figure 21. Map of putative lakes associated with erosion of eastern Grand Canyon (from Austin et al., 2020). Lakes on southern Colorado Plateau are understood to be successive and temporary, not simultaneous and enduring. Upstream basins initiated the fill-and-spill process. Canyonlands Lake formed first, then failed by spillover at Lees Ferry into Bidahochi Basin that was vacant of a big lake. Hopi Lake rose rapidly and overtopped East Kaibab Monocline. Then, rapid drainage of Hopi Lake caused Lake Toroweap to fill abruptly and breach Uinkaret Plateau at Toroweap. After drainage of lakes and erosion of canyons, plateaus and basin continued to be tilted, down on the north side, up on the south side.

as G. K. Gilbert (1890), that Lake Bonneville drained catastrophically and lost 105 meters depth of water through spillover erosion at Red Rock Pass, Idaho. However, as shown by Adams and Bills (2016), Lake Bonneville basin's interior topography has been significantly elevated by post-lake isostatic rebound. Adams and Bills (2016, p. 160) revise O'Connor's volume estimate of the Lake Bonneville Flood significantly upward to 5135 cubic kilometers. Because Hopi Lake was deeper than Lake Bonneville, the isostatic rebound effect would be enhanced in the case of Hopi Lake. Therefore, we estimate, conservatively, Hopi Lake's volume to be 5200 cubic kilometers (1250 cubic miles).

Our assumption of complete drainage of Hopi Lake makes the Hopi Lake Flood (5200 cubic kilometers) slightly larger than the Lake Bonneville Flood (5135 cubic kilometers). The largest Lake Missoula Flood, from the Ice Age constriction of Clark Fork River in Montana, has been estimated at 2500 cubic kilometers (600 cubic miles) by O'Connor et al. (2021). Thus, the Hopi Lake Flood was slightly larger than the Lake Bonneville Flood, and more than twice the size of the biggest Lake Missoula Flood. These lakes and their erosive floods can be compared to modern Lake Michigan (4900 cubic kilometers).

A very big question that needs to be discussed is the relationship of Bidahochi Basin and its Hopi Lake to upstream Utah and Colorado basins and their possible ancient lakes. Conventional, twentieth century geomorphic dogma since the time of William Morris Davis has asserted that streams erode upstream from lowland plains toward highland plateaus (Hilgendorf et al., 2020). That historically dominant viewpoint has been called "headward erosion" and has profoundly impacted geologist's thinking about Grand Canyon erosion. An alternate interpretation is that highland basins quickly fill with sediment and water as topographic barriers overflow or spillover. This new model has revitalized John Newberry's oldest 1858 thinking about Grand Canyon and promoted *top-down*, not bottom-up, drainage basin integration. Therefore, Bidahochi Basin and the putative Hopi Lake can be critical elements in Grand Canyon thinking.

Also, of critical importance in the top-down spillover discussion, is whether any lakes upstream of Hopi Lake broke their topographic barriers and filled Hopi Lake *before* it broke the Kaibab Plateau barrier to erode Grand Canyon. Figure 21 depicts the configuration of lakes, including a big lake in Utah. Edmond Holroyd, employed for many years as a Bureau of Reclamation scientist, was one of the earliest to rediscover the power of "top-down" thinking. In 1986 when living in Colorado next to Black Canyon of the Gunnison River, Holroyd discussed the Gunnison River drainage question with the resident USGS geologist Dr. Wally Hansen, one of the architects of the headward erosion hypothesis (Austin et al., 2020). During the discussion with Hansen about Black Canyon, Holroyd adopted top-down thinking that Black Canyon was excavated by spillover drainage of a high lake. Holroyd postulated other lakes downstream of Gunnison. Late in 1986 he used a government DEM to plot "big lakes" which could form on modern Colorado Plateau landscape if Grand Canyon was blocked at the 5,700-foot elevation (Austin et al., 2020). The computer chart made from the DEM allowed Holroyd to postulate a "big Utah lake" (Holroyd, 1987; Holroyd, 1988; Holroyd, 1990; Holroyd, 1994). Field work in July 1987 allowed Holroyd to recognize that the big Utah lake breached its bedrock dam at Lees Ferry and drained catastrophically to erode Marble Canyon. That big Utah lake was later called Canyonlands Lake (Austin, 1994). Then, a priority dispute occurred about who first proposed "the big Utah lake" and its breaching at Lees Ferry to form Marble Canyon. Walter Brown (2008) asserted, we believe incorrectly, that he had priority after field work in summer 1988 and public presentations later in 1988. Brown published a lake map in 1989 (Brown, 1989). However, Holroyd appears to have priority over Brown because Holroyd's lake map was circulated in 1987 and his written proposal (Holroyd, 1988) describing Lees Ferry breaching and Marble Canyon erosion was circulated in January 1988 (see Austin et al., 2020).

Was there a precursor to Hopi Lake within the Bidahochi Basin? Sedimentary evidence in the *lower* Bidahochi Formation indicates that the basin was vacant of a deep lake (Austin et al., 2020; Douglass et al., 2020). Good evidence of Hopi Lake being very deep (~1860 meters elevation) is first found in the *upper* Bidahochi Formation. That evidence is the green, gastropod-bearing, fresh water clays of the upper Bidahochi Formation.

Did Canyonlands Lake fail at Lees Ferry creating an abrupt addition of water to Bidahochi Basin quickly raising the level of Hopi Lake? That explanation would be in accord with the top-down perspective that has become consensus spillover thinking (Blackwelder, 1934; Meek, 2019; Helgendorf et al., 2020; Larson et al., 2022). Geological evidence of rapid filling of Hopi Lake is evident at the transgressive shoreline terraces at Wagon Box Draw Landform Tract. There the tufa is a very thin encrustation indicating that the lake did not endure at high level for a long time. Thus, we regard the *transgressive* shoreline depositional terraces at Wagon Box Draw to be evidence for rapid basin filling and abrupt disappearance of Hopi Lake. After Canyonlands Lake failed at Lees Ferry, the new basin configuration could allow the final filling of Hopi Lake to extend northward to Colorado. Therefore, an enormous temporary lake (much larger than 5200 cubic kilometers) could have resided directly east of Kaibab Plateau, and could have been ready to overtop Kaibab Plateau barrier, and erode Grand Canyon. We have not seen a *regressive* sequence of shoreline terraces for Hopi Lake that would be evidence for slow disappearance of Hopi Lake. Because we have not seen such a regressive shoreline sequence, we assume that highstanding Hopi Lake disappeared from its basin rapidly. That implies lake drainage by catastrophic spillover erosion. The same can be said for highstanding Lake Bonneville, that also lacks regressive shoreline terraces (Chen and Maloof, 2017; Oviatt, 2020). The catastrophic failure of Lake Bonneville's dam at Red Rocks Pass in Idaho produced the enormous flood on the Snake River Plain (O'Connor et al., 2021).

CONCLUSION

We interpret these tufa-encrusted landforms at Wagon Box Draw to be transgressive shoreline terraces carved within the Kaibab Limestone slope as Hopi Lake rose quickly to fill Bidahochi Basin. These shoreline landforms indicate a basin-filling, deep lake. We point to several similarities with the high shoreline terraces of Lake Bonneville. Using the consensus model for high shorelines of Lake Bonneville, our model specifies how the terrace is first eroded into thin-bedded limestone and then is later deposited with residual gravel. Our model specifies an erosional platform and landward erosional scarp are inscribed, and then, because of transgression, the platform and scarp are buried by residual coarse gravel. Finally, because of continued quick transgression, the shoreline depositional terrace is accreted with a thin crust of tufa. We believe that filling of Bidahochi Basin was accelerated by breaching of Canyonlands Lake upstream in Utah. Top-down overflow of higher basins promoted quick filling of Hopi Lake, initiated catastrophic spillover erosion of Grand Canyon, and caused rapid drainage of Hopi Lake.

ACKNOWLEDGMENTS

We appreciate the previous generation of researchers who, by conversation and example, directed us to remain focused and devoted to our quest to understand spillover erosion. Those researchers are Harold W. Clark, Byron C. Nelson, Clifford L. Burdick, Bernard E. Northrup, Walter Lang, Ed Nafziger, Henry M. Morris, Jr., and John D. Morris. The TNTmips software from MicroImages, Inc., of Lincoln, Nebraska, was used for our analysis of imagery and geographic data in this report. Use of the software was initiated in about 1990 by a research grant from the Creation Research Society in cooperation with MicroImages, and upgraded privately since then to the modern versions.

REFERENCES

Adams, K.D., and B.G. Bills. 2016. Isostatic rebound and palinspastic restoration of the Bonneville and Provo shorelines in the Bonneville Basin, UT, NV, and ID. In C.G. Oviatt and J.E. Shroder, Jr. (editors), *Lake Bonneville: A Scientific Update.* Developments in Earth Surface Processes. 20:145-164.

Austin, Steven A. 1994. How was Grand Canyon eroded? In S.A. Austin (editor), *Grand Canyon–Monument to Catastrophe*, pp. 83–110. Santee, California: Institute for Creation Research.

Austin, Steven A., Edmond W. Holroyd III, and David R. McQueen. 2020. Remembering spillover erosion of Grand Canyon. *Answers Research Journal* 13:153-188.

Bates, R.L., and J.A. Jackson (editors). 1984. *Dictionary of Geological Terms.* New York, Random House, third edition.

Billingsley, George H., Dedra Block, and Margaret H. Redsteer. 2013. Geological map of the eastern quarter of the Flagstaff 30' x 60' Quadrangle, Coconino County, Northern Arizona. *United States Geological Survey Scientific Investigations Map 3279*. 24 p.

Blackwelder, Eliot. 1934. Origin of the Colorado River. *Geological Society of America Bulletin* 45:551-566.

Brown, Walt. 1989. *In the Beginning: Compelling Evidence for Creation and the Flood.* 5th ed. Phoenix, Arizona: Center for Scientific Creation.

Brown, Walt. 2008. *In the Beginning: Compelling Evidence for Creation and the Flood.* 8th ed. Phoenix, Arizona: Center for Scientific Creation.

Cappezzuoli, Enrico, Ann Gandin, and Martyn Pedley. 2013. Decoding tufa and travertine (fresh water carbonates) in the sedimentary record: The state of the art. *Sedimentology* 61:1-21.

Chen, Christine Y., and Adam C. Maloof. 2017. Revisiting the deformed high shoreline of Lake Bonneville. *Quaternary Science Reviews* 159:169–189.

Clarey, Timothy. 2020. *Carved in Stone, Geological Evidence of the Worldwide Flood.* Dallas, Texas: Institute for Creation Research.

Dallegge, Todd A., Michael H. Ort, and William C. McIntosh. 2003. Mio-Pliocene chronostratigraphy, basin morphology and paleodrainage relations derived from the Bidahochi Formation, Hopi and Navajo Nations, Northeastern Arizona. *Mountain Geologist* 40(3):55–82.

Douglass, John C., Brian F. Gootee, Todd Dallegge, A. Jeong, Y.B. Seong, and Y.B. Yu. 2020. Evidence for the overflow origin of Grand Canyon. *Geomorphology* 369, docid: 107361, 19 p.

Felton, Alisa, Paul W. Jewell, Marjorie Chan, and Donald Currey. 2006. Controls of tufa development in Pleistocene Lake Bonneville, Utah. *Journal of Geology* 114(3):377–389.

Ford, T.D., and H.M. Pedley. 1996. A review of tufa and travertine deposits of the world. *Earth-Science Reviews* 41:117-175.

Gilbert, G.K. 1890. Lake Bonneville. *United States Geological Survey Monograph 1*, 438 p.

Harris, Raymond C., Robert S. Leighty, Robert B. Scarborough, and Jon E. Spencer. 1998. Uranium Levels and Radon Potential in Selected Areas North of Phoenix, in the St. Johns Area, and North of Tuba City, Arizona. *Arizona Geological Survey Open-File Report 98-10.* Tucson, Arizona: Arizona Geological Survey.

Hart, William S., Jay Quade, David S. Madsen, Darrell S. Kaufman, and Charles G. Oviatt. 2004. The 87Sr/86Sr ratios of lacustrine carbonates and lake-level history of the Bonneville paleolake system. *Geological Society of America Bulletin* 116:1107-1119.

He, John and Paul Kapp. 2021. The Bidahochi Basin hypothesis: Hopi Buttes volcanics and paleolake marks location of local, small-scale lithosphere foundering and asthenosphere upwelling beneath the Colorado Plateau. *American Geophysical Union Fall Meeting Abstracts*, published online at: https://ui.adsabs.harvard.edu/abs/2021AGUFM.T13A..02H

Helland-Hansen, W., and O.J. Martinsen. 1996. Shoreline trajectories and sequences: Description of variable depositional-dip scenarios. *Journal of Sedimentary Research* 66:670-688.

Hilgendorf, Zach, Greta Wells, Phillip H. Larson, Jason Millett, and Melissa Kohout. 2020. From basins to rivers: Understanding the revitalization and significance of topdown drainage integration mechanisms in drainage basin evolution. *Geomorphology* 352 (March): 1–17.

Holm, R.F. 2001. Pliocene-Pleistocene incision on the Mogollon slope, northern Arizona: Response to the developing Grand Canyon. In Richard A. Young and Earle E. Spamer (editors) *Colorado River Origin and Evolution.* Monograph 12, 59–63. Grand Canyon, Arizona: Grand Canyon Association.

Holroyd, Edmond W. 1987. Missing talus. *Creation Research Society Quarterly* 24(1):5–16.

Holroyd, Edmond W. 1988. Some research opportunities at Marble Canyon for creationists. Unpublished three-page research proposal submitted with cover letter dated January 24, 1988, to Steven Austin and Larry Vardiman.

Holroyd, Edmond W. 1990. Missing talus on the Colorado Plateau. In Robert E. Walsh and Christopher L. Brooks (editors). *Proceedings of the Second International Conference on Creationism*. pp. 115-128. Pittsburgh, Pennsylvania: Creation Science Fellowship.

Holroyd, Edmond W. 1994. A remote sensing search for extinct lake shore lines on the Colorado Plateau. In Robert E. Walsh (editor). *Proceedings of the Third International Conference on Creationism,* pp. 243-254. Pittsburgh, Pennsylvania: Creation Science Fellowship.

Larson, Phillip H., Ronald L. Dorn, Brian F. Gootee, and Yeong Bae Seong. 2022. Drainage integration in extensional tectonic settings. *Geomorphology* https://doi.org/10.1016/j.geomorph.2021.108082

Loper, Nate. 2022a. Bidahochi/Hopi Lake, Grand Canyon. Terrain model created by Nate Loper using Blender software, and posted on 3D hosting platform Sketchfab. https://sketchfab.com/3d-models/bidahochi-hopi-lake-grand-canyon-arizona-a9b9d2dcac3f4eeda7600a9bdfba3975

Loper, Nate. 2022b. Potential Hopi Lake Bidahochi Terrace Strandlines – Grand Canyon Breached Dam Spillover. Three-minute UAV video shot at Wagon Box Draw, Arizona, and posted on YouTube. https://www.youtube.com/watch?v=wbKdxMW9NgY

Meek, Norman. 2019. Episodic forward prolongation of trunk channels in the western United States. *Geomorphology* 340:172–183.

Meek, Norman, and John Douglass. 2001. Lake overflow: an alternate hypothesis for Grand Canyon incision and development of the Colorado River. In R.A. Young and E.E. Spamer (editors), *Colorado River: Origin and Evolution,* pp. 199-204. Grand Canyon, Arizona: Grand Canyon Association Monograph 12.

Nelson, S. T., M. J. Wood, A. L. Mayo, D. G. Tingey, and D. Eggett. 2005. Shoreline tufa and tufaglomerate from Pleistocene Lake Bonneville, Utah, USA: stable isotopic and mineralogical records of lake conditions, processes, and climate. *Journal of Quaternary Science* 20:3–19.

Newberry, J.S. 1861. *Report upon the Colorado River of the West.* Part III. Washington, DC: U.S. Government Printing Office.

Oard, Michael J. 2010. The origin of Grand Canyon, Part II: Fatal problems with the dam-breach hypothesis. *Creation Research Society Quarterly* 46: 290–307.

Oard, Michael J. 2016. *A Grand Origin for Grand Canyon.* Chino Valley, Arizona: Creation Research Society Books.

Oard, Michael J. 2021. A dam breach unlikely for the origin of Grand Canyon. *Creation Research Society Quarterly* 57:206-222.

O'Connor, J.E. 1993. Hydrology, hydraulics, and geomorphology of the Bonneville Flood. *Geological Society of America Special Paper 274*, 83 pp. DOI: https://doi.org/10.1130/SPE274

O'Connor, J.E., V.R. Baker, R.B. Waitt, L.N. Smith, C.M. Cannon, D.L. George, and R.P. Denlinger. 2021. The Missoula and Bonneville floods—A review of ice-age megafloods in the Columbia River basin. *Earth-Science Reviews* 208:103-181.

Oviatt, C.G. 2020. G.K. Gilbert and the Bonneville shoreline. *Geology of the Intermountain West* 7: 301-320.

Oviatt C.G., and P.W. Jewell. 2016. The Bonneville shoreline: Reconsidering Gilbert's interpretation. In C.G. Oviatt and J.E. Shroder, Jr. (editors), *Lake Bonneville: A Scientific Update.* Developments in Earth Surface Processes. 20:88-104.

Pedley, M., M. Rogerson, and R. Middleton. 2008. Freshwater calcite precipitates from in vitro mesocosm flume experiments: A case for biomediation of tufas. *Sedimentology* 56:511-527.

Reagan, A.B. 1924. Stratigraphy of the Hopi Buttes volcanic field, Arizona. *Pan-American Geologist* 41(5):355–366.

Scarborough, R.B. 1989. Cenozoic Erosion and Sedimentation in Arizona. In *Geologic Evolution of Arizona.* Edited by J.P. Jenney, and S.J. Reynolds, 515–537. Arizona Geological Society Digest, Vol.17.

Scarborough, R.B. 2001. Neogene development of Little Colorado River Valley and eastern Grand Canyon: Field evidence for an overtopping hypothesis. In R.A. Young and E.E. Spamer (editors). *Colorado River: Origin and Evolution.* Grand Canyon, Arizona: Grand Canyon Association Monograph 12.

Scarborough, R.B., and Jon E. Spencer. 1998. Uranium levels and radon potential in selected areas north of Phoenix, in the St. Johns area, and north of Tuba City, Arizona. *Arizona Geological Survey Open-File Report 98-10.* Tucson, Arizona: Arizona Geological Survey.

Vennin, E., and ten coauthors. 2018. The lacustrine microbial carbonate factory of the successive Lake Bonneville and Great Salt Lake, Utah, USA. *Sedimentology*. Doi: 10.111/sed.12499.

Williams, Howel. 1936. Pliocene volcanoes of the Navajo-Hopi country. *Bulletin of the Geological Society of America* 47:111-172.

THE AUTHORS

Steven A. Austin has Ph.D. degree in sedimentary geology from Pennsylvania State University. He serves as adjunct faculty at Cedarville University and researches special projects with Logos Research Associates. He has specialized in modeling catastrophic sedimentary process with specific application to strata of Grand Canyon. His 36-year investigation of a single fossil-bearing stratum within the Redwall Limestone has allowed him to camp two years below the rim of Grand Canyon. He is author of three books and more than a hundred technical geology papers. His wife is Dr. Kelly A. Austin, professor of pediatric surgery at Children's Hospital, University of Pittsburgh.

Edmond W. Holroyd, III earned his Ph.D. degree in atmospheric science from State University of New York. He specialized in cloud physics and weather modification working 31 years for the U.S. Bureau of Reclamation. Specialization in remote sensing allowed him to publish many technical science papers. He teaches adjunct at high schools and universities, and does volunteer work.

Thomas F. Folks is a retired U.S. Department of Interior, Bureau of Land Management Wilderness/Outdoor Recreation Planner who has lived, worked, and explored the lands north of Grand Canyon for over 50 years. He continues to make use of his regional knowledge and extensive experience in aerial photography interpretation, mapping, land use planning, government permitting and resource management to assist a number of scientists in planning and executing research field operations in the region.

Nate Loper is the Executive Director of Canyon Ministries and has spent nearly 1,000 days teaching at the Grand Canyon and throughout the Southwest, including leading dozens of river trips on the Colorado River. His background includes leading tours through national parks and museums and speaking at conferences and events throughout the US and UK on geology and biblical archaeology. A former pastor for many years, he is currently working on a master's degree in Ancient Civilizations and Egyptology.