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Hazard, risk and agrarian adaptations in a hyperarid watershed: El Niño floods, streambank erosion, and the cultural bounds of vulnerability in the Andean Middle Horizon

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ABSTRACT

Peru's Osmore drainage, also known as the Moquegua Valley, is one of the driest regions on Earth, yet agricultural development has supported complex societies in the basin for almost 4000 yrs because of canal construction and irrigation. We compare the distinct agrarian and settlement systems of three coeval archaeological cultures in this arid region, Huaracane, Wari and Tiwanaku, and how each adapted—or failed to adapt—to geomorphic and climatic hazards. Systematic settlement pattern survey and radiocarbon dating along with geomorphological analysis of flood history and riverine processes permit detailed discussion of agrarian strategies during the Formative (1800 BC–AD 500) and Middle Horizon (AD 500–1000) periods, with distinct settlement "niches" in terms of agricultural practices and longitudinal position in the drainage, and lateral location relative to the floodplain. These adaptive strategies each manifest distinct "bounds of adaptability" to natural hazard, climate events and social stressors, and thus varying risk profiles. Besides the continual risk associated with sustained droughts, the Atacama and Peruvian Coastal Desert and culturally connected highland Altiplano are also vulnerable to the vagaries of the El Niño-Southern Oscillation (ENSO) leading to catastrophic floods in the mid-valley during warm phase ENSOs, in tandem with simultaneous hazards in other regions inhabited by these transregional cultures. By comparing the archaeological record of Wari, Huaracane, and Tiwanaku culture settlements with geomorphic signatures of catastrophic El Niños, we show that the viability of each cultural sequence depended on specific relationships to floodplain streambank erosion, construction and reworking over multiple time scales.

1. Introduction

Peru's Osmore drainage, also known as the Moquegua Valley, is one of the driest regions on earth, yet agricultural development has supported complex societies in the basin for almost 4000 yrs because of canal construction and irrigation. Despite the significant limitations imposed by climate and frequent hazards, such as those associated with the El Niño Southern Oscillation (ENSO), the Moquegua Valley in southern Peru has been a site of rich cultural development with major settlements by the Wari, Huaracane, Tiwanaku, Chiribaya, and Estuquiña cultures. Through sophisticated canal construction, terracing, and extensive irrigation networks, agricultural development has supported social complexity in both the high altitude sierra and altiplano regions (Erickson, 2000; Kolata, 1996; Stanish, 2006) and in the river valleys of the Atacama and Peruvian Coastal Desert (Billman, 2002; Hayashida, 2006; Williams, 2006) even though many parts of the region receive <50–100 mm yr^{-1} of precipitation (Houston and Hartley, 2003). Moreover, extensive generalized droughts in the highland watersheds have occurred throughout the Late Holocene and have been implicated as a proximate cause of the collapse of Andean agrarian civilizations like the Moche circa AD 700 and Tiwanaku circa AD 1100 (Abbott et al., 1997; Kolata, 1996; Kolata et al., 2000; Ortloff, 1993; Shimada et al., 1991). Most previous research on agrarian risk and hazard has been directed at proxy records indicating fluctuations in rainfall, as water availability is critical for all agrarian systems in this hyper-arid region.

Besides this fundamental reliance on water availability, agricultural development in pre-Columbian Andean societies also had specific relationships to local geomorphic effects within the valley and floodplain system. The agrarian significance of floodplain geomorphology is often overlooked even though its attributes may also be significantly influenced by the vagaries of climate, especially the occurrence of mega-Niños that greatly re-alter floodplains and sediment supply regionally (Keefer et al., 2003; Magilligan and Goldstein, 2001) potentially limiting the availability of arable land (Manners et al., 2007). In this paper, we evaluate the cultural responses to the long-term geomorphic evolution of the Rio Moquegua floodplain and its susceptibility to extensive re-working

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by large floods associated with El Niño events from the perspective of archaeological analyses of settlement patterns and cultural practice within the Moquegua valley. In this way, we focus a much needed attention on the role and significance of floodplain sequences as a nexus of cultural, climatic, and geomorphic importance.

Archaeologists readily acknowledge that ancient societies can be distinguished by styles and preferences in their material culture, household, and mortuary traditions. When it comes to agriculture and its response to hazard, however, we often downplay the role of tradition and the inertia of cultural practice and assume universal and rational maximizing behavior in agrarian decision-making and response to hazard. Van Buren observes that “we have learned much more about the geophysical parameters of prehistoric natural hazards than we have about their relation to and impact on past societies” (van Buren, 2001:141). Conceptualizing the relationship between humans and nature has been heavily shaped by the predominance of geophysical science and technological approaches, and an impoverishment of social science theory on the effects of disaster. As a result, while research is often effective at identifying the effects of ENSO and other environmental conditions on settlements and agrarian systems, the linkages between disastrous episodes and social change have not been synthesized theoretically and there is a temptation to view ENSO and droughts as “deus ex machina” to be determined on a post hoc basis. Many disaster studies in South American Archaeology have followed a logic of detecting dramatic climate events like large floods or protracted droughts, and interpreting them as triggers to catastrophic cultural and agrarian collapse when stressors exceed thresholds of human adaptation (Beresford-Jones et al., 2009; Caviedes, 2001; Kolata, 1996; Kolata et al., 2000; Moseley, 2001; Sandweiss et al., 2008; Shimada et al., 1991). However, human irrigation systems are culturally constituted, in that they represent the “material form of social structures and relations” (Ertsen and van der Spek, 2009:178). Agricultural practice, along with related cultural variables like settlement patterns, demography, migration, cuisine and dietary intake, must be considered as cause, as well as consequence, in the interplay of hazard, adaptation, resource competition and sustainability over multiple time scales. Cultural practice may be seen as an independent variable that can alter the bounds of adaptability for human societies.

Beyond floodplains' potential to record both human culture history and geomorphological sequences, there is more to be revealed by examining the links between cultural activity and riverine geomorphic processes and landforms. Analyzing the sensitivity of floodplains to streambank erosion also reveals the floodplain's socio-economic value and vulnerability. This geomorphic/cultural duality highlights the importance of floodplains especially in arid regions where the availability of arable land is limited and floodplains represent one of the critically few areas where agriculture can exist. Recent work in the American southwest has brought geomorphological mapping to bear, emphasizing that behavioral interpretation of archaeological data requires an understanding of the geological contexts, for example noting the zonation of different Hohokam functional site types in different geomorphic zones of the Gila River basin, and how this changes over time (Huckleberry, 1995; Ravesloot and Waters, 2002; Waters and Ravesloot, 2001).

These arid region pre-Columbian societies relied on canals and irrigation, and periods of extensive streambank erosion have been implicated as causing cultural responses ranging from societal collapse and depopulation with the abandonment of major sites such as Snaketown (Huckleberry, 1995:178; Ravesloot and Waters, 2002; Waters and Ravesloot, 2001) to social change with population increase (Ingram, 2008:159). Recently, streambank erosion has also been implicated as one of several agriculturally significant responses to ENSO floods in northern Peru (Billman and Huckleberry, 2008:113).

While such studies effectively join interpretation of regional archaeological data to understanding of riverine geomorphological contexts, each assumes a single, culturally homogenous population reacting regionally to environmental change by adaptation over time. The context for our Andean research posits coeval, yet culturally distinct archaeological populations, and revolves around culturally-specific issues of social adaptability, vulnerability, and resilience to climatic and geomorphic hazards and risks. Although there has been considerable awareness in Andean archaeology of specific cultures' socio-economic responses to extreme events such as floods or droughts (Kolata et al., 2000; Kolata and Ortloff, 1996; Moseley, 1999, 2001; Williams, 2006), contemporary thinking within the social sciences has begun to more effectively distinguish between the characteristics of the stress (e.g. flood, climate change) and the ability of a specific, existing social system to mitigate or respond to it. According to the tenets of the emerging field of sustainability science (Kates et al., 2001; Turner et al., 2003), “hazard potential” depends on the synergistic interactions of the geographical context and social fabric such that the vulnerability of a place/region results from both biophysical vulnerability and social vulnerability (Cutter et al., 2000, 2003). As Turner et al. (2003) present, exposure to risk can be amplified or attenuated depending on the operationalization of social conditions and linkages, with three major social mechanisms identified: entitlement, coping through diversity, and/or resilience. This conceptual structure becomes an important template to investigate the social responses to environmental change. In the case of Andean valleys of Peru's western slope like the Moquegua Valley where flood hazards are linked to ENSO variability, the same flood magnitude may have had very differing social impacts depending on the scale of reliance on channel proximal irrigation, diversity of floodplain landforms, and the relationship between irrigation technology and resource availability.

2. Research questions

In what follows, we attempt to establish the dialectical relationship between the geomorphic and cultural development of the floodplain. This is to say that the geomorphic development of the floodplain has its own sensitivity and vulnerability to climate and that the sensitivity of culture to climatic hazards in these intensified irrigated systems depends on both water and land availability. At the same time, because of distinctly different sets of relationships to the floodplain, either through settlement pattern or level of irrigation intensification, not every cultural group within the Valley had the same level of risk or vulnerability to the climatic or hydrologic hazards, especially those associated with large ENSO events. As such, we have 3 major research questions. What is the magnitude and pace of floodplain development in the mid-valley Rio Moquegua and what is the relationship between floodplain processes and the occurrence of El Niños? Secondly, how have three different ancient cultural groups adapted to specific hydro-geomorphic niches within the valley? Lastly, how vulnerable were each of these three cultures to extreme events that eradicated floodplains during ENSO related floods? In this way we hope to link floodplain sensitivity to cultural adaptability and ultimately to the interconnected sustainability of the floodplain as a resource and the sets of social and economic practices. We will first lay out the processes and magnitude of streambank erosion during El Niño floods and then present the cultural adaptation and vulnerability to riverine characteristics and floodplain re-working.

3. Methods

The Osmore Drainage of southern Peru, a riverine oasis well-suited for temperate crop agriculture, provides an excellent test case for the interplay of several distinct cultural traditions with agrarian sociopolitical development, long term sustainability, and response to environmental hazard. Investigation of Pre-Columbian agrarian settlement patterns has been the goal of the Moquegua Archaeological

Survey (MAS), a regional systematic archaeological study begun in 1993. During the 1990s, the MAS team systematically surveyed the 150 km^2 of the Middle Moquegua Valley sector of the Osmore, between 900 and 2000 m.a.s.l., recording a total of 531 Pre-Columbian site components ranging from the late Archaic to the Inka period (Goldstein, 2000a, 2005) (Table 1). During the survey phase of this project, from 1993 through 1995, a systematic walkover reconnaissance was covered by a team of 6 archaeologists walking in straight lines at 20 m intervals. Full 100% coverage extended from the floodplain to the ridgeline overlooking the valley on either side, a survey area that extended 2 km. from the current river course. All settlement site components and related roads, agricultural works, geoglyphs and cemeteries were recorded on Servício Aerofotografía Nacional air photos and 1:10,000 Catastro Rural maps. Standardized survey forms and Brunton compass maps were completed and photographs were taken, and selected sites were later mapped in greater detail with plane table or total station theodolite, and locations confirmed with GPS. Data on site size, function and cultural affiliation from field observations and laboratory analysis were coded as a database in a Geographic Information System (GIS) permitting spatial analysis of each of the valley's occupations with terrain and environmental variables. Subsequent seasons of the project turned to systematic surface collections and test excavations at selected sites to date and detail the cultural sequence (Table 3) (Goldstein, 2000a, 2005). Concurrent archaeological research outside of the MAS mid-valley survey area has also contributed to the settlement history of the coastal Osmore valley, and of the tributary Torata and Tumilaca valleys (Owen, 1993, 1996; Owen and Goldstein, 2001).

Floodplain geomorphic characteristics have been collected since 1998 by a combination of field and remote sensing techniques. Profiles and cross-sections have been surveyed by a TOPCON Total Station and, most recently in 2009, with a TOPCON RTK GPS system providing sub-cm scale accuracy in X, Y, and Z coordinates. Field mapping has been augmented by differentially corrected GPS, air photo analysis, and by DEM construction from an ASTER image (see Manners et al., 2007, for detailed description of remote sensing methods). Each of these techniques has been used to represent changes in channel position and planform with the earliest image dating to 1946. The main focus of the geomorphic analysis is the mid-valley section of the Rio Moquegua. This ~20 km reach is the alluvial section downstream of the confluence of the Rio Torata, Rio Huaracane, and Rio Tumilaca (just downstream of the town of Moquegua), and it terminates at the gorge at Yaral where it becomes a bedrock river (Fig. 1). The Moquegua Formation is the dominant lithology throughout this 20 km section and consists primarily of early-to-mid Tertiary inter-bedded conglomerates, volcaniclastics, and fine-grained alluvial and lacustrine facies (Gregory-Wodzicki, 2000; Tosdal et al., 1984).

4. Regional geomorphic impacts of El Niños

Because of its location on the west side of the Andes, rainfall is limited in this basin averaging ~50–100 mm yr^{-1}. The flood regime differs between tributaries and the mainstem and is significantly affected by ENSO occurrence and magnitude. Heading in the Andean Highlands where the easterly trade winds and Bolivian High Pressure Cell dominate the hydroclimatology, the mainstem Rio Moquegua floods by a combination of rainfall and snowmelt. Precipitation can be intensified during La Niña episodes when the Bolivian High shifts northward allowing for wetter summers (Vuille, 1999). Unlike the mainstem, tributaries in the mid-valley lack any connection to the Andes and can only flood during localized rainfall associated with El Niño occurrences. These El Niño floods can be catastrophic and have wiped out villages in coastal and mid-valley locations (Keefer et al., 2003).

Several “mega-Niños” have occurred during the cultural period of focus of this study, with well-dated debris flow deposits of El Niños occurring circa AD 700 and AD 1607 (Magilligan and Goldstein, 2001) as well as the regionally extensive “Miraflores Flood” circa AD 1330 (Wells, 1990; Keefer et al. 2003; Magilligan et al., 2008). Stratigraphic evidence of alluvial terraces in the middle Moquegua Valley (Magilligan et al., 2008) suggests that El Niños have increased in magnitude and frequency during the Late Holocene, especially in the period from ~1300–1600 AD, as also appears to be the case in other coastal Peruvian watersheds (Wells, 1990).

On more contemporary scales, the 1997–1998 ENSO is estimated to have been one of the strongest and best developed ENSO events of the 20th century (Wolter and Timlin, 1998) with widespread flooding occurring across the western Andean region and associated with major floods throughout the western US. Flooding was especially pronounced along the Moquegua Valley where the '98 flood was estimated to be ~450 m^3 s^{-1}, approximately a 50-yr flood (Magilligan and Goldstein, 2001). This major event led to significant streambank erosion. Comparison of channel margins from a 2003 GPS field mapping with the 1997 air photo indicates ~415,000 m^2 (41.5 ha) of lateral widening and streambank erosion (Fig. 2), essentially 2 ha of arable land lost per river km amounting to a loss of as much as 30% of the richest floodplain lands (Manners et al., 2007). There is also considerable spatial variability with some valley reaches exhibiting ~3.8 ha lost per river km (Fig. 3). Major channel widening and braided conditions are often associated with these extreme events, especially those associated with El Niños (cf. Huckleberry, 1995) suggesting significant floodplain sensitivity to ENSO-related floods.

The predominance of channel widening is further revealed by the extremely young age of floodplain alluvium. Using an ASTER-derived DEM, Manners et al. (2007) show that topographic variation is

Table 1

Estimates of PreColumbian population in Moquegua, by total habitation area and total mortuary area.

Cultural affiliation	Number of habitation sectors	Habitation area (ha)	Habitation population estimate[a]	Number of cemetery sectors	Cemetery area (ha)	Mortuary population estimate
Huaracane, (mid-valley only)	169	73.5	7350	70	20.2	25,250[b]
Wari (mid and upper valleys)	15	20	2000	0	0	5[c]
Tiwanaku Omo style	12	28.7 ha	2870	3	.1	250
Tiwanaku Chen Chen Style	31	50.5 ha	5050	39	10.4	26,000[d]
Tiwanaku Tumilaca styles	45	42.0 ha	4200	10	.8	2000
Tiwanaku Total (all styles, mid-valley only)	88	121.2	12,120	64	11.3	28,250
Chiribaya	21	12.9 ha	1290	13	1.2	3000
Estuquiña	14	9	900	12	2.6	6500
Estuquiña-Inca	4	1.7 ha	170	3	1.4	3500

[a] Based on estimate of 100 people per hectare occupied area.

[b] Estimate of .125 burials per sq. m., based on excavation averages for Huaracane tumulo burials at M73 site. Huaracane interment density is lower than that of Tiwanaku cemeteries.

[c] Reported intramural burials at Cerro Baul. No Wari cemeteries are known in Moquegua.

[d] Estimate of .25 burials per sq. m., based on excavation averages for the Omo, Rio Muerto and Chen Chen Tiwanaku cemeteries.

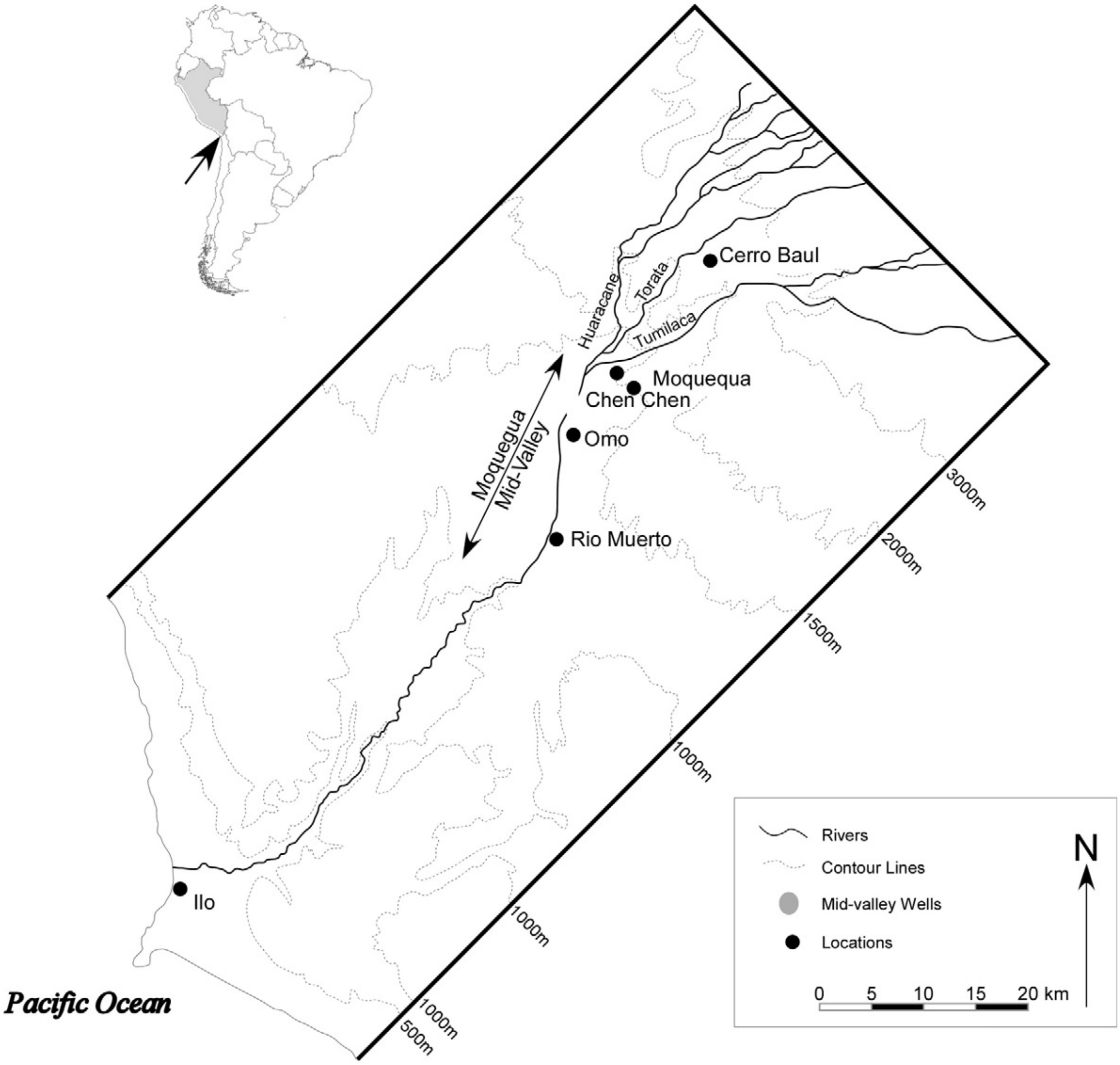

Fig. 1. Location and contour map of the Rio Moquegua (Osmore) with locations of key sites.

extremely limited in the mid-valley (Table 2) with most floodplain surfaces generally less than 4–6 m above the current river elevation. The predominance of these low-lying alluvial surfaces suggests that more than 70% of the total floodplain area was deposited <1 kya (Manners et al., 2007) further indicating the significant role of streambank erosion associated with prehistoric and historic El Niño floods.

Traditional farmers of the modern day floodplain in Moquegua are closely aware of the timing and mechanics of streambank erosion. Our research suggests very strong ENSO-related flood cycles like the 1998 event regularly remove as much as 3.8 ha per river km of the floodplain agricultural base, and similar effects were visible following previous events like the very strong 1983 ENSO. Farmers are equally cognizant of the costs and timing of floodplain land recovery, and aware that it is usually a slow, multigenerational process. Our research using a 60 year record of aerial photography suggests that the eroded floodplain land has a recovery cycle of approximately 40 years, including stages of natural vegetation colonization, low energy floods silting, soil development, and ultimately, the renewal of cultivation (Manners et al., 2007). Even with the recent availability of heavy machinery in a region of traditional hand farming, farmers are also aware of the high costs of attempting to accelerate the recovery cycle through various kinds of labor-intensive artificial fill inputs.

5. Cultural relationship to floodplain characteristics and riverine processes

Here, we will focus on the settlement patterns and agrarian systems of three distinct archaeological cultures, the Huaracane, Wari, and Tiwanaku, who overlapped in time during the Middle Horizon period (AD 500–1000) (Table 3) yet can be easily distinguished in the middle Moquegua valley by their pottery, architecture, settlement locations and material culture patterns. We argue that each settlement system was heavily invested in its own culturally distinct agrarian adaptation to this desert region. Where these cultures overlapped temporally, their coeval coexistence was facilitated by their occupation of distinct economic niches within the Moquegua valley, in terms of longitudinal or lateral locational preference, agrarian practices and labor management. Later, we will consider the differential sustainability of the three systems over multiple time scales in relation to recent research on climatic history and hazards in the region.

5.1. The Huaracane Tradition 2000 BC–AD 800: small scale floodplain agriculture

The middle elevation stretch of the Moquegua Valley was fully integrated in both seasonal rounds and long distance exchange

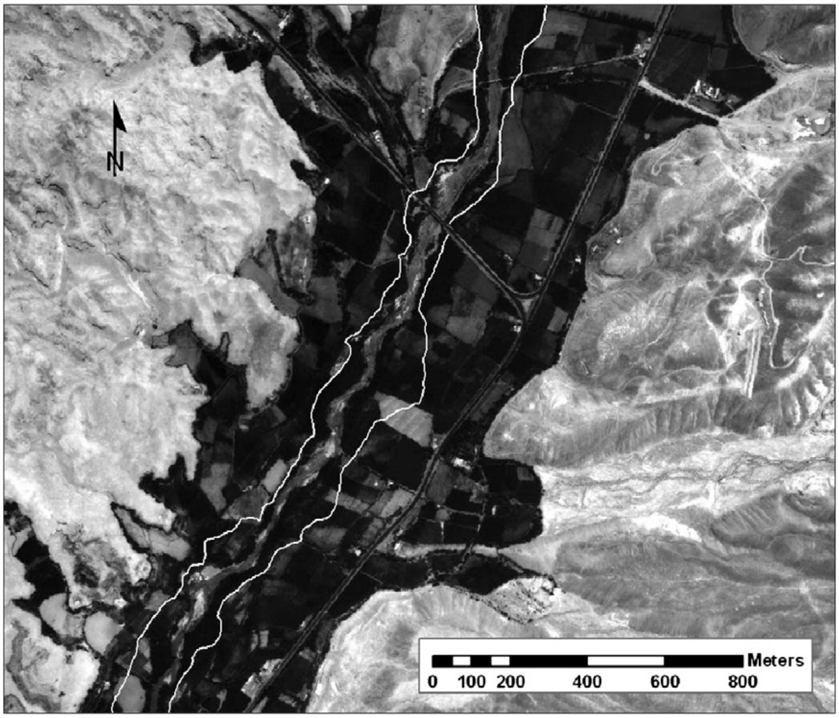

Fig. 2. 1997 airphoto showing position and size of the channel prior to the 1997 La Niña flood and 1998 El Niño flood. White line is the position of the channel margins mapped by field-based GPS in 2003 following the floods of 1997 and 1998.

networks between coast and altiplano by the time of introduction of camelid pastoralism at about 2500 BC (Aldenderfer, 1998; Kuznar, 1990; Moseley, 1998). Pre-agrarian occupation of the mid-elevation valleys of the south central Andes has been described as transitory and low-density, as compared to coastal maritime subsistence sites on the coast (Sandweiss et al., 2007) and to the well-preserved terrestrial subsistence sites found at higher elevations and in the puna (Grosjean et al., 2007:98). However, we believe that a significant part of the Archaic record in the mid-valleys may be missing due to the impressive rate of floodplain reworking during the late Holocene.

A better record exists after the origins of agrarian occupation and the beginning of an indigenous ceramic tradition in the Moquegua Valley, due to the more substantial nature of settlement and mortuary sites and their location on bluffs outside of the floodplain. Formative settlement was first identified at the type site of Pampa Huaracane with preliminary reconnaissance of the valley under the Contisuyo Program under Michael Moseley in 1983 (Feldman, 1989; Goldstein, 1989a) with mortuary sites initially dated ranging from cal 385 BC–cal AD 340 (Goldstein, 2000b). However, committed agriculture lifeways have been documented in the coastal Osmore as early as 1750 BC, with a gradual intensification and the introduction of maize by 920 cal BC (Owen, 2009:138). Our new dates indicate the full range of the Huaracane ceramic tradition may be extended back to cal 1600 BC in the middle valley, and persisted to the early Middle Horizon (Table 3, Fig. 4), with new evidence suggesting a terminal Huaracane presence as late as the 8th century AD (Costion, 2009; Green and Goldstein, 2009). Throughout, Huaracane tradition sites are characterized by a conservative ceramic assemblage of low-fired sand or

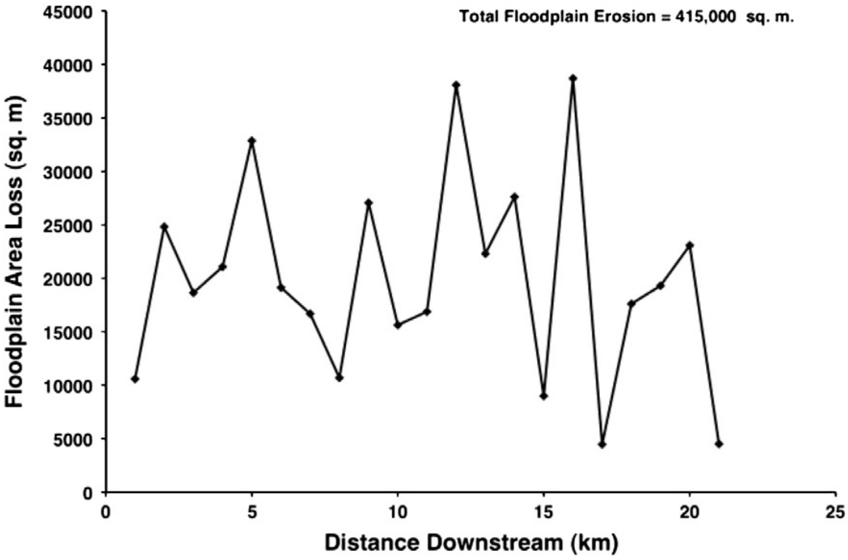

Fig. 3. Amount of channel and floodplain lateral erosion between 1997 and 2003 per river km.

Table 2
Percentage of valley occupied by floodplain and terrace surfaces of various heights (2 m bins) above the modern river bed.

Height (m)	Percentage of valley (%)
0–2	53.0
2–4	15.0
4–6	9.0
6–8	7.5
8–10	4.5
>10	11.0

fiber tempered neckless ollas similar to those that typify most Formative traditions, a locally unique tradition of fine-paste high fired serving bowls, and a wool and cotton textile tradition that evolves technologically from non-loom techniques to warp face plainweaves (Feldman, 1989; Goldstein, 1989b, 2000a).

Settlement pattern research on the Huaracane indicates an extraordinary density of habitation and mortuary sites along the bluffs overlooking the mid-valley floodplain (Table 4, Fig. 5). Huaracane habitation sites typically consisted of semicircular residential terraces, often without stone facing, with evidence of superstructures of organic materials. Site size is uniformly small, with a mean area per domestic component of only 0.44 ha and all but five domestic components under 2 ha. This and the absence of public architecture suggest a generally low level of political and economic integration.

The high predictability of Huaracane settlement location is relevant to our discussion of culturally distinct agricultural traditions. Huaracane habitation sites were found on virtually every hilltop or slope along the rim of the valley, and consistently located quite close to the Moquegua River (Table 4). This close relation to the floodplain indicates a reliance on agriculture fed by simple valley edge canals that could have been built, maintained and adjudicated by a village scale community; distinguish Huaracane's agrarian strategy from those of subsequent, politically more complex societies like Tiwanaku and Wari, who engaged in large-scale corporate agricultural works like complex transregional canals and terrace systems. The absence of specialized processing tools and storage features at Huaracane sites also suggest little agricultural intensification or surplus production, and a low level of political and economic integration. Huaracane's diverse diet also suggests a non-specialized agrarian subsistence strategy balancing a variety of plant foods, some maize, land animal and marine resources (Goldstein, 2003; Sandness, 1992:49). The Huaracane tradition's low level of political complexity, its modest demographic scale, and its generalized subsistence from a floodplain agricultural base, supplemented by herding, hunting and marine resources, suggests a system that had evolved to fit well within the "bounds of adaptability" set by decadal environmental hazards.

5.2. The Wari Enclaves AD 600–1000: upvalley terrace systems

The presence of enclaves in Moquegua culturally affiliated with the Wari (Huari) civilization of Ayacucho, Peru is considered the southernmost expansion of one of the Andes' first empires. Chief among these enclaves is Cerro Baúl, a site located atop a sheer-sided mesa in the upper Osmore tributary region. Cerro Baúl's impressive location suggested early on that it was an intrusive fortified settlement in territory that was heavily populated by Tiwanaku, while it's characteristically Wari architecture and ceramics place it in the expansive Ayacucho tradition. Radiocarbon dates place the Cerro Baúl Wari occupation in the sixth through tenth centuries A. D. (Nash and Williams, 2005; Williams, 2001; Williams et al., 2000; Williams and Nash, 2002). This range is supported by MAS project dates from a Wari house floor at the Cerro Trapiche site (Table 3); the lone Wari outpost in the middle Moquegua valley, confirming the Wari occupation's overall contemporaneity with the middle valley's Tiwanaku occupation.

In contrast to the Tiwanaku sites of the middle Moquegua Valley, the mountaintop Cerro Baúl and its companion sites suggest a distinctive mode of Wari colonialism in the upper Osmore tributaries. Survey of the Torata and Tumilaca valleys has given us a better understanding of the overall settlement pattern of the Cerro Baúl hinterland (Owen, 1999; Owen and Goldstein, 2001). The known Middle Horizon Wari sites in the upper Osmore are characterized by the presence of domestic terraces, defensive walls, and habitation debris including Ocros and Chakipampa B ceramics that date these settlements to Middle Horizon Epoch 1B. Owen concludes that Wari moved into an "empty or underpopulated region adjacent to Tiwanaku territory" to exploit the upper valleys and maintain a political and military frontier (1999).

The Wari occupation of the upper Osmore represents the first economically viable exploitation of a previously unoccupied agronomic niche in a part of the drainage where agrarian production is most limited by steep slopes. The Wari made this possible by introducing a new agricultural technology that they had perfected in their Ayacucho homeland and other colonized regions: agricultural terracing (Schreiber, 1992:131; Schreiber, 2001; Williams, 2006). Williams and Nash believe that elite investment in irrigation and terracing infrastructure allowed Wari settlers to greatly enhance the upper valley's agricultural potential (Williams and Nash 2002:249). A 20 km long canal system, sourced at 2600 m above sea level, was the first major irrigation work in the upper valley, and with it the Wari introduced extensive flights of mountainside bench terraces on a scale that would be unmatched until the Inca occupation.

The contrast between Wari's upland terracing and Tiwanaku mid-elevation desert reclamation described below is striking, and a clear indication of distinct technological styles in agriculture. Some 25 ha of stone-faced terraces have been archaeologically associated with the Wari el Paso canal (Williams, 2002:366) and the canal could have potentially watered as much as 324 ha, assuming maximum discharge (Moseley et al., 2005). While an argument has been made that the "hydraulic superiority" of the Wari terraced system led to Wari ascendancy in times of drought (Williams, 2002:366; Williams and Nash, 2002:249) upper valley terraced agriculture is also limited by rocky poorly watered soils, steep slope and cooler climate due to higher elevation, and require high labor investment in both terrace construction and soil inputs for marginal agricultural returns (Goodman-Elgar, 2008:3085). Moreover, our observations of the effects of present-day Pasto Grande irrigation project suggest that the lateral displacement of water by upstream irrigation may in fact recharge groundwater aquifers downstream and the mid-valley springs and wells (Magilligan et al., 2008). In any case, upvalley Wari irrigation sourced from the Torata tributary could have had a negative impact on floodplain agriculturalists in the Moquegua mid-valley mainstem, i.e. the Huaracane settlements but no effect on Tiwanaku field systems like that of Chen Chen, which sourced in the Tumilaca tributary. This suggests a political division between the two tributary watersheds and a modus vivendi between Wari and Tiwanaku that was more complex than the upstream/downstream hierarchy posited.

We believe that settlement pattern data derived from systematic survey provide more reliable estimates of agrarian population in the Osmore drainage than estimates based on the reconstructed *potential* for land use based only on maximum discharge of main canals. Actual settlement patterns thus can also be a useful proxy for extrapolating the scale of agrarian investment. The El Paso canal and associated terraced field systems of Cerro Baúl may indicate massive public works associated with the Wari occupation (Williams, 1997; Moseley et al., 2005). Yet despite assertions of a three-tiered settlement hierarchy with "several" Wari town sites and a system of hamlets located along the canal system (Williams, 2002:266; Williams, 2006),

Table 3
Radiocarbon dates of Huaracane, Wari, and Tiwanaku archaeological sites in Moquegua mid-valley.

Lab number	Specimen	Site	Material	Conventional age	1 sigma calibrated range(s)[a]	Affiliation	Context	Year	Reference
Beta-261514	M73 = 1264	Tres Quebradas	Wood	3220 ± 60 BP	cal BC 1603–1588, 1534–1425	Huaracane	Domestic sounding	2003	New
AA-38030	M73 = 9999	Tres Quebradas	Wood log	2220 ± 42 BP	cal BC 364–349,314–208	Huaracane túmulo	túmulo 1	1998	Goldstein (2000b)
Beta-120262	M17 = 1	Omo Bajo	Wood post	2140 ± 50 BP	cal BC 350–305, 209–92	Huaracane túmulo	túmulo	1994	Goldstein (2000b)
AA-38029	M73 = 1034	Tres Quebradas	Wood branch	2112 ± 42 BP	cal BC 194–90, 72–59	Huaracane túmulo	túmulo 1	1998	Goldstein (2000b)
Beta-212301	M103 = 1144	Montalvo	Wood	2090 ± 60 BP	cal BC 195–42	Huaracane habitation	Domestic sounding	2003	new
Beta-26651	M10 = 2197	Omo M10Y cemetery	Wood, tomb roof	1990 ± 70 BP	cal BC 91–71, cal BC 60–cal AD 84	Huaracane boot tomb	Boot tomb 6, level 8	1987	Goldstein (1989a, 2000b)
Beta-120263	M7 = 2	Trapiche M7	Wood post	1860 ± 70 BP	cal AD 77–234	Huaracane boot tomb	Looted boot tomb	2003	Goldstein (2000b)
Beta-212300	M76 = 1101	Los Joyeros	Wood	1640 ± 70 BP	cal AD 339–465, 482–533	Huaracane Joyeros	Looted cemetery	2003	new
Beta-212299	M7 = 1419	Trapiche M7	Charred material	1320 ± 70 BP	cal AD 650–772	Wari	Structure 3 patio group	2003	Goldstein (2005)
Beta-212298	M7 = 1053	Trapiche M7	charred material	1290 ± 60 BP	cal AD 663–775	Wari	Structure 3 patio group	2003	Goldstein (2005)
Beta-189445	M7 = 1248	Trapiche M7	Organic material	1190 ± 40 BP	cal AD 779–886	Wari	Structure 3 patio group	2003	Goldstein (2005)
Beta-36639	M12 = 1617	Omo M12	Wood post	1470 ± 80 BP	cal AD 466–481, 533–656	Tiwanaku Omo	Structure 2, domestic	1987	Goldstein (1993):31
Beta-242273	M70 = 2996	Rio Muerto M70	Wood	1360 ± 40 BP	cal AD 637–688	Tiwanaku Omo	Cemetery, tomb R69	2006	New
Beta-129938	M16 = 5500	Omo M16	Wood post	1290 ± 70 BP	cal AD 656–780, 793–803	Tiwanaku Omo	Tomb 15	1999	Goldstein (2005)
Beta-242271	M70 = 2296	Rio Muerto M70	Wood	1210 ± 50 BP	cal AD 723–740, 770–886	Tiwanaku Omo	Cemetery, tomb R11	2006	new
Beta-129939	M70 = 1509	Rio Muerto M70	Wood post	1160 ± 60 BP	cal AD 723–740, 770–886	Tiwanaku Omo	Unit 6y, domestic	1998	Goldstein (2005)
Beta-242274	M70 = 3466	Rio Muerto M70	Wood	1160 ± 40 BP	cal AD 782–790, 809–898, 920–945	Tiwanaku Omo	Cemetery, unit "i"	2006	New
Beta-242272	M70 = 2943	Rio Muerto M70	Wood	1140 ± 50 BP	cal AD 784–786, 826–840, 863–978	Tiwanaku Omo	Cemetery, tomb R62	2006	New
AA-38032	M70 = 1245	Rio Muerto M70	Wood	1132 ± 39 BP	cal AD 881–977	Tiwanaku Omo	Unit 4, domestic	1998	Goldstein (2005)
Beta-120264	M12 = 3016	Omo M12	Wood	1060 ± 70 BP	cal AD 892–1027	Tiwanaku Omo	Structure 7, domestic	1987	Goldstein (2005)
Beta-60762	M12 = 3388	Omo M12	wood post	1040 ± 70 BP	cal AD 894–929, 932–1042, 1107–1117	Tiwanaku Omo	Structure 7, domestic	1987	Goldstein (2005)
AA-44817	M10 = 3939	Omo M10	Wood	1198 ± 47 BP	cal AD 772–891	Tiwanaku Chen Chen	Temple, unit 117	1990	New
Beta-39679	M10 = 4014	Omo M10	Wood	1160 ± 60 BP	cal AD 804–900, 918–964	Tiwanaku Chen Chen	Temple, lintel, unit 113	1990	Goldstein (1993):34
AA-38031	M43 = 1067	Rio Muerto M43	Wood	1122 ± 44 BP	cal AD 886–983	Tiwanaku Chen Chen	Unit 1, domestic	1998	Goldstein (2005)
Beta-26650	M10 = 1758	Omo M10	Wood	1120 ± 70 BP	cal AD 823–841, 861–995	Tiwanaku Chen Chen	Structure 13, domestic	1987	Goldstein (1989a):69
AA-40628	M10 = 1121	Omo M10	Wood	1101 ± 35 BP	cal AD 896–924, 939–985	Tiwanaku Chen Chen	Structure 11, domestic	1987	Goldstein (2005)
Beta-242270	M43 = 2497	Rio Muerto M43	Charred material	1060 ± 40 BP	cal AD 901–916, 967–1020	Tiwanaku Chen Chen	Unit 3, domestic	2007	new

Stuiver, M. and P. J. Reimekr (1993). "University of Washington Quaternary Isotope Lab Radiocarbon Calibration Program Rev. 4.1.2." Radiocarbon **35**: 215–230.

[a] Ranges with probability >.015. Calibrated with intcal09.14c on CALIB REV6.0.0, http://calib.qub.ac.uk/calib/calib.html. Stuiver, M. and P. J. Reimer (1993). "University of Washington Quaternary Isotope Lab Radiocarbon Calibration Program Rev. 4.1.2." Radiocarbon **35**: 215–230.

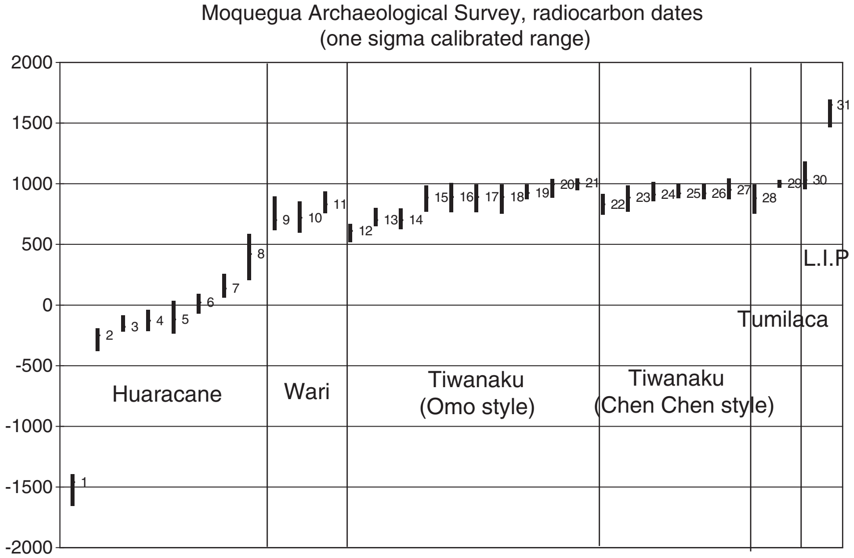

Fig. 4. Radiocarbon dates for Moquegua Mid-Valley Sites, grouped by cultural affiliation (1 sigma calibrated ranges).

details of no such settlement system has yet been published, and, only five Wari sites have been identified in total. Cerro Baúl and its published companion Wari habitation sites have an aggregate settlement area that appears to be well under 20 ha. and no Wari cemeteries are known in the region. Thus, using the estimate of 100 persons per hectare of domestic occupation, Williams' estimate of 2000 Wari agriculturalists at Cerro Baúl (Williams, 2006) may in fact represent the entire Wari population for the region (Table 1).

5.3. The Tiwanaku Colonization AD 600–1100: lateral desert reclamation and pastoralism

Perhaps the most successful of our agrarian cultural adaptations was the massive colonization of the middle Moquegua by settlers affiliated with the Tiwanaku civilization from the high Bolivian altiplano (AD 500–1000). Tiwanaku, at 3800 m.a.s.l. the world's highest ancient civilization center, benefited from access to temperate valley crops in Moquegua and similar lowland valleys. Tiwanaku settlers appeared in Moquegua in the 7th century and over the next five centuries, Tiwanaku and Tiwanaku-derived settlement came to occupy over 141 ha of residential site area in the middle Moquegua Valley (Table 1, Fig. 6), surpassing the scale of the indigenous Huaracane settlement. The Tiwanaku occupation was concentrated in four large cosmopolitan town sites at the new site groups of Omo, Chen Chen/Los Cerrillos, Rio Muerto, and Cerro Echenique, with little settlement outside of these enclaves. The Tiwanaku immigrants maintained their homeland traditions, with no evidence of “mestizaje” or transculturation with the local tradition. Moquegua's Huaracane people likewise did not adopt Tiwanaku cultural practices, live in Tiwanaku sites, nor, it appears, intermarry with Tiwanaku settlers (Blom et al., 1998).

Tiwanaku colonization represented two distinct migration streams. The Omo style occupation was Tiwanaku's pioneer colonization, dating from the late 7th century through the 10th century (Table 3). Fifteen site components covering a total of 28.7 ha associated with this style, suggest an Omo Style population of around 3000 in the middle Moquegua Valley (Table 1). Omo Style settlements were clustered furthest away from the irrigable valley floodplain (Table 4), close to desert caravan routes marked by llama geoglyphs. Omo Style communities consisted of impermanent structures of mats or skins on wooden post frames. This suggests that the Omo style Tiwanaku colonists may have been pastoralists, who deliberately located their camps near caravan routes and away from the farmsteads of the floodplain.

Either simultaneously or shortly after the Omo Style colonization, a second set of Tiwanaku communities appeared in Moquegua bearing a distinct subset of Tiwanaku material culture known as the Chen Chen Style. Chen Chen Style settlements in the middle Moquegua Valley covered a total of 54.6 ha of domestic area, with 48 cemeteries covering an additional 10.4 ha, suggesting a population between 10,000 and 20,000 (Table 1) (Goldstein, 2005; Owen and Goldstein, 2001). Chen Chen style sites tend to be closer to irrigable lands and demonstrate dense long-term occupation with an intensive agricultural focus.

Chen Chen style Tiwanaku settlement location in Moquegua demonstrates a cultural preference for an agrarian “niche” emphasizing flat planting areas that could be watered by springs and river-fed canals extended into the desert. Chen Chen settlers reclaimed desert land through laterally extended canal systems like the 10 km. valley-side canal from the Tumilaca valley that watered a 93 ha field system on the Chen Chen pampa (Williams, 1997:90). Although Williams has recently downplayed the productivity of the Chen Chen system, suggesting it would have fed less than a third of the capacity of Wari's El Paso canal and its terraced fields (Williams, 2006), the Chen Chen fields are only a small sample of a much larger array of reclaimed desert, spring-fed systems, and valley bottom floodplain lands farmed by the Tiwanaku colonists.

The mid-valley Tiwanaku colonies provided their own resident labor force, and also differed from the Wari by practicing agricultural

Table 4
Site distance from river and elevation above nearest river course.

Culture	Distance from River (m)		Elevation above river (m)	
	Mean	Median	Mean	Median
Huaracane (*n* = 256 sites)	375	320	51	40
Wari (*n* = 5 sites)	854	550	192	200
Tiwanaku Omo (*n* = 19 sites)	1249	1220	62	57
Tiwanaku Chen Chen (*n* = 93 sites)	1183	1390	61	50
Tiwanaku Tumilaca (*n* = 62 sites)	637	615	105	85
Chiribaya (*n* = 36 sites)	272	220	36	30
Estuquiña (*n* = 28 sites)	468	445	60	45

Survey data for three sites in middle Moquegua valley, plus Cerro Baul and Cerro Mejia in Torata valley.

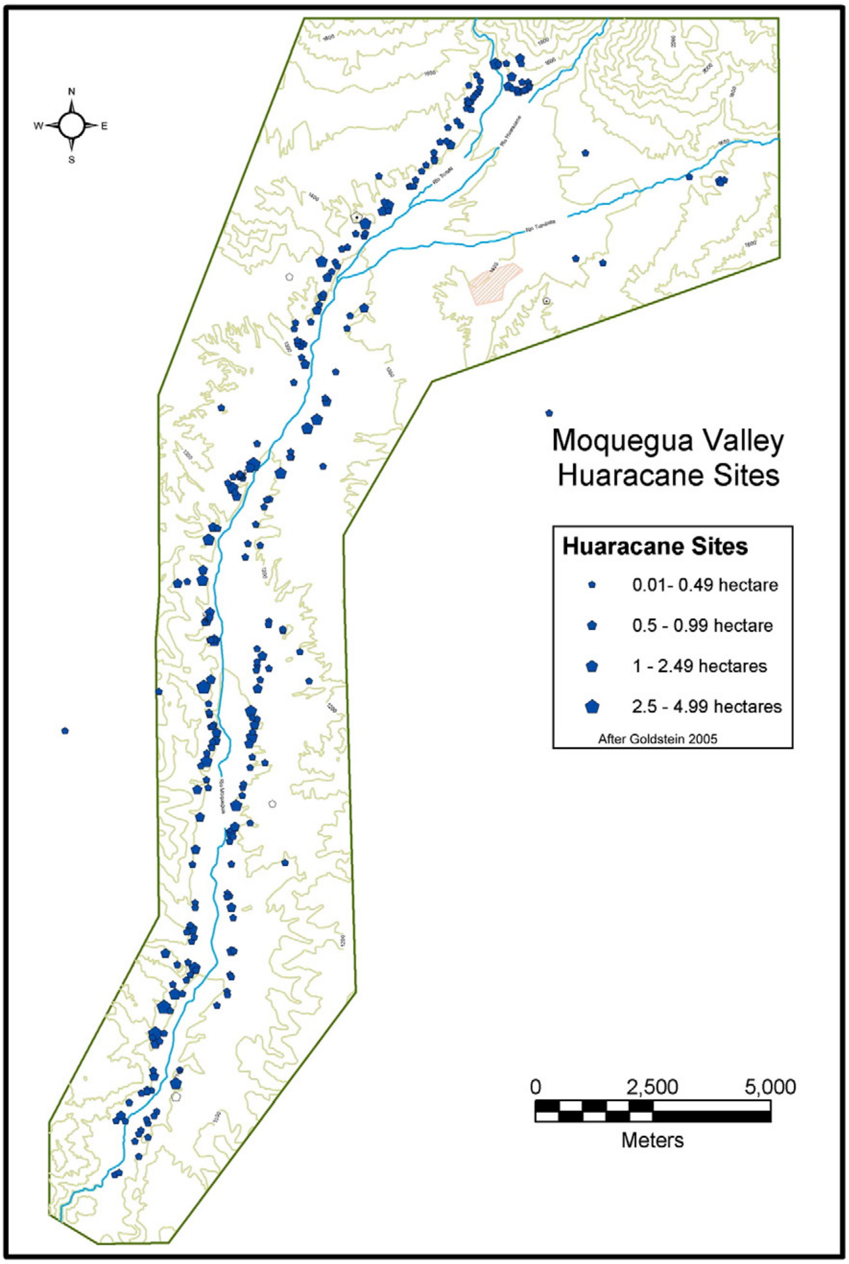

Fig. 5. Huaracane settlement map.

strategies requiring less labor investment in areas with better access to water, such as easily irrigable valley bottom lands. While the system of Tiwanaku towns and their reclaimed fields was located well away from the Huaracane sites, and far from the Moquegua River (Table 4), the discovery of Tiwanaku ceramics in field furrows indicates that the Tiwanaku also farmed the fertile valley-bottom floodplain (Magilligan et al., 2008), offering a more diverse agrarian base than that of the Huaracane settlements. Tiwanaku's flatland systems provided more usable surface area at lower labor costs than do terrace systems, plus mid-valley lands today are commonly triple cropped due to their more temperate climate. Moreover, unlike the Wari agrarian system, the later Tiwanaku residential sites are characterized by high densities of hoes, grinding stones and storage cists that indicate industrial scale processing and storage of maize and other temperate crops for export to the altiplano. Enormous quantities of macrobotanical and isotopic evidence confirms high maize dietary input, and Moquegua maize varieties have been identified as imports at the Tiwanaku type site in Bolivia (Goldstein, 2003, 2005; Hastorf et al., 2006; Sandness, 1992).

The final phase of Tiwanaku settlement in Moquegua, locally known as the Tumilaca Phase, was a period of agrarian retraction, with abandonment of some lateral irrigation systems, and settlement shifts suggesting increased between-site competition for land and water. This period has not produced geomorphic evidence of any triggering climatic disaster, and instead coincides with the collapse of Tiwanaku state coordination of agrarian resources in the 11th century, (Bermann et al., 1989; Owen, 2005; Stanish, 1992:86).

Tumilaca Phase Tiwanaku settlement pattern is typified by two trends. Within the middle Moquegua valley we see a “balkanization” (Bermann et al., 1989) of the Tiwanaku colony into small local polities in which the great Tiwanaku town sites, canal and field systems were largely depopulated, in favor of smaller, dispersed sites and a valley-wide population of about 4200 (Table 1). Mid-Valley Tumilaca Phase sites were typically surrounded by defensive walls or else located at

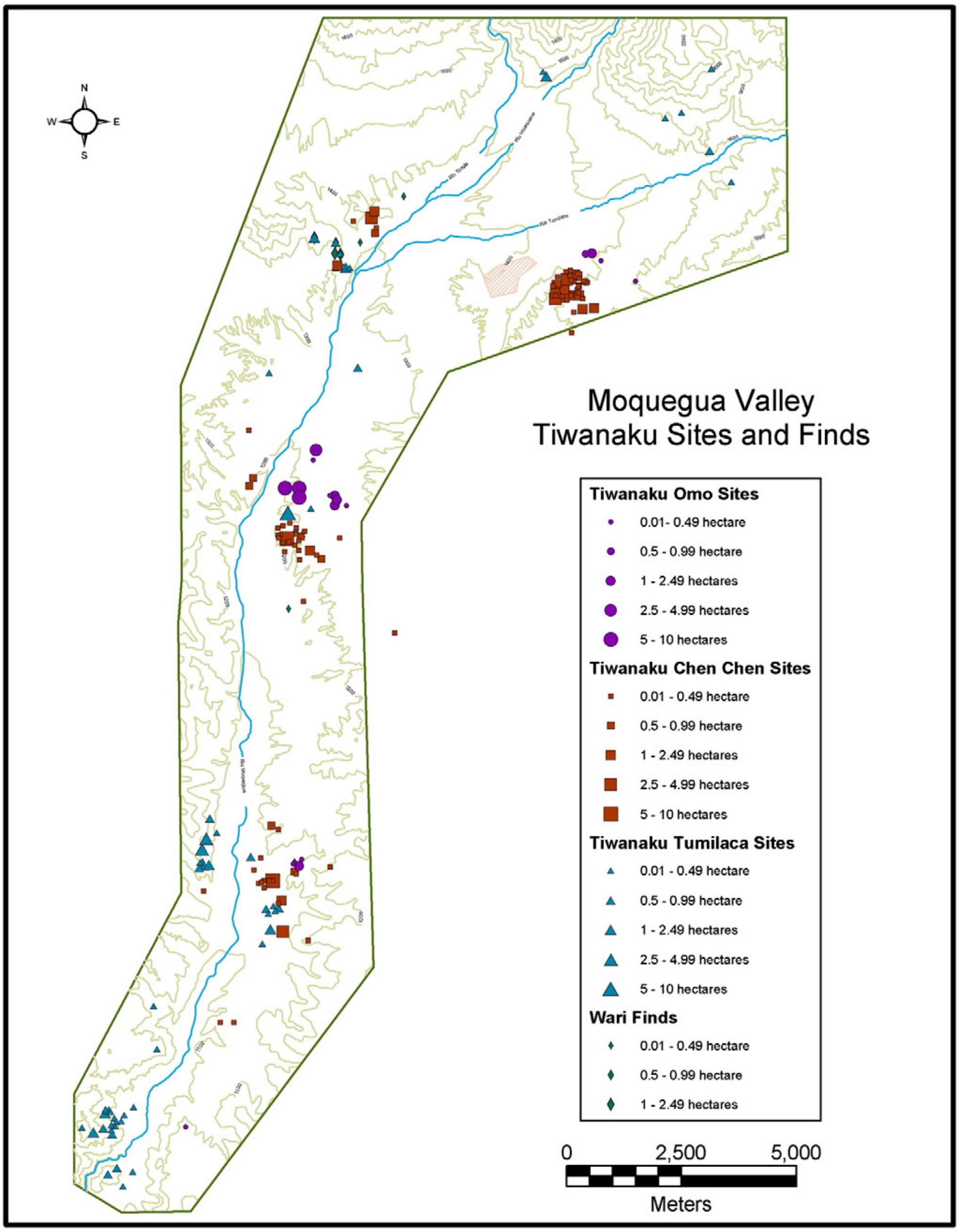

Fig. 6. Tiwanaku settlement map.

high elevations above the river floodplain, indicating local conflict (Table 4). Simultaneously, the Tiwanaku system underwent "explosive collapse", with an outmigration of refugee Tiwanaku peoples to the Coastal Osmore valley near Ilo (Owen, 2005) and the upper tributary valleys (Bawden 1989:289; Stanish, 1992:114). These two trends point to political hostilities consonant with the disintegration of the Tiwanaku provincial administration, the collapse of the agrarian canal systems, and increased competition over the more limited floodplain land resources.

Agrarian occupation of the Middle Moquegua Valley sector declined further following the Tiwanaku Tumilaca Phase. The entire Late Intermediate and Inca Period occupation of the MAS survey area never exceeded 28.5 ha, considerably reduced from occupation during the Tiwanaku and Huaracane tradition. Ongoing research is considering whether this retraction arose from political realignment of the mid-Moquegua valley into a depopulated frontier between the Chiribaya coastal chiefdoms of the coast and the highland Estuquiña culture, who took over and expanded the Wari terrace systems in the upper valley tributaries. The Miraflores event, a "mega-niño" a catastrophic ENSO flood at approximately AD 1330 (Keefer et al., 1998; Keefer and Moseley, 2004; Keefer et al., 2003; Wells, 1990) is also implicated in the collapse of the coastal Chiribaya (Moseley, 1998, 1999, 2001; Reycraft, 2000:115; Satterlee, 1993; Satterlee et al., 2000) and ongoing research is considering whether high energy flooding and streambank erosion would have handicapped middle valley agricultural productivity. This situation of low occupation did not change during the Late Horizon, when the Inca showed only token interest in this mid-valley floodplain, as a minority presence at the sparse Estuquina sites. The principal focus of Inca efforts appears to have been in the highlands, by expanding existing terraced agricultural systems and pasture lands in the Torata and Tumilaca valleys between 2000 and 3000 m.a.s.l. for wealth and tribute. The once-crucial Middle Moquegua Valley was reduced to an agricultural backwater and a political buffer zone between highland and coastal cultures until its revival for grape cultivation in the Spanish Colonial Period (Rice and Smith, 1989).

6. Discussion: towards a political ecology of disaster: one flood, three cultural responses

In a call for a more theoretically comparative "political ecology" of natural disasters, van Buren notes the importance of theorizing the factional implications of societies composed of distinct groups who compete for resources both within and between polities:

> "Thus, the relationship between "a society" and "the environment" is not unitary, but is characterized instead by a variety of interactions that involve different kinds of people, motivations, resources, places, and outcomes."(van Buren, 2001:144).

In the ancient Andes, any theory building on the nature of climate–society interactions must account for both a complex landscape of locally diverse geophysical responses to natural events and the complex cultural diversity and social factionalism across the same landscapes. There is tremendous spatial variability within a single ENSO event (Ortlieb, 2000:214) and a modern ENSO event can have little effect on some systems, or even produce favorable conditions for some specific human adaptations, while wreaking havoc in others. For example, Billman and Huckleberry report differential localized streambank erosion responses to the same ENSO events in different stretches of the same valley and between different valley systems in northern Peru. This may have placed lower Moche valley centralized polities at considerable political advantage over the Chicama Valley, which, despite its greater agricultural area, was subject to greater streambank erosion (Billman and Huckleberry, 2008:113). This kind of historic contextualization of the magnitude, agronomic effect and cultural consequence of climate and geomorphic events is often overlooked in the literature, which too often views archaeological ENSOs as universally catastrophic.

After two millennia of adaptation, the floodplain farmers of the formative Huaracane culture had built a close relationship to the bounds of adaptability set by flood and regeneration cycles consonant with normal ENSO cycles in the mid-valley reach of the Rio Osmore. It is reasonable to say that the Huaracane, by maintaining a low level of hierarchy and social complexity, were capable of sustaining streambank erosion of up to 30% caused by typical decadal strong ENSO-related flood cycles, and a recovery cycle of approximately 40 years. We believe the sustainability of this relationship was exceeded by the millennial event of the AD 700 "Mega-niño", which must have caused not only the typical cutting of canal intakes, which would have been reparable, but channel-widening and irredeemable loss of floodplain planting surfaces on a scale which with the Huaracane could not cope. The degree of floodplain loss we believe would have accompanied an ENSO of the magnitude of the AD 700 event thus would have severely affected the viability of the Huaracane agrarian settlement and political systems. Unlike long-term climate change, which might not be perceived by human populations, these short-lived events would have elicited immediate responses to rapid cycles of agricultural instability and competitive dynamics in both the Moquegua lowland and in the altiplano Tiwanaku homeland. In Moquegua, erosion caused by the far more modest 1998 El Niño resulted in the loss of as much as 30% of the richest floodplain lands (Manners et al., 2007). The floodplain soil losses of the far more severe AD 700 event would have been an agrarian disaster to indigenous populations of Formative "Huaracane" agriculturalists. Huaracane generalist strategies and simple floodplain irrigation, sustainable in place for centuries, were unable to adapt, and refugee populations had to either abandon the mid-valley and migrate upstream or downstream to reaches that experienced less farmland loss, or into conditions of dependency or peonage with their less affected neighbors whose alternate agricultural strategies of upland terraces, valley-side canal systems, and desert reclamation gave them more resilience in this instance.

Ethnographic studies of contemporary cultural groups remind us that catastrophe is a socially competitive phenomenon, and in many cases, one culture's or faction's catastrophe may present an opportunity for its competitors (Roscoe, 2008:91; Wilkerson, 2008). Wari colonists or refugees, perhaps "pushed" by ENSO-related droughts in their homeland of Ayacucho, found their way to Moquegua in the 7th century AD. Most significantly, these colonists brought a tradition of terraced canal-fed irrigation agriculture, allowing them to stake out a new niche in the deeply incised upper valleys of the region. Terraced planting surfaces themselves, located laterally above the river course, were not vulnerable to floodplain loss through channel migration. Although upland canals and their intakes may be vulnerable to flood damage, these are easily repairable and Wari colonists would have faced none of the disastrous loss of arable planting surface experienced by the Huaracane in the mid-valley. A comparison of settlement patterns, however shows the small scale of the identified Wari settlements, which total under 20 ha of aggregate residential area, indicating a population only a fifth the size of the Tiwanaku colonization, This placed the agrarian goals of the Wari settlers at a demographic disadvantage. If the canals and terracing of the Wari colony were even a fraction the size of the system extrapolated from the hydraulic capacity of the El Paso canal, the known Wari habitation sites would not have provided sufficient labor forces to build and maintain these systems. If agricultural intensification was the Wari state's goal, obtaining local labor would have been a key requisite. The sudden impoverishment of the Huaracane populations after the AD 700 floods may have served the Wari emigrants' interests by providing a mass of dispossessed farmers who had no choice but to be impressed or absorbed into the Wari system as subaltern peasantry.

The settlement pattern perspective indicates a different story for the most intensive and extensive agrarian system in the Osmore drainage, operated by the massive Tiwanaku migration from the Bolivian altiplano. The Tiwanaku diaspora may have been "pushed" by ENSO-related highland droughts or other disruptions related to the AD 700 event. However, the Tiwanaku colonists were considerably closer to home than the Wari adventurers, and maintained regular economic ties, following on a preexisting tradition of pastoralists and agriculturalist colonists. Tiwanaku colonists engineered a dramatically new agrarian niche of lateral land reclamation in the middle valley, with a settlement pattern closely related to spring water sources. Here, the AD 700 event may have represented more of an opportunity than a challenge. Among Hohokom farmers in the Salt river valley, for example, high discharge events led to regional population increase, rather than catastrophic decline as high discharge floods, even as they destroyed preexisting canal systems, presented new opportunities for immigrant farmers, perhaps due to diminished social controls on immigration and land tenure (Ingram, 2008:159). The Tiwanaku diaspora was stimulated by a similar moment of crisis and opportunity as the indigenous Huaracane floodplain regime fell into disarray following the disastrous effects of the AD 700 event. Indeed, Tiwanaku farmers who settled lateral lands were unaffected by floodplain soil loss, and may have been favored by recharge of springs. Additionally, stream recharge may have been a significant factor in attracting new altiplano populations to Moquegua, even as floodplain erosion crippled the existing Huaracane agrarian regime.

7. Conclusion: Culture plus hazard = catastrophe?

To the Greeks, "tragedy" was the dramatic form that epitomized the human condition as the interaction of the fates with human endeavor. "Disaster", literally an unfavorable aspect of a star or planet, is a necessary, but insufficient, element of tragedy, because disaster bears no element of human agency. According to Aristotle, true tragedy requires "Hamartia", some tragic flaw in the human protagonists, leading to their destruction in the "Catastrophe" (the third and final stage movement, following the strophe and antistrophe). In modern hazard research, this important distinction between “disaster” and “catastrophe” has been lost, and the terms conflated to generically describe “very bad stuff”. “Catastrophe”, literally “an overturning”, as the concluding action of tragedy must be born of nature *and* humanity.

Although clearly “disasters”, ENSO events do not, in themselves, automatically produce catastrophic cultural destruction. In an earlier publication, we demonstrated two significant flood events (AD 700 and AD 1330) in southern Peru that correlate with ancient ENSO (El Niño Southern Oscillation) events of great proportions (Magilligan and Goldstein, 2001) and considered some of the timing and spatial correlates of floodplain recovery (Manners et al., 2007). Considering the magnitude and regional extent of the later Miraflores flood on inland and coastal Peru (Wells, 1990; Magilligan and Goldstein, 2001; Satterlee et al., 2000), Easter Island (Nunn, 2000), and southern California (Schimmelmann et al., 1998, 2003) there is enormous potential variability in both physical effects and cultural vulnerabilities.

For the massive El Niño event that occurred in approximately AD 700, our examination of contemporary regional settlement patterns of three diverse cultural groups reminds us that human catastrophes are always both environmentally and historically contingent. Thus a catastrophic blow to indigenous Huaracane agriculturalists due to streambank erosion could be a catalyst to Wari and Tiwanaku agrarian colonies. The latter systems were not vulnerable to streambank erosion, and may even have benefited from other hydraulic effects of the same event. Moreover, agrarian catastrophe for the Huaracane provided a new dispossessed peasantry to be exploited by the Wari in the upper valley, and, after an extended period of floodplain recovery, vacant lands for the Tiwanaku to farm in the mid valley floodplain. Few clouds have no silver linings for someone, and our case shows that a “catastrophic” event that can shut down one agricultural system for generations, may benefit other cultural groups who use alternate agricultural practices. Further research integrating the archaeology of agricultural systems and settlement patterns with geomorphological approaches to disaster can shed light on both vulnerabilities and competitive advantages for multiple cultural actors, using a dynamic physical resource base.

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References

Abbott, M.B., Binford, M.W., Brenner, M., Kelts, K.R., 1997. A 3500 C–14 yr high-resolution record of water-level changes in Lake Titicaca, Bolivia/Peru. Quaternary Research 47 (2), 169180.

Aldenderfer, M.S., 1998. Montane Foragers: Asana and the South-Central Andean Archaic. University of Iowa Press, Iowa City.

Beresford-Jones, D., Lewis, H., Boreham, S., 2009. Linking cultural and environmental change in Peruvian prehistory. Geomorphological survey of the Samaca Basin, Lower Ica Valley, Peru, 78. Catena, pp. 234–249.

Bermann, M.P., Goldstein, P.S., Stanish, C., Watanabe, L., 1989. The collapse of the Tiwanaku State: a view from the Osmore Drainage. In: Rice, D.S., Stanish, C., Scarr, P. (Eds.), Settlement, History and Ecology in the Osmore Drainage, Southern Peru. : BAR International Series. British Archaeological Reports, Oxford, pp. 269–286.

Billman, B.R., 2002. Irrigation and the origins of the Southern Moche State on the north coast of Peru. Latin American Antiquity 13 (4), 371–400.

Billman, B.R., Huckleberry, G., 2008. Deciphering the politics of prehistoric El Niño events on the north coast of Peru. In: Sandweiss, D.H., Quilter, J. (Eds.), El Niño, Catastrophism, and Culture Change in Ancient America. Dumbarton Oaks Research Library and Collection. Distributed by Harvard University Press, Washington, D.C. [Cambridge, Mass.].

Blom, D., Hallgrímsson, B., Keng, L., Lozada, M.C., Buikstra, J.E., 1998. Tiwanaku state colonization: bioarchaeological evidence of migration in the Moquegua Valley, Perú. World Archaeology 30 (2), 238–261.

Caviedes, C., 2001. El Niño in History : Storming through the Ages. University Press of Florida, Gainesville.

Costion, K.E., 2009. Early Intermediate Social Differentiation in the Moquegua Valley, Southern Peru. Doctoral Dissertation Thesis, University of Pittsburgh, Pittsburgh.

Cutter, S.L., Mitchell, J.T., Scott, M.S., 2000. Revealing the vulnerability of people and places: a case study of Georgetown County, South Carolina. Annals of the Association of American Geographers 90 (4), 713–737.

Cutter, S.L., Boruff, B.J., Shirley, W.L., 2003. Social vulnerability to environmental hazards. Social Science Quarterly 84 (2), 242–261.

Erickson, C.L., 2000. The Lake Titicaca Basin: a pre-Columbian built landscape. In: Lentz, D. (Ed.), Imperfect Balance: Landscape Transformations in the Precolumbian Americas. Columbia University, New York.

Ertsen, M.W., van der Spek, J., 2009. Modeling an irrigation ditch opens up the world. Hydrology and hydraulics of an ancient irrigation system in Peru. Physics and Chemistry of the Earth, Parts A/B/C Water History 34 (3), 176–191.

Feldman, R.A., 1989. The early ceramic periods of Moquegua. In: Rice, D.S., Stanish, C., Scarr, P. (Eds.), Ecology, Settlement and History in the Osmore Drainage, Peru. : BAR International Series. British Archaeological Reports, Oxford, pp. 207–217.

Goldstein, P.S., 1989a. Omo, A Tiwanaku Provincial Center in Moquegua, Peru. Unpublished Ph.D. dissertation Thesis, Department of Anthropology, University of Chicago, Chicago.

Goldstein, P.S., 1989b. The Tiwanaku occupation of Moquegua. In: Rice, D.S., Stanish, C., Scarr, P. (Eds.), Ecology, Settlement and History in the Osmore Drainage, Peru. : BAR International Series. British Archaeological Reports, Oxford, pp. 219–256.

Goldstein, P.S., 2000a. Exotic goods and everyday chiefs: long distance exchange and indigenous sociopolitical development in the South Central Andes. Latin American Antiquity 11 (4), 1–27.

Goldstein, P.S., 2000b. Exotic goods and everyday chiefs: long distance exchange and indigenous sociopolitical development in the South Central Andes. Latin American Antiquity 11 (4), 1–27.

Goldstein, P.S., 2003. From stew-eaters to maize-drinkers: the Chicha economy and Tiwanaku. In: Bray, T. (Ed.), Pots as Political Tools: The Culinary Equipment of Early Imperial States in Comparative Perspective. Kluwer Academic Publishers, New York, pp. 143–172.

Goldstein, P.S., 2005. Andean Diaspora: The Tiwanaku Colonies and the Origins of Andean Empire. New World Diasporas. University Press of Florida, Gainesville.

Goodman-Elgar, M., 2008. Evaluating soil resilience in long-term cultivation: a study of pre-Columbian terraces from the Paca Valley, Peru. Journal of Archaeological Science 35 (12), 3072–3086.

Green, U.M., Goldstein, P.S., 2009. The nature of Wari presence in the Mid-Moquegua Valley: investigating contact at Cerro Trapiche. In: Jennings, J. (Ed.), Beyond Wari Walls: Exploring the Nature of Middle Horizon Peru away from Wari Centers. University of New Mexico Press.

Gregory-Wodzicki, K.M., 2000. Uplift history of the Central and Northern Andes: a review. Geological Society of America Bulletin 112 (7), 1091–1105.

Grosjean, M., Santoro, C.M., Thompson, L.G., Nunez, L., Standen, V.G., 2007. Mid-Holocene climate and culture change in the South Central Andes. In: Anderson, D.G., Maasch, K.A., Sandweiss, D.H. (Eds.), Climate Change and Cultural Dynamics: A Global Perspective on Mid-Holocene Transitions. El Sevier, New York, pp. 51–116.

Hastorf, C.A., Whitehead, W.T., Bruno, M.C., Wright, M.F., 2006. Movements of maize into middle horizon Tiwanaku, Bolivia. In: Staller, J.E., Tykot, R.H., Benz, B.F. (Eds.), Histories of Maize: Multidisciplinary Approaches to the Prehistory, Linguistics, Biogeography, Domestication, and Evolution of Maize. El Sevier Academic Press, Amsterdam, pp. 429–447.

Hayashida, F.M., 2006. The Pampa de Chaparri: water, land, and politics on the north coast of Peru. Latin American Antiquity 17 (3), 243–263.

Houston, J., Hartley, A.J., 2003. The central Andean westslope rainshadow and its potential contribution to the origin of hyper-aridity in the Atacama Desert. International Journal of Climatology 23 (12), 145364.

Huckleberry, G., 1995. Archaeological implications of late-Holocene channel changes on the Middle Gila River, Arizona. Geoarchaeology 10 (3), 159–182.

Ingram, S.E., 2008. Streamflow and population change in the lower Salt River Valley of central Arizona, ca. AD 775 to 1450. American Antiquity 73 (1), 136–165.

Kates, R.W., et al., 2001. Environment and development: sustainability science. Science 292 (5517), 641–642.

Keefer, D.K., Moseley, M.E., 2004. Southern Peru desert shattered by the great 2001 earthquake: implications for paleoseismic and paleo-El Niño-Southern oscillation records. Proceedings of the National Academy of Sciences of the United States of America 101 (30), 10878–10883.

Keefer, D.K., et al., 1998. Early maritime economy and El Niño events at Quebrada Tacahuay, Peru. Science 281 (5384), 1833–1835.

Keefer, D.K., Moseley, M.E., deFrance, S.D., 2003. A 38 000-year record of floods and debris flows in the Ilo region of southern Peru and its relation to El Niño events and great earthquakes. Palaeogeography Palaeoclimatology Palaeoecology 194 (1–3), 41–77.

Kolata, A.L. (Ed.), 1996. Tiwanaku and its Hinterland: Archaeology and Paleoecology of an Andean Civilization, 1: Agroecology. Smithsonian Institution Press, Washington, D.C.

Kolata, A.L., Ortloff, C., 1996. Agroecological perspectives on the decline of the Tiwanaku state. In: Kolata, A.L. (Ed.), Tiwanaku and its Hinterland: Archaeology and

Paleoecology of an Andean Civilization. Smithsonian Institution Press, Washington, pp. 181–202.

Kolata, A.L., Binford, M.W., Brenner, M., 2000. Environmental thresholds and the empirical reality of state collapse: a response to Erickson (1999). Antiquity 74 (no284), 424–426 June 2000.

Kuznar, L., 1990. Pastoralismo temprano en la sierra alta del Departamento de Moquegua, Peru. Chungará 24 (25), 53–68.

Magilligan, F.J., Goldstein, P.S., 2001. El Niño floods and culture change: a late Holocene flood history for the Rio Moquegua, southern Peru. Geology 29 (5), 431–434.

Magilligan, F.J., Goldstein, P.S., Manners, R.J., 2008. Climate change, floods, and alluvial adjustments in a hyper-arid watershed in the Atacama Desert: links to the El-Niño-Southern Oscillation, Binghamton Geomorphology Symposium, 2008. Fluvial Deposits and Environmental History, Austin.

Manners, R.B., Magilligan, F.J., Goldstein, P.S., 2007. Floodplain development, el Niño, and cultural consequences in a hyperarid Andean Environment. Annals of the Association of American Geographers 97 (2), 229–248.

Moseley, M.E., 1998. Andean coastal adaptations: uniformitarianism and multilinear evolution. In: Balke, M. (Ed.), Pacific Latin America in Prehistory. Washington State University Press, pp. 171–180.

Moseley, M.E., 1999. Convergent catastrophies: past patterns and future implications of collateral natural disasters in the Andes. In: Oliver-Smith, A., Hoffman, S. (Eds.), The Angry Earth: Disasters in Anthropological Perspective. Routledge, London, pp. 59–71.

Moseley, M.E., 2001. Modeling protracted drought, collateral natural disasters, and human responses in the Andes. In: Hoffman, S.M., Oliver-Smith, A. (Eds.), Catastrophe and Culture: The Anthropology of Disaster.

Moseley, M.E., et al., 2005. Burning down the brewery: establishing and evacuating an ancient imperial colony at Cerro Baúl, Peru. Proceedings of the National Academy of Sciences of the United States of America 102 (48), 17264–17271.

Nash, D.J., Williams, P.R., 2005. Architecture and power on the Wari–Tiwanaku Frontier. Archeological Papers of the American Anthropological Association 14 (1), 151–174.

Nunn, P.D., 2000. Environmental catastrophe in the Pacific Islands around A.D. 1300. Geoarchaeology 15 (7), 715–740.

Ortloff, C.R., 1993. Climate and collapse: agro-ecological perspectives on the decline of the Tiwanaku State. Journal of Archaeological Science 20 (2), 195–221.

Owen, B.D., 1993. A model of multiethnicity: state collapse, competition, and social complexity from Tiwanaku to Chiribaya in the Osmore Valley, Perú. Unpublished Ph.D. dissertation Thesis, Department of Anthropology, University of California, Los Angeles.

Owen, B.D., 1996. Inventario Arqueológico del Drenaje Superior del Río Osmore: Informe del Campo e Informe Final, Informe entregado al Instituto Nacional de Cultura, Lima y Moquegua.

Owen, B.D., 1999. Proyecto "Vecinos de Cerro Baúl", 1997, Informe del Campo e Informe Final, Informe entregado al Instituto Nacional de Cultura, Lima y Moquegua.

Owen, B.D., 2005. Distant colonies and explosive collapse: the two stages of the Tiwanaku diaspora in the Osmore drainage. Latin American antiquity : a journal of the Society for American Archaeology 16 (1), 45–80.

Owen, B.D., 2009. Early agriculture in the Coastal Osmore Valley, Peru. In: Marcus, J., Williams, P.R. (Eds.), Andean Civilization: A Tribute to Michael E. Moseley. Cotsen Institute, UCLA, Los Angeles, pp. 121–144.

Owen, B.D. and Goldstein, P.S., 2001. Tiwanaku en Moquegua: interacciones regionales y colapso. Boletín de Arqueología, Pontificia Universidad Católica del Perú, 5: Huari y Tiwanaku: Modelos vs, Evidencias: 169–188.

Ravesloot, J.C., Waters, M.R., 2002. Geoarchaeology and archaeological site patterning on the Middle Gila River, Arizona. Journal of Field Archaeology 29 (1–2), 203–214.

Reycraft, R.M., 2000. Long-term human response to El Niño in South Coastal Peru, circa A.D.1400. In: Bawden, G., Reycraft, R.M. (Eds.), Environmental disaster and the Archaeology of Human Response. Maxwell Museum of Anthropology, University of New Mexico, Albuquerque, pp. 99–119.

Rice, P.M., Smith, G.C., 1989. The Spanish colonial wineries of Moquegua, Peru. Journal of the Society for Historical Archaeology 23 (2), 41–49.

Roscoe, P., 2008. Catastrophe and the emergence of political complexity : a social anthropological model. In: Sandweiss, D.H., Quilter, J. (Eds.), El Niño, Catastrophism, and Culture Change in Ancient America. Dumbarton Oaks Research Library and Collection. Distributed by Harvard University Press, Washington, D.C, pp. 77–100. [Cambridge, Mass.].

Sandness, K., 1992. Temporal and Spatial Dietary Variability in the Osmore Drainage, Southern Peru: The Isotope Evidence. Unpublished M.A. thesis, Department of Anthropology, University of Nebraska, Lincoln.

Sandweiss, D.H., et al., 2007. Mid-Holocene climate and culture change in coastal Peru. In: Anderson, D.G., Maasch, K.A., Sandweiss, D.H. (Eds.), Climate change and cultural dynamics: a global perspective on mid-Holocene transitions. El Sevier, New York, pp. 25–51.

Sandweiss, D.H., Quilter, J., Dumbarton Oaks, 2008. El Niño, catastrophism, and culture change in ancient America. Dumbarton Oaks Research Library and Collection. Distributed by Harvard University Press, Washington, D.C. [Cambridge, Mass.].

Satterlee, D.R., 1993. The impact of a fourteenth century el niño flood event on an indigenous population near Ilo, Peru. Unpublished Ph.D. Dissertation Thesis, Department of Anthropology, University of Florida, Gainesville.

Satterlee, D.R., Moseley, M.E., Keefer, D.M., Tapia, J.E.A., 2000. The Miraflores El Niño disaster: convergent catastrophes and prehistoric agrarian change in southern Peru. Andean Past.

Schimmelmann, A., Zhao, M., Harvey, C.C., Lange, C.B., 1998. A large California flood and correlative global climatic events 400 years ago. Quaternary Research 49 (1), 51–61.

Schimmelmann, A., Lange, C.B., Meggers, B.J., 2003. Palaeoclimatic and archaeological evidence for a similar to 200-yr recurrence of floods and droughts linking California, Mesoamerica and South America over the past 2000 years. Holocene 13 (5), 763–778.

Schreiber, K.J., 1992. Wari imperialism in Middle Horizon Peru. Anthropological Papers, 87. Museum of Anthropology, University of Michigan, Ann Arbor.

Schreiber, K.J., 2001. The Wari Empire of Middle Horizon Peru: the epistomological challenge of documenting an empire without documentary evidence. In: Alcock, S.E., D'Altroy, T.N., Morrison, K.D., Sinopoli, C.M. (Eds.), Empires: Perspectives from Archaeology and History. Cambridge University Press, pp. 70–92.

Shimada, I., Schaaf, C.B., Thompson, L.G., Mosley-Thompson, E., 1991. Cultural impacts of severe droughts in the prehistoric Andes: application of a 1500-year ice core precipitation record. World Archaeology 22 (3), 247–270.

Stanish, C., 1992. Ancient Andean Political Economy. University of Texas Press, Austin.

Stanish, C., 2006. Prehispanic agricultural strategies of intensification in the Titicaca Basin of Peru and Bolivia. In: Marcus, J., Stanish, C. (Eds.), Agricultural Strategies. Cotsen Institute of Archaeology, University of California, Los Angeles, pp. 364–397.

Tosdal, R.M., Clark, A.H.a., Farrar, E., 1984. Cenozoic polyphase landscape and tectonic evolution of the Cordillera Occidental, Southernmost Peru. Geological Society of America Bulletin 95 (11), 1318–1332.

Turner, B.L., et al., 2003. A framework for vulnerability analysis in sustainability science. Proceedings Of The National Academy Of Sciences Of The United States Of America 100 (14), 8074–8079.

van Buren, M., 2001. The archaeology of El Niño events and other [natural] disasters. Journal of Archaeological Method and Theory 8 (2).

Vuille, M., 1999. Atmospheric circulation over the Bolivian Altiplano during dry and wet periods and extreme phases of the Southern Oscillation. International Journal of Climatology 19, 1579–1600.

Waters, M.R., Ravesloot, J.C., 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.

Wells, L.E., 1990. Holocene history of the El Niño phenomenon as recorded in flood sediments on northern coastal Peru. Geology 18, 1134–1137.

Wilkerson, F.J.K., 2008. And the waters took them: catastrophic flooding and civilization on the Mexican Gulf Coast. In: Sandweiss, D.H., Quilter, J. (Eds.), El Niño, Catastrophism, and Culture Change in ancient America. Dumbarton Oaks Research Library and Collection. Distributed by Harvard University Press, Washington, D.C, pp. 243–272. [Cambridge, Mass.].

Williams, P.R., 1997. The role of disaster in the development of agriculture and the evolution of social complexity in the South-Central Andean Sierra. Unpublished Ph. D. dissertation Thesis, Department of Anthropology, University of Florida, Gainesville.

Williams, P.R., 2001. Cerro Baul: a Wari center on the Tiwanaku frontier. Latin American Antiquity 12 (1), 67–83.

Williams, P.R., 2002. Rethinking disaster-induced collapse in the demise of the Andean highland states: Wari and Tiwanaku. World Archaeology 33 (3), 361–374.

Williams, P.R., 2006. Agricultural innovation, intensification, and sociopolitical development : the case of highland irrigation agriculture on the Pacific Andean watersheds. In: Marcus, J., Stanish, C. (Eds.), Agricultural strategies. Cotsen Institute of Archaeology, University of California, Los Angeles, pp. 309–333.

Williams, P.R., Nash, D.J., 2002. Imperial interaction in the Andes: Huari and Tiwanaku at Cerro Baúl, Andean archaeology I. Variations in Sociopolitical Organization. Kluwer Academic/Plenum, New York, pp. 243–265.

Williams, P.R., Moseley, M.E., Nash, D.J., 2000. Empires of the Andes: a majestic frontier outpost chose cooperation over war. Discovering Archaeology, 8.