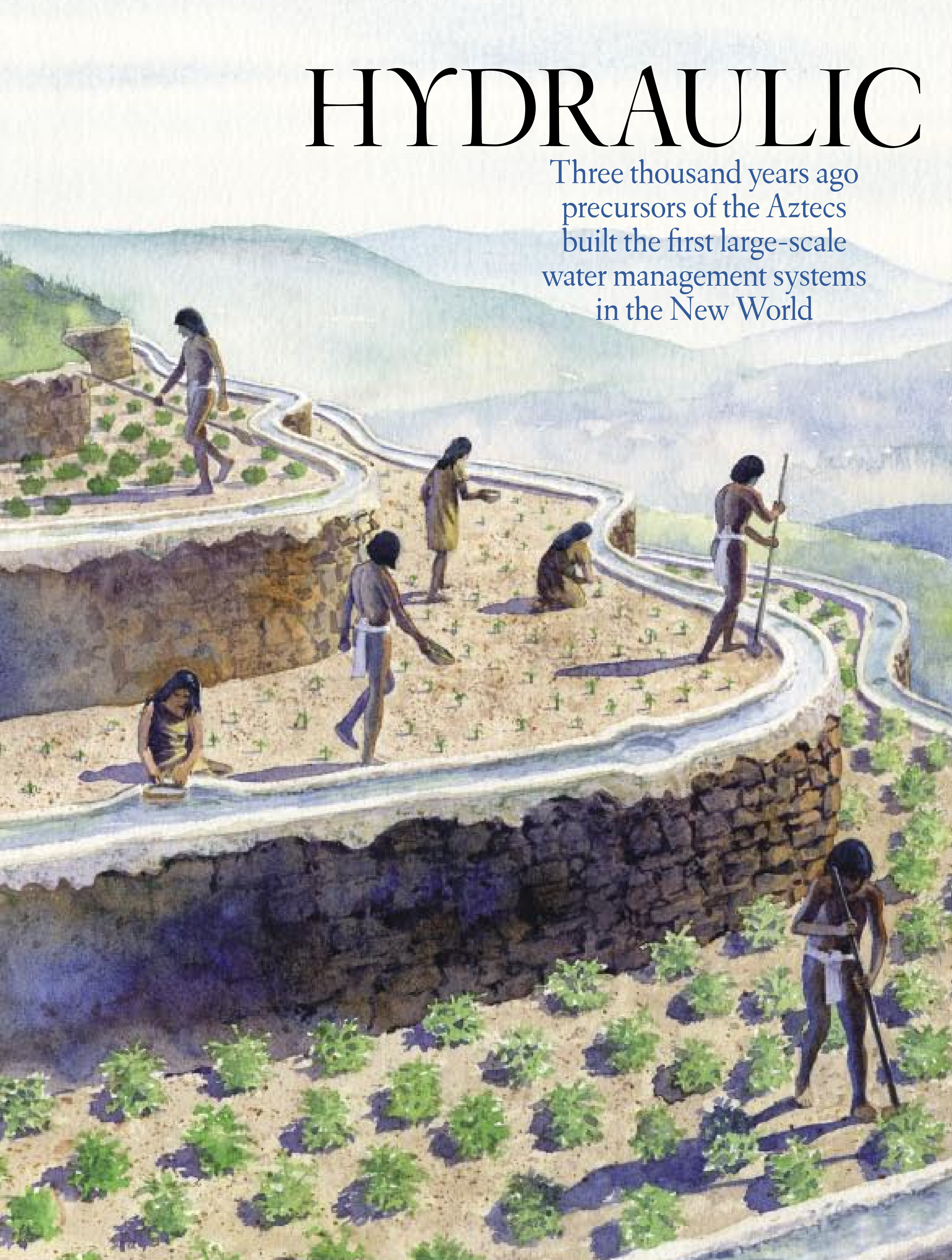
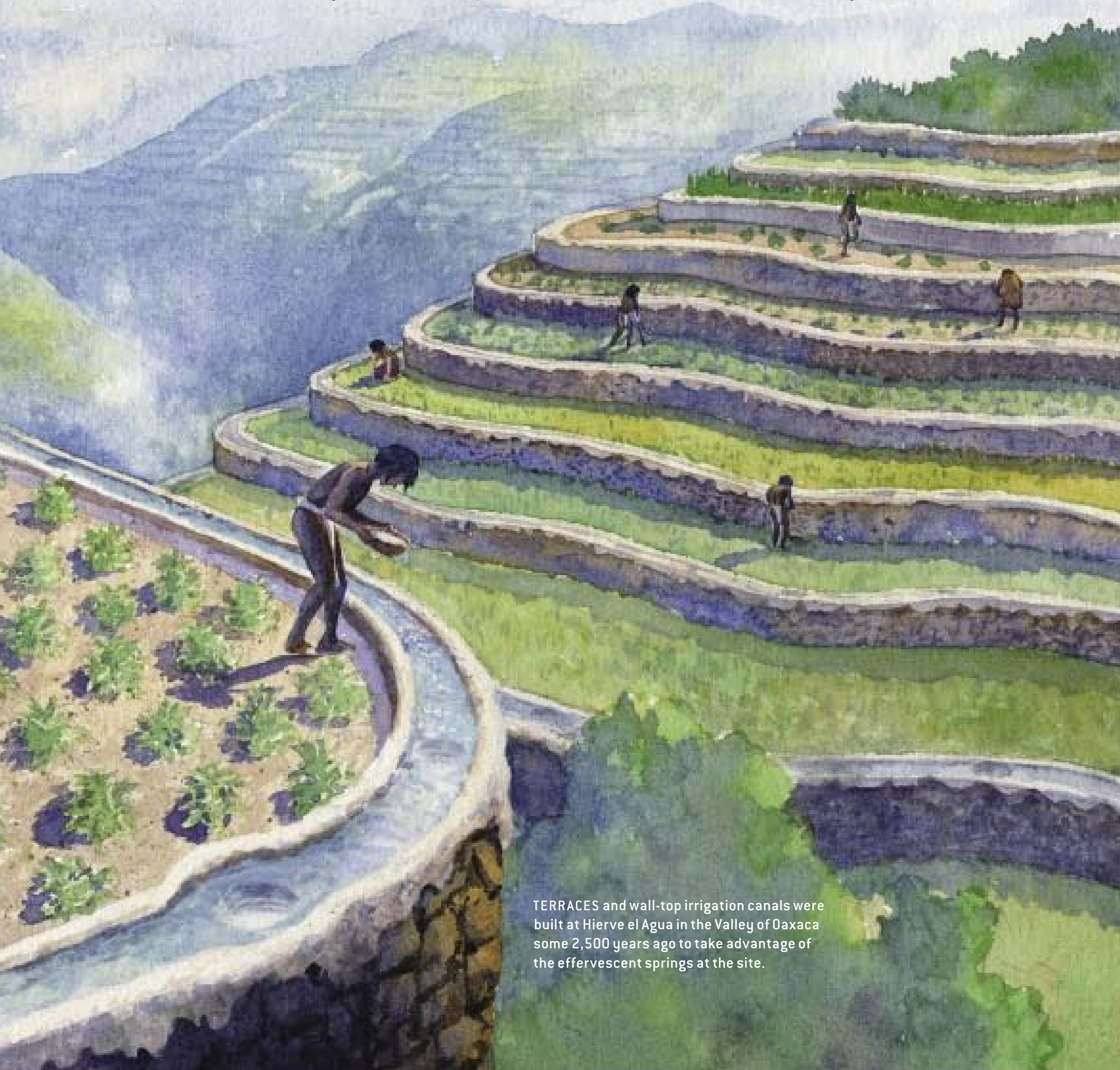
HYDRAULIC

Three thousand years ago precursors of the Aztecs built the first large-scale water management systems in the New World



ENGINEERING in Prehistoric Mexico

By S. Christopher Caran and James A. Neely



TERRACES and wall-top irrigation canals were built at Hierve el Agua in the Valley of Oaxaca some 2,500 years ago to take advantage of the effervescent springs at the site.

WATER MANAGEMENT systems were constructed at various sites throughout southern Mexico during the prehistoric period. The earliest known example, a well at San Marcos Necoxtla, is 10,000 years old. Construction of later systems continued until the arrival of the Europeans.

The prehistoric farmers of southern Mexico must have longed for a miracle. A tropical climate made their fertile valleys nearly ideal for planting, despite elevations approaching 2,000 meters, and heavy rains ensured bountiful crops during the six-month monsoon season. Under such favorable conditions, this region became the cradle of New World agriculture and the birthplace of corn. Yet these early agriculturalists faced one crucial limitation: during half the year, the weather was too dry for farming. With a year-round water supply, their hand-tilled fields might yield two or even three harvests annually. But how could the farmers get more water?

Their solution was not a miracle but a marvel of human ingenuity: large-scale engineering projects designed to store and transport water. From modest origins that left few traces, construction gradually progressed to a monumental scale. The Purrón Dam, for example, which was built in the Tehuacán Valley starting around 750 B.C., measured 400 meters long, 100 meters wide and nearly 25 meters high. Workers transported by hand, a few kilograms at a time, some 2.64 million cubic meters of earth. This dam probably remained the largest water retention structure in the Americas until the 18th century. Nearby, ancient engineers built thousands of kilometers of canals and aqueducts that predated the arrival of Europeans in Mexico by two millennia. They diverted water from springs and streams, conveying it across drainage divides, around canyons and down steep slopes. Other resourceful inventions collected rainwater from buildings and plazas. The people of southern Mexico exploited virtually every source of water in their environment.

Many of the major water collection and irrigation structures have survived in excellent condition for 1,500 to nearly 3,000 years—testimony to their superb design and construction. These accomplishments are extraordinary by any measure but are particularly notable because the builders had no metal tools, no wheeled transport and no draught animals. Even the oldest surviving features represent a high level of technological innovation—and hint at sophisticated management to maintain this massive infrastructure. Although prehistoric water management systems have been discovered at a number of locations in Mexico, a close look at two of them—the extensive canals of the Tehuacán Valley and the fantastic terraced irrigation network in the Valley of Oaxaca—will illuminate the ingenuity of the ancient hydraulic engineers.

Modern investigation of these two sites began in the late 1960s and early 1970s, when two legendary figures in archaeology led major surveys: Richard S. ("Scotty") MacNeish in the Tehuacán Valley and Kent V. Flannery in the Valley of Oaxaca. One of us (Neely) was then a young graduate student and was privileged to participate in both studies. Water management was not the focus of either survey, and despite the obvious significance of these systems, a long hiatus followed the original modest assessments. Neely's fascination with prehistoric water management persisted, however, and in the late 1980s he invited a geologist (Caran, co-author of this article) to join him in a more thorough analysis of these waterworks. Our findings, as will be seen, were astounding.

Overview/*Ancient Irrigation*

- Prehistoric farmers in southern Mexico faced a water shortage six months of the year.
- To overcome this impediment to year-round cultivation, they developed ingenious ways to bring water to their crops. Their inventions included dams, wells, canals, aqueducts and terraced fields.
- Two of these systems illustrate the resourcefulness of these early engineers—a network of canals in the Tehuacán Valley and, in the Valley of Oaxaca, terraced gardens irrigated from canals atop the retaining walls.

© ROB WOOD *Wood Ronsaville Harlin, Inc.* (*preceding pages*); MELISSA THOMAS (*this page*)

HIERVE EL AGUA today still shows clear traces of the ancient terraced fields, here bordering one of the effervescent spring pools.

COURTESY OF JAMES A. NEELY

Canals, Aqueducts and *Tecoatles*

THE CANAL NETWORK in southern Mexico's Tehuacán Valley turned out to be the largest known prehistoric water management system in the New World. The total length of these canals spans more than 1,200 kilometers. They provided water for 330 square kilometers of cropland—an area almost the size of the Gaza Strip—and they did so 2,500 years ago. The irrigators created a canal by excavating a channel in the soil, probably building small levees on either side. Each canal carried water from an uphill source to a lower lying field, often following a meandering course to keep a gentle gradient of two degrees or less.

Most irrigation water was diverted from large springs. The springwaters were rich in dissolved minerals, particularly calcite, which is a form of calcium carbonate. These minerals preserved the canals by forming a leakproof lining but ultimately threatened their long-term survival. As springwater flowed through a canal, evaporation and changes in pressure and temperature caused the chemicals to become so concentrated that a thin layer of minerals crystallized on the canal's interior surface. The mineral contribution of each liter of water was minuscule, but flow through a major canal probably exceeded half a million liters daily. Layer on layer hardened into a stony coating known as calcareous travertine, similar to most stalactites and stalagmites in caves. These layers accumulated at the average rate of one centimeter a year, or one meter a century.

Deposition was so extensive that many of the canals eventually began to fill in. Flow continued, however, because travertine was deposited wherever the water overflowed as well as on the canal's floor. As a result, the walls of the canal became elevated, forming dikes that generally held the water in, even above ground level. Water continued to overflow occasionally, depositing mineral layers far outside the original canal. In this way, a former small channel in the soil became a ridge as much as five meters high and 30 meters wide at its base, with a canal along its crest [*see illustration on next page*]. Perhaps aided by periodic maintenance, a canal could thus retain its U-shaped cross section and continue to rise and function.

The rocky nature and elongate, sinuous form of these "fossilized" canals inspired their name in the language of the Aztecs: *tecoatl,* or "stone snake." Kilometers-long *tecoatles* literally transformed the landscape, creating barricades that affected the alignment of roads and the design of cities and towns from the prehistoric and the Spanish colonial periods to the present day.

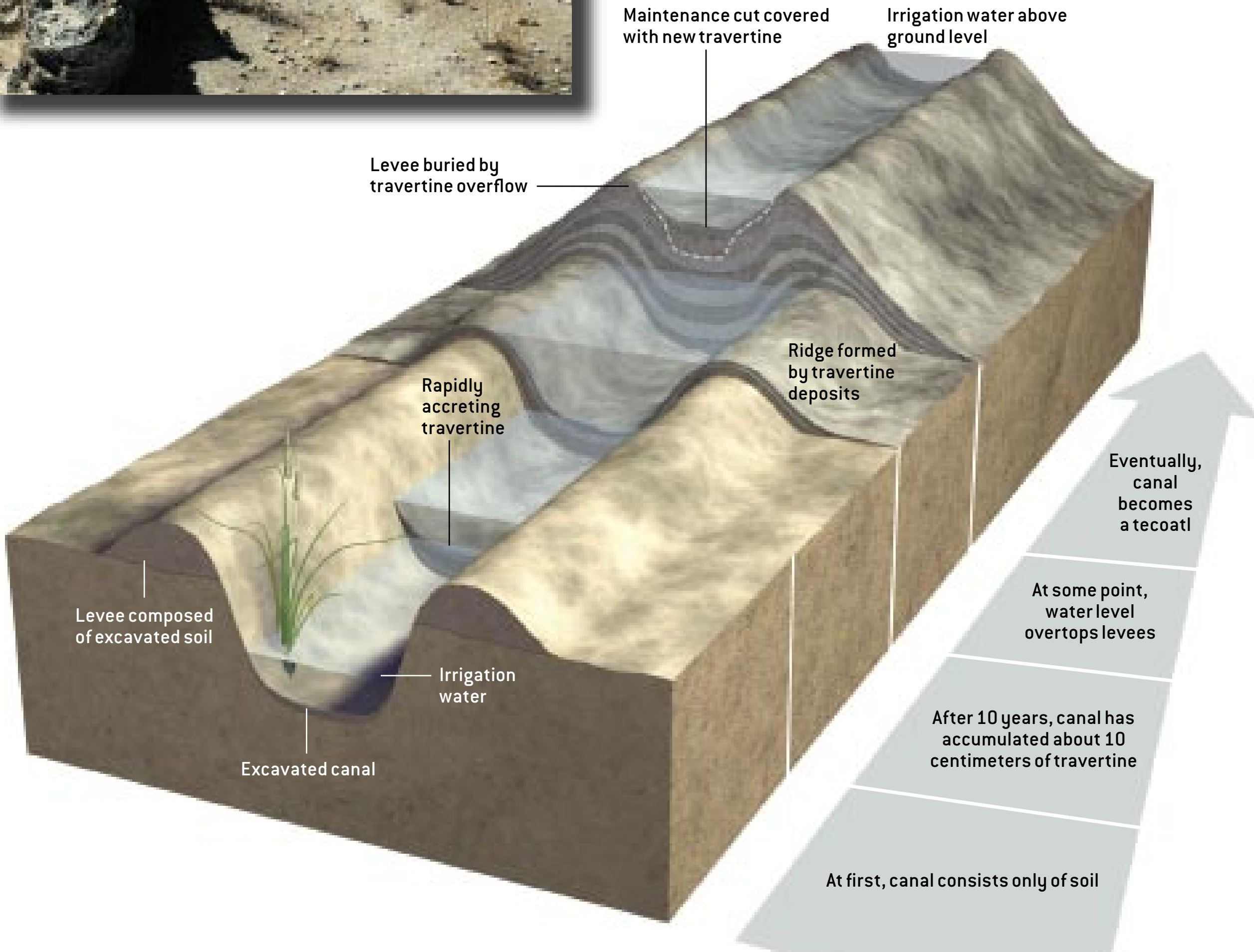
Where canals could not be constructed (across especially steep slopes, for example), the irrigators devised above ground channels—aqueducts—built of carefully laid unmortared stone and compacted earth. Compared with the largest Roman aqueducts from roughly the same period, these were relatively simple but were nonetheless effective structures.

The Rio Xiquila Canyon provides an interesting example. This site has two aqueducts, at different levels above the river. Both were about one meter wide and had a near constant grade despite the irregular canyon walls. Fragments of pottery of known type and antiquity indicate the age of the structures. The one-kilometer-long lower aqueduct, constructed in about A.D. 400, lay only four to 12 meters above the river. This segment was vulnerable to damage from floods and landslides and was abandoned in 700. The upper aqueduct, probably built about that time, was 20 to 22 meters above the river and more than six kilometers long. It remained in use until at least 1540. The aqueducts carried relatively fresh river water and did not become fossilized.

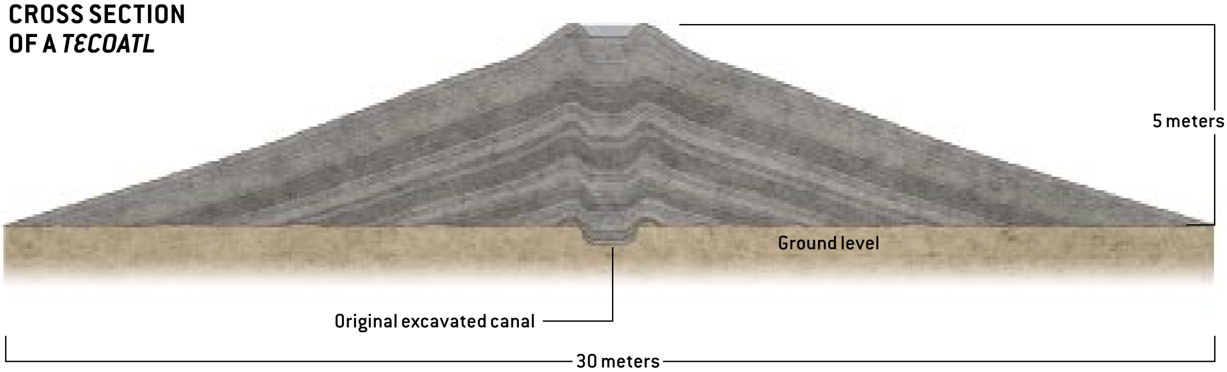
Those canals that were fossilized provide an indelible history of their use and the environment in which they oper-

THE FORMATION OF A *TECOATL*

The stone snake, or *tecoatl,* in the photograph is one of thousands that crisscross the Tehuacán Valley. Each *tecoatl* originated as a canal excavated into the soil (*diagram*). As springwater flowed through the canal, mineral deposits precipitated from the water, eventually forming a crust so thick that the water level in the canal rose aboveground. Despite this change in grade, the *tecoatles* continued to operate, rising as much as five meters, widening to 30 meters at the base and forming sinuous ridges as long as 15 kilometers.



CROSS SECTION OF A *TECOATL*



COURTESY OF JAMES A. NEELY (*photograph*); © MATTHEW FREY *Wood Ronsaville Harlin, Inc.* (*illustrations*) ated. Travertine layers trapped abundant remains of aquatic algae, diatoms, mosses and larger marsh plants that grew in and along the canals. Because these organisms are sensitive to variations in environmental conditions, we can reconstruct the water's chemical composition, nutrient load, flow rate and clarity. Travertine also preserved pollen from plants cultivated in nearby fields, revealing that the canals irrigated corn, peppers and tomatoes. Amaranth, harvested in modern and quite possibly ancient times, was either planted or grew wild at the borders of the fields. Cattails thrived along the canals—probably without cultivation—just as they do today, and ancient farmers may have collected these useful plants for food, fiber and arrow shafts.

Because the canals created an artificial aquatic habitat unlike the surrounding semiarid environment, we can be certain that the aquatic plants that make up most of the organic remains in the travertine were absolutely contemporary with the period of canal use. The preserved organic matter gave us a remarkable opportunity: we could use radiocarbon dating, which is based on the chemical properties of carbon from living organisms, to measure the age of the canals directly. Ordinarily, the age of ancient water systems must be inferred from habitation sites and artifacts in their vicinity, an approach fraught with ambiguity, because it is not always evident that these chronological indicators were contemporary. Radiocarbon analyses solved this problem, demonstrating that some of the canals were built as long ago as 800 B.C. and that work on these structures continued until the early 1500s.

Terrace Irrigation

SOME 170 KILOMETERS southeast of the Tehuacán Valley, in the mountains at the southern end of the Valley of Oaxaca, a truly remarkable archaeological site illustrates the inventiveness and adaptability of Mexico's prehistoric hydraulic engineers. At Hierve el Agua, irrigation supported continuous farming for at least 18 centuries, from about 500 B.C. to 1350. Several large perennial springs with unusual characteristics furnished the irrigation water. *Hierve el agua* is Spanish for "the water boils," but the water is not hot. Instead it is naturally carbonated, like the groundwater sustaining the famous bottled water industry of southern France. Naturally carbonated water contains an abnormally large amount of dissolved carbon dioxide gas, derived from magma, from the metamorphosis of limestone, or from other complex processes. Deep underground, the water is confined under great pressure, which keeps the gas in solution in the same way that a container keeps carbonated beverages pressurized.

At Hierve el Agua, fractures in the rock provide escape routes, allowing groundwater to rise to the surface very rapidly. As the water emerges, the sudden release of pressure is like removing the cap from a shaken bottle of soda: the water effervesces spontaneously, releasing gas bubbles that create small geysers and cause the springwater to churn as if boiling. The dissolved carbon dioxide also makes the groundwater acidic, so much so that it dissolves the predominantly limestone bedrock. Like the travertine in the Tehuacán Valley, limestone is composed of calcite, and the springwater at Hierve el Agua contains extremely high concentrations of dissolved calcium and bicarbonate. Thus, layers of water-deposited travertine preserved archaeological records at Hierve el Agua much as they did in the Tehuacán Valley.

A place where cool water boils must have sparked the curiosity of the area's early inhabitants, who discovered that they could use the water for irrigation during months when the monsoons were not bringing rain. The steep slopes just below the spring lacked natural soil cover, however, so the farmers moved five million cubic meters of soil to the site by hand to develop nearly two square kilometers of terraced fields. They appear to have selected the soil carefully, possibly even sieving it to produce an even, porous texture, thereby improving drainage. They began constructing the terraces by dry-laying stone retaining walls at carefully spaced intervals across the bare slopes. They placed soil on the upslope side of each wall to create a narrow terrace that was level with the top of the wall. The farmers then fabricated a small

THREE PARALLEL *TECOATLES* (*right*): The smaller ones are branches that led to nearby ancient fields. Beyond the white wall in the middle ground, the unexcavated main *tecoatl* can be traced toward what is now the center of Tehuacán City, where modern street construction (*below*) has damaged parts of the canal.

COURTESY OF JAMES A. NEELY

PURRÓN DAM (*at lower right in photograph above*) near Puebla, Mexico, is believed to be the largest water retention structure built in the Americas before the arrival of the Europeans. Construction began in 750 B.C. and continued at intervals until about A.D. 1150, when the dam stood almost 25 meters high and stretched 400 meters in length. The eroded southern profile of the dam (*far right*) dwarfs a six-foot-tall man.

COURTESY OF JAMES A. NEELY

"wall canal" atop each wall, in all constructing and maintaining more than 6.5 kilometers of such canals [*see illustration on pages 32 and 33*].

The wall canals had a gentle inclination, allowing water to be shunted into them from much larger water supply canals running directly down the slope from the springs. Additional small canals connected the downstream ends of the wall canals and carried water to terraces lower on the slope or returned flow to the supply canals. As water passed through a wall canal, it pooled in shallow circular basins, or *pocitos,* placed every few meters along its length in the floor of the canal. By dipping small vessels into the *pocitos,* the farmers obtained water for hand irrigating the plants growing on either adjacent terrace. In Spanish, this type of hand watering is known as *riego a brazo,* and it is still practiced in the region.

Close inspection of the terraces and canals reveals the brilliance of their design. The regular wall spacing and narrow width of the terraces restricted the amount of soil needed to create each terrace, while the immediate proximity of the wall canals and *pocitos* ensured ease of watering. Even on the steepest slopes, where the height of the retaining walls was as much as 2.4 meters, the width of the terraces was held relatively constant. Most are 2.4 to three meters wide, equivalent to two comfortable arm spans of a person 1.4 to 1.7 meters tall, which, as skeletal remains show, was the range in height of the ancient farmers. Small "weep holes" at the base of each terrace wall enhanced drainage and recapture of soil moisture. Hand watering and proper soil drainage were important because of the high mineral content of the water. If the amount of water were excessive or the water failed to drain properly, minerals would build up quickly, making the soil nonporous and too hard to turn by hand or to allow root growth.

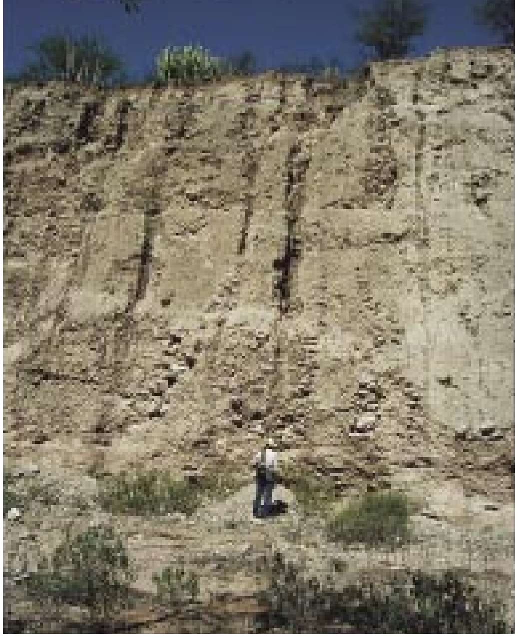
Flow was continually rerouted through the entire canal network, conveying water only to those wall canals where it was needed at a given time. Consequently, no single wall canal carried enough water to become a large *tecoatl*. Instead a relatively thin layer of travertine coats these canals, preserving many of the construction details. Particularly interesting is the absence of sluices or gaps through which water might have been diverted from the canals onto the terraces in quantity. This type of irrigation, known as flooding, would have caused the terraces to become entirely encrusted or infused with travertine, probably after only a few applications. By adopting a highly efficient method of hand watering, the farmers reduced mineral accumulation in the soil while minimizing the amount of water needed to maintain the plants on each terrace, thus increasing the total area that could be irrigated.

Watering was largely confined to the dry season. During the remainder of the year, rainwater helped to flush the accumulated minerals from the porous soil. This process was enhanced by decomposition of organic matter within the terrace soil. In addition to unharvested crop stubble, the organic matter may have included night soil and other domestic wastes, which were mixed in routinely to renew fertility.

We also found evidence for soil amendment using household debris: fragments of pottery of different ages lie within the terrace soil in chronological order, from the bottom to the top of the fill. Ceramic vessels can sometimes be dated directly by radiocarbon techniques or indirectly through stylistic classification of their form, composition and color pattern, once a particular type has been found at a site with an established chronology. Besides providing a record of ongoing waste disposal, the pottery at Hierve el Agua had the unintended archaeological benefit of defining which kinds of vessels were in everyday use and therefore most likely to be broken. In this way, we learned that the people who were working the fields disposed of trash that included both everyday domestic ceramics and finer serving wares, whereas much finer vessels are found only at a small temple at this site.

THE AUTHORS

S. CHRISTOPHER CARAN and *JAMES A. NEELY* share a longtime interest in the prehistoric water management systems of Mexico and the American Southwest. Caran has been a research geologist at the University of Texas at Austin, specializing in Quaternary studies, and is currently president of Quaternary Analysis Laboratories in Austin. Neely is professor emeritus in the department of anthropology at the University of Texas at Austin; his research has focused on the development of agriculture. Neely discovered most of the water management systems discussed in this article in the 1960s and 1970s; he has investigated them intensively since then, in part with Caran from 1988.



COURTESY OF JAMES A. NEELY

A Technological Saga

THE SEEMINGLY ABRUPT origin of fully developed, large-scale irrigation technology appears puzzling at first. But this apparent absence of more modest forerunners is most likely the result of gaps in the archaeological record. Our discovery in 1993 of what may be the oldest water well in the New World indicates that water management may have had a much older, albeit embryonic, beginning than was previously recognized. Excavated nearly 10,000 years ago, the well was five meters deep and 10 meters in diameter at the former ground level, which was subsequently buried. It may have remained in use for 2,000 years. The well, in what is now the village of San Marcos Necoxtla in the Tehuacán Valley, probably predates New World agriculture. Although it was most likely not used for irrigation, it does provide evidence that water management in this region began very early indeed.

We have found no examples of hydraulic construction in the intervening centuries between the digging of this well and about 3,000 years ago, when the first canals appear. It is, however, probable that small wells, temporary weirs for diverting water from streams, or other simple water supply features were built during this period. The earliest cultivation may have initially required water hauling or small-scale irrigation using canals that were not preserved or have not been discovered.

But the question still remains of how the early hydraulic engineers of Mexico managed to lay out canal routes many kilometers long over highly irregular terrain, while maintaining a continuous downward gradient of less than two degrees. Today comparable construction would be impossible without sophisticated surveying instruments. The ancient Egyptians used levels and calibrated rods for sighting over long distances. Although such simple yet effective tools and methods must also have been available to the engineers in Mexico, we have no direct evidence of these details.

We do have a partial answer to how they planned the canal systems. At a remote locality in the Tehuacán Valley, a line of small boulders leads away from a sharp bend in a *tecoatl*. This line extends down the short slope of a notch in a ridge, then up the other side to a slightly higher point immediately above a small valley lacking canals. The line of boulders may have been a "blueprint" for future canal construction. For water to reach the other side of the notch, the existing *tecoatl* would have to build upward at least a meter before the new branch could be constructed. If the builders allowed for normal travertine accretion, that goal might be reached in a century, at which time the farmers' descendants could add another irrigated field to the system.

Whether these projects were developed and controlled by individual users or by a more centralized authority is another of the many questions fascinating archaeologists. In the 1950s the well-known historian Karl A. Wittfogel advanced the hypothesis that large-scale exploitation and distribution of water resources were essential steps in the rise of civilizations worldwide. According to this principle, only "hydraulic societies" achieved the hallmarks of a sophisticated culture, such as permanent agriculture, economic diversity, record keeping and hierarchical administration. A hydraulic society became civilized because a reliable water source provided both the incentive and capacity to do so. Yet the inverse also seems implicit: construction and maintenance of an extensive water management infrastructure might require the focused attention of a well-organized state. Other investigators have questioned both these propositions, pointing out that small, loosely organized sociopolitical entities could build and operate water systems of at least moderate scale, perhaps in cooperation with similar neighboring organizations but without a central authority.

Evidence exists for each of these interpretations. Modern irrigation in the Tehuacán Valley, for example, is managed by community-based, nongovernmental *sociedades de agua* ("water societies"), which trace their ancestry to native traditions. Even today these highly coveted water rights are often conveyed by inheritance, a practice that can be traced back to precolonial times in the Aztec codices and in early Spanish documents. Each small community is responsible for proper use and maintenance of its part of a larger canal system, but overall management is effected by consensus among the various partner communities. Thus, the system operates both locally and collectively.

The debate about how ancient societies constructed and managed their hydraulic infrastructure will continue. What is not controversial is that the systems in southern Mexico stand as engineering marvels, ranking among the pinnacle achievements of prehistoric builders anywhere in the world. SA

MORE TO EXPLORE

The Keepers of Water and Earth: Mexican Rural Social Organization and Irrigation. K. I. Enge and Scott Whiteford. University of Texas Press, 1989.

Irrigated Agriculture at Hierve el Agua, Oaxaca, Mexico. J. A. Neely et al. in *Debating Oaxaca Archaeology.* Edited by J. Marcus. University of Michigan, Museum of Anthropology, Anthropological Papers No. 84, 1990.

A Late Paleo-Indian/Early Archaic Water Well in Mexico: Possible Oldest Water-Management Feature in the New World. S. C. Caran et al. in *Geoarchaeology: An International Journal,* Vol. 11, No. 1, pages 1–36; January 1996.

A Contextual Study of the "Fossilized" Prehispanic Canal Systems of the Tehuacán Valley, Puebla, Mexico. J. A. Neely in *Antiquity,* Vol. 75, No. 289, pages 505–506; 2002.