

5-2012

Reappraising the Land Behind Baghdad: Using CORONA Satellite Imagery to Reassess the Archaeological Landscape of the Diyala Plain, Iraq

James Henry Wesolowski
University of Arkansas, Fayetteville

Follow this and additional works at: <http://scholarworks.uark.edu/etd>

 Part of the [Archaeological Anthropology Commons](#), [Near and Middle Eastern Studies Commons](#), and the [Remote Sensing Commons](#)

Recommended Citation

Wesolowski, James Henry, "Reappraising the Land Behind Baghdad: Using CORONA Satellite Imagery to Reassess the Archaeological Landscape of the Diyala Plain, Iraq" (2012). *Theses and Dissertations*. 432.
<http://scholarworks.uark.edu/etd/432>

This Thesis is brought to you for free and open access by ScholarWorks@UARK. It has been accepted for inclusion in Theses and Dissertations by an authorized administrator of ScholarWorks@UARK. For more information, please contact scholar@uark.edu, ccmiddle@uark.edu.

REAPPRAISING THE LAND BEHIND BAGHDAD

**USING CORONA SATELLITE IMAGERY TO REASSESS THE
ARCHAEOLOGICAL LANDSCAPE OF THE DIYALA PLAIN, IRAQ**

REAPPRAISING THE LAND BEHIND BAGHDAD
USING CORONA SATELLITE IMAGERY TO REASSESS THE
ARCHAEOLOGICAL LANDSCAPE OF THE DIYALA PLAIN, IRAQ

A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Arts in Anthropology

By

James Henry Wesolowski
Indiana University
Bachelor of Arts in Sociology with emphasis in Anthropology, 2009
Indiana University
Bachelor of Science in Geology, 2009

May 2012
University of Arkansas

ABSTRACT

High-resolution low-cost declassified CORONA spy satellite imagery is used to detect archaeological sites and relict canals in the Diyala Plain to the east of Baghdad, Iraq. This project seeks to improve upon the ground survey conducted there in the 1950s by providing better geographic control and discovering sites and canals that were not included in the original survey. CORONA imagery provides a sub-2-meter spatial resolution and was acquired shortly after the original ground survey was conducted, providing an excellent medium for comparison. CORONA imagery is subject to significant spatial distortions because of its camera technology and the LPS package for ERDAS Imagine was used for orthorectification. This procedure eliminates the need for camera ephemeris data or mathematical models and relies on ground control points. Google Earth was successfully used as the geographic reference. An attempt was also made to utilize the stereographic nature of the product to photogrammetrically extract digital elevation models, but low topographic relief and poor image contrast contributed to poor results. The highly accurate orthorectified images were then visually inspected for evidence of archaeological sites and relict canals. A total of 655 sites were found in the study area, essentially doubling the number of sites found in the ground survey, although this number likely underrepresents the actual number of sites present on the landscape due to difficulty in distinguishing some features. The sites found generally were smaller in area than those in the ground survey, establishing CORONA's utility for finding sites difficult to detect on the ground. The canal network of the original survey was also greatly extended. The usefulness of CORONA as a tool for archaeological survey is amply demonstrated, although some refinements will be required in establishing the distinguishing characteristics of sites before it can be used in lieu of ground-based survey.

This thesis is approved for recommendation
to the Graduate Council

Thesis Director:

Jesse Casana, Ph.D.

Thesis Committee:

William F. Limp, Ph.D.

Jackson Cothren, Ph.D.

Copyright © 2012 by James Henry Wesolowski
All Rights Reserved

THESIS DUPLICATION RELEASE

I hereby authorize the University of Arkansas Libraries to duplicate this thesis when needed for research and/or scholarship.

Agreed

_____ *James Henry Wesolowski*

Refused

_____ *James Henry Wesolowski*

ACKNOWLEDGEMENTS

Special thanks to Dr. Jesse Casana, Dr. Jackson Cothren, Tuna Kalayci, the Center for Advanced Spatial Technologies (CAST) at the University of Arkansas, and the Archaeological Atlas of the Middle East project for providing the CORONA imagery used in this project.

Thanks also go to Adam Barnes of CAST for his assistance with the orthorectification of the CORONA imagery.

DEDICATION

For my mother, who has always been there for me.

TABLE OF CONTENTS

I. INTRODUCTION	1
The Adams Survey.....	2
Critiques of the Adams Survey	4
The Current Project.....	8
II. CITY AND COUNTRYSIDE.....	11
Geography and Environment of the Southern Mesopotamian Plain	11
The Cultural Development of the Diyala Region	15
III. PREVIOUS WORK AND TECHNICAL BACKGROUND	26
Satellite Remote Sensing in Archaeology.....	26
The CORONA Spy Satellite Program	29
Background.....	29
Problems with and Approaches to Using KH-4 imagery.....	33
The Use of CORONA Imagery for Archaeology in the Middle East.....	40
IV. MATERIALS AND METHODS	57
Preparation of the GIS Database.....	57
Preparation of CORONA Imagery.....	59
Orthorectification.....	60
DEM Extraction	63
Analysis.....	66
V. RESULTS AND CONCLUSIONS.....	69
Identification of Landscape Features	69
Identification of Canals.....	75
Identification of Settlement Sites.....	77
Conclusions.....	82
VI. REFERENCES	85

I. INTRODUCTION

The value of archaeological survey above and beyond its utility for locating sites has been demonstrated by its contribution to a greater understanding of regional culture through establishing relationships among settlements, their surrounding landscapes, and human activity (T. J. Wilkinson 2000a). The great archaeological surveys of southern Mesopotamia performed

by Robert McCormick

Adams (1965; 1981) are

among those which form the

foundation of our

understanding of the rise of

complex societies. These

surveys introduced many

novel concepts and

techniques and, in many

ways, revolutionized the way

that archaeological survey

was carried out.

Adams conducted his survey of the Diyala Plains to the east of Baghdad in 1957

and 1958 (Figure 1) and

published his findings in a

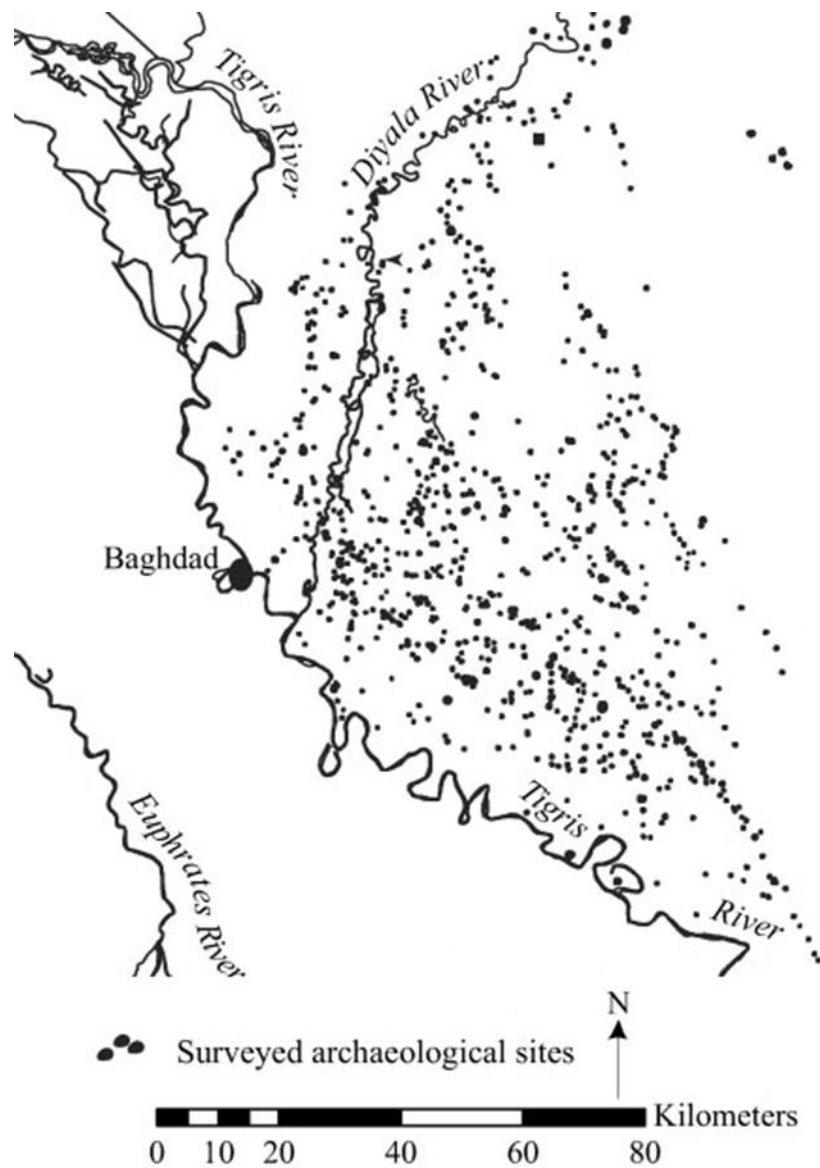


Figure 1. Area of Adams' *Land Behind Baghdad* survey. Modified from Hritz (2010).

well-known and widely-cited volume entitled *Land Behind Baghdad* (1965). The objective of this project was to provide information about the geographic backdrop upon which the earliest civilizations developed, focusing on land use, locating ancient settlements, and their relationship to watercourses over the last 6,000 years, not an unambitious goal (Adams 1981). In the years since, no significant archaeological survey work has been conducted in the region, in great part due to violent conflict over recent decades. One notable exception is the study of Gasche et al. (2002), who performed a ground-based survey along with satellite imagery to better understand how natural and anthropogenic factors influenced the geomorphological change in the alluvial plain near Sippar (Richason and Hritz 2007).

The Adams surveys provide a great deal of information about settlement practices in southern Mesopotamia, but limitations in the technology available at the time and improvements to archaeological survey methods in the time since present the opportunity to reexamine these regions and improve upon the already substantial contributions they have made to archaeology.

The Adams Survey

Adams (1965, 33) characterized his survey as “intensive (but not exhaustive)” and conducted it during a single seven-month field season. Because of the time limitation, Adams expected that the entire area could not be fully surveyed, so he instead pursued a “rough and preliminary coverage” of the approximately 8,000 sq. km comprising the survey area.

Ultimately, Adams was unable to complete the project in the time that he had available, leaving several small areas in the lower Diyala Plains, the upper reaches of the Khālis canal, and the northern parts of the Diyala River basin unsurveyed (Adams 1965).

Adams' project was based in large part on Thorkild Jacobsen's survey of 1936-1937 which identified 119 sites, mostly in the north and central regions of the Diyala Plains, that were included in Adams' report. Adams based his survey methodology on two concepts that he felt were amply demonstrated by Jacobsen. The first was that settlements must be near water and, thus, ancient settlements can be used to approximately locate ancient waterways. The second is that these sites and their associated waterways can be dated and their occupational history determined by surface artifacts alone. Because many of the settlements were occupied either continuously or more than once, the surface artifacts required analysis to determine which cultural periods were represented at each site. The primary goals of these analyses were to understand how settlement occupation changed, both temporally and in terms of density (Adams, 1965).

The survey was conducted in two stages. First, 1:50,000 maps of various types, including topographic and soils maps, were carefully examined to find evidence of tells. Additionally, in many cases aerial photographs were used to augment the map data as soil color was an important indicator of ancient mud bricks. Using these tools, Adams and his team constructed a survey basemap showing the location of ancient sites and canal levees (Adams, 1965).

The second stage was conducted in the field. The survey team drove along levees because of the visibility they afforded as well as the proximity of most sites to these waterways. The previously mapped sites were visited, located by resection, and briefly described. Because of the size of the survey area and the fact that many sites were not well-preserved, detailed site descriptions were avoided. Sherds were also collected, then later typed and provisionally dated. Some new styles were found and there were also some challenges to traditional site

chronologies. Finally, maps were produced of the discovered sites and watercourses. (Adams, 1965).

Critiques of the Adams Survey

Land Behind Baghdad forms the first in a series of three volumes published by Adams over the course of 16 years. All deal with surveys in southern Mesopotamia, the third—*Heartland of Cities* (1981)—being a synthetic volume which reflects new ideas and technologies in the field. All three works are widely cited in the literature as they form probably the largest archaeological survey undertaking in the region. Unfortunately, political and social unrest in Iraq has prevented any significant Western archaeology from being conducted in the region since the publication of Adams' survey (T. J. Wilkinson 2000a). Thus, these works form the most up-to-date and relied-upon sources of data available on southern Mesopotamia. However, even though Adams' later work improves upon the original survey, there are still advancements that can be made with modern methods of remote sensing, which will once again allow Western archaeology to work in Iraq. The most important area where the survey can be improved is by improving the accuracy of maps of settlements and waterways.

Adams was unable to acquire good topographic maps of the survey region (Adams 1981). They were either available at very small scales unsuitable for survey use or, where more detailed maps were available, concentrated on areas of modern economic interest and development, leaving much of the survey area poorly described. Another problem was the distortion inherent in the aerial photographs caused by camera angle, curvature of the earth, and topographic features (Adams 1981). This, together with inadequate maps, increased the difficulty in determining the actual locations of discovered settlements and landscape features. Furthermore,

the survey maps are published with coarse 15 arc-minute (~28 km) grid squares, are not represented as being in any particular projection, and have very large symbols that are many times larger on the map than what they represent on the ground (Adams 1965; Sherratt 2004). This allows for significant opportunity for later error. A third issue is the method Adams used in conducting ground survey. By favoring survey along the tops of levee systems (Adams 1965), larger sites lying along them were systematically favored over smaller or more distant sites (Adams 1981; Redman 1982). Ultimately, this results in an underestimation of the number of sites and a mischaracterization of the types of sites present.

The assumption that Adams makes regarding the use of solely surface artifacts, as opposed to excavation, to determine site occupational history is troubling. The movement of artifacts to the surface is explained by several factors, some small-scale and some large-scale: “well-digging, brick-making, construction of house foundations, grave-digging, and the like” and “city walls and foundation terraces for monumental buildings” (Adams 1965, 122). These appear, at first glance, to be valid mechanisms for the upward transport of archaeological materials. However, several things should be noted that call into question whether these kinds of mechanisms provide an accurate and complete explanation for any surface collection in general but also for this region in particular with its unique combination of natural and anthropogenic processes.

The first of these relate to geologic and taphonomic processes. The depositional environment may have buried materials beyond the reach of these activities. Most, if not all, of the survey region is located in an active alluvial plain that has seen the courses and characteristics of rivers large and small change dramatically over the last 6,000 years, including changes between single channels and channel networks. Equally possible is the erosion of

materials as a result of channel migration or hillside erosion, which results in secondary deposition of the artifacts at another location. These simple fluvial and alluvial processes have the potential to essentially erase evidence of occupation. Although canals were built for water management, the ancient literature speaks often about flooding, either seasonal or at greater time scales, and these floods overtopped the canals at times (T. J. Wilkinson 2003; Heyvaert and Baeteman 2008; T. J. Wilkinson 2000a).

Finally, the construction-related activities occur only in certain places. This results in an uneven distribution of artifacts brought to the surface by these mechanisms. This method is further troublesome because it very much has the potential to miss extant occupational evidence buried somewhere else, even less than a meter away. Thus, it is important to realize that there are probably holes in the archaeological landscape, and some material may be found in places of secondary deposition. It is also possible that what is recorded as a cluster of several small sites may actually be a surface expression of the nonuniform upward migration of archaeological materials from a single large occupation.

There are also several shortcomings to this survey methodology in the literature. Adams (1981) himself indicated that there may have been a systematic bias in favor of larger and more visible sites because of his levee-based reconnaissance, a sentiment echoed by Redman (1982). The assumption that sites are more likely to be found along such waterways reduces the effort to look elsewhere, and material will certainly not be found if it is not looked for. This results in underestimating the number of sites actually present and it provides an incomplete picture of what kinds of sites were present (Banning 2002). This has potential wide-ranging ramifications in understanding settlement dynamics, economy, and social and political stratification.

Redman (1982) also addresses the problem of using surface artifacts to date periods of occupation. He asks whether we should interpret such materials to represent the only periods during which a site was occupied or rather make the assumption that occupation was continuous, even between periods represented on the surface. Redman further asks whether site boundaries should be limited to where artifacts are found (many small sites) or assumed to be continuous between (fewer larger sites). Cole and Gasche (1998) indicate that on several occasions, sites included in the Adams survey which have later been excavated have revealed artifacts from periods not represented by the surface finds. In addition, there have been sites which contain no materials for periods represented on the surface. Furthermore, some of the diagnostic artifacts used by Adams were not securely tied to the periods they were associated with.

There is also a question of whether Jacobsen's approach to levee-site alignment is appropriate. Jacobsen felt that if sites belonging to the same period were aligned along a canal, then that canal can be considered to have been in use during that time. Conversely, if a site fell alongside a canal in alignment with other sites, then the dates obtained from those other sites may be applied to the site in question (Adams 1965). However, this link has been challenged. First, there is uncertainty surrounding the dating of sites using surface artifacts as mentioned above. Second, it ignores a whole host of factors which affect the shape and position of levees, including fluvial and alluvial processes, climate change, isostasy and tectonics, and anthropogenic modifications (Cole and Gasche 1998). Third, using sites to infer the existence of canals is not very rigorous. Cole and Gasche (1998) determined that for many alignments of sites, there is no evidence for the existence of a canal and for others, the canals ran straight through levees (T. J. Wilkinson 2003). Fourth, it makes the assumption that no earlier channels existed which later occupations could have simply reused (T. J. Wilkinson 2003). Finally,

Pournelle (2003a) suggests that, at least further to the south, site alignments are not related to former watercourses but the result of settlement on turtlebacks, which are higher-elevation relict terraces that provide protection from seasonal inundation. The alignments, she argues, are designed to facilitate boat traffic during the wet season.

No easy solutions to these issues exist, but they should be considered in any interpretation of the data. Ideally, new work should be done to address the shortcomings of the Adams survey and create a revised model of landscape evolution in the region. Because of the security situation in present-day Iraq, ground-based resurvey of the Diyala Plain using modern techniques is not possible. However, a remote-sensing approach is perfectly suited to this application.

The Current Project

Satellite imagery has provided a new window onto the Mesopotamian landscape. In recent years, remote sensing applications of high-resolution satellite imagery have enabled a better understanding of sites and landscapes. Numerous studies have demonstrated the utility of satellite imagery and topography data from the Shuttle Radar Topography Mission (SRTM) in finding new, previously undetected settlement sites and landscape features as well as correcting the locations of sites found in previous surveys. Much of the free or low-cost satellite data available are prone to having resolution too low for meaningful remote-sensing analysis of archaeological features and often lack coverage in the study area (Casana and Cothren 2008). For example, LANDSAT ETM+ panchromatic imagery is prone to overestimating the size of sites because of its 15-m resolution (Menze, Ur, and Sherratt 2005). Much of the high-resolution imagery available, however, comes at high cost.

An ideal solution to this quandary is the declassified CORONA satellite imagery, acquired between 1959 and 1972. With up to sub-2-m resolution, this low-cost imagery was taken much closer to the time of the survey and thus would avoid many of the problems inherent in the use of newer imagery, namely the effects of development on the landscape. This imagery, however, also has additional benefits. The first is that because of its age, it corresponds very well with the time of Adams' original survey. Thus, the landscape can be seen with, essentially, the eyes of an original survey team member. Perhaps more importantly, it avoids the problems of recent rapid development in Iraq which has resulted in significant alteration of the landscape. The second is that the two last series of images are stereoscopic, which allows the production of digital elevation models (DEMs) at a much higher resolution than available in the 90-m SRTM topographic data. The Center for Advanced Spatial Technologies (CAST) at the University of Arkansas is currently in the final stages of orthorectifying CORONA satellite imagery for the Middle East so that it can be made publicly available for research (Jesse Casana, personal communication). The current project is independent from the CAST project, although future work may compare the methods and results of the orthorectification and DEM extraction processes from both projects.

The current project will attempt to address some of the shortcomings in Adams' work and utilize CORONA satellite imagery for the Diyala Plain, provided by CAST, to evaluate the potential for this imagery to produce a new, spatially-accurate survey of the region. Adams' 1965 survey data within this project's study area will first be digitized and indicated sites will then be located and georeferenced by comparison to CORONA imagery using GIS software. Ancient irrigation systems as described by Adams (1965) will similarly be located and recorded. The creation of a DEM from the stereo CORONA imagery will then be attempted. Finally, the study

area will be examined for new sites and landscape features that escaped Adams' original survey. The 2-m resolution CORONA imagery and elevation data should powerfully facilitate the detection of small, low relief sites and watercourse levees. Based on the biases inherent in the original survey and successful detection of new sites in other areas using satellite imagery (for example, Hritz 2010), it is anticipated that a great number of new sites and canal levees will be discovered.

II. CITY AND COUNTRYSIDE

Geography and Environment of the Southern Mesopotamian Plain

This subject of this study is the Diyala River plain, with a focus on the area surrounding the ancient city of Eshnunna. The plain lies in southern Mesopotamia, a region that is geographically and environmentally complex. Mesopotamia lies between and around the Euphrates and Tigris Rivers in a foreland basin associated with the convergent tectonic plate boundary between the Arabian and Eurasian plates, which is currently raising the

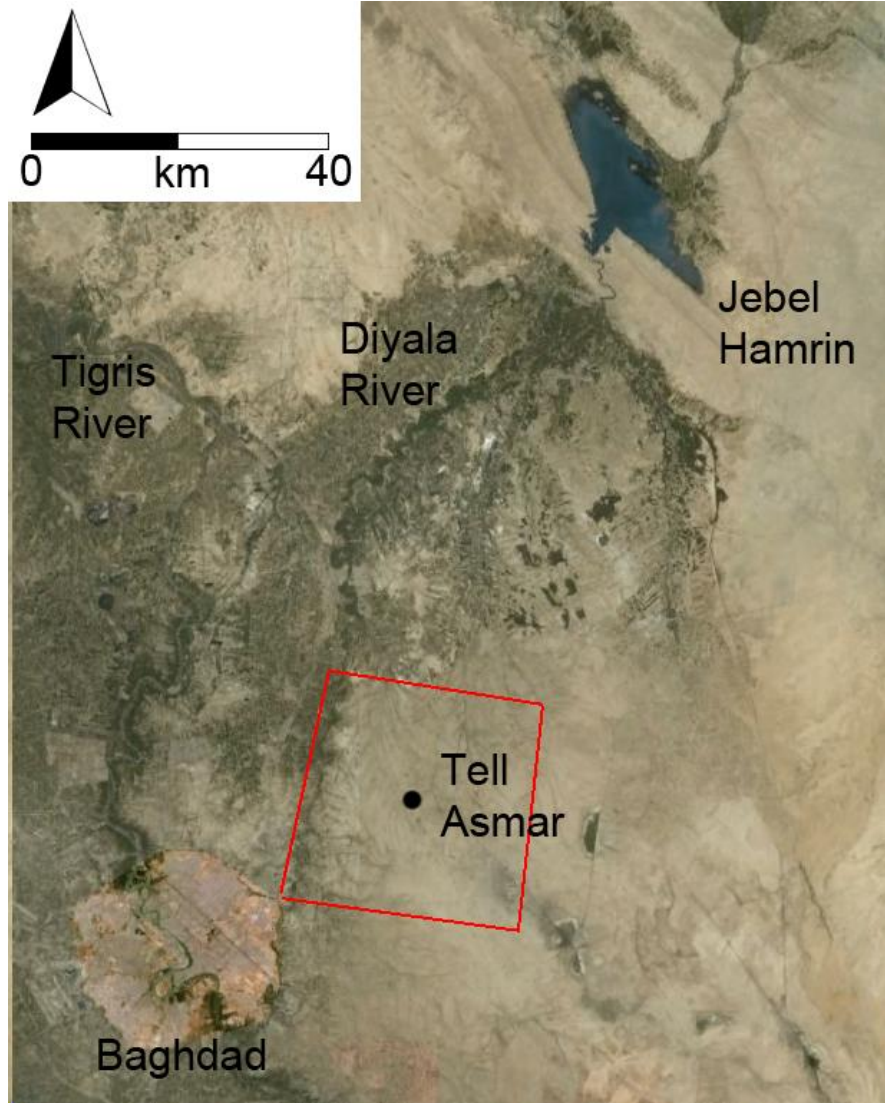


Figure 2. Study area (in red) and surrounding region. Image courtesy of and copyright Google Earth, Europa Technologies, DigitalGlobe, and Cnes/Spot.

Zagros Mountains. It extends to the Zagros in the north and east and to the Badiyat ash-Sham and Sahra al-Hijarah deserts to the west and southwest, respectively (Hritz 2010).

Southern, or lower, Mesopotamia is an alluvial floodplain created and modified by the Tigris and Euphrates Rivers and their tributaries. It lies in a deep, broad basin over which several hundred meters of sediment have been deposited, transported there by the rivers after being eroded from the surrounding highlands, primarily the Zagros and Taurus Mountains. Most of the basin features low relief, varying only 2 to 5 meters in elevation (T. J. Wilkinson 2003). Within the floodplain, numerous features are common, including channels, natural levees (with relief of 3-4 m), and crevasse splays (small alluvial fans caused by a stream breaking through its levee) (Morozova 2005). Flooding is common in many areas and was likely a frequent and dangerous hazard to the people who settled in southern Mesopotamia ((Rowton 1969; Verhoeven 1998)). In addition, some areas are no longer undergoing active fluvial or alluvial processes and, in many cases, eolian processes have taken over, producing dune fields and deflated basins (Morozova 2005).

Soils on the alluvial plain vary considerably in fertility depending on sediment texture, geomorphology, and elevation above the floodplain. Fertilizer, such as manure and ashes, is necessary to satisfy deficiencies in nitrogen and phosphorus. In general, the fertility of the soils in the Euphrates floodplain is better than that of the Tigris because of the different geological environments the rivers flow through (T. J. Wilkinson 2003). The continuous use of water from the rivers resulted in the increasing salinization of the soil, requiring innovation on the part of the people who lived there (Verhoeven 1998).

The Tigris and Euphrates have had a complex history which has greatly affected the archaeology of southern Mesopotamia. Though the rivers today each occupy single channels, this was not the case in the past. During the fourth millennium BCE, the rivers likely ran together but in a network of channels with several mouths into the Persian Gulf. Later, the Tigris probably

flowed further to the east than its present course, pushed there by the heavy deposition of the Euphrates. It is possible that the alluvial deposits produced by the Diyala later forced the Tigris into its current channel, although the modern-day configurations of the Tigris and Euphrates are most likely also strongly influenced by the human management of water over the last several millennia (Adams 1981).

More water flows through the Tigris than the Euphrates, but it is more prone to erratic flooding and its high levees in many areas makes it more difficult to use for irrigation (Morozova 2005). Adams (1981) suggests that the Tigris was not widely used for irrigation until the Sassanian period (226-637 CE), though some epigraphic evidence describes the Tigris as the source for some canals. The Euphrates, more likely to divide into multiple channels, was probably a more important source of irrigation water for the regions between the rivers (Morozova 2005).

The Diyala River rises in the Zagros Mountains of Iran and flows in a generally southwestern direction until its confluence with the Tigris in the southern reaches of modern Baghdad. It is fed primarily by seasonal rainfall and, to a far lesser extent, snowmelt. The Diyala Plain upon which Adams' survey was conducted lies between the Jebel Hamrin, a series of geologic folds, and the Tigris. The plain is, for the most part, alluvium in a fan shape radiating outward from where the Diyala exits the Jebel Hamrin and is characterized by a network of natural and artificial waterways (Adams 1965). Artificial canals, when large enough and absent maintenance, can acquire flow characteristics of natural channels and, conversely, natural rivers were often modified by humans, taking on the characteristics of constructed waterways (T. Jacobsen and Adams 1958). These watercourses, of both origins, for these reasons and the fact

they have become so important to human life in the region, that the language does not even distinguish between them (Adams 1965; T. Jacobsen and Adams 1958).

The Diyala Plain has a relief of about 40 m and a length of 171 km between the Jebel Hamrin and the Tigris. In the past, the river has had an anastomosing channel system, but today most of its length occupies a single channel. Toward the Jebel Hamrin, the Diyala is wide, over a kilometer, and has a braided channel. Further downstream, the river is a single, entrenched meandering channel that is sufficiently deep to prevent overbanking. The lower portion of the channel meanders through the plain, having natural levees which have been enhanced with artificial embankments and are rarely overtopped (Adams 1965; Verhoeven 1998). There have been 8-11 meters of deposition on the Diyala Plain since the Jemdet Nasr period (T. J. Wilkinson 2003), and the depth of the earliest remains at Tell Asmar are over 10 m below the modern surface (Adams 1965)

The modern plain features a complex network of basins and canal levees (both natural and anthropogenic) which is a result of the long-term use of irrigation in the region (Verhoeven 1998). The Diyala was so heavily depended upon for watering crops that it was common for the river to be dry at its confluence with the Tigris toward the end of summer because all the water had been diverted into the fields (Adams 1965).

Period	Approximate Dates
Ubaid	4000-3500 BCE
Warka and Protoliterate	3500-3000 BCE
Early Dynastic	3000-2300 BCE
Akkadian and Gutian	2300-2100 BCE
Ur III and Isin-Larsa	2100-1800 BCE
Old Babylonian	1800-1600 BCE
Kassite	1600-1100 BCE
Middle Babylonian	1100-625 BCE
Neo-Babylonian	625-537 BCE
Achaemenian	527-311 BCE
Seleucid-Parthian	311 BCE - 226 CE
Sassanian	226-637 CE
Early Islamic and Samarran	637-883 CE
Post-Samarran Abbasid	883-1258 CE
Ilkhanid and later	1258-1500 CE

Table 1. The Adams (1965) chronology used in this study.

The Cultural Development of the Diyala Region

Although this project is primarily methodological in nature, a brief overview of the cultural development of the Diyala region is important to provide context and to examine some of the interpretations of the original survey. This section comprises a summary of the conclusions of *Land Behind Baghdad* (Adams 1965), it being the most comprehensive understanding we have of the history of the region. Adams divides the chronology of the Diyala region into 15 periods as indicated in Table 1. In this section, settlements will be referred to as large towns (over 10 hectares), small towns (4 to 10 hectares), and villages (less than 4 hectares), in accordance with Adams' categorization. All settlement counts given in this section refer to the entire study area as shown in Figure 1.

The initial occupation of the Middle East by pastoralists and agriculturalists commenced in the seventh millennium BCE, but no real record of them exists in the Diyala region. Starting in the Ubaid period (ca. 4000-3500 BCE), there is sparse evidence of occupation, about 22 settlements, but it is not widespread. Ubaid ceramics were discovered at Tell Asmar, but only in association with later periods. During this time, the course of the Diyala ran westward of its current location and joined the Tigris through numerous channels. There appear to be some incipient irrigation systems during this time as evidenced by a few linear arrangements of sites in the southern areas of the Diyala region, only one of which includes Tell Asmar, running southeast from there to sites outside of the present study area. However, it is likely that during this period, settlements were located along natural channels rather than the constructed ones which would appear later. The great distance and small size of the settlements would seem to indicate a lack of political or economic cohesion among them (Adams 1965).

During the Warka (Uruk) and Protoliterate periods (ca. 3500-3000 BCE), there was likely growth in the size and number of settlements, increasing to about 43, but, again, there are very few diagnostic ceramics to be found from this time. Most of the growth was along the former western channel of the Diyala, especially to the north. There were two new, short channels between the Diyala and Tigris that appeared during this time, which may indicate the beginning of moderate-scale irrigation efforts but which may rather simply be new natural channels (Adams 1965).

The earliest settlement for which we have definite and unmistakable evidence throughout the region is the Early Dynastic period (ca. 3000-2300 BCE). Abundant ceramics from the period have been found in surface scatters and especially at Tell Asmar, Tell Agrab, and Khafajah, where significant excavation has taken place. The size and number of settlements have again increased (to 96 sites) but the area in which those settlements are found has remained roughly the same. Large areas of land remained available for use by mobile pastoralists for grazing. The three large towns mentioned above were now walled, suggesting political strength and the need for defense. Many excavations have revealed temples, however palaces have been notably absent in this region compared to other areas of southern Mesopotamia at the time. This suggests that religious authority persisted here when other polities were moving toward more secular government (Adams 1965).

There was now greater differentiation among the settlements, suggesting for the first time a settlement hierarchy, with a few large towns of 10-33 hectares having greater political and economic influence than the smaller ones. Notably, a large cluster of 41 settlements was located just to the east and southeast of Tell Asmar with a definite size hierarchy; five were large towns, five were small towns, and 31 were smaller villages. However, such clusters are unusual and

most large towns are not accompanied by smaller ones. The distance between each of the large towns suggests that they were each largely responsible for their own food production and larger towns, for the most part, did not depend on the tribute of surpluses by smaller surrounding communities. For this reason, the development of specialists was probably limited (Adams 1965).

While the larger towns have received attention, little work has been done on the smaller settlements, leaving us with an incomplete understanding of them and their relationship to the larger towns. We do not know how these towns were laid out, what their functions were, or if they were fortified. Based on the layout of the waterways of this time, it seems that natural channels continued to be predominant as radiating networks of canals around larger settlements do not appear until later. The relatively small population could still be sustained by flood irrigation with rudimentary water control dams and small ditches. If more sizable canals were dug, they were not great in number and were no more than a few kilometers in length from their source. Such a system did not require a complex political authority. Thus, the Early Dynastic was probably characterized by fairly independent polities of various sizes (Adams 1965).

During the Akkadian and Gutian periods (ca. 2300-2100 BCE), settlement patterns in the Diyala region continue essentially as they were during the Early Dynastic. There were 97 sites during this time, but almost a third of them were new settlements, indicating abandonment of other sites. Ceramic remains from this period are not particularly distinct and they are often found under thick debris and, as a result, the size of Akkadian-period settlements is not well known. For example, some settlements interpreted as towns may have been much smaller, indicating a decline in population since the Early Dynastic. This would fit well with the abandonment of many settlements mentioned above. Deposits of Akkadian materials are

abundant at Tell Asmar and Khafajah; at Tell Asmar there are remains of monumental architecture as well as houses. These large public buildings underwent a period of abandonment at the end of the Akkadian period, which was possibly related to the unwelcome arrival of the Gutians during that time. Private homes, however, continued to be occupied and the public buildings were later rebuilt (Adams 1965).

In general, the scope of settlement in the region did not expand significantly during the Akkadian. The only notable exception is near the confluence of the Diyala and Tigris. The linear arrangement of four sites between the former Diyala channel and the Tigris suggests a new waterway connecting the rivers, but it is again unknown whether this is due to natural causes or human efforts. Otherwise, no significant improvements or extensions of the canal network were made (Adams 1965).

It was during the Third Dynasty of Ur and Isin-Larsa period (ca. 2100-1800 BCE) that the Diyala region became a major participant in southern Mesopotamian society. For the first time king lists are available and other epigraphic sources help us to understand the function of the temple as well as commerce. These documents describe the city of Eshnunna as being under the authority of the kings of Ur, represented locally by an appointed governor. Later during this period, the town became independent, followed by a time when the political fortunes of Eshnunna varied, sometimes having hegemony over other towns and at others under the control of foreign rulers. During Hammurabi's reign Eshnunna came under the control of Babylon (Adams 1965).

Although these documentary sources give us information about such political conditions, there is little in the way of archaeological materials during Ur III. What does exist is often mixed with materials from other periods. During the Isin-Larsa period, however, archaeology becomes

much more plentiful. Stamped bricks and other materials at Tell Asmar, Khafajah, and Ischali can usually be correlated with the king lists and there are abundant architectural remains at two other sites (Adams 1965).

The settlement patterns of the Ur III and Isin-Larsa periods continue to remain much as they were before, with all but one new settlement being established in the pattern of earlier periods. That is, areas which had not been previously settled continued to remain open. Eshnunna itself had grown to twice its previous size (to 24 hectares) but it never eclipsed the size of other long-established towns. The only notable changes in settlement pattern were a move toward more dispersed settlement, where town populations began to decline while village-based populations increased, and a major increase in the size of one of the linear collection of settlements in the southeastern region of the Diyala Plain which originally formed during the Ubaid. The first may be explained by the development of Eshnunna as a strong political power, resulting in the decreased political importance of other towns. This is not to say that quality of life or economic strength decreased in those places; they simply no longer needed to support their own administrative functions to the extent previously necessary. The latter may be related to a change in the course of the Tigris or the influence of the Daban River which may have existed there. It is possible that swamps may have been present in this area in the past, preventing the establishment of sufficient agriculture to support a large population (Adams 1965).

At the end of the twenty-first century, during the beginning of Ibbi-Sin's reign (2028-2004 BCE), Eshnunna established itself as an independent kingdom, breaking away from Ur. The history of Eshnunna during its period of independence can only be reconstructed at the most basic level because information about the chronology of the kings of Eshnunna is limited.

Beginning at the time of Nippur's independence from Isin, Ipiq-Adad of Eshnunna (ca. 1862 – ca.1818 BCE) enlarged its territories to include other cities in the region, up to the confluence of the Diyala and Tigris Rivers. After this time, Ipiq-Adad's sons worked to further enlarge the kingdom, which eventually came into conflict with other polities in the region. By 1762, Eshnunna fell to Hammurabi of Babylon. Thereafter, the town had a weak government and became less important (van de Mieroop 2007).

The Babylonian conquest left a substantial archaeological record of widespread destruction. The town of Ischali seems to have been uniquely fortunate in escaping a violent end during the Babylonian takeover, as most towns and villages were destroyed, often by fire. In many cases Old Babylonian architecture never appeared over that of the Isin-Larsa period. The latest occupations at Tell Asmar are from the time of Ipiq-Adad and his sons and there is no evidence of future settlement there (Adams 1965).

During the Old Babylonian period (ca. 1800-1600 BCE), population in the region decreased, probably as a result of the Babylonian encroachment. There was possibly dispersion from urban centers to villages, a return in some quarters to a more nomadic life, and migration to other areas. However, in some places, new settlements developed and new canals were dug. It should be noted that Old Babylonian and subsequent Kassite materials are easily conflated, so these building projects may have occurred during the Kassite period (ca. 1600-1100 BCE), when Babylon and the Diyala region were under the control of the Kassites. Similarly, it is nearly impossible to determine when population decline occurred, but it is assumed that it happened as a result of the Babylonian conquest and that by the time of the Kassite period, populations were again on the rise. The region became a contested border area among the Kassites, Elamites, and Assyrians during the Kassite period. In addition, "mounted barbarians" from the Zagros region

began raiding the area. By the end of this period, the settled population of the Diyala region was the smallest it had been for over two millennia (Adams 1965).

During the Middle Babylonian period (ca. 1100-625 BCE), we see an even lower population with only 34 recorded sites. Many sites which were occupied during the Kassite period now lay abandoned and many areas formerly under cultivation were no longer in use. The irrigation systems remained in the same configuration that they had for millennia, potentially because the large network of channels which characterized the Diyala did not necessitate the construction of major canals which later came to dominate the area. However, it was during this period that the Diyala's course was simplified; some of the former channels no longer flowed (Adams 1965).

The Neo-Babylonian period (625-537 BCE) saw a moderate resurgence in population, growing to 53 sites, although these new settlements were invariably small villages. These villages appeared along previously existing waterways and, because of their wide distribution, do not seem to be the result of any coordinated effort to form politically meaningful clusters of settlements. During the following Achaemenian period (ca. 527-311 BCE), the number of settlements increased slightly to 57 with the appearance of a few towns. Their arrangement remains the same as during the Neo-Babylonian period, following already existing waterways. There is some concern that the level of settlement during these two periods is underestimated compared to the previous periods because the latter were never built upon again, whereas the Neo-Babylonian and Achaemenian sites are generally buried under the extensive ruins of later periods. However, there is no mention of the region in any textual sources so it is likely that what settlement did exist in this period was not considered particularly important. Although Cyrus the Great mentioned gathering the citizens of Eshnunna and restoring its deities to their rightful

place, there is no archaeological record of an occupation there during this period. It is suggested that either the location of the city had been lost or perhaps only a token shrine was erected over its ruins (Adams 1965).

During the Seleucid and Parthian periods (311 BCE - 226 CE), new great cities were established in southern Mesopotamia, a few of which were built within Adams' study area. Improvements in roads brought an increase in trade, communication, and political connections among the cities and smaller settlements. The Diyala region became part of a large empire, leaving behind its small, politically isolated, fragile settlements in favor of centralized administration. It was largely unaffected by the war with Rome that was being waged in other areas, allowing the number of settlements to grow to 199 in number and significantly larger in scale during this period. It is important to note, however, that there were still several significant expanses in the study area which remained unsettled during this time. Although settlements in the region were substantially larger, Adams hesitates to assume that the population experienced a similarly large increase. This reluctance is based on the influence that Hellenistic city planning ideas most likely had in the building of these new settlements as well as the assumption that not all sites of this rather long period were occupied contemporaneously. It is significant, though, that it was during this period that the population of the region probably became very close to that of 1960s, excluding the city of Baghdad (Adams 1965).

The increased size of settlements and the tendency for them to be nearby each other in some places raise the question of how sufficient water was supplied to the population. The Diyala is thought to come up short of providing enough and it is suggested that the Tigris was used as a supplementary source now that simple machinery and animal traction were available to raise the water from the entrenched channel. The increased area of cultivated land required the

construction of long, lateral canals between the rivers and distant fields. The largest cities probably used their land continuously and relied upon a network of waterways rather than the branching patterns seen elsewhere. One of the consequences of such heavy water use was the increased deposition of silt as well as less frequent flooding, which normally carries deposited silt downstream. Thus, maintenance likely became required, where canals were dredged and straightened to keep them open. Some of the Parthian canal levees are still visible on the landscape and are in fact the oldest ones still extant. The locations of earlier canals must be determined by the linear arrangement of sites (Adams 1965).

During the Sassanian (226-637 CE), the Diyala region gradually came under stronger centralized authority which, according to documentary sources, established numerous new cities. Many of these cities were built to reinforce the power of the king but, in the process, populations were relocated and there was a significant negative effect on the social and economic stability of the region even as commerce expanded with the new markets. War with Rome continued and affected the study area more than in the preceding period, yet not so much as to be a hindrance to growth. This is possibly a result of the intentional reservation of the Diyala plain as an agricultural resource needed to support the warring cities to the west. The population during the Sassanian reached its greatest extent in all of history, with 437 sites that had populations about 35 times denser than those during the Achaemenian (Adams 1965).

Sassanian cities comprised just over 50% of the settled area while small villages remained at about the same proportion as they were in the Parthian, signifying that the population of these cities came not from rural settlements but towns and smaller cities. The cities had little vertical relief and were irregular in layout, with narrow avenues of occupation extending away from the cities along levees. The substantial growth of the population required

essentially the entire Diyala region for subsistence. The population and need for agricultural lands further stressed the water supply, probably resulting in shortages and demanding new, more creative ways to obtain and use the valuable resource. One of these ways was to supply all settlements west of the Tigris with water from the Euphrates, reserving the Tigris for settlements to the east. Two others were significant feats of engineering. First, a tunnel was dug through the Jebel Hamrin, pierced along its ceiling as it ran beneath the mountains and connected at both ends to a canal. The system collected water from beyond and above, delivering it to the plain below. Second, a large canal was constructed, called the Katul al-Kisrawi, or Cut of Chosroes, to carry water from the Tigris to the Diyala. This became part of the well-known Nahrawan canal. All of these solutions to the problem of water shortage indicate a high level of planning, administration, and investment which had not before occurred (Adams 1965).

The end of the Sassanian saw a drastic reduction in the occupation of the Diyala region as central authority weakened. In many areas, reoccupation did not occur until the twentieth century. The abandonment of settlements did not occur in the same way in different regions, however, suggesting that other influences were at work as well. For example, in some areas the abundance of water created by the great engineering projects mentioned above may have resulted in the oversalinization of the soil, especially in large, flat areas. In other areas, canal maintenance likely diminished to the point where the deposition of silt prevented the flow of water through the canals. In still other places, the formation of standing swamps may have resulted from changes in the course of the Tigris and levees being breached during floods. These swamps would have rendered the land unusable for agriculture. The extensive nature of the canal system in the region meant that as the waterways went into disrepair, large areas of land were affected downstream, making it difficult for local populations to support themselves (Adams 1965).

In the following Early Islamic and Samarran periods (637-883 CE), the Diyala region saw the building of the great city of Baghdad, an order of magnitude larger than the Sassanian capital of Ctesiphon, and Samarra. The cities were inhabited largely by economic specialists who depended on the provision of subsistence by the rural regions. The settlement of the plain away from the cities, however, remained sparse and the increased urbanization may have been a result of the aforementioned devastation to the cultivable land and water systems. 331 sites were recorded during this period, including the two cities. Settlement was particularly dense along the Nahrawan canal, where in many places the ruins run continuously along its edges. Agriculture flourished along the canal, but food production did not reach the level of that during the Sassanian (Adams 1965).

The Post-Samarran Abbasid period (883-1258 CE) saw continuing decline in population and the number of settlements, 158 of which were occupied during this period of political and economic breakdown. Although the area was invaded by Mongols during this time, their focus seemed to be on the large cities, such as Baghdad, and not the relatively empty countryside of the Diyala plain. The population of Baghdad was devastated by the Mongols, but moving into the Ilkhanid period (1258-1500 CE), the settlement of the rural Diyala plain remained much as it was. About 100-180 settlements existed during this period. The uncertainty is based on a number of villages listed in historic records but which are suspect. The primary source of water during this time was the Tigris, and the northern part of the Diyala plain was fed by canals coming from where the Diyala exits the Jebel Hamrim. This configuration of the region continued largely unchanged until the 19th century (Adams 1965).

III. PREVIOUS WORK AND TECHNICAL BACKGROUND

Satellite Remote Sensing in Archaeology

Remote sensing has been in use in the field of archaeology for over a century, beginning with the aerial photographs of the Salisbury Plain taken by P.H. Sharpe in 1906 (Parcak 2009). Over the next few decades, it had become commonly available to archaeologists of the Middle East, especially when they became part of government reconnaissance and mapping programs. One of these pioneers was Antoine Poidebard, who during World War I took aerial photographs of Persia and realized how they could be useful for archaeology. During the time of the French Mandate, he took photographs of Roman road networks, fortifications, and irrigation systems in Syria. Eric Friedrich Schmidt used aerial photography to map Alexander's Wall and locate ancient cities in Iran (Gerster and Trümpler 2005). One of the consequences of the development of aerial photography in archaeology was the ability to plan fieldwork in new ways; it has already been described how Adams (1965) used aerial imagery in planning his survey work on the Diyala River plain. It was now possible to see features of archaeological interest: tells, ancient roads, canals, field systems, and structures. It provided a new way to view archaeology at a regional scale, where previously unrelated ground-based observations could now be connected (Kouchoukos 2001).

Satellite-based methods first arose in the 1960s when the Cold War spurred advances in U.S. space technology (Parcak 2009). Satellite imagery has several differences from aerial photography, some of which are beneficial and others which are not. For example, satellite images cover vast areas of land in a single scene. This is much more useful than an enormous mosaic where many small aerial photographs are stitched together, often taken at different times and at different angles. It costs less and saves processing time. In addition, satellite sensors often

record data in several bands across the electromagnetic spectrum, making new methods of analysis, such as soil composition, vegetation health, or detection of subtle landscape features, possible. While aerial photographs are not often repeated for the same area, satellites routinely image the same locations over and over, building a record of landscape and environmental change over time. Finally, a troublesome aspect of satellite images is their spatial resolution. Although in the past such imagery has had low resolution, this is becoming less problematic with the advent of newer satellite platforms and, surprisingly, one old one (Kouchoukos 2001).

Some of the earliest satellite imaging platforms were the Keyhole series of spy satellites, known as CORONA (KH-1 through KH-4B), ARGON (KH-5), and LANYARD (KH-6), which flew from 1960 to 1972. Details of this program are discussed at length in the next section. The LANDSAT program then began, which consisted of six successful satellites with multispectral capabilities, which would revolutionize the utility of satellite imagery for archaeology by allowing various characteristics of the landscape, such as land use, geomorphology, rock or soil type, and many others, to be determined (Parcak 2009; Ur 2003).

Although early LANDSAT MSS was useful in many ways, its low 80-meter resolution made it difficult to identify archaeological features (Philip et al. 2002; Ur 2003; Challis et al. 2004). In spite of this, some groundbreaking work was done. For example, it was used as a basis for predictive modeling of site location by Donoghue and Shennan (1987) in their study of Morton Fen, Lincolnshire, UK. Custer et al. (1986) also created a predictive model for the Delaware Coastal Plain using LANDSAT. Shuttle Imaging Radar (SIR) imagery, which in some cases provides subsurface data, was responsible for the discovery of relict stream channels in the Sahara and contributed, along with LANDSAT and other data, to finding what some believe to be the lost city of Ubar by tracing ancient road networks (Blom et al. 1997; Edgell 2002; Challis

Sensor	Spatial resolution (m)	Spectral resolution (nm)	Cost (US\$) per scene	Scene size (km)
AVHRR	1100	5 bands, 0.58-12.5	100	3000 x 1500
Landsat MSS	80	4 bands, 0.5-1.1	Free ²	170 x 185
Landsat TM	30 (120 ¹)	7 bands, 0.45-2.35	Free ²	70 x 185
Landsat ETM +	15	Pan (band 8), 0.52-0.90	Free ²	170 x 185
SPOTXS	20	3 bands, 0.5-0.89	1250	60 x 60
SPOT PAN	10	1 band, 0.51-0.73	1250	60 x 60
IKONOS	1	4 bands, 0.45-0.88	6050	11 x 11
QuickBird Pan	0.61-0.72	1 band 0.45-0.90	6120	16.5 x 16.5
QuickBird MS	2.44-2.88	4 bands 0.45-0.90	6800	16.5 x 16.5
CORONA	2+	Single photographic image	30	17 x 232

Table 2. A comparison of different satellite imagery products in terms of spatial resolution, spectral resolution, cost per scene, and scene size. 1: band 6; 2: scenes that have been ordered in the past are available free, those which have never been order will incur a fee of a few hundred dollars per scene. Modified from Challis et al. (2004).

et al. 2004). Later LANDSAT platforms had higher resolution (Table 2). By the 1990s, other satellite platforms were in use for archaeology, such as SPOT and later IKONOS, which offered significantly better spatial resolution and applicability to archaeological problems. In the last decade, Quickbird has been able to provide archaeologists with submeter spatial resolution which approaches that of aerial photography. Combined with its multispectral capabilities and wide coverage area, this and future satellite products are likely to become the dominant data source for above-the-ground archaeology (Parcak 2009).

One of the great drawbacks to such data products are their cost. Table 2 compares several satellite platforms, their characteristics, and their cost per scene. While earlier satellite imaging programs were governmental, most of the recent ones, especially those with high spatial resolution, are operated by for-profit companies. This poses a problem for archaeologists, especially those conducting regional-scale studies, who are limited in their funding. One potential solution to this problem is the CORONA satellite program of the 1960s and early

1970s, which provides a host of benefits and is low in cost. As CORONA imagery was acquired for espionage purposes, most of it covers areas of the former USSR but also parts of the Middle East. Over 800,000 scenes are available at the low cost of \$30 each, which is significantly less expensive than commercial or even much of the other government imagery (Challis et al. 2004).

The CORONA Spy Satellite Program

Background

Many applications of satellite imagery to archaeology in the past have been limited to understanding past environmental settings because the majority of available imagery products had low spatial resolution, making it difficult to identify smaller features on the ground (Philip et al. 2002; Ur 2003). Other studies have looked at landscape in terms of how it affected settlement location decisions or land use (Challis et al. 2004). It is only fairly recently that satellite imagery

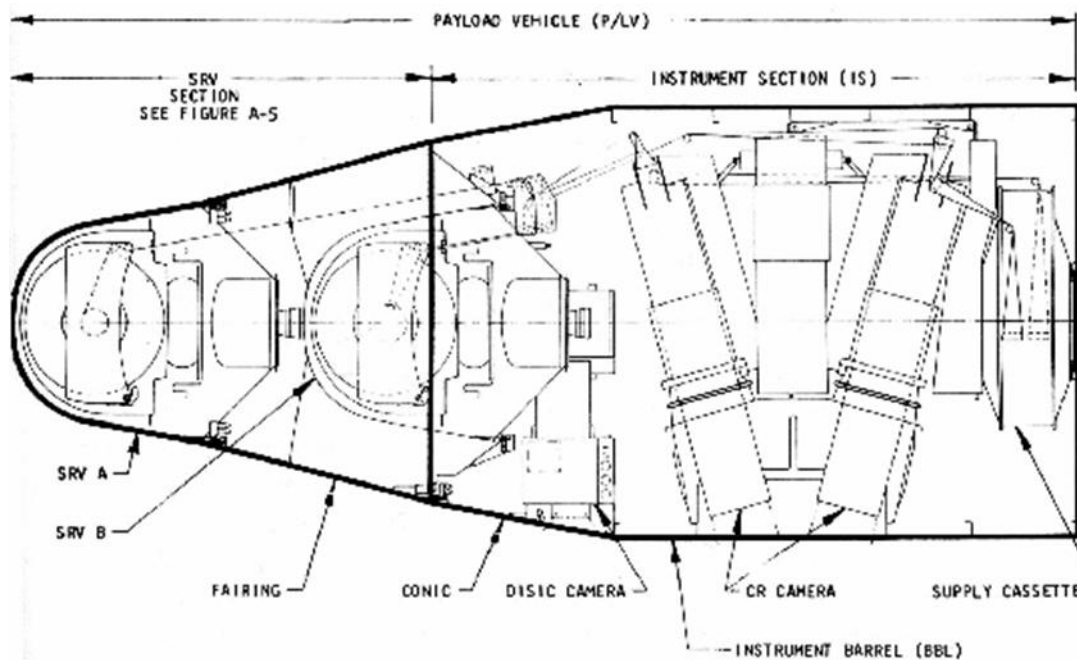


Figure 3. Internal arrangement of KH-4B hardware. From Day et al. (1998).

has become available to perform meaningful archaeological survey. One of these tools is the imagery acquired by the CORONA spy satellite program.

The CORONA satellites were one of the earliest imaging satellites launched by the United States for intelligence purposes. Begun during Eisenhower’s presidency, the program was primarily an effort to monitor the Soviet Union during the Cold War, substituting for U-2 aerial reconnaissance. CORONA formed the first part of the Keyhole series of satellites (KH-1 through KH-4B), followed by ARGON (KH-5) and LANYARD (KH-6) (De Meyer 2004). These images were taken from 1960 to 1972 and declassified in 1995 by the Clinton administration (Philip et al. 2002; Ur 2003; Galiatsatos 2004).

Satellite System	Mission Designator	Successful Missions	Film Acquisition Periods	Best Ground Resolution	Camera Type
CORONA	KH-1	9009	8/1960	40 feet	Single panoramic
CORONA	KH-2	9009, 9017, 9019	12/1960-7/1961	30 feet	Single panoramic
CORONA	KH-3	9022, 9023, 9025, 9028, 9029	8/1961-12/1961	25 feet	Single panoramic
CORONA	KH-4	9031-9032, 9035, 9037-9041, 9043-9045, 9047-9048, 9050-9051, 9053-9054, 9056-9057, 9062	2/1962-12/1963	25 feet	Fore/aft panoramic
CORONA	KH-4A	1001-1002, 1004, 1006-1031, 1033-1052	8/1963-9/1969	9 feet	Fore/aft panoramic
CORONA	KH-4B	1101-1112, 1114-1117	9/1967-5/1972	6 feet	Fore/aft panoramic
ARGON	KH-5	9034A, 9046A, 9058A, 9059A, 9065A, 9066A	5/1962-8/1964	460 feet	Single frame
LANYARD	KH-6	8003	7/1963-8/1963	6 feet	Single panoramic

Table 3. Comparison of Keyhole satellite systems. Modified from USGS chart accessed at http://eros.usgs.gov/#/Find_Data/Products_and_Data_Available/Declassified_Satellite_Imagery_-_1 with information from De Meyer (2004).

Each of the Keyhole satellite series had different characteristics (see Table 3), such as spatial resolution and camera type. Rather than staying in a continuous orbit as modern systems do, the Keyhole satellites were launched into a decaying orbit and were operational from one to sixteen days. After acquiring photographs, they ejected the film in a canister

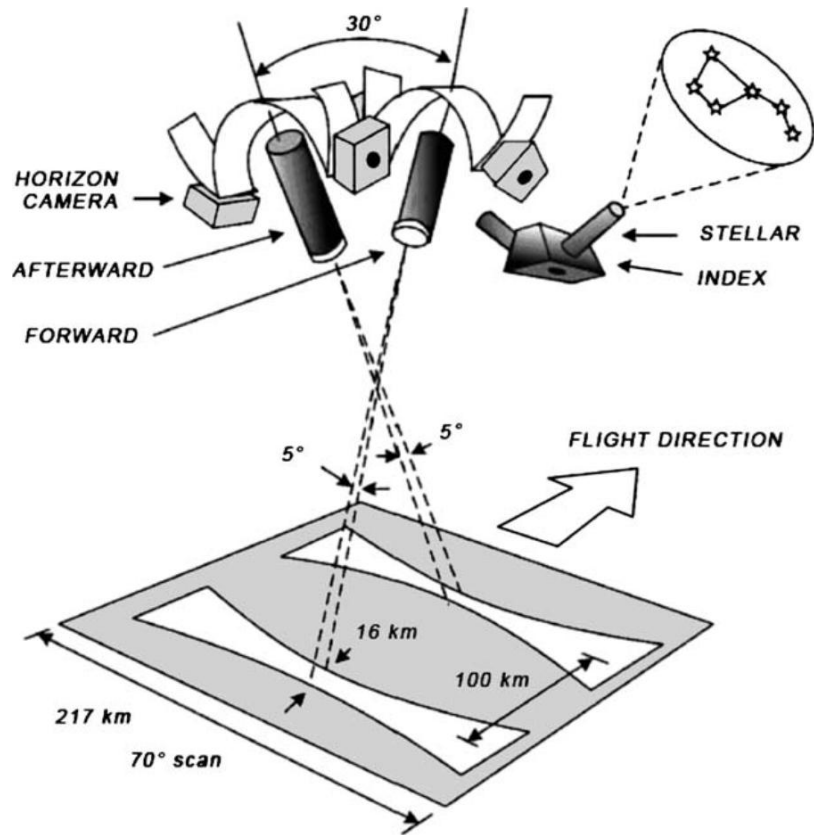


Figure 4. Camera system of the KH-4B satellites. From Goossens et al.(2006).

which then fell to the earth, slowed by a parachute and caught by a specialized plane (De Meyer 2004). Later satellites had two film canisters, allowing the length of each mission to be doubled (Galiatsatos 2004).

The CORONA KH-4B mission series has two characteristics that make it particularly useful for archaeology. First, it is one of the two highest-resolution series in the Keyhole program, and it also produced stereoscopic imagery. Because of its relatively low orbit of 150 km, the KH-4B platform (Figure 3) has a maximum 6-foot (1.83-meter) spatial resolution at nadir when converted to digital format, fine enough to see most archaeological features. The complex camera system (Figure 4) of this series has seven separate cameras, including the two main panoramic camera plus four horizon cameras and a combined stellar and terrain camera to

assist in orientation of the main images. The two main cameras are panoramic rather than frame cameras, meaning that they rotate, projecting the image along a curved path and exposing the 70 by 900 mm film strip gradually as they turn instead of exposing the entire scene simultaneously. The panoramic cameras are oriented to point 15° from normal both ahead and behind

Lens	Petzval f/3.5 T 3.8
Focal Length	609.602mm (24.0 in)
Scan Angle	70 deg +/- 35 deg from track)
Field of View	5.12 deg (along track)
Usable Format	29.323" X 2.147"
Shutter	Focal Plane
Slit Widths	Variable-- from 0.17 in to 0.30 in
Film Load	1. 70mm Wide 2. 8,000 ft per recoverable sub-system (part 1 or 2 of a mission) for each camera 3. 16,000 ft per recoverable sub-system 4. 16,000 ft per camera per mission 5. 32,000 ft total load for both cameras for a mission (part 1 and 2)
End Lap	7.6%
Image Motion Compensation (IMC)	Camera nods proportional to velocity/height (V/H) ratio
Stereo Angle	30.46 degrees
Filter	Variable -2 position commandable
Film Type	3404, Estar Base

Table 4. Technical specifications of the CORONA KH-4B satellite system. From National Reconnaissance Office (1967).

the satellite path of flight, producing the approximately 17 by 232-km fore and aft images (Figure 5), respectively (National Reconnaissance Office 1967; Challis et al. 2004; Galiatsatos 2004).

Because these images overlap and have a 30° parallax, or difference in viewing angle, they can then be used to photogrammetrically extract elevation data to produce a topographic model of the image area (Casana and Cothren 2008). Early satellites in the Keyhole program were plagued by significant cloud cover. However, the CORONA KH-4B satellites, due to better control and weather forecasting, provided the best imagery in terms of cloud cover. In these images, there was only about 30% cloud cover and many images are cloud-free, a significant improvement over its predecessors (Fowler 2004b). This further enhances its applicability to

archaeological purposes. See Table 4, Day et al. (1998), and National Reconnaissance Office (1967) for detailed technical specifications on the KH-4B and other Keyhole satellites.

CORONA's other great advantage lies in its age. The imagery used in this study, acquired in 1968, conform closely to the time when Adams conducted his survey, so essentially the current study will be looking at the same landscape his team did. But even more importantly, the images were acquired before the significant urban development that has occurred in the study area since that time. Thus, archaeological sites and features which have been destroyed, covered, or rendered otherwise undetectable by buildings, roads, and agriculture can still be seen (Philip et al. 2002; K. N. Wilkinson, Beck, and Philip 2006).

Problems with and Approaches to Using KH-4 imagery

When any photograph is taken, it does not accurately represent the spatial relationships of imaged features. Distances among objects are different in different areas of the photograph. Thus, the photograph can be said to have deformations, or distortions, which do not accurately reflect the shape, size, and location of objects. The same is true for satellite imagery in general, but CORONA is especially subject to these distortions because of the way the photographs are acquired. These distortions render the photography unsuitable as a basis for creating maps without correction (Goossens et al. 2006).

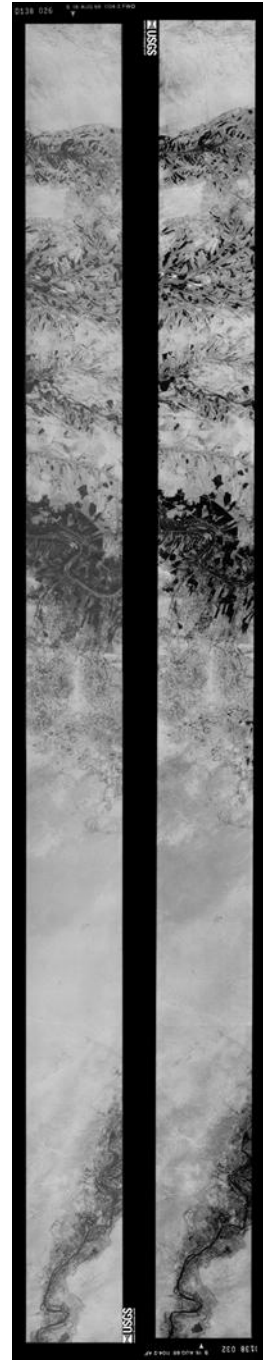


Figure 5. A stereo pair of CORONA imagery.

The distortions present in CORONA images are produced from a combination of several factors. The first is the conical distortion. This is produced by any optical system looking at a surface from a point above. At nadir, the location directly below the camera is the place closest to the camera. As one moves away from nadir, the distance between the surface and the camera increases, but this is not accounted for as the image is projected onto the film. Thus, as one moves away from the center point of the image, which represents the nadir point, objects appear closer together than they actually are. The panoramic camera of the KH-4B satellite complicates this effect, producing a distortion as shown in Figure 6 (Altmaier and Kany 2002; Goossens et al. 2006; Bayram et al. 2004).

The second type of distortion results from the forward motion of the satellite as it acquires the image. Because KH-4B does not use a single-exposure frame camera but instead a camera with a rotating aperture which exposes the film progressively, approximately a half

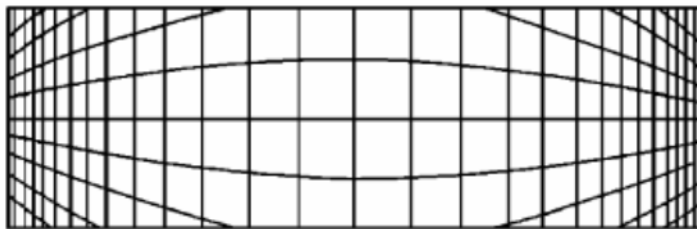


Figure 6. Panoramic distortion as it is found in CORONA imagery. Each quadrangle is 5x5 km. From Goossens et al. (2006).

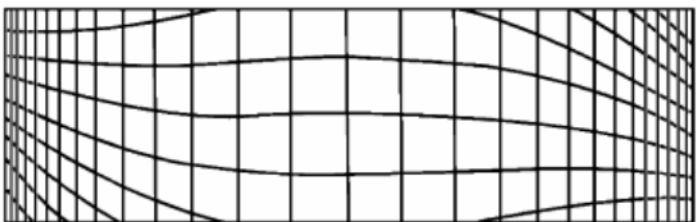


Figure 7. S-shaped distortion produced by the forward motion of the KH-4B satellite during image acquisition. Each quadrangle is 5x5 km. From Goossens et al. (2006).

second passes as the image is being made. As the satellite moves forward by about 4 km during this time, an S-shaped distortion appears in the recorded image as shown in Figure 7 (Goossens et al. 2006; Casana and Cothren 2008; Bayram et al. 2004).

A third type of distortion is a result of changes in orientation of the satellite. There may be differences in pitch, roll, and yaw of the spacecraft

as it moves, and altitude is also not constant (Goossens et al. 2006). There are also vibrations present as the machinery operates (Galiatsatos 2004). Although these factors may appear minor, when one considers the vast amount of land area being imaged, small changes in the orientation of the camera can produce noticeable changes in the photographs produced.

When all of these distortions are taken together, a land area being photographed is not rectangular but a strip that is narrower in the center and wider toward the edges, in a “bow tie” shape (see image footprint on ground in Figure 4). This imaged area is then recorded on a rectangular piece of film. The effects of such distortion are evident in the images as objects do not appear as their actual shape and are distorted differently on the fore and aft images of the same area as shown in Figure 8. As such images are useless for creating accurate maps and, the distortions being opposite for the fore and aft images, also unusable for viewing stereoscopically or photogrammetric applications, the images must be corrected to their true geometry before they can be of any real use (Goossens et al. 2006; Casana and Cothren 2008).

Traditionally, the correction of image distortions to show true geometry, a process called orthorectification, requires specific knowledge about the internal geometry of the camera as well

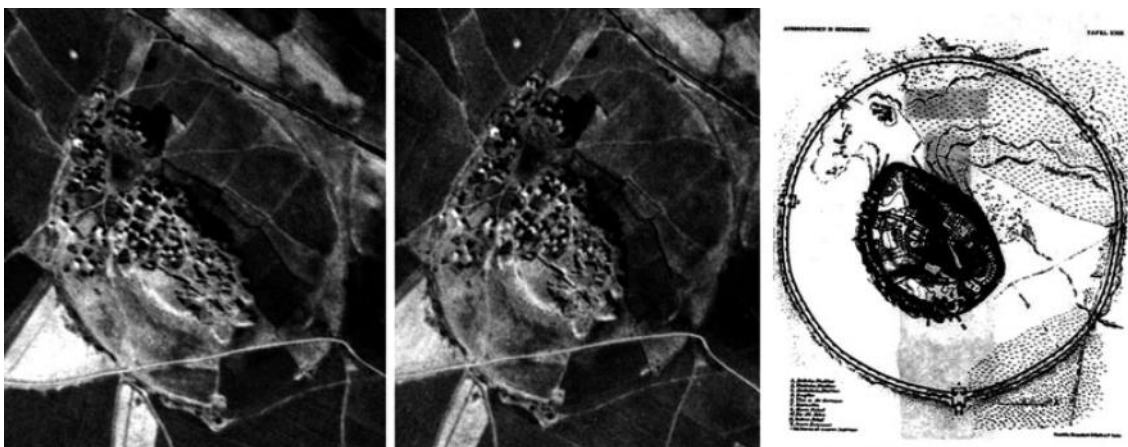


Figure 8. Image distortion appearing in CORONA image of the site of Zincirli, Turkey. A: fore image; B: aft image; C: perfectly round shape of the city wall as mapped in the 1890s. From Casana and Cothren (2008).

as its position and orientation relative to the surface being photographed. Typically, metric cameras are used for images which are planned to be orthorectified, and these produce marks, called fiducials, as part of the image. As the interior camera positions of these marks are known, it is an easy way to determine scale and amount of distortion, facilitating the orthorectification process. However, KH-4B does not use a metric camera or even a single-frame camera. The shape of and method of acquiring KH-4B images pose unique challenges to the orthorectification process (Altmaier and Kany 2002).

There are two approaches to correcting the distortion of KH-4B images (Galiatsatos, Donoghue, and Philip 2008). The first is to use a mathematical model to adjust the image, in effect undoing the distortion and creating an orthogonal view based upon an equation describing the distortion effect (Sohn, Kim, and Yom 2004). The problem with this approach is that it requires a detailed knowledge of the camera system and its orientation to the surface at every line in the image (a line being a small enough segment of the image that can be treated as though it had been exposed simultaneously), which are essentially unavailable (Goossens et al. 2006; Casana and Cothren 2008; K. Jacobsen 2008; Galiatsatos, Donoghue, and Philip 2008). This approach is also not practicable to most archaeologists because this type of model is not supported in commonly available software packages, thus requiring specialized or custom-written software (Casana and Cothren 2008; Galiatsatos, Donoghue, and Philip 2008).

The second approach requires the use of ground control points (GCPs), which represent known locations on the ground in three dimensions and can be matched to the satellite imagery. Then, by using resection, software such as ERDAS Imagine's LPS package (formerly known as OrthoBASE) can calculate the distortion of the image and correct it to show the actual locations of objects (Casana and Cothren 2008). A significant benefit to this approach is that if enough

GCPs are used, then detailed camera information is unnecessary (Galiatsatos, Donoghue, and Philip 2008). Altmaier and Kany (2002) undertook such a project in Morocco where, using differential GPS, they obtained ground control points in the field by taking direct measurements. Although they had to discard a large portion of their GCPs, this method was fairly successful for them, with horizontal errors of 2.0 to 9.7 meters and vertical error of 8.4 to 38.1 meters. Obtaining GCPs manually on the ground may be the theoretically most accurate way of doing so, but there are many areas of the world where there is good archaeology but archaeologists have a hard time getting there, such as the area of the present study. In addition, the equipment and other costs involved with an expedition can be prohibitive. Another option is needed.

Challis et al. (2004) used other satellite imagery as a base layer to obtain GCPs for correcting CORONA data. Their study utilized SPOT data (though it is not clear whether the 10-m panchromatic or 20-m multispectral images were used), which was previously corrected, as a layer to which the CORONA images could be registered. Because they encountered difficulty in locating points in common because of the 20 years between the acquisition of the SPOT and CORONA data, only a single CORONA “master” scene was registered to SPOT and the other CORONA images were then registered to that master image. The relationship among these images is unclear; it is not indicated but only implied that the other CORONA images were subsets of the “master” image. The product seemed to meet their needs, but no quantitative analysis of their results is provided other than to say that individual GCPs with high error were discarded. Ur (2003) also corrects CORONA imagery using SPOT data as a base layer but provides no details as to its accuracy.

Galiatsatos et al. (2008) set out to determine whether previously orthorectified satellite imagery could be used to establish GCPs with which to correct CORONA data and then use its

stereo feature to create a digital elevation model (DEM). They used IKONOS imagery with 1-m (panchromatic) and 4-m (multispectral) spatial resolution as the base layer. The IKONOS data used is geometrically corrected and accurate up to 10 m horizontally. As the IKONOS product did not contain elevation information, 1:25,000 scale topographic maps of the study area were registered to the IKONOS imagery and used to provide the elevation for each GCP. Using ERDAS OrthoBASE Pro, the only input parameters needed for the non-metric camera model employed were the focal length of the CORONA camera and the resolution at which the film was converted to a digital product. They then began locating GCPs common to the IKONOS and CORONA images, which proved challenging owing to the 30-year difference between their acquisition. They used only 11-13 GCPs per CORONA scene and from 0-21 automatically-generated tie points to produce their final product. OrthoBASE produced a DEM with approximately 3-m horizontal accuracy. The vertical accuracy was validated with Shuttle Radar Topography Mission (SRTM) data with three arcsecond (approximately 90 m on the ground) spatial resolution. Because of the difference in resolution, the CORONA DEM contains much more information than SRTM, but it also makes comparison difficult as variations will appear in CORONA that are averaged out in the larger pixel size of SRTM. Their product showed excellent agreement with the SRTM elevations (>0.96 correlation) and can be considered successful. An extensive quantitative analysis of their results can be found in their paper.

Beck et al. (2007) used additionally corrected IKONOS imagery as a base layer for correcting CORONA. The existing orthorectified IKONOS data was further georeferenced with GCPs obtained on the ground with differential GPS. The resulting CORONA data was accurate to approximately 5-8 m.

Casana and Cothren (2008) wished to determine whether freely available imagery could be used to orthorectify CORONA. They utilized free 10-m SPOT imagery as a reference layer for GCPs and successfully produced orthorectified CORONA scenes with ERDAS Imagine's LPS software which they then overlaid on their CORONA-derived digital terrain models.

The problem with using SPOT, IKONOS, and other commercial satellite data is its significant cost and having to obtain it in addition to CORONA defeats its significant advantage of low cost. However, it is proposed that Google Earth, a free, widely available, and high resolution satellite image archive, may satisfy the need for a base layer with which to correct CORONA imagery. Google Earth provides full coverage of the earth's surface and in many cases uses Quickbird multispectral imagery. Its resolution is not necessarily as good as the raw image data, but it is more than sufficient for locating GCPs. The major concern with Google Earth imagery is that the method used by Google to georeference its images is proprietary and unknown, making its use for scientific purposes less inviting. However, the accuracy of its product can be tested (Potere 2008).

While browsing Google Earth, it is not uncommon to see places where adjacent image tiles do not perfectly match along the edges, indicating a registration error in one or both of the images involved. Potere (2008) explores these accuracy issues by selecting 436 control points throughout the world and comparing their Google Earth location to their location on LANDSAT imagery, which is accurate to about 50 m. The results indicate that on average, Google Earth is more accurate than LANDSAT, with an error of 39.7 m. However, a couple of factors not apparent in this result must be considered. First, control points in developed areas of the world are significantly better than in less developed countries, presumably due to the lack of good ground control. Second, areas of Google Earth that use satellite imagery are significantly more

accurate than those which use aerial photography. Thus, Google Earth is more appropriate to use in more highly developed parts of the world which are represented with Quickbird or other high-resolution satellite imagery instead of aerial photography. Although the area of the present study is in a developing country, it is represented with high-resolution satellite imagery, and so this method will be tested here.

The Use of CORONA Imagery for Archaeology in the Middle East

Kennedy (1998) published one of the early studies using CORONA imagery for archaeological purposes. Like many of the early papers, his was intended to establish excellence



Figure 9. The ancient town of Samosata and environs as they appear on CORONA imagery. City walls are readily visible (indicated by arrows) as is the tell, the teardrop shape with the clearly defined flat top and sloped sides. Modified from Kennedy (1998).

of the CORONA imagery as an archaeological tool. It demonstrated the imagery's capabilities of showing detailed views of structures and other archaeological features surrounding the ancient Roman town of Samosata (Figure 9), as well as classifying different areas of the landscape, such as agricultural fields and non-arable land. This was the first time that overhead images of the city were ever available to archaeology and, sadly, among the last, as a reservoir now occupies the land where Samosata once stood.

Another study uses SPOT and CORONA imagery to discover offsite archaeological features around Tell Beydar, located in the Khabur basin of the upper Jazirah (T. J. Wilkinson

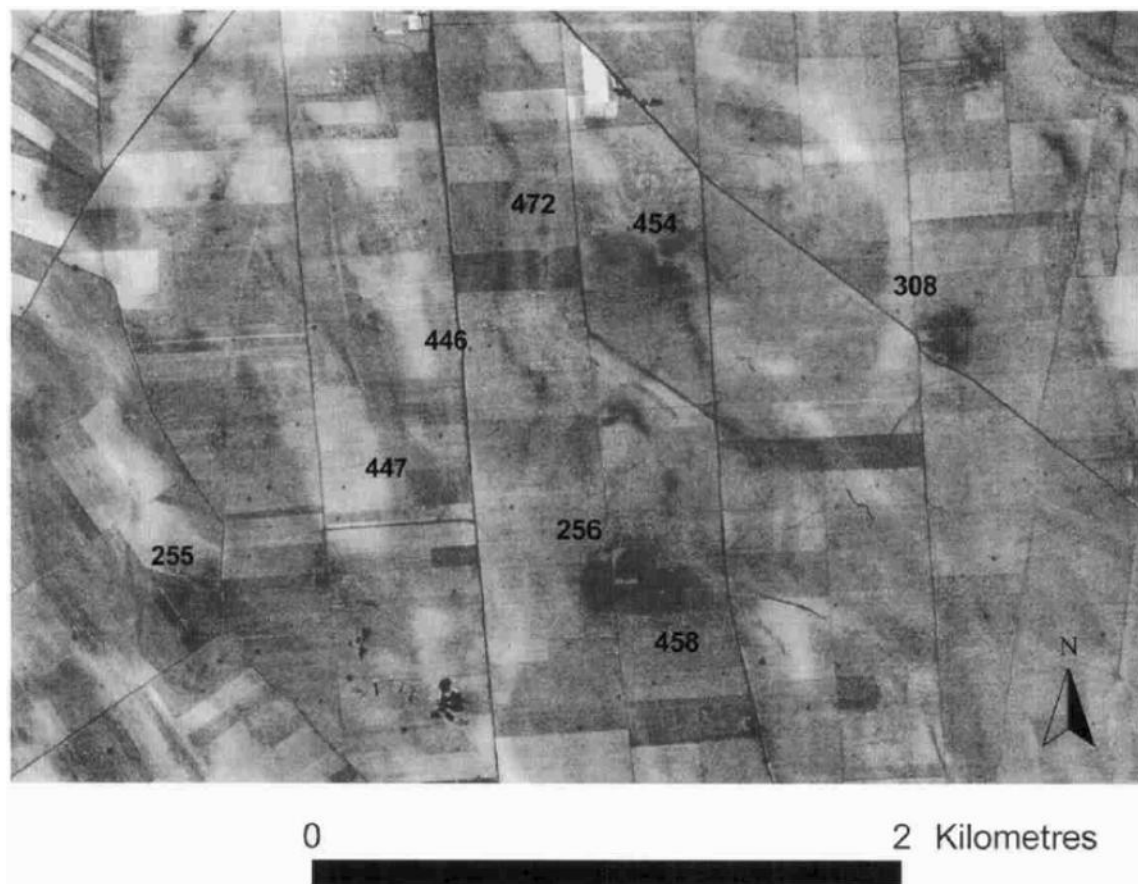


Figure 10. Archaeological remains in the southern area of the Orontes Valley, Syria as they appear on CORONA imagery. 255: tell, 5 m high, 0.7 ha; 256: tell, 10 m high, ~2 ha; 308: sherd/tile scatter, 1.5 ha; 446: olive press; 447: surface scatter of unknown extent; 454: sherd/tile scatter, 1.2 ha; 458: sherd/tile scatter, extent uncertain due to recent tree planting; 472: basalt/flint scatter, 30-m diameter. From Philip et al. (2002).

2000b). SPOT images were utilized as a basemap, which guided survey activities. The CORONA images were used to identify the features both before and during pedestrian survey. These features included hollow ways, agricultural fields, animal pens, quarries, and surface scatters.

In their early study on the applicability of CORONA imagery to archaeology, Philip et al. (2002) searched for previously identified sites in the Orontes Valley, Syria on CORONA. The imagery was also useful in detecting new artifact scatters and establishing relationships between agricultural fields, cairns, and walls constructed as early as the Roman period (Figure 10, Figure 11). They found that in some cases archaeological materials extended beyond the previously established boundaries (later verified in the field).

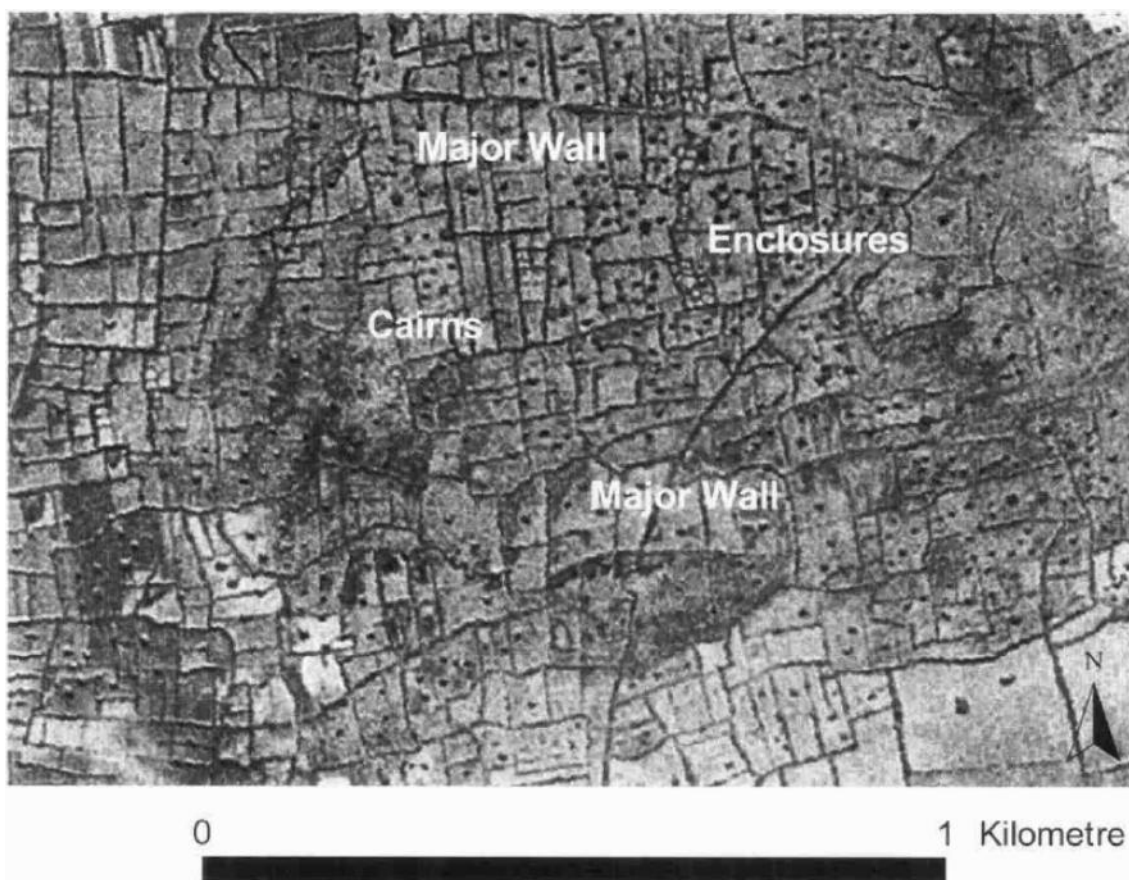


Figure 11. Cairns and enclosures in the northern Orontes Valley, Syria, as they appear on CORONA. From Philip et al. (2002).

Pournelle (2003b) uses CORONA imagery to more accurately locate ancient settlements and relict levees in the area surrounding Uruk and Larsa, which is to the south of the current project's study area, as originally described in Adams (1981). Little detail is given on the appearance of sites, although levees in many cases were described as being lighter than surrounding soils due to a lower level of moisture retention.

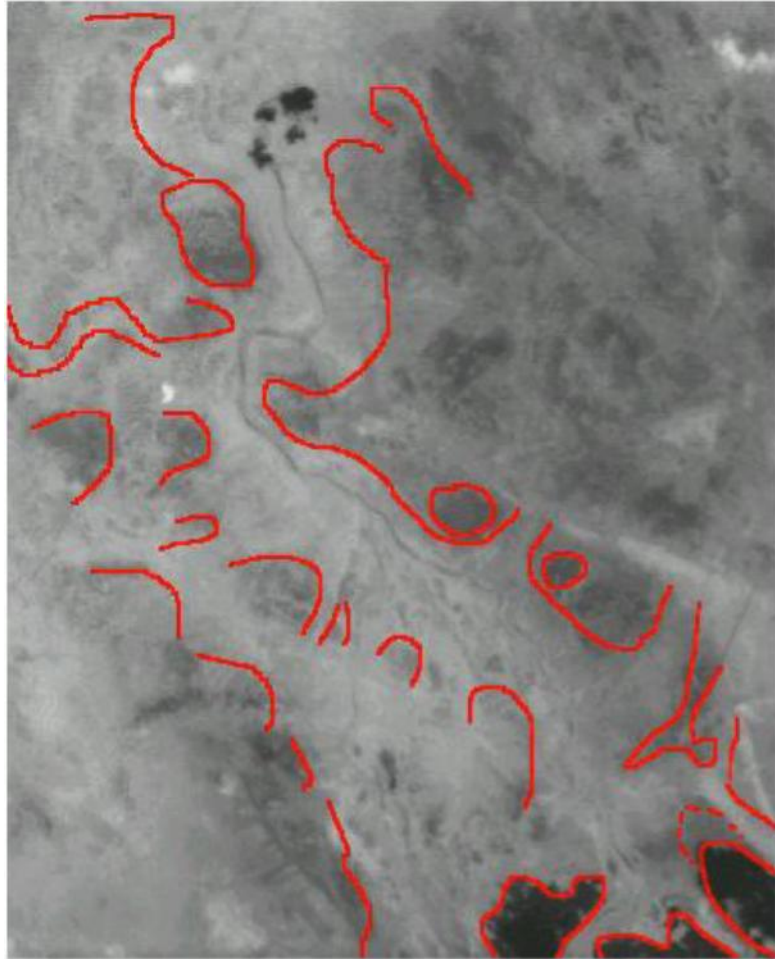


Figure 12. Relict levees. The consolidated soils of levees are less permeable by water, leaving them to appear lighter. From Pournelle (2003a).

Pournelle (2003a) uses CORONA imagery to trace changes in landscape over time, with special attention paid to river channels, levees, deltas, and other alluvial features in southern Mesopotamia. Of particular interest is the appearance of relict canal levees appearing brighter in comparison to adjacent soils during the wet season (Figure 12). Back swamps appear as darker areas because of the accumulation of silt. From her analysis of the imagery, Pournelle develops an alluvial history of southern Mesopotamia far to the south of the Diyala region, where she posits that linear arrangements of sites are not necessarily indicative of alignments along former watercourses but

may represent settlement on higher-elevation relict terraces to avoid inundation during flood season.

Ur (2003) used CORONA imagery for locating and mapping archaeological sites and hollow ways in the Khabur basin of northeastern Syria (Figure 13). Tells in this region appear as light areas of soil compared to the background soils. They developed as a result of human

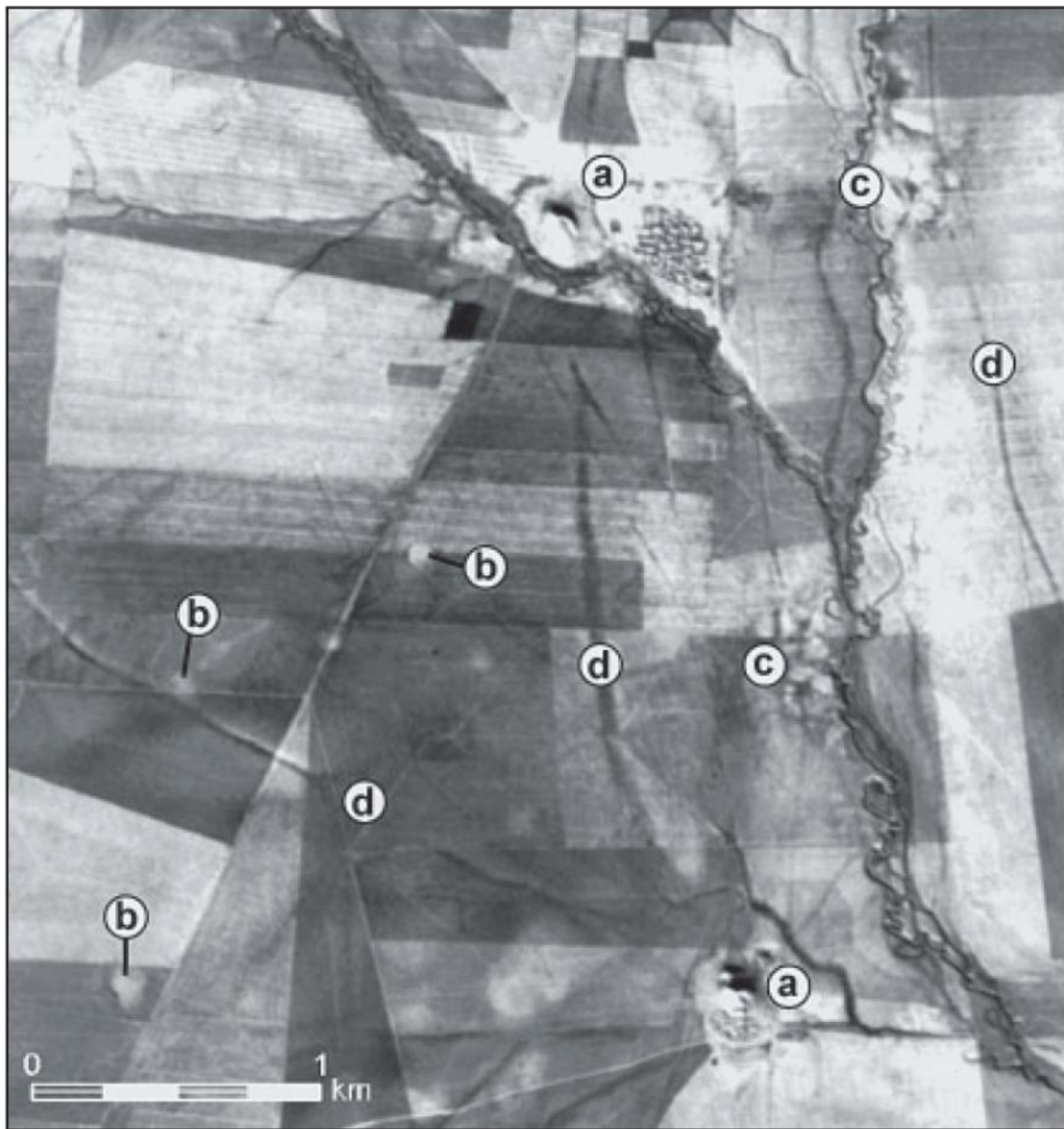


Figure 13. Tells and landscape features appearing on CORONA. a: high mounded tell sites; b: lower mounds (2-3 m in height); c: multiple mounds and pits; d: hollow ways. From Ur (2003).

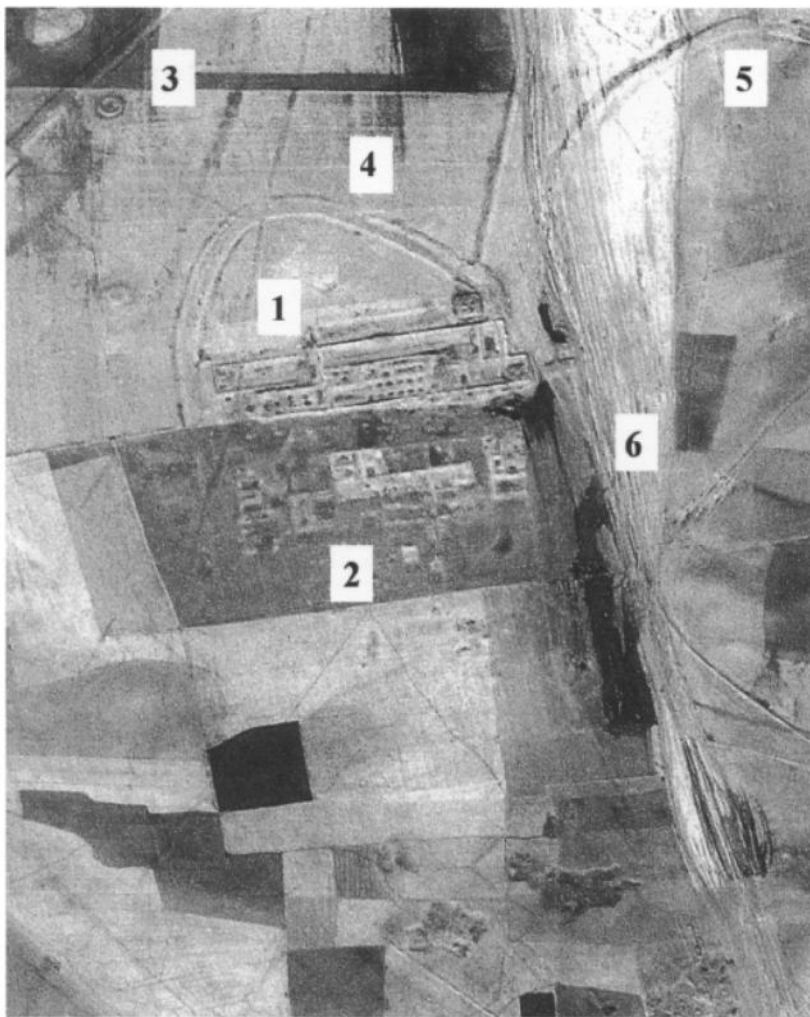
habitation and do not retain moisture as readily as the surrounding soils, thus appearing lighter. Similarly, in hollow ways, the soils retain more moisture, appearing darker, while the slopes along the sides drain into the depression, making them appear lighter.



Figure 14. A variety of archaeological sites, both large and small, as seen on CORONA imagery in the Amuq Valley, Turkey. From Casana and Wilkinson (2005).

In a series of publications (Casana 2003; Casana and Wilkinson 2005; Casana 2007; Casana 2008), CORONA imagery was used to locate numerous sites and features in the Amuq Valley of Turkey. Paleochannels of the Orontes, Afrin, Kara Su, and Yaghra Rivers were clearly visible, as were marshland deposits and canal systems surrounding Lake Antioch, providing insights on the geomorphological history of the landscape. It was also used to update our knowledge of the archaeological settlements of the region, in some cases demonstrating that maps from earlier surveys were variably incorrect in size, placement, boundaries, and condition of sites. Roads, drainage ditches, town walls, and walls between agricultural fields were also apparent on CORONA imagery. Finally, it was useful in finding numerous new sites, especially smaller ones that had eluded detection by earlier surveys.

Challis et al. (2004) used CORONA imagery to examine the landscape of the ancient Syrian city of al-Raqqa (Figure 15). They used CORONA imagery in several applications. First, relict river channels were identified in an attempt to understand the history of avulsion in the Euphrates as it related to landscape change, settlement location, and dating. Second, it was used to create regional-scale maps of ancient al-Raqqa and environs including the city area, roadways, irrigation canals, and other contemporaneously and formerly occupied areas such as places of



ceramic production and quarries. In addition, several previously unknown structures were found on the CORONA images (Figure 15).

Challis et al. (2004) also used image enhancement techniques to increase the visibility of features. Using Adobe Photoshop, the high-resolution CORONA imagery was subjected to a 2x2 median filter to remove the graininess apparent in the image from the silver halide crystals present in the emulsion on the original

film. In addition, contrast was

Figure 15. Newly discovered occupation to the northwest of al-Raqqa. Includes buildings (1 and 2), canals or other irrigation features (3-5), and a modern trackway (6). From Challis et al. (2004).

improved by applying a histogram stretch to the image.

Fowler (2004a) used two CORONA KH-4B images to identify Roman forts and other structures in the desert of central Jordan (Figure 17). The study is primarily concerned with establishing the utility of CORONA imagery as a low-cost alternative to aerial photography for archaeological research in areas where aerial imagery or ground-based study are unrealistic.

Altaweel (2005) used CORONA imagery in conjunction with 15-meter ASTER multispectral imagery to identify hollow ways (linear road-like depressions common in northern Mesopotamia), irrigation canals, and archaeological sites (Figure 18). The utility of CORONA images for these applications posed problems for Altaweel. In one example, a CORONA image shows a possible linear feature that without the multispectral capabilities of the ASTER imagery is difficult to identify as a

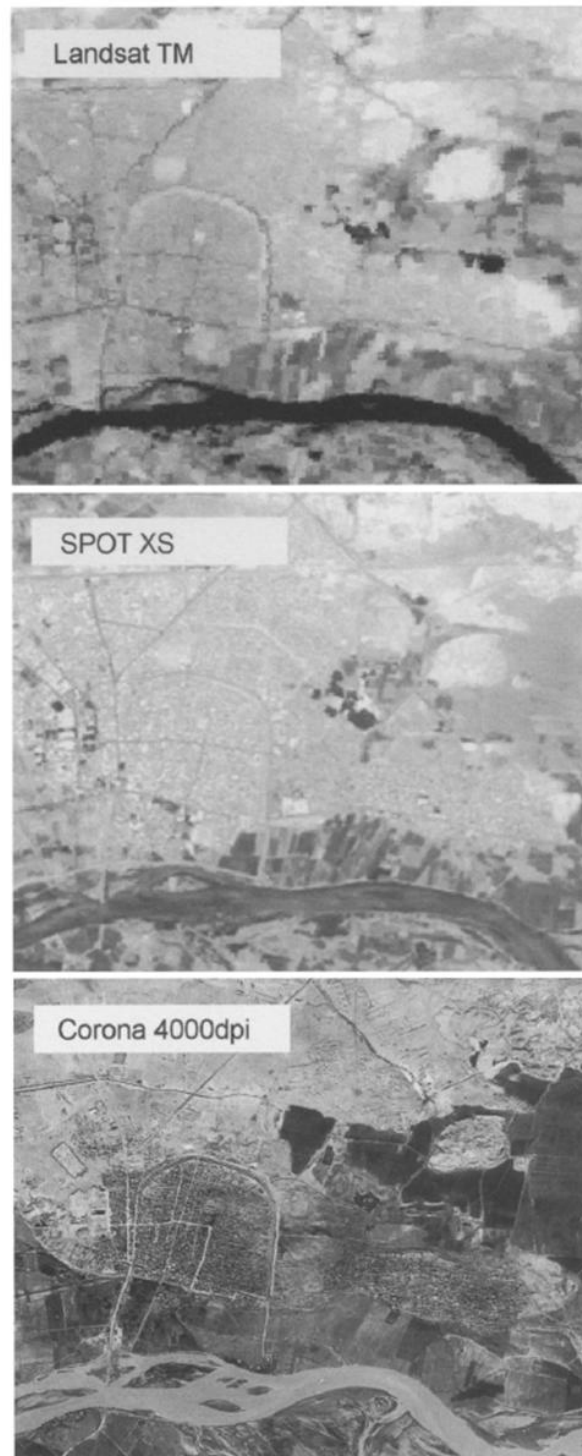


Figure 16. A comparison of the same view in Landsat TM (30-m spatial resolution), SPOT XS (20-m), and CORONA (sub-2-m). Note the significant difference in development between the older CORONA and younger Landsat and SPOT images. Modified from Challis et al. (2004).

hollow way. Although the CORONA imagery has a higher spatial resolution, differences in soil, moisture, and vegetation between suspected features and the surrounding landscape are impossible to determine from a panchromatic format. Likewise, ASTER provided the ability to determine soil differences in canal levees and tells to differentiate them from other

linear and circular features.

Menze, Ur, & Sheratt (2005) used SRTM, LANDSAT ETM+, and CORONA data for locating and estimating the areas of tell sites in the Khabur basin of northern Mesopotamia. The tells were located by developing a classifier algorithm using visually

identified sites in the SRTM data and verifying them with LANDSAT imagery and topographic maps. The algorithm performed rather poorly, correctly identifying 85 of 133 known sites but

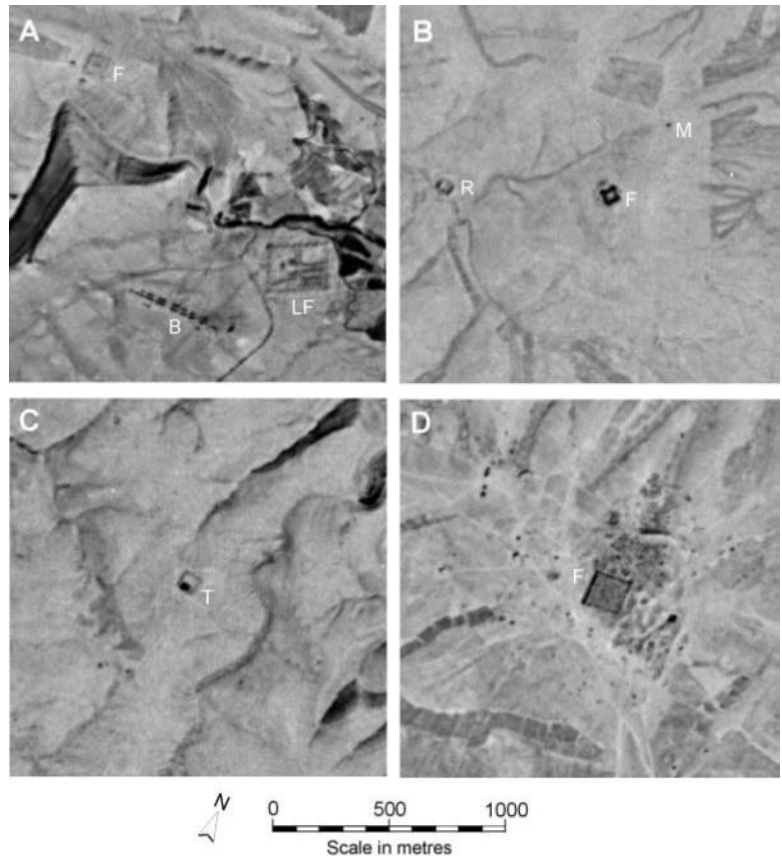


Figure 17. Roman sites in central Jordan. From Fowler (2004a).

A: legionary fortress at el-Lejjun and fort at Khirbet el-Fityan

LF: outline of fort at el-Lejjun

B: two lines of 20th-century Ottoman barracks

F: outline of fort at Khirbet el-Fityan

B: fort at Qasr Bshir

R: remains of reservoir

F: outline of fort at Qasr Bshir

M: ancient building, possibly a watchtower, later a mosque or shrine

C: tower at Qasr Abu el-Kharaq (at location T)

D: fort at Umm er-Resas (at location F) with indications of surrounding town

producing 327 false positives. For the sites that were correctly identified, their areas, as they appear on LANDSAT and CORONA images, were compared. Generally, larger sites have similar areas on both sets of imagery and smaller sites are larger in area on CORONA than on LANDSAT. This suggests that the larger pixel size of the LANDSAT imagery makes smaller sites appear larger.

Ur (2005) used CORONA and 0.6-m resolution (Fowler 2004b) KH-7 GAMBIT imagery to reconstruct the Sassanian-period canals of Sennacherib surrounding the city of Nineveh. Ur registered these images to previously orthorectified SPOT imagery and used them in conjunction with a 30-m-resolution DEM of unspecified origin. Ur made use of a number of temporally separated images to get a more complete view of landscape features (Figure 19), as some



Figure 18. Archaeological features discovered on CORONA imagery. From Altaweel (2005). A: Hollow ways appearing as dark traces (see arrows) radiating outward to the south of Tell Kashaf. B: Tell al-Buweir, within the oval, and arrows indicating hollow ways in a radial pattern around the tell.



Figure 19. Top left: KH-7 GAMBIT image of the Kisiri canal, several km north of Nineveh,, showing several features including other canals, a weir, and a tell. Top right: CORONA image of the same main canal further downstream, showing the appearance of several canals. Bottom: CORONA image of the Tarbisu canal, 8 km northwest of Nineveh, with visible canals. From Ur (2005).

appeared better in different years and seasons than others. Good results were obtained with this study, where canals, tells, weirs, and extensive earthworks were clearly visible.

K. N. Wilkinson et al. (2006) use IKONOS and CORONA imagery to locate non-tell sites near the city of Homs in Syria, adjacent to the Orontes River. Extensive survey has been largely successful in the Middle East for locating tells but fails in many cases when seeking smaller sites that are more widely distributed across the landscape, which are more typical of later periods. The authors suggest that satellite

imagery is a good approach for finding these smaller sites. In this study, the IKONOS imagery was used primarily for georeferencing and correcting the CORONA imagery but also for its multispectral properties.

Their project had the unusual step of collecting soil samples from numerous locations in the study area and analyzing their grain size, chemical composition, and magnetic susceptibility. There were significant differences in soil characteristics, especially grain size, between samples collected within a site and those taken offsite; these differences correlated well with the differences in soil reflectivity as recorded by the satellites (Figure 20, Figure 21). Ancient settlements in the Middle East typically have high clay content in their soils as a result of centuries of using mud bricks which, over time, disintegrate. Thus, this study demonstrates that

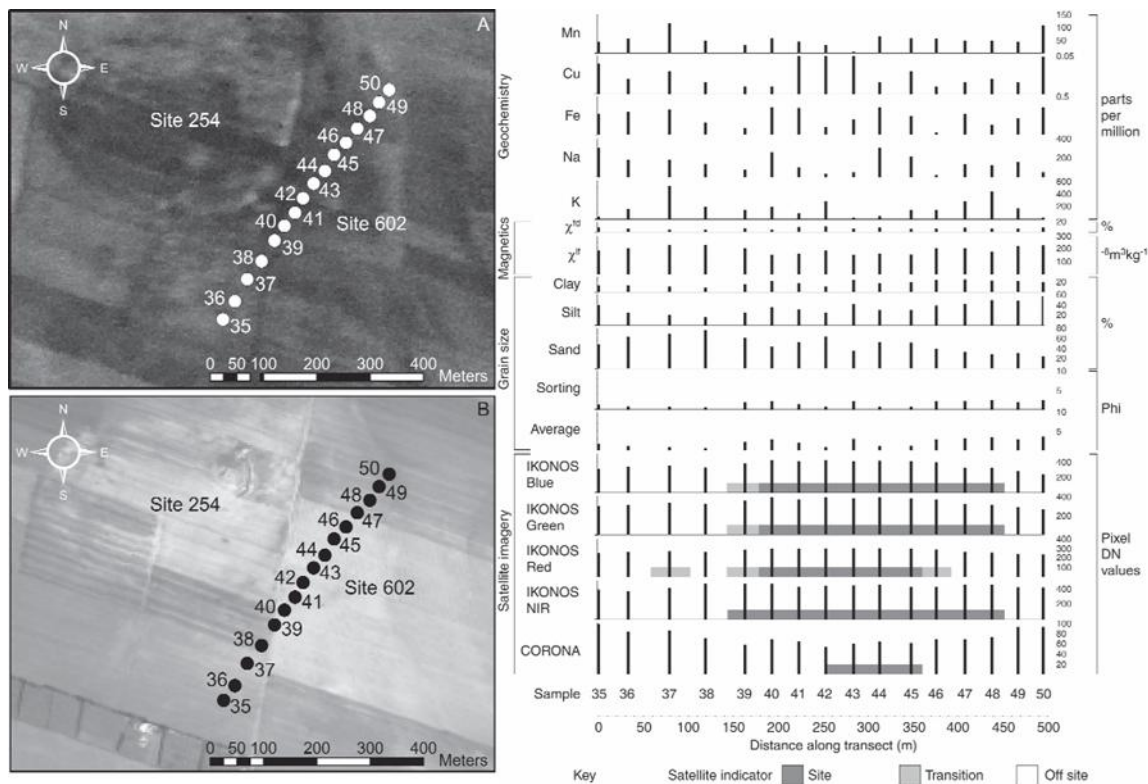


Figure 20. A: CORONA negative showing area of increased relative reflectance to the south and east of Tell Arquni (labeled Site 254) and locations of soil samples collected; B: the same area on IKONOS; C: Pixel values, grain sizes, and magnetic and chemical properties of soil samples. Modified from K.N. Wilkinson et al. (2006).

areas of former occupation can be detected by areas of higher soil reflectance. There are few cases where low reflectance is associated with the presence of a site; the one discussed in this study has a relatively large grain size produced by aeolian erosion of the finer particles, the presence of ash, and debris originating from stone architecture. The study found 51 sites by detecting surface scatters using CORONA imagery. The authors conclude by cautioning that while satellite imagery can be useful, it cannot replace ground-based reconnaissance; there are many features that cannot be observed with satellite imagery and sites with too short of an occupational time frame may not develop enough clay to be visible (K. N. Wilkinson, Beck, and Philip 2006).

Goossens et al. (2006) used CORONA imagery for mapping at larger scales than were

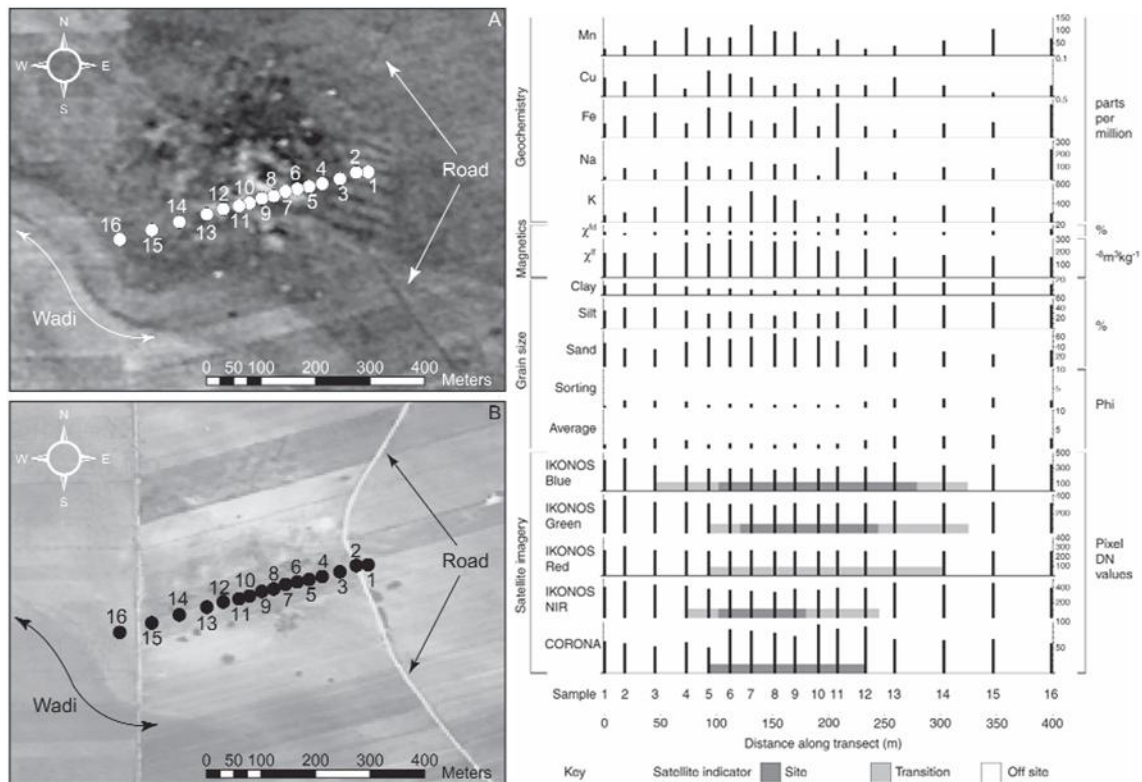


Figure 21. A strip of low reflectance trending WSW-ENE within an area of high reflectance. A: CORONA negative; B: IKONOS image; both showing locations of soil samples; C: Pixel values, grain sizes, and magnetic and chemical properties of surface samples. Modified from K.N. Wilkinson et al. 2006.

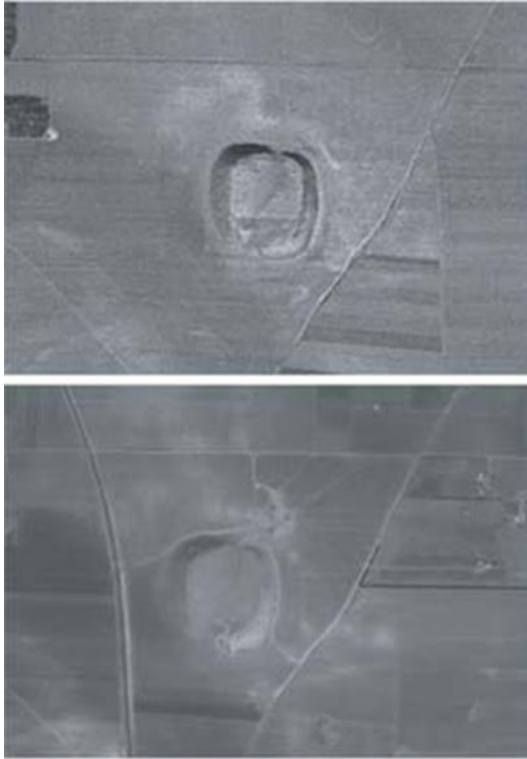


Figure 22. A comparison of a tell imaged with CORONA (top) and IKONOS 11 (bottom). There is not a significant amount of improvement in the IKONOS imagery, and it has the disadvantage of including the large amount of development which has occurred since the CORONA imagery was acquired. Modified from Beck et al. (2007).

available from civilian and military sources, which were insufficiently detailed to be useful to archaeology.

Hritz (2006) uses SPOT and CORONA imagery to find tells and canals in the region of Nippur, to the south of the current study area. She uses CORONA positives scanned at 9m per pixel and does not make any mention of correcting the imagery. Tells, canals, and other features of the landscape are successfully found and were extended beyond their previously known limits. In addition, a better understanding of settlement relationships in the study area emerged. Hritz stresses the utility of using multiple data sources to better facilitate the locating of features.

Richason and Hritz (2007) utilize CORONA and other satellite imagery products to detect landscape features in the region of Nippur. They discuss the application of image enhancement techniques to make interpretation easier. In one example, a CORONA photograph is colorized to take advantage of human vision's greater sensitivity to color than grayscale. Again, there is emphasis that the use of multiple data sources can be very helpful in distinguishing features, drawing on each image type's strengths.

Beck et al. (2007) used CORONA and IKONOS imagery for detecting sites in western Syria (Figure 22). The relatively high cost of the IKONOS imagery was mitigated, according to

the authors, because of its high (1-meter) spatial resolution, multispectral characteristics, and the fact that it is available already georeferenced. It is worth noting that Beck et al. did not see any significant advantage to the IKONOS imagery over that from the CORONA program in terms of spatial resolution. However, CORONA was necessary because of the high levels of agricultural and urban development that occurred during the time between the CORONA and IKONOS imagery acquisition. CORONA imagery provided an important means of comparison for suspect areas identified in the IKONOS imagery, such as areas of high reflectance which in some cases can represent archaeological sites. Another disadvantage to the IKONOS imagery is that while georeferenced, some products have a positional accuracy exceeding 25 meters, which is unsuitable for mapping of archaeological sites and features. Thus, care must be taken to either obtain the most accurate imagery (~10-m accuracy) or perform additional corrections before use (Galiatsatos, Donoghue, and Philip 2008).

Beck et al. used GPS-derived ground control points to further correct the IKONOS imagery and then used the resulting images to correct the CORONA imagery using tie points. The final accuracy of the recorrected images was between 5 and 8 meters. It should be noted that unless fieldwork is already planned as part of a project, the necessity of obtaining ground control points in the field can pose a significant obstacle in terms of cost, time, and potentially security.

Parcak (2007) uses CORONA imagery alongside SPOT, Quickbird, and LANDSAT data to identify tells in Egypt. She argues that CORONA is useful for looking at sites but that it is not the best option for detecting sites because it does not have the multispectral features of the other platforms. Multispectral imagery is well suited to detecting archaeological features because it is able to distinguish ancient settlements from modern ones, even though its coarser spatial resolution is a challenge to finding the numerous smaller sites. Parcak also argues that it is

difficult to use CORONA for project planning as modern features, such as roads and buildings, are not necessarily present on the now over 40-year-old imagery. However, she acknowledges its utility in finding sites that have been destroyed by development, giving researchers the ability to search for and collect any surface materials that may yet remain.

Hritz (2010)

discusses the use of

CORONA imagery in

conjunction with other data sources and GIS to improve our understanding of the physical and cultural landscape of the Tigris River plain of southern Iraq. Here, SRTM and ASTER data were supplemented with CORONA imagery to discover meander scars of the Tigris (Figure 23) and reconstruct past river channels and determine how they have affected settlement and the preservation of the archaeological record. This study demonstrates that the migration of river

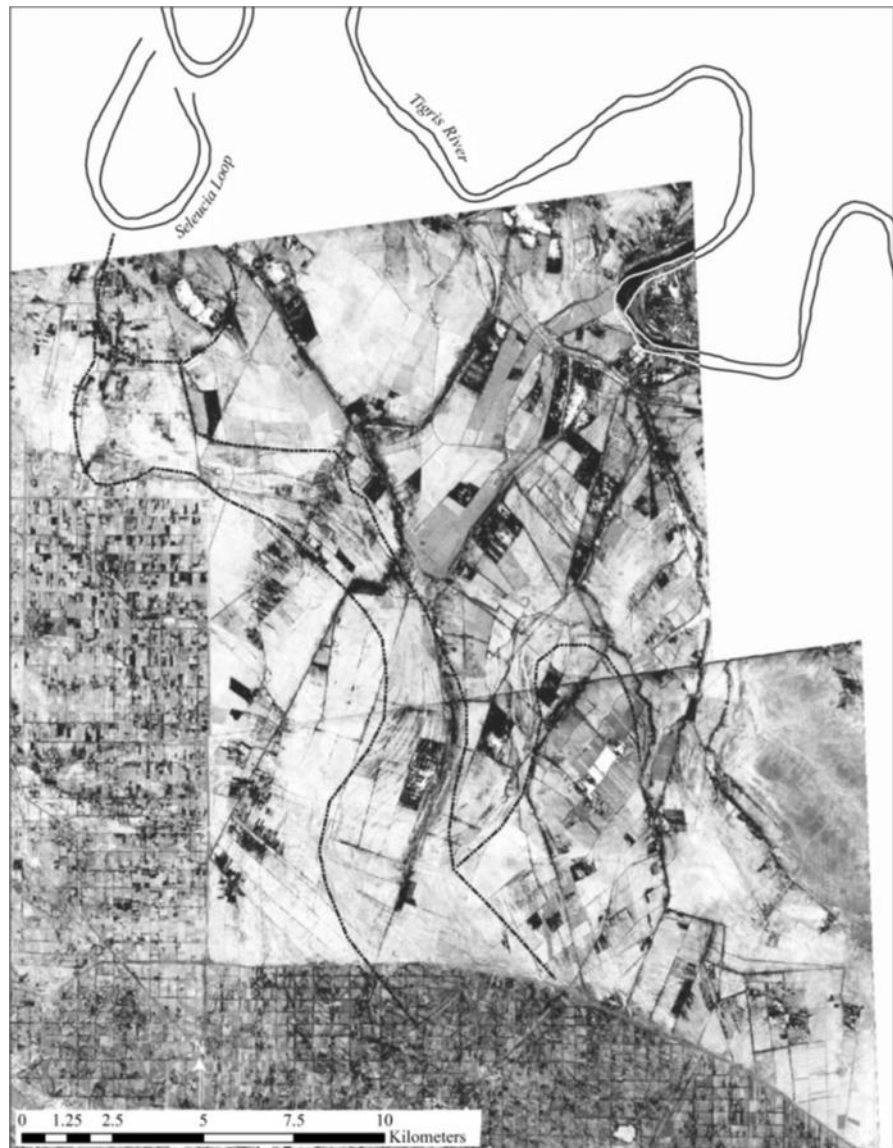


Figure 23. Meander scars as they appear on CORONA imagery. Adams (1981) and Buringh (1960) as cited in Hritz (2010).

channels and the changing usage of canals through time has produced a complex archaeological landscape that suggests a much wider area of former habitation than is readily apparent from more traditional surveys such as those of Adams.

As these studies indicate, CORONA imagery is well-suited to archaeological purposes in the Middle East. It has been amply demonstrated to have sufficient resolution to detect all manner of archaeological features from surface scatters to tells, canals, and earthworks. CORONA has also been used with great success in other areas of the world, and a summary of these projects is provided in Fowler (2004b).

IV. MATERIALS AND METHODS

Preparation of the GIS Database

The initial task of this study was to create a GIS database of the study area. Imagery from LANDSAT 5 Thematic Mapper (L5TM) and Earth-Observing 1 Advanced Land Imager (EO-1 ALI) were obtained from USGS EarthExplorer (<http://earthexplorer.usgs.gov>). Composite images were formed from the individual bands using the ArcGIS tool. They were then loaded as a base reference.

Next, digital elevation data was also obtained. Shuttle Radar Topography Mission

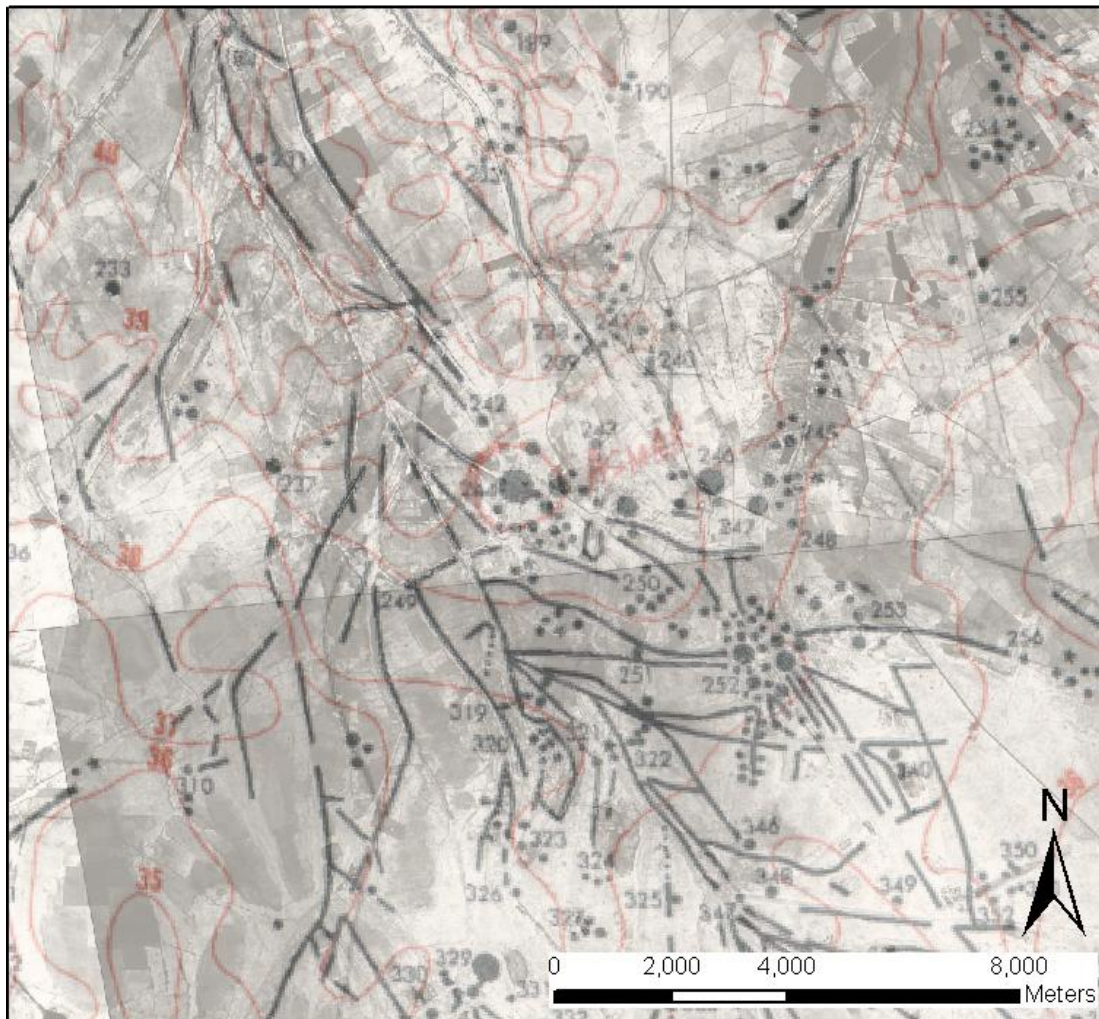


Figure 24. Georeferenced map from Adams (1965) overlaid on CORONA imagery showing good agreement between canals on the map and the ground.

(SRTM) data came from EarthExplorer and Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) data were acquired from NASA's Warehouse Inventory Search Tool (WIST, <http://wist.echo.nasa.gov>).

The following step was to take the data provided by Adams (1965) in his published survey map and bring it into the GIS database. This was a multiple-step process. The map was

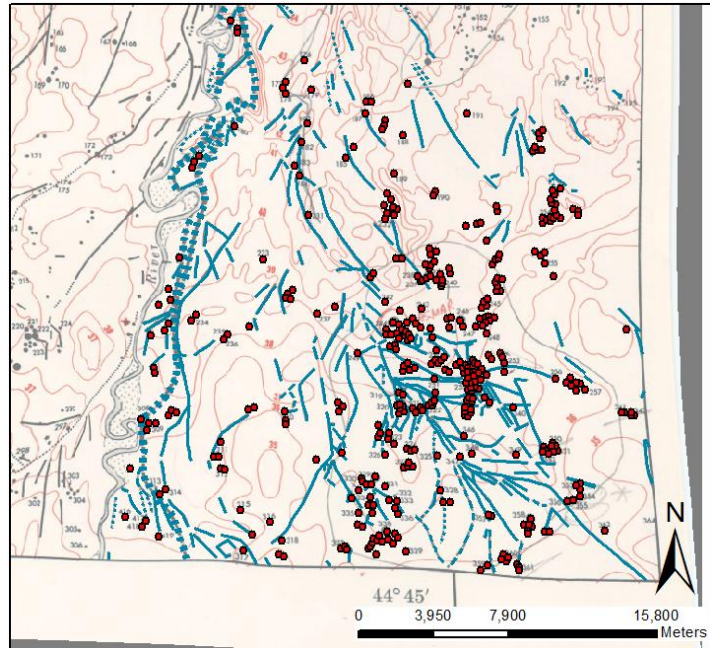


Figure 25. Scanned and georeferenced site map from Adams (1965) with sites in study area around Tell Asmar digitized as points and canals as lines.

copied from the PDF file, saved as JPEG format, and opened in ArcMap 9.3.1. It was assigned a spatial reference of UTM grid 38 north, which is consistent with the existing imagery products in the database. Next, using the georeferencing features of ArcMap, ground control points were chosen based on identifiable features present in both the map and the higher-resolution EO-1 ALI imagery. Most often, these control points were canal junctions but, in some areas, such features were difficult to find in sufficient quantity. Because of the dynamic nature of meanders in the Tigris and Diyala Rivers, using them as control points was avoided when possible. However, because of the relatively short passage of time between the Adams survey and when the imagery was acquired, the meanders should be in approximately the same location. Furthermore, no noticeable changes in the overall shape of the rivers were noticed. Because of these factors, river meanders were occasionally used as control points when canals were not

available. There was good agreement between the canals indicated on the Adams map and those in the satellite imagery (Figure 24).

Once the Adams map was georeferenced, all of the sites in the present study area were digitized as points in a new feature class in ArcMap (Figure 25). The canals were also digitized as lines. As it was useful to have the site descriptions and occupational periods of each site as part of the database, they were scanned from the Adams survey and processed with optical character recognition. Some text formatting filters were applied to create a comma-delimited version of the site descriptions. These were then imported into a database, added to the ArcMap document, and joined to the attribute table for the digitized sites.

Preparation of CORONA Imagery

The CORONA imagery used in this study is from mission 1104-2138, which was acquired on August 16, 1968 with a KH-4B satellite. Four stereo pairs were obtained from the Archaeological Atlas of the Middle East project of the University of Arkansas' Department of Anthropology and Center for Advanced Spatial Technologies. They were provided as raster images of the CORONA negatives scanned at a resolution of 7 μm per pixel.

Challis (2004) suggests some image processing techniques to enhance the visibility of the imagery. They applied a sharpening filter and then a 2x2 median filter to remove the graininess caused by the silver halide crystals in the film emulsion. The process was tried, but the end product, while not grainy, lost much of the detail necessary for good interpretation of the image.

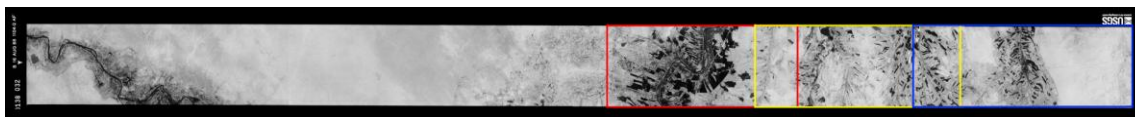


Figure 26. CORONA image showing overlapping segments split from the original scene.

Therefore, the images were left as they came, and any histogram stretching to improve contrast could be accomplished at the end with ArcMap.

The approach being used in the present study to orthorectify the images is to divide the images into segments and treat each as a single frame from a non-metric camera in ERDAS Imagine LPS. As the study area does not extend into the western half of the images, that portion was discarded. The remaining eastern half of each was split into three overlapping images (Figure 26). The 12 stereo pairs were then loaded into an LPS block file.

Orthorectification

The block file was configured as a non-metric camera using WGS 84 as both the horizontal datum and vertical spheroid and datum. The projection was set to UTM zone 38 north. The standard deviation for the GCPs was set to 10 m in all dimensions, and the average flying height of the camera was set to 145,800 m (National Reconnaissance Office 1967). The frame editor properties, which contain the camera specifications, were then configured. The sensor focal length was set to 609.602 mm (National Reconnaissance Office 1967) with the principal point set to zero in both dimensions. The pixel size of the scan was set to 7 μm .

After configuring the block file, the next step was to select GCPs (Figure 27). Using Google Earth as a reference, 95 control points were defined linking CORONA to the geographic coordinates of the same locations in Google Earth. An additional 49 tie points were created among the CORONA images that did not refer back to Google Earth but which would assist LPS in orthorectifying the images. An attempt was made to space out the GCPs as evenly as possible and to avoid straight lines, as an even distribution of points is essential to getting good results. Although some earlier studies (see section on problems with and approaches to using KH-4B imagery for details) noted significant difficulty in finding control points between images

acquired 40 years apart, there were more than sufficient common points found during the present exercise.

After the manual selection of control and tie points was completed, the software was instructed to automatically generate additional tie points. Using the default search window and correlation size, which define the size of the local area and number of pixels, respectively, that LPS uses to make matches between images, resulted in a large number of inaccurate tie points. Thus, the search window was increased to 75 pixels across and the correlation size was increased to 45, requiring that a match had to be large enough to avoid random noise. The autotie process produced an additional 862 tie points spread across all of the images. While they were not all checked individually for accuracy, a significant number of them were verified and no errors were found.

Once the control and tie points were established, LPS was able to triangulate the images in order to produce orthophotos. This was attempted twice: once for manually selected tie points only, and again with the automatically generated ones. The parameters provided to LPS for triangulation were as follows. Maximum iterations was set to 10 with a convergence value of 0.00100 and image coordinates in pixels. The image point standard deviation was set to 2.00 for both dimensions. The GCP type was set to same weighted value with values of 10.0 for the horizontal dimensions and 16.0 for the z-dimension, reflecting the reduced certainty of the 90-m-resolution SRTM image providing the elevation data. The interior type was set to fixed for all images and the standard deviation was set to 0.10 for all values. Exterior was set to no weight. No additional parameters were specified, and both “use image observations of check points” and “consider earth curvature” options were selected.

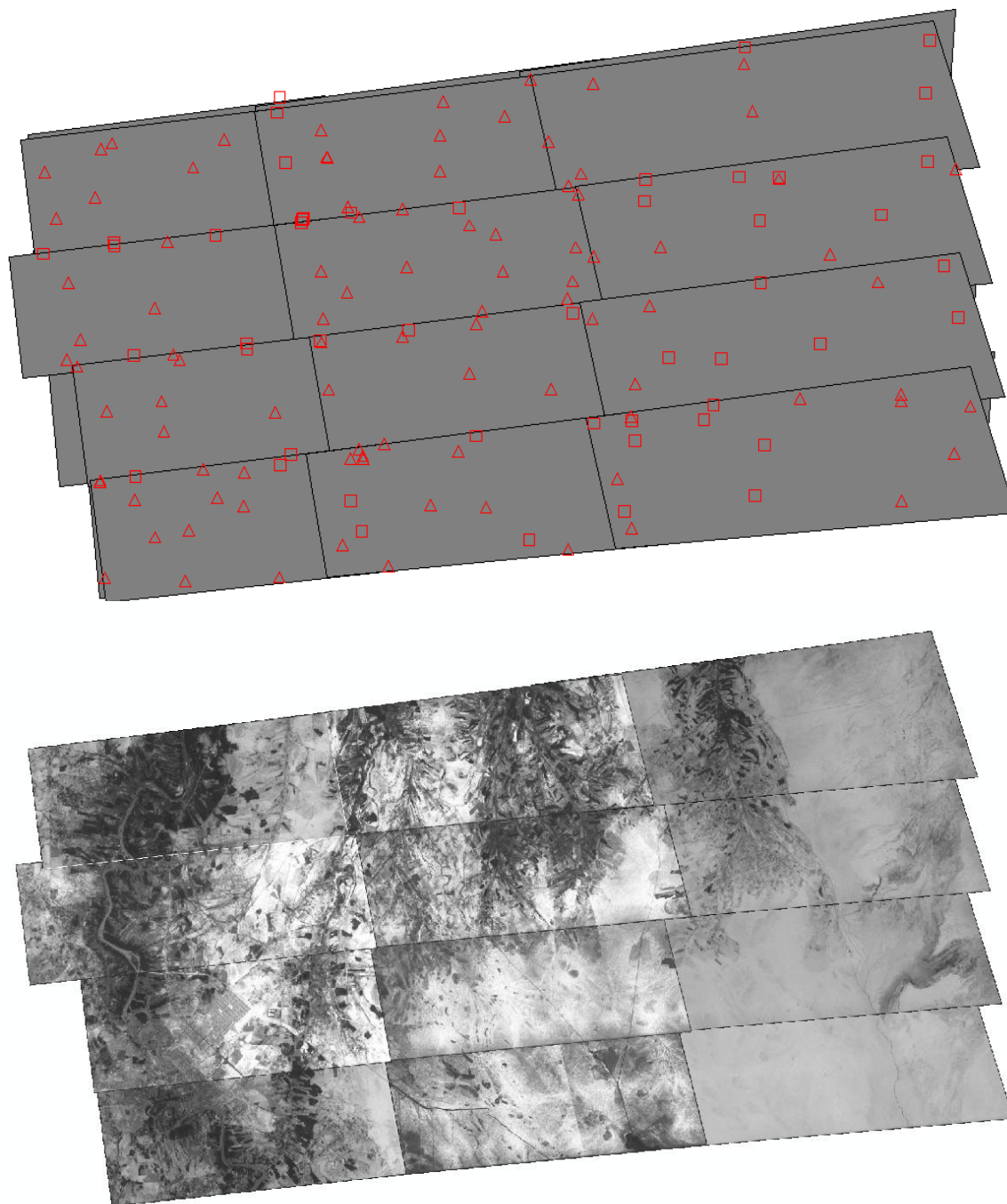


Figure 27. Top: Footprints of orthorectified images showing correct orientation and bow-tie shape (eastern half only). Manually selected control points are indicated by triangles and tie points by squares. Bottom: Orthorectified fore images.

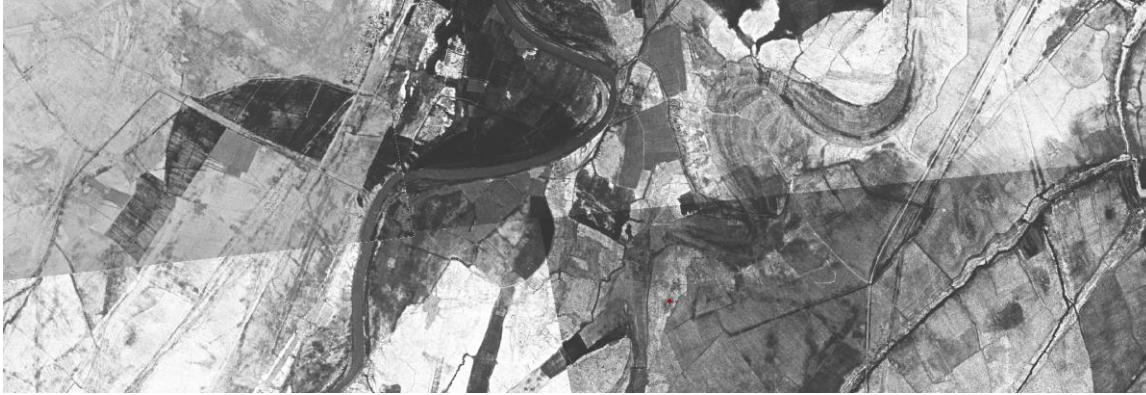


Figure 28. Four-way junction of orthorectified CORONA images. All but the upper left image coregister excellently. The pattern of misalignment along the edges of the upper left images suggests that it needs to be stretched or moved slightly to the south.

The triangulation process using only manually-selected was very successful, returning an RMS error of 3.0187 pixels in x and 4.2001 in y. The resulting images from the automatically generated tie points had strange artifacts around the edges and did not overlap correctly. Thus, the images with the manually selected tie points only were used. These images were loaded into the ArcMap database and they registered excellently with other previously orthorectified imagery such as EO-1 ALI. There was some minor offsetting at the edges of the images (Figure 28), suggesting that finer ground control may improve the orthorectification process, but in general this method works quite well.

DEM Extraction

Once the triangulation process was completed, the DEM extraction process was begun. The DTM extraction properties were set to WGS 84 for the datum and UTM for the projection. All of the checkboxes were clear. For accuracy, block GCPs were used along with tie points and SRTM elevation data. The seed was set to block GCPs and tie points, but not check points.

LPS offers two DEM extraction tools, the classic version as well as eATE, or Enhanced Automatic Terrain Extraction. Both methods were utilized to see if one would produce a better

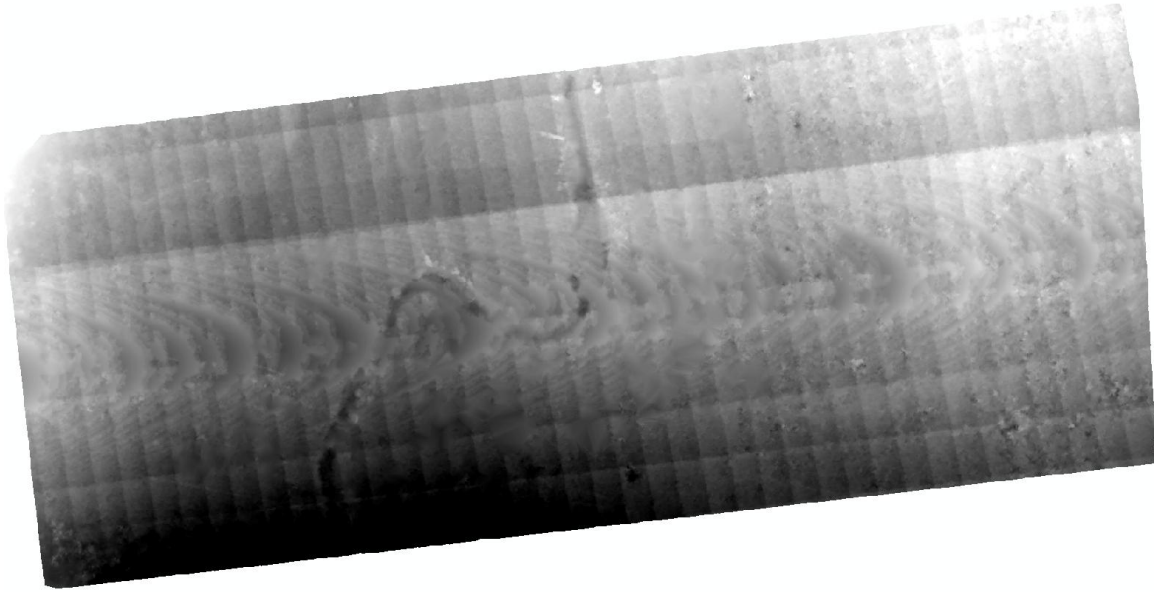


Figure 29. DEM produced with LPS' classic extraction tool. Note striping and curved pattern appearing throughout the image.

result. For the classic tool, the properties were set as follows. The type of output was DEM, with each image producing individual output files. The cell size was set to 16 m with square pixels. For eATE, the default options were left in place, the output cell size remaining 16 m.

The resulting DEMs did not meet expectations. The first, from the classic tool, exhibits significant striping as well as a curved pattern repeating through the center of the raster from west to east (Figure 29). The only recognizable feature on the image is the Tigris River. Galiatsatos, Donoghue, and Philip (2008) encountered a similar striping phenomenon and were able to determine that it likely originated in the CORONA images themselves as an artifact of the scanning process. These stripes were not visible in the normal CORONA images but they were able to detect them after using an image filter. Although an attempt was made to bring out similar features in the current project using image filters, nothing was apparent, although this is still the most likely explanation for the features.

The second DEM, produced with the eATE tool, at first appears to be potentially more useful. Most of the raster has no value, but distinct shapes such as river channels and levees can

be seen (Figure 30). This suggests that features with higher relief were detected. However, upon closer inspection, the areas which appear in the DEM are more highly correlated with areas of higher contrast on the CORONA imagery. As can be seen in Figure 27, much of the study area has little contrast, and this may be a contributing factor to LPS being unable to produce a suitable DEM. However, even in areas where there is significant contrast, the DEM still does not accurately reflect elevation.

For example, in places where tells are numerous and distinct, the eATE DEM does not accurately identify them. As shown in Figure 31, even when tells are easily recognizable in the CORONA photographs, there is no clear correlation among them and the areas of higher elevation indicated on the DEM.

Similarly, when attempting to find canal levees on the DEM, there are mixed results (Figure 32). The DEM suggests that there are features there, but they are indicated as having inconsistent elevation. In addition, many other areas, including places within agricultural fields

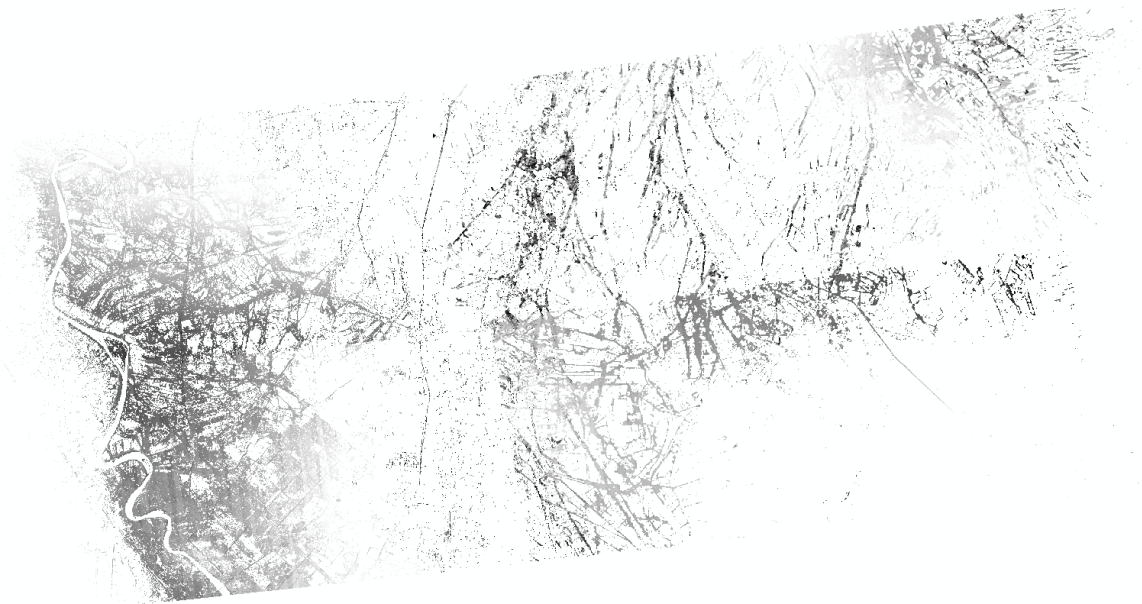


Figure 30. DEM output from LPS' eATE tool.

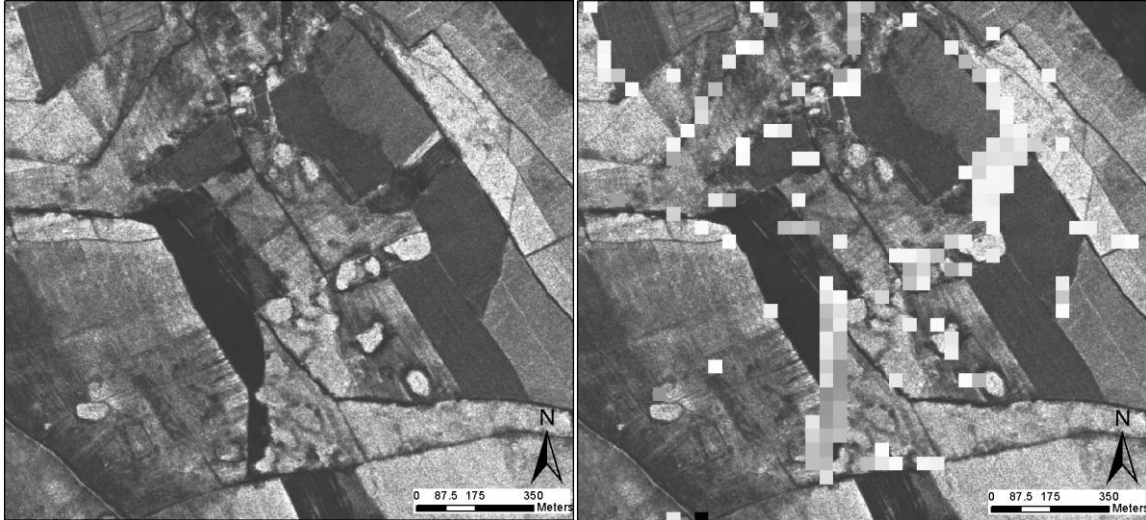


Figure 31. This region has many distinct tells, which appear on the left. When the DEM is overlaid (right image), there is no distinct relationship between the tells and areas of higher elevation.

that likely have a constant elevation, are indicated as having relief by the DEM. As a result, the DEM produced through either method is not useful for this project although, in areas where there is greater contrast or abundance of landscape features, better results might be had.

Analysis

Once all the data sources were brought into the GIS, the process of identifying sites and

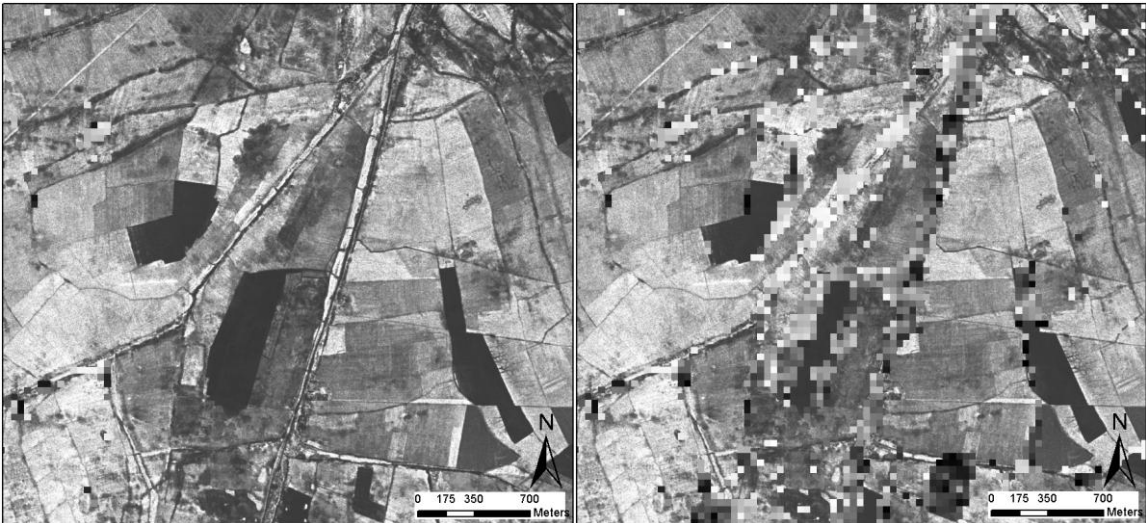


Figure 32. In the left image, canal levees can be seen as thick, whitish, linear landforms running alongside the darker canals. In the right image, the DEM is overlaid (larger pixels).

features began. The first goal was to locate the sites from the Adams survey on the CORNA imagery and record their locations. The second was to match Adams' canals with those on the surface. Once these were accomplished, new sites and canals were located. The details of this process are discussed in the following chapter.

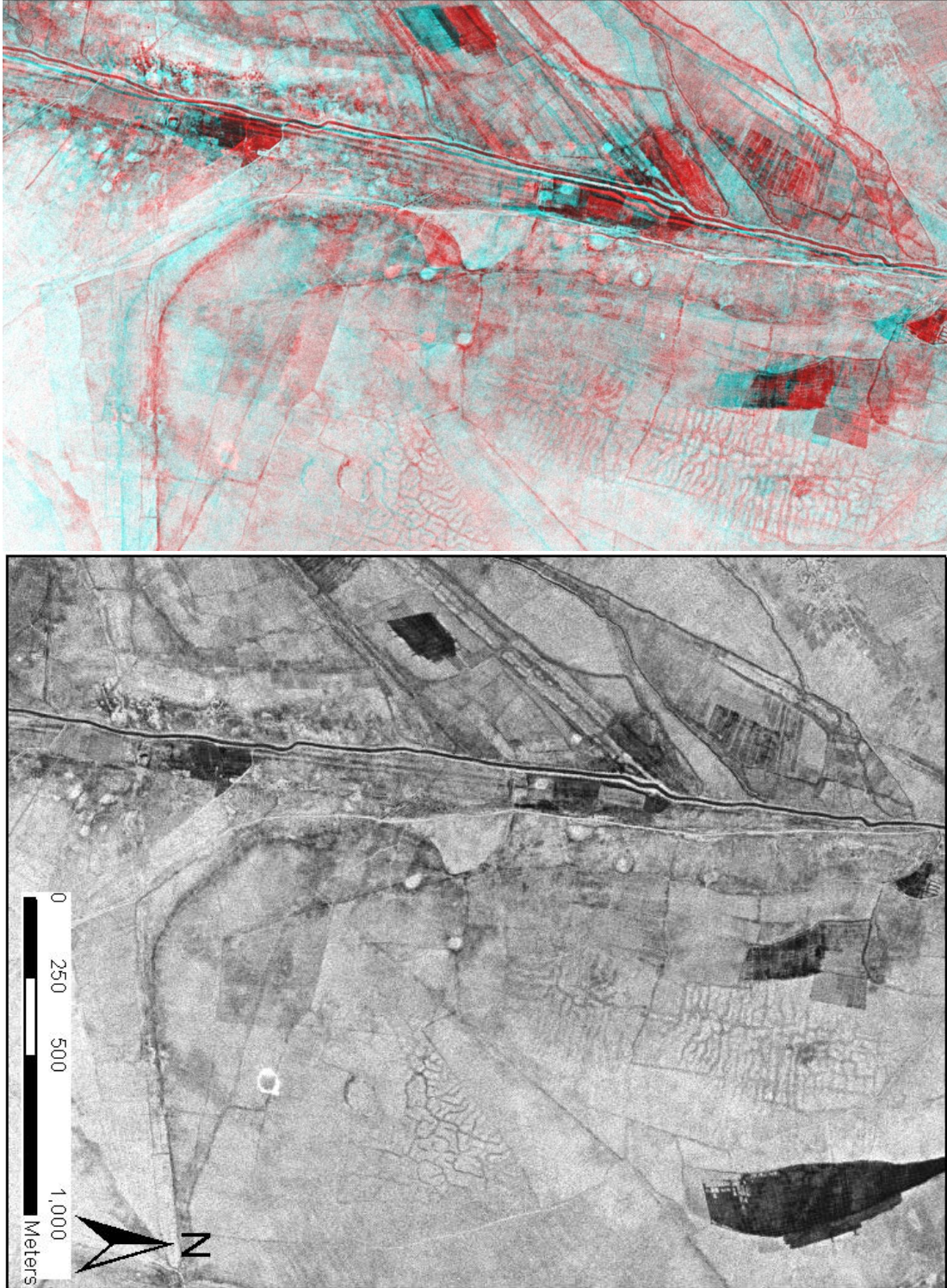


Figure 33. An area with a large variety of features. Top image is anaglyph stereo. Because of the orientation of CORONA photographs, the stereo photos must be rotated. The bottom image is the panchromatic image rotated to match the orientation of the other.

V. RESULTS AND CONCLUSIONS

Identification of Landscape Features

The landscape that appears on the CORONA imagery is complex. In many areas, the identification of features on the landscape is easily accomplished. Figure 33 shows a scene to the west of the study area. Visible on this image are tells (round features), active canals and levees (linear features), and agricultural fields. There is another feature, however, which is not immediately identifiable. These are the dendritic patterns found to the east of the largest canal and the tells. Figure 34 shows another set of these features. They were initially thought to be some sort of drainage feature or dry basin. However, there was also the possibility that they could represent some sort of constructed feature. Comparison with more recent images was impossible for several reasons. First, in some areas development has obscured the landscape. Second, LANDSAT 5 TM imagery is too coarse to resolve the features. Finally, EO-1 ALI imagery has sufficient resolution, but even in areas where no noticeable development has occurred, the features do not appear or it is impossible to determine what they are. However, a comparison of

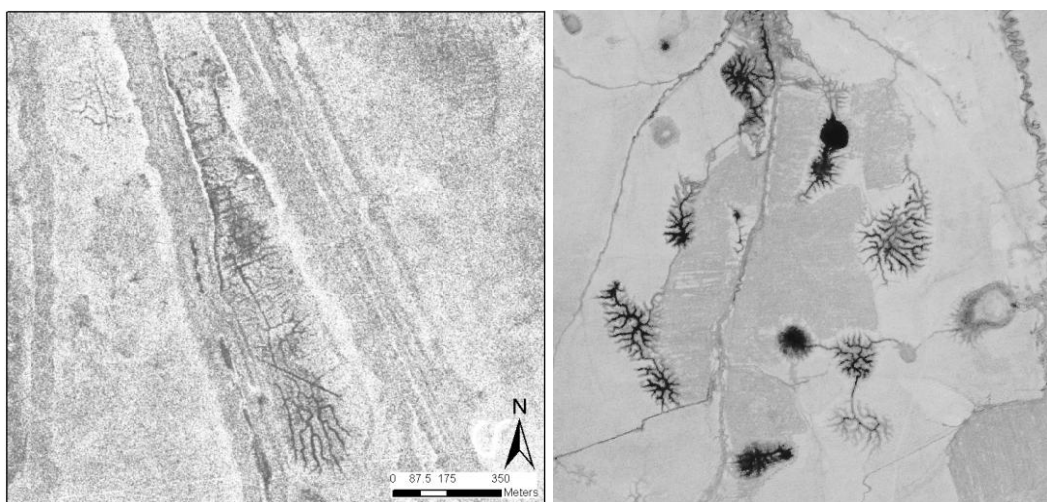


Figure 34. Left: peculiar dendritic features appearing in the study area. On either side of the dendritic features are relict canals. Right: similar features from the Balikh Valley in Syria.

these features to others that appear in CORONA imagery of the Balikh Valley in Syria are more enlightening. These images clearly show that the features are basins which collect water at certain times. In the Balikh Valley, they appear to be small lakes that are in the process of drying out. Thus, they are interpreted as basins.

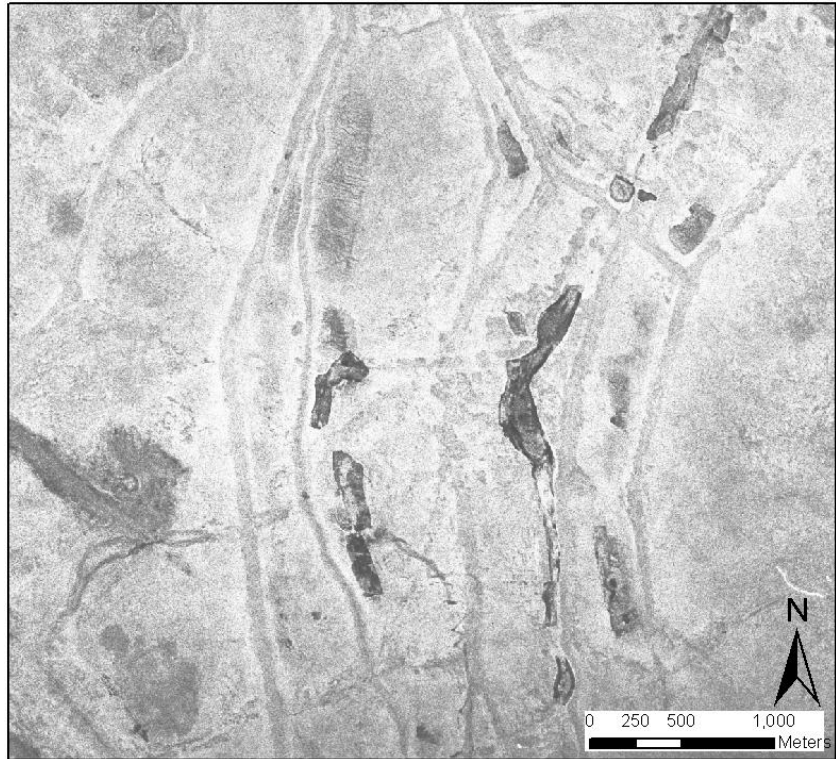


Figure 35. A tell, linear features interpreted as levees, and irregular, sharply defined features of unknown nature.

Figure 34 also contains another feature of interest to this study. To the east and west of the basin containing the dendritic features are linear traces of darker-appearing soil. These are relict canals which form a complex network over the study area and correspond in many places to the canals recorded by Adams (1965). They interconnect frequently with other relict canals as well as those still in use.

Another set of features also poses a challenge to interpretation. In Figure 35, several features are visible. The round feature in the center of the northeast quadrant is clearly a tell. The dark linear features are waterways and immediately adjacent to them are the lighter-appearing soils which are interpreted as relict levees (which typically no longer have any relief). The sharply defined, irregular features pose more of a problem for identification, however. They seem in most cases to run alongside the waterways on top of or immediately adjacent to the relict

levees, suggesting that they represent human modifications of the soils associated with settlement. They also appear similar in soil color to the tell. However, just to the west of center, the image shows one of these features intersecting a basin with dendritic patterns. This suggests that these are small bodies of water, which may appear dark and with distinct edges.

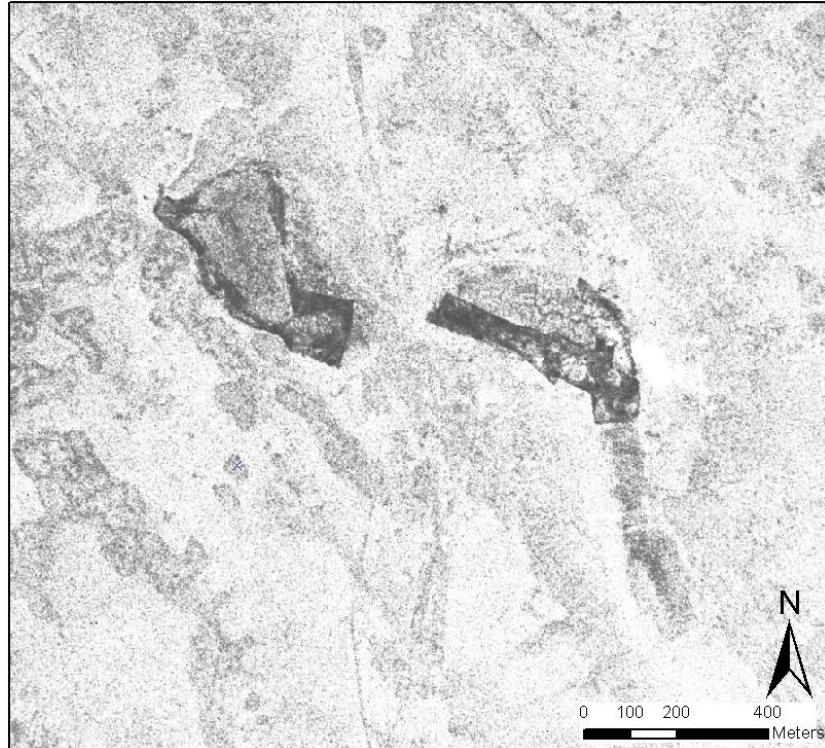


Figure 36. Linear features similar to those found in Figure 35. The one on the left runs alongside the canals and is probably a levee. However the one on the right is located in a low-lying area as indicated by the dendritic drainage pattern that is present in the other areas of the oval-shaped depression.

Their irregular shape is also distinctly different from the round or nearly round character of tells. Because these features cannot be reasonably considered evidence of human settlement, they will not be counted as such.

A third set of features also pose a problem to interpretation. Figure 37 shows an area where a number of dark, round features appear on CORONA imagery. As these do not have the appearance of relief as many tells do, it is difficult to determine whether these are remains of settlements. In comparing the CORONA imagery with that of the later EO-1 ALI satellite, some differences can be seen. Most of the features appearing on CORONA are indistinguishable on ALI. However, a few of the features do have the appearance of tells (shown by arrows).

The identification of these features is further complicated by the appearance of similar round features just to the east, as shown on Figure 38. In the lower ALI image, a settlement is accompanied by a number of similar features, which are probably pits from which building material was dug. They have similar shape and many show shadows along some edges, indicating relief. On Google Earth, many of them are filled with water. They, as well as the settlement, do not appear on CORONA. Another set of these features appears to the east of the canal on CORONA, which are barely visible on ALI.

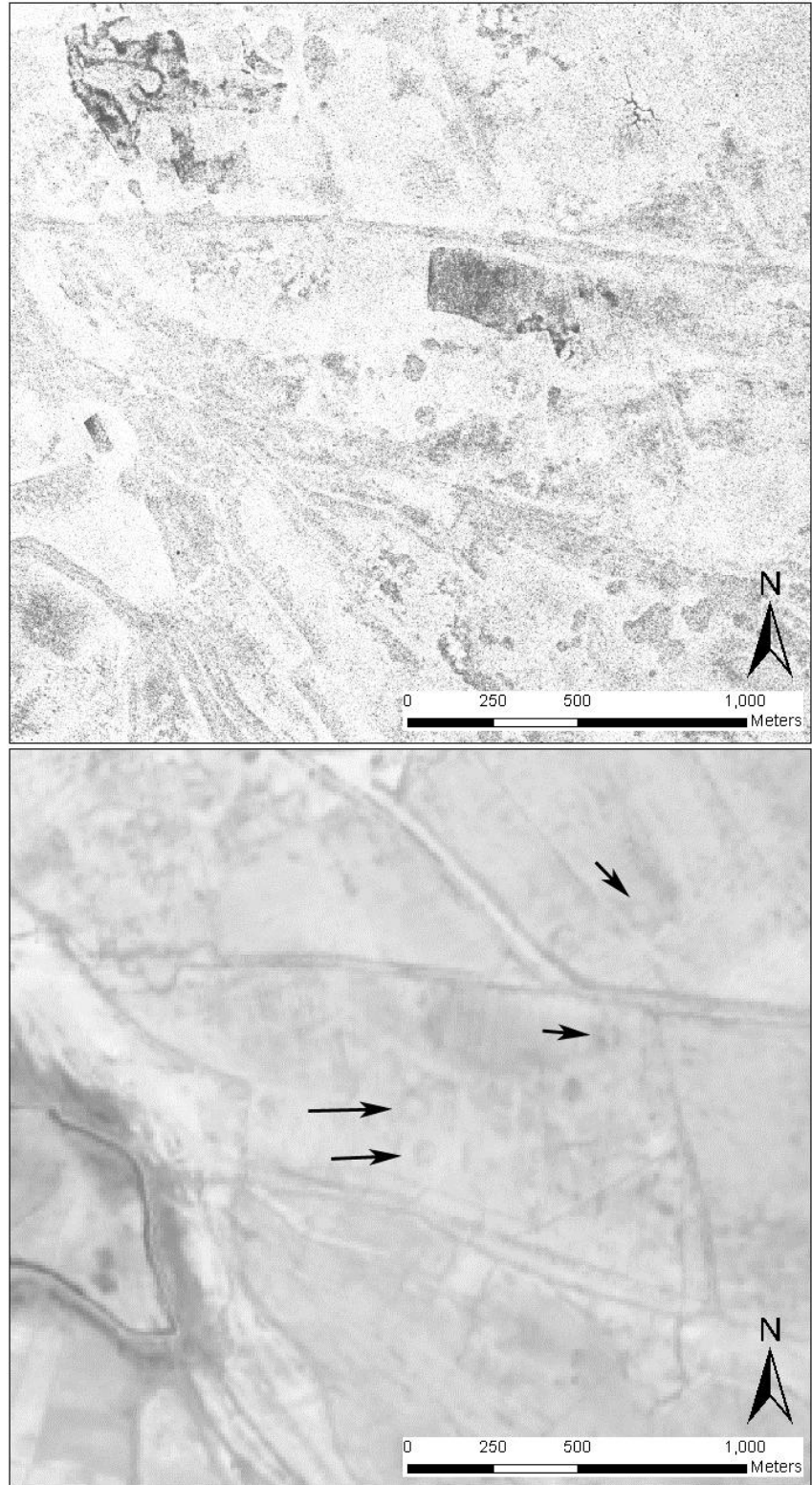


Figure 37. Top: CORONA image showing somewhat round features in center and bottom right and an irregular cluster of features in the upper left. Bottom: EO-1 ALI image of the same area with possible tells indicated by arrows.

Thus, while in a few cases these “pock marks” resemble tells and Adams indicates the presence of sites in the area, their clustered nature and association with modern settlement provide enough doubt to dismiss the majority of them as evidence for occupation in antiquity. However, the few features that appear on ALI correspond well with sites in the Adams survey, so they will be included.

Returning to Figure 37, there is a group of features in the upper left which are also difficult to identify. The shapes and soil colors are irregular. The ALI image shows a



Figure 38. Another area showing dark, round and irregular features. Top: CORONA. Bottom: EO-1 ALI of same area, showing modern settlement to the west and new round features.

round feature in the center which may be a tell, and the surrounding dark areas in the CORONA image might represent an area of high moisture retention. The fairly defined, straight edges are possibly relict canals, but it is difficult to link most of them with other visible waterways. There is enough uncertainty surrounding this group of features that they were not counted.

Figure 39 shows an area being used for agriculture. The identification of settlements here can be difficult. Looking at the upper left arrow, a round feature can be seen which at first resembles a tell, but it is at the terminus of a relict channel (to the north) and there is no visible edge or boundary between the round feature and the more linear channel.

However, the two round features just below it do not appear to be associated with any watercourses are far more likely to be tells. As for the three rightmost arrows, they point to

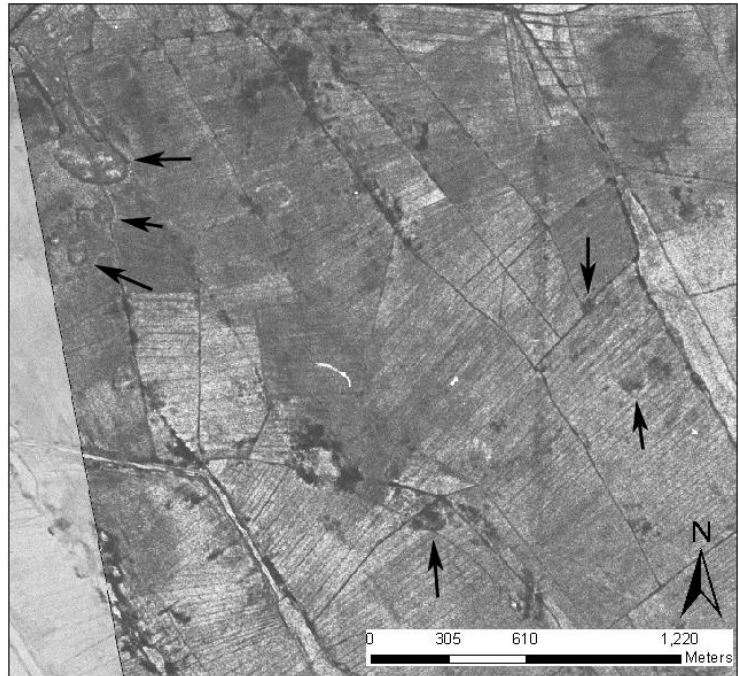


Figure 39. Possible tell features in agricultural fields.

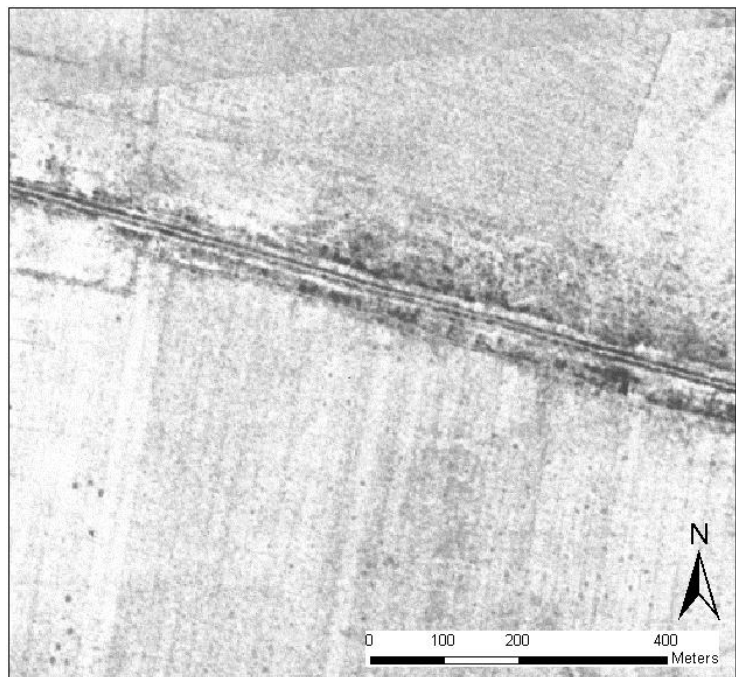


Figure 40. Example of a modern canal following the path of an ancient one.

roughly round features which appear darker but do not seem to have any relief. While these may be areas where anthropogenic soil modification has resulted in higher moisture retention, they could also just be low areas where water tends to collect. In many areas they are immediately adjacent to a canal, which could support two opposing possibilities. First, that they are more likely to receive water frequently, thus contributing to their darkened color. Second, that they are indeed traces of earlier settlement, which was common along waterways. Because they generally do not have very distinct edges and their exact nature is not readily apparent, they were not counted.

Identification of Canals

The identification of canals on the landscape was a fairly straightforward and unproblematic task. In the previous section, the appearance of canals on the landscape was discussed. For the most part, ancient canals appear as fairly wide, linear features that are darker than the surrounding soils. Canals in use at the time the CORONA imagery was acquired are typically characterized by narrower, better defined linear features. Figure 40 shows a modern canal following the same course as an ancient one, where the wider ancient channel is superimposed by the narrow light-dark-light modern waterway. Care was taken to select only those canal features which are ancient in origin, although many modern canals follow the same paths.

Figure 41 shows the network of ancient canals as seen on CORONA. The canals discovered by Adams (1965) are shown for comparison. The Adams canals line up nicely with those which appear on CORONA, but CORONA has provided a far more complete picture of the

ancient network of waterways in the study area. For this particular application, CORONA has demonstrated its great utility.

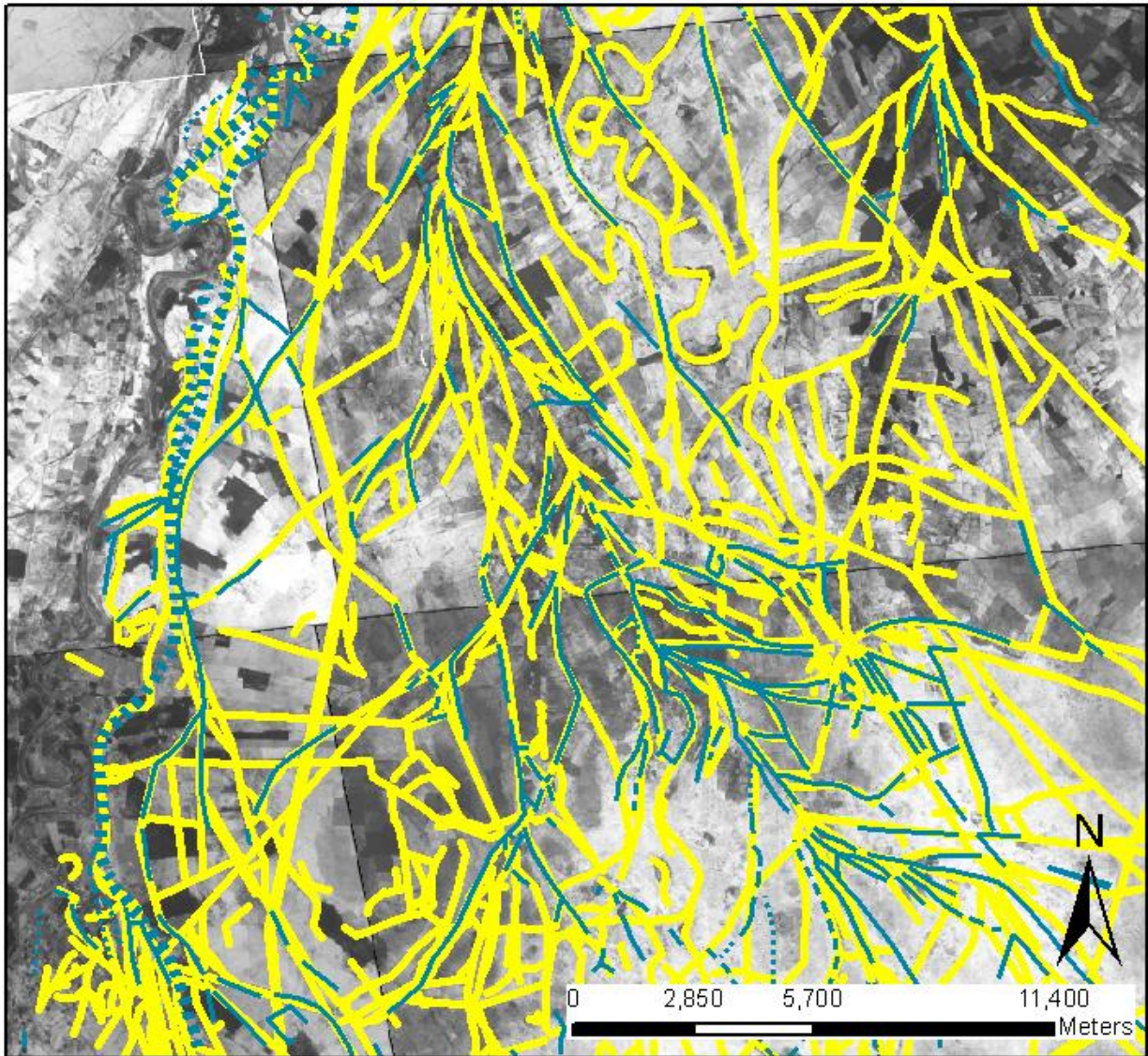


Figure 41. Network of ancient canals (in yellow) discovered on CORONA imagery. Adams (1965) canals in blue for comparison.

Identification of Settlement Sites

The identification of ancient settlements had mixed results. As digital elevation models were not available, reliance on visual detection was necessary. Many areas where Adams (1965) indicated the presence of sites did not show evidence on CORONA. For example, the site of Tell Abu Ja'ari (Figure 42), an extensive settlement to the southeast of Tell Asmar, was very difficult to interpret from the satellite imagery. There are very few features that appear as tells. Numerous

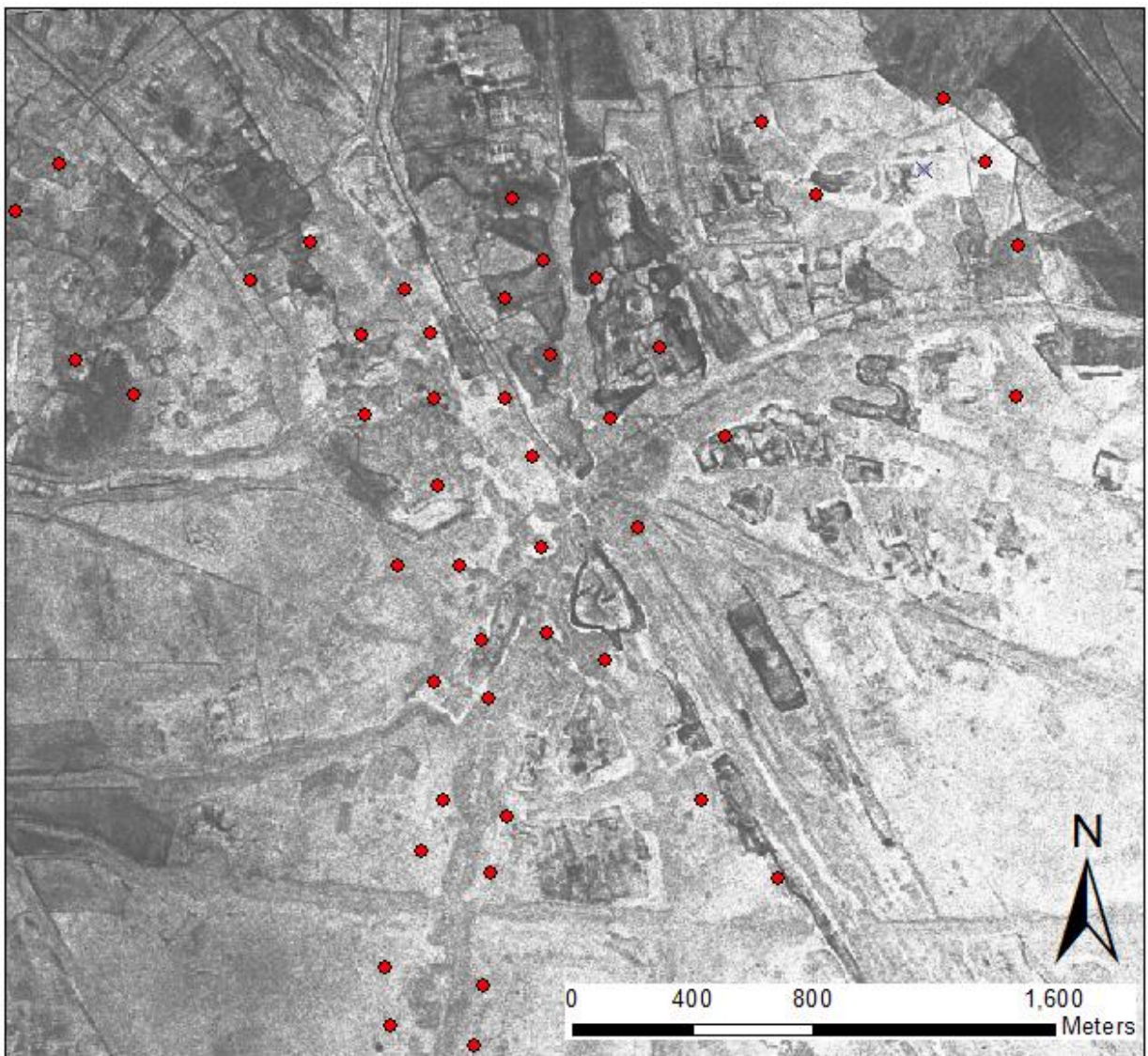


Figure 42. Tell Abu Ja'ari. Sites indicated by Adams (1965) appear in red.

roughly rectilinear features appear, but their exact nature is not readily discernible. Many of them appear to be associated with waterways or resemble agricultural fields which encroach upon this area from the west. There is no record of excavation in the literature, so it is difficult to determine if any of the features are remnants thereof. While they could be evidence of settlement, there is not enough information to accurately determine its boundaries.

Tell Asmar itself (Figure 43), the site of the ancient city of Eshnunna, presented its own problems. Although tells are apparent here (lower three arrows), there are other places where

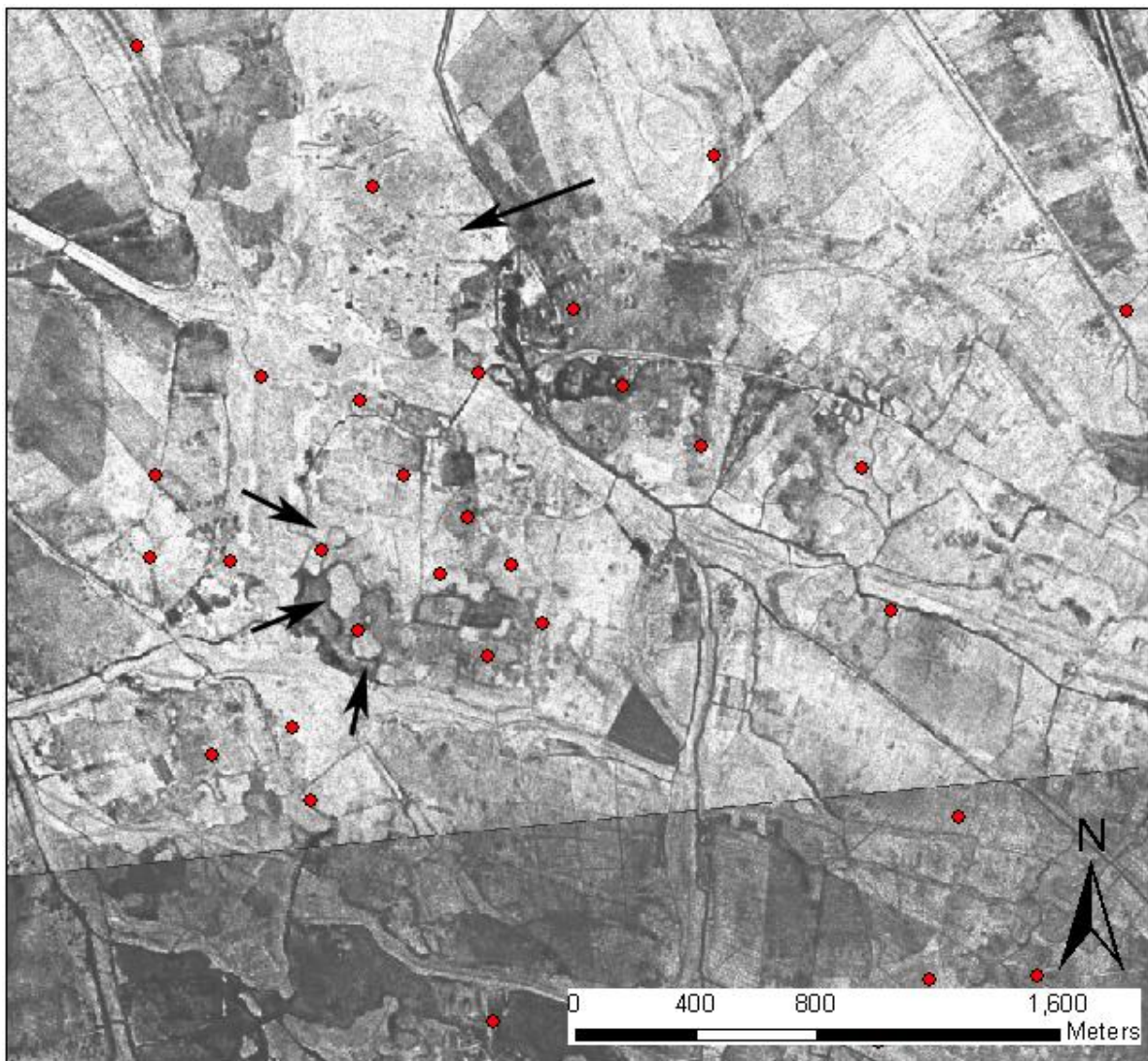


Figure 43. Tell Asmar, site of the ancient city of Eshnunna. Sites indicated by Adams (1965) are in red.

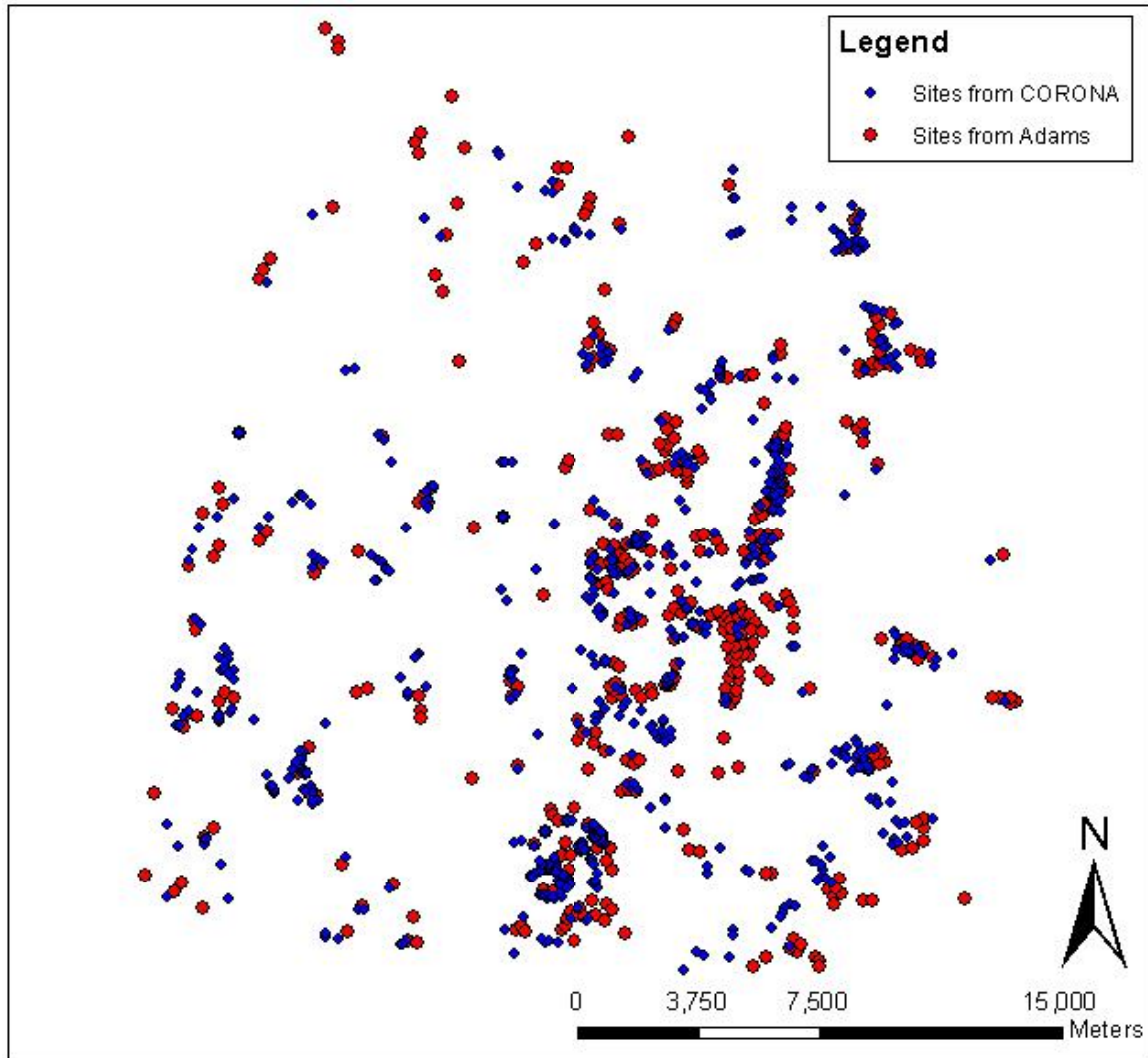


Figure 44. All sites in the study area, from both Adams (1965, red points), and this study as visible on CORONA imagery (blue points).

interpretation was more challenging. The upper arrow indicates an area in which some rectilinear features appear, yet it is uncertain what they represent. They do appear on the later ALI imagery, but more faintly. Though it had been over 30 years between the excavation of Tell Asmar and the acquisition of the CORONA imagery, it is possible these features are remnants of that project. An aerial photograph of the 1931-1932 field season (see Figure 2 in Frankfort 1933, not reproduced here due to copyright) clearly shows structures built to assist with excavation which are identical to those found on the CORONA imagery.

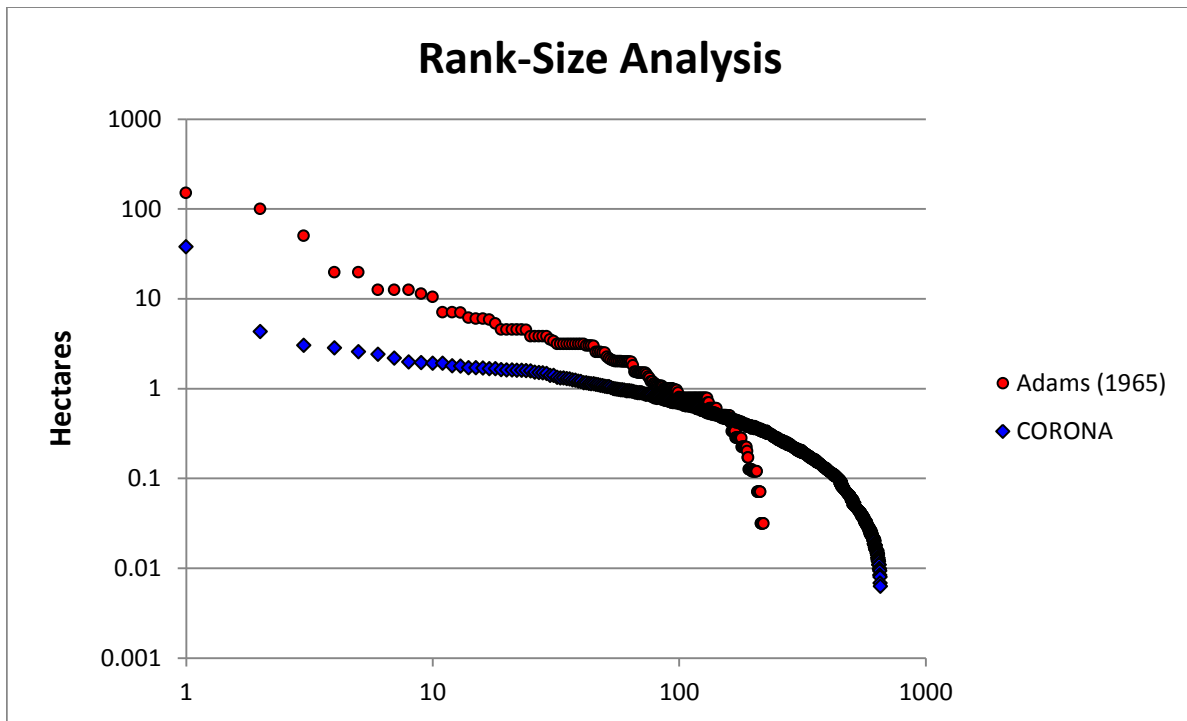


Figure 45. Rank-size curve for Adams (1965) and CORONA sites.

These difficulties with identifying sites and correlating them to the sites Adams (1965) describes are based in part on the definition of what a site is. In some cases, Adams represents a group of tells as clusters of points, but for some of them it is not clear whether they are separate sites or simply parts of a single large one. Conversely, what was identified as a single large site on CORONA may in fact be several smaller sites that appear as one large feature. In addition, Adams does not assign numbers to all points on the maps, so it is impossible to determine how they fit into the larger landscape.

In total, there were 393 sites in the study area described by Adams (1965). Visual inspection of the CORONA imagery has yielded 655 probable sites (Figure 44). While in most cases it was impossible to determine one-to-one associations among them, many of the CORONA-derived sites are in close proximity to individual or clusters of sites discovered by Adams. In many cases, alignments or groupings of Adams' sites are mirrored and, in some cases,

extended. The number of sites discovered on CORONA is probably less than actually exist, as in cases where doubt existed, selections were made conservatively.

Examining the relationship among sites and canals, a clear trend is evident (Table 5) that sites are more likely to be located near sources of water. Although Adams' survey method favored sites within proximity of canals, the question arose as to how many sites were missed because they were not close enough. During this project, there was a pointed effort made to locate sites away from canals, but the vast majority was within 500 m. Thus, while the Adams survey method was not theoretically sound in this respect, it was not likely to miss many sites.

A rank-size analysis (Figure 45) was performed. A total of 221 Adams (1965) sites were used for this comparison, the areas determined from Adams' site descriptions. In many cases, estimates were made from the information available, but it is likely that some or even most of these values are overstated, as maximum extents and diameters were provided in the text. In numerous instances, single site location points on the Adams map corresponded to multiple areas of former settlement on the ground, and the best attempt was made to derive accurate figures for the areas of multiple smaller sites instead of combining them into one larger site. Thus, the 221 data points do not correspond to the same number of site locations represented by them on the Adams map.

Assuming the rank-size analysis is accurate, the CORONA imagery is better capable of finding smaller sites compared to Adams' survey methods. This is demonstrated both by the relative proportion of site size as well as the detection of absolutely smaller sites by using

Distance (m)	<i>n</i>
0-100	247
101-200	174
201-300	116
301-400	50
401-500	24
501-600	10
601-700	4
701-800	3
801-900	4
901-1000	1

Table 5. Distance between sites and nearest canal. *n* = 633.

CORONA. Because smaller tells have a fairly consistent shape and appearance on CORONA, they are, for the most part, readily identifiable. However, the imagery is not as useful for finding large, poorly defined sites such as Tell Abu Jacari.

Conclusions

In general, the goals of this project were successfully attained. Using a widely available software application, the LPS package for ERDAS Imagine, the CORONA imagery, known for its heavy distortion, was successfully corrected using free and publicly available Google Earth imagery. The ability to make these corrections without camera ephemeris data or reliance on complex mathematical algorithms extends the utility of CORONA imagery to a wide group of archaeologists and professionals.

One goal which was not met was the generation of accurate digital elevation models from the stereo pairs of CORONA photographs. As there has been success with this endeavor in other projects (for example, Altmaier and Kany 2002; Casana and Cothren 2008), it is believed that the lack of sufficient topographic relief as well as poor image contrast have both contributed to this result. Further work is needed to determine whether this issue persists in other areas of low topographic relief, as the availability of high-resolution DEMs would greatly enhance the process of discovering low-relief sites and landscape features. Using CORONA imagery acquired at different times may provide better contrast and feature expression. In addition, increasing the number of manually selected tie points may allow for better image matching in the photogrammetry software. Furthermore, different approaches to preprocessing the images may be able to enhance feature details, facilitating better matching by the software.

The corrected images were successfully used to produce a geographically accurate map of probable site locations, although this process did not lack in challenges. The presence of infrastructure and development in some locations within the study area presented some difficulty to determining what distinguishing characteristics reflected archaeological sites. Because of these challenges and the decision to make selections conservatively, it is likely that many additional sites remain unrecorded. It would be useful to visit the sites detected on CORONA to refine this method by verifying discovered sites and further defining their distinguishing characteristics, as well as eliminating those characteristics likely to produce a false positive.

CORONA provided an excellent resource for locating canal and levee features. The long, linear shapes appear readily in most areas and their continuous nature allows for less error locating them. To avoid identifying modern canals, care was made to select only canals that have fairly wide levees. In some cases, modern canals follow the same routes as ancient ones, and in such cases only those segments where the ancient levees were clearly visible were selected. The canal network discovered on CORONA closely aligns with the canals presented by Adams (1965) and greatly extends them. There was also a clear correlation between sites and the presence of canals; few sites were found that were more than 500 m away from a water source.

Although a few linear alignments of sites are apparent in the results, the very long alignments described by Adams (1965) are beyond the scope of the study area. In addition, it was not possible to correlate CORONA-derived sites to Adams sites in order to get dating information to test the alignment-dating hypothesis discussed in the introduction. Building upon this project to cover the entire *Land Behind Baghdad* survey area would provide the necessary scope to do so, but the poor geographic control of the Adams maps will make it extremely difficult to correlate sites.

For places in the world where ground-based survey is physically impossible or politically unlikely, CORONA imagery has demonstrated its great worth and makes an important contribution to the toolbox of archaeologists. Its improved application will require a period of ground-truthing so that questionable features appearing on the imagery can be positively identified, but once this has been accomplished it is likely that CORONA will be able to serve as a standalone survey method.

VI. REFERENCES

- Adams, Robert McCormick. 1965. *Land Behind Baghdad: a History of Settlement on the Diyala Plains*. Chicago: University of Chicago Press.
- . 1981. *Heartland of Cities : Surveys of Ancient Settlement and Land Use on the Central Floodplain of the Euphrates*. Chicago: University of Chicago Press.
- Altaweel, Mark. 2005. “The Use of ASTER Satellite Imagery in Archaeological Contexts.” *Archaeological Prospection* 12 (3): 151–166. doi:10.1002/arp.254.
- Altmaier, A., and C. Kany. 2002. “Digital Surface Model Generation from CORONA Satellite Images.” *ISPRS Journal of Photogrammetry and Remote Sensing* 56 (4): 221–235.
- Banning, Edward Bruce. 2002. *Archaeological Survey*. New York: Springer.
- Bayram, B., H. Bayraktar, C. Helvacı, and U. Acar. 2004. “Coast Line Change Detection Using Corona, SPOT and IRS-1D Images.” In *XXth Congress of the International Society for Photogrammetry and Remote Sensing (Istanbul, Turkey), Commission VII, WG VII/3*, 437–441.
- Beck, A., G. Philip, M. Abdulkarim, and D. Donoghue. 2007. “Evaluation of Corona and Ikonos High Resolution Satellite Imagery for Archaeological Prospection in Western Syria.” *Antiquity* 81 (311): 161–175.
- Blom, R., J. Zairins, N. Clapp, and G. R Hedges. 1997. “Space Technology and the Discovery of the Lost City of Ubar.” In , *IEEE Aerospace Conference, 1997. Proceedings*, 1:19–28 vol.1. IEEE. doi:10.1109/AERO.1997.574258.
- Casana, Jesse. 2003. “From Alalakh to Antioch: Settlement, Land Use, and Environmental Change in the Amuq Valley of Southern Turkey”. Ph.D. Dissertation, Chicago: University of Chicago.
- . 2007. “Structural Transformations in Settlement Systems of the Northern Levant.” *American Journal of Archaeology* 111 (2): 195–221.
- . 2008. “Mediterranean Valleys Revisited: Linking Soil Erosion, Land Use and Climate Variability in the Northern Levant.” *Geomorphology* 101 (3): 429–442.
- Casana, Jesse, and Jackson Cothren. 2008. “Stereo Analysis, DEM Extraction and Orthorectification of CORONA Satellite Imagery: Archaeological Applications from the Near East.” *Antiquity* 82 (317): 732–749.
- Casana, Jesse, and Tony J. Wilkinson. 2005. “Settlement and Landscapes in the Amuq Region.” In *The Amuq Valley Regional Projects, Vol. 1: Surveys in the Plain of Antioch and Orontes Delta, Turkey, 1995-2002*, ed. Kutlu Aslihan Yener, 25–65. Oriental Institute Publications 131. Chicago: Oriental Institute of the University of Chicago.

- Challis, Keith, Gary Priestnall, Adam Gardner, Julian Henderson, and Sarah O'Hara. 2004. "Corona Remotely-Sensed Imagery in Dryland Archaeology: The Islamic City of al-Raqa, Syria." *Journal of Field Archaeology* 29 (1/2): 139–153.
- Cole, Steven W., and Hermann Gasche. 1998. "Second- and First-Millennium BC Rivers in Northern Babylonia." In *Changing Watercourses in Babylonia: Towards a Reconstruction of the Ancient Environment in Lower Mesopotamia*, ed. Hermann Gasche and Michel Tanret, 1:1–64. Ghent: Univeristy of Ghent.
- Custer, Jay F., Timothy Eveleigh, Vytautas Klemas, and Ian Wells. 1986. "Application of LANDSAT Data and Synoptic Remote Sensing to Predictive Models for Prehistoric Archaeological Sites: An Example from the Delaware Coastal Plain." *American Antiquity* 51 (3): 572–588. doi:10.2307/281753.
- Day, D.A., J.M. Longson, and B. Latell, eds. 1998. *Eye in the Sky: The Story of CORONA Spy Satellites*. Wasihington, DC: Smithsonian Institution Press.
- Donoghue, D.N.M., and I. Shennan. 1987. "Remote Sensing of Morton Fen, Lincolnshire: Summary of Recent Work." *Fenland Research* 4: 46–53.
- Edgell, H. Stewart. 2002. "Shuttle Imaging Radar Scenes of the Legendary Arabian Lost City of Ubar and the Reality of Ubar." In *Annual Meeting of the Geological Society of America*. Denver, CO.
- Fowler, M. J. F. 2004a. "Declassified CORONA KH-4B Satellite Photography of Remains from Rome's Desert Frontier." *International Journal of Remote Sensing* 25 (18): 3549–3554. doi:10.1080/0143116031000098887.
- Fowler, M. J.F. 2004b. "Archaeology Through the Keyhole: The Serendipity Effect of Aerial Reconnaissance Revisited." *Interdisciplinary Science Reviews* 29 (2): 118–134.
- Frankfort, Henri. 1933. *Tell Asmar, Khafaje and Khorsabad: Second Preliminary Report of the Iraq Expedition*. Oriental Institute Communications 16. Chicago: University of Chicago Press. <http://oi.uchicago.edu/research/pubs/catalog/oic/oic16.html>.
- Galiatsatos, Nikolaos. 2004. "Assessment of the CORONA Series of Satellite Imagery for Landscape Archaeology: a Case Study from the Orontes Valley, Syria". Ph.D. Thesis, Durham, U.K.: University of Durham.
- Galiatsatos, Nikolaos, Daniel N. M. Donoghue, and Graham Philip. 2008. "High Resolution Elevation Data Derived from Stereoscopic CORONA Imagery with Minimal Ground Control: An Approach Using IKONOS and SRTM Data." *Photogrammetric Engineering and Remote Sensing* 74 (9): 1093–1106.
- Gasche, Hermann, Michel Tanret, Steven W. Cole, and Kris Verhoeven. 2002. "Fleuves Du Temps Et De La Vie: Permanence Et Instabilité Du Réseau Fluvial Babylonnien Entre 2500 Et 1500 Avant Notre Ère." *Annales: Histoire, Sciences Sociales* 57 (3): 531–544.

- Gerster, Georg, and Charlotte Trümpler. 2005. *The Past from Above: Aerial Photographs of Archaeological Sites*. Los Angeles: Getty Publications.
- Goossens, R., A. De Wulf, J. Bourgeois, W. Gheyle, and T. Willems. 2006. "Satellite Imagery and Archaeology: The Example of CORONA in the Altai Mountains." *Journal of Archaeological Science* 33 (6): 745–755.
- Heyvaert, Vanessa Mary An, and Cecile Baeteman. 2008. "A Middle to Late Holocene Avulsion History of the Euphrates River: a Case Study from Tell ed-Der, Iraq, Lower Mesopotamia." *Quaternary Science Reviews* 27 (25-26): 2401–2410.
- Hritz, Carrie A. 2006. "The Changing Mesopotamian Landscape as Seen from Spot and Corona Images." In *GIS and Archaeological Site Location Modeling*, ed. Mark W. Mehrer and Konnie L. Wescott, 413–436. Boca Raton, FL: Taylor & Francis.
- . 2010. "Tracing Settlement Patterns and Channel Systems in Southern Mesopotamia Using Remote Sensing." *Journal of Field Archaeology* 35 (2): 184–203.
- Jacobsen, Karsten. 2008. "Geometric Modelling of Linear CCDs and Panoramic Imagers." In *Advances in Photogrammetry, Remote Sensing and Spatial Information Sciences*, ed. Zhilin Li, Jun Chen, and Emmanuel Baltsavias, 145–155. Leiden: CRC Press.
- Jacobsen, T., and R. M Adams. 1958. "Salt and Silt in Ancient Mesopotamian Agriculture." *Science* 128 (3334): 1251–1258.
- Kennedy, D. 1998. "Declassified Satellite Photographs and Archaeology in the Middle East: Case Studies from Turkey." *Antiquity* 72 (277): 553–561.
- Kouchoukos, N. 2001. "Satellite Images and Near Eastern Landscapes." *Near Eastern Archaeology* 64 (1-2): 80–91.
- Menze, B. H, J. A. Ur, and A. G. Sherratt. 2005. "Tell Spotting-surveying Near Eastern Settlement Mounds from Space." In *Proceedings of the CIPA International Symposium, Torino*.
- De Meyer, Mathieu. 2004. "Archaeological Research Using Satellite Remote Sensing Techniques (CORONA) in the Valleys of Shirwan and Chardawal (Pusht-i Kuh, Luristan), Iran." *Iranica Antiqua* 39: 43–103. doi:10.2143/IA.39.0.503892.
- van de Mierop, Marc. 2007. *A History of the Ancient Near East: Ca. 3000-323 BC*. Malden, MA: Blackwell.
- Morozova, Galina S. 2005. "A Review of Holocene Avulsions of the Tigris and Euphrates Rivers and Possible Effects on the Evolution of Civilizations in Lower Mesopotamia." *Geoarchaeology* 20 (4): 401–423. doi:10.1002/gea.20057.
- National Reconnaissance Office. 1967. *The KH-4B Camera System*. National Photographic Interpretation System.

- Parcak, Sarah H. 2007. "Satellite Remote Sensing Methods for Monitoring Archaeological Tells in the Middle East." *Journal of Field Archaeology* 32 (1): 65–81.
- . 2009. *Satellite Remote Sensing for Archaeology*. New York: Routledge.
- Philip, G., D. Donoghue, A. Beck, and N. Galiatsatos. 2002. "CORONA Satellite Photography: An Archaeological Application from the Middle East." *Antiquity* 76 (291): 109–118.
- Potere, David. 2008. "Horizontal Positional Accuracy of Google Earth's High-Resolution Imagery Archive." *Sensors* 8 (12): 7973–7981. doi:10.3390/s8127973.
- Pournelle, Jennifer. 2003a. "The Littoral Foundations of the Uruk State: Using Satellite Photography Toward a New Understanding of 5th/4th Millennium BCE Landscapes in the Warka Survey Area, Iraq." In *Chalcolithic and Early Bronze Age Hydrostrategies: Papers Held at the International Union of Prehistoric and Protohistoric Science 2001 Congress, Liège*, ed. Dragos Gheorghiu, 5–23. BAR International Series 1123. Oxford: Archaeopress.
- . 2003b. "Marshland of Cities : Deltaic Landscapes and the Evolution of Early Mesopotamian Civilization". Ph.D. Dissertation, University of California, San Diego.
- Redman, C. L. 1982. "Archaeological Survey and the Study of Mesopotamian Urban Systems." *Journal of Field Archaeology* 9 (3): 375–382.
- Richason, Benjamin F., and Carrie Hritz. 2007. "Remote Sensing and GIS Use in the Archaeological Analysis of the Central Mesopotamian Plain." In *Remote Sensing in Archaeology*, ed. James Wiseman and Farouk El-Baz, 283–325. New York: Springer.
- Rowton, Michae. 1969. "The Role of Watercourses in the Growth of Mesopotamian Civilization." In *Lisan Mithurti : Festschrift, Wolfram Freiherr Von Soden Zum 19.4.1968*, ed. Wolfram von Soden, Manfred Dietrich, and Wolfgang Rollig, 307–316. *Alter Orient Und Altes Testament* 1. Kevelaer: Butzon & Bercker.
- Sherratt, Andrew. 2004. "Spotting Tells from Space." *Antiquity* 78 (301). <http://www.antiquity.ac.uk/projgall/sherratt301/>.
- Sohn, Hong-Gyoo, Gi-Hong Kim, and Jae-Hong Yom. 2004. "Mathematical Modelling of Historical Reconnaissance CORONA KH-4B Imagery." *The Photogrammetric Record* 19 (105): 51–66. doi:10.1046/j.0031-868X.2003.00257.x.
- Ur, Jason. 2003. "CORONA Satellite Photography and Ancient Road Networks: a Northern Mesopotamian Case Study." *Antiquity* 77 (295): 102–115.
- . 2005. "Sennacherib's Northern Assyrian Canals : New Insights from Satellite Imagery and Aerial Photography." *Iraq* 67 (1): 317–345.

- Verhoeven, Kris. 1998. "Geomorphological Research in the Mesopotamian Flood Plain." In *Changing Watercourses in Babylonia: Towards a Reconstruction of the Ancient Environment in Lower Mesopotamia*, 1:159–245. Ghent: Univeristy of Ghent.
- Wilkinson, Keith N., Anthony R. Beck, and Graham Philip. 2006. "Satellite Imagery as a Resource in the Prospection for Archaeological Sites in Central Syria." *Geoarchaeology* 21 (7): 735–750. doi:10.1002/gea.20136.
- Wilkinson, Tony J. 2000a. "Regional Approaches to Mesopotamian Archaeology: The Contribution of Archaeological Surveys." *Journal of Archaeological Research* 8 (3): 219–267.
- . 2000b. "Archaeological Survey of the Tell Beydar Region, Syria, 1997: A Preliminary Report." In *Tell Beydar: Environmental and Technical Studies*, 1–37. Subartu VI. Turnhout, Belgium: Brepols.
- . 2003. *Archaeological Landscapes of the Near East*. Tuscon, AZ: University of Arizona Press.