studied four Ancestral Puebloan reservoirs at Mesa Verde National Park in Southwestern Colorado.

In WPI's interdisciplinary team investigations at the four sites, an objective was to conduct a thorough technical evaluation of the many theories previously presented on the functions that each of the four sites had served. Theories on these functions ranged from ceremonial locations for social gatherings, to meeting places for leaders of the community, to ceremonial burial sites, to water storage facilities. The sites, now known as Morefield Reservoir, Far View Reservoir, Sagebrush Reservoir, and Box Elder Reservoir, were not all recognized as reservoirs when studies began, and, indeed, the Box Elder site was not even discovered until 2001 when its mound was exposed due to a forest fire.

Starting with the "Morefield Mound", the conclusion was reached that it provided storage for water based on the presence of layered redoximorphic soils (color patterns in the soil caused by saturated conditions) and evidence of earthwork. Larry V. Nordby, Research Archeologist and Field Director of the Archeological Site Conservation Program at Mesa Verde National Park, after visiting the Morefield site and examining the sediment layers in the excavated cut and standing on top of the mound, stated there was no longer any theory about the site; it was a water storage facility. Further studies found similar evidence that indicated that all four archaeological sites were reservoirs constructed and used by the Ancestral Puebloans in the A.D. 750 through 1180 period.

These ancient engineers had some geotechnical savvy. The recent evidence shows that without formal training or written language, the ancient people of Mesa Verde discerned a great deal about embankment construction, seepage, slope stability, dredging, and other geotechnical considerations. They operated and maintained these public works projects for as long as 350 years. In the case of Morefield Reservoir, WPI researchers found evidence that the Ancestral Puebloans learned the hard way about the appropriate sloping of berms. Evidence of a failure that occurred around A.D. 900 provides a record of what happened.

Table 1. Site Locations and Approximate Dates and Periods of Use

Reservoir	Location	Time Span (A.D.)	Period
Morefield	Morefield Canyon	750-1100	Pueblo I Pueblo II
Far View	Chapin Mesa	950-1180	Pueblo II Pueblo III
Sagebrush	Unnamed Mesa	950-1100	Pueblo II
Box Elder	Prater Canyon	800-950	Pueblo I Pueblo II

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RESERVIOR CONSTRUCTION

Physical features at the four reservoirs varied considerably. The locations and approximate periods of use, based on potsherds and carbon dating of artifacts in the sediments, are shown in Table 1. Morefield (Figure 1) and Box Elder (Figure 2) Reservoirs were located in canyon bottoms, both with upstream drainage basins of about 10 square kilometers (about 4 square miles). At both sites, the original impoundment was dug by hand either in, or adjacent to, the main canyon thalweg. The initial pits varied from an estimated 1 to 2.5 meters (about 4 to 8 feet) deep. The original source of water into these two canyon-bottom ponds was likely from groundwater.


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FIGS. 1 and 2. The raised earthen mounds of Morefield (L) and Box Elder (R) Reservoirs are located in canyon bottoms.

Diversion of water from the main canyon thalweg became a later source of water for Morefield and Box Elder Reservoirs. At Morefield, the location of the final intake canal or ditch is easily identified by the hand-placed stones leading from the main channel along the bank of the terrace and raised berm to the reservoir. At Box Elder Reservoir, only a few stones were found as evidence of an intake ditch along the upstream terrace.

Far View (Figure 3) and Sagebrush (Figure 4) Reservoirs were located on mesa tops, with limited catchment areas. For Far View Reservoir, the original excavation to the sandstone bedrock was about 1.5 to 1.8 meters (5 to 6 feet); while at Sagebrush Reservoir, the depth to the sterile clay bottom was from 1.2 to 1.5 meters (4 to 5 feet) below the natural ground elevation. Each of these mesa tops had identifiable access entrances to the water storage area. Inflow of water to the reservoirs from the drainage basins was from agricultural areas and compacted topsoil.

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FIGS. 3 and 4. The Far View Reservoir (L) remains easy to recognize because of its rock wall construction. The Sagebrush Reservoir (R), marked by two intersecting archaeological excavation trenches, is shown from above.

Morefield and Box Elder Reservoirs

Sediments from the upstream drainage basins were diverted into the reservoirs along with the inflow of water. Over the years, the sediment accumulation reduced the reservoirs' storage volume, so the Ancestral Puebloans occasionally dredged the sediments with flat stones, digging sticks, and baskets to maintain an adequate domestic water pool. The dredged material became berm material which provided definition and raised the reservoir perimeters. These berms consisted of clays and silt-size material which, under the compaction of foot traffic, resulted in excellent embankments. The dense clay controlled seepage.

Stratigraphic interpretation of the sediments exposed in the archaeological trench dug at Morefield in 1997 (Figure 5) provides a history of maintenance activities for the water storage facility. Based on the relative position and shape of the sand-rich units observed on the trench wall and using the principles of overlap and truncation, at least six reservoir periods were evident (Figure 6). Each period represents multiple runoff events during which sediments were transported into the reservoir, reducing storage capacity. Truncation of some of the sand-rich units shows that these sediments subsequently were removed and discarded over the adjacent berm area. For instance, the abrupt termination of sandy zones shown in Figure 6 tells us that dredging occurred and that the sandy zones to the side were spoil areas. The six reservoir periods represent deposition of an estimated 14.3 meters (47 feet) of sediments during a 350-year period, an average deposition rate of 40 millimeters (1.6 inches) per year.

Because dredging did not remove all the sediment during each cleaning, it was not long until the water storage ponds began to rise in elevation and take the form of mounds into which water would no longer flow by gravity. The early people determined that water could be diverted from the canyon bottoms into a delivery canal leading to the rising ponds, but sediment deposits still had to be occasionally cleaned out and cast to the side, where berms were formed. After 350 years, by A.D. 1100, this process brought the Morefield Reservoir up in elevation about 6.4 meters (21 feet) above the original reservoir bottom.

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FIG. 5. This archaeological trench was excavated in May 1997 to allow analyses of the sediment layers.

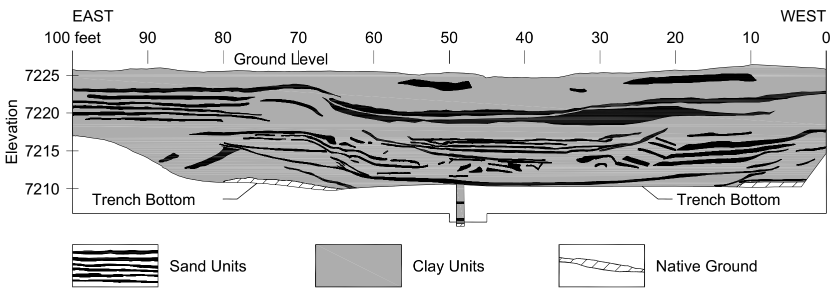

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FIG. 6. The truncation of sediment layers at Morefield Reservoir indicates its maintenance history.

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The present-day reservoir mound at Morefield is 4.9 meters (16 feet) above the valley bottom, with a circular 61-meter (200-foot) base and a flat top 40 meters (130 feet) in diameter. At Box Elder Reservoir, the mound rises 6 meters (20 feet) above the existing canyon thalweg and is elliptical with a minimum diameter of about 36 meters (120 feet) and a maximum diameter of about 49 meters (160 feet.) Analyses of the dense berm material of the mound were aided by Mr. Richard Wiltshire of the U.S. Bureau of Reclamation. Increased sedimentation rates were a result of both natural occurrences, such as forest fires, and man-induced activities, such as upgradient agricultural land use practices.

The volume of total sediment deposited in the canyon-bottom Morefield and Box Elder Reservoirs was estimated at 12,180 cubic meters (430,000 cubic feet [ft^3]) and 4,300 cubic meters (152,000 ft^3), respectively. The computed annual sediment yield for the drainage basins was 3.19 cubic meters per square kilometer (0.0067 acre-feet per square mile [AF/mi^2]) for Morefield Canyon and 2.76 cubic meters per square kilometer (0.0058 AF/mi^2) for Prater Canyon. Considering the sediment that may have bypassed the diversion structure or overflowed the canal or reservoir, the sediment yield for both drainage basins was probably about 4.76 cubic meters per square kilometer (0.01 AF/mi^2) per year.

Far View and Sagebrush Reservoirs

After the early success of water storage facilities at both Morefield and Box Elder Reservoirs, similar water storage ponds were subsequently constructed at the Far View and Sagebrush Reservoir sites. Earlier archaeological excavations were done at Far View Reservoir (then known as Mummy Lake) in 1967 under the direction of Dr. David Breternitz of the University of Colorado. The exploration trenches at Sagebrush Reservoir shown in Figures 4 and 6 were dug in 1972-1974, under the direction of Dr. Jack Smith.

The pond size varied from the approximate 27-meter (90-foot) circular dimension at Far View Reservoir to an elongated pit with a short width of about 16 meters (55 feet) to a maximum width of about 24 meters (80 feet) at Sagebrush Reservoir. The depth of the ponds was limited, which required construction of a stone wall completely around the storage area. To provide storage for the dredging material, a parallel stone wall was built around a portion of the downslope side of the storage pit. At Far View Reservoir a third wall was discovered buried between the outer walls that exist today. The set of walls on the south and east sides of the Far View Reservoir are from 3 to 6 meters (10 to 20 feet) apart. The area between the two walls was filled with sediments from both the initial pit excavation and dredged sediments from the reservoir.

The berms and fill at Far View Reservoir represent approximately 840 cubic meters (1,100 yd^3), roughly 200 percent of the excavated natural soils. Without considering wind-deposited sediments, the sediment volume at Far View Reservoir would indicate an average inflow of sediment of about 1.8 cubic meters (2.4 yd^3) per year over 230 years. Wind and water erosion of the banks, if considered, would tend to raise this sedimentation rate. The unit sediment yield in cubic meters per square kilometer per year was similar to Morefield Reservoir.

The plotted profile of Sagebrush Reservoir's Trench I included in the Smith report (1999) identified an excavated depression in the southern part of the reservoir. This

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depression was an excavation pit dug to a depth of about 1.3 meters (4.3 feet) in a likely circular pattern 7.9 meters (26 feet) in diameter probably for containment of about 45,412 liters (12,000 gallons) of water for domestic use. Spoil from the excavation was likely deposited around the southern area as a berm surrounding the excavation. The bottom of the pit was the sterile red clay stratigraphic formation, which created an ideal impervious bottom layer. This excavation was considered to be Phase I of the water development project.

During Phase III, stones were placed to confine the berm and to surround the excavated pit in a pattern similar to that on the adjacent mesa's successful Far View Reservoir development. Stones were also used to define a narrow entranceway about 0.8 meters (2.7 feet) in width at the northwestern part of the reservoir.

Data from the Smith report (1999), along with the soil testing by augers in 2000, and 2001 topographic mapping of the reservoir, were used to estimate the volume of sediment deposited in Sagebrush Reservoir. The first step in these computations was to identify the volume of the initial excavation under Phase I for the approximate 7.9-meter (26-foot)-diameter pit. As dug to a depth of about 1.3 meters (4.3 feet), the material excavated from the pit and deposited in the berm surrounding the storage area was about 46 cubic meters (60 yd^3).

Total sediment deposited in Sagebrush Reservoir over the 150-year period from A.D. 950 to A.D. 1100 was about 170 cubic meters (220 yd^3). This included sedimentation of the excavated depression of Phase I. It did not include the approximate 84 cubic meters (110 yd^3) of sediment subsequently deposited by wind after abandonment of the reservoir, to a depth of about 0.3 meter (1 foot) overlay of the reservoir sediment deposits. Some dredging of deposited sediments took place during the period of occupation at the site. Some of these sediments would have been placed in the area between the two walls of stone and primarily to the south of the reservoir. Evidence shows that the dredged material was also cast to the reservoir sides. It is estimated that about 10 cubic meters (13 yd^3) of sediment dredging would have been added to the berm, primarily from Phase I activities. This gives a total computed volume of sediment deposited in the 150-year period of occupation at the site of about 180 cubic meters (233 yd^3).

The Sagebrush Reservoir berm, as it exists today, was built during its Phase III period. The southerly portion of the berm was raised above the natural earth surface to tend to account for the higher ground surface reservoir edge to the north. The south berm represents about 0.7 meters (2.4 feet) of elevation gain. It was this construction that significantly increased the storage volume. This construction provides evidence of good engineering, knowledge of water containment principles and ability to work within the natural constraints of elevation differences. The berm contains about 100 cubic meters (130 yd^3) of fill material.

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ANCIENT BERM FAILURE

About A.D. 900 the ancient operation of Morefield Reservoir experienced a berm failure that is recorded within the sediments of the mound. The berm had an interior slope of 4 to 1 and was about 1.2 meters (4 feet) high with five horizontal sandy layers (Figure 7). The berm consisted mostly of dense silt and clay, however. Evidence indicates that during dredging operations the stability of the berm was impacted.

A slip failure occurred that caused the 1.2-meter (4-foot)-wide displaced berm section to slide down about 0.6 meter (2 feet) while rotating clockwise, causing an upward bulge 1.8 meters (6 feet) out from the toe. The stratification evidence (Figure 7) led the field researchers to conclude that weakening of the toe of the interior berm likely caused the apparent slip failure. Examination of sandy strata markers tells a story of continued reservoir operations with the failed berm continuing to serve to impound stored water until the next berm building phase.

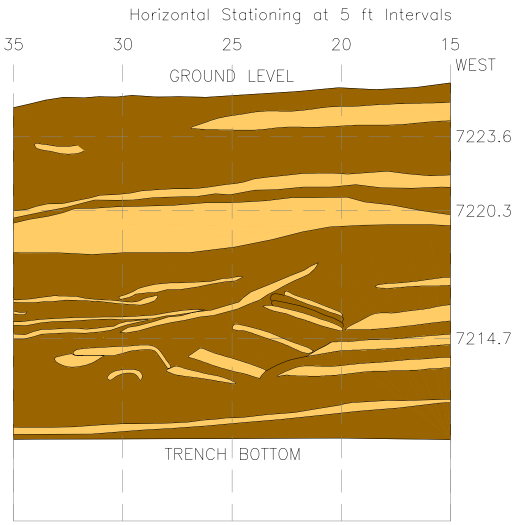

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FIG. 7. Displaced sediment layers are evidence of a prehistoric berm failure at Morefield Reservoir.

SEDIMENT AND SOIL SAMPLING

The May 1997 excavation of a 38.1-meter (125-foot)-long trench to a depth of 4.9 meters (16 feet) across the Morefield Reservoir mound was a unique undertaking during the WPI investigations (Figure 5). The excavation was completed under a permit from Mesa Verde National Park. The backhoe excavation was much deeper, and was near the same location as the shallower trench dug in 1967 under the direction

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of Dr. Smith and Ezra Zubrow of the University of Colorado Mesa Verde Research Center. The WPI research team observed and documented the sediment layering and the exposed characteristics of material along the south trench wall. The backhoe-excavated trench depth was limited to 4.9 meters (16 feet) due to density of the deposited sediments. Hand augering of an additional 1.5 meters (5 feet) identified the original natural soil horizon below the bottom of the trench for a total reservoir height of 6.4 meters (21 feet).

At the Morefield Reservoir mound, the sediment layering exposed on the trench wall provided clear evidence that waterborne sediments had been deposited within a reservoir. Sediment layers of fine sand-size material, with traces of charcoal, proved the inflow of sandy material occurred occasionally, likely due to extreme thunderstorm events and drainage basin erosion (Figure 8). The larger portion of the exposed sediments on the trench wall, about 65 percent, was a densely compacted clay matrix. Over the 350-year life of the reservoir, there were about 21 instances of measurable sand to sandy clay depositional occurrences that would have represented larger inflows to the reservoir during canyon flooding periods. There were approximately 14 different thin, continuous layers of charcoal deposits, which likely represented fluvially transported charcoal from forest fires. Sediment samples of the exposed material were collected for particle size gradation analysis.

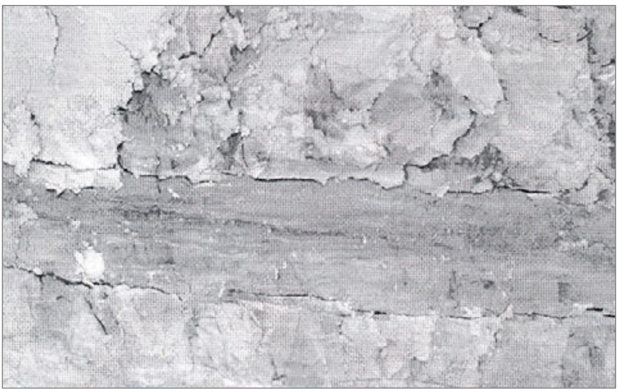

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FIG. 8. Layer with fine sand size sediments and charcoal at Morefield Reservoir.

Sediment sampling at Box Elder, Far View, and Sagebrush Reservoirs consisted of hand augering and classification of soils extracted from auger holes at several locations within the reservoir area. Samples collected at the mesa-top Far View and Sagebrush Reservoirs showed iron staining, proving that the depressions had held water. There was also evidence of the textural interlayering in some samples and variations in soil classification. Auger hole samples showed that the native soil samples collected outside the reservoir were relatively uniform in color and texture compared to the reservoir sediments.

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Mechanized drilling of four holes in May 2003 at Box Elder Reservoir, using U.S. Bureau of Reclamation equipment, enabled analyses of the deep native soil horizon near the reservoir center at a depth of over 6.2 meters (20.2 feet) or 617 centimeters (243 inches). Continuous samples collected by the jackhammer drilling rig were analyzed by Doug Ramsey of the Natural Resources Conservation Service. Selected samples were later tested by the U.S. Bureau of Reclamation Soils Laboratory at the request of Richard Wiltshire. The U.S. Bureau of Reclamation testing included grain-size gradation and Atterberg limits testing.

ASCE RECOGNITION

On September 26, 2004 Pat Natale, Executive Director of the American Society of Civil Engineers (ASCE), dedicated these four prehistoric reservoirs in Mesa Verde National Park as a National Historic Civil Engineering Landmark (Figure 9). The dedication of the reservoirs as an ASCE landmark was special, as ASCE has recognized only four other National Historic Civil Engineering Landmark sites in the state of Colorado. The recognition of these water storage projects was a tribute to the early Mesa Verdeans who successfully undertook these water-storage projects.

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FIG. 9. Dedication of the ASCE Landmark plaque occurred on September 26, 2004. ASCE Executive Director Pat Natale, Ken Wright, David Breternitz, and former Mesa Verde National Park Research Chief Linda Towle are shown.

The success of the four reservoirs used as domestic water supplies and storage facilities was remarkable; however, they required extensive maintenance throughout their useful life. We believe that ultimately the maintenance and hand dredging of sediments became too great due to excessive sediment deposition, not unlike the accumulation of sediment in many reservoirs throughout the world in operation today.

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ACKNOWLEDGEMENTS

Reservoir analyses were aided by federal agencies such as the U.S. Bureau of Reclamation, the National Park Service, the U.S. Geological Survey, and the Natural Resource Conservation Service. Individual participants included specialists in geology, hydrology, soil science, water law, surveying, archaeology and palynology. The ten years of research studies were undertaken by volunteers and experts serving the Wright Paleohydrological Institute, under permits from the National Park Service and with financial support from the Colorado Historical Society. The assistance of the staff of Mesa Verde National Park is gratefully acknowledged.

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