Cyber-Archaeology in the Holy Land

The Future of the Past

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Table of Contents

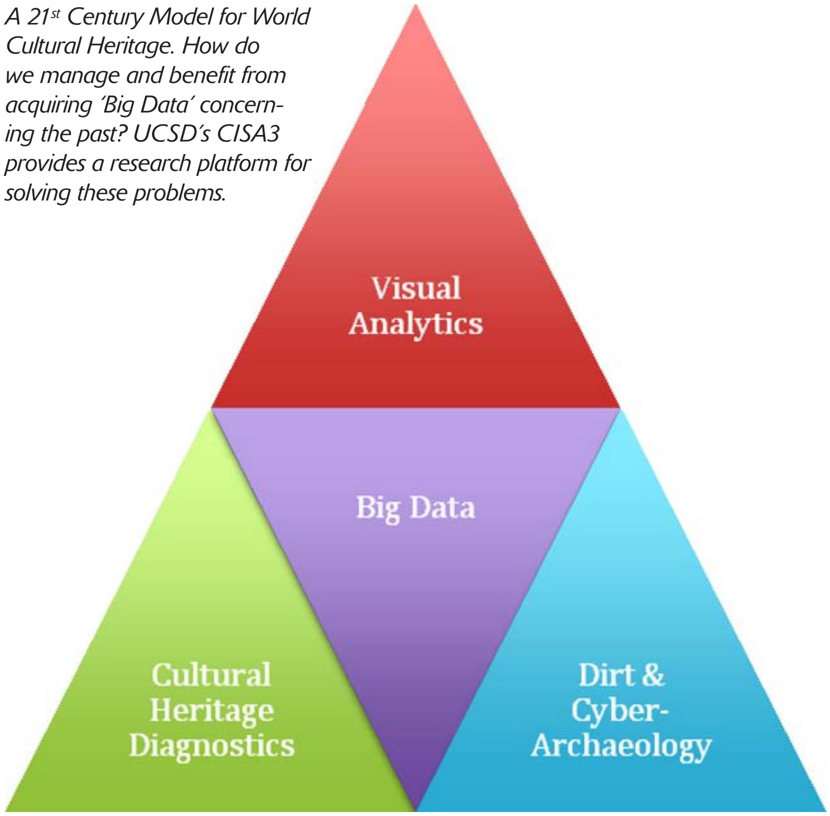
Introduction

Student helps monitor the LiDAR (Light Detection and Ranging) laser scanner at Khirbat Faynan (Biblical Punon) in Jordan. LiDAR enables researchers to collect billions of geo-referenced data points (accurate to +/- 1 cm) to create 3D maps and models of ancient sites and their environments.

All peoples and cultures around the world have their sacred places. In our modern world, whether you follow a religious tradition or are agnostic, there are places that hold your imagination and passion. These places can be as diverse as Elvis Presley's Graceland, the Lorraine Motel where Dr. Martin Luther King was assassinated, the Alamo or the Burkhan Khaldun, a sacred mountain thought by Mongolians to be the location of Genghis Kahn's tomb. These places mean different things to different people, but they all invoke deep emotional responses. For some of the world's great religions, entire regions are embedded with cultural, historical and religious meaning. Perhaps the two most significant regional Holy Lands are the subcontinent of India, so central to Hindu faith, and the Middle East's Holy Land —modern Israel, Jordan, the Palestinian territories and neighboring lands—which contains innumerable holy sites for Jews, Christians and Muslims. The Middle East's Holy Land is such an emotionally charged region that when people from these different faiths and traditions look at the landscape, they each see something remarkably different. How can archaeologists develop recording equipment, analytical methods, visualization tools and data-sharing structures that all peoples can engage? We need a new pragmatic approach that will enable everyone to engage the past in an as unprejudiced manner as possible.[1] The answer is Cyber-Archaeology.

We want to share some of the Cyber-Archaeology research we are doing in Faynan, Jordan's ancient copper mining and metal production region. This Arabic name is derived from the Hebrew *Punon,* one of the places (or "stations") visited by the Israelites during the Exodus from Egypt (Numbers 33:42). Our research focuses on anthropological and historical questions related to the role of technology in social evolution – from the Neolithic period to Medieval Islamic times. Of particular interest is the Iron Age (c. 1200 – 500 B.C.E.), the period most closely linked to the study of Biblical archaeology, when copper production was at its peak in Faynan. The remote location of Faynan makes it necessary to bring as much data home to

A 21st Century Model for World Cultural Heritage. How do we manage and benefit from acquiring 'Big Data' concerning the past? UCSD's CISA3 provides a research platform for solving these problems.



San Diego after each excavation season as possible. Finally, the relatively cheap price of so many digital tools today (GPS units, high definition digital cameras, laptop computers, tablets and more) means there is a "data avalanche" in archaeology today. We need solutions, and we need them fast, to integrate the mass of archaeological data that is growing exponentially each year.

Cyber-Archaeology is a new field. It can be conceived of as the melding of the latest developments in computer science, engineering and hard science with archaeology.[2] We adopt a broad definition of archaeology: the study of material culture and human behavior. Everyone on the planet has a history and archaeology is a touchstone with which all humanity can identify. Cyber-Archaeology offers a way forward in a world where thinking, perception and interacting with the world is so closely tied to Information Technology. Add this to the fact that we think in 3D, so visualizing archaeological data this way opens up new opportunities to study, interpret and experience the past. Cyber-Archaeology provides a remarkable mechanism for bringing together people who are concerned about their own and the world's cultural heritage.

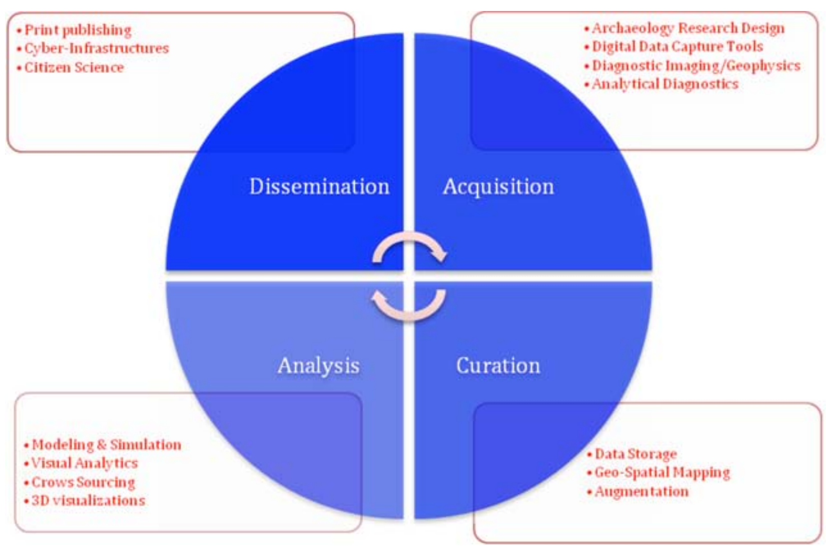
How do we navigate through the conflicting views over the past? How can we do it in an emotionally charged region – in the Holy Land?* Our team, based in the Center of Interdisciplinary Science for Art, Architecture and Archaeology (CISA3) at the California Institute of Telecommunications and Information technology (Calit2) at the University of California, San Diego, is helping to "push the envelope" forward in Cyber-Archaeology on the world scene.[3]

* See – Hershel Shanks, First Person: "LaBianca's Four Different Kinds of 'Past,'" **BAR**, July/August 2012.

Cyber-Archaeology Today

As CISA3 focuses on material culture and concerns all aspects of world cultural heritage, it connects archaeology with almost every division in a research university (arts & humanities, social science, medicine & biological sciences, engineering, business). In the 21st century all fields face the challenge of "Big Data," so archaeology provides an excellent test-bed to deal with this "data avalanche." Simply put, "Big Data" refers to data sets that are so large that "off the shelf" database management tools can't handle them. Field archaeologists create a quantity of "Big Data" that researchers struggle to deal with. As early adopters of numerous technologies, archaeologists provide a model for acquiring, analyzing, curating and disseminating data – issues that are pertinent in all fields. Our archaeological research in Jordan is a case in point. Our research team has pushed to develop new methods and approaches to face the challenges of quickly and accurately collecting masses of archaeological data, visualizing it and sharing it with colleagues and the public. This process can be visualized with a four-part model that focuses on acquisition, curation, analysis and dissemination of data.

The overarching goal of our work is to create a future for the past. We apply interdisciplinary research methodologies and prototype technologies for the preservation of cultural heritage worldwide, while serving as a training ground for a new generation of scholars and engineers. Our vision has developed over the past two years thanks to a National Science Foundation (NSF) Integrative Graduate Education and Research Traineeship (IGERT) grant. We are now going into year three of this five-year, $3.2 million grant that brings together graduate students from computer science, engineering and anthropological archaeology to develop new methods of collecting and presenting data. Students are fully funded for a two-year period, during which they focus on one Cyber-Cultural Heritage area and apply it to their doctoral research in their respective home discipline.[4] By the end of the grant period, we will have supported around 42 graduate students who are truly leading the way in developing Cyber-Archaeology. These 21st-century graduate students are developing disruptive technologies to supplement and replace traditional archaeological data col-



Cyber-Archaeology integrates the latest advances in computer science, engineering and the hard sciences to address anthropological, archaeological and historical questions. It provides methods for the acquisition, analysis, curation and dissemination of data related to world cultural heritage. UC San Diego researchers have helped 'push the envelope' in Cyber-Archaeology research by applying it to Biblical archaeology problems in the desert of southern Jordan.

lection with innovative methods for discovery and objective ways of understanding and conserving the past.

From Analog to Cyber-Archaeology

In the 1980s and early 1990s, Thomas Levy had the privilege of serving as the Assistant Director of the W.F. Albright Institute of Archaeological Research and the Nelson Glueck School of Biblical Archaeology in Jerusalem. In those days, all archaeologists recorded their data using dumpy-levels (or *Builders Level*), tape measures, compasses, graph paper and pencils. It was easy to drive out to a site in Israel's Negev Desert or go to the storerooms to study excavated artifacts. By 1992, when Levy took a position at UCSD, he continued to run archaeological projects and field schools in the Negev, but it became increasingly difficult to study the material found due to the "short" two-month periods of the expeditions. By 1996, digital video cameras with the ability to capture single frame photographs were used to photograph individual artifacts, which were made available on early UCSD-hosted websites. Levy summarized the state of technology and archaeology for **BAR** 17 years ago.*

Beginning of Digital Field Archaeology in Jordan

The adoption of digital technologies for archaeology has been a global phenomenon; however, our story relates to helping to push these frontiers in the Holy Land. Living in San Diego, far away from the research area in Jordan and the Middle East, Levy decided that our expedition should move from a paper excavation recording system to a totally digital system in 1999. Digital cameras were just becoming available then. The cost of Total Stations (electronic distance measurers) dropped and it was possible to pick up used ones quite cheaply on *eBay*. By going digital, we could leave the field with almost our entire excavation dataset in hand – photos of every object, maps ready for publication and more.

In 1999, by mounting a small digital camera on the end of a wooden pole, we could georeference a photo, drop it into a Geographic Information System (GIS) program and draw precise maps in the field – all ready for publication. Our digital archaeology field system was in its early stages but it was up and running. In 2001, the system was featured on the cover of the *Society for American Archaeology Record.*[5] We didn't know it then, but by digitally recording 3 coordinates (X, Y, and Z – elevation) for every artifact, wall, and other realm of ancient material culture, we had pre-adapted our archaeological research in Jordan to the most advanced forms of scientific data visualization that were available to general researchers at Calit2 in 2005.

'Aerial Photography' system used in 2004. A small digital camera was attached to the end of the stick and raised over the 5 x 5 meter excavation trench. Photos were taken and were downloaded to a GIS to be combined with architectural drawings.

By 2002, Levy and his research partner Mohammad Najjar had excavated Neolithic sites where copper ore from Faynan was used as a pigment for the spectacular anthropomorphic statues found at Ain Ghazal,[6] as well as Early Bronze Age (ca. 3000 - 2000 B.C.E.) sites corresponding to the emergence of cities and the first mass production of copper in Faynan. For our "deep-time" study of ancient mining and metallurgy,[7] it was now time to investigate the Iron Age, between 1200 and 500 B.C.E., when the first historic kingdoms or state-level societies emerged in the Holy Land. The Iron Age is closely linked to

* Levy, Thomas E, "From Camels to Computers: A Short History of Archaeological Method." **BAR**, Jul/Aug 1995.

The Cyber-Archaeology 'Mother-Ship': Calit2 at UC San Diego. Calit2 is an experiment in inventing the university research environment of the future to help fuel innovation in the global economy. With field projects in Jordan, Mongolia, Italy and other regions, Cyber-Archaeology plays an increasingly important role in furthering the Calit2 mission. Photo: Courtesy Calit2 UC San Diego.

Biblical archaeology. Biblical archaeology can be a highly contentious subject, especially the 10th c. B.C.E., but we needed to understand how an early state-level society manipulated copper production in this desert region to its advantage. The only "problem" is that the 10th c. B.C.E. is traditionally linked to David and Solomon, which opens up a proverbial "can of worms" concerning an ancient Israelite presence in Jordan today. Rather than using pottery for absolute dating Iron Age sites, we wanted a more objective approach. Instead of relying on the traditional archaeological assumptions that are used to date pottery to a chronological period based on style,* we decided to use a large number of high-precision radiocarbon dates anchored into the stratigraphy of the site with the best contextual/cultural data that Cyber-Archaeology can offer.

Biblical maximalists – who believe the Hebrew Bible (Old Testament) is mostly a true history, assert that everything related to David and Solomon is true. On the other side, Biblical minimalists argue that since the Bible was only codified around 500 B.C.E., anything earlier, like the 10th century B.C.E. David and Solomon must be pure myth or at best, David and Solomon were like petty mafia dons. In fact for the Biblical minimalists, there were no kingdoms or small states in the Holy Land during the 10th century B.C.E. – thus, archaeologically, there should be no reflection of state power – no fortresses, administrative buildings or evidence of state levels of production.** As anthropological

* See Lily Singer-Avitz, Archaeological Views: "Carbon 14 – The Solution to Dating David and Solomon?" **BAR**, May/June 2009.

** The "Minimalist" – "Maximalist" debate has been recently summarized in **BAR**. See Yosef Garfinkel and Philip Davies. "The Great Minimalist Debate." Biblical Archaeology Society, available online at: http://www.biblicalarchaeology.org/scholars-study/the-great-minimalist-debate See also Yosef Garfinkel, "The Birth and Death of Biblical Minimalism" **BAR**, May/June 2011.

archaeologists, we did not have a dog in this fight. We felt that by applying science-based methods and rigorous recording techniques to prehistoric archaeology, we would use the most objective approach for tackling the contentious Iron Age in a region where very few excavations had taken place.

Khirbat en-Nahas and Edom: A Test Bed for Cyber-Archaeology

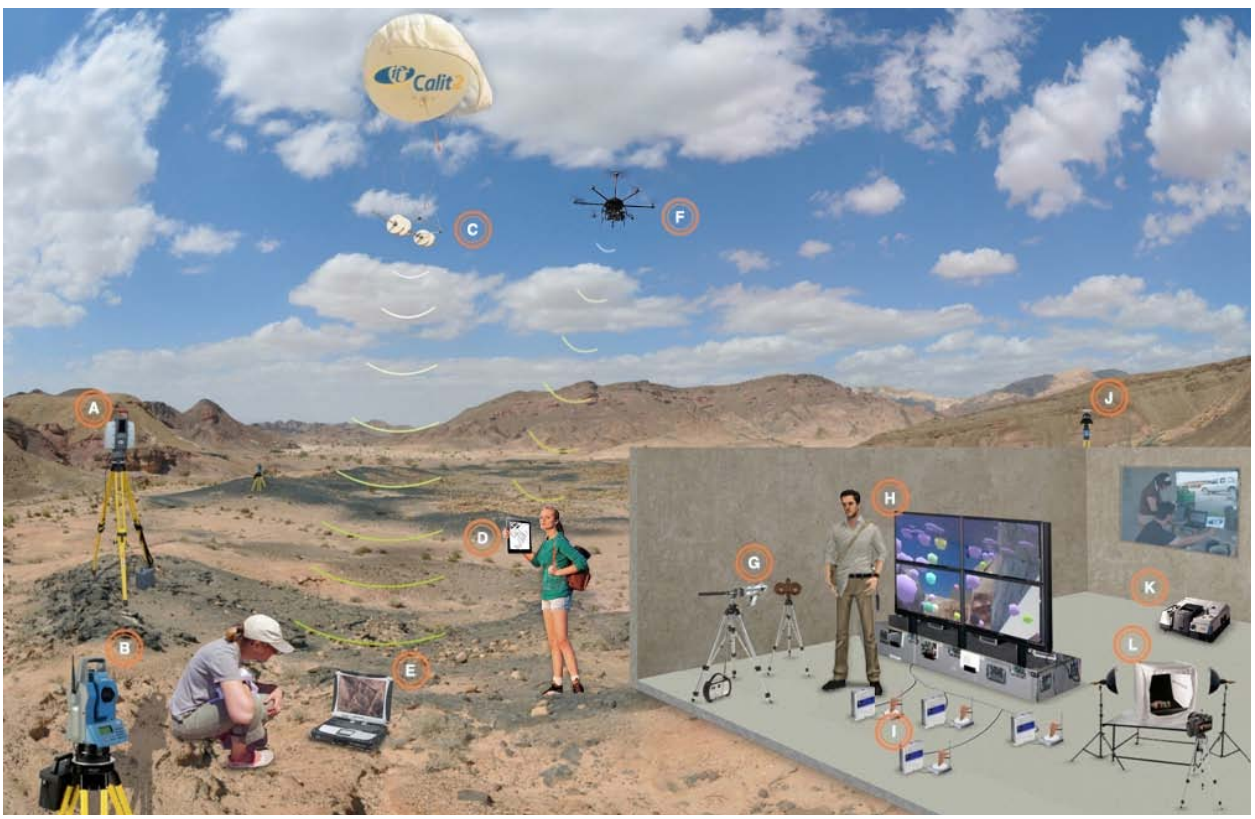
In Faynan, our Iron Age research took us to the site of Khirbat en-Nahas (Arabic for "Ruins of Copper") – over 24 acres in size. It is the largest copper production site in the southeast Mediterranean. The site is covered in black mounds of ancient industrial slag. However, before our excavations, researchers assumed it dated to around 700 B.C.E. or even the Roman period, so it would have nothing to do with early Biblical history or figures such as David, Solomon, the Israelites or Edomites. The site's first detailed report was written by the American archaeologist Nelson Glueck in the 1930s, stating that he had identified part of "King Solomon's Mines," but Biblical minimalists dismissed the idea after his death. On the surface of the site, we see a massive fortress, the remains of public buildings and masses of black slag from smelting. As we highlighted in a 2006 article in BAR,* we didn't find King Solomon's mines, but we did demonstrate that a local (not Egyptian and not Mesopotamian) complex society was responsible for industrial scale copper production during the 10th c. B.C.E. This flew in the face of researchers such as Israel Finkelstein who claimed there were no kingdom level societies in the southern Levant during this period.[8] We have found that the methods of Cyber-Archaeology provide the most objective way of testing hypotheses about the relationship between the Hebrew Bible and the archaeological record. In fact, Cyber-Archaeology is a pragmatic approach that is useful for any region in the world where ancient historical and sacred texts interface with field archaeology.[9] This applies to Scandinavia and the Icelandic Sagas, south India and the *Mahabharata*, Medieval Mongolian sources and Genghis Khan and so on.

* Thomas E. Levy and Mohammad Najjar, "Edom and Copper: The Emergence of Ancient Israel's Rival," **BAR**, July/August 2006.

Cyber-Archaeology On-Site

We have developed an integrated "tool box" of digital data-capture tools for archaeological fieldwork. To give you a feel for the on and off-site Cyber-Archaeology system, it can be summarized as follows: We still dig like our 19th-century predecessors with shovels, picks, trowels, dustpans, tooth brushes and so on. What is different is the use of digital tools to record data – and lots of it.

On a daily basis we integrate Global Positioning Systems (GPS) or Total Stations to collect individual geo-referenced artifacts and other finds; these precise X, Y, Z coordinate points are automatically collected with a real-time Geographic Information System (GIS) recording program we developed that is operated on an iPad or laptop computer called ArchField. The contextual information (or metadata) concerning the different archaeological contexts or loci excavated is entered in another program called OpenDig, which eliminates the need to enter information on paper "loci sheets." Opendig was developed by our graduate student Matt Vincent.[10] To help map the excavation area on a daily



Model of the 2012 Cyber-Archaeology field and lab methods deployed by the UCSD-Calit2- team in Jordan's Faynan district. In the field: A) LiDAR Scan-Station 2; B) Leica Reflectorless Total Station; C) Helium Balloon with gimbal platform for HD photography, D) iPad or Tablet computer for ArchField and OpenDig recording, note – operator has WHS British trowel; E) Tough-Book Laptop Computer for wireless control and viewing of balloon cameras; F) Octocopter aerial imaging platform. In the lab: G) Portable Bruker XRF; H) 3D Opti-portable visualization platform; I) NextEngine 3D scanners; J) RTK-GPS; K) Nicolet FTIR spectrometer; L) Digital HD photography studio.

Seal of the Palestine Exploration Fund from 1865 showing a surveyor under an umbrella, shading a theodolite used for making some of the earliest accurate topographic maps of the Holy Land.

basis and eliminate the need for a professional surveyor, we fly one or two high definition (HD) cameras on a helium balloon fixed with an electronic stabilizing gimbal that can be wirelessly rotated from the ground using a computer that is continuously powered with solar panels. To create 3D models of sites we use LiDAR – Light Detection and Ranging laser scanning – to collect billions of geo-referenced data points of the site. And there is more.

Let's look at how our Cyber-Archaeology data collection tools work in the field.

GPS and Total Stations

A Total Station is an electronic optical survey instrument (or electronic distance measurer, EDM) – the modern equivalent of the old theodolite (transits) that were used by Lord Kitchener when the Palestine Exploration Fund carried out a mapping survey of the Holy Land with Claude Conder from 1874 to 1877. Total Stations record coordinates (X, Y and Z) and slope distances from the instrument to the point of interest. The older Total Stations rely on a prism attached to a pole that is placed over the artifact or archaeological feature. An infrared signal is sent from the instrument's optical path and is reflected off the prism. Measurements up to 1.5 miles are possible. Newer Total Stations are reflectorless and can measure distances up to several hundred meters from any surface that is in the light. Reflectorless Total Stations are extremely useful for helping to measure and draw difficult-to-reach excavation sections. Recently, we used one to record a more-than-80-foot-high section we excavated at a Roman period slag mound at Skouriotissa in Cyprus.[11] To geo-reference the instrument, the starting location is shot in by line of sight with a reference point known as a datum. In the southern Levant, these are usually trig points (fixed survey points) established by the local government. Some Total Stations have a built-in GPS system that eliminates this process. Surveying with these instruments provides up to a half-inch accuracy.

The newer Total Stations have built-in data recorders that store the electronic records concerning distance, horizontal angle, and vertical angle. The older models require an external data collector. We started our field recording on the older instruments and used different kinds of *Recon Data Collectors.* When we began our Cyber-Archaeology work in 1999, at the end of the day we would download the survey data into an AutoCAD

UC San Diego graduate student, Aaron Gidding, setting up a Total Station at Khirbat Nuqayb al-Asaymir — an Islamic period copper production site in Jordan's Faynan copper ore district. The site was first recorded by Nelson Glueck and is part of the UC San Diego Edom Lowlands Regional Archaeology Project deep-time study of ancient metal production.

Latest version of ArchField running natively on the iPad.

program and draw our maps. By the 2001, GIS programs developed more simple applications to take care of this. The aim was to create all the expedition maps before returning home to the USA. As will be shown below, with our new ArchField program, we can create maps "on-the-fly" while digging. Today, the price of Total Stations has gone down drastically. You can buy an excellent used one for under $3,000, making this technology easily affordable for all researchers.

For surveys we use a Static GPS system that allows us to travel long distances in the field and still acquire 1-inch accurate coordinates. A high quality GPS receiver is only accurate to about +/- 50 feet, but when combined with a second GPS receiver set up as a base reference station, the roving GPS's measurements can be corrected to +/- 1 inch. When we return to the lab each evening, we correct our recordings with our base GPS receiver. For excavation, where we need immediate, high-precision recording, we use a Real Time Kinematic (RTK) GPS system. In RTK systems, the rover and base GPS receivers are always wirelessly connected, allowing "Real-Time" correction of the recordings. RTK GPS is very effective on excavations because there is no post-processing and you are rarely far enough from the base station to lose wireless connection.

ArchField

Once the 5 x 5 meter excavation squares are laid out, we are ready to record data as we excavate. In working toward a paperless environment, we record the location of artifacts, architecture and loci (the 3D archaeological and sediment layers) using ArchField.[12] This is an open-source, real-time, 3D recording system developed as a solution to archaeologists' digital field recording needs. ArchField is a GIS tool that streamlines the procedures to properly record the provenance of artifacts in 3D space and display them in a format understandable to archaeologists. Currently several flavors of the program exist, including the web-based version, compiled c++ versions for various operating systems, and an iOS version for the iPhone and iPad. We are continually developing ArchField and testing it in the field at various archaeological sites. This fall we introduced our tablet-based version that takes advantage of the iPad's multi-touch screens and accelerometers to visualize, zoom and rotate as well as naturally enter data. It frees registrars from their desk and allows them to record data as they walk around the site. The actual capture of high-precision 3D coordinates of artifacts and loci still involves a Total Stations or GPS; however, these instruments now feed directly into the iPad ArchField app wirelessly. As a bonus, we are able to create labels for all our artifacts and locus baskets with auto-generated unique barcodes.

Using a 3D recording system means that the archaeological data is immediately captured in a Geographic Information System. Archaeological excavation and survey data has a spatial component that reflects its cultural context and gives it meaning – whether it was associated with the floor of a room or an archaeological feature of some kind. The locations of artifacts, or loci, are plotted real-time onto a "digital" top plan the moment data is recorded in the field. The top plan is highly accurate, due to the use of a Total Station or GPS unit, and properly stores and displays all pertinent data. By the end of the morning's excavation, ArchField provides a complete top plan that would have taken us several hours to create in the past. When we return to our "clean" lab after lunch, we wirelessly sync the data recorded in the field with our servers and can then access it from any of our lab computers or study it on our 3D immersive systems.

Open-Dig – Metadata Database

By 1971, the Hebrew Union College excavations at Tel Gezer perfected a handwritten data recording system for loci – the key contextual data that archaeologists record during the course of the excavation. There were separate mimeographed sheets for each kind of locus – fills, floors, pits, walls, features, etc. Many digs in the southern Levant adopted this system. The idea was that each 5 x 5 meter excavation square would have a graduate student or staff member record the excavation in "his" square. This resulted in the exponential growth of paper forms for the dig that took years to sort through in order to publish meaningful information. Over the past few years, UC San Diego graduate student Matt Vincent developed a digital database for the field that accomplishes the loci recording on an iPad platform.[13] The system was first implemented at Tall Al-'Umayri and is now being successfully used at Balu'a and Khirbat Faynan. It allows the archaeologist to browse the database by field, square, object type and more. In Faynan, we are linking OpenDig with ArchField to create a unified digital recording system that answers all the needs of 21st century Cyber-Archaeology research.

Helium Balloon Aerial Photography

In 1999, the same year we "went digital," Her Majesty Queen Noor, wife of late His Majesty King Hussein bin Talal of Jordan, kindly put at our disposal a Royal Jordanian Air Force Super Puma helicopter for a day of photography in the Faynan research area. The views above Khirbat en-Nahas and other sites were spectacular. That very rare helicopter experience and resulting photos helped us appreciate the magnitude of ancient copper production in the area. That day, a dream was born: We should have our own air-born platform, not only for

A helium balloon system was developed for high definition aerial photography and mapping by UC San Diego aerospace engineering department undergraduate students. The image on the upper right shows a large-scale six-room building with interior courtyard dated to the 10th century B.C.E. that was probably an elite residence at the site. The large image below is an overview of the 24-acre copper production site at Khirbat en-Nahas. The large square structure is the fortress with a gatehouse that has also been dated to the 10th century B.C.E. These architectural features demonstrate the instruments of state power—a military fortress, industrial-scale copper production and elite residences.

contextualizing our sites with oblique photography, but to help with our growing digital mapping needs. By the summer of 2009, Aerospace Engineering undergraduate David Hernandez was leading a group of UCSD students in the design of a helium balloon system that could serve as a platform for high definition stereo digital photography. In the end, they designed a stable aluminum platform equipped with two 15-megapixel digital SLR cameras monitored with a wireless live-feed, powered by solar panels. The balloon of choice we use is the Kingfisher™ Aerostat from Southern Balloon Works, which is tethered to an operator on the ground who positions it over an excavation area up to 7,500 square feet. It can capture images up to a height of about 650 feet with excellent stability. The idea of using the balloon is to go beyond the "camera on a stick" method described above, can only cover an area of about 5 x 5 m and requires a great deal of photo stitching to cover the entire excavation area. With the balloon system, we can shoot one image and drop the geo-referenced photo into ArcMap in the ArcGIS suite to produce beautiful publication quality maps.

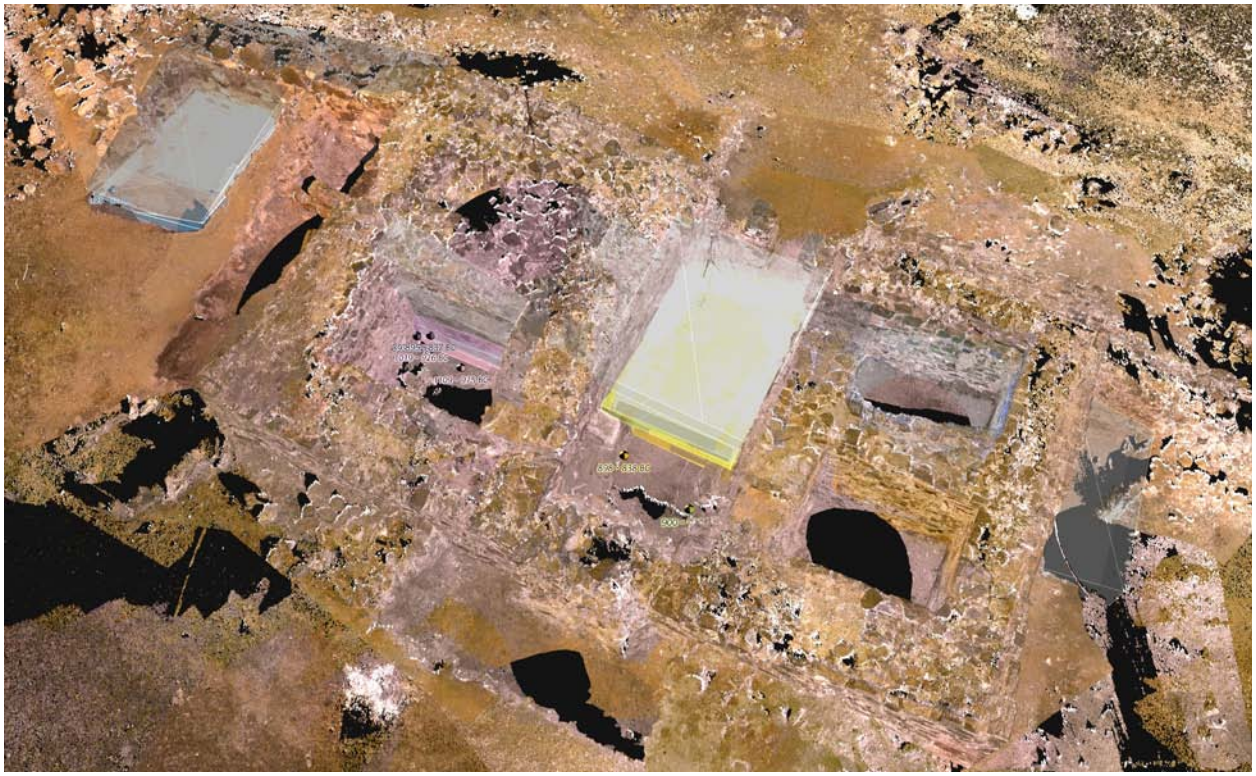
After the 2009 expedition, we realized we needed a more stable aerial platform for the helium balloon system. This led one of our undergrads, Alan Turchik, to develop a stabilization aerial camera platform with the new UCSD National Geographic Engineers for Exploration program.[14] With balloon or drone photography, we need total control of all aspects of the camera—exposure, shutter speed and aperture—by remote access. We also need an automatically activated stabilization system for the camera. The latter was achieved using an array of active stabilization servomotors. During our 2011 expedition, the system worked beautifully for about a month until the balloon and rig mysteriously disappeared one night, never to be seen again. We have a new an improved system that will be deployed in the fall of 2012.

LiDAR – Light Detection and Ranging Laser Scanning

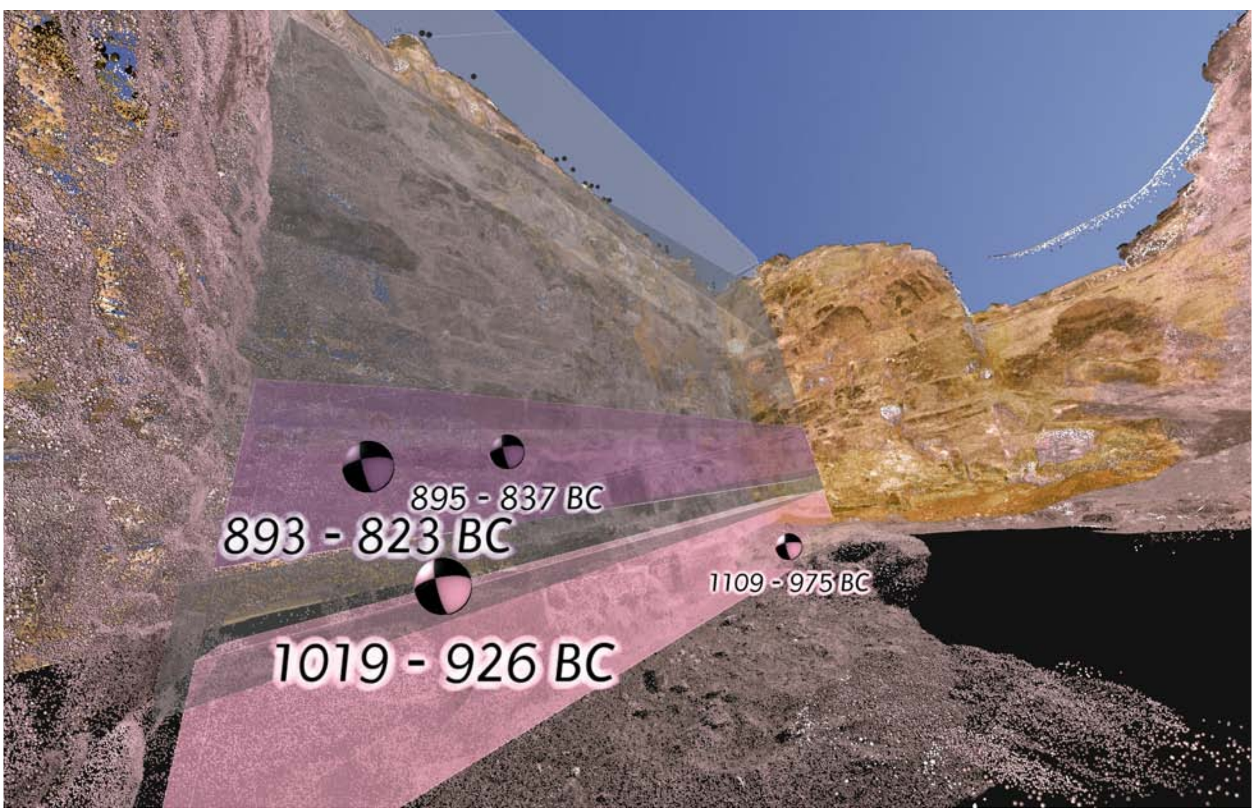
LiDAR scanning has been an important part of our toolbox since 2009. It augments the mapping, recording, analysis and conservation of archaeological sites by providing a 3D scaffold on which different datasets can be placed. We still use an older, rather bulky Leica ScanStation 2™ that collects 3D points by sampling the geometry and color of objects in its field of view. At Khirbat en-Nahas we acquired over 1.75 billion geo-referenced points with a relatively high resolution (c. 0.5–1 in). In 2011, we collected over 5 billion points from the massive ancient mound site of Khirbat Faynan (Biblical *Punon;* Roman *Phaino*).* Deploying LiDAR in harsh field conditions is difficult and requires a great deal of planning. Prior to our research, most terrestrial archaeological LiDAR applications focused on recording sites as a means of ancient monument conservation. However, thanks to graduate student Vid Petrovic's computer program VisCore, we can render 3D LiDAR and Structure from Motion (SfM) point cloud data as a scaffold for embedded archaeological datasets for spatial analysis of the site and its excavation.[15] Using LiDAR data in this way enables archaeologists to examine and reexamine field data to test hypotheses concerning ancient societies. For example, at Khirbat en-Nahas, by examining the spatial relationship between radiocarbon dates and the fortress using LiDAR and 3D visualization tools, we have proven conclusively that the monumental structure was constructed early in the 10th century B.C.E.[16]

The data adds new evidence to support the existence of 10th century B.C.E. kingdoms in the Holy Land, a heavily debated chronology in Biblical archaeology. The evidence includes: Large-scale construction of defensive structures that reflect instruments of state power, a ceramic assemblage that is distinctly local in nature (Edomite) and the widespread evidence of industrial-scale copper production at the site. This pragmatic approach to a contentious archaeological subject weakens

* Thomas E. Levy and Mohammad Najjar, "Condemned to the Mines." **BAR**, Nov/Dec 2011.



LiDAR image of the 10th century B.C.E. Iron Age gatehouse at Khirbat en-Nahas, Jordan. The billions of geo-referenced data points serve as a "scaffold" on which layers (colored geometric shapes seen here) and artifacts can be "hung."



Detail view of the inside the passageway of the gatehouse at Khirbat en-Nahas, showing loci of radiocarbon dated finds with black and white spheres. The initial construction phase dates to the 10th century B.C.E., followed by re-usage and "decommissioning" of the structure in the 9th century B.C.E.

the Biblical minimalist perspective on Iron Age societies in southern Jordan.

Visual display of the calibration of images and motion. The digital photographs were taken at the site of Khirbat al-Iraq near Showbak, Jordan.

Structure from Motion

We use Structure from Motion (SfM) to create a rapid 3D reconstruction of our sites using only photographed images. In essence, SfM provides a situated context for all the artifacts and loci recorded using ArchField. The name Structure from Motion comes from the method of how the 3D point cloud structure is extracted from the images. Rather than standing in a fixed position and capturing data, SfM uses a change in camera position for each image to find the distance (motion) between them and then calculates the actual 3D positions of each pixel found in the photographed images. Therefore, the more motion and movement around the site, the more complete the 3D point cloud model. With SFM, we can capture millions of 3D points, allowing us to reconstruct excavation surfaces and architecture. Although its resolution is much lower than a LiDAR scan, it is much faster, easier to do and vastly more accurate than architects' illustrated plans. In order to meet the demands of archaeological documentation, we have been working at Calit2 to push SfM's capabilities to its limits. In order to determine ground truth accuracy, we use our LiDAR scans of the same archaeological sites to provide a reference model to evaluate the quality of the SfM. Since we can essentially capture an entire site within only a couple minutes, our plan is to use SfM on a daily basis to create time-lapsed 3D point cloud models of the site. We can then peel away layers of our site's excavation over time, from the first day the spade strikes the topsoil to bedrock. The goal of the project is to provide a digital tool for highly accurate and visually informative time-lapsed documentation of archaeological field excavations that we can directly load into our 3D GIS visualization environment, ArtifactVis2.

Combination of SfM and LiDAR from the Iron Age (c. 750 B.C.E.) site Khirbat al-Iraq near Showbak, Jordan.

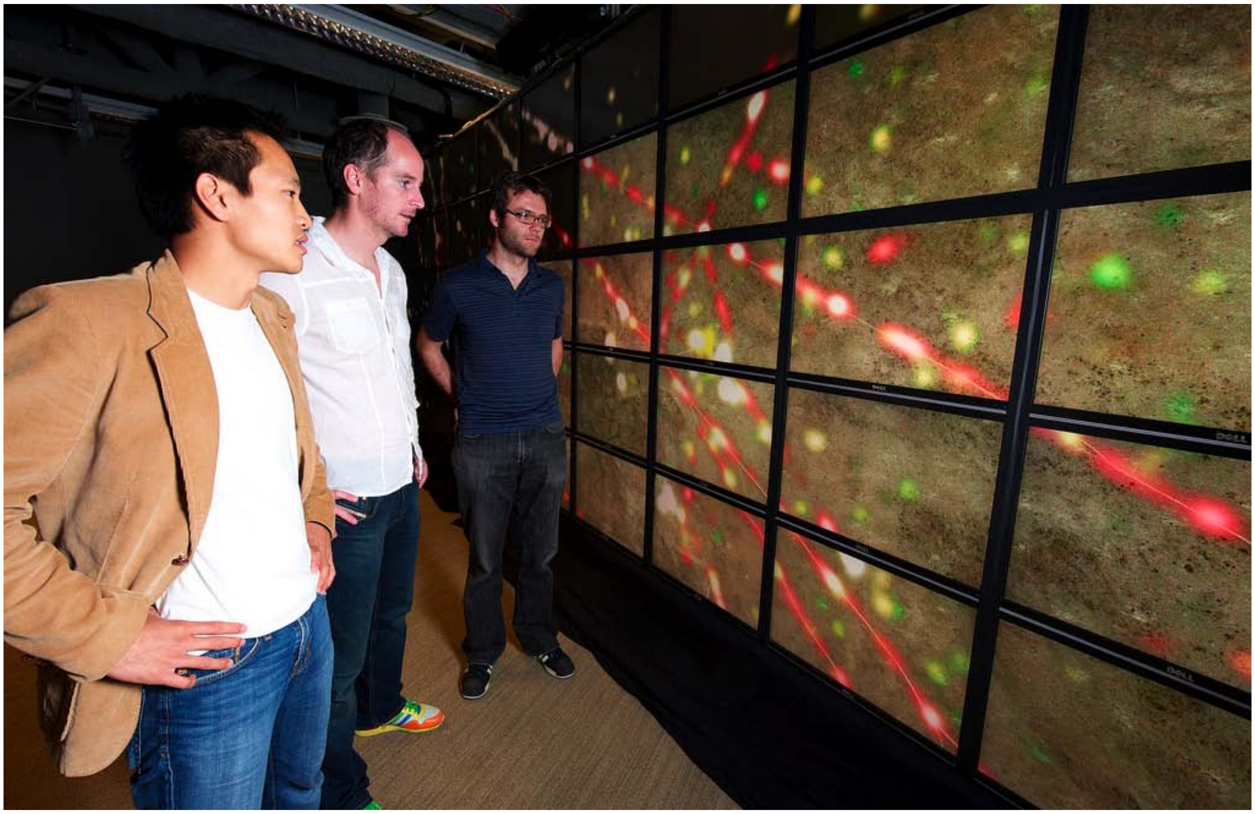
Drones for Archaeology

Since the invention of photography, archaeological research has used aerial images to understand the spatial context of ground features and accentuate features that would not be apparent otherwise. Buried features can produce small changes in surface conditions, such as slight differences in ground level, soil density and water retention, which in turn induce vegetation patterns (crop marks), create variability in soil color (soil-marks) or even shadows (shadow-marks) that can be seen from above. At Calit2, multi-rotor unmanned aerial remote sensing tools prove to be valuable for scientific research. Created to provide aerial imaging and photogrammetry for the international Valley of the Khans Project in Mongolia, these unmanned systems were designed as inexpensive but robust remote sensing and sensor platforms. The nature of archaeological fieldwork requires design criteria that exceed off-the-shelf alternatives in robustness, dependability and repeatability. Electronically powered platforms were engineered with lithium polymer batteries and programmed to conduct specific flight operations, guided by either onboard GPS or ground radio control. Altitude and location are measured through onboard pressure sensors and GPS, respectively. Internal control systems facilitate steady flight and hold position (within 5 ft of error) in wind conditions tested up to 30 mph. This imaging capability resulted in rapid on-the-go assessment of newly identified archaeological features, providing valuable guidance for further ground and geophysical surveys.[17]

Crowd Sourcing

The introduction of earth-sensing satellites has helped integrate remote sensing in archaeology. The ability to detect features on the ground from space is largely dependent upon the ratio of feature size to data resolution. As sensor technologies have improved,

Aerial survey of an archaeological feature observed in northern Mongolia using the UCSD Calit2 Octocopter for high-definition site photography.



Crowd-sourcing in action. Albert Yu-min Lin (left), Luke Barrington (center) and Gert Lanckriet (right) examining millions of crowd-generated image analytical tags on Calit2's HiPerSpace visualization facility.

the potential to utilize satellite imagery for landscape surveys has also improved. However, the perpetual increase in sensor resolution capability provides an exponentially growing data size challenge. Furthermore, automated approaches for image analytics (i.e. computer vision) do not easily apply to archaeology, as ground features are often difficult or impossible to predefine, a requirement for "training" automated systems. Thus, we have explored human-web based networks to develop innovative distributed solutions: crowdsourcing.[18] This effort, led by Albert Yu-Min Lin, created tens of thousands of imagery subtitles to be processed by randomly generated groupings of volunteer participants. Asked to "tag" locations of interest or potential archaeological activity, participants worked in isolation and in parallel to generate a map of the region from independently-generated human consensus. The platform was designed to create highly parallel "blind tests" for imagery analytics of any given location. As clusters of agreement emerged, ground teams would explore on foot and horseback to test the public input. Over the course of two summer field sessions, nearly 2,000 square miles of area were surveyed at 0.5-meter resolution from millions of human-generated tags. Hundreds of locations were ground truthed and dozens of archaeological anomalies were verified along the Mongolian steppe.[19]

Cyber-Archaeology in the Field Lab

Along with the field recording and collection of archaeological materials, our Jordanian expeditions have always included a wide range of laboratory activities. We now have a "dig house" called Qasr Faynan in the Rashaida Bedouin village of Faynan. Prior to the 2011 excavation season, we lived on the edge of another Bedouin village in rougher conditions. Each year we had to rent a village house for the expedition "clean laboratory," where much of the preliminary analyses and digital recording of artifacts took place. With Qasr Faynan we have a superb permanent laboratory setting for our field research. Our team in Jordan puts as much effort into the lab as they do in the field.

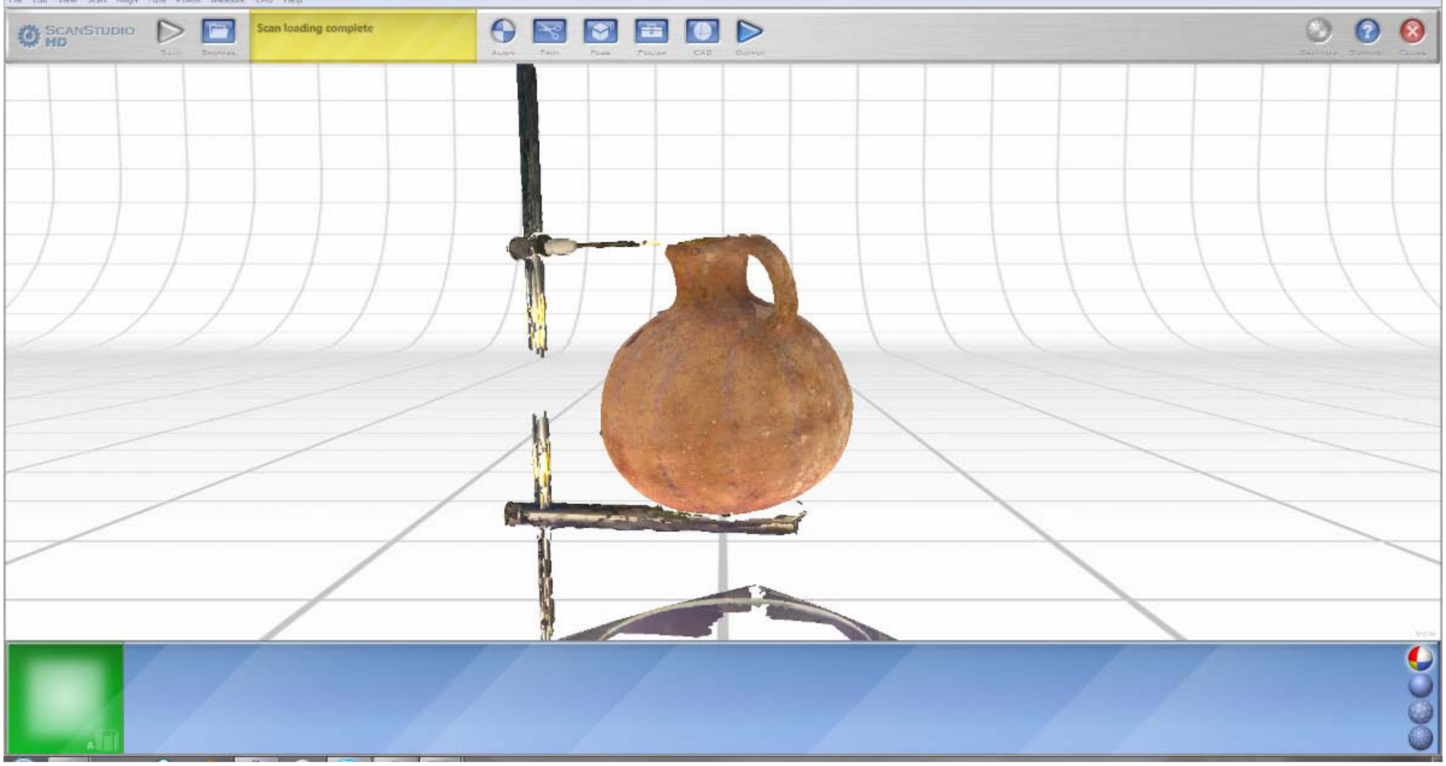
HD Photography

We use high-definition digital photography on a daily basis and take an average of 5,000 to 10,000 artifact photographs each season. Our system is based on both Nikon (D90, D70) and Canon (50D) 35 mm cameras with a suite of lenses including a macro for close-up photography at 1:2 or 1:1, 50 mm, and a versatile 18 mm–200 mm zoom lens. All images are shot on a tripod or MagicArm. To facilitate focus and data-flow, our Canon cameras are connected to a laptop computer with Canon RemoteCapture software that enables the photographer to focus the image and shoot the picture without looking through the camera eyepiece. To control light and color tones, two kinds of portable tabletop studios are utilized in the field lab: MyStudio PS5 PortaStudio Portable Photo Studio with 5000K Light and the Lumiere Portable Photo Studio Cube with four color backgrounds. Both of these are approximately 50 x 50 cm. A minimum of two angles are shot of each object and all images are geotagged so that they can be linked to the different GIS and 3D visualization platforms discussed below. An undergraduate can easily be trained to take publication-quality images that are ready for publication by the end of the excavation season.

This Cyber-Archaeology lab in the desert of southern Jordan provides a wonderful laboratory complex for the UCSD team's digital archaeology fieldwork.

3D Artifact Scans

At present, the most portable and economic 3D scanner is the NextEngine, which produces micron-resolution triangulated meshes of potsherds and other artifacts. The potsherds can then be used to extract the exact curvature of their profile in a standard 3D vector format. The computed vector profile is amenable to mathematical manipulation. Since 2009, 3D artifact scanning has been a key part of our research. Most of the 3D scans are of diagnostic pottery sherds and other objects used to produce publication-quality drawings and 3D models



3D scan of an Iron Age ceramic juglet from the Showbak area of southern Jordan.

of those artifacts for different "informatics" databases we have developed, such as the Pottery Informatics database (described below). At about $3,000 per unit and an additional $1,000 to upgrade the scanning software, it will probably take some time before 3D artifact scanning becomes common on most excavation projects.

In-Field Microarchaeology

High precision portable analytical tools are enabling archaeologists to bring the geo-archaeology laboratory to the field. Researchers in Israel have helped lead the way in applying a wide range of techniques to characterize artifacts and archaeological contexts. They have analyzed microscopic environmental data (bones and seeds) to reconstruct subsistence and economic strategies. A special subfield has evolved that is referred to as geo-archaeology or microarchaeology.[20] The "game changer" of characterization studies has been the development of handheld X-ray fluorescence (XRF) and portable Fourier Transform Infrared Spectrometry (FTIR) units that make it possible to answer questions in "real time" that previously took months or years of laboratory work. We use the Bruker Tracer III-V+ to characterize artifacts and measure the bulk chemical composition of materials. The Nicolet IS5 Spectrometer FTIR is employed to identify mineralogy, sedimentology, diagenesis and ancient pyrotechnology. These analyses can be done at the side of the excavation trench (e.g., Aren Maeir's excavations at Tell es-Safi/Gath)* or in a field lab like Faynan. These kinds of chemical "fingerprints" become important "metadata" for artifacts that tell us a great deal about ancient human technology, production and trade.

* For a photo of the on-site field lab at Tell es-Safi, see Noah Wiener, "The Diggers Return" **BAR**, Jan/Feb 2013.

3D Visualization Platforms

We think in three dimensions, not two, so developments in 3D visualization are opening up new analytical research worlds. The advent of consumer three-dimensional high-definition stereo televisions (3D HDTV) for the home, as well as 3D graphics cards for computers have, over the past year or so, made 3D a low-cost feature in any visualization system. Our Cyber-Archaeology team is taking full advantage of these developments. Even head and hand tracking, which was the most expensive single part of virtual reality systems, is being replaced by consumer gear. The drop in cost, which results from using mass-market components, means that a high-quality 3D visualization platform is now easily obtainable, and parts are replaceable in the field.

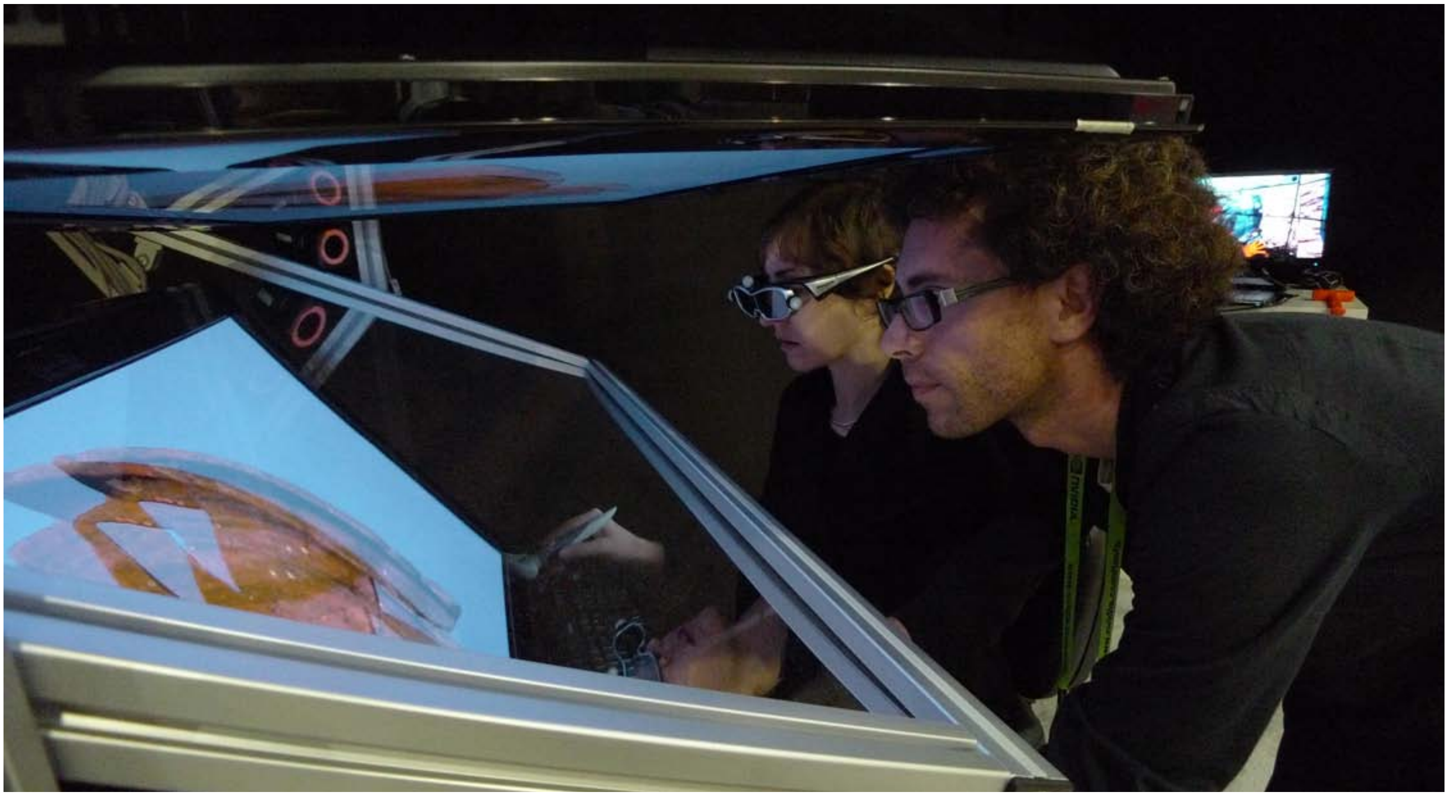
A similar cost drop has occured in software for 3D display, and virtual reality in particular, due to open sourcing of the basic software frameworks (Calit2's CalVR, for example, is available free of charge to university educators and researchers). Immersive 3D visualization is quickly gaining attention as a tool for archaeology workflows and database integration.

Thomas Levy and Sami Al Maghlouth in the Calit2 KAUST NexCAVE (computer-generated image shown in mono). Photo: Tom DeFanti.

Jurgen Schulze in the Calit2 TourCAVE showing the mono version of a 360° CAVEcam stereo photograph of the Egyptian site of Medinet Habu. These images provide both a site conservation tool and an analytical environment to study ancient remains. Photo: Tom DeFanti.

CAVE Environments and Heads-Up Virtual Reality

Using micropolarization techniques, stereo displays can be tiled together into various arrangements, to create ultra-high resolution displays. We have several different configurations we call the StarCAVE, NexCAVE and TourCAVE.[21] The most recent design is the TourCAVE. These can be used for collaboration among several users, or for public exhibition of 3D stereo. We have used CAVE environments to analyze the spatial location of high precision radiocarbon dates in relation to monumental architecture and industrial copper production remains at Khirbat en-Nahas. These data were published in the prestigious *Proceedings of the*

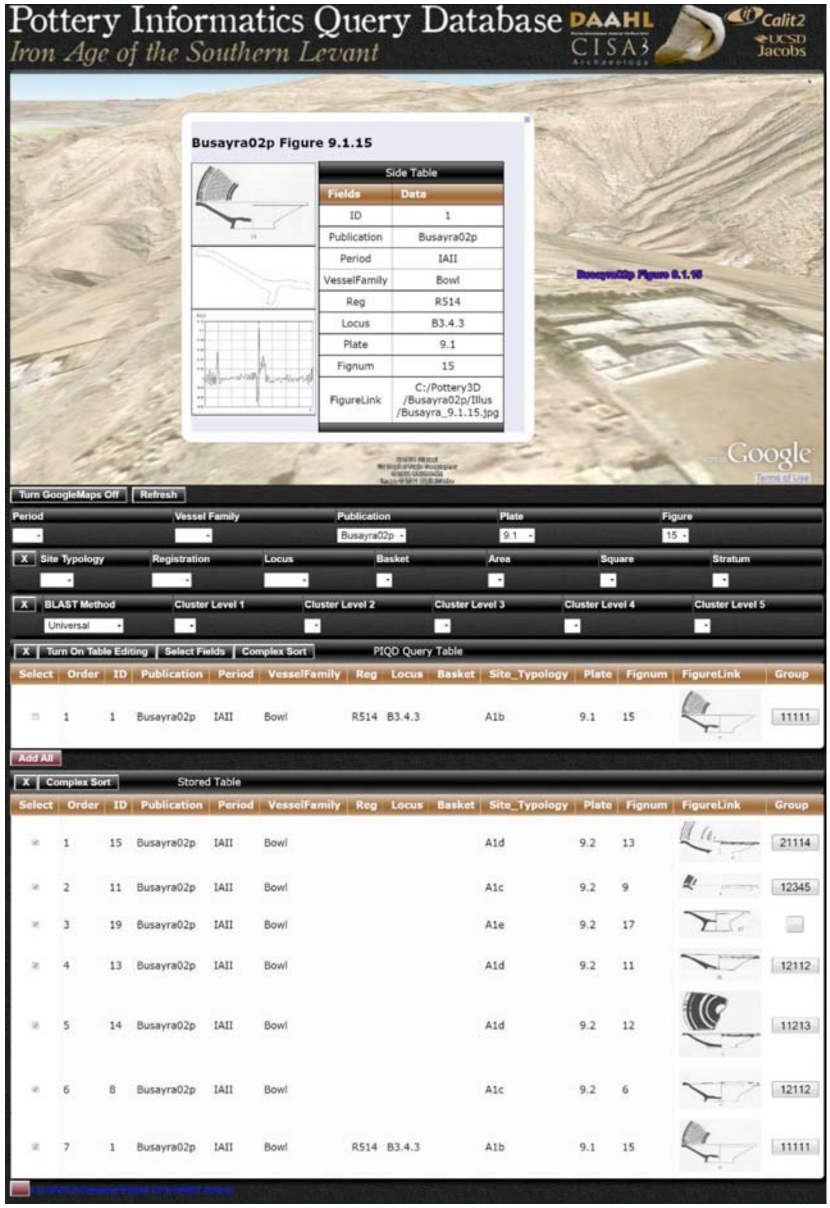


Calit2's Heads-Up Virtual Reality (HUVR) system uses a consumer active stereo HDTV and a half-silvered mirror to generate a virtual image in 3D. HUVR can be used with a keyboard, 3D trackball and a Phantom™ touch feedback device. Photo: Tom DeFanti.

National Academy of Sciences[22] and demonstrate that, contrary to the Biblical minimalist school of thought, there is no question that complex kingdom level societies existed in southern Jordan during the 10th century B.C.E. and controlled local metal production. The jury is still out as to whether it was the Edomites or Israelites who controlled the mines and metallurgy in Faynan during this hotly debated century.

Pottery Informatics Query Database

The Pottery Informatics Query Database[23] (PIQD) is another Cyber-Archaeology tool we use to digitize, organize, query and analyze volumes of published and unpublished ceramic assemblages from our excavations and other sites in the southern Levant. The PIQD is an online tool designed to test interpretations and ideas against an ever-expanding digital medium of ceramic datasets in ways not possible with conventional print data. The Iron Age (c. 1200–586 B.C.E.) southern Levant was chosen as the initial study area for the PIQD because it is a well-documented region with hundreds of excavated sites. Our data is "pre-adapted" to online storage and analyses, since every artifact we collect in the field is georeferenced using digital recording tools. The PIQD stores published 2D vectorized images and 3D scans of ceramic sherds using several mathematical programs developed by our colleagues Avshalom Karasik and Uzy Smilansky from The Hebrew University of Jerusalem and the Weizmann Institute. The PIQD is actually a collaborative project between Calit2 and the Computerized Archaeology Lab at The Hebrew University. These mathematical programs encode and store the morphological data of the ceramic sherds. The ingestion of new datasets is divided between a group of students and researchers distributed around the world who are invested in southern Levantine Iron Age ceramic research. This is accomplished by providing digital contentcreation tools for processing 2D illustrations and 3D scans of ceramic data in a standardized digital format. Since the final output of both the 2D illustrated profiles and 3D scanned profiles is a mathematical representation, we can directly combine them into a fully comprehensive analytical environment. We hope to eventually store every significant ceramic assemblage from the southern Levant to allow us to preserve and compare published ceramic assemblages and new 3D scanned assemblages from the many participating archaeological projects. The encoded storage of the ceramics in the PIQD allows us to rapidly search the whole database of digitally stored vessels in an objective mathematically-grounded approach, which we call a BLAST search. By providing archaeologists with a rich analytical database, as well as digital conversions of published ceramic illustrations from most of the significant Iron Age southern Levantine excavations, we hope that the PIQD will start a revolution in how regional ceramic analyses are conducted. As more researchers become involved, further collaboration and novel research can be conducted through the PIQD on a level that was impossible in the past.



The Pottery Informatics Query Database (PIQD) main web page (http://adaa.ucsd.edu/PIQD/).

ArtifactVis2

ArtifactVis2 is the 3D immersive environment we use to visualize and analyze everything recorded at the archaeological site in our CAVE (e.g., TourCAVE). It is a 3D Geographic Information System (GIS) that is much more powerful than Google Earth, ArcGIS or other programs commonly used today to digitally view and study the world around us. ArtifactVis2 provides a Cyber-Archaeology-based collaborative environment to query and analyze in real-time archaeological datasets stored in our online server database. Users are able to select and dynamically load any artifact's 3D model and interact with it within the context of the laser scanned (LiDAR and SfM) archaeological site.[24] By using ArtifactVis2, we can fully immerse archaeologists within their data. Since the majority of data is dynamic, archaeologists are able to interact with, manipulate and study it in real-time. This can be done in the field as data are recorded or during the off-season when archaeologists study their data and conduct analyses with the complete data sets. ArtifactVis2 allows us to rewind or fast forward all the minute details of a site's excavation and preserve

Neil Smith demonstrating ArtifactVis2 *in the immersive TourCAVE, showing Khirbat al-Iraq Shmaliyeh (Jordan) in the background. Such CAVEs allow archaeologists to analyze their data in a 3D environment.*

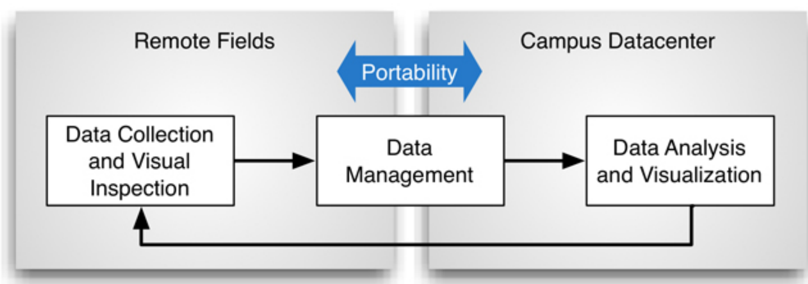
everything in a lifelike immersive environment that recreates the archaeological excavation. It resolves the fundamental problem in archaeology: Once a site is excavated it is gone forever. It enables anyone to see the excavation of the site as the field archaeologist saw it from start to finish. Moreover, it provides tools that are not available during the excavation to examine patterning in both artifact distribution and the information recovered from loci. All of this can be done in the comfort of an air-conditioned room where researchers can collaborate, discuss and propose questions in a fully immersive environment, just as if they were standing at the site during the excavation. In sum, the goal of ArtifactVis2 and the many other interrelated projects is not to recreate a fictional model of what a site might have looked like 3,000 years ago, but to visualize and examine the evidence uncovered and recorded in our thorough and rigorous excavations.

High Precision Radiocarbon Dating

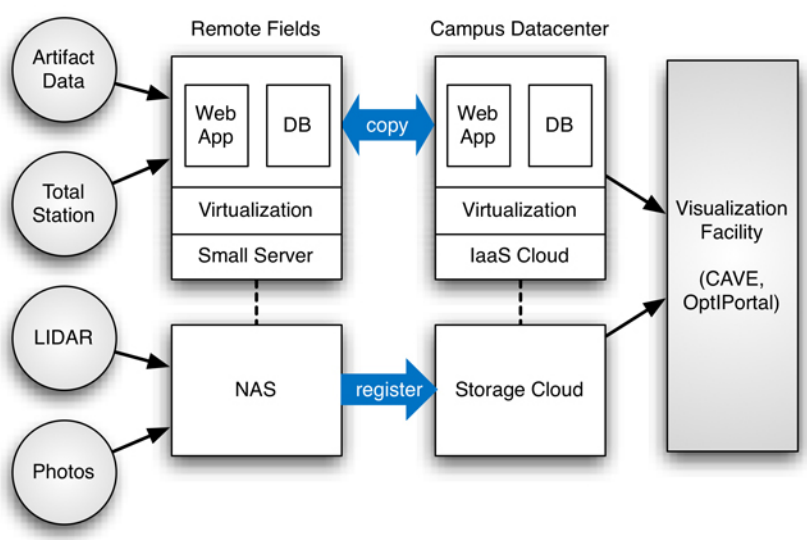
High precision radiocarbon dating is a key element in our Cyber-Archaeology toolbox. It is the most commonly used scientific dating method in archaeology today and provides a degree of accuracy not possible in traditional typological studies of pottery and other artifacts. Without going into dating principles, what can be dated, complications due to contamination and other factors, the importance of radiocarbon dating for objective Biblical archaeological research cannot be understated. We collaborate closely with Tom Higham of the Oxford Radiocarbon Accelerator unit. The newer Accelerator Mass Spectrometry (AMS) method allows us to date extremely small samples (1–2 mm of carbon, rather than + 10 gr with traditional methods), such as a small seed embedded in a piece of slag or pottery, in order to determine information such as when the material was formed. What provides the "high precision" is the calibration and analyses of the chronological information obtained from the radiocarbon dates. The Oxford lab's own OxCal program is perhaps the most popular calibration program, which changes a radiocarbon date into a calendric date with a small margin of error (nowadays as little as +/- 20 years). OxCal is available on-line and easy to use.[25] The statistical methods used for calibration are mostly Bayesian. According to Christopher Bronk Ramsey of the Oxford lab, Bayesian statistics use both the information from the new radiocarbon (^{14}C) measurement and information from the ^{14}C curve.[26] Most archaeological excavations produce a large number of ^{14}C dates that are needed to determine when an event happened in the past. Our excavations at Khirbat en-Nahas produced the most dates (over 100) at a single Iron Age site. Bayesian statistics provide the necessary framework to analyze collections of ^{14}C dates. By relying on science-based radiocarbon chronologies (rather than artifact typologies), it is possible to work in relatively unknown regions, like Edom in southern Jordan, and establish objective chronologies and sequences of cultural development and change. Artifacts and ^{14}C dates need to be studied together, but the framework should begin with ^{14}C dates.

ArcheoStor and MedArchNet: eScience and the Archaeological Frontier

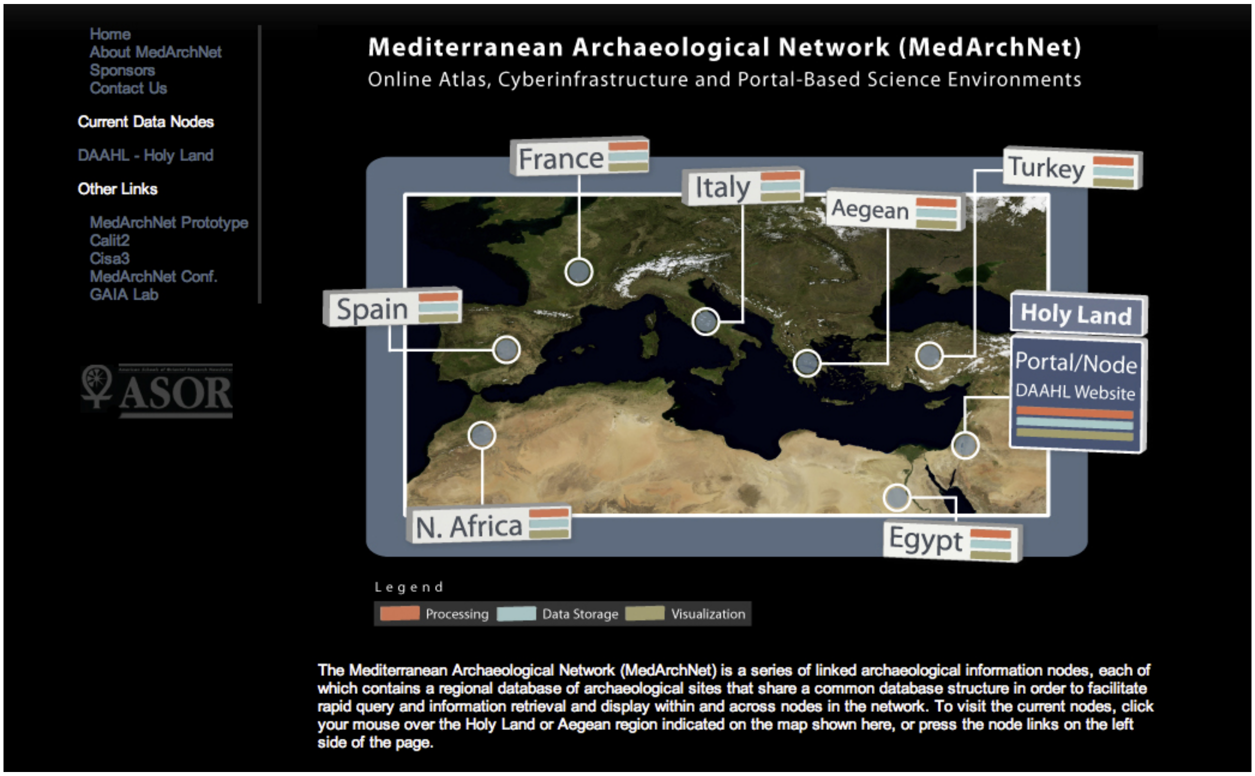
In concluding our review of Cyber-Archaeology in the Holy Land today, a question arises: How can we organize the wealth of digital data being recorded with the diagnostic and analytical techniques discussed above? UC San Diego graduate student Aaron Gidding and Calit2 researcher Yuma Matsui have spearheaded a database pipeline we call ArcheoStor. With so many different types of data and associated formats used at our field sites in Jordan, ArcheoStor is used in the field and lab to manage data ingestion and immediate geospatial presentation. As our fieldwork takes place in a remote part of Jordan with limited Internet access, we use a portable computer



The lifecycle of field research data in Cyber-Archaeology.



The system components of Cyber-Archaeology infrastructure.



The MedArchNet web page (http://medarchnet.org) *has "hot links" to the Digital Archaeology Atlas of the Holy Land* (http://daahl.ucsd.edu/DAAHL).

infrastructure with common data access methods that can be linked to our university cloud computing as soon as we get home. This provides a flexible cyber-infrastructure where we can integrate all our data.[27]

While ArcheoStor accommodates our need for field recording and large-scale Cyber-Archaeology site databases, it is essential to share regional settlement pattern data for the entire southern Levant to get the "big picture" of the archaeology of the Middle East. Stephen Savage and Thomas Levy have developed a digital archaeology atlas system called the Mediterranean Archaeology Network (or MedArchNet[28]) that is a series of linked archaeology information nodes, each of which contains a regional database of archaeological sites. These share a common database structure to enable rapid query and information retrieval and display across nodes in the network. To date, the most developed node is the Digital Archaeology Atlas of the Holy Land (DAAHL)[29] that stores tens of thousands of sites delivered over a Google Earth platform. DAAHL is a useful on-line research tool that allows anyone to select a time period to view all sites regardless of type; or you can select only a site/feature type and find all the sites of that type regardless of time period; or you can choose both a time period and a feature type to find all the sites from the selected period. A relevant bibliography is presented for all published sites. There is also a "virtual museum" that presents 3D scans of select artifacts from different sites. The cyber-infrastructure in DAAHL is set up to deliver much of the data organized in ArcheoStor.

Conclusion

We should not lose sight of what drives our quest to perfect Cyber-Archaeology in the field and lab: historical and cultural questions that lie at the center of anthropology, history and other fields. The new developments in digital technologies and their relative low costs have made it essential for archaeologists to figure out ways to ingest, manage, curate, analyze, publish and share these large datasets with colleagues and the public. We believe the Cyber-Archaeology research in Jordan will not only reshape research in the southern Levant, but also the broader world of archaeology.

Authors

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Neil G. Smith earned his Ph.D. in Anthropology at UC San Diego. Since 2009, he has directed the UCSD Cyber-Archaeology Laboratory in the town of Showbak, Jordan. He is currently a post-doctoral research fellow in the Scientific Visualization Laboratory (VisLab) at Calit2, San Diego Division.

Mohammad Najjar was director of excavations and surveys for the Department of Antiquities of Jordan and is head of "Discover Islamic Art," a Jordanian project sponsored by Euromed Heritage to create a virtual museum of Islamic art on the Internet. Najjar is a research affiliate of the UC San Diego Levantine Archaeology Laboratory.

Thomas A. DeFanti, Ph.D., is a research scientist at the California Institute for Telecommunications and Information Technology, University of California, San Diego, and distinguished professor emeritus of Computer Science at the University of Illinois at Chicago. He received the 1988 ACM Outstanding Contribution Award and was appointed an ACM Fellow in 1994. He shares recognition with Daniel J. Sandin for conceiving the CAVE virtual reality theater in 1991.

Falko Kuester is principal investigator on the IGERT-TEECH project funded by the National Science Foundation, and Director of the Center of Interdisciplinary Science for Art, Architecture and Archaeology (CISA3) in the California Institute for Telecommunications and Information Technology (Calit2), where he is the Calit2 Professor for Visualization and Virtual Reality. Kuester also directs Calit2's Graphics, Visualization and Virtual Reality (GRAVITY) Center, and holds dual appointments as associate professor in the UCSD Jacobs School of Engineering as well as the computer science and engineering departments.

Albert Yu-Min Lin, Ph.D., is a research scientist at the University of California, San Diego, and an Emerging Explorer of the National Geographic Society in the field of technology enabled exploration. He founded and co-directs the UC San Diego, National Geographic Engineers for Exploration Program and currently leads a major international effort known as the Valley of the Khans Project. Lin is a researcher at CISA3. He is also co-founder of California based Tomnod Inc., where he currently serves as chairman of the board of directors.

Endnotes

[1] For a discussion of this pragmatic approach, see Thomas E. Levy, ed., *Historical Biblical Archaeology and the Future–The New Pragmatism* (London: Equinox, 2010). In 2011, the Biblical Archaeology Society named this volume the Best Academic Book in Archaeology.

[2] For recent views, see Maurizio Forte, ed., *Cyber-Archaeology* (Oxford, England: Archaeopress, 2010).

[3] This article is based on a TEDx Sonoma County presentation given by author Thomas Levy on June 16, 2012 at the Sonoma Country Day School. He is grateful to Debbie and Paul Johnson and Shannon Ledger for the invitation to speak. View the presentation online: http://www.youtube.com/watch?v=LfmIU0MXksU

[4] For more on the National Science Foundation's Integrative Graduate Education and Research Traineeship grant and program, see: http://culturalheritage.calit2.net/igert-teech

[5] Thomas E. Levy, J.D. Anderson, M. Waggoner, N. Smith, A. Muniz and R.B. Adams, "Interface: Archaeology and Technology—Digital Archaeology 2001: GIS-Based Excavation Recording in Jordan," *The SAA Archaeological Record* 1.3 (2001), pp. 23 - 29.

[6] Gary O. Rollefson, "Ritual and Social Structure at Neolithic 'Ain Ghazal," in I. Kuijt ed., *Life in Neolithic Farming Communities Social Organization, Identity, and Differentiation.* (New York: Kluwer 2000), pp. 165–190.

[7] Thomas E. Levy and Mohammad Najjar, "Ancient Metal Production and Social Change in Southern Jordan: The Edom Lowlands Regional Archaeology Project and Hope for a UNESCO World Heritage Site in Faynan," in T.E. Levy, M. Daviau, R.W. Younker and M. Shaer, eds., *Crossing Jordan - North American Contributions to the Archaeology of Jordan.* (London: Equinox, 2007) pp. 97–105.

[8] Israel Finkelstein and Neil Asher Silberman, *David and Solomon: In Search of the Bible's Sacred Kings and the Roots of Western Tradition,* (New York: Free Press, 2006).

[9] Levy presents a detailed overview of this pragmatic approach to Biblical archaeology in Thomas E. Levy, "The New Pragmatism: Integrating Anthropological, Digital, and Historical Biblical Archaeologies," in *Historical Biblical Archaeology and the Future* (see endnote 1) pp. 3–44.

[10] See http://opendig.org

[11] Erez Ben-Yosef, Ron Shaar, Lisa Tauxe, Thomas E. Levy & Vasiliki Kassianidou, "The Cyprus Archaeomagnetic Project (CAMP): Targeting the Slag Deposits of Cyprus and the Eastern Mediterranean," *Antiquity* 85.330 (2011). (Available online at http://antiquity.ac.uk/projgall/ben-yosef330).

[12] See http://adaa.ucsd.edu/ArchField. ArchField's development was initially funded by an NEH Digital Humanities Startup Grant.

[13] Digital database for Tall Al-'Umayri: http://umayri.opendig.org/home

[14] See - http://ngs.ucsd.edu/stabilized-aerial-camera-platform.html

[15] Vid Petrovic, Aaron Gidding, Tom Wypych, Falko Kuester, Thomas A. DeFanti and Thomas E. Levy, "Dealing with Archaeology's Data Avalanche," *IEEE Computer Society,* July 2011 pp. 56–60.

[16] See Thomas E. Levy, Thomas Higham, Christopher Bronk Ramsey, Neil G. Smith, Erez Ben-Yosef, Mark Robinson, Stefan Münger, Kyle Knabb, Jürgen P. Schulze, Mohammad Najjar and Lisa Tauxe, "High-Precision Radiocarbon Dating and Historical Biblical Archaeology in Southern Jordan." *Proceedings of the National Academy of Sciences* 105.43 (2008), pp. 16460–16465; Thomas E. Levy, Vid Petrovic, Thomas Wypych, Aaron Gidding, Kyle Knabb, David Hernandez, Neil G. Smith, Jurgen P. Schlulz, Stephen H. Savage, Falko Kuester, Erez Ben-Yosef, Connor Buitenhuys, Casey Jane Barrett, Mohammad Najjar and Thomas DeFanti, "On-Site Digital Archaeology 3.0 and Cyber-Archaeology: Into the Future of the Past–New Developments, Delivery and the Creation of a Data Avalanche," in M. Forte, ed., *Introduction to Cyber-Archaeology,* (Oxford: Archaeopress, 2010), pp. 135–153.

[17] Albert Yu-Min Lin, Alexandre Novo, Shar Har-Noy, Nathan D. Ricklin and Kostas Stamatiou, "Combining GeoEye-1 Satellite Remote Sensing, UAV Aerial Imaging, and Geophysical Surveys in Anomaly Detection Applied to Archaeology." *IEEE J-STARS* 4.4 (2011), pp. 870–876.

[18] See http://exploration.nationalgeographic.com

[19] Publication in process, but see the TEDx lecture: http://www.youtube.com/watch?v=5Xv9kqxVMH0

[20] Paul Goldberg and Richard Macphail, *Practical and Theoretical Geoarchaeology,* (Oxford: Wiley-Blackwell, 2006); Stephen Weiner, *Microarchaeology: Beyond the Visible Archaeological Record* (New York: Cambridge University Press, 2010).

[21] CAVE is a trademark of the Board of Trustees of the University of Illinois.

[22] See Levy et al., "High-Precision Radiocarbon Dating" (see endnote 16).

[23] The Pottery Informatics Query Database is available at http://adaa.ucsd.edu/PIQD/

[24] ArtifactVis2 is built on top of an interdisciplinary visualization system called CalVR, an in-house, open-source program developed by Calit2 based on Open Scene Graph and a similar design to OpenCover COVISE. CalVR is fully scalable from a single 3D TV to a fully immersive CAVE environment.

[25] Oxcal online: http://c14.arch.ox.ac.uk/embed.php?File=oxcal.html

[26] Christopher Bronk Ramsey, "Bayesian analysis of radiocarbon dates," *Radiocarbon* 51.1 (2009), pp.337–360.

[27] Yuma Matsui, Aaron Gidding, Thomas E. Levy, Falko Kuester, Thomas A. DeFanti, "Portable Data Management Cloud for Field Science," *IEEE Fifth International Conference on Cloud Computing* (2012), pp. 1000–1001; Aaron Gidding, Yuma Matsui, Thomas E. Levy, Tom DeFanti and Falko Kuester, "e-Science and the Archaeological Frontier," *IEEE Seventh International Conference on E-Science* (e-Science), 2011.

[28] The Mediterranean Archaeology Network (MedArchNet) is available at http://medarchnet.org

[29] Digital Archaeology Atlas of the Holy Land (DAAHL) is available at http://daahl.ucsd.edu/DAAHL