FACTORS CONTRIBUTING TO THE 2005 TAUM SAUK UPPER RESERVOIR FAILURE

December 14, 2005
Reynolds County, Missouri

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RECONSTRUCTED FAILURE SEQUENCE

using the outflow hydrograph constructed by the Federal Energy Regulatory Commission (FERC) after the December 2005 failure

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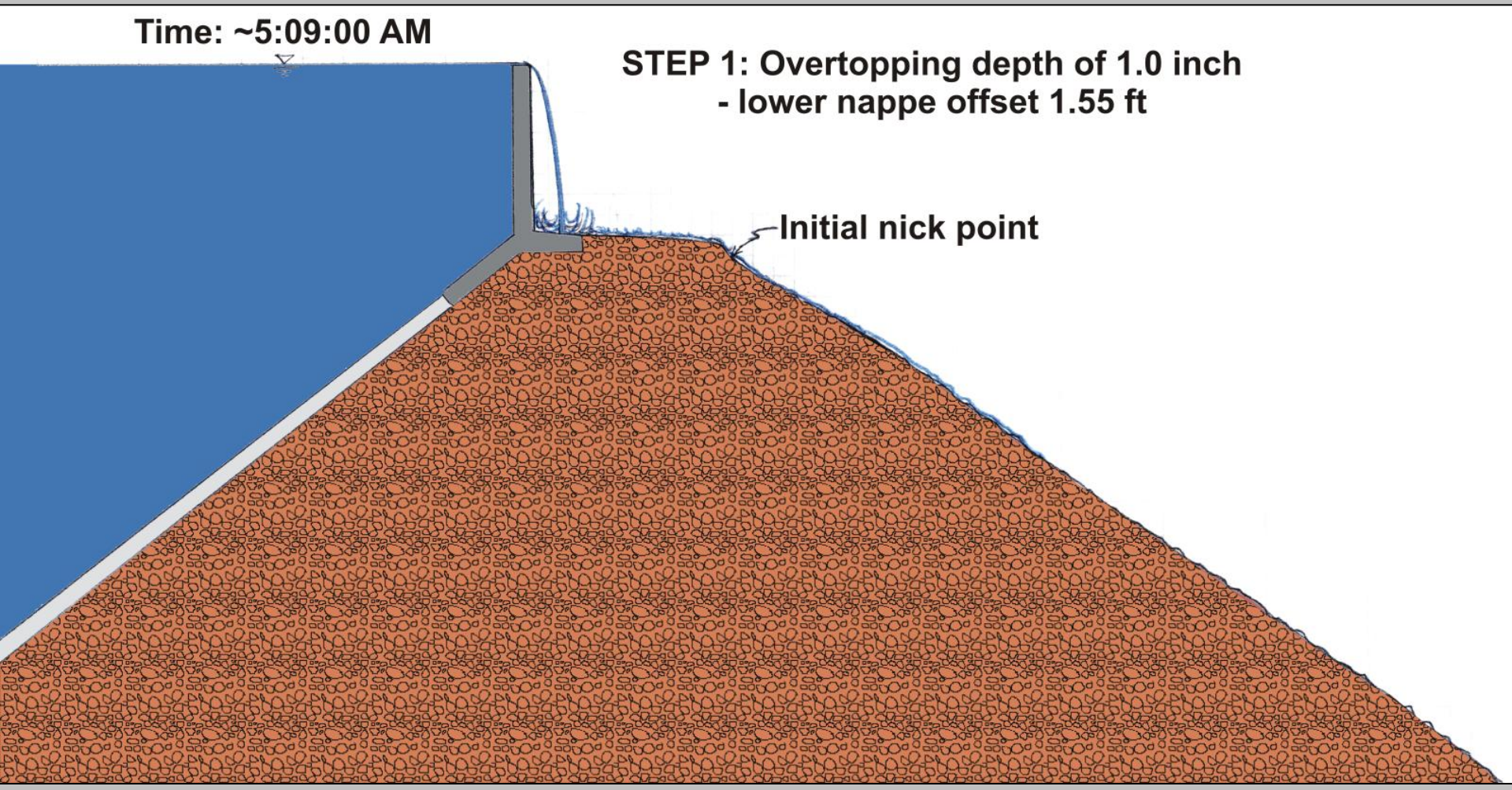
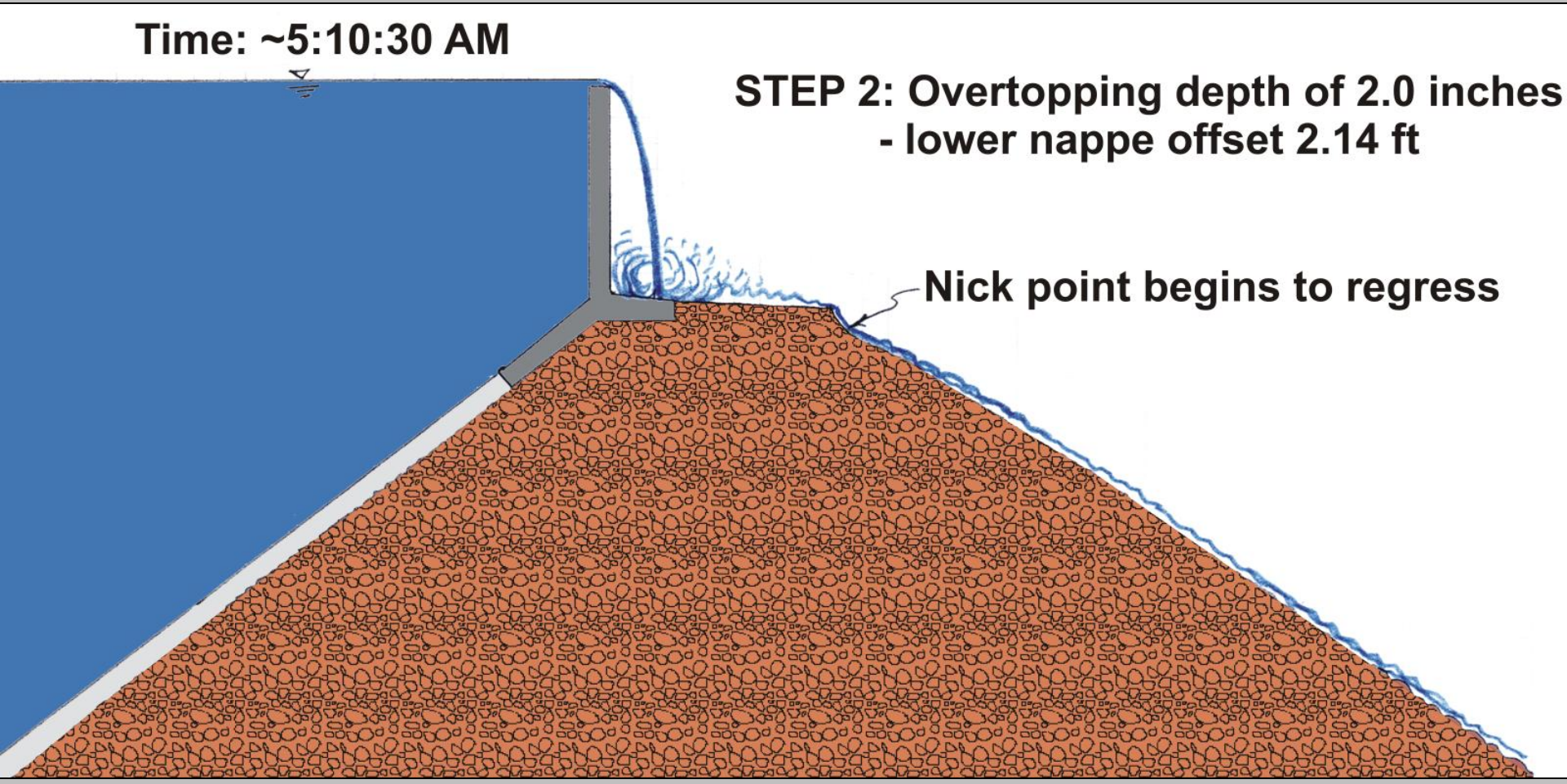
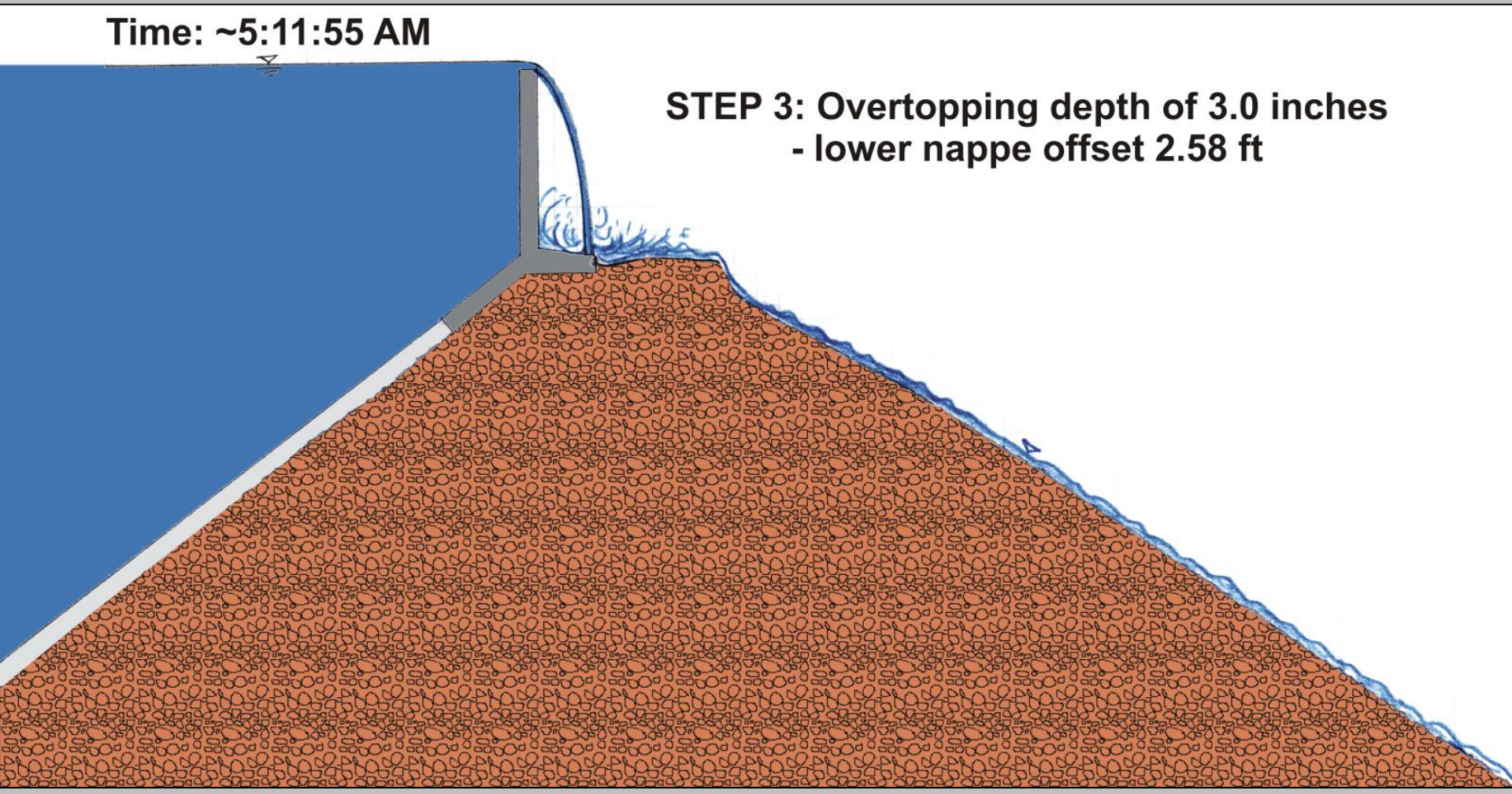
The Upper Reservoir Failure Sequence ~5:09 to 5:32 AM

- During the morning of Dec 14th, the upper reservoir was completing its nightly filling. Faulty sensors and "fail safe" backups failed to turn the pumps off, allowing water to be pumped over the reservoir's parapet wall in at least four locations, where it scoured away the rockfill embankment. Records indicate that the last pump shut-off automatically, but the reservoir was already overflowing and near failure at this time.
- The failure occurred at the NW portion of the dike where the Sept. 25th "Niagara Falls" incident occurred.
- Instruments at the reservoir suggest it emptied in approximately 12 minutes, with a peak outflow of 289,000 cubic feet per second. This is a larger than the average flow of the Mississippi River just above its confluence with the Ohio River at Cairo, IL (~200,000 cfs).
- Ironically, an emergency drill was scheduled to be conducted at the facility on Dec 14 and responders assumed that initial reports were part of this planned drill and not an actual incident.


Time: ~5:09:00 AM
STEP 1: Overtopping depth of 1.0 inch
- lower nappe offset 1.55 ft
Initial nick point


Time: ~5:10:30 AM
STEP 2: Overtopping depth of 2.0 inches
- lower nappe offset 2.14 ft
Nick point begins to regress


Time: ~5:11:55 AM
STEP 3: Overtopping depth of 3.0 inches
- lower nappe offset 2.58 ft

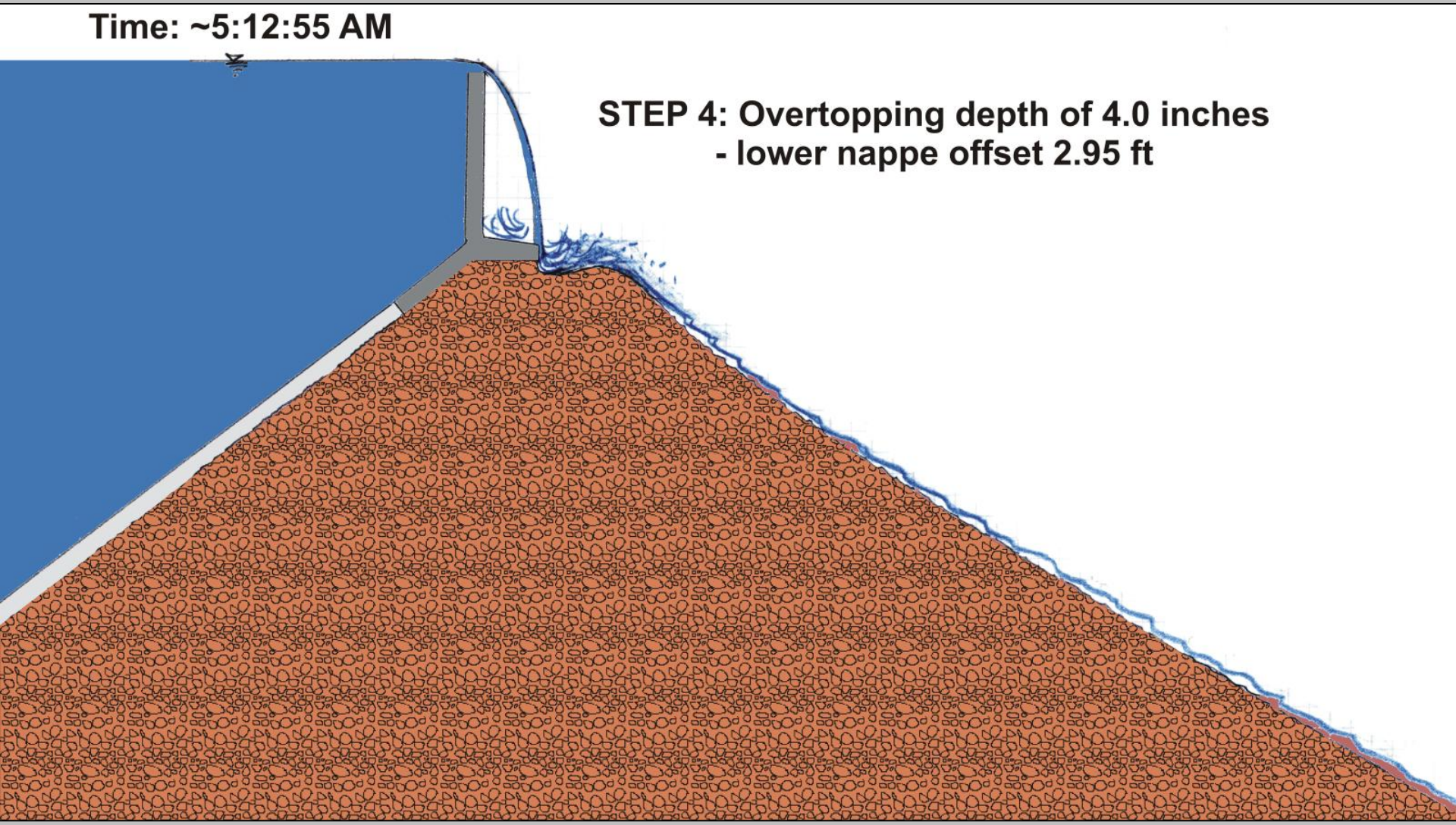

Time: ~5:12:55 AM
STEP 4: Overtopping depth of 4.0 inches
- lower nappe offset 2.95 ft

Photo by David Hoffman

Time: ~5:13:35 AM

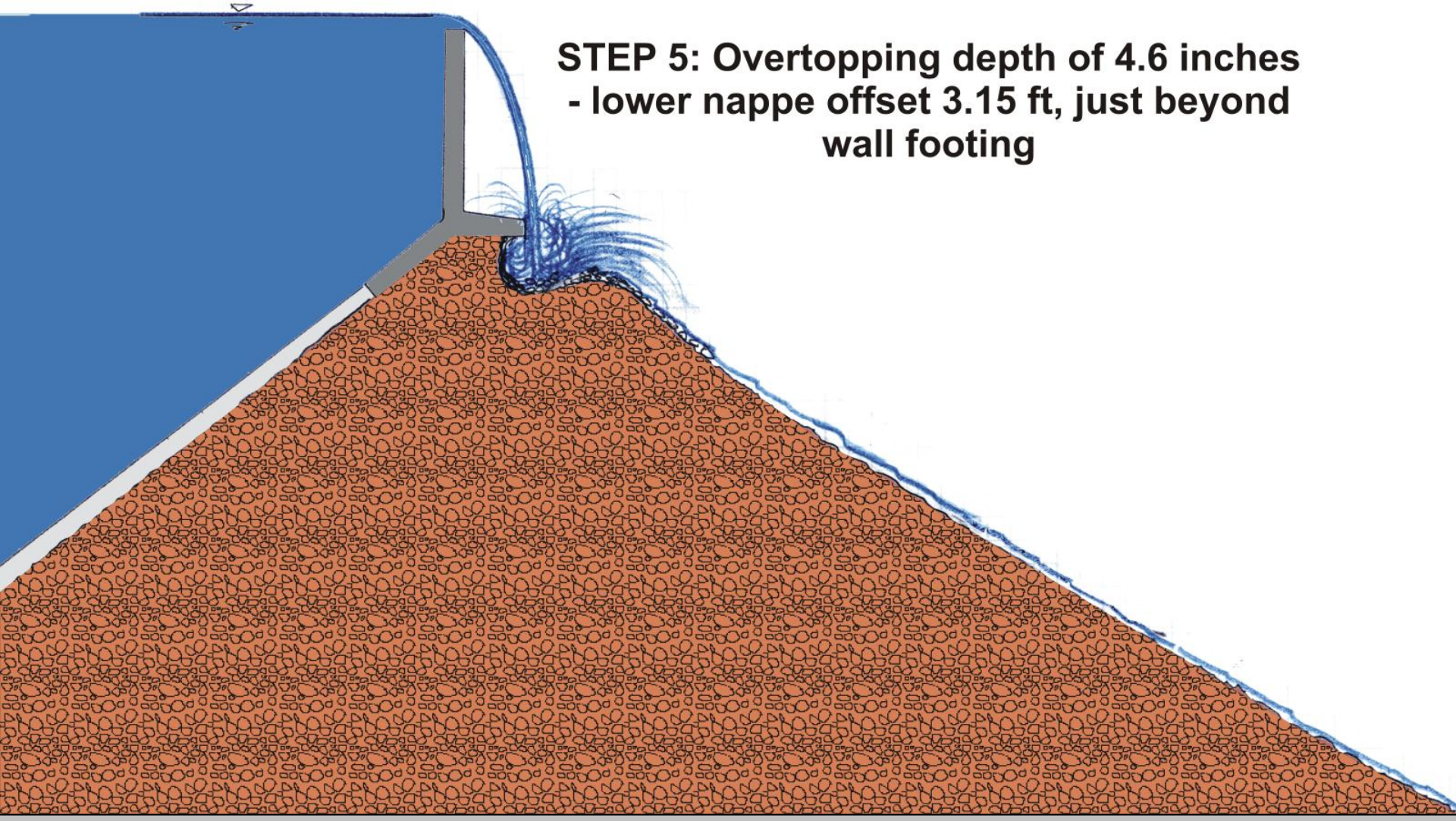
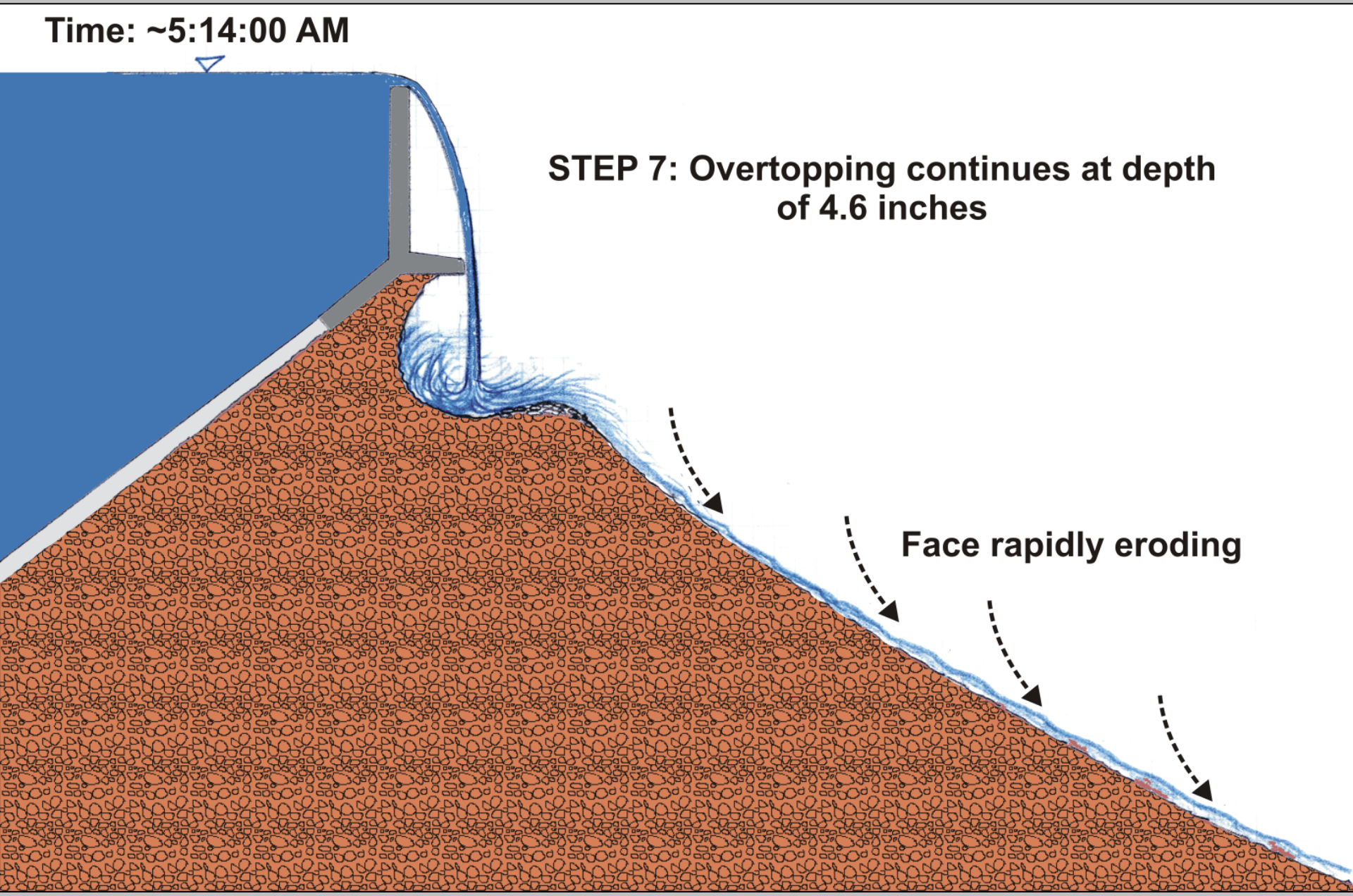
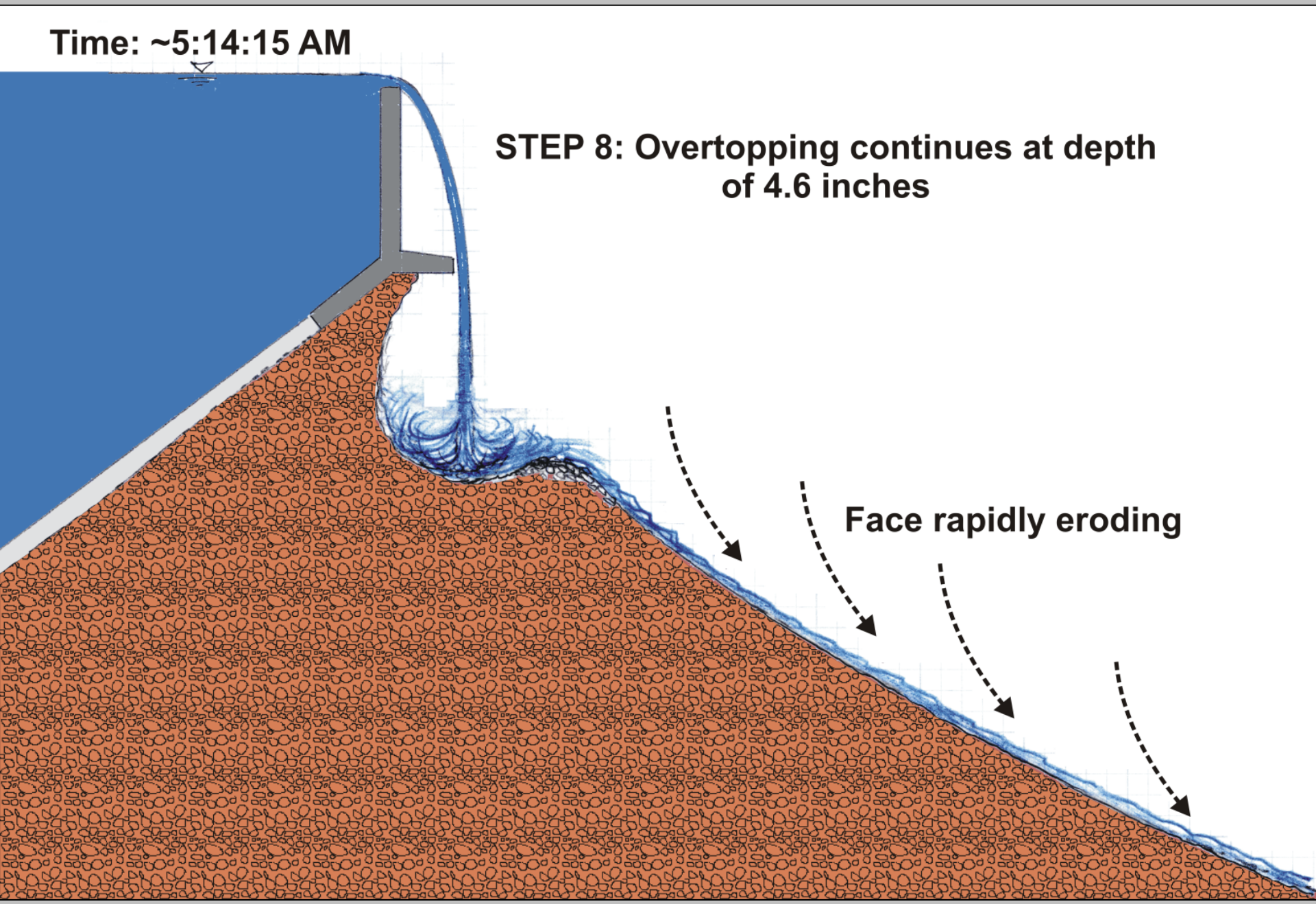
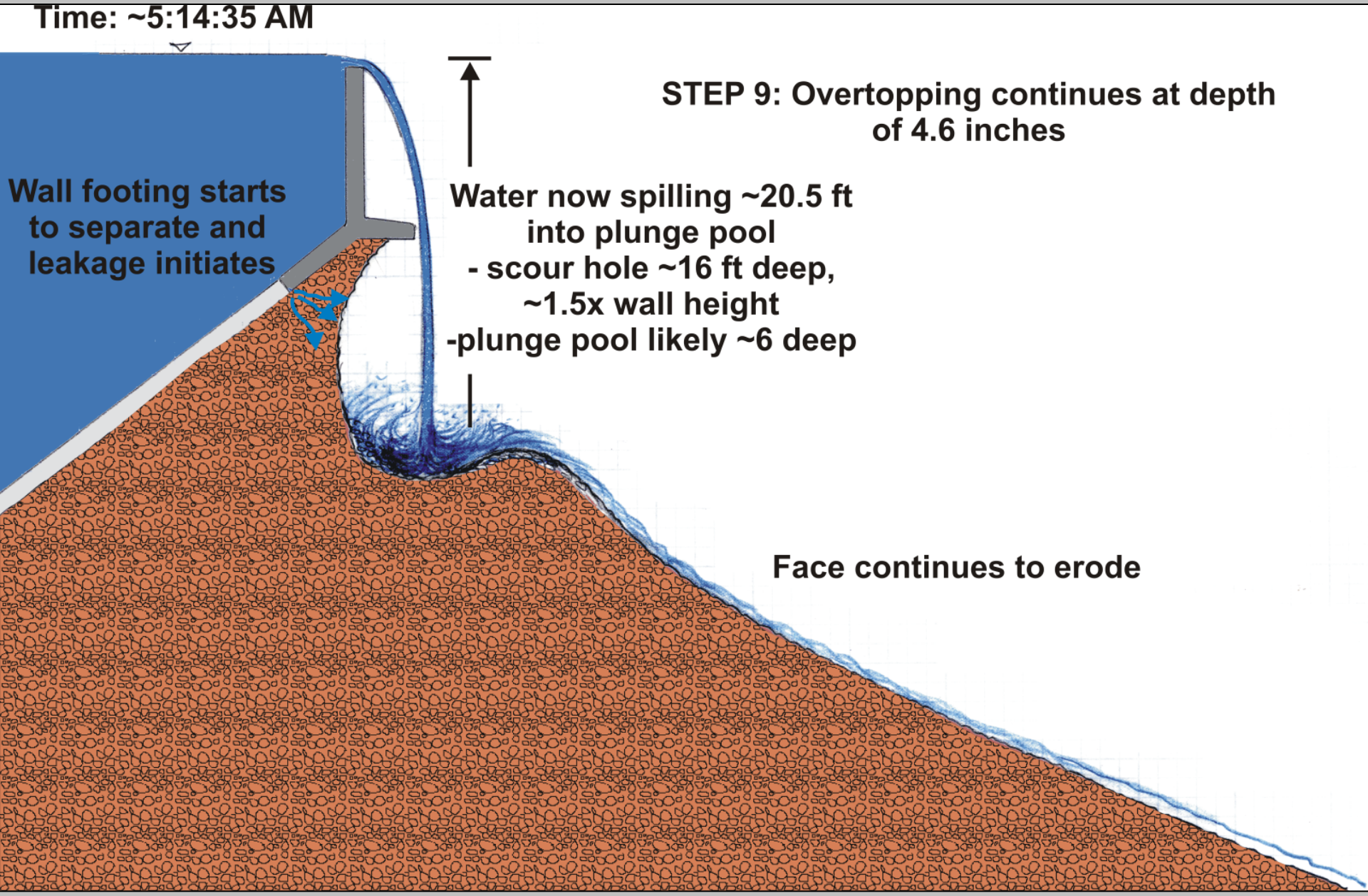



Photo by David Hoffman


Time: ~5:14:00 AM
STEP 7: Overtopping continues at depth of 4.6 inches
Face rapidly eroding

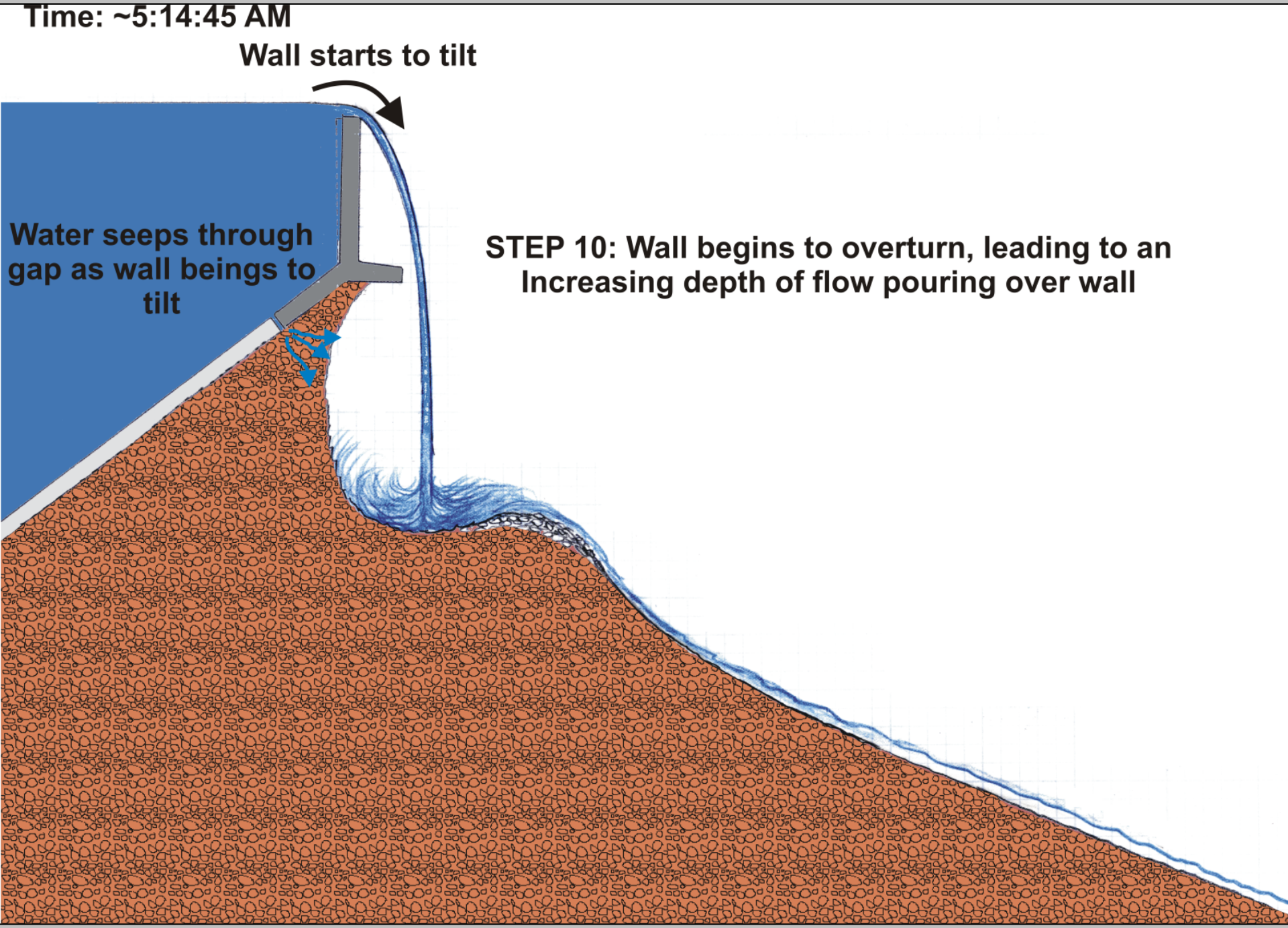


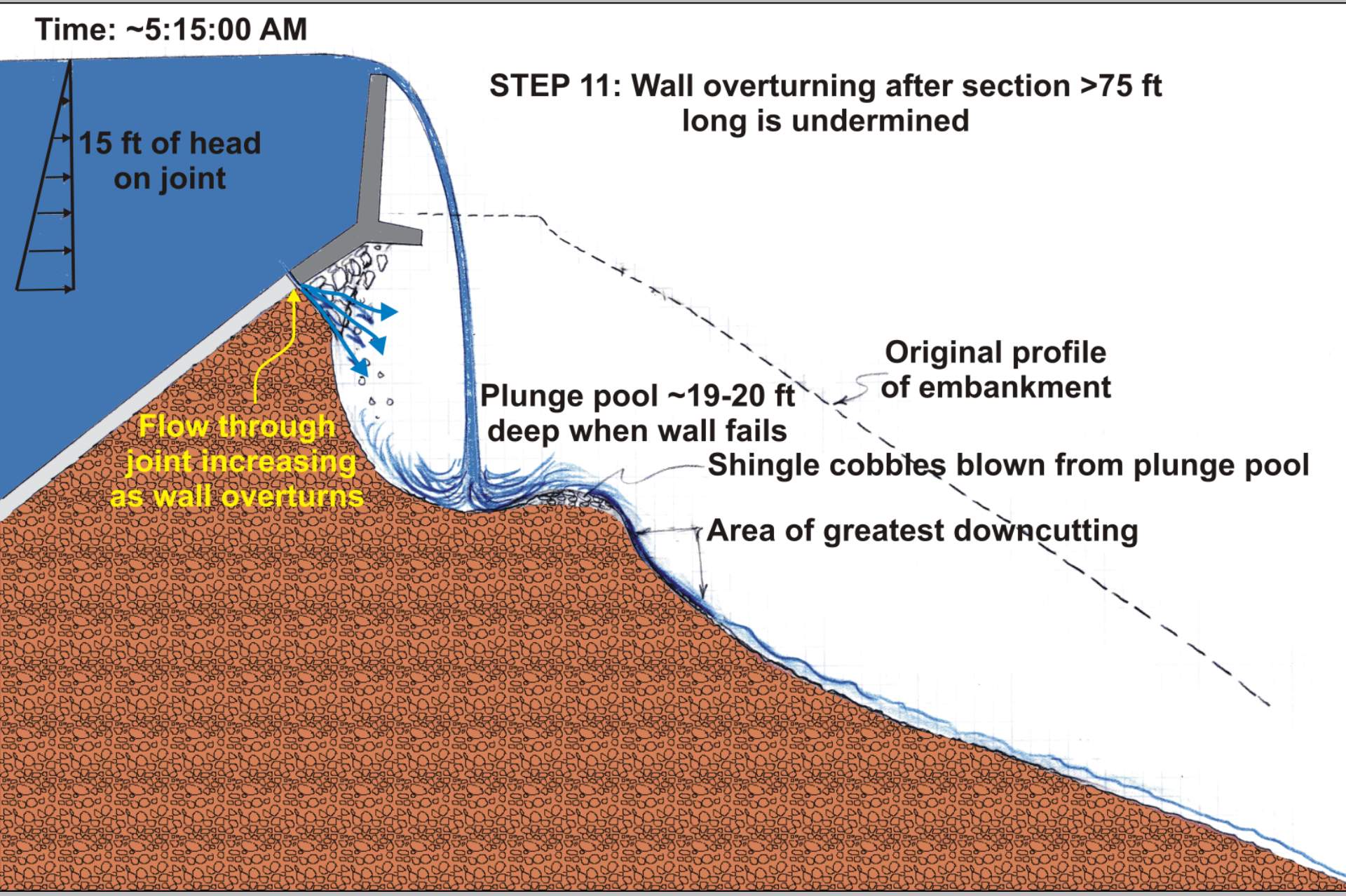
3 Dimensional effects allowed wall to stand with extensive undermining


Time: ~5:14:35 AM
STEP 9: Overtopping continues at depth of 4.6 inches
Wall footing starts to separate and leakage initiates
Water now spilling ~20.5 ft into plunge pool
- scour hole ~16 ft deep, ~1.5x wall height
-plunge pool likely ~6 deep
Face continues to erode

Water pouring over the parapet wall scoured away the fill supporting the wall's foundation. A portion of the wall appears to have toppled, unleashing a flow of water that catastrophically eroded a 680 foot wide section of the embankment, emptying the reservoir in ~12 minutes. This view shows the joint between wall Panels 72/73.

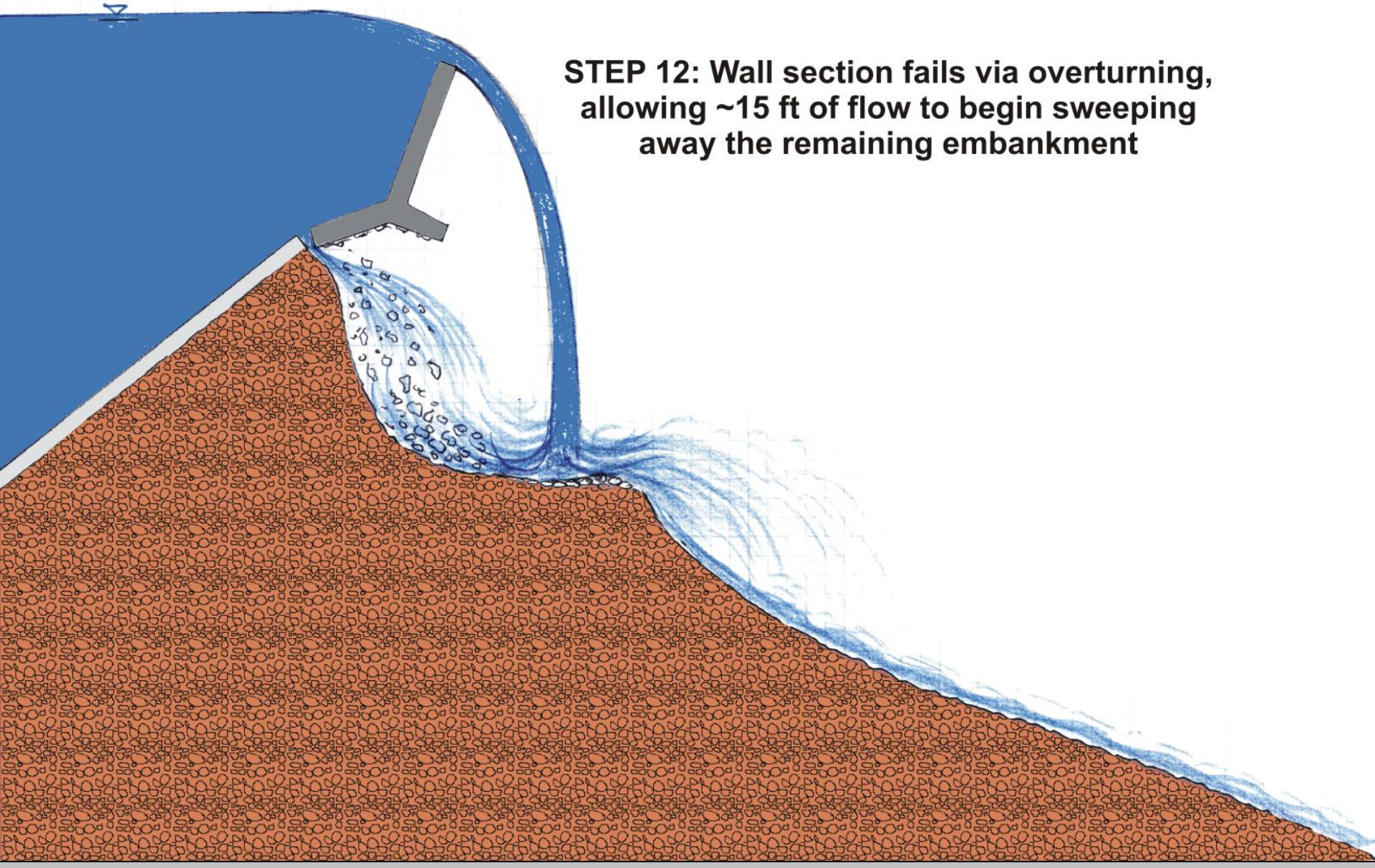

The parapet wall was completely undermined near the joint between wall panels 72/73. Note the clean character of the rockfill at this location.
Photo by David Hoffman


Time: ~5:14:45 AM
Wall starts to tilt
Water seeps through gap as wall beings to tilt
STEP 10: Wall begins to overturn, leading to an Increasing depth of flow pouring over wall


Time: ~5:15:00 AM
STEP 11: Wall overturning after section >75 ft long is undermined
15 ft of head on joint
Flow through joint increasing as wall overturns
Plunge pool ~19-20 ft deep when wall fails
Original profile of embankment
Shingle cobbles blown from plunge pool
Area of greatest downcutting

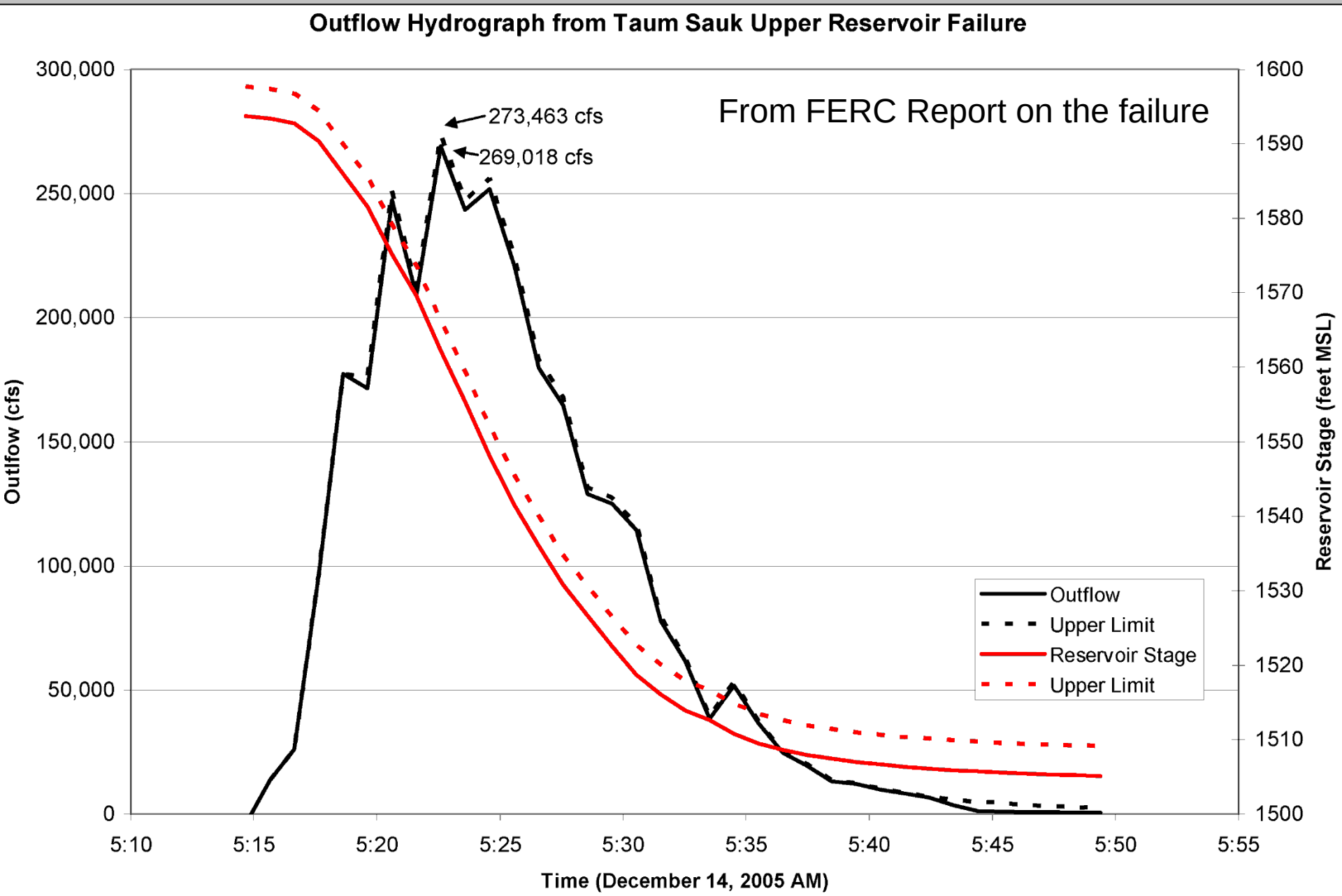

Exposed foundation
of parapet wall
72
Photo by David Hoffman

Time: ~5:15:00 AM

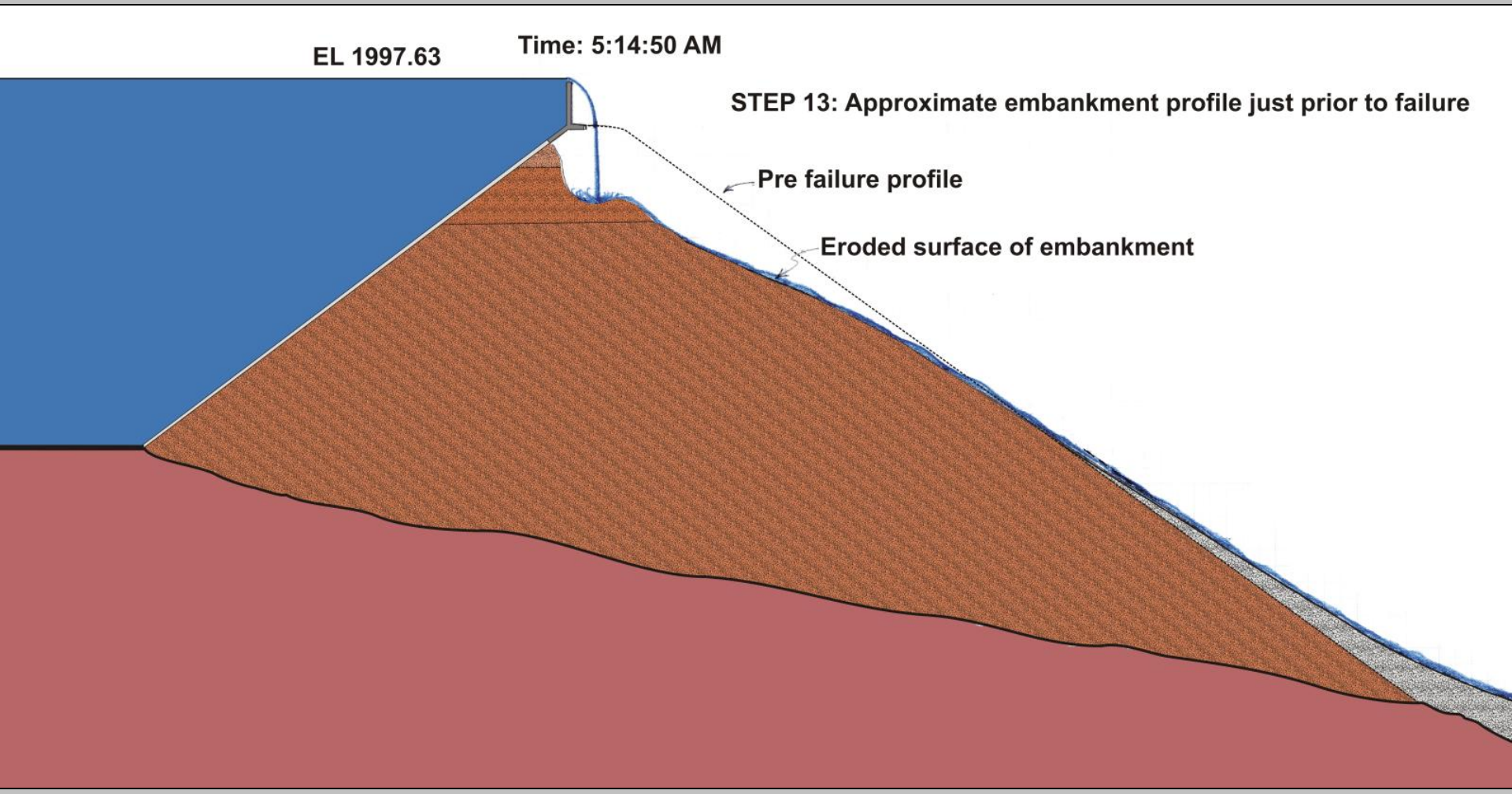


STEP 12: Wall section fails via overturning, allowing ~15 ft of flow to begin sweeping away the remaining embankment

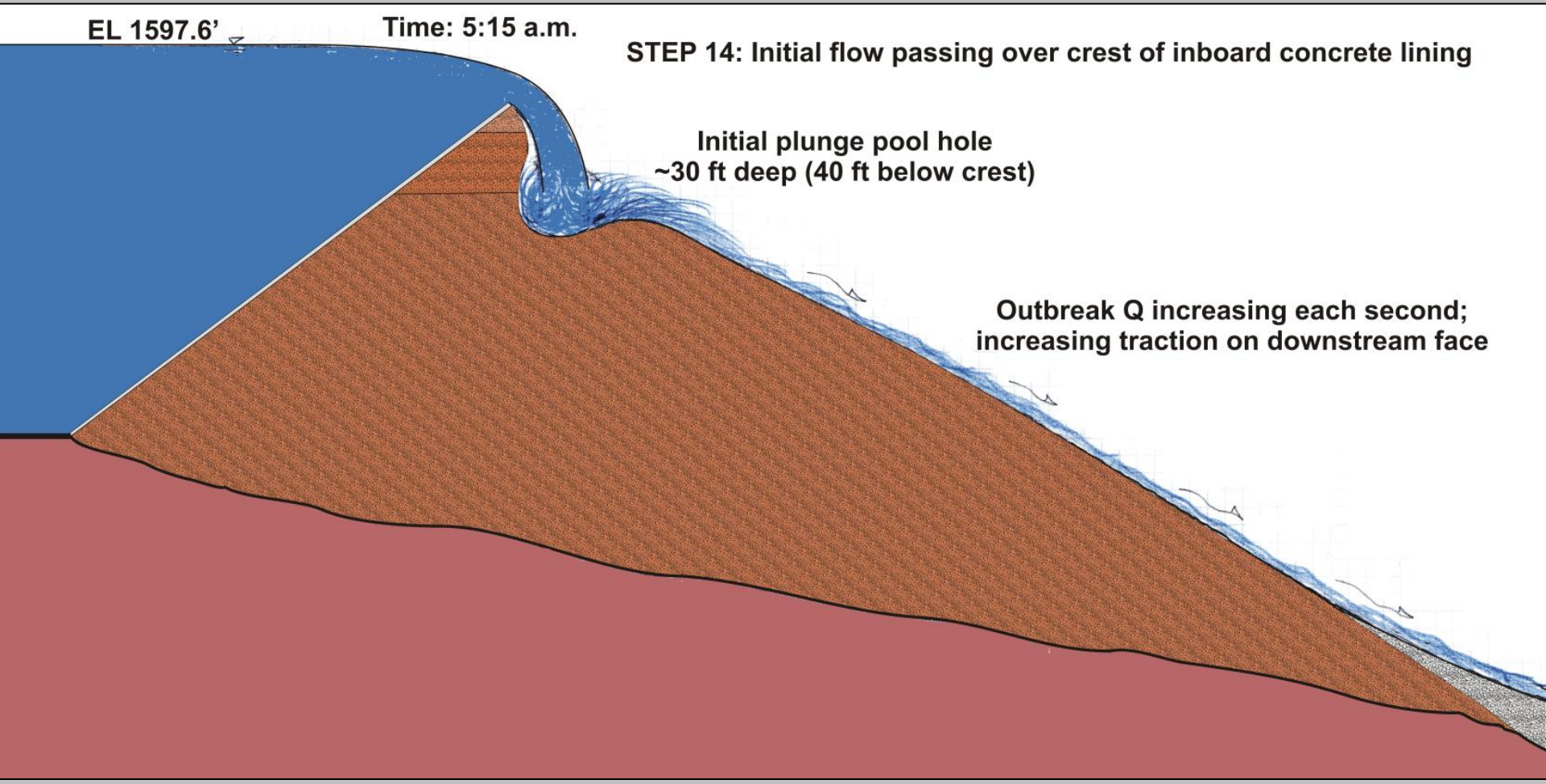
Wall panels toppled over after extensive undercutting, initiating the catastrophic failure sequence.

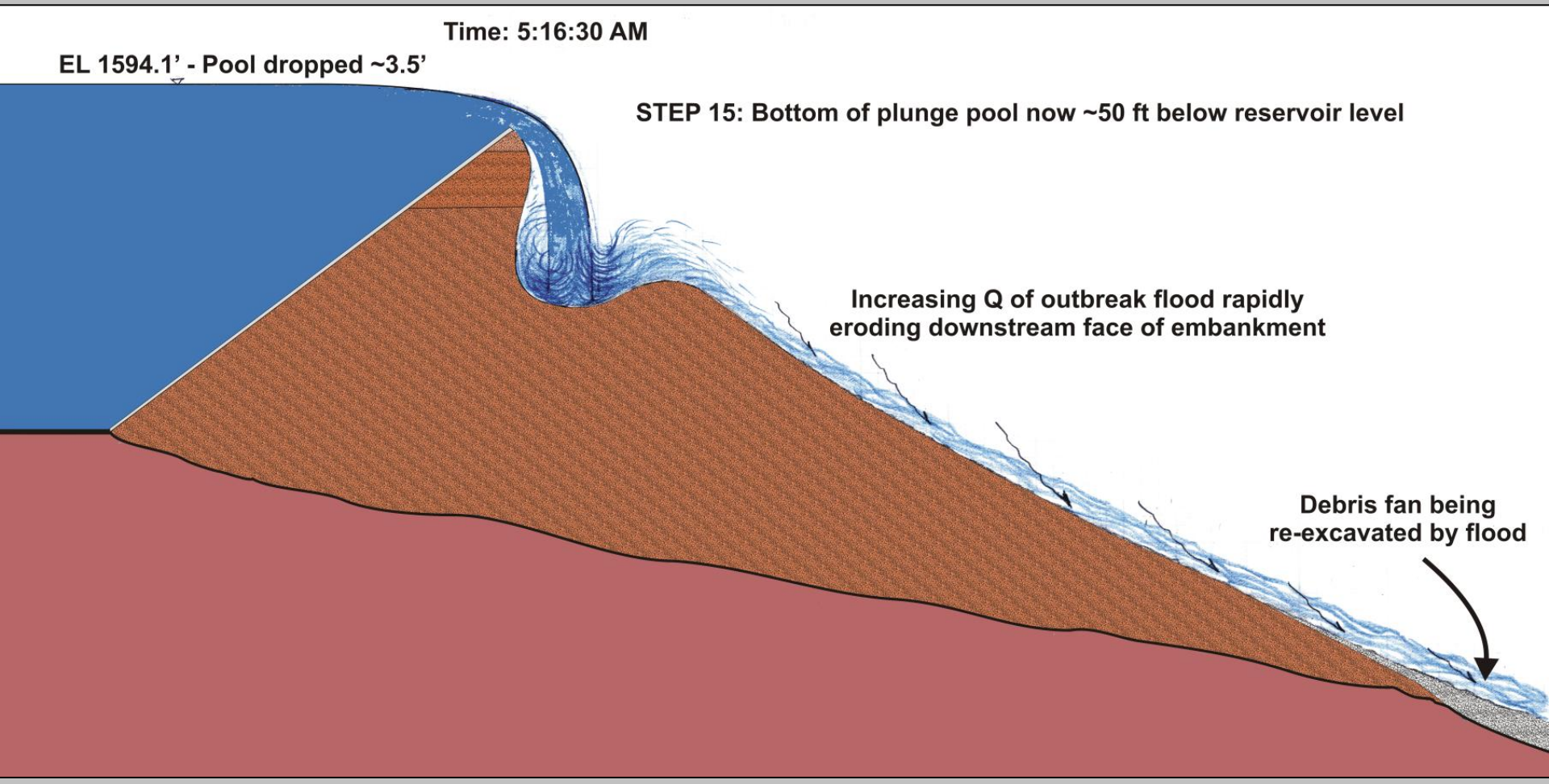


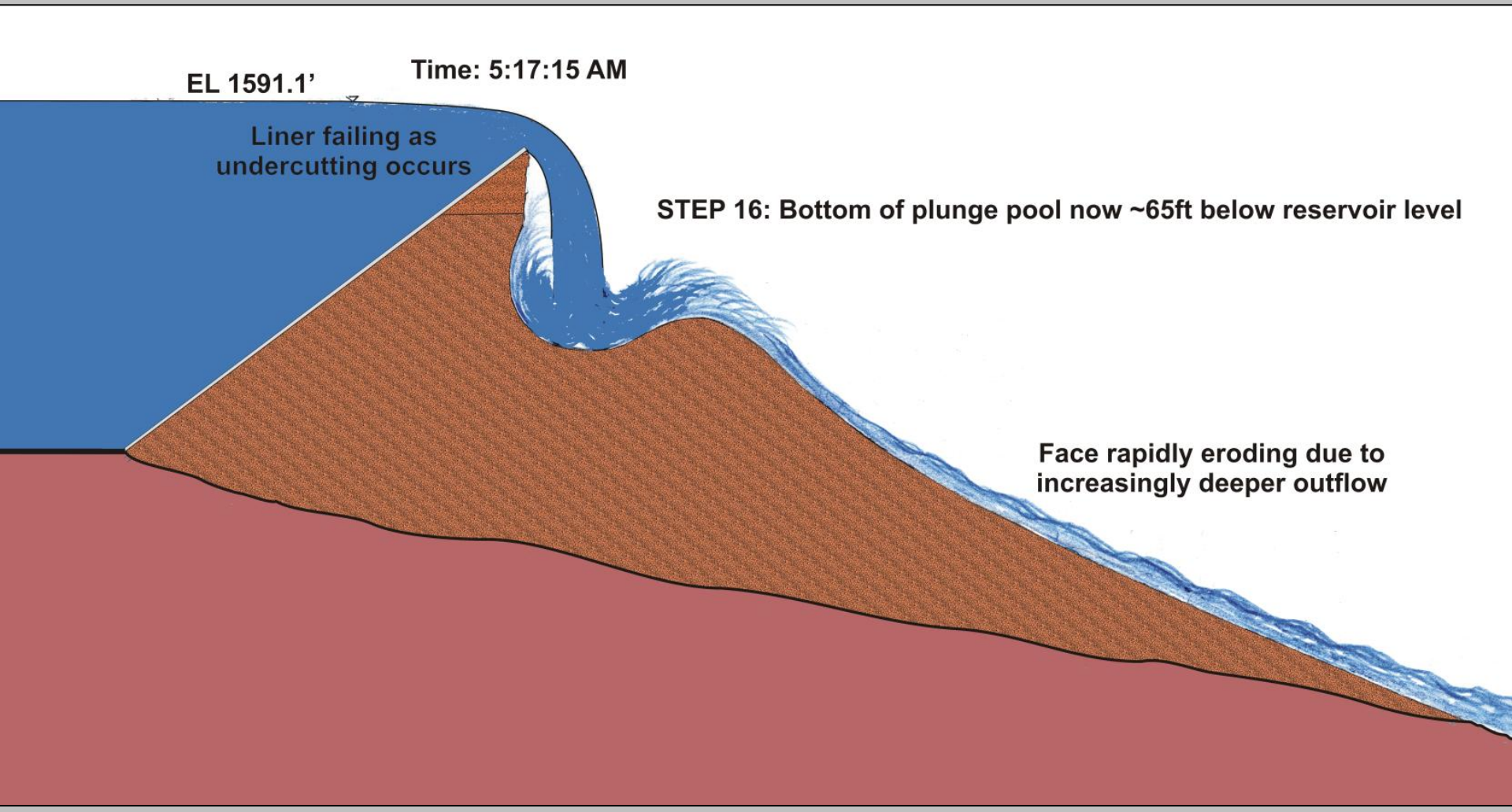
Calculated Outflow Hydrograph for Taum Sauk Breach

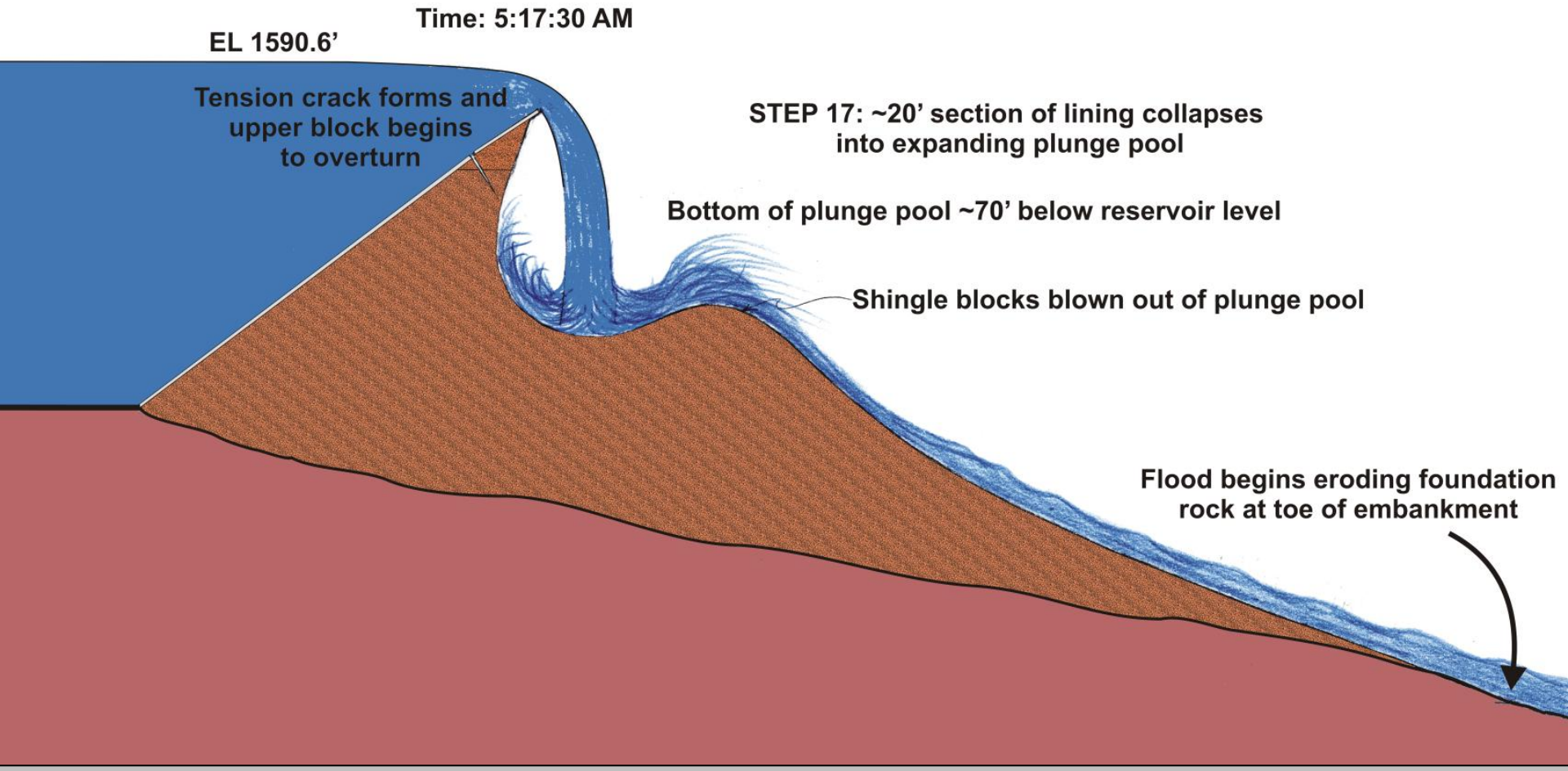

EL 1997.63
Time: 5:14:50 AM
STEP 13: Approximate embankment profile just prior to failure
Pre failure profile
Eroded surface of embankment

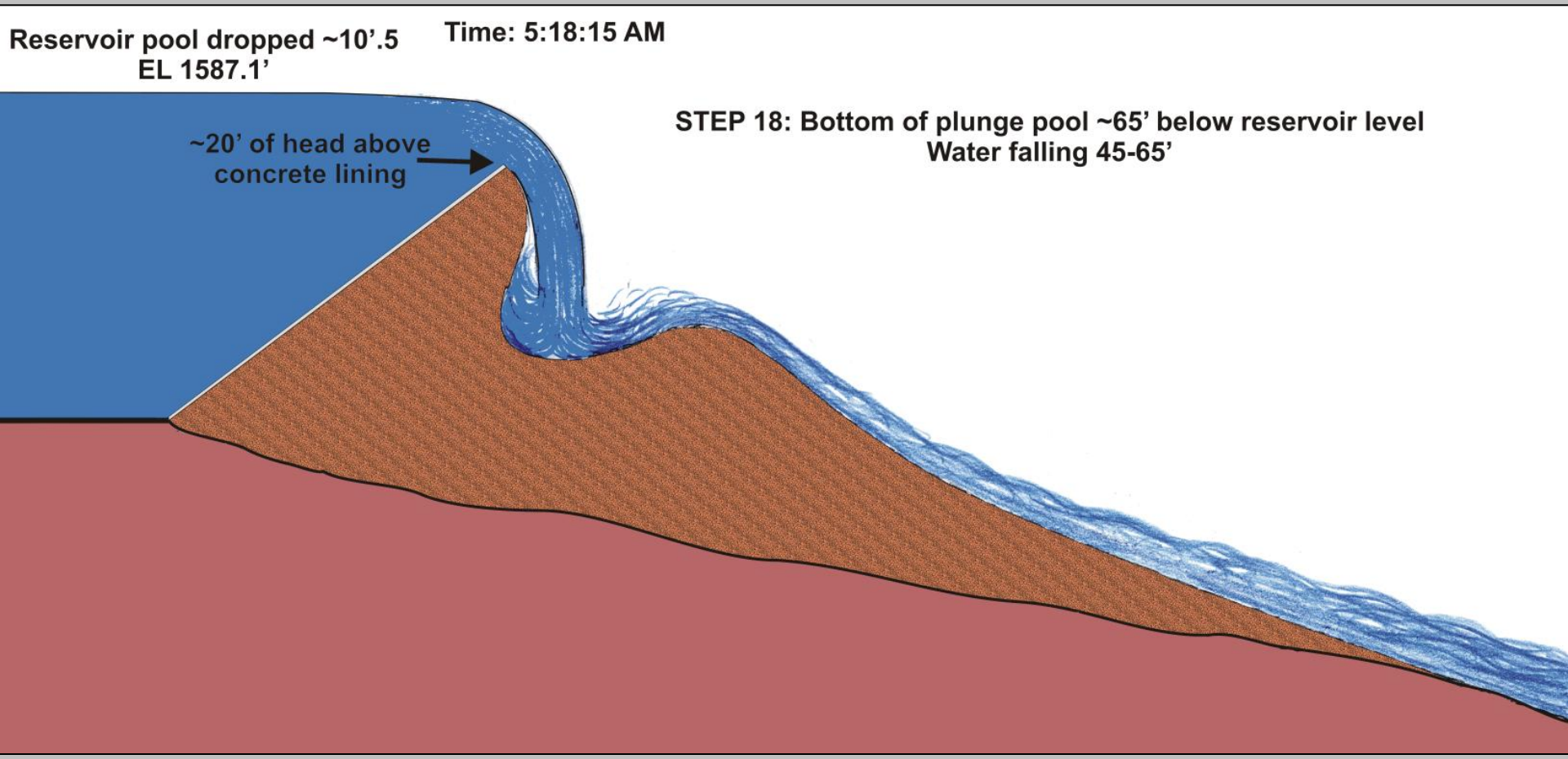

Debris cone at toe
of embankment
below panels 72/73

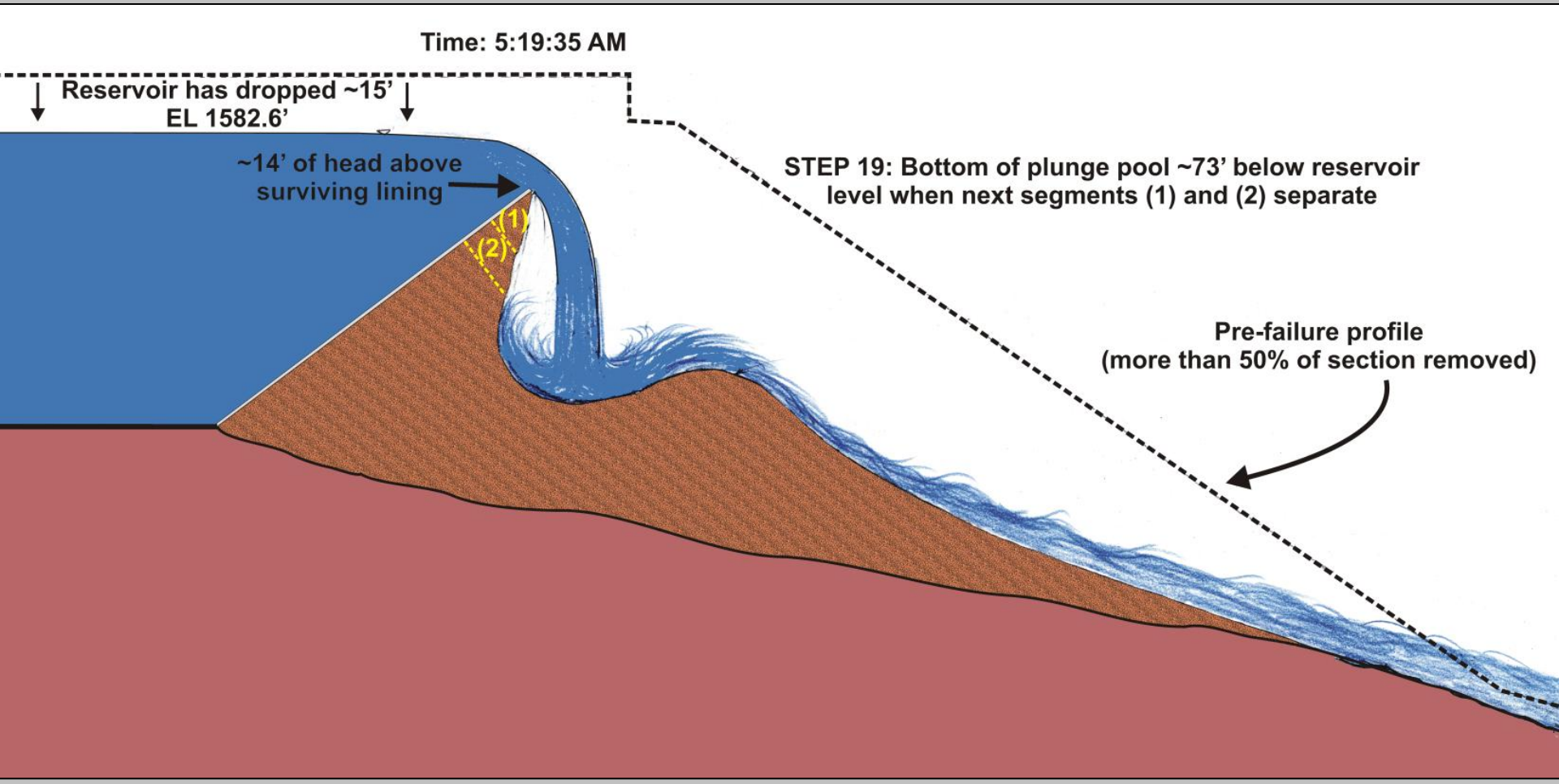

EL 1597.6’
Time: 5:15 a.m.
STEP 14: Initial flow passing over crest of inboard concrete lining
Initial plunge pool hole
~30 ft deep (40 ft below crest)
Outbreak Q increasing each second;
increasing traction on downstream face

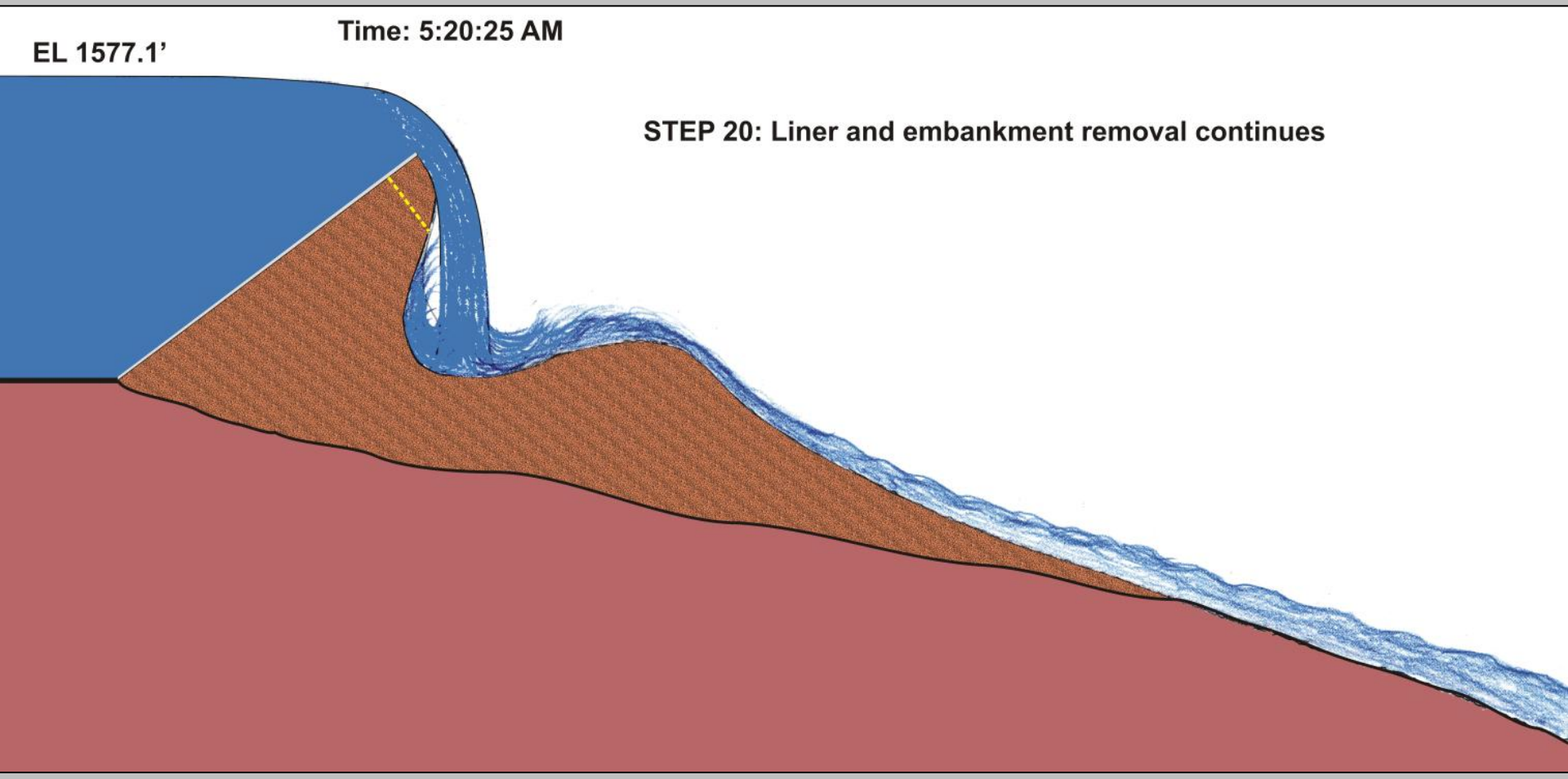

Time: 5:16:30 AM
EL 1594.1' - Pool dropped ~3.5'
STEP 15: Bottom of plunge pool now ~50 ft below reservoir level
Increasing Q of outbreak flood rapidly
eroding downstream face of embankment
Debris fan being
re-excavated by flood

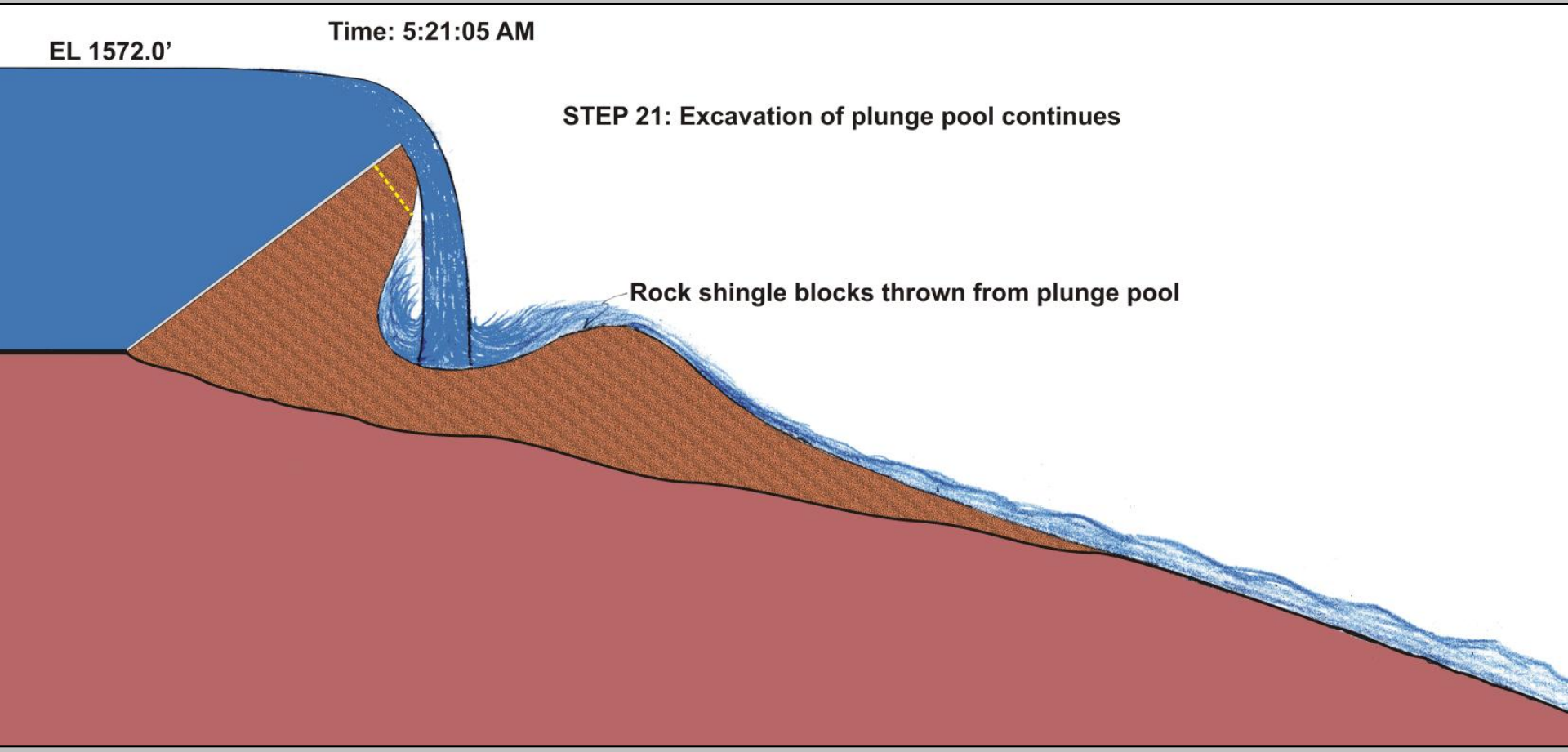

EL 1591.1'
Time: 5:17:15 AM
Liner failing as undercutting occurs
STEP 16: Bottom of plunge pool now ~65ft below reservoir level
Face rapidly eroding due to increasingly deeper outflow

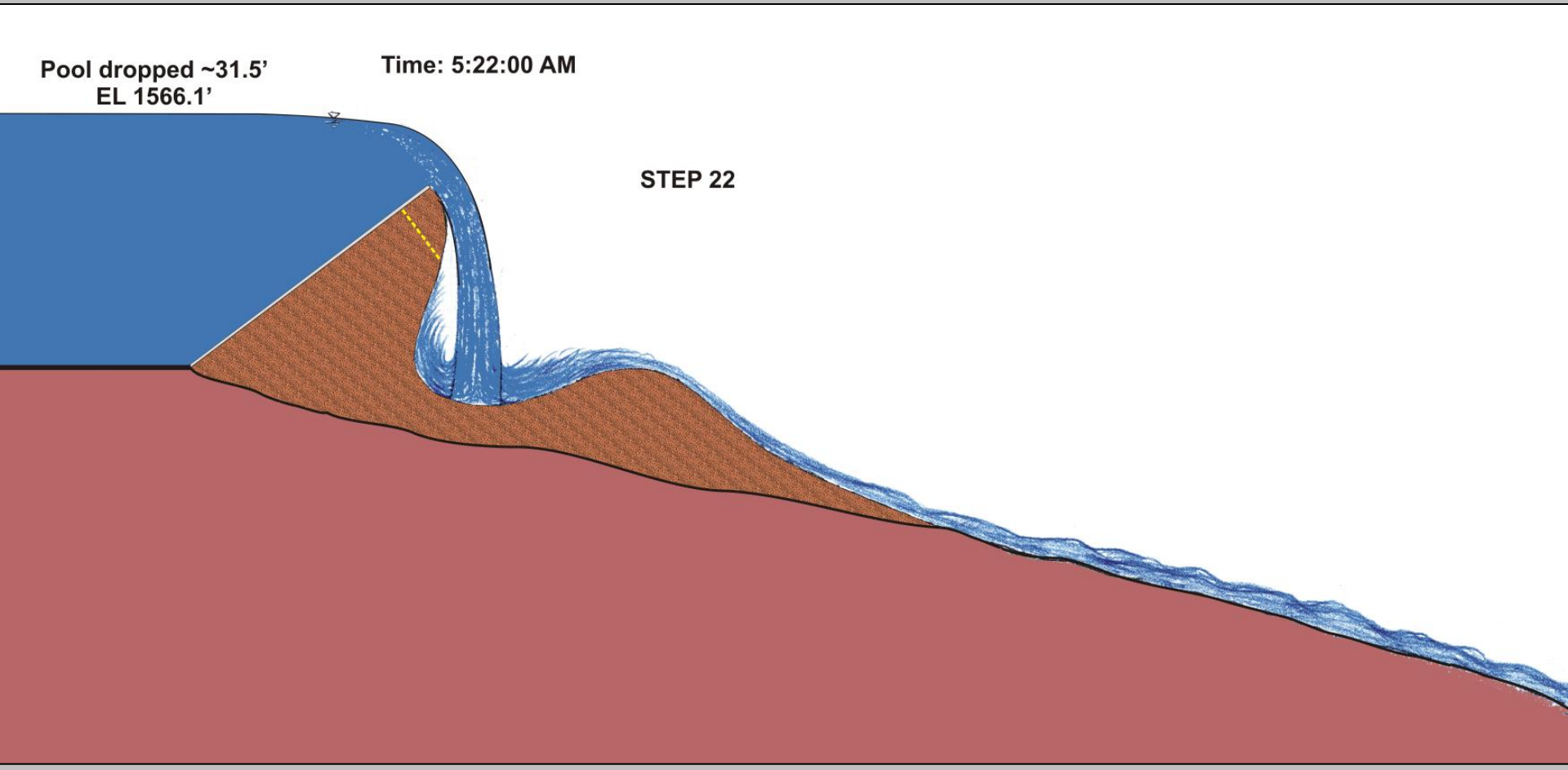

Time: 5:17:30 AM
EL 1590.6’
Tension crack forms and upper block begins to overturn
STEP 17: ~20’ section of lining collapses into expanding plunge pool
Bottom of plunge pool ~70’ below reservoir level
Shingle blocks blown out of plunge pool
Flood begins eroding foundation rock at toe of embankment

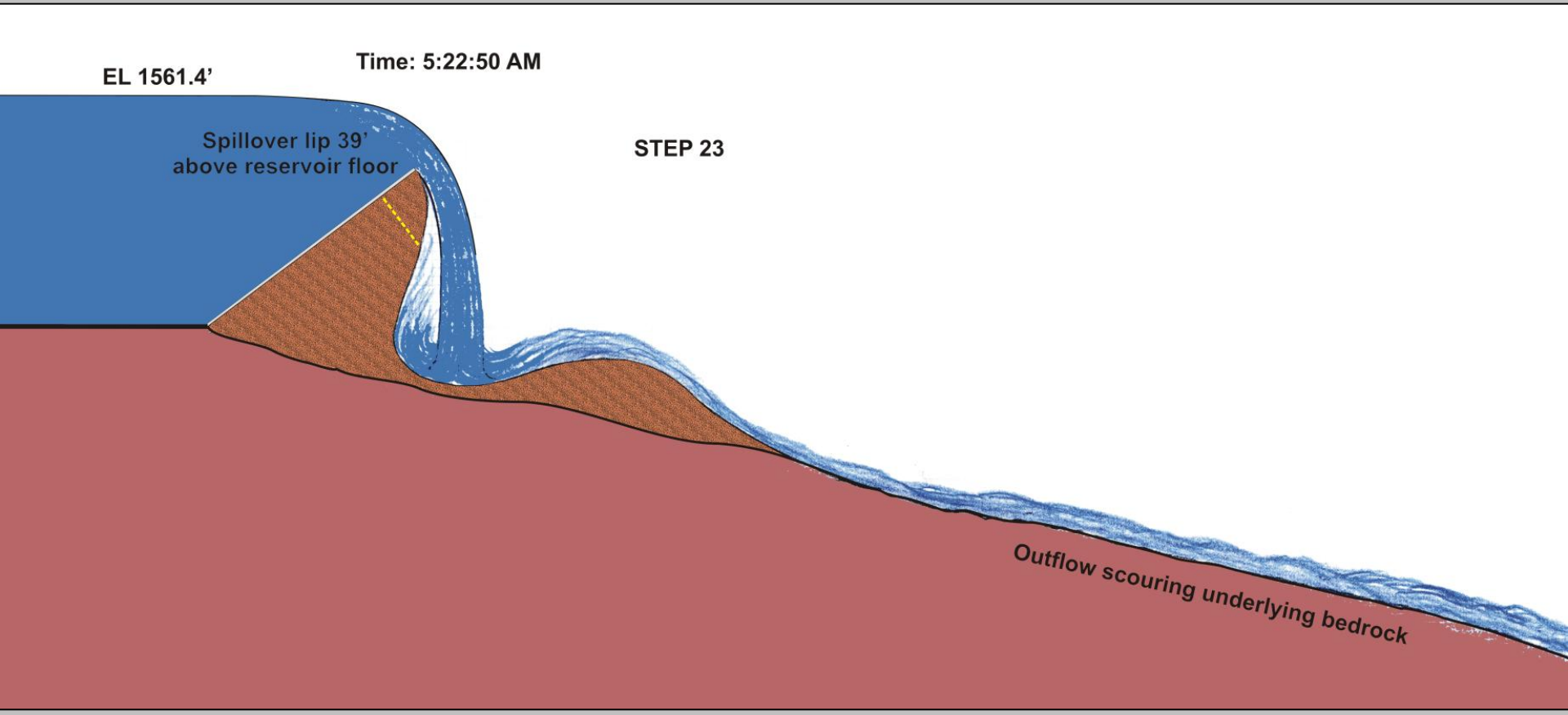

Reservoir pool dropped ~10'.5
EL 1587.1'
Time: 5:18:15 AM
~20' of head above
concrete lining
STEP 18: Bottom of plunge pool ~65' below reservoir level
Water falling 45-65'

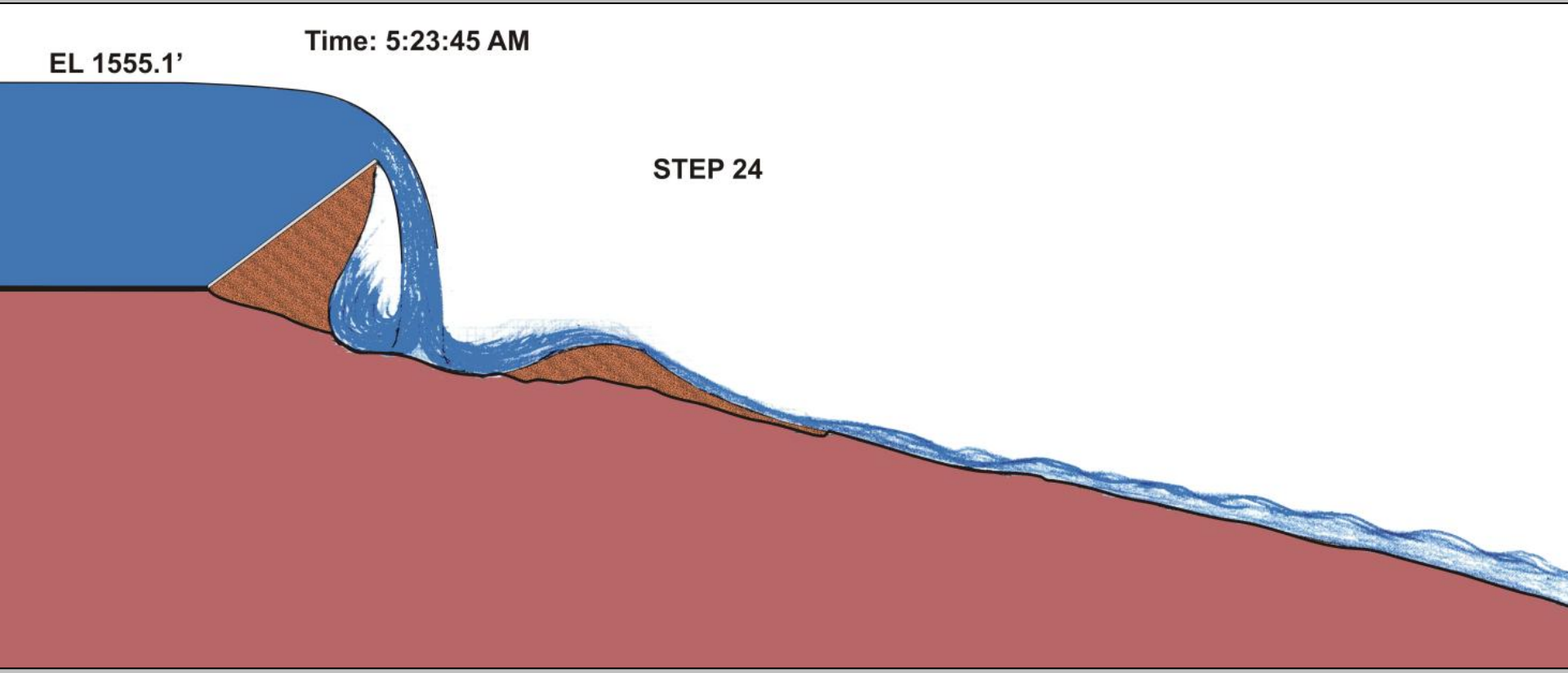

Time: 5:19:35 AM
Reservoir has dropped ~15'
EL 1582.6'
~14' of head above
surviving lining
(1)
(2)
STEP 19: Bottom of plunge pool ~73' below reservoir
level when next segments (1) and (2) separate
Pre-failure profile
(more than 50% of section removed)

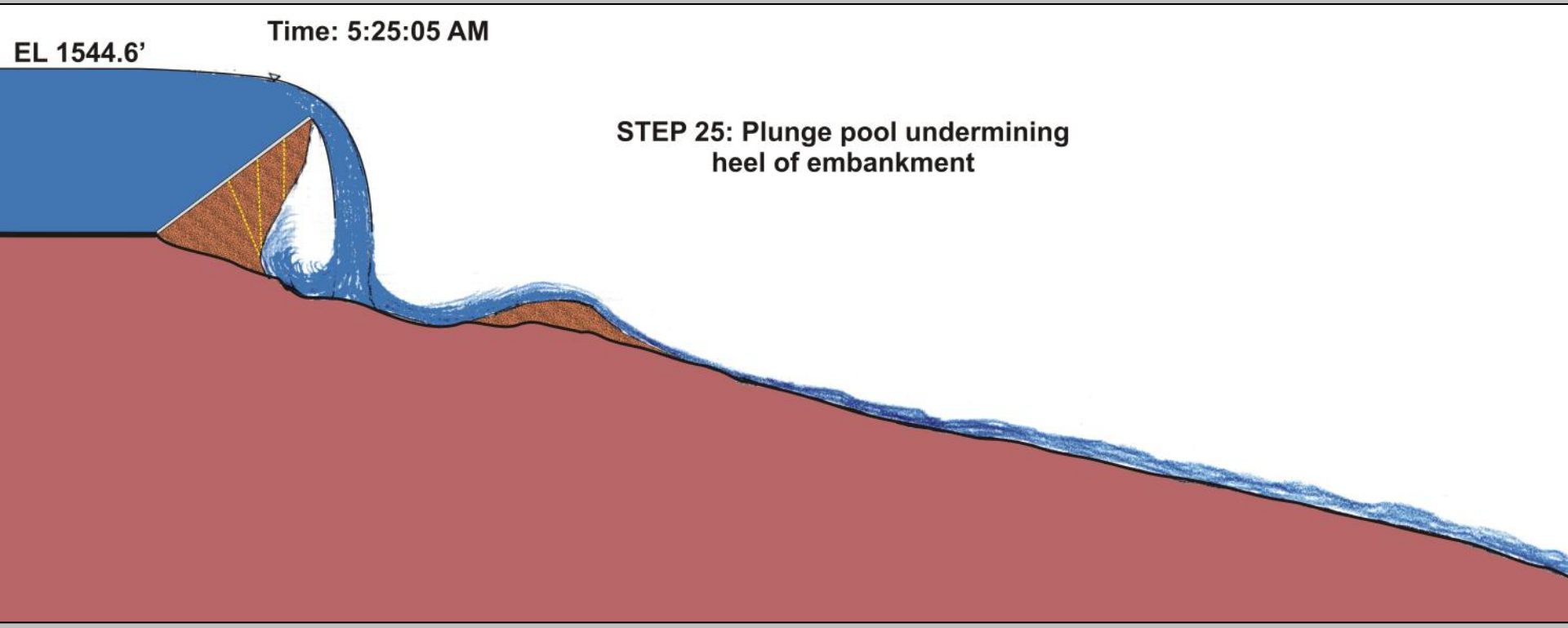

Time: 5:20:25 AM
EL 1577.1’
STEP 20: Liner and embankment removal continues

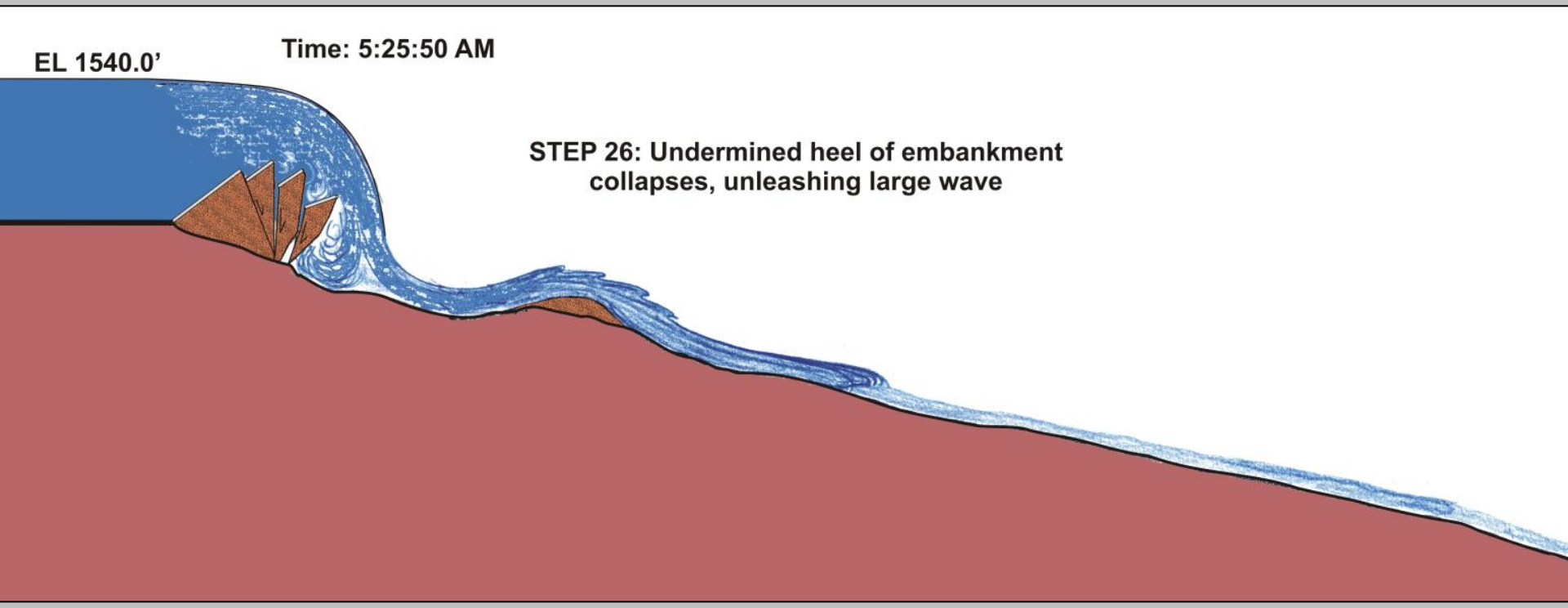

Time: 5:21:05 AM
EL 1572.0’
STEP 21: Excavation of plunge pool continues
Rock shingle blocks thrown from plunge pool

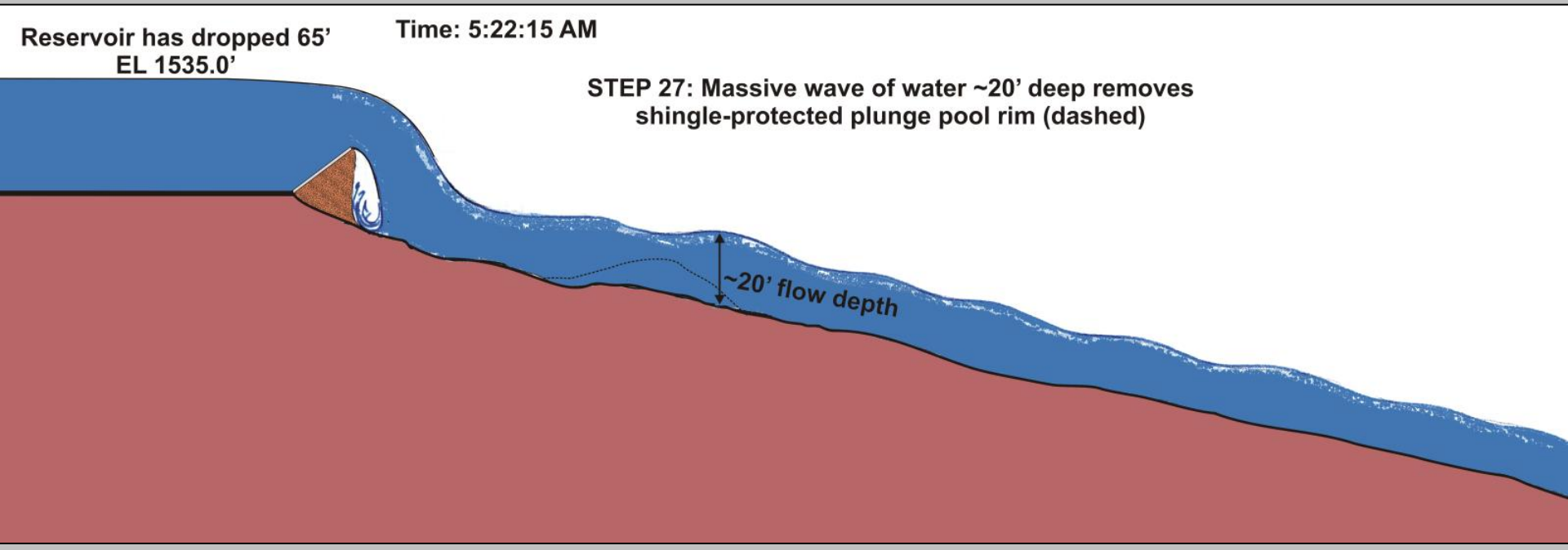

Pool dropped ~31.5’
EL 1566.1’
Time: 5:22:00 AM
STEP 22

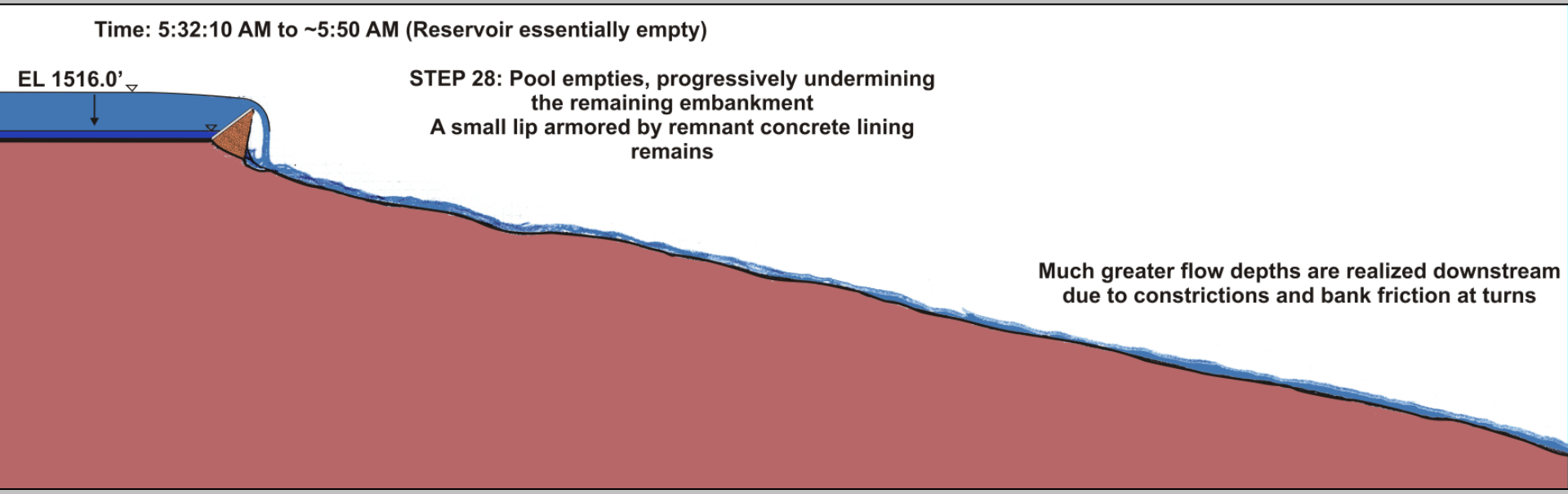

EL 1561.4’
Time: 5:22:50 AM
Spillover lip 39’
above reservoir floor
STEP 23
Outflow scouring underlying bedrock


Time: 5:23:45 AM
EL 1555.1’
STEP 24


Time: 5:25:05 AM
EL 1544.6’
STEP 25: Plunge pool undermining
heel of embankment

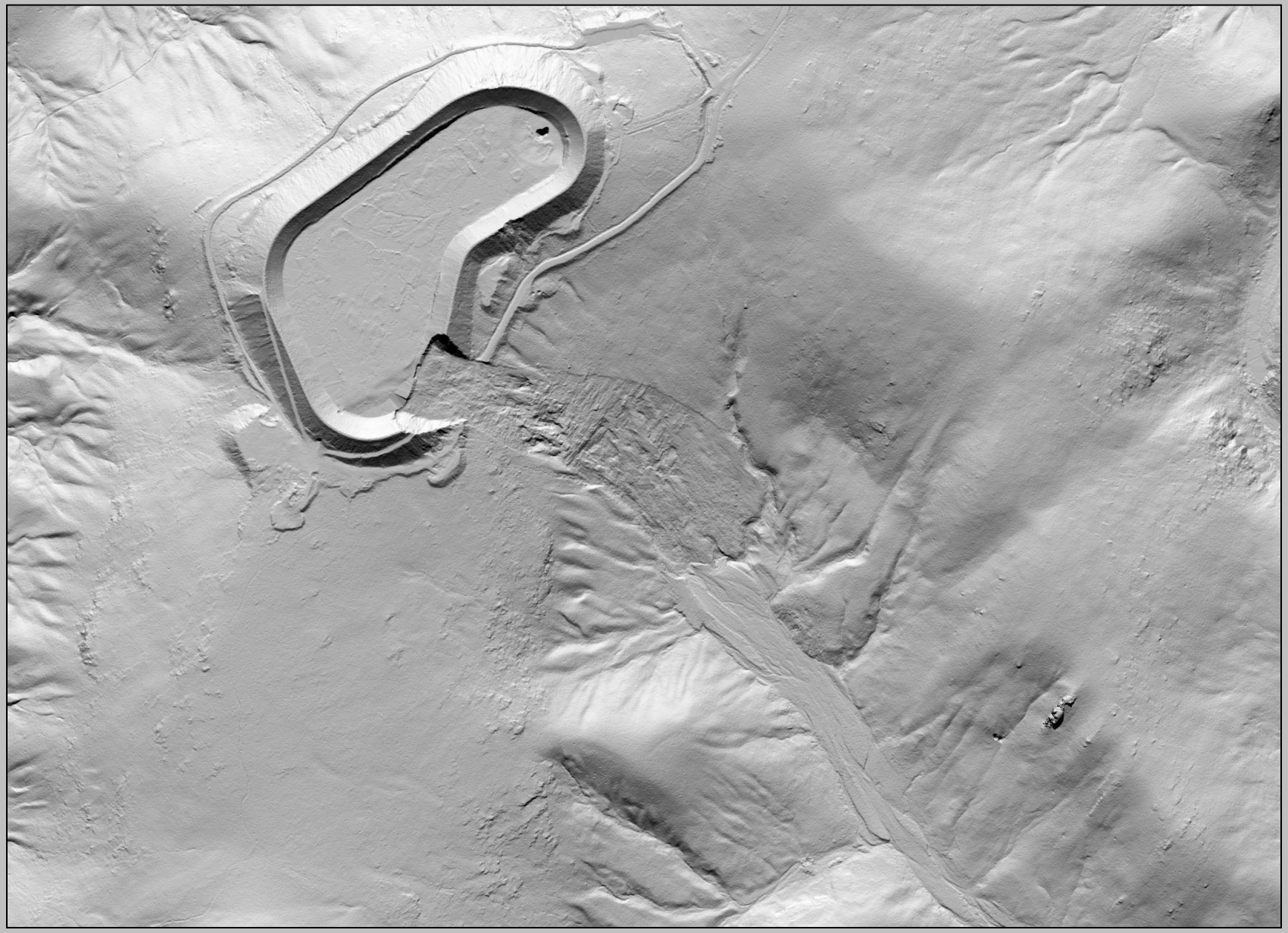

EL 1540.0’
Time: 5:25:50 AM
STEP 26: Undermined heel of embankment
collapses, unleashing large wave


Reservoir has dropped 65’
EL 1535.0’
Time: 5:22:15 AM
STEP 27: Massive wave of water ~20’ deep removes
shingle-protected plunge pool rim (dashed)
~20’ flow depth


Time: 5:32:10 AM to ~5:50 AM (Reservoir essentially empty)
EL 1516.0'
STEP 28: Pool empties, progressively undermining the remaining embankment
A small lip armored by remnant concrete lining remains
Much greater flow depths are realized downstream due to constrictions and bank friction at turns

A small lip of material armored by portions of the concrete liner remained in a few locations at the breach site.

SCENES ALONG THE PATH OF THE OUTBREAK FLOOD



- **0.7 m LiDAR “bare earth” image of the Upper Reservoir area flown for MoDNR after the failure.**

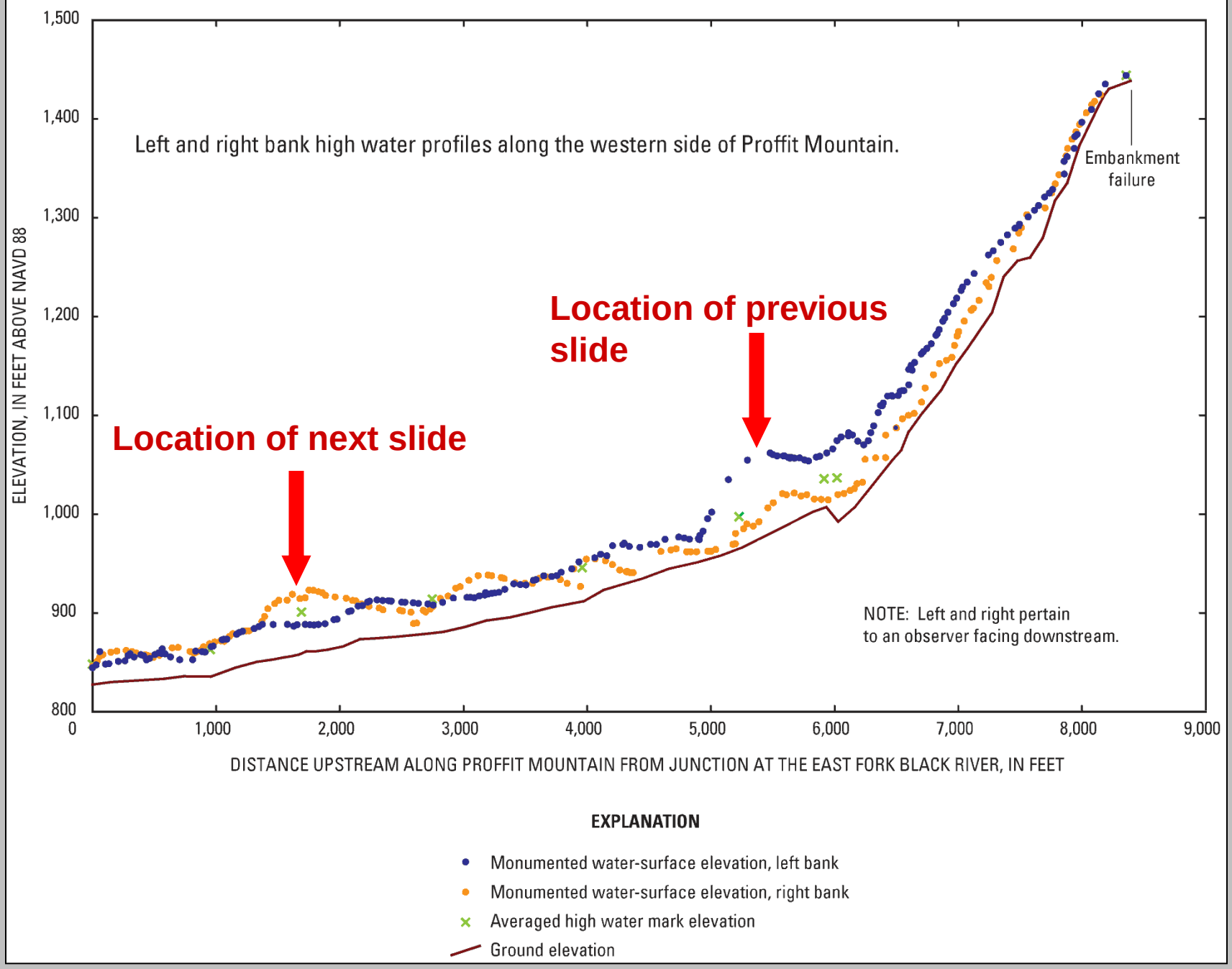
- **Note details in LiDAR derived digital elevation model, and scour of the outbreak flood path.**

Standing on residuum looking at exposures of the Munger Granite.

The flow path down the slope of Proffit Mountain was stripped down to the underlying bedrock (photo by Jeff Spooner (USGS).

The raging flood incorporated soil, rock, concrete, rebar, and HDPE liner, forming a very turbid flow. This flood accumulated soil, rock, and thousands of trees. The momentum of the water allowed it to ramp up the side slopes around the bends.

The momentum of the surging waters allowed them to flow up and over this hill (an old landslide), which formed a flow constriction ~100’ above the valley floor. Note hydraulic jump and deposition of coarse detritus.



Flows reached almost 100’ in depth as the flood banked around turns.

A massive hydraulic jump (near center) developed as the gradient of the slope decreased where Ordovician carbonates onlap onto Precambrian igneous formations underlying Proffit Mountain. The water dropped over 400 feet down this now barren slope of Proffit Mountain.

A massive scour hole >20 feet deep formed at the hydraulic jump where the channel gradient suddenly decreased. The coarse bedload fraction began to drop out of the flow, although the bed of the channel remained active. This transition appears to have been "rinsed" by one final wave of water, towards the end of the flood sequence.

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Huge pieces of rock and concrete were carried downslope by the turbid flow. A large section of a concrete wall panel is shown here.

Toppled wall panel at north end of breach. The stem was 10 feet high.

Lower portion of the scour channel and precipitous drop, immediately below the reservoir. Note demarcation between bedrock and gravels.

Much of the coarse debris fraction appears to have been reworked and sluiced of fines by tail flows, as the flood waters subsided. Note the coarsening upward nature of this deposit and the inclusion of steel rebar, from the shotcrete liner.

The upstream side of two trees had all of their bark abraded by the turbid outflow.

Reworked boulders, cobbles, and gravels fill the lower portion of the scour channel, along with twisted remnants of concrete and rebar.

Concrete and rebar from the dike littered the scour channel.

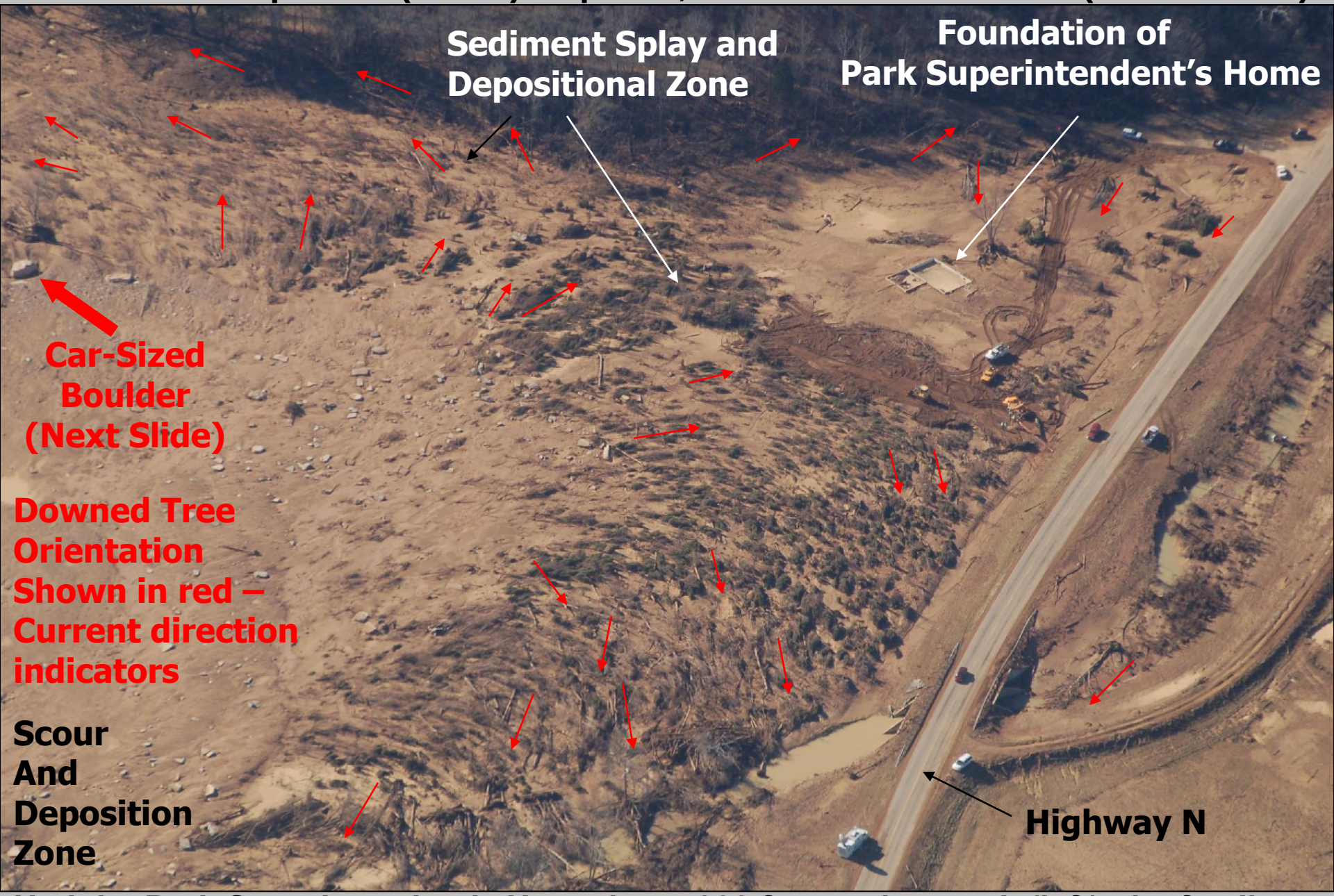
The flood waters surged into the East Fork of the Black River, just upstream from Johnson's Shut-ins State Park, and about 700 ft below the reservoir.

Scour holes were excavated into the residuum and weathered carbonate rock near the junction with the flood plain of the Black River.

As the flood roared into the Black River flood plain, it scoured a deep hole, seen here. The sudden drop in gradient caused the flood waters to drop its sediment, forming a debris dam that backed up this six acre lake (photo by Jeff Spooner USGS-MCGSC).


Source: Missouri Attorney General's website

Sources: Jeff Spooner (USGS) Airphoto, Dr. David Wronkiewicz (Annotations)



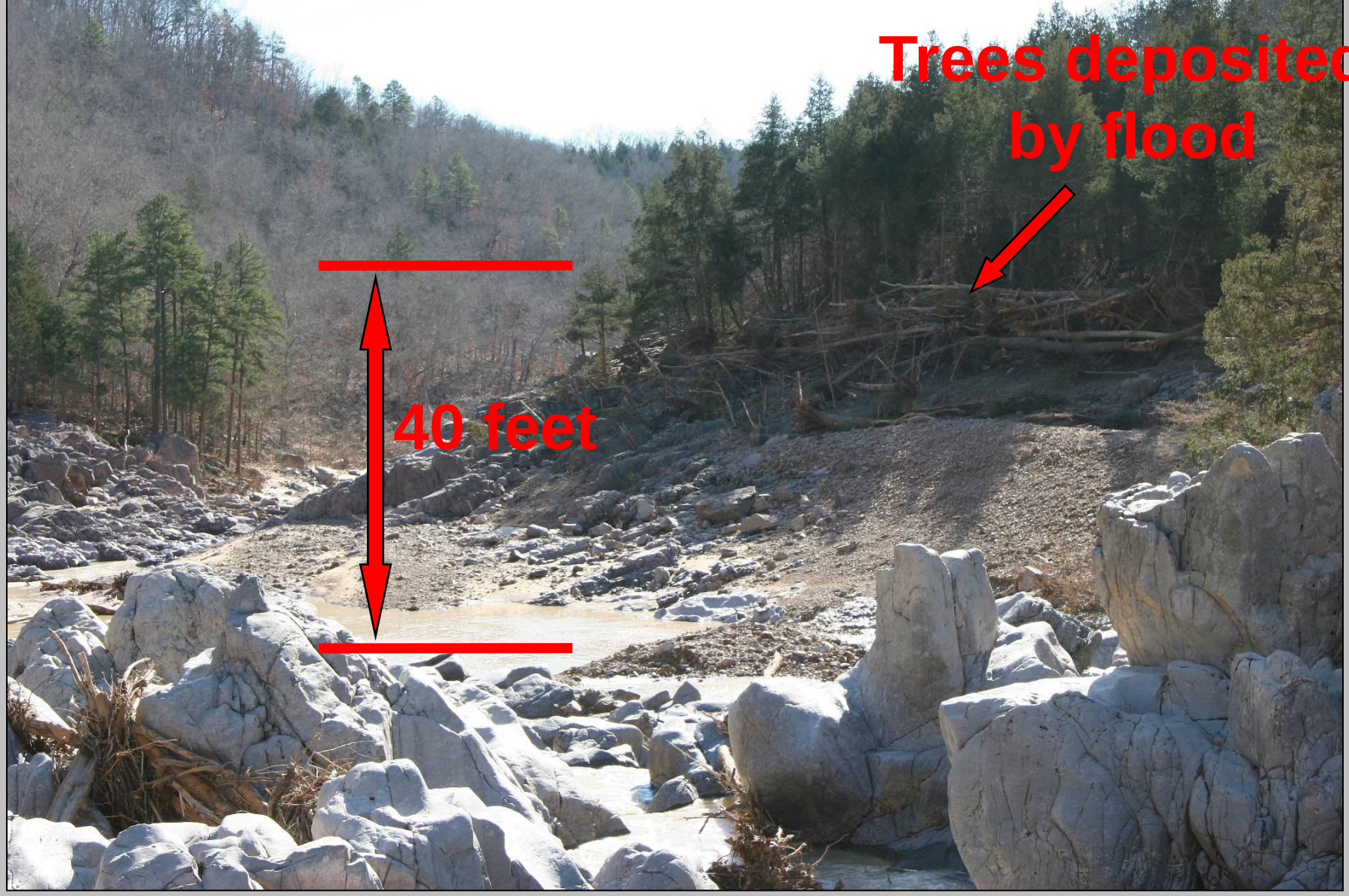
Had the Park Superintendent's Home been 200 feet to the south (left), the family would have been washed down into the shut-ins and almost certainly killed.

This boulder was carried over a down the slopes of Proffit Mountain and was deposited a few hundred feet from the Superintendent's home.

The Family of Five That Survived

- Park Superintendent Jerry Toops and his family lived near the entrance of Johnson's Shut-ins.
- At ~5:20 a.m., Jerry awoke to his wife Lisa screaming about a loud rumble she thought was a tornado heading their way.
- Jerry was aware of the reservoir and realized that it had broken and that the family was in grave danger.
- He began to get out of bed to gather his family when the wall of water and debris hit their house, ripping it to pieces.
- The family was caught in a back-eddy and carried upstream, across Hwy N (road to Johnson's Shut-ins).
- All three of their children survived and their most serious injuries were caused by rescuers burning them while attempting to assuage their hypothermia.

A hydraulic jump formed as the flow changed from an upper to lower flow regime, between the upper and lower shut-ins. Gravel was deposited in this once open hole after the transition to a low flow regime.



A pile of trees was deposited 40 feet above the main channel by the flood. If anyone had been in the shut-ins at the time of the flood, they probably would not have realized how grave of a predicament they were in until it was too late to get out.

Deposition of boulders, mud, and trees in the campground at Johnson's Shut-ins State Park.

Had campers been in the state park campground during the flood, they would have almost certainly been swept into the shut-ins and killed.

The trail leading to the shut-ins was covered by a thick layer of mud and other debris. The shut-ins below restricted the flow and slowed the waters in this portion of the park.

The boardwalks leading to the shut-ins were damaged and covered by debris.

Before After Photos of Scour Zone

Areas inundated by the flood, as mapped by the USGS-MCGSC team.

This lecture will be posted at

www.mst.edu/~rogersda/dams

in .pdf format for easy downloading and use by others.

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