GIS for SCIENCE

APPLYING MAPPING & SPATIAL ANALYTICS

**Book Chapter Excerpt:
Mapping Ancient Landscapes**

DAWN WRIGHT & CHRISTIAN HARDER, EDITORS

GIS for SCIENCE

APPLYING MAPPING AND SPATIAL ANALYTICS

DAWN J. WRIGHT AND CHRISTIAN HARDER, EDITORS

Esri Press | Redlands, California

Esri Press, 380 New York Street, Redlands, California 92373-8100

Printed in the United States of America
23 22 21 20 19 1 2 3 4 5 6 7 8 9 10

Christian Harder and Dawn J. Wright, eds.; *GIS for Science: Applying Mapping and Spatial Analytics*; DOI: https://doi.org/10.17128/9781589485303

Library of Congress Control Number: 2019936340

Ask for Esri Press titles at your local bookstore or order by calling 800-447-9778, or shop online at esri.com/esripress. Outside the United States, contact your local Esri distributor or shop online at eurospanbookstore.com/esri.

Esri Press titles are distributed to the trade by the following:

In North America:
Ingram Publisher Services
Toll-free telephone: 800-648-3104
Toll-free fax: 800-838-1149
E-mail: customerservice@ingrampublisherservices.com

In the United Kingdom, Europe, Middle East and Africa, Asia, and Australia:
Eurospan Group
3 Henrietta Street
London WC2E 8LU
United Kingdom
Telephone: 44(0) 1767 604972
Fax: 44(0) 1767 601640
E-mail: eurospan@turpin-distribution.com

All images courtesy of Esri except as noted. Developmental editing by Mark Henry; Technology Showcase editing by Keith Mann; Cover layout and book design by Steve Pablo; Cover concept by John Nelson.

The cover image shows a lidar-derived colored hillshade of glacial ice and snowfields on Mount Rainier in Washington State, United States, compared to the glacial extent of the same area from 1924. The lidar data is from a survey completed in 2008 by the National Park Service. Image by Daniel Coe, Washington Geological Survey. The lidar portion of the image was modified from Robinson, Joel E., Thomas W. Sisson, and Darin D. Swinney. 2010. Digital Topographic Map Showing the Extents of Glacial Ice and Perennial Snowfields at Mount Rainier, Washington, based on the LIDAR survey of September 2007 to October 2008: US Geological Survey Data Series 549. The 1924 extent of glacial ice was derived from: US Geological Survey, 1924, Mount Rainier Quadrangle, Washington: US Geological Survey, 1 sheet, map scale 1:125,000.

See this book come alive at

GISforScience.com

PRAISE FOR *GIS FOR SCIENCE*

"This book is beautiful as well as illuminating, and it dramatizes the ways in which the new science of geospatial information is enriching and empowering all other scientific disciplines."

—James Fallows, staff writer, *The Atlantic*; former chief speechwriter for President Jimmy Carter

"If you love maps like I do, you'll be drawn to this book. But you'll quickly discover so much more: the power of harnessing multiple perspectives and data types that infuse maps with even more meaning and catalyze new insights. A veritable treasure trove of ideas. "

—Jane Lubchenco, environmental scientist, marine ecologist, former Administrator of the National Oceanic and Atmospheric Administration (2009-2013); former U.S. Science Envoy for the Ocean (2014-2016); university distinguished professor

"GIS has become *the* foundational tool for all things environmental—from conservation to climate change to environmental justice. This astonishing book beautifully displays GIS in all its scientific, artistic, and creative splendor."

—Peter Kareiva, director, UCLA Institute of the Environment and Sustainability

"Dawn Wright and Christian Harder have given us a geoscience book for the twenty-first century! Cutting-edge research examples and gloriously illustrated state-of-the-art, GIS-enabled techniques come together to show us how to understand our planet in ways not possible even a few years ago."

—Margaret Leinen, Director of Scripps Institution of Oceanography and UC San Diego Vice Chancellor for Marine Sciences

"The only thing changing faster than Earth's environment and our species' imprint on it, for better and worse, is the information environment. In that noisy realm, trolls and other troublemakers get the headlines. But this essential and beautiful book illuminates how a host of innovators are gleaning meaning from data and helping shape a sustainable human journey."

—Andrew Revkin, strategic adviser, National Geographic Society, and coauthor of *Weather: An Illustrated History, from Cloud Atlases to Climate Change*

"The Science of Where® comes alive in *GIS for Science*. The book is, yes, informative, helping us understand how the world works, how it looks, and how we see it through images, maps, and more. Above all, it is dazzling, combining knowledge with a sense of wonder, bringing a desire to press for more discovery, and invoking a deep appreciation for why smart decisions spring from taking science to action."

—Lynn Scarlett, vice president, The Nature Conservancy; chair, Science Advisory Board, NOAA

"A textbook and a work of art."

—Len Kne, U-Spatial associate director,
University of Minnesota Research Computing, Office of the Vice President for Research

"Illustrating the power of geospatial analytics to address pressing challenges facing our planet, *GIS for Science* is a *tour de force*. The editors and contributors have produced a visual delight that will inspire and enlighten researchers, citizen scientists, and the public about the contribution of the geographic perspective to the scientific process."

—Sergio Rey, director, Center for Geospatial Sciences, UC Riverside

"The editors and authors of this unique graphical science book, published by Esri Press, show the criticality of asking the 'where' question when looking for answers to the 'why' question. It is visually stunning and will certainly lead to an expanded cohort of citizen scientists."

—Noel Cressie, distinguished professor, University of Wollongong, Australia

"Given the relevance of this geospatial perspective for all aspects of society, I hope this beautiful book will inspire a wide range of people to embrace The Science of Where®."

—Thomas Crowther, director, Global Forest Biodiversity Initiative, ETH-Zurich

"With vivid imagery, lucid writing, interactive learning, and compelling, relevant examples from Earth's past, present, and future, *GIS for Science* is a modern manual for understanding that integrative spatial analysis and visualization is the big data revolution most vital to the quality of all life on Earth."

—Healy Hamilton, chief scientist, NatureServe

"There is no better tool to understand our place in the world than GIS, and this book puts its power on beautiful display. It's a book for scientists and all of Earth's stewards."

—Jessica Hellmann, director, Institute on the Environment, University of Minnesota

"This beautifully illustrated and inspiring book brings home the power of today's technology with unique effectiveness, telling and illustrating stories from the earth sciences in novel and powerful ways. A must-have book for anyone concerned about the planet's future."

—Mike Goodchild, distinguished emeritus professor and research professor of geography, UC Santa Barbara

CONTENTS

GIS FOR SCIENCE: A FRAMEWORK AND A PROCESS

by Jack Dangermond, Founder and President, Esri
and Dawn J. Wright, Chief Scientist, Esri

Science—that wonderful endeavor in which someone investigates a question or a problem using reliable, verifiable methods and then broadly shares the result, has always been about increasing our understanding of the world. In the beginning, we applied geographic information systems (GIS) to science—to biology, ecology, economics, or any of the other social sciences. It wasn't until around 1993, when Professor Michael Goodchild coined the term *GIScience,* that the world began to realize that GIS is a science in its own right. Today, we call this The Science of Where®. GIS incorporates sciences such as geology, data science, computer science, statistics, humanities, medicine, decision-support science, and much more. It integrates all these disciplines into a kind of metascience, providing a framework for applying science to almost everything, merging the rigor of the scientific method with the technologies of GIS. The study of where things happen, it turns out, has great relevance.

So why is this work all so important right now? We live in a world that faces more and more challenges. We see, we hear, and we read daily about such issues as growing population (some would say overpopulation), climate change, loss of nature, loss of biodiversity, social conflicts, urbanization, natural disasters, pollution, and political polarization. We also confront the realities of food, water, and energy shortages, and general overconsumption of resources. These concerns are not trivial for the individuals and organizations working in these fields. We must do everything we can to better understand these crucial issues and form better collaborations to address the challenges.

Our world at the same time is undergoing a massive digital transformation. Science always has been about increasing our understanding of the world. But it is also about using that understanding to enable innovation and transformation. It is about what we can measure, how we analyze things, what predictions we make, how we plan, how we design, how we evaluate, and ultimately, how we weave it all together in a kind of fabric across the planet.

What GIS provides is a language to help us understand and manage inside, between, and among organizations, to positively affect the future of the planet. It is also a framework in which we can compile and organize maps, data, and applications. We can visualize and analyze the relationships and patterns among our datasets, perform predictive analytics, design and plan with the data, and ultimately transform our thinking into action to create a more sustainable future. This technology also delivers a new way to empower people to easily use spatial information. As Richard Saul Wurman has said, "Understanding precedes action." Esri is driven by the idea that GIS as a technology is the best way to address the challenges of today and the future.

Science itself is driven by the organic human instinct to dream, to discover, to understand, to create.

This book is full of examples that show how GIS advances rigorous scientific research. It shows how many science-based organizations use ArcGIS as a comprehensive geospatial platform to support spatial analysis and visualization, open data distribution, and communicate. In some cases, we use this research to preserve and restore iconic pieces of nature—revered and sacred places worthy of being set aside for future generations. These places belong to nature, and they also belong to science.

As scientists, the discipline of the scientific process is the central organizing principle of our work. But science itself is also driven by the organic human instinct to dream, to discover, to understand, to create. The Science of Where is a concept that brings these impulses together as we seek to transform the world through maps and analytics, connecting everyone, everywhere, every day through science. At Esri, we can't wait to see what you and your colleagues will achieve with geospatial technology.

Jack Dangermond   Dawn J. Wright

INTRODUCTION BY THE EDITORS

This book is about science and the scientists who use GIS technology in their work. This contributed volume is for professional scientists, the swelling ranks of citizen scientists, and anyone interested in science and geography. Our world, now two decades into the twenty-first century, seems to be entering a crucial time in history in which humanity still can create a sustainable future and a livable environment for all life on the planet. But if we look critically at the facts, no informed observer can refute the reality that the current downward trajectory does not bode well.

Our first objective in assembling this volume was to select relevant and interesting stories about the state of the planet in 2019. We looked for a cross section of sciences and scientists studying a wide range of problems.

GIS has found its way into virtually all the sciences, but the reader will notice that earth and atmospheric sciences are especially well represented. Web GIS patterns and a simultaneous explosion of earth-observation sensors fuel this growth. Between all the satellites, aircraft, drones, and myriad ground-based and tracking sensors, the science community is now awash in data. Well-integrated GIS solutions integrate all this big data into a common operating platform—a digital, high-resolution, multiscale, multispectral model of our world.

Despite all these advances, science is under attack on many fronts. From fake news to political pressure, science is too often being used as a political tool at a time when level-headed, objective scientific thinking is required. We are convinced that GIS offers a unique platform for scientists to elevate their work above the fray. We invite you to read these stories in any order; the common thread is that all this work happens at the intersection of GIS and science. As you read through these stories, you'll see that GIS is a cross-cutting, enabling technology, whose use is limited only by our imaginations.

In some cases, like the fascinating work of the US Geological Survey in developing global ecosystem characterizations of the land and ocean, GIS and spatial analysis are at the core of the science. These innovations in science could only happen in the context of an advanced GIS. In other cases, like the story of glaciologists using ground-penetrating radar to measure ice loss in the high-country glaciers of Wyoming, GIS embeds itself in the science but is still mission-critical in terms of expedition planning, backcountry navigation, and analysis. GIS also serves as a vital storytelling platform that brings critical details of important research to stakeholders in the local community.

How the book and website work together

It's impossible to describe the full breadth and scope of what GIS means for science and scientists without showing digital examples. So we have created a companion and complement to this book online. You can access it here:

GISforScience.com

This unique website, comprising collections of ArcGIS® StoryMaps℠ stories, apps, and digital maps, brings the real-world examples to life and demonstrates the storytelling power of the ArcGIS® platform. The website also includes links to learning pathways from the Learn ArcGIS site (Learn.ArcGIS.com) and blogs related to the practical use of ArcGIS in each of the case studies.

MAPPING ANCIENT LANDSCAPES

Racing against the clock as development encroaches on important Kurdish heritage sites, a team of landscape archaeologists deploys drones and comparative image analysis to capture previously undetected ancient settlements.

By Jason Ur and Jeffrey Blossom, Harvard University

Drone-acquired image[1] of the site called Qasr Shamamok, located not far from Erbil, in the Kurdish region of Iraq. It was recently excavated by a team of archaeologists who showed that the occupation probably dates to the Chalcolithic, with important Assyrian remains from the late fourteenth century to the seventh century BCE.

THE ASSYRIAN EMPIRE

In late spring of the year 612 BCE, the combined armies of the Babylonians and Medes arrived outside the gates of Nineveh on the Tigris River in what is today northern Iraq. At the time, Nineveh was still the capital of the Assyrian state, but Assyria's fortunes were on the wane. Two years earlier, the ancestral city of Ashur had fallen to the Medes. The attacking forces besieged the city for a few months before ultimately breaking through its defenses and sacking and burning it. The royal court survived for a few years in northern Syria, but for all intents and purposes, the Assyrian Empire came to a violent end that day. It was an ignominious end for what had been the most powerful state in the Near East in its day and arguably the first unambiguous world empire.

At its height, the Assyrian kings ruled the lands of the Fertile Crescent, from the Nile River to western Iran from the imperial heartland along the Tigris River. Originating at the city of Ashur in the middle of the second millennium, the

The extent of the Assyrian Empire, ca. 705 BC.[2] The extent of the Erbil Plain Archaeological Survey is indicated by the black polygon.

kingdom's fortunes grew and fell (but mostly grew) to include most of modern Iraq and Syria and large parts of Iran, Turkey, Jordan, Lebanon, and Israel. From Ashur, its kings relocated its capital to Nimrud, Khorsabad, and ultimately to Nineveh, which at the time of its destruction was the largest city in the world. These cities were supported by massive landscape projects—dammed rivers, long canals, and carefully engineered aqueducts. Most of these projects were covered by ideologically charged inscriptions and reliefs that made it clear to all the power of the Assyrian king and his divine supporters. But who inhabited these cities and landscapes?

In cuneiform inscriptions on the walls of their palaces, the kings themselves describe their conquests and how they removed entire kingdoms—their people, animals, and possessions—and brought them back to Assyria or other parts of the empire. Such inscriptions are inherently propagandistic and not to be read without skepticism, but in at least one case, the accounts of the victims of Assyrian deportation practices tell us the same story.

The heartland of ancient Assyria thus presents a series of interesting geographic questions. In what ways, and to what degree, did Assyrian kings and planners deliberately alter the landscape? Did they really deport several million conquered persons, and if so, where did they go? What impact did these forced migrations have on the landscape? Did these precocious transformations survive the political power behind them? As powerful as they were, the Assyrians were neither the first nor the last great power to dominate the Near East; how do their impacts compare with what came before them, and how did they structure those that followed?

Archaeologists' ability to answer these and other geographic questions about past civilizations have been revolutionized by the use of GIS. This chapter describes how a Harvard-led international team of archaeologists uses georeferenced drone imagery, historical satellite imagery, and good old-fashioned boots on the ground to investigate the traces of this once-mighty empire in its former core provinces, today the autonomous Kurdistan region of Iraq.

The Assyrian Empire was ruled from a sequence of capital cities on the Tigris River. King Ashurnasirpal founded the city of Kalkhu (modern Nimrud)[3] at the start of his reign in the ninth century BCE. A citadel mound held his palace and important temples. It was a vast lower town enclosed within a city wall (blue). Processional boulevards 20 m wide (red) have been found using satellite imagery.

The Assyrian kings built great cities with large palaces, most of which were adorned with marble reliefs showing the king performing various royal duties. On this stone carving,[4] King Ashurnasirpal conducts a ritual after a successful lion hunt, with attendants and courtiers looking on.

LANDSCAPE ARCHAEOLOGY

The discipline of archaeology reanimates the past using its material remains. In public perception, these remains are artifacts—most often the detritus of daily life such as broken pottery, discarded stone tools, the waste of meals and mundane activities—but occasionally sensational finds such as the contents of royal tombs, palaces, and temples. Archaeologists find these objects via excavation and record them in 3D space. In more than 150 years of archaeology as an academic discipline, we have developed robust methods for turning them from data into interpretations.

In the later twentieth century, however, archaeologists realized that we cannot dig ourselves into answers for many important questions—particularly geographical questions about matters such as the migrations of hominids, the environmental impacts of agriculture, the origins of cities, and the nature of imperial landscapes. No excavation trench will ever be large enough.

For these and many other questions, the discipline of landscape archaeology has emerged. It shifts focus away from objects to a broader dataset of artifacts, sites, and landscape features—often captured from remote sensing platforms such as satellites, aircraft, and most recently drones—positioned and analyzed in time and 3D space. The origins of landscape archaeology were in the realization that the distribution of surface artifacts on a site was meaningful, and the arrangement of sites across a landscape could give important clues to the nature of past society, including its economic, political, and even religious structures. More recently, the spaces between sites (the traditional subject of archaeological study) have been recognized to contain a range of "off-site" features, such as tracks, roads, irrigation canals, field systems, and various symbolic monuments. These features are often more ephemeral than the sites that result from habitation, but they can be detected and mapped sometimes quite readily through the study of imagery.

Declassified intelligence satellite imagery from the 1960s reveals spectacular landscapes that are often invisible on the ground or since destroyed. The lines of light spots in this CORONA photograph[5] from February 1967 mark collapsed shafts leading down to subterranean water channels. These features fed water to the medieval town at lower left. Today they have been completely obliterated by industrial agriculture.

GPS device and CORONA photographs.

In the distance, a large mounded archaeological site rises over the Erbil Plain. In the foreground, a small low site is capped by a solitary abandoned structure. Today most of the plain is agricultural land, but it is rapidly developing as the city of Erbil expands.[6]

The tools of landscape archaeology have evolved radically in the past decades. In the twentieth century, archaeologists surveyed the landscape with a compass, pencil, paper, and their feet on the ground. Lucky ones might have access to aerial photographs. Landscape-scale phenomena are well studied from a vertical or remote perspective, and the availability of commercial high-resolution satellite imagery and declassified historical satellite imagery has been transformative. Around 2000, compasses began to be replaced by global positioning system (GPS) receivers; pencil and paper gave way to GIS software—first in the lab and later on mobile devices in the field.

Today, landscape archaeological research can be entirely digital, with precision global navigation satellite system (GNSS) receivers, smartphone-based mapping apps, imagery courtesy of a drone buzzing overhead in real time, and spatial data shared instantly with team members and even the public via cloud storage and web maps. Of course, we still do a great deal of walking; feet on the ground have yet to become obsolete.

Bashtapa from an altitude of about 400 ft.

Drones have revolutionized landscape archaeology, especially our ability to visualize ancient sites such as Bashtapa, as shown in the accompanying image. Here, team members Khalil Barzinji (left) and Nader Babakr oversee a drone mapping flight.

In rapidly developing areas, the traces of ancient land use are often threatened by the modern landscape. In this river valley, a 20-m-wide Assyrian dam was revealed by industrial gravel mining, which now threatens to destroy it.

THE KURDISTAN REGION OF IRAQ

Our research on the Mesopotamian past takes place in the modern Kurdistan region of Iraq. The Kurdistan region is predominantly mountainous, the western flanks of the Zagros Mountain chain that has been the traditional home of the Kurds and their ancestors for millennia. Farmers grew crops in narrow highland valleys and plains below the foothills, and pastoralists led their animals from high summer pastures to winter grazing on the plains near the Tigris River. Some towns existed, such as Rowanduz and Erbil, but the Kurds were predominantly a rural people.

At the start of the twentieth century, the Kurds lived as part of the Ottoman Empire, where they were restive but largely autonomous. After World War I, their lands were divided among the new countries of Turkey, Syria, and Iraq, also with communities in western Iran. Within the Republic of Iraq, the twentieth century was a time of fluctuating levels of strife between the Kurds in the north and the Arab-dominated national governments in Baghdad. It culminated in the genocidal Anfal campaign of the late 1980s, in which towns were gassed, approximately 3,000 villages were destroyed, and more than 50,000 men and boys were taken away, never to be seen again.

The Republic of Iraq and its autonomous Kurdistan region.[7]

As of this writing, the Kurdistan region of Iraq has rebounded. The rural countryside is being repopulated, and the cities of the Kurdistan region are being developed rapidly, particularly Suleimaniya and Erbil, the capital. The region is politically stable, safe, and welcoming to foreigners, including Western researchers. The Erbil Plain Archaeological Survey (EPAS) is a Harvard-led collaboration between foreign and local archaeologists in Erbil (population 850,000) in the Kurdistan region. It is identifying and mapping all archaeological sites on the plain of Erbil using all available tools and resources.

The renaissance in the Kurdistan region includes a desire to understand its past. In the twentieth century, the national governments in Baghdad promoted a national history, which focused almost exclusively on the civilizations of the southern plain between Baghdad and Basra. The Kurdistan region was left out of this history; few excavations were conducted, and foreigners were explicitly kept out of the region.

Today, the Kurds are interested in developing their own history, and the place to start is with documentation of the full cultural landscape of the region. Local archaeologists have been trained in traditional excavation methods, which are poorly suited for such a broad geographic undertaking. For this reason, they have been willing to partner with foreign research projects to develop a region-wide inventory of archaeological sites and historical places and to learn to use modern technologies such as drones, accessible historical imagery, and related geospatial tools and techniques.

A Royal Air Force plane took this oblique view[9] of Erbil in November 1938. It serves as an invaluable snapshot on which to build an understanding of the ancient landscape.

At the center of the modern city of Erbil sits the qala (citadel) mound.[8] After six millennia of settlement, it is still crowned by traditional mud-brick houses. In 2016, it was named as a World Heritage Site.

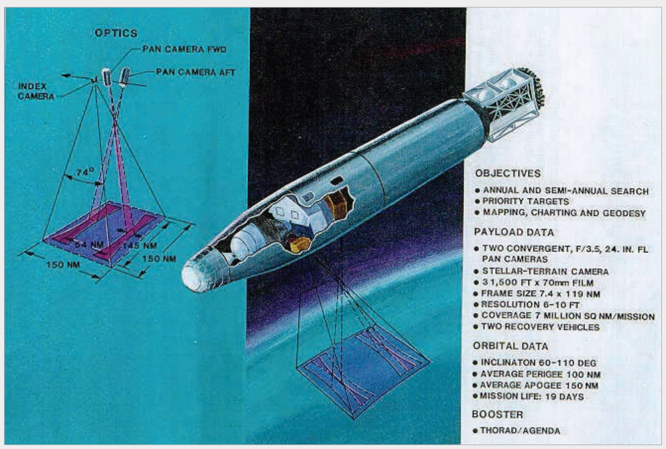
Traditional Kurdish lifeways revolved around agriculture and animal husbandry, which still characterize the rural plains around Erbil.[10]

SPYING ON ANTIQUITY

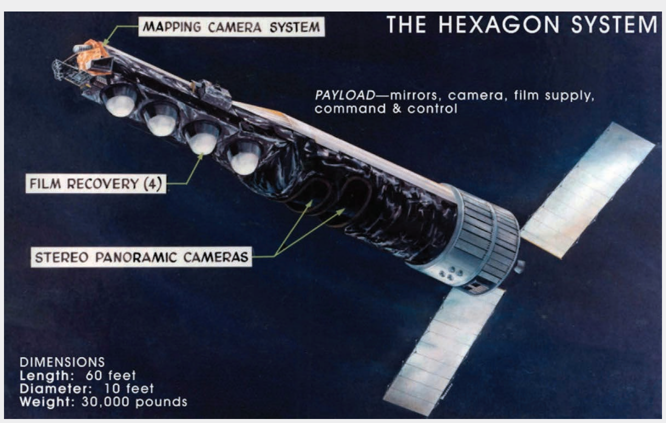
Archaeologists often fantasize about time machines that would allow us to witness firsthand the people and places of the past. Landscape archaeologists increasingly rely on the next best thing: historical remote sensing sources. The late twentieth century was a time of global development, particularly in the countries of the Middle East. As a result, the remains of past settlements and landscapes have often been badly degraded by the time archaeologists attempt to study them: cities and roads grow over them, agricultural developments plow them up, or hydroelectric dams flood them. If we can find aerial or satellite imagery that predates these developments, we can often reconstruct elements of the past that barely survive or no longer survive at all. Historical imagery has proven to be extremely powerful for this work.

Site identification depends heavily on historical remote sensing sources, especially U2 aerial photographs (1958–1960), KH-4 CORONA (1966–1968), and KH-9 HEXAGON (1972–1984) satellite photographs.

U2 aerial photographs (code named CHESS).[11] *In the late 1950s, the United States flew missions over Middle Eastern countries from a base in Adana, Turkey. The photos were taken from an altitude of over 21,000 m and included vertical and near obliques and occasionally obliques up to the horizon. At best, they are better than 50 cm spatial resolution. The cameras ran continuously and covered a swath that was roughly 35 km wide along the plane's flight path. Eleven missions comprising over 50,000 frames have been declassified and their film deposited in the US National Archives. U2 images have been instrumental in identifying ancient sites and canal systems in the EPAS region.*



KH-4 satellite photographs (code named CORONA).[12] *The first US intelligence satellite program acquired imagery from 1960 to 1972. Spatial resolution was much coarser than U2 (1–2 m in the later systems) but geographic coverage was much greater. CORONA was declassified in 1995, and its imagery has been available since 1998. Many scenes can be downloaded freely from the US Geological Society (USGS) EarthExplorer portal. It has emerged as a critical resource for Middle Eastern archaeology, serving as the basis for dozens of projects. EPAS relies heavily on Mission 1039 (February 28, 1967) to identify sites, and we use it as a base image for mobile GIS.*



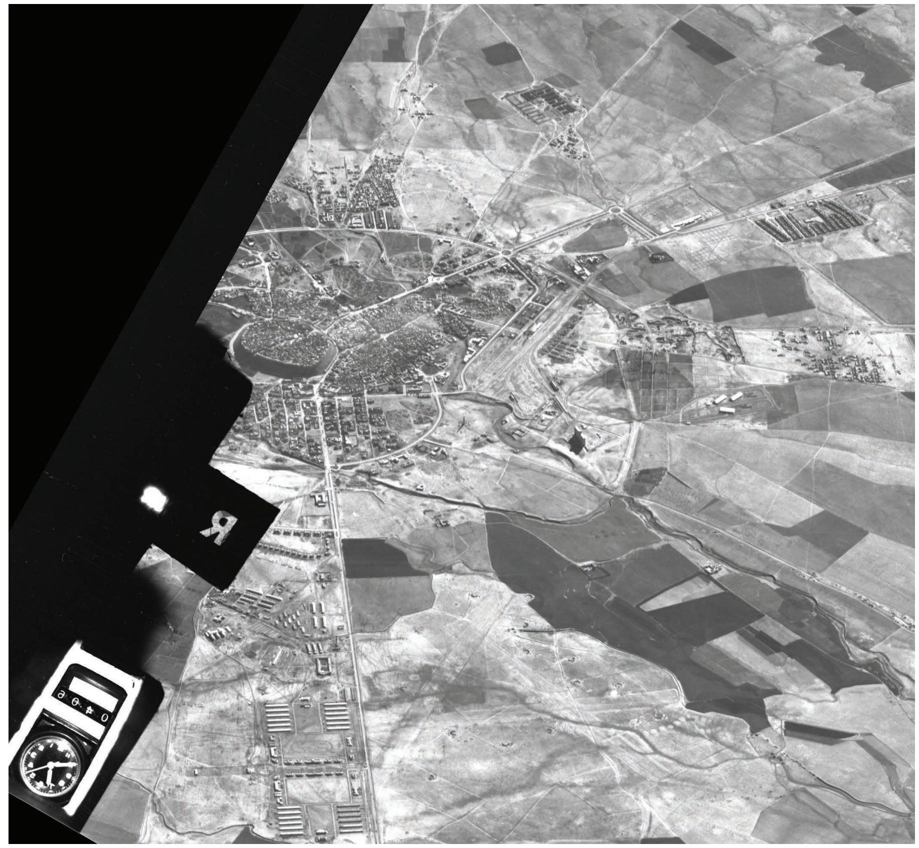
KH-9 satellite photographs (code named HEXAGON).[13] *Running from 1971 to 1984, HEXAGON was the successor to CORONA, with a similar footprint but much higher resolution (ca. 50 cm) and more frequent target revisits. HEXAGON satellites flew over the Erbil Plain at least a dozen times. Like the U2 films, HEXAGON film is held by the US National Archives.*

Because of the extreme geometric challenges of CORONA and HEXAGON, most scenes were georeferenced with a global third-order polynomial transformation. Scenes for our primary base imagery dataset, CORONA mission 1039 (February 28, 1967), were transformed using the spline method, which emphasizes local accuracy of specific ground control positions. Geo-corrected images are stored in a raster mosaic dataset in an ArcGIS geodatabase.

These source datasets are all panchromatic film—scanned into high-resolution grayscale raster imagery—which when incorporated into the geodatabase, become extraordinarily powerful tools for identifying ancient places. When a mud-brick settlement is abandoned, natural agencies will cause it to decay back into an earthen mound, with a lighter, looser soil texture than the natural soils that surround it. These anthropogenic soils often stand out strikingly as light areas on panchromatic photographs because they are drier and often host less vegetation. Conversely, depressed features such as canals and trackways collect moisture, and therefore promote vegetation growth; they appear as dark lines.

EPAS team members have georeferenced dozens of declassified historical images by using ArcGIS® Online basemap imagery as ground control. These visual signatures help researchers recognize potential ancient features, which are vectorized into points, lines, and polygons within the desktop software ArcGIS® Pro. In this manner, EPAS recognized over 1,600 potential sites, nearly 170 km of ancient canals, and over 340 km of premodern trackways before setting foot in the field.

But while remote sensing is clearly a powerful tool, it is still only the first step—these features must be confirmed on the ground. While rooted in old traditions of archaeology, the fieldwork described next has in its own way been revolutionized by geospatial technologies, most notably the use of highly accurate GPS receivers and other internet-connected devices that allow real-time access to maps and features in the geodatabase.



A U2 spy plane took this oblique view of Erbil in January 1960[14] as it banked sharply to the left. Nearly all the agricultural land visible in this photograph is now under the modern city. The analog clock face on the corner was a predigital means of what we would today call an image time stamp.

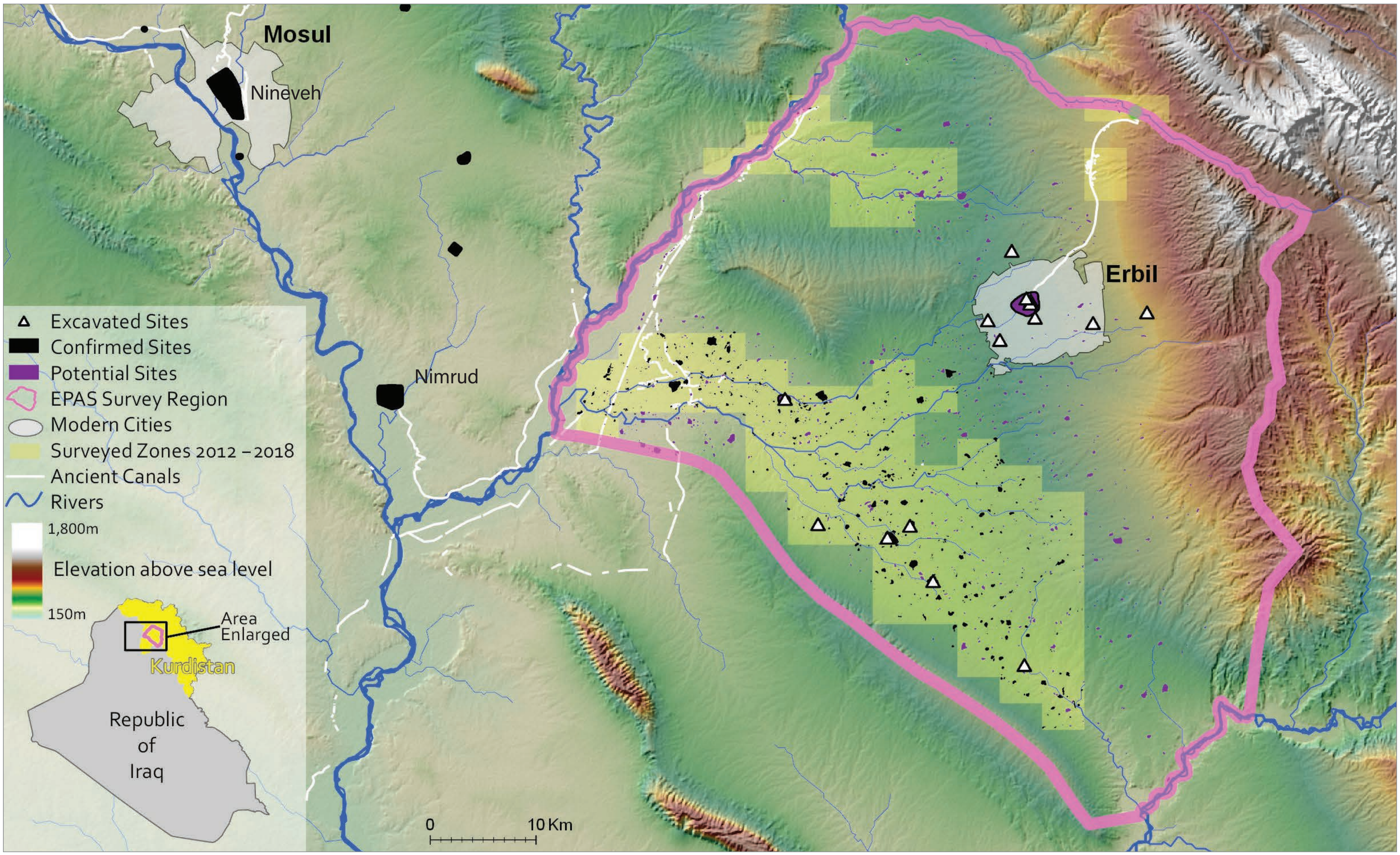
The Assyrian provincial capital city of Kilizu (modern Qasr Shemamok) shown in successive images taken in 1960, 1967, 1972, and 2018. The oval city wall is clear, with a citadel mound at its northern edge. The village of Saadawa, with a dozen houses, sat just to the south. Today, the site is being investigated by a French archaeological team, and people have returned to Saadawa village, which was destroyed by the Iraqi Army in 1987.[15]

FIELDWORK: MAPPING SITES ON THE GROUND

A durable pair of hiking shoes and a good hat are critical for the next step: field survey. Potential sites identified from aerial photographs and satellite imagery must be located on the ground, mapped, and sampled for chronologically sensitive artifacts.

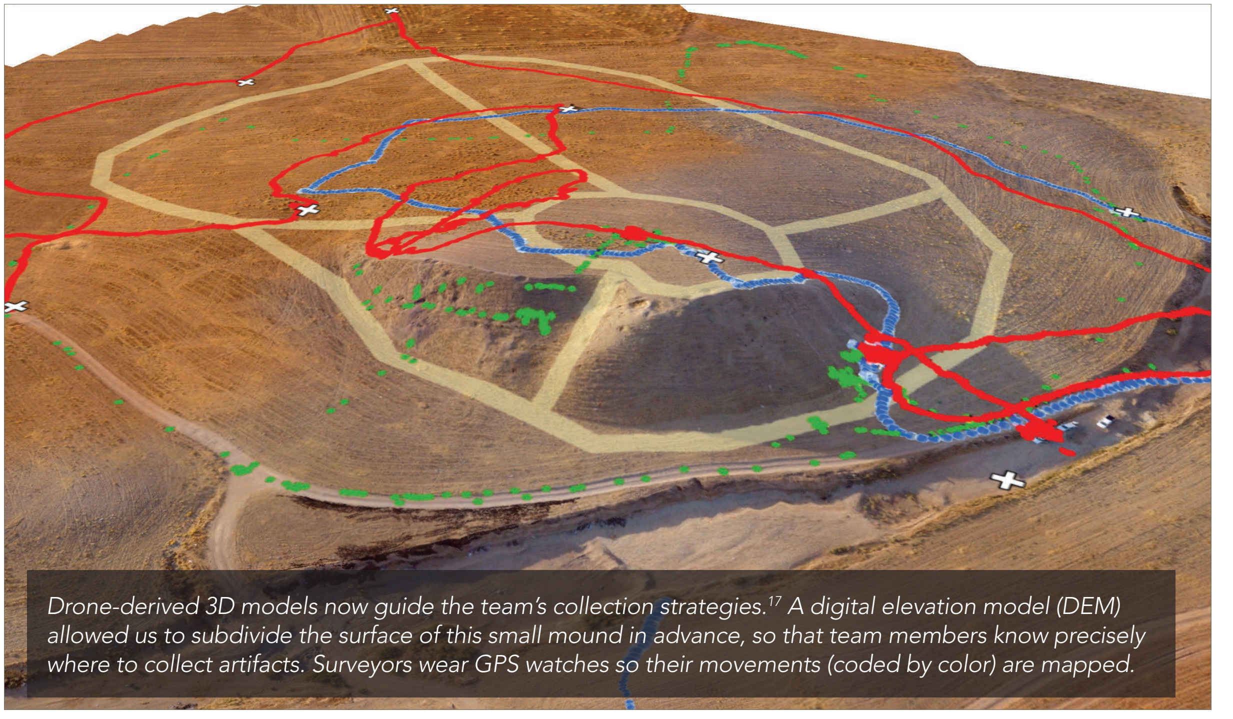
Our field lab is the plain around the city of Erbil, capital of the autonomous Kurdistan region of Iraq. The modern city sprawls around an ancient citadel mound that encases within it the stratified remains of settlements going back an estimated 6,000 years. In 2011, Harvard archaeologist Jason Ur signed a contract with the Directorate of Antiquities to survey 3,200 sq km around the city—an area that was at one time the heart of the Assyrian Empire, and today is rapidly developing as Erbil becomes a successful modern city.

Preliminary identification of potential archaeological sites and landscape features was done by visual interpretation of remote sensing datasets, mostly panchromatic aerial and satellite photographs from the late 1950s through 1980s. Because eroded mud brick has a loose soil structure that sheds moisture more quickly than the natural soils, potential sites appear as light discolorations on a darker background. These sites were vectorized as polygon features. Landscape features such as premodern tracks and irrigation canals are often slightly depressed and therefore appear on imagery as dark lines. These features were vectorized as polylines. All datasets were uploaded as hosted feature layers in ArcGIS Online, where they could be shared with team members.



EPAS is examining 3,200 sq km of historically rich landscape around the city of Erbil, formerly the core of the Assyrian Empire.[16] Sites visited and confirmed are shown in black; purple sites are potential ancient places that have not yet been visited. Since 2012, the survey team has covered some 930 sq km of our 3,200 sq km project region. In the early first millennium BC, the Erbil Plain was part of the core of the Assyrian Empire, which had capital cities at Nimrud and Nineveh.

The survey region is divided into blocks of 10 sq km. Intensive archaeological surveys often opt to walk transects across the landscape, often at close intervals. Unfortunately, the growth of Erbil does not allow us this luxury—the city and other developments are happening too fast. We visit our sites in vehicles, which enable us to cover large areas, albeit at a low intensity. We have found, however, that nearly all sites are visible in one or more of our imagery sources.



Drone-derived 3D models now guide the team's collection strategies.[17] A digital elevation model (DEM) allowed us to subdivide the surface of this small mound in advance, so that team members know precisely where to collect artifacts. Surveyors wear GPS watches so their movements (coded by color) are mapped.

When the team reaches a site, its members spread out across it to collect chronologically sensitive artifacts from the surface. These are overwhelmingly broken pieces of pottery, the detritus of daily life until the arrival of inexpensive plastics in the twentieth century. If the site is large, its surface will be divided into two or more areas, ideally based on topography. Increasingly, we rely on our drone program to produce digital terrain data for this purpose. The spatial distribution of artifacts from different time periods is the basis for our estimations of site size at various points in the past.

While some team members collect artifacts, others fan across the site to map its boundaries and the edges of the collection areas and to take elevation points of the site and its surrounding plain. When cellular data allows it, each team member's additions to our geodatabase are immediately visible to the rest of the team, wherever they are on site. We attempt to describe and document the condition of the site, especially any damaged or looted places, and to document any impending threats that it might face in the future. Early in our project, this documentation involved pencils, notebooks, and ground photography; now it features centimeter-resolution orthophotos, low-level drone oblique photographs, and voice-dictated digital notes. When the team has finished at any given site, they have often collected dozens of waypoint observations, dozens of artifacts, and hundreds of unmanned aerial vehicle (UAV) photographs. The team is then ready to move on to the next site.

Surface artifacts are cleaned and dried in the sun before they are analyzed.[18] Pottery can be chronologically sensitive, allowing us to determine when people lived on a site.

Potential sites recognized in historical remote sensing sources must be confirmed on the ground. Sites and other datasets are organized into web maps via ArcGIS Online and visible to all team members through the Explorer for ArcGIS® or Collector for ArcGIS® apps, depending on the team member's ability to edit or only view spatial data. Most team members use Bluetooth-enabled Garmin GLO GPS receivers; others who need to make precise measurements (e.g., ground control for drone photogrammetry) use Trimble R1 units with real-time correction via the ViewPoint RTX service. Team members switch between Esri imagery (various dates, but mostly the last five years) and CORONA satellite photographs (1967) as base imagery.

Team members collect surface artifacts within discrete subareas of sites, using the GIS apps on their mobile devices to guide them, and they mark the boundaries of the site based on the declining density of artifacts.

DRONES IN ARCHAEOLOGY

For nearly all its history, the villages, towns, and cities of ancient Assyria were constructed of earth. In this stone- and tree-poor region, sun-dried mud bricks were the best and only material available for peasant and king alike. Mud-brick architecture will not last for more than a few decades, and eventually, any structure must be leveled and a new one rebuilt in its place. As a result, settlements grow vertically when they remain occupied for centuries or millennia. When they were abandoned, they decayed back into earthen mounds. Their volume can tell archaeologists something about their duration and continuity. Furthermore, their topography can give clues to settlement histories. In the past, archaeologists created topographic site plans using standard surveying total stations, a slow process that involved two persons, a prism pole, a bubble level, and a great deal of patience.

Drones have changed all of this. In the past few years, they have become inexpensive and easy to use, and flight planning and photogrammetric software has followed suit. On the Erbil Plain, most sites can be planned and flown in ten or fifteen minutes. Our drones fly at a height that produces orthophotos with a resolution of 1 to 2 cm and digital terrain around 5 cm.

The project first adopted drones in 2016, and they quickly became much more than a novel source of interesting views—they are a standard part of basic site recording. Our drone protocol unfolds over three days. On the first day, the drone team visits a site, lays out and records ground control positions, and flies a preplanned mission. On the second day, the images and ground control points are brought together in photogrammetric modeling software to produce orthophotos and terrain models, which are then used to plan the team's surface collection areas. These polygons are added to the hosted feature layer in ArcGIS Online. On the third day, the collection team revisits the site to make precise artifact collections, guided by the collection area polygons on their GPS-enabled mobile devices. The team repeats this process on most sites.

Usually, increasing the speed of research requires a corresponding reduction in accuracy. This combination of drone survey and cloud-based mobile GIS allows the teams to move more quickly but with enhanced spatial precision. This is a critical combination, since we are often working in advance of new development projects that might damage or destroy the archaeological landscape before our next field season.

Team member Pshtiwan Ahmed sends up the project's quadcopter to map an archaeological site.

In 2018, the survey added a fixed-wing UAV. It has a flight time of around 45 minutes and a precision GPS on board. Here a SenseFly eBee Plus sits on the ground near an Erbil Plain mound.

Team member Dr. Bjoern Menze (Technische Universität München) devised our original drone mapping protocol in 2016.[19]

This site at Qatawi shows the encroachment of the surrounding modern town. Rapid development in the region lends urgency to the archaeological mission.

Team member Shilan Ramadan records the position of a nylon sack in the field. High-contrast debris can often be used as ground control points in situations where the team must move too quickly for formal photogrammetry targets.

The details of this archaeological site, which include military trenches, a modern cemetery, and encroaching housing, would have taken a week or more to map using traditional methods. Our drone program mapped this site in 15 minutes with 300 photographs.

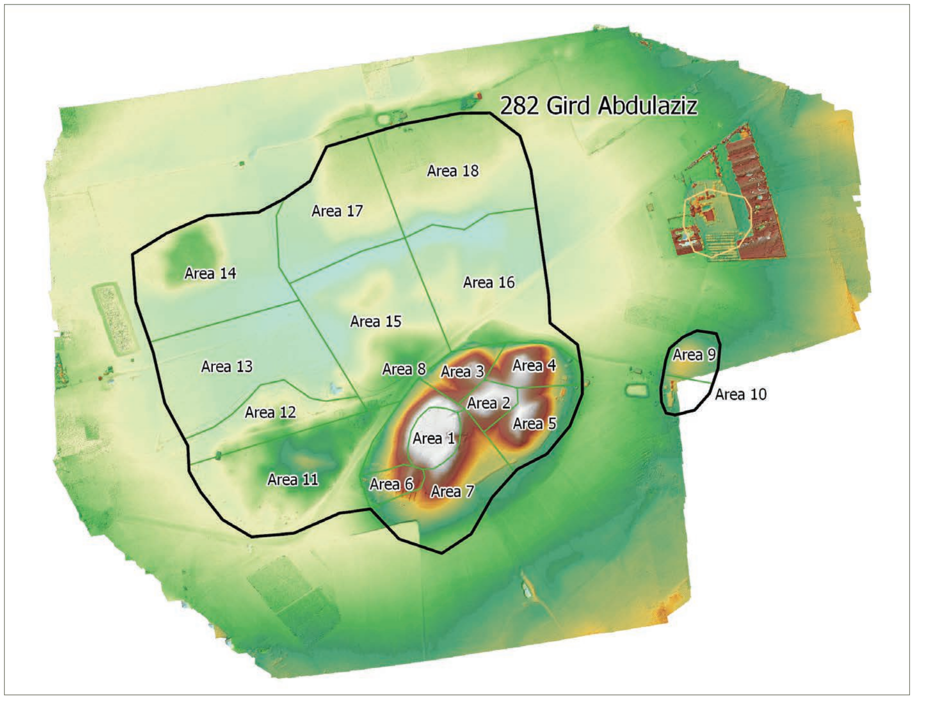
DATA COLLECTION AND PROCESSING

To reconstruct its settlement history we must subdivide any particular mound into artifact collection areas. Girdi Abdulaziz is a sprawling complex of high mounds and low rises near Erbil. It lies outside the Erbil core urban area where overdevelopment is taking place. This site will serve as an example of exploring the advantages of drone data.

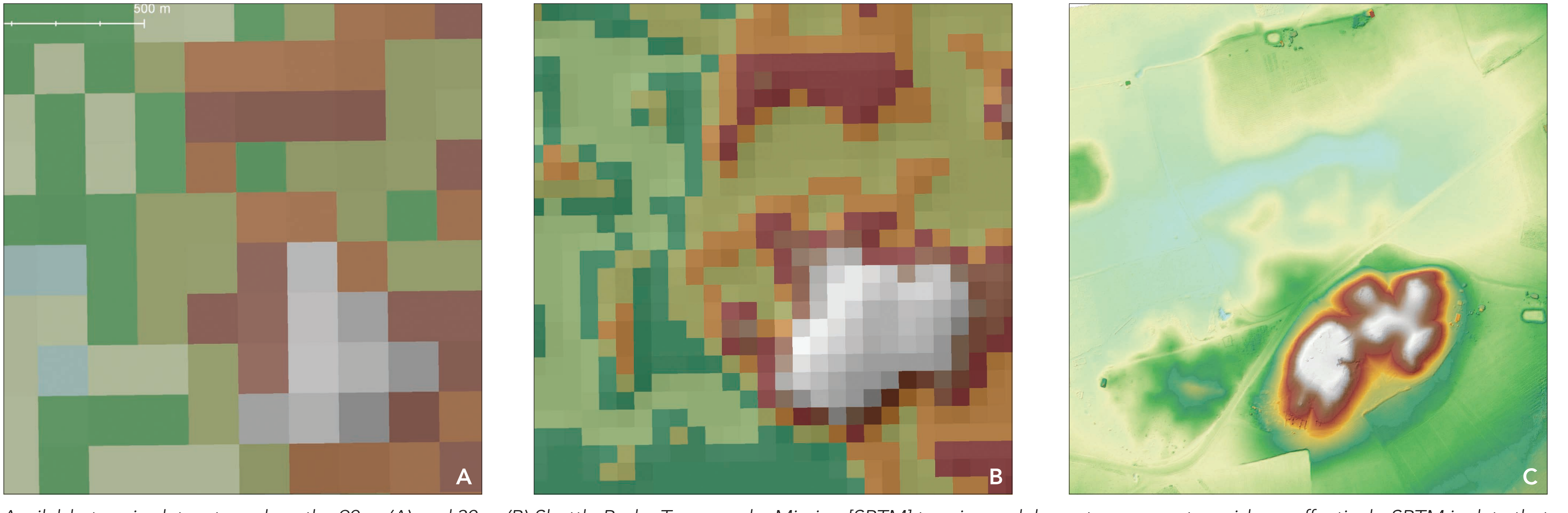
For large and complex sites like this one, topographic mapping is done days before collection via drone photogrammetry. The drone team has used quadcopters since 2016, and in 2018 the project added a fixed-wing drone for greater areal coverage. Vertical coverage is planned via drone apps with 60–70 percent overlap and generally at a height of 75–100 m, depending on the area to be covered and available battery life. For a detailed list of what hardware was flown, see the endnotes.[20]

For reasons of shadows and sunlight intensity, flights are made between 7 a.m. and 10 a.m. local time. Image GNSS positions from eBee flights are post-processed with reference to Continuously Operating Reference Station (CORS) data from a base station in south Erbil to around 8–10 cm accuracy, but quadcopter flights require manually collected ground control points via Collector and a Trimble R1 unit. Team members place sheets of paper within the flight area, or opportunistically identify high-contrast ground objects (most often rubbish such as black or white plastic bags) on the order of 15–20 cm.

The same afternoon and evening, drone images from the day's missions are processed in Drone2Map® for ArcGIS, most often as a batch that runs overnight. Output orthophotos have a spatial resolution of 1–2 cm, and digital surface models (DSMs) have around 4–8 cm. The next day, the DSM is used to plan subareas for artifact collection on complex sites. The subarea polygons are created in ArcGIS Online–hosted feature layers and are immediately available to all team members to guide field navigation and collection.



Girdi Abdulaziz 15 cm resolution DEM with labeled collection areas.[21]



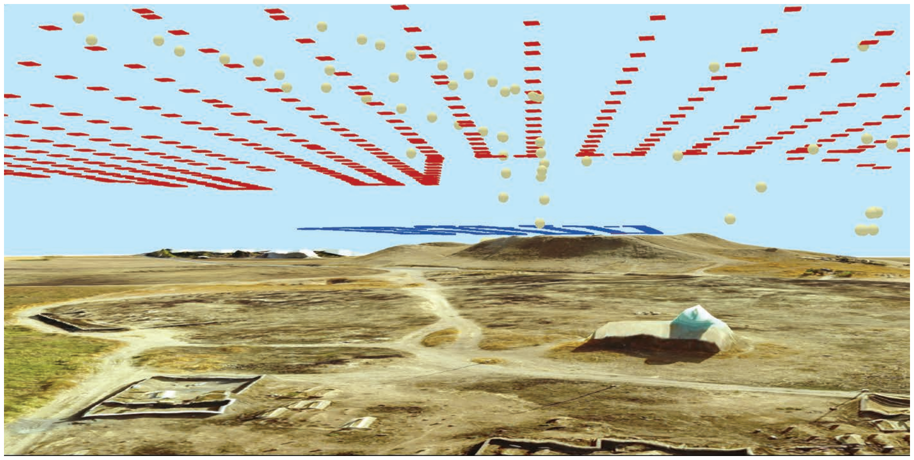
Available terrain datasets such as the 90 m (A) and 30 m (B) Shuttle Radar Topography Mission [SRTM] terrain models are too coarse to guide us effectively. SRTM is data that originated from a specially modified radar system that flew on board the space shuttle Endeavour *in 2000, and that produced global digital elevation models at a 30 m resolution. In contrast, a UAV flight collected 1,236 overlapping vertical and oblique photographs that were used to construct the 15 cm digital terrain model (C). All three terrain models cover the same extent.*

PROCESSING DRONE DATA

The use of drones has revolutionized the work of landscape archaeologists by providing a means of putting a camera in the air at relatively low altitudes. This technlogical leap forward delivers imagery that is higher resolution by orders of magnitude than satellite imagery. And while the imagery itself is inherently useful, its power is multiplied when processed through Drone2Map for ArcGIS, which streamlines the creation of professional imagery products from drone-captured still imagery for visualization and analysis in ArcGIS.

Through the magic of software, a series of individual photos taken from the drone are overlapped and stiched together to create seamless imagery products, including orthomosiacs; 3D models (aka DEMs); and point clouds, which enable analysis of natural and built-up features, including volumetric measurements, change detection, lines of sight, and obstructions.

An orthomosaic image is an aerial photograph that has been "orthorectified" (geometrically corrected) such that the scale is uniform and the image is placed in geographic space, which means it can be loaded into a GIS and combined and analyzed with other geodata, including vector. As such, an orthomosiac can be used to measure true distances, because it is an accurate representation of Earth's surface, having been adjusted for topographic relief, lens distortion, and camera angle.



Drone missions like this one at Girdi Abdulaziz include autonomous transects planned for vertical overlapping coverage and also manual flights for oblique views.[22]

This oblique view was created by draping a geographically correct orthophoto over the 15 cm digital elevation model of Girdi Abdulaziz.

A revisit of the site in January 2019 revealed not the typical dry, brown views, but a much greener landscape than on previous expeditions.

CASE STUDY: DISCOVERING A LOST KINGDOM

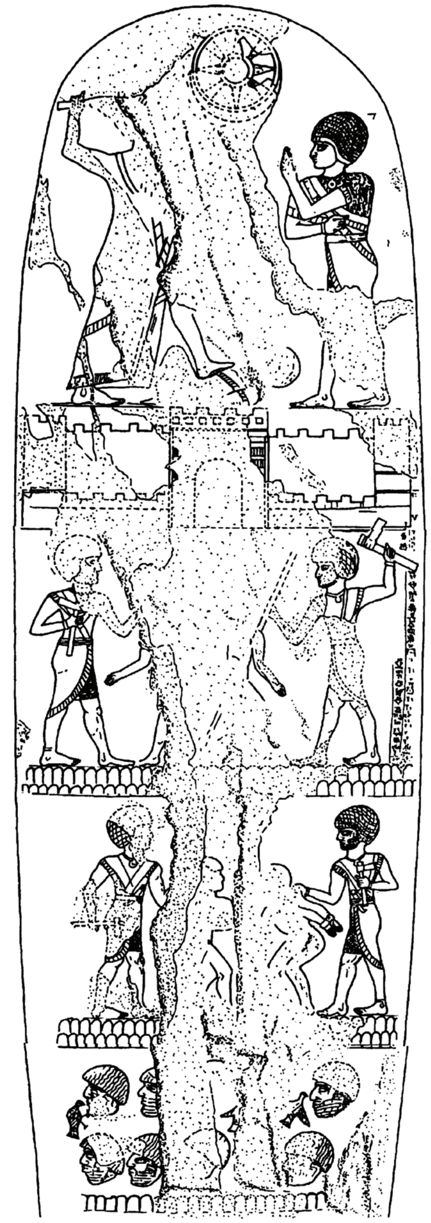
After two centuries of archaeology, there are still "lost cities" awaiting rediscovery. Modern archaeology increasingly makes such discoveries from space.

In the 1970s, the Iraqi State Board of Antiquities and Monuments recognized a small mound of the Middle Bronze Age (ca. 2000–1500 BC) at a place called Kurd Qaburstan ("cemetery of the Kurds"), a short drive south of Erbil. In preparation for the first season of field research, project director Jason Ur identified this and many other sites on a CORONA satellite photograph from 1967. What made Kurd Qaburstan stand out was not its ruin mound but rather the odd linear feature that surrounded it. It seemed far too straight to be a natural watercourse, and in some places, it was paralleled by areas of light discoloration. It had the potential appearance of a massive wall enclosing the site. At 100 hectares, it would therefore be one of the largest cities of its time.

It happened that archaeologists and ancient historians had been searching for just such a place for decades. It was known from other ancient sources that two kings had temporarily allied themselves to attack the kingdom of a third king, whose capital, known as Qabrā, was located somewhere on or near the Erbil Plain. One of the two conquerors had even commissioned a depiction of Qabrā and its city wall on a stone monument, as shown in the drawing.

The American CORONA spy satellite flew over Kurd Qaburstan on February 28, 1967. The light discolorations are areas of mounding, which contain collapsed mud brick. The yellow line highlights the curving oval shape of the buried city wall [23].

Kurd Qaburstan has a mound at center, today covered by a cemetery. These fields cover an area of dense urban housing that flourished almost 4,000 years ago.



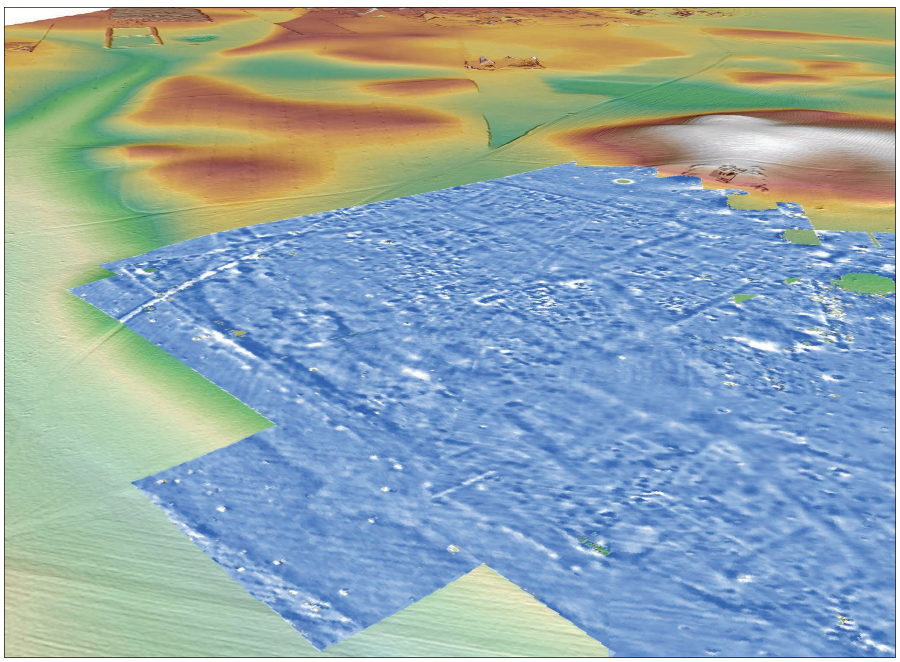
A farmer near Baghdad found this stone monument in a field. This drawing[24] of Qabrā shows King Dadusha of Eshnunna defeating the king of the walled city.

The city of Qabrā had been lost to history, but now just such a walled place was visible in a declassified spy satellite photograph at Kurd Qaburstan. The survey team arrived at the site in July 2012 with a sense of excitement. The hypothesized city wall was a low rise in the midst of agricultural fields in some places, but in other spots, it was invisible. The surface yielded broken pottery from many different time periods, but most frequently occurring were artifacts of the Middle Bronze Age—and scattered across the whole of the site.

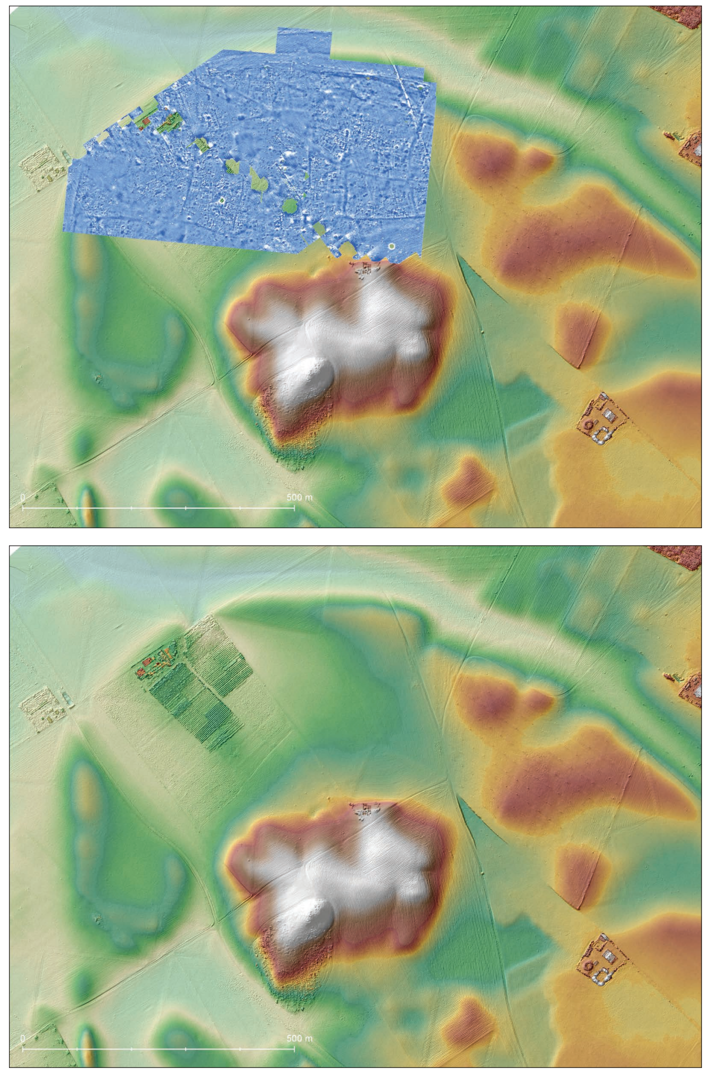
The dating of this city seemed assured, but we needed more confirmation of its wall. That confirmation has come in two forms. One confirmation was topographic. Using more than 1,000 drone photographs, we created a 3-cm resolution terrain model of the site, in which the wall could be traced around the entire site and even under a nearby village. Further confirmation came from colleagues at Johns Hopkins University, who began excavations at the site in 2013. Their project included a magnetometry survey, which revealed stunning images of the buried wall, including rectangular towers at 20-m intervals, as well as a dense network of streets in urban neighborhoods beneath the fields. Excavations confirmed that the wall had been constructed in the Middle Bronze Age.

We cannot be 100 percent certain that this place is indeed Qabrā until some ancient inscription from the site confirms it; that will have to await future results of the excavation.

In raking morning light, the mounds at the center of Kurd Qaburstan stand out.[25]



The magnetometry survey was carried out by Dr. Andrew Creekmore, who found a dense urban grid and a city wall with towers at 20-m intervals along the city's northern edge.



The geophysical survey revealed a dense network of streets beneath the fields and a thick city wall with towers. The massive bulk of the ancient city at Kurd Qaburstan is visible from this drone-derived DEM.

REVEALING EVIDENCE OF FORCED MIGRATION

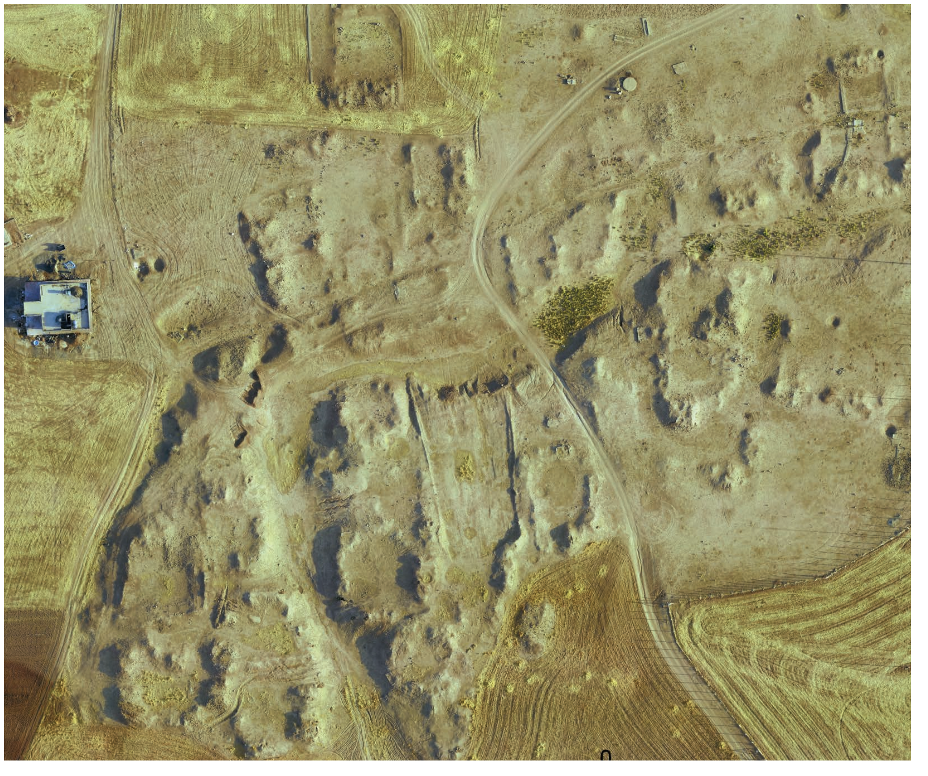
One focus of the survey is the investigation of possible forced immigration under the kings of the Assyrian Empire of the first millennium BC, but forced migration did not end with the collapse of the empire; it has continued as a tool for control over rebellious populations globally up to the present. Village destruction and population relocation was carried out by the Iraqi Army under the regime of Saddam Hussein's Ba'ath Party up to its fall in 2003. Victims included various minority groups that were determined to be disloyal, including the Marsh Arabs of southern Iraq and the Kurds in the mountains of the north.

In the late 1980s, the Iraqi Army moved to punish the rural populations of Kurdistan, who stood accused of supporting Iran during the Iran–Iraq conflict. This genocidal campaign is most notorious for the use of chemical weapons against civilian Kurds in 1988, but it began the previous summer, with the depopulation and destruction of hundreds of rural villages across Kurdistan, including nearly every village of the Erbil Plain.

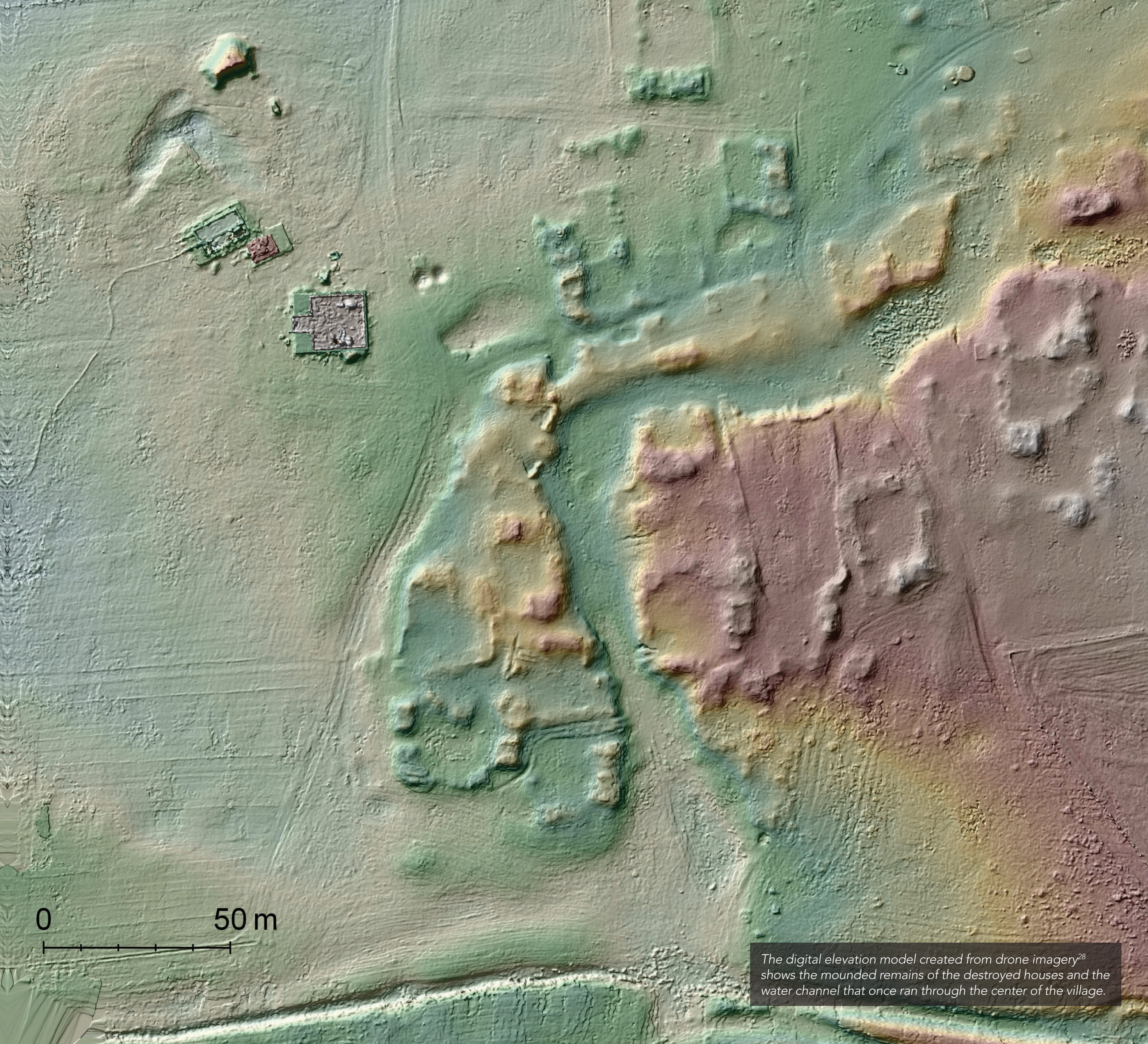
As we locate and map sites of much greater antiquity, our team members often encounter the ruined villages of the 1980s. As peace has returned to Kurdistan, many of them returned to life. Although our research objectives are deeper in the past, we feel obligated to give these villages the same level of attention that we apply to more ancient places in the hopes that they will not be forgotten.

Today the remains of Biryam Malak appear as a series of low mounds on the plain.[27]

In February 1972, Biryam Malak was a village of at least a dozen courtyard houses, as shown by this HEXAGON satellite photograph.[26]



In April 1987, the village was evacuated and destroyed by the Iraqi Army, along with nearly all other villages on the Erbil Plain. This orthophoto from September 2017 shows the remains of the bulldozed houses.



The digital elevation model created from drone imagery[28] shows the mounded remains of the destroyed houses and the water channel that once ran through the center of the village.

METHODS AND RESULTS

Over the course of five field research seasons, the Erbil Plain has revealed an amazingly rich archaeological landscape. Leaving aside for the moment the "big question" about the landscape impacts of formation of the Assyrian imperial core, we can consider some numbers:

- 930 sq km visited on the ground
- 585 sites identified and mapped (out of 841 potential sites visited, a success rate of 70 percent for our remote sensing site identification program)
- Almost 350 km of ancient trackways identified
- 140 premodern canal segments mapped, extending almost 170 km
- 1,739 bags of artifacts collected, and almost 55,000 artifacts analyzed
- Over 80,000 drone images acquired, encompassing 61 percent of our sites to date

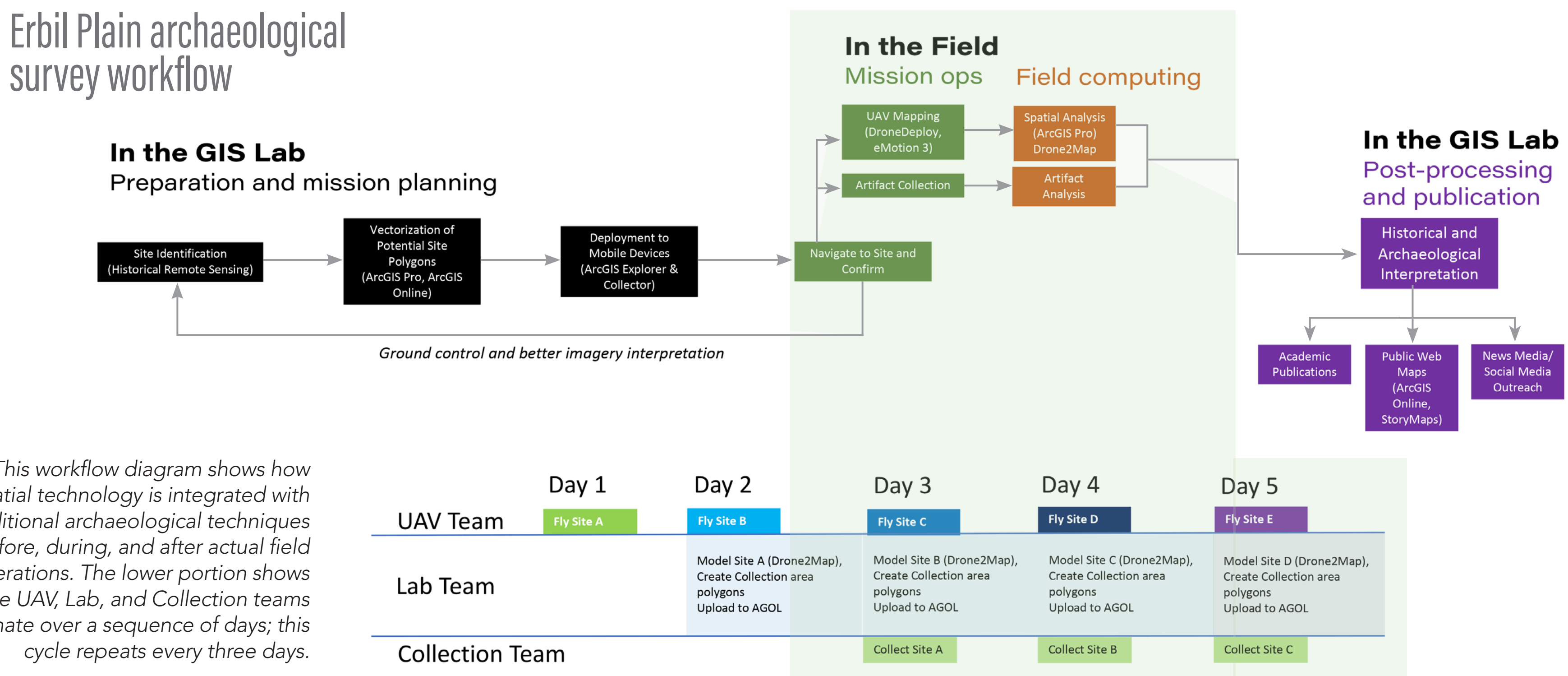
Ultimately, we intend to describe the history of human settlement on the Erbil Plain, from the first sedentary farmers up to the modern era. To do so, we must spend much time analyzing the artifact collections, and at present, we have done so only in a preliminary manner. Nonetheless, a historical pattern is emerging. The earliest villages were small and few, and they adhered closely to permanent water sources. Starting in the fourth millennium BCE, site numbers and maximum site sizes began to grow as the social and political structures necessary for urbanization emerged. The first unambiguously urban place appeared around 2500 BCE.

Sometime after the rise of the Assyrian Empire around 900 BCE, the plain witnessed the greatest expansion of settlement in its history—both in terms of the number of sites and probably also in terms of population. The number of settled places spiked to a level not seen before, or since. With a few urban exceptions, these Assyrian settlements were very small—possibly the villages of forced migrants from elsewhere in the empire, as depicted on the walls of the royal palaces. In the phase that followed the collapse of Assyrian power, settlement numbers receded dramatically. It is tempting to think that perhaps these deportees (or their descendants) chose to return home once the Assyrian army was no more.

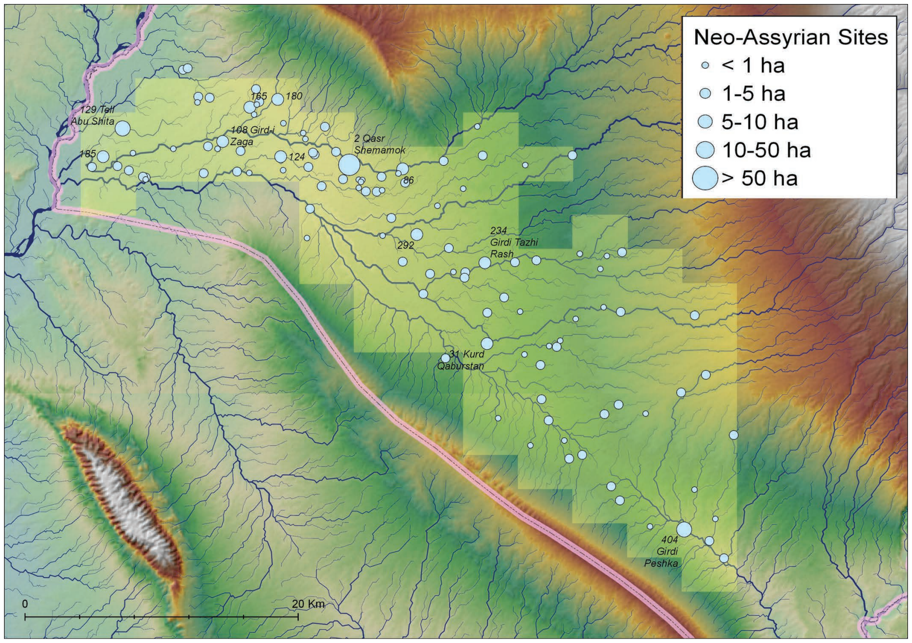
The Assyrian settlement expansion occurred with some monumental transformations of the landscape. One artificial canal moved water almost 5 km across a watershed, ending in a 300-m-wide basin. Its appearance on CORONA satellite imagery is impressive but does not do it full justice; its 100-m width and 8-m depth are best appreciated through drone oblique imagery. It must have required the excavation of nearly 4.5 million cubic meters of earth at a time long before mechanization. North of Erbil, our drone program discovered the remains of a 20-m-wide dam across a river, which would have diverted its flow into a subterranean channel toward Erbil. Smaller irrigation features have also been recognized, and many more have probably been removed by development.

The imperial impact on the landscape is continuing to emerge. What has become clear is that archaeological research on the scale of empires needs geospatial tools such as these. Imagery sources, especially historical imagery, are especially powerful, both in the lab and in field navigation and site mapping. The best circumstance comes when historical imagery can be used in tandem with up-to-date commercial imagery and on-demand drone-derived orthophotos.

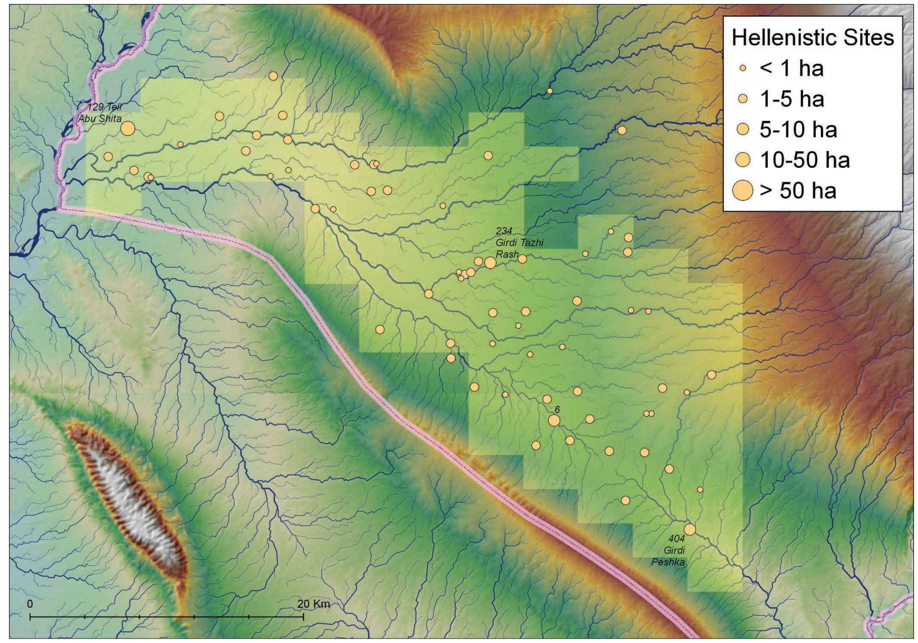
Our archaeological survey has far more work to do. We still must confirm and record almost 900 potential sites. Time is not on the side of the historical landscape, and Erbil continues to thrive and expand (see story map linked at GISforScience.com). Fortunately, the partnership between foreign and local archaeologists is strong, and our geospatial tools and methods are in place.



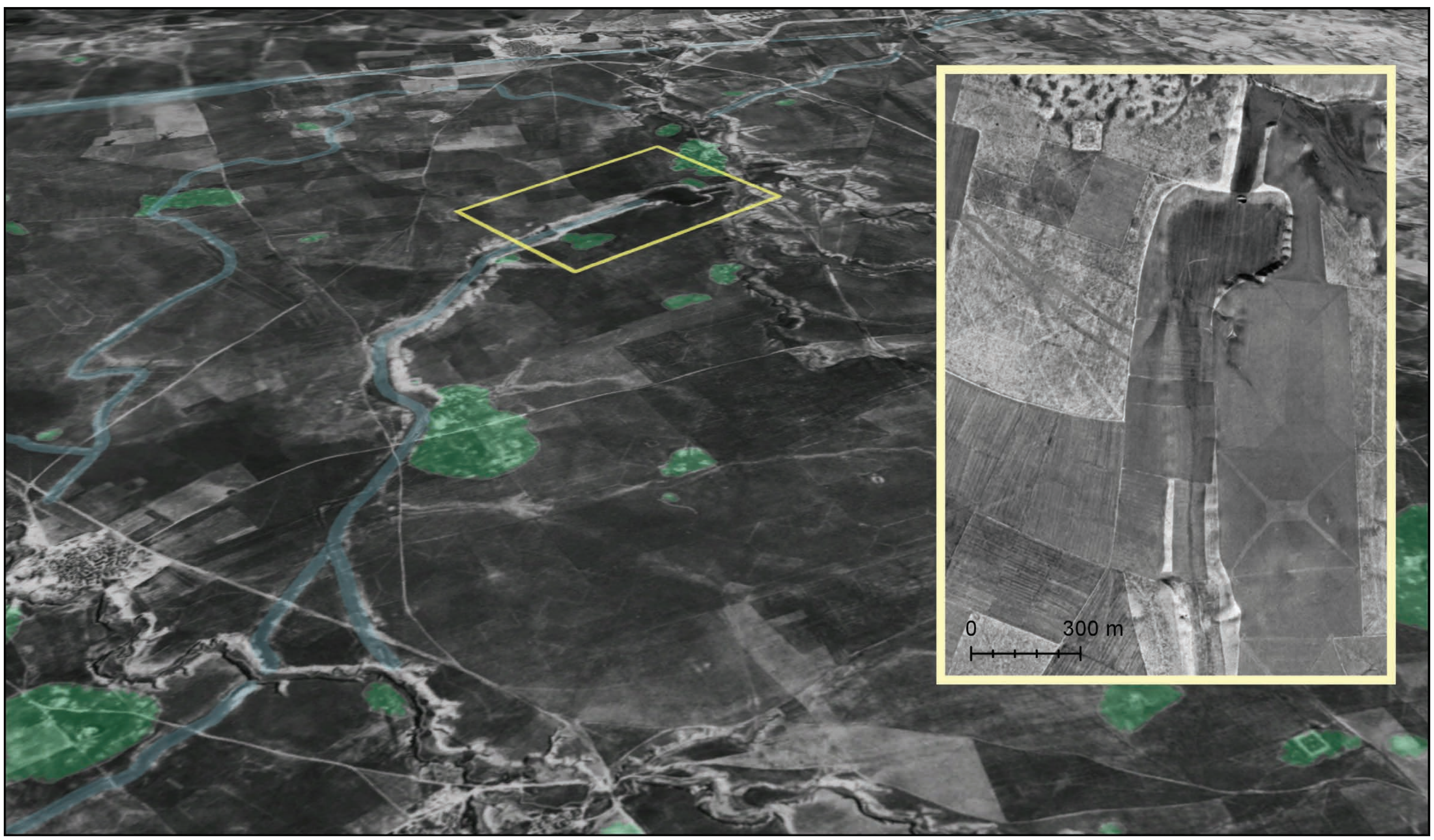
This workflow diagram shows how geospatial technology is integrated with traditional archaeological techniques before, during, and after actual field operations. The lower portion shows how the UAV, Lab, and Collection teams coordinate over a sequence of days; this cycle repeats every three days.



The southwest part of the project's research area has almost been completely surveyed. At the time of the empire, it hosted the densest scatter of villages and towns in the region's premodern history, including the city of Kilizu (modern Qasr Shemamok). Pink indicates the boundary of the survey research area; transparent yellow areas have been fully surveyed (to 2018).



After the conquests of Alexander, the plain looked radically different, with many settlements abandoned or reduced in size. The pattern of settlement did not survive the dissolution of imperial power.



Assyrian labor management transformed the hydrology of the Erbil Plain. This 100-m-wide, 8-m deep canal (shown here in a 1967 CORONA satellite photograph) would have required the excavation of 4.5 million cubic meters of soil by human labor. At its end was a 300-m-wide collection basin (inset, a 1972 HEXAGON satellite photograph).

THE ARCHAEOLOGISTS

The pursuit of the past in the Middle East is a long story, mostly narrated by archaeologists from great Western institutions. The earliest expeditions were sponsored by imperial governments via national museums. The collections of the British Museum and the Louvre, for example, derived from this tradition of exploration. In the twentieth century, the institutions were increasingly European and American universities; the finds remained in their countries of origin (now all independent of colonial control) but the tools, techniques, funding, and direction still originated in the West. In the twenty-first century, all of this is changing rapidly.

EPAS is led by Jason Ur, a professor of archaeology in Harvard's Department of Anthropology. Ur had led surveys of ancient landscapes in Syria, Iran, and Turkey. These projects had revealed to him landscapes that seemed to have emerged from the bottom up—the earliest cities that seemed to have self-organized around the interests of urban farmers and pastoral nomadic landscapes that took form from the cumulative decisions of small camping groups. The landscape of ancient Assyria, now in the Republic of Iraq, seemed to present a radically different case: an imperial core with hints of being planned from the top in all aspects. Iraq has been a dangerous place since the 2003 invasion and ousting of Saddam Hussein, but the autonomous Kurdistan region provided a secure and welcoming environment for research. It has proven to be an ideal place to test ideas about the geography of the Assyrian imperial core.

Our project started in 2012 with several co-directors, including Dr. Jessica Giraud, a French landscape archaeologist, and Dr. Lidewijde de Jong, a Dutch Classical archaeologist. Our official representative from the Kurdistan region's Directorate of Antiquities was Khalil Barzinji, an Erbil-based archaeologist with a degree in archaeology from the University of Baghdad. In this way, EPAS initially fit the twentieth-century model of foreign expeditions.

Starting in 2018, the survey project maintains all its spatial data in the cloud. Team members use ArcGIS Explorer and Collector for navigating and recording via smartphones and other handheld devices. With project data hosted in the cloud, all team members have immediate and total access to our spatial data.

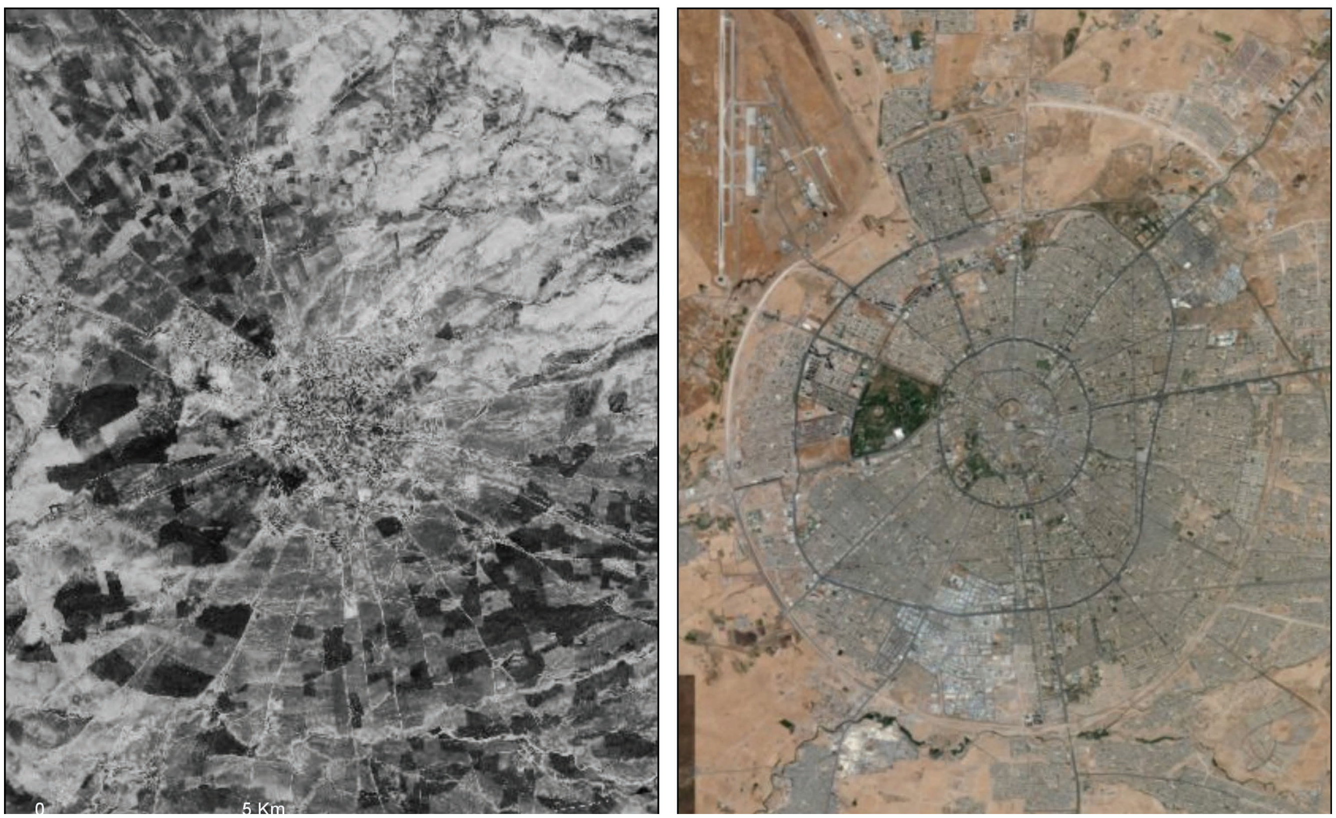
Since that first year, the team's composition has evolved. The modern city of Erbil has grown outward, and, in the process, it is covering or threatening the historical landscape. It is not possible for a small team of Western researchers visiting for a couple of months to document its past before it disappears under new roads and buildings. We have, therefore, trained Khalil and other young local archaeologists in the techniques of landscape archaeology, so that they can participate as equal team members and conduct this work in the absence of the foreign team. Advances in mobile GIS and cloud-based data sharing have been instrumental—our database is now accessible via smartphone apps to every team member. Khalil directs our drone documentation program and pilots drones over sites for the Directorate of Antiquities when EPAS is not in the field. In 2018, our team was majority Kurdish and is now co-directed by Nader Babakr, the Director of Antiquities for Erbil Governorate. Our research is a true partnership between foreign and local archaeologists, what we hope will be a model for future work in this region.

Most field days start with a briefing by project directors Jason Ur and Nader Babakr (third and fourth from left, respectively.)

ENDNOTES

This research was funded by the US National Science Foundation (Award #1261118), the National Geographic Society, and the Dumbarton Oaks Research Library and Collection. We gratefully acknowledge the support of the Directorate of Antiquities of the Kurdistan Regional Government and the KRG's representation in the US.

1. Image courtesy of the Erbil Plain Archaeological Survey (EPAS).
2. Map by John Nelson, Esri.
3. Map by Jeffrey Blossom, Harvard University.
4. Image courtesy of Semitic Museum: (modern resin copy of original plaster cast courtesy of the British Museum).
5. CORONA image courtesy of USGS.
6. All images on this page courtesy of EPAS.
7. Map by Jeffrey Blossom, Harvard University.
8. Image courtesy of EPAS.
9. Courtesy of the Royal Air Force.
10. Image courtesy of EPAS.
11. US Air Force photo. Reproduced with the permission of Air Force.
12. Image of KH-4B Corona courtesy of National Reconnaissance Office.
13. U2 and HEXAGON photos courtesy of the US National Archives and Records Administration (NARA). CORONA photograph courtesy of USGS. Basemap imagery courtesy of Digital Globe.
14. Photo courtesy of the US National Archives and Records Administration (NARA).
15. Images courtesy of USGS.
16. Map by Jeffrey Blossom, Harvard University.
17. Map by Jeffrey Blossom, Harvard University.
18. Image courtesy of EPAS.
19. All images on this page courtesy of EPAS.
20. All images on this page courtesy of EPAS.
21. DJI quadcopters (Mavic Pro and Phantom 4) since 2016; in 2018 the project added a fixed-wing senseFly eBee Plus for greater areal coverage.
22. All maps on this page courtesy of EPAS.
23. CORONA image courtesy of USGS.
24. Drawing courtesy of Robert Rollinger, University of Innsbruck.
25. All images on this page courtesy of EPAS.
26. HEXAGON image courtesy of USGS.
27. Drone images on this page courtesy of EPAS.
28. All images on this page courtesy of EPAS.



From 1967 to the present, the city of Erbil has grown from a large town to the urban capital of the Kurdistan region. An interactive version of this slider comparison app can be accessed at GISforScience.com.