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### 3 From the River to the Fields

#### The Contribution of Micromorphology to the Study of Hydro-Agrosystems in Semi-Arid Environments (Phoenix, Arizona)

*Louise Purdue*

##### **Abstract**

This chapter presents a field and laboratory approach for better understanding human-environment interactions in past agricultural societies in semi-arid environments. The field approach aims at studying the formation and evolution of anthropic landscapes based on a geomorphic approach to fluvial dynamics, combined with the geoarchaeological study of irrigation systems, considered as anthropic and environmental structures, and connected agricultural fields. To frame these dynamics chronologically and provide a more precise description of environmental and social dynamics (e.g., dynamics of deposition, flooding events, vegetation cover, fire regime, slash and burn, manuring), systematic sampling for chronology and soil analysis (micromorphology) is conducted in these three connected environments. The selection, description, and quantification of markers in soil thin sections allows for the statistical classification of past dynamics, interpreted based on historical or current references. The multiplication of local studies is key to documenting large-scale socioenvironmental dynamics, which can then be juxtaposed with climatic, archeological, and demographic data. This approach is illustrated through the socioenvironmental study of the hydrosystem of the Salt River in the semi-arid Phoenix Basin (Arizona) and the Hohokam irrigated agrosystem. This case study demonstrates how the field and micromorphological study of two irrigation canals and intertwined fluvial deposits at the headgates of one of the largest canal systems, Canal System 1, in use from the seventh to the fifteenth century A.D., provides vital information about past water management and land use as well as fluvial regime and climate change.

##### **Introduction: State of the Art and Objectives**

Water management has contributed to the construction and organization of human communities since the emergence of the first agricultural societies. Societies have built water systems for food production, energy, industry, transport, and/or commerce purposes, and they have dealt with water

resources facing the combined effects of social (water need) and environmental constraints (water availability and capacity). As a result, the evolution of water availability and allocation strategies through time and its impact on cultural shifts is a socioenvironmental question necessarily raised by researchers. Approaches to the study of water systems and irrigation communities have traditionally revolved around the fields of theoretical anthropology (e.g., Wittfogel 1957; Mitchell 1973; Netting 1974; Service 1975), ethnography (Hunt and Hunt 1973; Lees 1973; Downing and McGuire 1974; Hunt and Hunt 1976), social history (e.g., Glick 1996; Nabhan 1986), and spatial archaeology (e.g., Gentelle 1980; Bruins et al. 1986; Francfort and Lecomte 2002; Mouton 2004; Ortloff 2009). In parallel, researchers have developed high-resolution tools to study water networks, such as geomatics and geophysics (e.g., Jones et al. 2000; Powlesland et al. 2006; Keay et al. 2009), as well as aerial and satellite imagery (e.g., Sanders 1982; Fowler 2002; Pournelle 2003; Wilkinson 2003; Clarke et al. 2005), and have adapted new approaches from such fields as environmental history (e.g., Crook et al. 2008), geography and geomorphology (e.g., Marcolongo and Morandi Bonacossi 1997; Harrower 2006), and hydrology (e.g., Orengo and Alaix 2013).

These various approaches and methods have allowed for the study of water systems on the one hand (water management and related social structures) and water networks on the other (spatial structure and links with the landscape and river systems). To understand past agricultural communities, it is necessary to reconstruct the environment they lived in, adapted to, and modified through time. The agrarian landscape they built, which is defined by agricultural practices and production, has evolved over the long term under the influence of climatic fluctuations and human activity. Some recent large interdisciplinary projects have focused on the interaction between climate, water management, and human adaptation (e.g., *Long Term Vulnerability and Transformation Project* coordinated by M. Nelson (cf. Nelson et al. 2010)). However, the study of ancient water systems themselves, as signatures of both the agrosystem and the hydrosystem, is still scarce. These systems are rarely considered as objects which can be studied at various spatial and temporal scales and connected to agricultural fields and practices, as well as local and micro-regional geomorphic changes (e.g., Wilkinson 1998; Berger 2000; Beach et al. 2009; Purdue 2011; Bernigaud 2012).

To reconstruct the dynamic interplay (phases of stability and instability) between the agrosystem and the hydrosystem, diachronically and synchronically, it is necessary to reconstruct fluvial dynamics, irrigation canal function and management, and agricultural practices. This chapter presents an overview of how to study these three connected dynamics and their interactions based on a systematic field geomorphic, geoarchaeological, agronomic, and archaeological approach refined by laboratory analysis. Chronological control is necessary to understand the temporalities of fluvial dynamics and water and soil management, but I focus here more specifically on the

geoarchaeological and micromorphological approach. Micromorphology is the description of soils at a microscopic scale, based on the interpretative concepts of petrography and pedology (Kubiěna 1938; Brewer and Sleeman 1960; Bal 1973; Bullock et al. 1985; Fédoroff and Courty 1994; Stoops 2003) and is considered as one of the major tools for understanding landscape evolution when correlated with other environmental analyses (Gebhardt 2000). Micromorphology has been used widely in semi-arid fluvial environments, where research has mainly focussed on paleoenvironmental and climatic issues (e.g., Courty 1990; Fédoroff and Courty 1989; 1999; Courty and Fédoroff 1999; Singhvi and Derbyshire 1999). In agrarian contexts, micromorphology has aimed at understanding the properties of cultivated soils (e.g., Courty and Fédoroff 1985; Mathieu and Ruellan 1987; Courty 1990; Verba et al. 1995; Hallaire et al. 1998; Lebedeva-Verba and Gerasimova 2009); these studies often serve as references for recognition of past agricultural practices (e.g., Courty 1990; Verba et al. 2002; Presley et al. 2004) and estimate the impact of long-term agriculture on current soil properties (e.g., Wilson et al. 2002; Goodman-Elgar 2007; 2008; Sandor et al. 2007). The micromorphological study of hydraulic structures, in contrast, is nearly nonexistent in arid environments (Purdue et al. 2010; Purdue 2011) and very rare in temperate environments (e.g., Gebhardt 1988; 1993; Courty 1990; Leroyer and Krier 1991; Berger 2000). The combination of signatures of human practices (canal cleaning, slash and burn, irrigation practice, manuring) and hydroclimatic dynamics (flow, sediment origin, erosion processes, sedimentary load, flood regime, water supply, vegetation development, fire regime) has rarely been used.

This approach and method will be highlighted through the example of Hohokam irrigation systems in the Phoenix Basin in central Arizona. Possibly continuing and elaborating upon a tradition previously established by early agricultural groups, the prehistoric Hohokam people were dependent upon and more or less adapted to arid environmental conditions, especially fluvial dynamics. To survive, they built major irrigation systems as early as A.D. 100 (Henderson 1989), which persisted until A.D. 1450 (Haury 1976; Doyel 1979; Gumerman 1991). Their chronology is articulated around the Formative Period (A.D. 1–600), the Pioneer Period (A.D. 600–750), the Pre-classic Period (A.D. 750–1150), and the Classic Period (A.D. 1150–1450). Both social and environmental hypotheses have been put forward to explain these cultural shifts: warfare (LeBlanc 1999) and overpopulation (Ensor et al. 2003) on the one hand, and droughts and floods (Nials et al. 1986; Gregory 1991; Huckleberry 1999; Waters and Ravesloot 2001) or channel metamorphosis and widening/downcutting events (Waters and Ravesloot 2001; Graybill et al. 2006) on the other. The cause of the “collapse,” however, is still in debate. A case study (Riverview at Dobson, AZ U:9:135 (ASM)) in Mesa, Arizona, provides an example of how environmental surroundings, fluvial dynamics, and human adaptation can be understood at a local scale to help answer these socioenvironmental questions.

## Approach and Methods

### *The Field Approach*

To understand the interactions between the hydrosystem, water systems, and the agrosystem in the field, various spatial and temporal scales should be considered (i.e., geomorphic unit per system, per canal, and per stratigraphic unit; and phases of stability or cultural shift) (Chouquer and Favory 1991; Chouquer 2000). The field approach requires three steps: (1) First, it is necessary to reconstruct the current and past environmental framework based on a topographical, hydrological, and geomorphological study of alluvial archives, which allows for the understanding of lateral and vertical river dynamics through time (aggradation, incision, fluvial migration); (2) Second, hydraulic networks can be studied from a geoarchaeological perspective. Fossil traces are identified and mapped using aerial photographs or historic maps, for instance. Transversal or longitudinal crosscuts of hydraulic features allow the reconstruction of episodes of canal construction and abandonment and the link between these temporalities and the dynamics of the hydrosystem. Indeed, canals are often filled with clastic or geochemical sediments which record paleoecological dynamics (Bertrand 1975) as well as local and regional hydrosedimentary dynamics ranging from short-term events (storms, floods, vegetation development) to long-lasting environmental shifts (fluvial metamorphosis, incision, soil erosion) (Berger 2000). The major limits in the geoarchaeological study of canals are, first, their regular maintenance that removes sedimentary information and, second, the hierarchy of water systems, with headgates acting like sedimentary filters. This approach therefore requires diachronic and synchronous systematic studies; (3) Last, it is possible to identify and study cultivated deposits (more easily discernible towards the terminal end of the network) which are fed with water and sediments from adjacent hydraulic structures. The color, texture, structure, and inclusions in cultivated deposits are a reflexion of human practices as well as the dynamics, management, and efficiency of the irrigation system.

Traditionally, numerous samples for paleoenvironmental studies and chronology are collected in these three environments of study. Sherds recovered in irrigation canals, if well preserved, can provide a more or less precise period of construction or use. However, it is usually necessary to derive radiocarbon dates from organic material. Datable materials from the base of hydraulic structures can provide a date of construction, while datable material from upper fills corresponds to abandonment. Chronological assessments related to each episode of visible maintenance and natural erosion are also crucial. Alternative methods, such as OSL dating, can be adopted (Berger 1986). The period of use of the connected agricultural fields can be estimated based on chronostratigraphy, and numerous sherds are traditionally encountered in this environment. Fluvial deposits should also be dated,

by radiocarbon, or OSL when organic material is scarce. Bulk sediment samples in these three environments will allow pursuit of paleoenvironmental studies, such as paleobotanical studies, ostracodes, and diatoms (Palacios-Fest 1994; Palacios-Fest et al. 2001), and soil studies, such as grain size and geochemical analyses. Micromorphology is much less commonly employed in such contexts, but can be used to distinguish events not visible through more common methods (fire signals, origin of the sediments, etc.) (Gebhardt 1988; Leroyer and Krier 1991; Berger 2000).

### *The Micromorphological Approach*

#### *Sampling Strategy, Processing, and Study Protocol*

When simultaneously studying fluvial deposits, sediments that fill hydraulic structures, and associated agricultural fields, there are various lines of inquiry which allow one to understand past socioenvironmental dynamics such as sedimentary, pedological, ecological, and anthropic processes. To properly understand these processes, micromorphological sampling is usually continuous in every deposit studied or discontinuous within homogeneous units (Courty et al. 1990). Blocks of  $12 \times 6 \times 6$  cm are sampled and wrapped in plaster bands and manila paper to protect them. The samples are then processed according to P. Guilloiré's (1983–1987) method. Thin sections are observed with the naked eye, under a binocular, and last under an optical microscope with plane polarized light, cross-polarized light, and incident light for the description of microfabric and microfacies (Goldberg and McPhail 2006).

#### *Topics of Enquiry in Fluvial Deposits, Canal Fills, and Agricultural Fields*

Sedimentological, pedological/pedoclimatical, ecological and anthropic processes have their own signatures—markers that enable differentiation and possible interpretation (cf. Table 3.1). When reconstructing sedimentary processes, we aim at understanding the environment of deposition (e.g., alluvial, eolian), the fluvial dynamic (e.g., flooding event, water stagnation, and rhythmic sedimentation), the origin of the sediments, and their hydroclimatic significance. Pedological and pedoclimatical studies include rhythm in sedimentation, episodes of water stagnation, evaporation, and presence of salts. The type of data selected are the microstructure (size, form, and arrangement of aggregates and grains), soil crusts (Evans and Buol 1968; Chen et al. 1980; Bresson and Valentin 1994), and three pedological features: biological features (Courty 1994), textural features, and crystalline features such as oxidation and reduction processes or the accumulation and depletion of carbonated/gypsum/salt crystals (e.g., Sehgal and Stoops 1972; Monger et al. 1991; Courty 1994). Investigations of ecological dynamics

include the presence of vegetation and its type, origin, and impact on water level and flow, which provides information on the local to regional vegetation cover, processes of erosion with the deposition of decayed plant matter, and also on the in situ plant growth and its kind (e.g., characeae, cyperaceae). Charcoals are also very relevant as they provide information about regional or local fire regimes (including slash and burn cultivation), its intensity, and the type of vegetation burned. Shells and ostracodes provide signatures of typical water temperature and salinity, while the presence of excremental pellets is indicative of a well-aerated soil, specific humidity, and biological activity (Courty 1990). Lastly, human activities identified at the microscopic scale correspond to signatures of irrigation, slash and burn, tillage, and structures to protect hydraulic features. To identify these specific activities, micromorphologists traditionally study soil structure, porosity, organic matter, illuviation processes (coatings, e.g., Pal et al. 2003) and surface crusts (e.g., Bresson and Valentin 1994), and crystalline features (iron, carbonates, gypsum) (e.g., Alonso et al. 2004).

#### *Data Quantification, Processing, and Interpretation*

Qualitative descriptions are often used when thin sections are sampled to answer a specific question. However, in the context of systematic sampling, some quantification is necessary. The chart of semi-quantification proposed by Fitzpatrick in 1980 or the semi-quantification proposed by Harden (1982) and Dorronsoro (1994), which assigns a value of 1 to 100 (multiple of 10) to each interval of proportion or size, can be used on well-identified markers to identify large trends. Markers can also be described based on their presence or absence. Due to the subjectivity of these approaches, it may be preferable to quantitatively describe markers, e.g., by point counting (Eswaran 1968; Murphy and Kemp 1987; Amonette 1994) or by image analysis (e.g., Purdue 2011 for grain size studies).

Once all these markers are described, they can be classified by multivariate statistical analyses to compare and group synchronous sequences of sedimentation and/or paleoenvironmental dynamics (Berger 2000; Purdue 2011). While more and more studies provide keys for interpretation (eg. Stoops et al. 2010), these are not easily transposable to other environmental and archaeological contexts (Courty and Nornberg 1985; MacPhail 1986; 1990; 1992; MacPhail et al. 1987; 1990; Gebhardt 1993; Berger 1996). Also, interpretation often puts aside the principle of equifinality (Valentine and Dalrymple 1976; Pawluk 1978; Kemp et al. 1993). In order to mitigate both issues, it is necessary to compare archaeological data with samples from modern or historical contexts for whose dynamics we have written archives. Models of function and paleoenvironmental dynamics at the scale of the irrigation network and then the valley can be formulated. Ultimately, one can then put forward models of landscape evolution.

## Case Study: Hohokam Irrigation Along the Lower Salt River, Arizona

### *Environmental Background: Climate, Geography, and Geomorphology*

The Salt River watershed in Central Arizona covers an area of approximately 35,000 km<sup>2</sup>. The Salt River, 320 km long, originates in the White Mountains east of Arizona, in the Fort Apache Indian Reservation, at an average altitude of 3,500 m. The Salt River leaves the mountains near its confluence with the Verde River, its major tributary, and flows through the urban area of Phoenix until its confluence with the Gila River, tributary of the Colorado River, 37 km downstream. This area, referred to as the lower Salt River Valley in the Phoenix Basin, belongs to the Basin and Range Province (Gilbert 1875; Davis 1902), characterized by narrow mountain chains and low altitude fertile plains (300–350 m), gently sloping to the east (Fenneman 1931). The lower Salt River, dry today as a consequence of dam building, presents a channel-into-channel configuration (Gregory and Park 1974; Richards 1982), with flow contained in a braided channel during high discharges and a meandering channel set in a large floodplain (400 m) during dry years. This cut-and-fill floodplain is characterized by overbank aggradation, channel accretion (Nanson and Croke 1992), and gully erosion. Precipitation in this area is bimodal: average annual precipitation reaches 190 mm (average from 1933 to 2015; Western Regional Climate Center 2015) with monsoonal summer precipitation, short and intense due to convective storms, and winter precipitation, long and less intense as a result of frontal storms, between November and March (Sellers 1965). Average monthly precipitation for these two seasons reaches 20 mm.

Intense urbanization and erosion of superficial formations precludes precise geomorphic mapping of the lower Salt River Valley. The most substantial maps were provided by Péwé in 1978 and Pearthree and Huckleberry in 1994, and were completed by Cultural Resource Management projects upstream and downstream of the valley (Onken et al. 2004; Phillips et al. 2004) as well as recent publications (Huckleberry et al. 2013; Purdue 2013). Five terraces are generally described. The Pleistocene Sawik (T1, 15 to 72 m above modern river-bed level) and Mesa terraces (T2, 9–29 m) are morphologically very similar due to their carbonate content. The Blue Point Terrace (3–24 m above modern river-bed level) is composed of coarse gravels and rocks with calcium carbonate coatings. The Holocene Lehi Terrace (T3), composed of fluvial deposits, lies 1.5 to 6 m above the modern stream-bed level. Another lower terrace has been identified in parts of the lower valley (Huckleberry et al. 2013; Purdue 2013). Deposition only occurred on these two most recent alluvial formations during the last 2,000 years. A synthesis of the above-mentioned projects and publications has allowed identification

of several phases: (1) Landscape stability and soil development occurred from the first century B.C. to the third century A.D.; (2) Fluvial and eolian accretion is recorded from that date until the ninth century A.D.; (3) A second phase of pedogenesis has been noticed between A.D. 800–950 with the development of cienegas in the direct vicinity of the stream; (4) Increasing flooding events are recorded between A.D. 900–1150 with fluvial morphological evolution towards a braided system; (5) Signatures of a downcutting event (eleventh to twelfth century A.D.) are evident along the Gila River and its tributaries associated with soil development on the upper part of the Lehi Terrace; (6) The chronological interval between the fifteenth to the nineteenth century A.D. witnessed channel fill and floodplain accretion.

### *Archaeological Background: Hohokam Chronology and Irrigation Systems*

Because they lived along the Salt and Gila Rivers in the semi-desert Phoenix Basin in Arizona, the Hohokam (A.D. 100–1450), like both their descendants the Akimel O’odham (after 1694) and white pioneers (nineteenth century), were dependent on fluvial dynamics. To survive, the Hohokam built major irrigation systems as early as A.D. 100 (Henderson 1989), and continued until A.D. 1450 (Haury 1976; Doyel 1979; Gumerman 1991). It was mainly during the Preclassic Period (A.D. 750–ca. 1150) that major canals were built and expanded (Doyel 1991), in parallel with an increase in settlement size, functional diversity, and social differentiation, the construction of ball courts, and the emergence of regional trade and networks (Gregory 1991). By the end of the Preclassic Period, 16 gravity-fed irrigation systems, some measuring nearly 30 km long, organized as a large “spider web,” were in use (Figure 3.1(a)). The transition to the Classic Period (A.D. 1050–1150) seems to represent a break in Hohokam social structure, shown by a major settlement reorganization (village aggregation, construction of compound walls, etc.), evolution in architecture, evolving ceramic production, decreasing trade and connectivity, and diversification in agricultural techniques and architecture (cf. Gumerman 1991). This new equilibrium and short-term reorganization was followed by the society’s collapse around the fifteenth century. The Salt River Valley subsequently remained unoccupied for a few centuries.

From a technical standpoint, Hohokam canals were organized in tertiary systems: main canals diverted water from the river and supplied secondary structures, the latter bringing water to tertiary canals, from which it was then evacuated into fields. In general, these tertiary canals were straight and regularly spaced, parallel or perpendicular to secondary canals. Head-gates probably controlled the entrance of water into the canals. In the lower Salt River Valley, salvage archaeology conducted over the last 20 years has enabled the creation of a very precise map of the irrigation systems (Howard and Huckleberry 1991) (Figure 3.1(a)). Numerous paleoenvironmental

studies have also been conducted in irrigation structures themselves (e.g., Howard and Huckleberry 1991; Doyel et al. 1995; Hackbarth et al. 1995), but these have never been based on a micromorphological analysis.

### *The Riverview at Dobson Project*

The Riverview at Dobson Project (AZ U:9:135(ASM)), which is nearly 32 acres in extent, is located south of the Red Mountain Freeway 202 and east of the Price Road, less than 1 km from the river (Figure 3.1(a)). Fieldwork was carried out in 2005 in collaboration with Arizona Museum of Natural History and Arizona State University. This project, as well as previous projects in this area (Masse 1987; Ackerly and Henderson 1989; Mitchell and Motsinger 1998), unearthed more than 20 canals belonging to one of the biggest irrigation systems along the lower Salt River: Canal System 1. Their concentration in the area is favored by the presence of a narrow and low-elevation strip of land between the alluvial plain (currently the T3 Lehi Terrace) and the T2 Mesa Pleistocene Terrace. The canals excavated were oriented west-east and supplied water to the south and in areas of what is now Mesa, Tempe, Chandler, and the Gila River Indian Community. While numerous trenches were dug and canals encountered during this project, I only studied two of them (T1 and T2).<sup>1</sup> The study of canal profiles so close to their headgates enabled simultaneous study of fluvial archives, irrigation canal fills, and signatures of maintenance. The socioenvironmental signatures obtained also indirectly provide information about the amount of water supplied to the secondary and tertiary canals downstream. Unfortunately, these samples do not allow investigation of connected and well-identified agricultural soils. While some bioturbated fluviosols were encountered adjacent to the canals, we do not think they were cultivated in this central area of canal construction. As a result, while some agricultural fields were studied further downstream in this system (Purdue 2011), they are not presented here, as they cannot be clearly connected to the irrigation canals studied here.

### *Chronostratigraphy and Micromorphological Sampling*

Two overlapping canals were observed in T1 (Figure 3.1(b)) (Canal 1a and 1b). The lower canal (Canal 1a) is built on top of finely prismatic brown silts (T1, S VI)<sup>2</sup> and measures 2.6 m deep and 1.4 m wide. Based on the identification of discontinuous stratigraphic limits between the strata, which correspond to traces of past cleaning episodes, we distinguished 6 cleaning events within this structure filled with sand, silt, and clay and eroded in its upper part by a Salt River channel and flood deposits (T1, S VII and S VIII). Canal 1b was excavated into T1, S VIII. Much smaller in size than its predecessor, Canal 1b (75 cm deep, 75 cm wide) seems quickly filled by clayey deposits alternating with coarse sands. Charcoals recovered from the base of these fill deposits (T1, S24) provided a construction date in the interval

A.D. 1030–1189<sup>3</sup> and we obtained a date of A.D. 1489–1651 in the upper part of the canal fills (T1, S30)<sup>4</sup> (possible post-abandonment date) (Figure 3.1). Thirteen micromorphological samples were taken: 9 in the canal and 4 in flood deposits. Unfortunately, one went missing during transportation (T1, S VII).

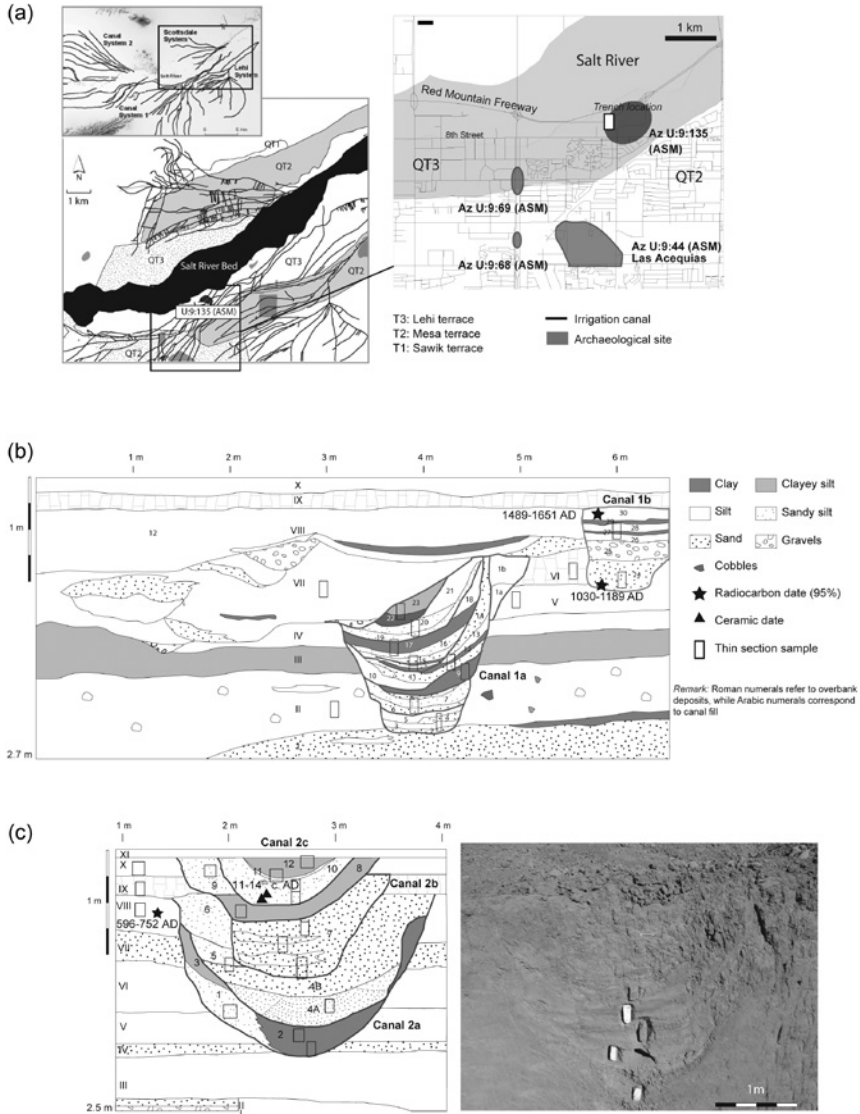


Figure 3.1 (a) Geographic and geomorphic location of AZ U:9:135 (ASM); (b) stratigraphy and chronology in Trench 1 (West profile), AZ U:9:135 (ASM), with Canal 1a and 1b identified; (c) stratigraphy and chronology in Trench 2 (North-East profile), AZ U:9:135 (ASM), with Canal 2a, 2b, and 2c identified.

Three superposed canals were uncovered in Trench 2 (Figure 3.1(c)) (Canal 2a, 2b, and 2c). The lower one, Canal 2a (1.75 m deep, 2m wide), was dug into sandy silts rich in charcoals (T2, S VIII) dated to A.D. 596–752<sup>5</sup> (Preclassic Period), and is filled with fine deposits. After a first cleaning episode, this structure was filled with cross-stratified sand and buried under two flood deposits (T2, S IXa and b). Canal 2b (1.25 m deep, 1.5 m wide) was then dug, but is also filled with cross-stratified sand and buried under new flood deposits (T2, S X). Canal 2c, wider and much smaller in size (2 m wide, 85 cm deep), was excavated into these deposits and is filled with alternating silty clay and laminated sands. One cleaning event was noticed. Numerous sherds were discovered in its fill (T2, S10) dating its use between A.D. 1000 and 1300 (Classic Period). Nineteen micromorphological samples were taken, three of which were in the flood deposits.

### *Marker Selection*

As mentioned in the methodological section, numerous markers can be selected depending on the initial question. In the Riverview at Dobson Project, the fill of the canals directly reflects changes in the Salt River flow. We therefore selected and systematically described 11 markers (Table 3.1). Their interpretation is based on reference materials from historic canals (Huckleberry 1999; Purdue 2011) and geological formations (Purdue 2011), as well as pedological references (Soil Survey Staff 1975) and research on charcoal (Whitlock and Millspaugh 1996; Enache and Cumming 2006). However, we present here only the most relevant ones:

- 1 Flow intensity (texture obtained from image analysis; see Purdue 2011 for more details)
- 2 Sediment origin (mineral assemblage obtained by presence/absence, description, and counting of basalt grains followed by a multivariate statistical analysis integrating reference samples from the Salt River Basin (sedimentary basin) and Verde River Basin (volcanic basin)) (see Figures 3.2(b) and 3.2(d) and Purdue 2011 for more details)
- 3 Sediment transport (sedimentary structure, qualitative description)
- 4 Rhythmicity and rate of sedimentation (soil structure, qualitative description)
- 5 Fire regime inferred from charcoal content (+, +++, +++) and size (< or > 125  $\mu\text{m}$ )
- 6 Organic matter content (+, +++, +++)

### *Results and Interpretation*

#### EVOLUTION OF THE ALLUVIAL PLAIN

Out of the five flood events chronologically framed, four of them occurred between A.D. 596–752 and A.D. 1030–1189, and while modern agricultural

Table 3.1 Topical enquiry, micromorphological markers, and significance (Riverview at Dobson Project)

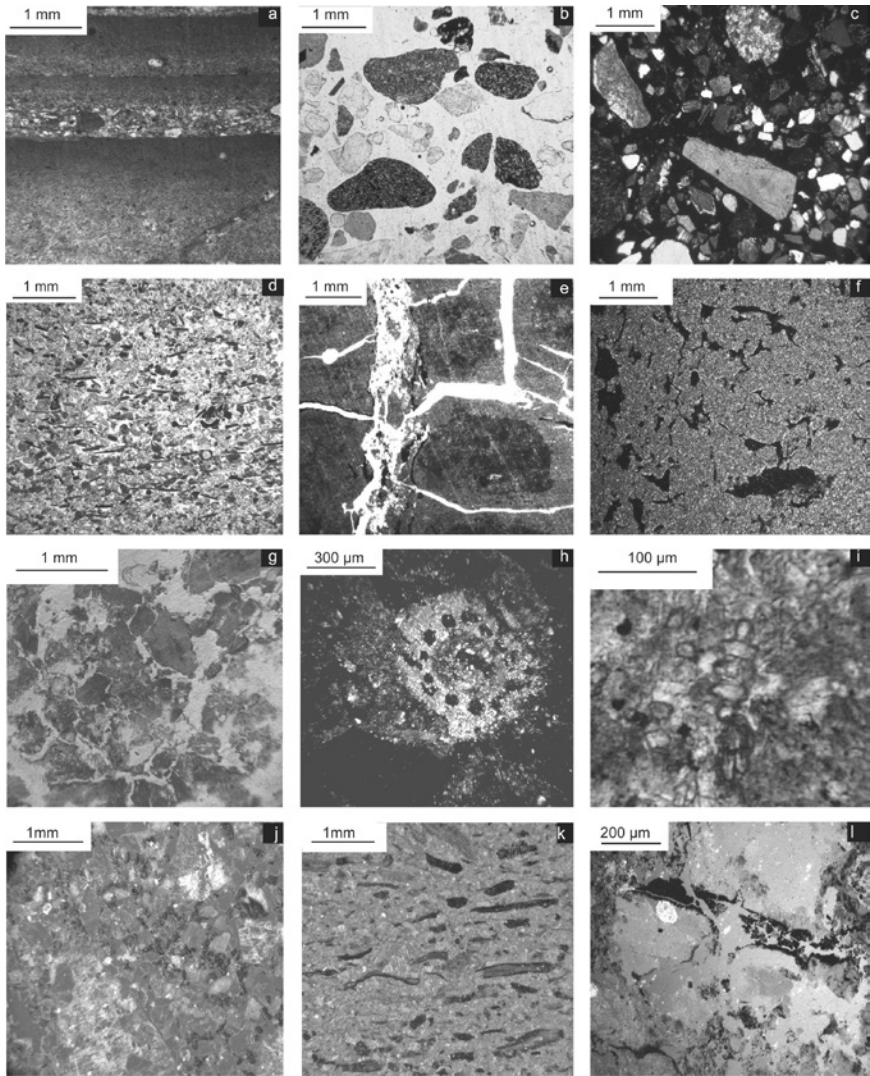
	<i>Topic</i>	<i>Marker</i>	<i>Marker Differentiation</i>	<i>Possible Interpretation</i>
SEDIMENTOLOGY	<i>Flow intensity</i>	Texture	Sand Silt	High fluvial discharge Average fluvial discharge
			Clay	Decantation and low water circulation
	<i>Sediment transport</i>	Sorting and composition of the sediments	Positively graded	Rhythmic sedimentation, gradual rise and fall of the water level (anthropic or climatic); does not imply flooding (Fig. 3.2a)
			Homogeneous: uniform grain size and fabric	Balance between discharge and sediment supply (Fig. 3.2d)
Heterogeneous: weak sorting + soil aggregates			Flooding episodes with turbulent flow, or sudden increase/decrease in water level or bioturbation	
		Local	Berm breakage or local water diversion (Fig. 3.2c)	
	<i>Source to sink</i>	Petrography	Basalt, microcline, etc.	Sediment origin, possible geomorphic and climatic extrapolation (Fig. 3.2b, 3.2d)
PEDOLOGY	<i>Biological activity and sedimentation rate</i>	Microstructure	Simple grain	Fast sedimentation (Fig. 3.2d)
			Massive to vughy	Fast sedimentation to hydromorphy (Fig. 3.2f)
			Blocky	Wetting and drying cycles (Fig. 3.2e)
			Channel/granular	High bioturbation and soil moisture (Fig. 3.2g)
	<i>Water presence or absence</i>	Pedological crusts		Scarce vegetation, canal drying out, increased sensitivity to erosion

(Continued)

Table 3.1 (Continued)

	<i>Topic</i>	<i>Marker</i>	<i>Marker Differentiation</i>	<i>Possible Interpretation</i>
ECOLOGY	<i>Fire regime</i>	Charcoal	%	Intensity of the fire regime (Fig. 3.2j, 3.2k)
			Microcharcoal	Regional fire (Fig. 2j), effect of bioturbation or granulometric sorting
		Charcoal size	Macrocharcoal (> 125 $\mu\text{m}$ )	Local fire (Fig. 3.2l)
		Charcoal shape	Elongated	Possible gramineae vegetation (Fig. 3.2k)
	<i>Vegetation cover</i>	Organic matter	%	Vegetation cover
			Fresh Humic	Local vegetation Vegetation cover (local to regional) (Fig. 3.2i)
Organic matter shape		Aggregates / microparticules Roots, phytoliths	Soil erosion Type of vegetation (Fig. 3.2h)	

activity might have eroded other signatures, only 20 cm of arable land was identified on top of the last flood event dated after the sixteenth to seventeenth century. Of the earlier four flood deposits, three deposited sediments with similar texture and sorting: T1, SV / T2, SVIII; T1, SVII / T2, SIXB; T1, SVIII / T2, SX (Figure 3.3(a)). These flood deposits are composed of weakly sorted coarse silts to sands (Figure 3.3(b) and 3.3(c)), rich in quartz grains, feldspar, pyroxene, sandstone, plagioclase, amphibole, and most of all basalt grains, whose origin and type has been traced to the Verde River Basin, tributary of the Salt River (Purdue 2011; reference sample shown in Figure 3.2(a)). The use of micromorphology in source-to-sink analysis allowed link age of mineral assemblages to precipitation regimes. Indeed, both the Salt and Verde basins are sensitive to winter and summer precipitation, as part of the bimodal regional precipitation pattern. However, the Verde Basin, as a result of its topography and high altitude, as well as its north-south orientation, is supplied mainly by the input of winter precipitation and snow. Higher discharges and larger floods occur during the winter along the Verde River (Graf 1983; Hirschboeck 1985; Ely et al. 1993; House and Hirschboeck 1997). Therefore, the occurrence of sediments from both basins suggests that flow occurred probably dominantly during the winter. Over time, the absence of sediments from the Verde River could also



*Figure 3.2* Microphotographs of features commonly observed in irrigation canals, flood deposits, and agricultural fields. PPL: Plane Polarized Light; XPL: Crossed Polarized Light; IL: Incident Light. (a) Positively graded sediments; (b) Subrounded basaltic grains (origin: Verde River) (PPL); (c) Heterogeneous subangular sands (local); (d) Well-sorted and homogeneous fine sand with horizontal mica particles, massive soil structure (PPL); (e) Water stagnation deposits and subangular blocky soil structure (PPL); (f) Vughy microstructure due to structural collapse under hydromorphic conditions (XPL); (g) Granular and subrounded blocky structure due to bioturbation (PPL); (h) In situ transversal cross-cut of a characeae stem (XPL); (i) Phytolith of the cyperaceae family (PPL); (j) Rounded to angular microcharcoal (IL); (k) Elongated charcoals and organic matter in flood deposits (IL); (l) In situ burnt organic matter and charcoals (IL).

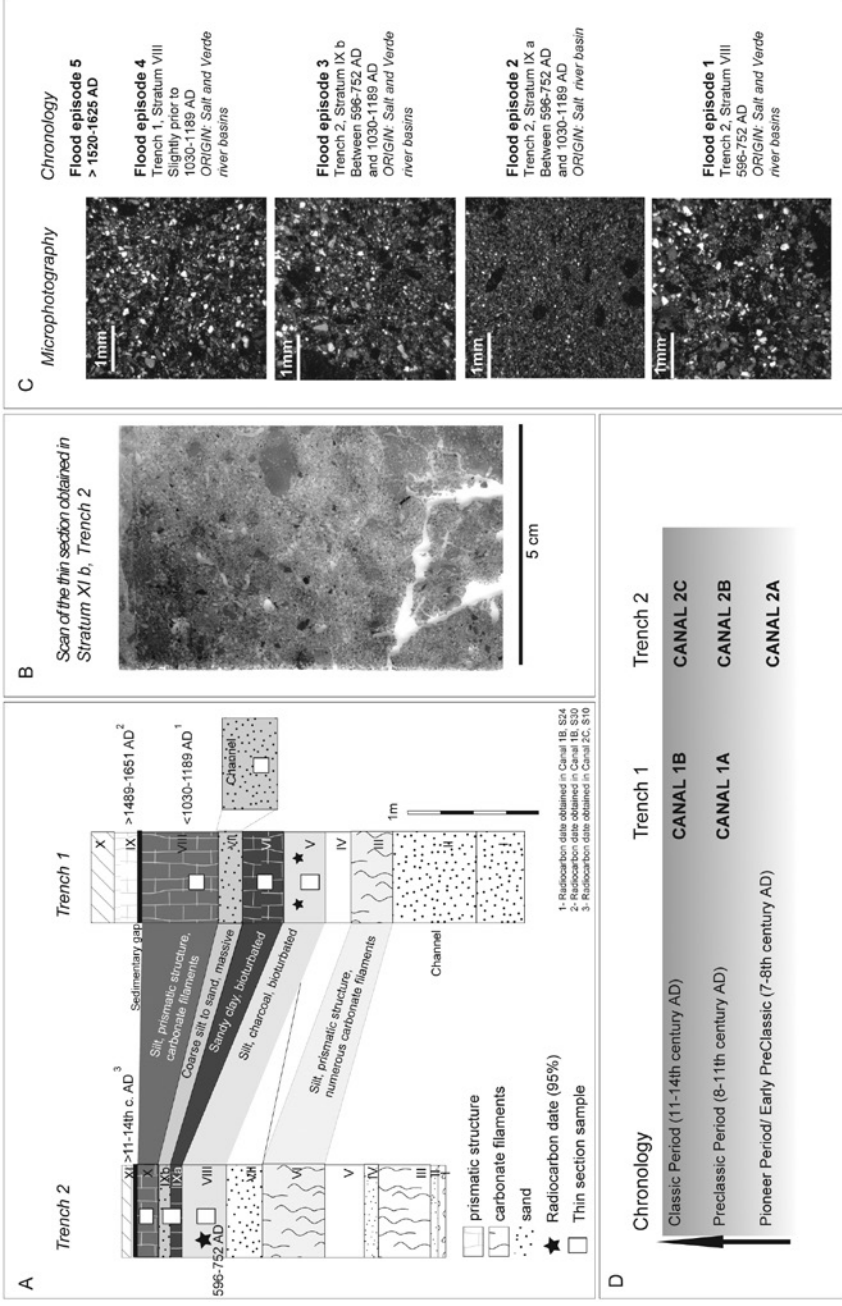


Figure 3.3 Stratigraphic correlation between T1 and T2, flood episodes, pedogenesis, and micromorphological characteristics.

- (a) Stratigraphic correlation between Trenches 1 and 2 based on radiocarbon and ceramic dating obtained in both flood deposits and canal fills. In Trench 2, Stratum VIII was radiocarbon dated (A.D. 596–752), while Stratum XI buries Canal 2c, dated by ceramics to the eleventh to fourteenth century in its upper part (Figure 3.2(b)). In Trench 1, Stratum VIII corresponds to a flood deposit into which Canal 1b was excavated between A.D. 1049–1169 (Figure 3.1(c)). The last deposits filling Canal 1b were dated to A.D. 1520–1625. Therefore, Stratum IX, which covers Canal 1b, was deposited after that date. There is a sedimentary gap on the terrace between the twelfth and fifteenth century.
- (b) Scan and binocular observation of the thin section sampled in Trench 2, Stratum IXb. The aim of the thin section samples was to pursue a source-to-sink analysis. First observations under the binocular highlight weakly sorted silts and sands, partly bioturbated, numerous soil aggregates, traces of organic matter, and rounded macrocharcoal.
- (c) Microphotographs and chronology of the major flood deposits that occurred between the seventh and the sixteenth century. Description of the mineral and organic assemblage under the microscope allows identification of deposits originating from both the Verde and Salt River basins. Coarse and weakly sorted deposits rich in quartz, basalt, and amphibole originate from the Verde and Salt River basins, while finer deposits lacking basalt grains originate mainly from the Salt River Basin.
- (d) Chronology of use of the irrigation canals based on stratigraphic correlations.

indicate reduced winter precipitation and shifts in precipitation patterns (summer precipitation) (Purdue 2011). The last flood deposit studied was composed of fine silt, with a homogeneous assemblage (T1, S VI; T2, S IXa), originating mainly from the Salt River Basin, which could point towards changing precipitation patterns.

The study of mineral assemblages also confirmed the first chronostratigraphic correlations established in the field. Based on radiocarbon dates obtained in the canals fills and overbank deposits, it was possible to date the use of the canals (Fig 3.3(d)). Of those canals sectioned by these two trenches, only one was extant during the early Preclassic Period, two during the Preclassic Period, and two much smaller ones were in operation at the beginning of the Classic Period.

#### MICROMORPHOLOGICAL DESCRIPTIONS

Based on the chronology established (Fig. 3.3(d)) and micromorphological observations, four phases were identified. The description of the deposits encountered in canals in T1 and the ones in T2 are presented in Table 3.2. Detailed micromorphological description of each stratum and microstratum are available in Purdue (2011). Strata identified in the field are numbered while microstrata identified in thin sections are identified by appending alphabetical letters to the stratum designation.

The first phase of canal construction and use in the area occurred around the seventh century. The silts rich in charcoal (T2, S VIII) into which T2, Canal 2a was excavated indicate probable slash and burn to clear vegetation. The deposits studied in the canal (T2, S 1 to 6) are composed of weakly sorted and cross-stratified coarse silts and sands, originating from both the Verde and Salt River basins (indicating regional erosion). Their configuration mimics natural channels and reveals high intensity turbulent flow, which probably favored berm breakage. The high content of organic matter throughout this structure and the presence of macrocharcoals suggest the presence of riparian vegetation at the scale of the watersheds as well as local fire events. Last, the dominant massive, vughy, and subangular structures indicate humid conditions, with well-expressed wetting and drying cycles. The thickness and homogeneity of the canal fill indicate a high sediment load but also a high discharge, as confirmed by the flood deposits (originating in the Salt River Basin), which plugged and buried the canal (T1, S VI; T2, S IXa).

The second phase corresponds to Canal 2a observed in T2, dug into S VIII. At the bottom of the canal (S 2 to 5), sediments are composed of microlaminae of very fine sand and sandy silt, from both the Salt and Verde basins. These deposits are homogeneous and very well-sorted; some are positively graded, while others are heterogeneous suggesting irregular flow. The single grain and massive to slightly bioturbated microstructure indicates fast sedimentation with occasional phases of evaporation and biological activity.

Table 3.2 Selected micromorphological results

Trench / Canal	Phase	Stratum / Microstratum	Texture	Sediment Origin	Sediment Structure	Soil Microstructure	Organic Matter Content	Organic Matter Shape	Charcoal Content	Charcoal Size
T1/1A	2	2a	ss	S	Het	c	+++	MP	+	mi
T1/1A	2	2b	vfs	V	Het	sg	X	X	+++	mi
T1/1A	2	2c	vfs	U	PG	sg	X	X	+	mi
T1/1A	2	2d	vfs	S	PG	m	X	X	+++	mi
T1/1A	2	3a	a	S	Hom	sg	+	MP	+	mi
T1/1A	2	3b	ss	U	Hom	m	+	MP	++	mi
T1/1A	2	3c	vfs	V	Het	c	+	MP	+++	mi
T1/1A	2	4a	vfs	V	Het	sg	X	X	+++	mi
T1/1A	2	4b	ss	U	Het	c	++	MP	+	mi
T1/1A	2	4c	ca	S	Het	m	++++	MP	+++	ma
T1/1A	2	4d	vfs	V	Het	mix	+	MP	++	mi
T1/1A	2	5	/	/	/	/	/	/	/	/
T1/1A	3	6	vfs	U		sg	X	X	+++	ma
T1/1A	3	7a	ca	US	Het	m	+	Ag	+++	mi
T1/1A	3	7b	ca	S	Het	sb	+	H	+++	mi
T1/1A	3	8	/	/	/	/	/	/	/	/
T1/1A	3	9a	ca	S	Het	c	+++	H	+++	ma
T1/1A	3	9b	ss	U	Het	sb	++++	H	+++	mi
T1/1A	3	9c	ss	S	PG	sb	+	MP	+	mi
T1/1A	3	9d	vfs	U	Het	sg	+	MP	+	mi
T1/1A	3	10	/	/	/	/	/	/	/	/
T1/1A	3	11	cs	U	Het	sb	+	F	++	ma
T1/1A	3	12a	ca	S	PG	sb	X	X	+	mi
T1/1A	3	12b	ca	V	Het	sb	++	H	++	ma
T1/1A	3	13	vfs	V	Het	sg	+	H	++	mi
T1/1A	3	14	cs	V	Het	sb	+	MP	++	ma

(Continued)

Table 3.2 (Continued)

Trench/ Canal	Phase	Stratum / Microstratum	Texture	Sediment Origin	Sediment Structure	Soil Microstructure	Organic Matter Content	Organic Matter Shape	Charcoal Content	Charcoal Size
T1/1A	3	15a	vfs	U	Het	sb	+	MP	++	ma
T1/1A	3	15b	a	S	B	sb	+	MP	+	mi
T1/1A	3	15c	ss	S	Het	m	+	MP	+	mi
T1/1A	3	15d	vfs	V	Het	sg	+	MP	+	mi
T1/1A	3	15e	vfs	V	Het	v	+	MP	+++	mi
T1/1A	3	16	a	S	B	sb	+	MP	+	mi
T1/1A	3	17a	a	S	B	sb	+	MP	+	mi
T1/1A	3	17b	a	S	B	sb	+	Ag	+	mi
T1/1A	3	18	X	X	X	X	X	X	X	X
T1/1A	3	19	ca	S	B	sg	+++	H	++	mi
T1/1A	3	20	ca	S	Hom	m	++++	H	+++	mi
T1/1A	3	21	/	/	/	/	/	/	/	/
T1/1A	3	22	/	/	/	/	/	/	/	/
T1/1A	3	23	/	/	/	/	/	/	/	/
T1/1A	3	LOST	/	/	/	/	/	/	/	/
T1/1B	4	24a	vfs	V	Het	v	++++	H	++	ma
T1/1B	4	24b	cs	V	Het	v	+++	MP	+++	mi
T1/1B	4	26	cs	S	Het	m	++	MP	+++	mi
T1/1B	4	27	ca	S	PG	sb	+	MP	++	mi
T2/2A	1	1	vfs	U	Eolian	v	+++	H	++	mi
T2/2A	1	2a	cs	V	Het	sb	++	H	++	mi
T2/2A	1	2b	vfs	V	Het	m	+++	H	+++	mi
T2/2A	1	2c	ca	V	Het	sb	+++	F	+++	mi
T2/2A	1	3	/	/	/	/	/	/	/	/
T2/2A	1	4a	cs	US	Eolian	sg	+	MP	+++	mi
T2/2A	1	4b	ss	US	Het	v	+++	H	+++	ma
T2/2A	1	5	ss	S	PG	m	++++	H	++	mi

T2/2A	1	6	vfs	V	B	v to c	+++	H	++	mi
T2/2B	3	7a	vfs	S	PG	sg	++	H	++	mi
T2/2B	3	7b	vfs	US	PG	sg	X	X	+	mi
T2/2B	3	7c	vfs	V	Het	sg	X	X	+	mi
T2/2B	3	7d	vfs	US	Hom	sg	X	X	+	mi
T2/2B	3	7e	vfs	V	PG	sg	X	X	+	mi
T2/2B	3	7f	vfs	S	PG	sg	X	X	+	mi
T2/2B	3	7g	vfs	U	Het	sg	X	X	+	mi
T2/2B	3	7h	a	S	Het	c	+++	Ag	++	mi
T2/2B	3	7i	vfs	US	Het	sg	X	X	+++	ma
T2/2B	3	7j	ss	S	PG	sg	++	Ag	++	mi
T2/2B	3	7k	vfs	V	Het	sg	++	H	+++	mi
T2/2B	3	7l	vfs	V	PG	sg	X	X	+++	ma
T2/2B	3	7m	vfs	V	Het	sg	X	X	+++	ma
T2/2B	3	7n	vfs	V	Het	sg	+	MP	+++	mi
T2/2B	3	7o	vfs	US	Het	sg	+	Ag	+++	mi
T2/2B	3	7p	ss	S	Het	c	+++	H	+++	mi
T2/2C	4	8a	ca	S	B	sb	+++	Ag	++	mi
T2/2C	4	8b	ca	US	PG	sb	+++	H	+++	mi
T2/2C	4	8c	cs	V	Het	sg	+	MP	+++	ma
T2/2C	4	9	ss	V	Het	c	+	MP	+++	mi
T2/2C	4	10a	ca	S	Hom	sb	+++	H	+++	mi
T2/2C	4	10b	cs	US	Het	sg	++	H	+++	ma
T2/2C	4	10c	ca	U	Het	v	++	H	++	mi
T2/2C	4	10d	cs	U	Het	sg	+	H	++	mi
T2/2C	4	10e	ca	S	Hom	v	+++	H	+++	mi
T2/2C	4	10f	ca	U	Het	v	+++	H	+++	mi
T2/2C	4	11	ss	V	Hom	sb	+++	H	+++	ma
T2/2C	4	12a	ss	S	Hom	sb	++	MP	+++	mi
T2/2C	4	12b	ss	V	Het	sb	+	H	+++	ma
T2/2C	4	12c	ca	V	Het	sb	+++	F	+	mi

(Continued)

Table 3.2 (Continued)

List of abbreviations

Sedimentology	Texture: vfs: very fine sand; cs: coarse silt; ss: sandy silt; ca: clayey silt; a: clay Sediment origin: US: upstream Salt River; S: Salt River Basin; V: Verde and Salt River basins; U: undetermined (no basalt grains)
Organic components	Sediment structure: Het: heterogeneous deposits; PG: positively graded; Hom: homogeneous deposits; B: bioturbated Type of organic matter: F: fresh; H: humic; MP: microparticles; Ag: organic soil aggregates Content in organic matter: +: 0–2%; ++: 3–4%; +++: 5–8%; ++++: > 8% Content in charcoal particles: +: 0–2%; ++: 3–4%; +++: 5–8%; ++++: > 8%
Pedology	Size of charcoal: ma: macrocharcoal (> 125 µm); mi: microcharcoal (< 125 µm) Soil microstructure: sb: subangular blocky; sg: simple grain; v: vughy; c: channel; mix: complex cleaning event

This is a typical signature of seasonal sedimentation (Courty 1990). Only a few organic microparticles have been observed in association with numerous rounded microcharcoal specks (possibly suggesting diminution of the vegetation cover and riparian vegetation upstream). The discrete change in canal shape suggests that this structure was possibly cleaned following that phase.

The third phase visible in T1 (Canal 1a, S 6 to 23) corresponds to a period of decreasing flow intensity but regular canal maintenance (5 cleaning events). Well-sorted positively graded silty clays and clays were initially deposited (T1, S 6 to 8) indicating rhythmic sedimentation in the canal but very low flow. Most of the sediments originate in the Salt Basin. Their blocky structure suggests episodes of complete drying out, and the abundance of charcoal and macrocharcoal points towards possible in situ burning events to clear vegetation. Coarser and weakly sorted sediments as well as numerous angular soil aggregates suggest episodes of berm breakage (T1, S9). Stratigraphic unconformities suggest that the canal was subsequently cleaned. Despite a temporary phase of turbulent flow characterized by deposits (T1, S13 to 14) composed of weakly sorted sands, silty sands, and coarse silts from the Verde and Salt Basin, maybe resulting from a sudden increase in water level in the river, massive well-sorted positively graded clayey silts (T1, S15 to 20) suggest low- to average-intensity flow as well as a rhythmic and fast sedimentation. Despite this sediment structure suggesting flows favorable to the transport and deposition of elongated particles of charcoals and organic matter, these two markers were only observed as isolates in low overall frequency (possibly suggesting regional decrease in the vegetation cover and/or drier conditions). The environment linked to the final use of the canal is unknown as the thin section sample was lost during shipping, but field data highlights a major in situ burning event in T1, S22. During its final use, Canal 1a was eroded and buried under flood deposits and channel sediments (T1, SVII; T2, SIXb) indicating fluvial morphological change; this probably occurred slightly prior to A.D. 1030–1189, based on the date obtained in T1, Canal 1b.

Before or during this flood event, Canal 2b was built in T2. This structure was filled with massive laminated or weakly sorted fine sands originating from the Verde Basin and various areas of the Salt River Basin (T2, S7). The mineralogical assemblage is much more diversified than the other sediments studied. We progressively observe increasing quantities of micro- and macrocharcoal in the upper part of T2, S7, suggesting local and regional fire events; landscape denudation may have contributed to an increasing sediment load. Canal 2b in T2, as well as the channel deposits in T1, was then buried under new flood deposits (T1, SVIII; T2, SX).

The fourth and last phase corresponds to two small Classic Period canals (T1, Canal 1b, S24 to 30; T2, Canal 2c, S8 to 12). Canal 1b in T1 was probably built prior to the Canal 2c in T2. Indeed, the massive weakly sorted sands rich in macrocharcoal, sands (from both the Verde and Salt rivers)

and gravels (T1, S24 and 25) observed at the bottom of Canal 1b are very similar to the deposits into which this structure was excavated (T1, SVIII), suggesting a high bedload. Their heterogeneity, as well as vughy structure, implies uncontrolled flow and humid conditions (structural collapse due to humidity). Above, the graded and homogeneous coarse silts observed in both structures (T1, Canal 1b, S26 to 29; T2, Canal 2c, S8 to 12) indicate rhythmic flow alternating with temporary drying out as suggested by the massive to sub-angular soil structure (seasonal sedimentation, Courty 1990). Only small charcoals and altered fragments of organic matter have been identified. The upper deposits are weakly sorted and rich in angular soil aggregates possibly resulting from post-abandonment slope wash events and pedogenesis (T1, S30; T2, S12).

### *Discussion*

The chronostratigraphic correlation between canal fills and flood deposits made it possible to distinguish four hydrosedimentary trends from the seventh to the thirteenth century, three of which took place during the Preclassic Period (A.D. 750–1150), and the last one during the Classic Period (A.D. 1150–1450). Correlating these results with dendroclimatic, climatic, paleodemographic, and archaeological data makes it possible to situate the hydrosedimentary trends in relation to broader socioenvironmental dynamics and discuss the sociopolitical versus environmental factors that control human-environment interactions. Results in the Phoenix Basin suggest that this co-evolution was overall controlled by hydroclimatic factors during the Preclassic Period, mixed anthropic and climatic influences during the transition to the Classic Period, and social drivers during the Classic Period.

### *The Preclassic Period (Seventh–Eleventh Century)*

This study has enabled us to show a first period of canal construction at the middle of the Preclassic Period. The Canal 2a in T2 is filled with laminated and cross-stratified coarse sands, conditions seem humid, and the high content of both charcoals and organic matter testifies to landscape evolving possibly at the regional scale. However, it would be necessary to multiply local studies to validate this hypothesis. This dynamic is well correlated to the (dendro) climatic records, which reveal optimal conditions for irrigation with a high groundwater level and a possible narrow Salt River channel from which water could have been easily diverted (Graybill et al. 1989). This period of fluvial accretion favored water and sediment supply in downstream canals and fields but required coordination and management closer to the headgates to maintain canals and rebuild them after flood events.

The second trend corresponds to Canal 1a built in T1, on top of the flood deposits that buried the earlier Canal 2a visible in T2. The initial flow in the canal was turbulent and rhythmic, with possible signatures of seasonal sedimentation and regional soil erosion (i.e., sediments derived from both the Salt and Verde basins, rich in charcoal). This suggests efficient water delivery, but the high sediment load probably favored fast siltation. However, flow progressively decreased, as shown by the occurrence of positively graded very fine sediments (originating from the Salt River Basin) and traces of regular wetting and drying cycles. Graded sediments imply a regular increase and decrease in water level in the river or the action of headgates. The numerous cleaning events and ashes indicate local vegetation growth, contributing to low water flow. During this second period, the agricultural areas downstream, dependent on that canal, may have suffered from this reduced water supply. No definite chronology is available for this period, but we do know that it occurred between the eighth and the eleventh century. How to explain this shift in fluvial dynamic, as well as changes in sediment origin and high maintenance? The first hypothesis, supported by climatic data, is a regional decrease in precipitation and discharge. Numerous researchers have noticed increasingly drier conditions at regional scale during this chronological interval, and related them to the Medieval Climate Anomaly (e.g., Cook et al. 2004; Jones and Mann 2004; Moberg et al. 2005; Graybill et al. 2006). The dominance of Salt River deposits could also suggest evolution towards a summer precipitation pattern. The second possibility is that increasing population along the Salt River Valley and in the upstream watersheds (Verde and Tonto basins, lower Salt River Valley) (e.g., Hackbarth 1992; Ciolek-Torrello et al. 1994; Doelle 1995; 2000; Deaver 1997) could have contributed to increasing erosion through land clearance (evidenced by abundant charcoals in the deposits) and could subsequently also have diverted most of the available flow in the river leading to decreasing flow in canals.

Canal 1a in T1 is buried under flood deposits and channel sediments originating from both the Salt and Verde basins. The lack of bioturbation indicates fast sedimentation and burial. The only chronology available is that these destructive flood events and associated fluvial morphological change occurred after A.D. 596–752 and prior to A.D. 1030–1189 (2 sigma calibrated date), with a most probable date range prior to A.D. 1049 and 1169 (1 sigma calibrated date), remarkably close to the transition from Preclassic to Classic Period, which witnessed a major cultural, social, economic, and agricultural change around A.D. 1050–1150. This phase of floodplain instability may have led to two issues: (1) lateral soil erosion with possible loss of land close to the river, as well as issues cultivating it; and (2) water supply issues associated with necessary cooperation and collaboration to repair canals and/or build new ones. Decreasing agricultural activity on the Lehi Terrace slightly after the Preclassic to Classic cultural transition (Cable and

Doyel 1984; Greenwals et al. 1994; Henderson and Clark 2004) could be a result of these events. In the framework of understanding the controlling factors of socioenvironmental interactions, one can discuss the origin of this floodplain instability: was it anthropic or natural? While we know that our chronological framework needs refinement, other paleoenvironmental data available in the Southwest do indicate (1) increasing discharges associated with the Salt River's morphological change to a braided-like stream between A.D. 1051–1196 (Graybill et al. 2006); (2) a wetter and colder period within the Medieval Climate Anomaly and more precisely between A.D. 1034–1150 (Cook et al. 2004) associated with regional flooding at the scale of the American Southwest (Ely et al. 1992; 1993; 1994; Hirschboeck 1987; 1988) as a result of El Niño-Southern Oscillation anomalies (ENSO) (Waters and Haynes 2001), which increase the frequency of winter frontal storms; (3) a change from monsoon-dominant precipitation to winter-dominant precipitation during the eleventh century (indicated by dendroclimatic data; Ni et al. 2002). These results seem to confirm that our source-to-sink analysis is a marker of precipitation patterns, showing a shift from summer-dominant to winter-dominant precipitation during this period. They also emphasize that (1) the Phoenix Basin is sensitive to short-term climatic change, (2) seasonal precipitation shifts impact flooding events, and (3) winter floods are the most damaging along the lower Salt River. Summer storms, by their intensity, increase soil sensitivity to erosion, but their short duration does not favor soil transport over long distances, unlike the longer but less intense winter rains (Etheredge et al. 2004).

Going back to the Riverview at Dobson Project, it is also interesting to notice that following these events indicative of fluvial morphological change, only 20 cm of sediments were apparently deposited (as recorded in Trench 1 and 2). From a purely hydrogeomorphic perspective, if the discharge is higher than the sediment supply, the river will downcut. While no direct traces of downcutting events are visible on the site, we strongly support the hypothesis that this occurred along the Salt River, similarly to the Gila River (Waters and Ravesloot 2001) and its tributaries (e.g., Waters 1998; Cook et al. 2010). The anthropic impact on both the fluvial morphological changes and associated downcutting should, however, not be neglected. Indeed, the dominance of deposits rich in charcoals is in accordance with an increasing human occupation and agriculture in the upstream basins and tributaries of the Salt River (e.g., Hackbarth 1992; Hegmon 2002; Swanson and Diehl 2003). I therefore suggest that the transition from the Preclassic to the Classic Period was controlled by both short-term climatic shifts and long-term anthropic effects on the environment.

### *The Classic Period (> Eleventh Century)*

The final trend, observed in the two small Classic Period canals (T1, Canal 1a; T2, Canal 2c) is one of contrasting sedimentation. Coarse and laminated

deposits from both the Salt and Verde basins suggest rhythmic sedimentation, but phases of scarce water supply have also been identified. This combined signature could indicate a well-expressed increase and decrease of the water level in the river. Dendroclimatic data at the scale of the Verde and Salt River basins indicate phases of above average flow, possibly from winter-dominant precipitation, alternating with periods of very low discharge (Graybill et al. 2006). In both trenches, canal management decreased during this period. A plausible explanation for the evolution in canal size and maintenance could be a change in the organization of the agrosystem during the Classic Period. As a result of fluvial morphological change and a probable downcutting event, new systems had to be built upstream to meet water demands, such as the Lehi System, built upstream of Canal System 1 (Howard 1987). The potential issue is that water supply could have generated individualization within agricultural groups more than their collaboration, which could explain the evolution in canal size and management. The reuse over the long term of these irrigation canals does, however, imply a durability of traditions and techniques, with a desire for efficiency and maintenance of agricultural practices and plot locations even in geomorphologically sensitive areas. Finally, canals were abandoned, although no environmental constraint has been identified.

## **Conclusion**

When studying human-environmental co-evolution, it is necessary to conduct systemic and multi-scalar studies that span both temporal scales (from single events to multi-century dynamics) and spatial scales (local to the scale of the watershed). Combined systematic geoarchaeological and micromorphological studies make it possible to examine these interactions as precisely and accurately as possible in past agricultural societies in semi-arid environments, as they exploited water and soils using gravity-fed irrigation systems. This direct linkage of agricultural fields to rivers through irrigation systems makes it possible to assess long-term socioenvironmental dynamics by examining these three elements. I have used the case of Hohokam prehistoric irrigation systems to illustrate the potential of a field geoarchaeological approach combined with the micromorphological study of irrigation canal fill and flood deposits from sedimentological, pedological, ecological, and anthropic perspectives in enabling reconstruction of these socioenvironmental interactions. In order to discuss which of climate or anthropic activities controlled these interactions, it is also necessary to incorporate archaeological, climatic, and demographic data, which I have done here by drawing on the rich record of published work for the area. Results highlight that when alluvial plains are stable (as evidenced by soil development or low intensity overbank deposition), adaptation to shifts in water supply (from, e.g., high flow leading to berm breakage and erosion

or low flow favoring siltation) is visible through regular canal maintenance (cleaning and in situ burning events) and canal reconstruction. However, low frequency events (sudden floodplain accretion, repeated fluvial morphological change, and downcutting as a result of an abrupt climate change and shifting precipitation patterns, in parallel with the indirect impact of increasing population) can lead to social reorganization (e.g., the transition from Preclassic to Classic Period in our case study). On the one hand, the maintenance and reconstruction of water structures in similar locations highlights the resilience of past Hohokam communities. On the other, the smaller size and weak maintenance of these structures in the Classic Period, despite an existent labor force, followed by their abandonment a few centuries later in the absence of environmental constraints, suggest that the restructuring of the agrosystem was not durable. In this case, then, it seems that low-frequency environmental shifts were a triggering factor in agricultural reorganization, but the complete abandonment can be traced also to other factors.

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### **Methodological Vignette: Micromorphology and Agrosystems**

In arid environments, gravity-fed irrigation systems have allowed agricultural societies to cope with social imperatives (water needs) and environmental constraints (water availability). The resulting intertwined social, natural, and/or artificial system, referred to as an anthroposystem (Lévêque et al., 2003), exists at multiple embedded spatial and temporal scales (micro-local to regional; past, present, or future). Simultaneously pursuing geomorphic, geoarchaeological, and agronomic studies

to connect river dynamics to water networks and adjacent fields makes possible the relatively precise reconstruction of human-environment co-evolution, structured around phases of stability, thresholds, and shifts. The systematic analysis of alluvial archives, irrigation canal design, maintenance and sedimentary fill, as well as agricultural fields, can productively be combined with laboratory soil analyses such as micromorphology (Berger 2000; Purdue et al. 2010). Micromorphology is the study of sediments under the microscope (Bullock et al. 1985; Stoops 2003) and has proven extremely useful in the understanding of sedimentary processes (e.g., environments of sedimentation, dynamics of flow, identification of flood and soil erosion events), pedological and ecological dynamics (e.g., rhythm in water supply, soil development, vegetation cover, fire regime), human activities (slash and burn, cleaning events, manuring, irrigation), and dynamics related to soil climate (water stagnation/evaporation) (cf. Fédoroff et al. 1987; Courty et al. 1990; Kapur and Stoops 2008; Stoops et al. 2010). The systematic description of markers of these processes allows for their statistical classification and the grouping of synchronous events. Their interpretation, based on current or historical references and bibliography (e.g., Stoops et al. 2010), enables formulation of dynamic socioenvironmental models, such as reconstructions of changing irrigation regulars or impacts of climate changes. The multiplication of local studies is key for enlarging the scale of study to water networks or even entire catchments and discussing the controlling factors of socioenvironmental interactions.

## Notes

- 1 T1 refers to Riverview at Dobson (RAD) project conducted in 2005, T 206, Feature 121; T2 refers to RAD 2005, T 204, Feature 119.
- 2 Overbank flood deposits are indicated by Roman numerals and canal fills by Arabic numerals. Stratigraphic units are designated with an S.
- 3 T1, S24: Microcharcoal, Lyon 45–15,  $915 \pm 30$  B.P.,  $2 \sigma$  calibrated date (95.4%): A.D. 1030–1189 (Reimer et al. 2013).
- 4 T1, S30: Microcharcoal, Lyon 49–43,  $305 \pm 30$  B.P.,  $2 \sigma$  calibrated date (95.4%): A.D. 1489–1651 (Reimer, 2013).
- 5 T2, S VIII: Microcharcoal, Lyon 49–42,  $1380 \pm 35$  B.P.,  $2 \sigma$  calibrated date (95.4%): A.D. 596–752 (Reimer et al. 2013).

## References Cited

- Ackerly, N. W. and T. K. Henderson (editors) 1989 *Prehistoric Agricultural Activities on the Lehi-Mesa Terrace. Perspectives on Hobokam Irrigation Cycles*. Northland Research Inc, Tempe.

- Alonso, P., C. Dorronsoro and J. A. Egidio 2004 Carbonatation in palaeosols formed on terraces in the Tormes River Basin, Salamanca, Spain. *Geoderma* 118:261–276.
- Amonette, J. 1994 *Quantitative Methods in Soil Mineralogy*. Soil Science Society of America. SSSA Miscellaneous Publication, American Society of Agronomy, Madison, WI.
- Bal, L. 1973 *Micromorphological Analysis of Soil*. The Netherlands Soil Survey Institute, Soil Survey Papers 6, Wageningen.
- Beach, Timothy, S. Luzzadder-Beach, N. Dunning, J. Jones, J. Lohse, T. Guderjan, S. Bozarth, S. Millspaugh and T. Bhattacharya 2009 A review of human and natural changes in Maya Lowland wetlands over the Holocene. *Quaternary Science Reviews* 28:1710–1724
- Berger G. W. 1986 Dating Quaternary deposits by luminescence—recent advances. *Geoscience Canada* 13:15–21.
- Berger, J.-F. 1996 Climat et Dynamique des Agrosystèmes dans la Moyenne Vallée du Rhône. In *Le III ème Siècle en Gaule Narbonnaise. Données Régionales sur la crise de l'Empire*, edited by Jean-Luc Fiches, pp. 299–332. Apdca, Sophia Antipolis.
- 2000 Les Fossés Bordiers Historiques et l'histoire Agraire Rhodanienne. *Etudes Rurales: 153–154 La Très Longue Durée*:59–90.
- Berger, J.-F. and C. Jung 1996 Fonction, evolution et “Taphonomie” des Parcelles en Moyenne Vallée du Rhône. Un Exemple d'approche Intégrée en Archéomorphologie et en Géoarchéologie. In *Les Formes Du Paysage, Tome 2*, edited by G. Chouquer, pp. 95–112. Errance, Paris.
- Bernigaud, N. 2012 Dynamique des Interactions Socio-Environnementales autour des Marais de Bourgoin-la Verpillière et du Grand Plan (Isère), depuis le Néolithique jusqu'au XIXe Siècle. Unpublished Doctorate in Archaeology, University of Nice Sophia Antipolis.
- Bertrand, G. 1975 Pour une Histoire Ecologique de la France Rurale. In *Histoire de la France Rurale*, edited by G. Duby and A. Wallon, pp. 34–113. T.1. Editions du Seuil, Paris.
- Bresson, L. and C. Valentin 1994 Soil surface crust formation: Contribution of micromorphology. In *Soil Micromorphology: Studies in Management and Genesis*, edited by A. J. Ringrose and G. S. Voase, pp. 737–762. Humphreys, Elsevier, Amsterdam.
- Brewer, R. and J. R. Sleeman 1960 Soil structure and fabric. Their definition and description. *Journal of Soil Science* 11:172–185.
- Bruins, H. J., M. Evenari and U. Nessler 1986 Rainwater-harvesting agriculture for food production in arid zones: The challenge of the African famine. *Applied Geography* 6:13–32.
- Bullock, P., N. Fédoroff, A. Jongerius, G. Stoops, T. Tursina and U. Babel 1985 *Handbook for Soil Thin Section Description*. Waine Research Publications, Wolverhampton.
- Cable, J. S. and D. E. Doyel 1984 The implications of field houses for modeling Hohokam agricultural systems. In *Archaeology of the Original Townsite: The Murphy's Addition*, edited by J. S. Cable, S. L. Henry, D. E. Doyel, pp. 259–280. City Of Phoenix, Soil Systems Publications in Archaeology No. 8, Phoenix, AZ.
- Chen, Y., J. Tarchitzky, J. Brouwer, J. Morin and A. Banin 1980 Scanning electron microscope observations on soil crusts and their formation. *Soil Science* 130:49–55.

- Chouquer, G. 2000 *L'étude des Paysages. Essai sur leurs Formes et leur Histoire*. Editions Errance, Paris.
- Chouquer, G. and F. Favory 1991 *Les Paysages de l'antiquité, Terres et Cadastres de l'Occident Romain*. Editions Errance, Paris.
- Ciolek-Torrello R., S. M. Whittlesey and J. R. Welch 1994 A synthetic model of prehistoric land use. In *The Roosevelt Rural Sites Study. Vol. 3: Changing Land Use in the Tonto Basin*, edited by R. Ciolek-Torrello and J. R. Welch, pp. 437–472. J.R. Statistical Research Technical Series 28, Tucson.
- Clarke, D., R. Sala, J.-M. Deom and E. Meseth 2005 Reconstructing irrigation at Otrar Oasis, Kazakhstan, AD 800–1700y. *Irrigation and Drainage* 54:375–388.
- Cook, E. R., C. A. Woodhouse, C. M. Eakin, D. M. Meko and D. W. Stahle 2004 Long-term aridity changes in the western United States. *Science* 306:1015–1018.
- Cook, J. P., P. A. Pearthree, J. Onken, A. Youberg and E. R. Bigio 2010 *Mapping of Holocene River Alluvium along Oak Creek, Wet Beaver Creek, West Clear Creek, Fossil Creek, and the East Verde River, Central Arizona*. Arizona Geological Survey, 40, Tucson, AZ.
- Courty, M.-A. 1990 *Environnements Géologiques dans le Nord-Ouest de l'Inde. Contraintes Géodynamiques au Peuplement Protohistorique*, Thèse d'état, Université de Bordeaux.
- 1994 Le Cadre Paléogéographique des occupations humaines dans le Bassin du Haut-Khabour, Syrie Du Nord-Est. Premiers Résultats. *Paléorient* 20:21–59.
- Courty, M. A. and N. Fédoroff 1985 Micromorphology of recent and buried soils in a semi-arid region of Northwestern India. *Geoderma* 35:287–332.
- 1999 L'apport de la Micromorphologie des sols à la Reconstitution des Paléopaysages (Application au Bassin Méditerranéen pour la période 3000 av. J.C.—1800 ap. J.C.). In *Environmental Reconstruction in Mediterranean Landscape Archaeology*, edited by P. Leveau et al., pp. 55–65. The Archaeology of Mediterranean Landscapes 2, Oxford.
- Courty, M. A., P. Goldberg and R. Macphail 1990 *Soils and Micromorphology in Archaeology*. Cambridge Manuals in Archaeology, Cambridge University Press, Cambridge.
- Courty, M. A. and P. Nornberg 1985 Comparison between buried uncultivated and cultivated Iron Age soils of the west coast of Jutland, Denmark. *Iskos* 5:57–69.
- Crook, D. C., R. J. Jones, M. Elvin, J. Shen and J. A. Dearing 2008 The history of irrigation and water control in China's Erhai catchment: Mitigation and adaptation to environmental change. In *Mountains: Sources of Water, Sources of Knowledge*, edited by E. Wiegandt, pp. 21–42. Springer, Dordrecht.
- Davis, A. P. 1902 *Water Storage on the Salt River, Arizona*. US Geological Survey Water Supply Paper 73.
- Deaver, W. L. 1997 Chronological issues of the LVAP. In *Vanishing River. Landscapes and Lives of the Lower Verde Valley*, edited by S. M. Whittlesey, R. S. Ciolek-Torrello and J. H. Altschul, pp. 447–490. Statistical Research Inc., Tucson.
- Doelle, W. H. 1995 Tonto basin demography in a regional perspective. In *The Roosevelt Community Development Study. New Perspectives on Tonto Basin Prehistory*, edited by M. D. Elson, M. T. Stark and D. A. Gregory, pp. 201–226. Center for Desert Archaeology Anthropological Papers 15, Tucson.
- 2000 Tonto basin demography in a regional perspective. In *Salado*, edited by J. S. Dean, pp. 81–105. Amerind Foundation New World Studies Series 4, Dagoon, AZ.

- Dorronsoro, C. 1994 Micromorphological index for the evaluation of soil evolution in central Spain. *Geoderma* 61:237–250.
- Downing, T. and G. Mcguire 1974 *Irrigation's Impact on Society*. University of Arizona Press, Tucson.
- Doyel, D. E. 1979 The prehistoric Hohokam of the Arizona desert. *American Scientist* 67:544–554.
- 1991 Hohokam cultural evolution in the Phoenix basin. In *Exploring the Hohokam: Prehistoric Desert Peoples of the American Southwest*, edited by G. J. Gumerman, pp. 231–278. University of New Mexico Press, Albuquerque.
- Doyel, D. E., A. Black and B. Macnider 1995 *Archaeological Excavations at Pueblo Blanco. The MCDOT Alma School Road Project*. Archaeological Consulting Services Cultural Resources Report 90, Tempe.
- Ely, L. 1992 *Large Floods in the Southwestern United States in Relation to Late-Holocene Climate Variations*. Ph.D. Dissertation, University of Arizona, Tucson.
- Ely, L., Y. Enzel, V. R. Baker and D. R. Cayan 1993 A 5000 year record of extreme floods and climate change in the southwestern United States. *Science* 262:410–412.
- Ely, L., Y. Enzel and D. R. Cayan 1994 Anomalous North Pacific atmospheric circulation and large winter floods in the southwestern United States. *Journal of Climate* 7:977–987.
- Enache, M. D. and B. F. Cumming 2006 Tracking recorded fires using charcoal morphology from the sedimentary sequence of prosser lake. British Columbia (Canada). *Quaternary Research* 65:282–292.
- Ensor, B. E., M. Ensor and G. V. De Vries 2003 Hohokam political ecology and vulnerability: Comments on waters and ravesloot. *American Antiquity* 68:169–181.
- Eswaran, H. 1968 Point-count analysis as applied to soil micromorphology. *Pédologie* 18:238–252.
- Etheredge, D., D. S. Gutzler and F. J. Pazzaglia 2004 Geomorphic response to seasonal variations in rainfall in the southwest United States. *GSA Bulletin* 116(5–6):606–618.
- Evans, D. D. and S. W. Buol 1968 Micromorphological study of soil crusts. *Soil Science Society America Proceeding* 32:19–22.
- Fédoroff, N., L. M. Bresson and C. A. Courty (editors) 1987 *Micromorphology des sols, Soil Micromorphology*. AFES, Paris.
- Fédoroff, N. and C. A. Courty 1989 Indicateurs Pédologiques d'Aridification: Exemples du Sahara. *Bulletin de la Société Géologique Française* 5:43–53.
- 1994 Organisation du Sol aux Echelles Microscopiques. In *Pédologie: Constituants et Propriétés Du Sol, 2ème Edition*, edited by M. Bonneau and S. Souchier, pp. 349–375. Edition Masson, Paris.
- 1999 Soil and soil forming processes under increasing aridity. In *Paleoenvironmental Reconstructions in Arid Lands*, edited by A. K. Singhvi and E. Derbyshire, pp. 72–108. Oxford Et Ibh Publishing, Calcutta.
- Fenneman, N. M. 1931 *Physiography of Western United States*. Mcgraw-Hill, New York.
- Fitzpatrick, E. A. 1980 *The Micromorphology of Soils, a Manual for the Preparation and Description of Thin Sections of Soils*. University of Aberdeen, Aberdeen, UK.
- Fowler, M. J. F. 2002 Satellite remote sensing and archaeology: A Comparative study of satellite imagery of the environs of Figsbury Ring, Wiltshire. *Archaeological Prospection* 8(2):55–69.
- Francfort, H.-P. and O. Lecomte 2002 Irrigation et Société en Asie Centrale des Origines à l'époque Achéménide. In *Annales. Histoire, Sciences Sociales* 57(3):625–663.

- Gebhardt, A. 1988 Evolution du paysage bocager sub-atlantique en morbihan. Apport de la micromorphologie. *Bulletin de l'association Française pour l'étude du Quaternaire* 4:197–203.
- 1993 Soil micromorphological evidence of soil deterioration since the Mid-Holocene in Brittany, France. *The Holocene* 3(3):333–341.
- 2000 Le Rôle de la micromorphologie des Sols dans la formation des Paysages. *Etudes Rurales, La Très Longue Durée* 153–154:139–149.
- Gentelle, P. 1980 Le croissant fertile. *Le Monde de la Bible et Terre Sainte* 15:4–8.
- Gilbert, G. K. 1875 Report of the geology of portions of Nevada, Utah, California and Arizona Examined in the years 1871 and 1872. *U.S. Geographic Surveys West Of the One-Hundredth Meridian* 3:17–187.
- Glick, T. 1996 *Irrigation and Hydraulic Technology: Medieval Spain and its Legacy*. Aldershot, Variorum.
- Goldberg Paul and Richard I. Macphail 2006 *Practical and Theoretical Geoarchaeology*. Blackwell Science, Oxford.
- Goodman-Elgar Melissa 2007 Evaluating soil resilience in long-term cultivation: A study of pre-columbian terraces from the Paca Valley, Peru. *Journal of Archaeological Science* 35:3072–3086.
- 2008 Agricultural fields. Identification and study. *Encyclopedia of Archaeology* 1:110–115.
- Graf, W. 1983 The arroyo problem: Paleohydrology and paleohydraulics in the short term. In *Background to Paleohydrology*, edited by K. E. Gregory, pp. 279–302. Wiley, New York.
- Graybill, D. A. 1989 The reconstruction of prehistoric salt river streamflow. In *The 1982–1984 Excavations At Las Colinas: Environment and Subsistence*, edited by D. A. Graybill, D. A. Gregory, F. L. Nials, S. K. Fish, R. E. Gasser, C. H. Miksicek and C. R. Szuter, pp. 25–38. Arizona State Museum Archaeological Series 162, Tucson.
- Graybill, D. A., D. A. Gregory, G. S. Funkhauser and F. L. Nials 2006 Long-term streamflow reconstructions, river channel morphology, and aboriginal irrigation systems along the salt and Gila Rivers. In *Environmental Change and Human Adaptation in the Ancient Southwest*, edited by J. S. Dean and D. E. Doyel, pp. 69–123. University of Utah Press, Salt Lake City.
- Greenwals, D. H., M. Zyniecki and D. M. Greenwals (editors) 1994 *Early Desert Farming and Irrigation Settlements: Archaeological Investigations and the Phoenix Sky Harbor Center, Volume 2, Dutch Canal Ruin*. Anthropological Research Papers No. 4. Swca Environmental Consultants, Flagstaff and Tucson.
- Gregory, D. A. 1991 Form and variation in Hohokam settlement pattern. In *Chaco and Hohokam: Prehistoric Regional Systems in the American Southwest*, edited by P. L. Crown and W. J. Judge, pp. 159–193. School of American Research Press, Santa Fe.
- Gregory, K. J. and C. Park 1974 Adjustment of river channel capacity downstream from a reservoir. *Water Resources Research* 10:363–374.
- Guilloré, P. 1983 *Méthode de Fabrication Mécanique et en Série de lames Mincees*. Institut National Agronomique Paris Grignon, Département Des Sols.
- Gumerman George 1991 Understanding the Hohokam. In *Exploring the Hohokam: Prehistoric Desert Peoples of the American Southwest*, edited by G. J. Gumerman, pp. 1–27. University of New Mexico Press, Albuquerque.
- Hackbarth, M. R. 1992 *Archaeological testing at Verde Park, City of Phoenix*. Northland Research Archaeology Series 3, Phoenix, 127 pp.

- Hackbarth, M. R., T. K. Henderson, D. Craig, G. Huckleberry, C. Miksicek, M. Palacios-Fest, S. Smith 1995. *Archaeology at the Head of the Scottsdale Canal System. Vol. 3 : Canal and Synthetic Studies*. Northland Research Anthropological papers of the University of Arizona, No. 95–1.
- Hallaire, V., M. Hachicha and C. Cheverry 1998 Evolution structurale d'un horizon de surface argileux sous irrigation. *Etude et Gestion des Sols* 5(2):107–116.
- Harden, J. 1982 A Quantitative index of soil development from field descriptions: Examples from a chronosequence in central California. *Geoderma* 28:1–28.
- Harrower, Michael J. 2006 *Environmental versus Social Parameters, Landscape, and the Origins of Irrigation in Southwest Arabia (Yemen)*. Unpublished Ph.D., Ohio State University.
- Haurly, Emil W. 1976 *The Hohokam, Desert Farmers and Craftsmen*. University of Arizona Press, Tucson.
- Hegmon M. 2002 Recent issues in the archaeology of the Mimbres region of the North American Southwest. *Journal of Archaeological Research* 10(4):307–357.
- Henderson, T. K. 1989 The chronology of the Las Acequias Canals. In *Prehistoric Agricultural Activities on the Lehi-Mesa Terrace: Perspectives on Hohokam Irrigation Cycles*, edited by N. W. Ackerly and T. K. Henderson, pp. 184–199. Northland Research Inc, Flagstaff, AZ.
- Henderson, T. K. and T. C. Clark 2004 Changing perspectives: Considerations of past agricultural use of the Salt River floodplain. In *Hohokam Farming on the Salt River Floodplain: Refining Models and Analytical Methods*, edited by T. K. Henderson. Anthropological Papers No. 43. Tucson, AZ: Center for Desert Archaeology.
- Hirschboeck, K. K. 1985 *Hydroclimatology of Flow Events in the Gila River Basin, Central and Southern Arizona*. Ph.D. Dissertation, University of Arizona.
- 1987 Catastrophic flooding and atmospheric circulation anomalies. In *Catastrophic Flooding*, edited by L. Mayer and D. Nash, pp. 23–56. Allen and Unwin, Concord, Massachusetts.
- 1988 Flood hydroclimatology. In *Flood Geomorphology*, edited by V. R. Baker, R. C. Kochel and P. C. Patton, pp. 27–49. John Wiley & Sons, New York.
- House, P. K. and K. K. Hirschboeck 1997 Hydroclimatological and paleohydrological context of extreme winter flooding in Arizona, 1993. Storm-Induced Geologic Hazards. In *Case Histories From The 1992–1993 Winter in Southern California and Arizona*, edited by E. R. Larson and J. E. Slosson, pp.1–25. Geological Society of America Reviews in Engineering Geology.
- Howard J. B. 1987 The Lehi Canal System: Organization of a Classic Period community. In *The Hohokam Village: Site Structure and Organization*, edited by D. E. Doyel, pp. 211–255. Southwestern and Rocky Mountain Division of the American Association for the Advancement of Science, Glenwood Springs, CO.
- Howard, J. B. and Gary Huckleberry 1991 *The Operation and Evolution of an Irrigation System: The East Papago Canal Study*. Soil Systems Publication in Archaeology 18, Phoenix.
- Huckleberry, Gary 1999 Stratigraphic identification of destructive floods in relict canals: A case study from the middle Gila River, Arizona. *The Kiva* 65:7–33.
- Huckleberry, Gary, J. Onken, W. Graves and R. Wegener 2013 Climatic, geomorphic, and archaeological implications of a late quaternary alluvial chronology in the lower Salt River, Arizona, USA. *Geomorphology* 185:39–53.
- Hunt, E. and R. C. Hunt 1973 Irrigation, conflict, and politics: A Mexican case. In *Irrigation's Impact on Society*, edited by T. Downing and G. Macguire, pp. 129–157. University of Arizona Press, Tucson.

- Hunt, R. C. and E. Hunt 1976 Canal irrigation and local social organization. *Current Anthropology* 17(3):389–411.
- Jones, P. D. and M. E. Mann 2004 Climate over past millennia. *Reviews of Geophysics* 42(2):1–42.
- Jones, R. E., B. S. J. Isserlin, V. Karastathis, S. P. Paramarinopoulos, G. E. Syrides, J. Uren, I. Balatsas, C. Kapopoulos, Y. Maniatis and G. Facorellis 2000 Exploration of the Canal of Xerxes, Northern Greece: The role of geophysical and other techniques. *Archaeological Prospection* 7:147–170.
- Kapur, S. and G. Stoops (editors) 2008 *New Trends in Micromorphology*. Springer-Verlag, Berlin.
- Keay, S., G. Earl, S. Kay, J. Ogden and K. Strutt 2009 The role of integrated geophysical survey methods on the assessment of archaeological landscapes: The case of portus. *Archaeological Prospection* 16(3):154–166.
- Kemp, R. A., C. A. Whiteman and J. Rose 1993 Palaeoenvironmental and stratigraphic significance of the valley farm and barham soils in Eastern England. *Quaternary Science Reviews* 12:833–848.
- Kubiëna, W. L. 1938 *Micropedology*. Collegiate Press, Ames, IA.
- Lebedeva-Verba, M. P. and M. I. Gerasimova 2009 Micromorphology of diagnostic Horizons in aridic soils (complementary to the new classification system of soils of Russia). *Eurasian Soil Science* 42(13):1427–1434.
- Leblanc, S. A. 1999 *Prehistoric Warfare in the American Southwest*. University of Utah Press, Salt Lake City.
- Lees, S. 1973. *Sociopolitical aspects of canal irrigation in the valley of Oaxaca*. Memoirs of the Museum of Anthropology, University of Michigan, Ann Arbor.
- Lees, S. and K. V. Flannery (editors) 1973 *Sociopolitical Aspects of Canal Irrigation in the Valley of Oaxaca*. University of Michigan, Memoirs of the Museum of Anthropology, Ann Harbor.
- Leroyer, C. and V. Krier 1991 Etudes Environnementales des Remplissages de Fossés: Premiers Résultats Micromorphologiques et Palynologiques Expérimentaux. In *Archéologie Expérimentale, Tome 2 — La terre: l'os et la Pierre, la Maison et les Champs*, Actes du Colloque International Expérimentation en Archéologie: Bilan et Perspectives, pp. 228–235. Editions Errance, Paris.
- Lévêque, C., T. Muxart, L. Abbadie, A. Weil and S. van der Leeuw 2003 L'anthroposystème: entité structurelle et fonctionnelle des interactions sociétés-milieus. In *Quelles natures soulons-nous?*, edited by C. Lévêque and S. van der Leeuw, pp. 110–129. Elsevier, Paris.
- Macphail, Richard I. 1986 Paleosols in archaeology: Their role in understanding flandrian pedogenesis. In *Paleosols, Their Recognition and Interpretation*, edited by P. Wright, pp. 263–290. Blackwell Scientific Publication, Oxford.
- 1990 *Soil Report on the Deansway Archaeology Project, Worcester*. Ancient Monuments Laboratory Report 82/91, English Heritage.
- 1992 Soil micromorphological evidence of ancient soil erosion. In *Past and Present Soil Erosion*, edited by M. Bell and J. Boardman, pp. 197–2015. Oxbow Monograph 22, Oxford.
- Macphail, Richard I., M. A. Courty and A. Gebhardt 1990 Soil micromorphological evidence of early agriculture in North-West Europe. *World Archaeology* 22: 53–69.
- Macphail, Richard I., J. C. C. Romans and L. Robertson 1987 The application of micromorphology to the understanding of Holocene soil development in the British Isles, with special reference to early cultivation. In *Micromorphologie des*

- Sols, edited by N. Fédoroff, L. M. Bresson and M. A. Courty, pp. 647–656. Afes, Plaisir.
- Marcolongo, B. and D. M. Morandi Bonacossi 1997 L'abandon du Système d'irrigation Qatabanite dans la Vallée du Wadi Bayhan (Yémen): Analyse Géochronologique. *Comptes Rendus de l'Académie des Sciences—Series Iia—Earth and Planetary Science* 325 (1):79–86.
- Masse, W. B. 1987 *Archaeological Investigations of Portions of the Las Acequias-Los Muertos Irrigation System*. Arizona State Museum Archaeological Series 176, University Of Arizona, Tucson.
- Mathieu, C. and A. Ruellan 1987 Evolution Morphologique des Sols Irrigués en Région Méditerranéenne Semi-Aride: l'exemple de la Basse Moulouya (Maroc). *Cahiers Orstom Pédologie* 13:3–25.
- Mitchell, D. R. and T. Motsinger (editors) 1998 *Life at the River's Edge: Hohokam Irrigation and Settlement along the Red Mountain Freeway between Price Road and Mckellips Road*. Swca Archaeological Report 97–23, Scottsdale.
- Mitchell, W. 1973 The hydraulic hypothesis. A reappraisal. *Current Anthropology* 14:532–534.
- Moberg, A., D. M. Sonechkin, K. Holmgren, N. M. Datsenko and W. Karlen 2005 Highly variable northern hemisphere temperatures from low- and high-resolution proxy data. *Nature* 433:613–617.
- Monger, H. C., L. A. Daugherty, W. C. Lindemann and C. M. Liddell 1991 Microbial precipitation of pedogenic calcite. *Geology* 19:997–1000.
- Mouton, M. 2004 Irrigation et Formation de la Société Antique dans les Basses-Terres du Yémen: un Essai de Modèle, *Syria* 81:81–104.
- Murphy, C. and R. Kemp 1987 Micromorphology and the argillic Horizon—a reappraisal. In *Micromorphologie des Sols*, edited by N. Fédoroff, L. M. Bresson and M. A. Courty, pp. 257–261. Afes, Plaisir.
- Nabhan, G. P. 1986 Papago indian desert agriculture and water control in the sonoran desert, 1697–1934. *Applied Geography* 6:43–59.
- Nanson, G. C. and J. C. Croke 1992 A genetic classification of floodplains. *Geomorphology* 4:459–486.
- Nelson, M.C., K. Kintigh, D. R., Abbott and J. M. Anderies 2010 The cross-scale interplay between social and biophysical context and the vulnerability of irrigation-dependent societies: Archaeology's long-term perspective. *Ecology and Society* 15(3):31.
- Netting, R. 1974 The system nobody knows: Village irrigation in the swiss alps. In *Irrigation's Impact on Society*, edited by T. E. Downing and G. Mcguire, pp. 67–75. Anthropological Papers of the University of Arizona 25, Tucson.
- Ni, F., T. Cavazos, M. K. Hughes, A. C. Comrie and G. Funkhauser 2002 Cool-season precipitation in the Southwestern USA Since AD 1000: Comparison of linear and nonlinear techniques for reconstruction. *International Journal of Climatology* 22(13):1645–1662.
- Nials, F. L., D. A. Gregory and D. A. Graybill 1986 Salt River streamflow and the Hohokam irrigation system. In *The 1982–1984 Excavations at Las Colinas. Vol. 5: Environment and Subsistence*, edited by D. A. Graybill, D. A. Gregory, F. L. Nials, S. K. Fish, R. E. Gasser, C. H. Miksicek and C. R. Szuter, pp. 59–78. Arizona State Museum Archaeological Series 162, Tucson.
- Onken, J., M. R. Waters and J. A. Homburg 2004 *Geoarchaeological Assessment for the Tres Rios Project, Maricopa County, Arizona*. Statistical Research Inc., Technical Report 03–68, Redlands, California.

- Orengo, H. and C. Miro i Alaix 2013 Reconsidering the water system of Roman Barcino (Barcelona) from supply to discharge. *Water History* 5:243–266.
- Ortloff, Charles E. 2009 *Water Engineering in the Ancient World*. Oxford University Press, Oxford.
- Pal, D. K., P. Srivastava and T. Bhattacharyya 2003 Clay illuviation in calcareous soils of the semi-arid part of the indo-gangetic plains, India. *Catena* 115:177–192.
- Palacios-Fest, M. R. 1994 Nonmarine ostracode shell chemistry from ancient Hohokam irrigation canals in central Arizona: A paleohydrochemical tool for the interpretation of prehistoric human occupation of the western United States. *Geoarchaeology: An International Journal* 9:1–29.
- Palacios-Fest, M. R., J. B. Mabry, F. Nials, J. P. Holmlund, E. Miksa and O. K. Davis 2001 Early irrigation systems in southeastern Arizona: The ostracode perspective. *Journal of South American Earth Sciences* 14(5):541–555.
- Pawluk, S. 1978 The pedogenic profile in the stratigraphic section. In *Quaternary Soils*, edited by W. C. Mahaney, pp. 61–75. Geo Abstracts, Norwich.
- Pearthree, P. A. and G. Huckleberry 1994 *Surficial Geologic Map of the Mesa 30' × 60' Quadrangle, Arizona*. Arizona Geological Survey Open-File Report 94–23, Scale 1:100,000.
- Péwé, T. 1978 Terraces of the lower salt river valley in relation to the late cenozoic history of the phoenix basin, Arizona. In *Guidebook to the Geology of Central Arizona, State of Arizona*, edited by D. M., Burt and T. L. Péwé, pp. 1–46. Bureau of Geology and Mineral Technology, No. 2, Tucson, AZ.
- Phillips, B. G., A. Gibbson, A. Miller, M. S. Droz and L. A. Walker 2004 Paleoenvirronnement. In *Life on the Lehi Terrace: The Archaeology of the Red Mountain Freeway between State Route 87 and Gilbert Road*, edited by S. Powell, R. L. Boston, pp 11–47. Archaeological Consulting Services Cultural Resources Report 135, Tempe.
- Pournelle, J. R 2003 The littoral foundation of the Uruk State: Using satellite photography toward a new understanding of the 5th/4th millennium bce landscapes in the warka survey area, Iraq. In *Chalcolithic and Early Bronze Age Hydrostrategies*, edited by D. Gheorghiu, pp. 5–23. Bar International Series 1123, Oxford Archeopress, Oxford.
- Powlesland, D. J., J. Lyall, D. Hopkinson, D. N. M. Donoghue, M., Beck, A. Harte and D. Stott 2006 Beneath the sand—remote sensing, archaeology, aggregates and sustainability: A case study from Heselton, the Vale of Pickering, North Yorkshire, UK. *Archaeological Prospection* 13:291–299.
- Presley, D. R., M. D. Ransom, G. J. Kluitenberg and P. R. Finnell 2004 Effects of thirty years of irrigation on the genesis and morphology of two semiarid soils. *Soil Science Society of America Journal* 68:1916–1926.
- Purdue, Louise 2011 *Dynamique des Paysages Agraires et Gestion de l'eau dans le Bassin Semi-Désertique de Phoenix, Arizona, de la Préhistoire à l'époque moderne*. Unpublished Ph.D. Dissertation, Université of Nice.
- 2013 Dynamiques Alluviales et Adaptations aux Contraintes Hydro-Climatiques dans le Sud-Ouest Américain au cours des deux Derniers Millénaires (Phoenix, Arizona). *Géomorphologie: Relief, Processus, Environnement* 19(3):243–264.
- Purdue, Louise E., W. Miles, K. Woodson, A. Darling and J.-F. Berger 2010 Micro-morphological study of irrigation canal sediments: Landscape evolution and hydraulic management in the Middle Gila River Valley (Phoenix Basin, Arizona) during the Hohokam occupation. *Quaternary International* 216:129–144.
- Reimer, P. J., E. Bard, A. Bayliss, J. W. Beck, P. G. Blackwell, C. Bronk Ramsey, C. E. Buck, H. Cheng, R. L. Edwards, M. Friedrich, P. M. Grootes, T. P. Guilderson,

- H. Haflidason, I. Hajdas, C. Hatté, T. J. Heaton, D. L. Hoffmann, A. G. Hogg, K. A. Hughen, K. F. Kaiser, B. Kromer, S. W. Manning, M. Niu, R. W. Reimer, D. A. Richards, E. M. Scott, J. R. Southon, R. A. Staff, C. S. M. Turney and J. van der Plicht 2013 IntCal13 and Marine13 radiocarbon age calibration curves 0–50,000 years cal BP. *Radiocarbon* 55(4):1869–1887.
- Richards, G. E. 1982 *Rivers: Form and Process in Alluvial Channels*. Methuen, London.
- Sanders, William T. 1982 *Introduction, a Reconstruction of a Classic Period Landscape in the Teotihuacan Valley: Report to the National Science Foundation*, 1–19. Manuscript on File, Department of Anthropology, Pennsylvania State University.
- Sandor, A. S., J. B. Norton, J. A. Humburg, D. A. Muenchrath, S. E. Williams, C. I. Havener and P. D. Stahl 2007 Biochemical studies of a North American runoff. *Geoarchaeology* 22(3):359–386.
- Sehgal, J. L. and G. Stoops 1972 Pedogenic calcite accumulations in arid and semi-arid regions of the indo-gangetic alluvial plain of Erswile Punjab (India)—their morphology and origin. *Geoderma* 8:59–72.
- Sellers, W. D. 1965 *Physical climatology*. University of Chicago Press, Chicago.
- Service, Elman R. 1975 *Origins of the State and Civilization: The Process of Cultural Evolution*. W. W. Norton, New York.
- Singhvi, A. K. and E. Derbyshire (editors) 1999 *Paleoenvironmental Reconstruction in Arid Lands*. A. A. Balkema, Rotterdam, Netherlands.
- Soil Survey Staff 1975 *Soil Taxonomy, a Basic System of Soil Classification for Making and Interpreting Soil Surveys*. US Department Of Agriculture Handbook.
- Stoops, G. 2003 *Guidelines for Analysis and Description of Soil and Regolith Thin Sections*. Soil Science Society of America, Madison, Wisconsin.
- Stoops, G., V. Marcelino and F. Mees 2010 *Interpretation of Micromorphological Features of Soils and Regoliths*. Elsevier Science, Amsterdam.
- Swanson S. and M. W. Diehl 2003 Mimbres pithouse dwellers. *Archaeology Southwest* 17(4):3
- Valentine, K. W. G. and J. B. Dalrymple 1976 Quaternary buried paleosols: A critical review. *Quaternary Research* 6:208–222.
- Verba, M., L. Aidabekova and I. Yamnova 2002 *Micromorphological and Mineralogical Peculiarities of old-Irrigated Soils on Aral Sea Basin*. Proceedings of the 17th World Congress of Soil Science, Bangkok, Thailand, Poster.
- Verba, M. P., A. S. Al-Kasiri, N. A. Goncharova and N. P. Chizhikova 1995 Impact of irrigation on micromorphological features of desert soils of Hadramout Valley (Yemen). *Eurasian Soil Science* 27:108–124.
- Waters Michael, R. 1998 The effect of landscape and hydrologic variables on the prehistoric salado: Geoarchaeological investigations of the Tonto basin, Arizona. *Geoarchaeology* 13:105–160.
- 2000 Alluvial stratigraphy and geoarchaeology in the American southwest. *Geoarchaeology* 15:537–557.
- Waters, Michael R. and C. Vance Haynes 2001. Late quaternary arroyo formation and climate change in the American southwest. *Geology* 29(5):399–402.
- Waters, Michael R. and J. Ravesloot 2001 Landscape change and the cultural evolution of the Hohokam along the Middle Gila River and other river valleys in south central Arizona. *American Antiquity* 66(2):285–299.
- Western Regional Climate Center 2015 Historical climate information. <http://www.wrcc.dri.edu/>

- Whitlock, C. and S. H. Millspaugh 1996 Testing assumptions of fire history studies: An examination of modern charcoal accumulation in Yellowstone National Park. *The Holocene* 6:7–15.
- Wilkinson, Tony J. 1998 Water and human settlement in the Balikh Valley, Syria: Investigations from 1992–1995. *Journal of Field Archaeology* 25(1):63–87
- 2003 Hydraulic landscapes and irrigation systems of sumer. In *The Sumerian World*, edited by H. Crawford, pp. 33–54. Routledge, London, New York.
- Wilson, C., I. A. Simpson and E. J. Currie 2002 Soil management in pre-Hispanic raised field systems: Micromorphological evidence from Hacienda Zuleta, Ecuador. *Geoarchaeology* 17(3):261–283.
- Wittfogel, Karl A. 1957 *Oriental Despotism. A Study of Total Power*. Yale University Press, New Haven.