ISSN 0097-4463

ANNALS of CARNEGIE MUSEUM

CARNEGIE MUSEUM OF NATURAL HISTORY

4400 FORBES AVENUE • PITTSBURGH, PENNSYLVANIA 15213

VOLUME 52 16 SEPTEMBER 1983 ARTICLE 13

PRINCIPLES OF AGRARIAN COLLAPSE IN THE CORDILLERA NEGRA, PERU

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Abstract

The amount of land under cultivation on the arid north coast of Peru has decreased by 35 to 40% during the last 1000 years. Two physical processes are implicated in this agrarian collapse. The basic contributory process is uplift along the Peruvian continental margin, which causes ground slope changes, The second process involves rare but recurrent rains caused by El Niño perturbations of the normal marine and meteorological conditions. Uplift leads to river entrenchment, and El Niño rains aggravate erosional downcutting. Downcutting strands canal intakes, forcing abandonment of irrigation systems in favor of newer, lower canals which irrigate less land.

Introduction

The largest irrigation reclamation projects ever put into operation in South America are sophisticated pre-Columbian canal delivery sys-

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Submitted 22 March 1983.

tems designed to feed highland runoff from the Pacific watershed of the Cordillera Negra to arid lands along the desert coast of Peru between ca. 6° and 9° south latitude (Kosok, 1965; Schaedel, 1951). Built principally after A.D. 500, but abandoned prior to European arrival, these networks, discovered four decades ago with the advent of systematic aerial photography, include multi-valley canal linkages (Kus, 1972; Ortloff et al., 1982; Eling, 1981; Shimada, 1981) as well as intra-valley canal systems, remnants of which surround and enclose the 30 to 40% smaller confines of contemporary irrigation agriculture (Moseley and Deeds, 1982). Significantly, financing and technology imported from industrialized nations are presently employed to erect large-scale reclamation projects within the ruins of these abandoned networks without knowledge of why the older and larger agrarian systems collapsed.

Within the lower Rio Moche valley (8° south latitude), between 1976 and 1980, 578 excavations were opened in abandoned canals and related agricultural structures (Pozorski and Pozorski, 1982). Hydraulic analyses of channel configuration and engineering parameters indicate that pre-Hispanic canal systems constructed during the past millennium employed essentially modern hydrological concepts of critical and sub-critical flow design techniques (Ortloff et al., 1982, 1983*a*, 1983*b*). This is not to imply either that native hydraulic engineering is well explored, or that all abandoned canals are free of design errors. However, these analyses support the contention that the roots of agrarian collapse do not lie with human error or technological inadequacies of the societies which built the reclamation works (Ortloff et al., 1982, 1983*b*). Proceeding from this position, it is possible to analyze irrigation agriculture as an artificial extension of the natural hydrological regime and to identify the long-term principles of agrarian collapse within the Moche Valley and adjacent river basins.

Both regional processes have been implicated and local causes identified in the break-down of irrigation systems between 6° and 9° south latitude (Ortloff et al., 1982; Eling, 1981; Shimada, 1981; Kus, 1972, 1983; Ericksen et al., 1970; Plafker, Ericksen, and Concha, 1971; Nials et al., 1979; Moseley et al., 1981).

Steep-gradient rivers of the watershed are eroding in response to two regional processes. The basic contributory process is uplift related to high rates of tectonic activity along the continental margin, which can cause ground slope change. The second process entails rare, but recurrent torrential rainfall on the otherwise completely arid coastal desert caused by El Niño perturbations of the normal Pacific marine and meteorological conditions. When the rare, major rains do fall—as last transpired in 1925—it is upon steep, unvegetated land surfaces covered with accumulated debris. As a result, the drainage system is flooded and extensive and intensive erosion and mass wasting occurs.

Canal intakes physically tie irrigation to the drainage systems. As rivers downcut and alter course, canal intakes loose efficiency and become stranded above the entrenched stream channel. Intakes may be reworked, but bedrock obstacles in the valley necks eventually curtail recutting, leading to final intake stranding and channel abandonment.

Due to the lack of annual precipitation below ca. 1500 m, the lower 48% of the watershed lies within the world's driest desert (Lettau and Lettau, 1978) so the water table of the coast land can only be recharged by river runoff. As uplift and river downcutting proceed, the water table falls and agriculture dependent upon groundwater constricts toward the coast.

At the valley mouths, disgorged sediment is sorted by constant north-northwest longshore currents and distributed along the shoreline. Coastal flats exposed by uplift provide abundant sand that is transported inland by constant north to north-northwest daily winds. Sand drifts inundate agricultural systems and force their abandonment. If they stabilize, the sands may be farmed over and subsequently experience flooding, erosion, or deflation, forcing renewed abandonment.

Locally, displacements along faults alter ground slope and change canal gradients, thereby curtailing water supply to the distal reaches of the channels. These tectonic events may lead to channel reconstruction, new course placement, or canal abandonment (Ortloff et al., 1983*b*).

This paper will focus on one of the above factors—river downcutting—and the effects it had on irrigation and human settlement in the Moche Valley.

PHYSICAL FACTORS

The Watershed

In concordance with adjacent drainages (Table 1), the Moche basin rises a short distance inland at a high elevation (3988 m) and descends the western slope of the Cordillera Negra at a very steep average gradient (2.2 degrees) over a very short (102 km) linear course perpendicular to the coast (Fig. 1). The steep river gradient and the often precipitous bedrock landscape through which the river descends suggests apparent ongoing uplift of the watershed, probably related to tectonic processes at the active Peruvian continental margin, where two lithospheric plates converge. The plate rotation model of Minster et al. (1974) predicts that the Nazca oceanic plate is converging with the South American continental plate at rates ranging from 8.9 cm per year near the equator to 11.1 cm per year in central Chile. Deep sea cores from the vicinity of the study area have been interpreted as compatible with convergence rates of ca. 10 cm per year; such a rate appears to have been the norm for the last 5 million years (Kulm et al., 1976:795, 800).

Table 1.—*Characteristics of rivers of western Peru.*

River	Basin size (km^2)	Irrigated area (km^2)	Length (km)	Flow volume ($m^3 \times 10^6$)	150 m elevation (km from mouth)	% Gradient 1000-Omasl
Chancay	3375	523.42	194	701	58	1.1
Zaña	1125	191.13	119	202	51	1.0
Jequetepeque	4050	295.78	154	945	30	1.1
Chicama	3004	403.71	164	783	27	1.1
Moche	1562	200.26	105	320	19	2.1
Virú	1308	164.05	89	105	24	2.2
Chao	600	NA	78	NA	22	2.4
Santa	11,250	86.43	332	4594	27	0.9

The Moche basin and adjacent drainages between 6° and 9° lie within the second of five longitudinal seismic provinces subdividing the Andean Cordillera (Barazangi and Isacks, 1976; Sillitoe, 1974). In recent decades, seismic activity has included, in 1970, the most devastating historic earthquake in the New World (Ericksen et al., 1970; Plafker et al., 1971), as well as prior gradual vertical oscillation of the coastline at an average rate of 1.8 cm per annum (Wyss, 1978).

Although the 1970 earthquake (which registered 7.7 on the Richter Scale) was not known to be associated with surface fault displacement, the watershed is cut by numerous geologic linears, many of which are presumably geological structures. A pronounced scarp parallels the Cordillera and subdivides the watershed into two longitudinal sections:

1. A coastal lowland consisting, not of marine sediments, but of Quaternary and recent alluvium and aeolian sands overlying igneous bedrock.
2. A broken highlands of highly dissected bedrock exposures with limited cover of Quaternary and recent alluvium.

The pronounced scarp intersects the coast at a low angle in the region between ca. 8° and 9° south latitude (Fig. 1), resulting in a wedge-shaped coastal lowland. The major scarp is, in turn, cut by transverse linears. Where these intersect the coast, inflections suggest offset and the occurrence of related fault displacement.

Like the adjacent rivers, the Rio Moche's valley coincides with a transverse linear. In the highlands the river channel is entrenched within a steep bedrock canyon. After crossing the scarp face, the flood plain widens as the valley is not restricted by bedrock. Below ca. 150 m, beyond the confines of the scarp, the gradient is lower and the river traverses alluvial fill to the coast. As in adjacent drainages, the northern side of the lower valley is characterized by mountain outliers which

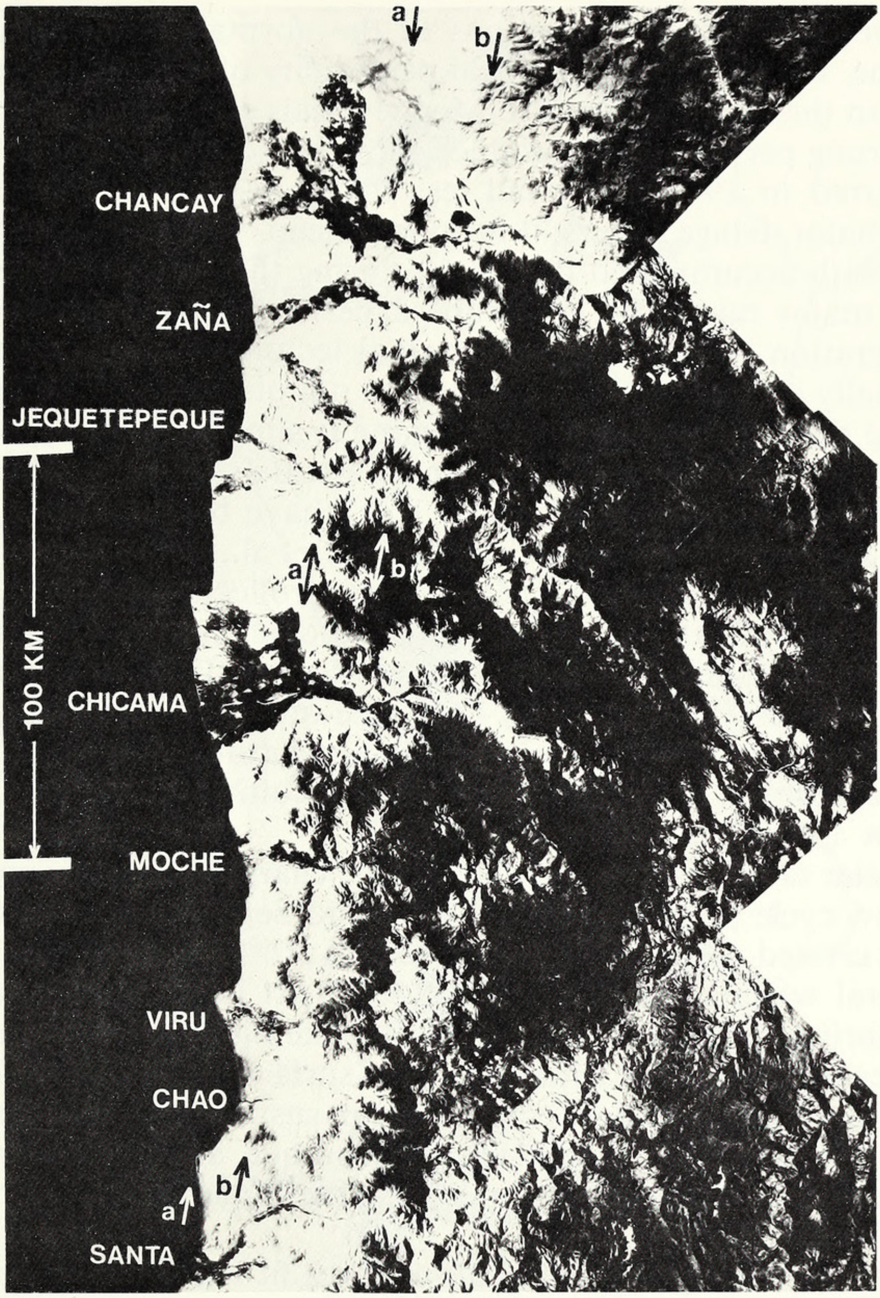

Fig. 1.—Uncorrected mosaic of LANDSAT images showing the Peruvian north coast from the Chancay drainage south to the mouth of the Santa River. Lines a-a and b-b mark the high-flexure scarp that divides the coastal plain from the mountains.

crop out from the ocean from within large expanses of relatively flat land, whereas south of the river the mountain fringe extends down to the coast and there is relatively little flat land.

The lower 48% of the Moche watershed lies in a hyperarid desert (Lettau and Lettau, 1978), where normally there is no annual precipitation below 1500 m. Infrequent desert rains occur only in association with strong El Niño perturbations of the normal ocean-atmosphere conditions, which have a statistical periodicity of about one per 15 or 16 years in the region of the Rio Moche (Nials et al., 1979). However, not all strong perturbations produce showers, so major rains—such as last occurred in 1925—may fall less than once per century or two. When a major deluge occurs, it is upon a steep, unvegetated landscape covered with accumulated debris. If, during the decades or centuries between major rains, the landscape experiences even minor ground slope alteration from seismic or gradual tectonic activity, then all of the normally dry desert drainages will be out of erosional equilibrium. When the destabilized hydrologic regime is supercharged by flooding, erosion and mass wasting can occur on a scale so vast that Holocene incidents, as last occurred ca. A.D. 1100, have been misidentified as products of earlier glacial epochs (Moseley et al., 1981).

Only the upper 52% of the Moche basin collects significant precipitation. Highland rainfall is markedly seasonal, with more than 75% falling in 25% of the calendar year. River flow peaks between February and March, then drops rapidly. For three-quarters of each year most river discharge is drawn off by irrigation agriculture in the lower valley, where there are ca. 19,950 ha of land under cultivation, most of which lies below 150 m.

The water table of the coastal lowlands, charged by river runoff, has a high-low cycle peaking between June and September, well after the river has crested. Groundwater provides ca. 16% of the present coastal agricultural water supply (ONERN, 1973). It is exploited via channelized springs or pukios, pumps, and sunken gardens. The latter are an indigenous technique where the land surface is excavated down to the level at which natural soil moisture can sustain plant growth. Sunken gardens are an efficient agricultural technique, although one restricted to areas with a high water table by the large labor expenditures needed for excavation.

The Moche basin and its agricultural area fit within a graded north-to-south sequence of large to small river valleys with agricultural areas of proportional size (Table 1; Fig. 2). This pattern begins with the Rio Chancay (6.5° south latitude) and, with one exception (Rio Zaña) continues south to the Rio Santa, where it is broken. The Santa is the largest river basin along the entire Andean desert coast, and while it carries 14 times the volume of the Rio Moche, it supports a significantly smaller agricultural area (43%).

The Hydrological Regime

If irrigation agriculture is to be analyzed as an artificial extension of the hydrological regime, then it must be recognized that this regime evolves in a mechanical manner in response to changes in land-to-sea level at the river mouth and along the littoral zone. Due to eustatic

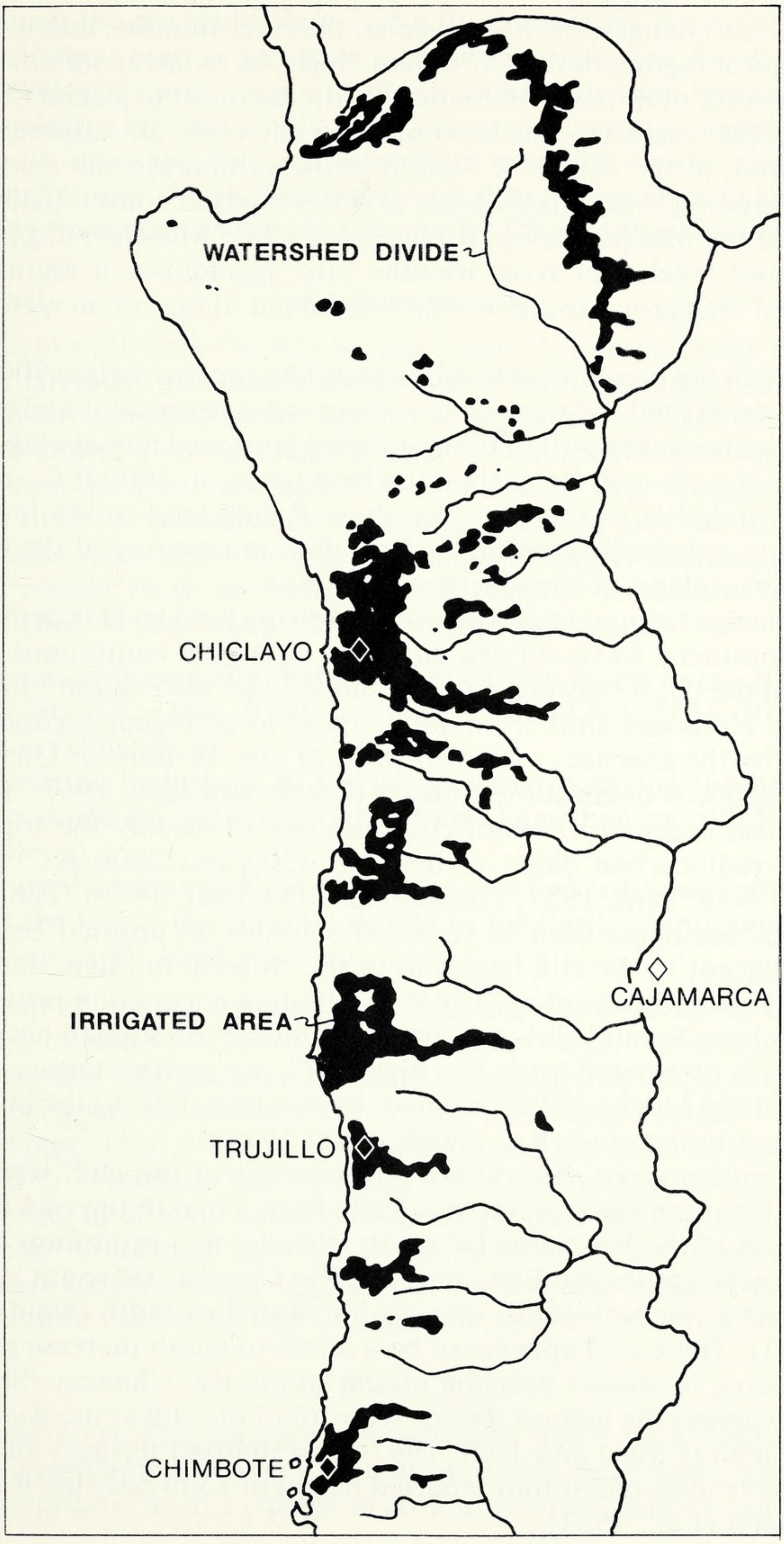

Fig. 2.—Cultivated areas of the Peruvian north coast.

and tectonic changes, the littoral zone, the river mouths, and the entire hydrological regime of the Cordillera Negra have never stabilized during the course of human occupation. With the onset of glacial meltback some 15,000 years ago, the level of the oceans rose an estimated 85 to 135 m and, in the course of 10,000 years, submerged the continental shelf, including more than 75 km of once-exposed coastal plain at the mouth of the Moche Valley (Richardson, 1981; Moseley, n.d.). Rising sea-to-land levels put river mouths into aggradational regimes and generated high groundwater conditions inland of the submergent coastline.

Although the ocean level began to stabilize approximately 5000 years ago, the watershed did not. Rather, there was a reversal of hydrological conditions because uplift of the watershed remained an ongoing proces. Whereas the sea rose faster than the land up to ca. 3000 B.C., the land has risen relative to the sea since then. Rising land-to-sea levels put rivers into a degrading regime and resulted in lowering of the groundwater table inland of the emergent coastline.

The change from a rising sea level to a rising land level is demarcated by a prominent wave-cut sea cliff that is largely continuous for the length of the coast between ca. 6.5° and 9°. The association of this cliff with the Holocene shift from submergent to emergent regimes is indicated by the absence, inland from it, of any Tertiary or Quaternary marine deposits or coastline features (Cossio and Jaen, 1967). Further, the earliest sedentary human communities to occupy the top of the cliff are radiocarbon dated to between 3200 and 2000 B.C. (Cardenas, 1977–78; Bird, 1951; Pozorski and Pozorski, 1979). The earliest mollusks, occurring both as stranded colonies on uplifted beach surfaces adjacent to the cliff base and in the cliff-top midden, date to ca. 3200 B.C. (Sandweiss et al., 1981). No human occupation prior to this date has been found below the sea cliff. The earliest human occupation tentatively associated with the highest (8 m) marine terraces at the mouth of the Moche Valley is dated, by ceramic style, to the latter half of the first millennium B.C. (Nials et al., 1979).

The contemporary littoral zone is seaward of the cliff, with intervening distances grading systematically from a maximum of 5 km near the mouth of the Rio Santa (9° south latitude) to a minimum of a few tens of meters at Puerto Eten, near the Rio Chancay (6° south latitude), indicating a north-to-south increase in shoreline width (Sandweiss et al., 1981). There also appears to be a north-to-south increase in uplift; no terracing is present near the mouth of the Rio Chancay (Shimada, 1981), whereas the highest terrace seaward of the cliff at the Rio Moche is 8 m. high (Cossio and Jaen, 1967), and uplifted terraces and beach ridges have their maximum reported height of 15 m near the Rio Santa (Sandweiss et al., 1981).

Although the sea cliff is largely continuous across the mouth of the Moche Valley, marine terracing and beach ridges are found in their most developed form on the northern, leeside of bays bracketing the valley mouth. The bays only have seaward projecting headlands on their south sides and they represent fault-bounded coastal deflections. The distribution of well developed raised beach surfaces in these settings may reflect consistent relative uplift of the south side of the faults.

The River Banks

In recent millennia the Rio Moche, below 150 m, has both downcut and cut laterally, principally southward. This movement has resulted in an asymmetrical erosional profile, with gentle slopes north and west of the river and a vertical bank formed by undercutting of valley-floor deposits on the south and east side of the river. Beginning ca. 6.5 km in from the river mouth and continuing upstream for more than 7 km to the valley neck, undercutting has exposed a largely continuous stratigraphic profile 10 m or more in height. Salient features of a 12+ m column (Fig. 3) near the profile's seaward end include:

A) Basal peat deposits that are radiocarbon dated to ca. 1000 B.C. (WSU No. 2190: 3010 ± 100 B.P.; WSU No. 2194: 3020 ± 60 B.P.) (Fig. 3h, i).
B) Ceramic inclusions in fluvial deposits overlying the peats that are dated on stylistic grounds to no later than ca. 500 B.C. (Fig. 3f).
C) Buried agricultural furrows and a small sherd-lined feeder canal at the top of the column, dating to the Early Chimu phase prior to ca. A.D. 1000.

The top of the column has been deflated, and behind the bank are yardangs, or butte-like erosional remnants of sandy loam, which stand several meters high and contain Early Chimu sherds. Early and Middle Chimu occupational debris are found on the deflated surfaces between the yardangs. Thus, the end of deposition and the onset of erosion can be dated to within the Early Chimu phase (Table 2).

The onset of erosion is the postulated product of river downcutting in response to tectonic activity. Unfortunately, the stratigraphy of the south bank sequence does not crop out downstream as far as the littoral and therefore cannot be tied to a specific uplifted beach surface.

The Water Table

Because river flow charges groundwater, uplift with consequently increased gradients and river downcutting would, expectably, alter water table conditions. Such a change in groundwater conditions can be seen

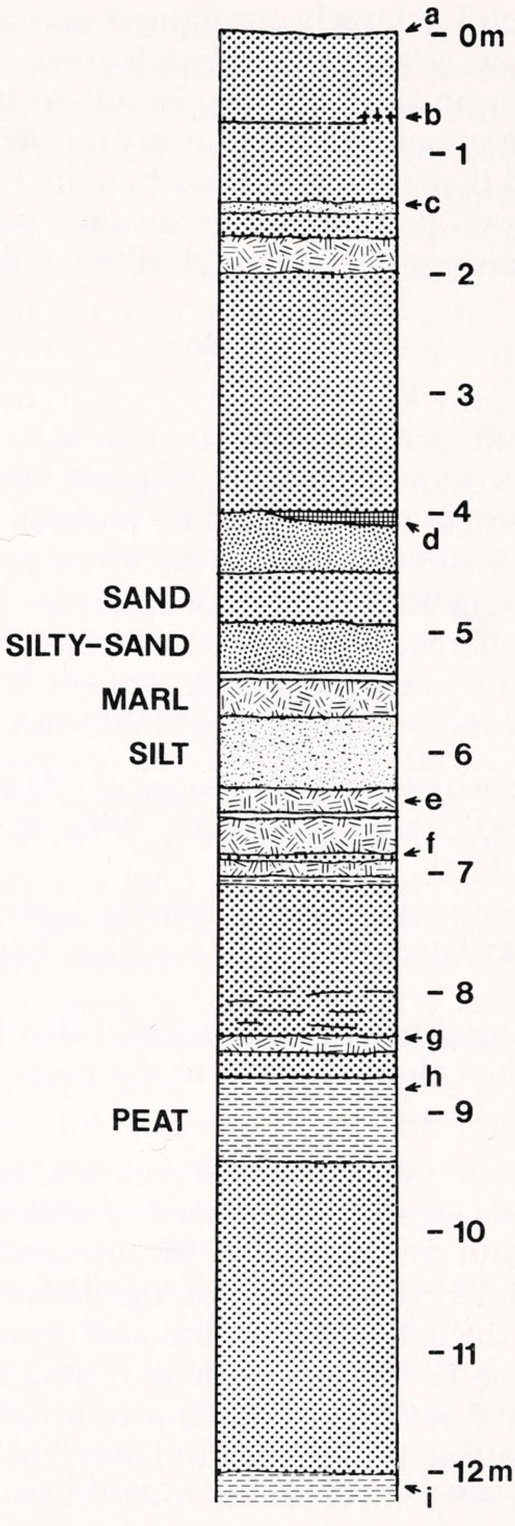

Fig. 3.—Rio Moche stratigraphic column at Pampa Casique. a) Chimu fields; b) Chimu feeder canal; c) buried fields; d) hearth; e) 2180 ± 170 B.P. (WSU-2192); f) pottery sherds; g) 2490 ± 90 B.P. (WSU-2193); h) 3020 ± 60 B.P. (WSU-2194); i) 3010 ± 100 B.P. (WSU-2190).

Table 2.

	PERUVIAN RELATIVE CHRONOLOGY	LOCAL PHASES	MAJOR SITES
1500	LATE HORIZON	CHIMU-INCA	
	LATE INTERMEDIATE PERIOD	LATE BRICK MIDDLE BRICK CHIMU EARLY BRICK	CHAN CHAN
1000			
	MIDDLE HORIZON	EARLY CHIMU V	GALINDO
500	EARLY INTERMEDIATE PERIOD	IV III MOCHE II I	MOCHE HUACAS
0 AD			

in the horizontal distribution of two agricultural techniques—spring fed canals and sunken gardens.

The earliest historical map of the valley's agricultural configuration, made in 1760, shows two spring fed canal systems north and west of the river (Kosok, 1965). The highest system was fed from a pond located about 75 m above sea level, 12 km inland, and 1.5 km north of the river. By 1942, when aerial photographs of the lower valley were made, this system was no longer operative, and the area it once irrigated was supplied by the major northside river fed canal (the N1). The lower canal system fed by groundwater was shown in the 1760 map as coming from a pond located about 42 m above sea level, 9 km inland, and 2 km north of the river. By 1942, this system (the Pukio system, Fig. 4) was no longer fed from a pond, but rather from two springs or seeps approximately 1 km apart. Today it is fed only by the lower spring.

Sunken gardens, which rely upon high groundwater conditions, extended inland at least 4.5 km at the beginning of the Chimu phase (Fig. 4). By 1942, this technique had dramatically contracted coastward and all sunken garden farming was limited to a region within 1 km or less of the shoreline, principally seaward of the wavecut cliff. Areas formerly cultivated by groundwater exploitation were irrigated from river and spring fed canals. Coastward encroachment of irrigation agriculture into these areas has continued in recent decades without the significant salinization problems that would be expected if the water table had not subsided, improving drainage. A measure of this subsidence is reflected by remnants of abandoned early Chimu gardens situated 4.5 km inland that now lie 10 to 12 m above the contemporary water table. Although this drop is a cumulative measure that includes the effects of mechanical pumping, the seaward contraction of groundwater agriculture which preceded pumping is most simply explained as a corollary of coastal uplift, river downcutting, and water table lowering.

Canal Strategy

In a context of high aridity for unlined canals, less than 55% of the water that a canal receives from its river source reaches farmland, less than 45% is absorbed by the soil, and only about 16% is actually utilized by crops (USDA, 1955; West, 1981). Much of the loss occurs as seepage or evaporation during transport. Therefore, the highest system efficiency in open channel flow design entails moving the maximum amount of water the minimum possible distance to the largest possible planting area.

For the steep-gradient rivers of the Cordillera Negra, maximum design efficiency is represented by canals that transport and distribute water along a course perpendicular to the rivers. This configuration expresses a balanced relationship between separate functions of supply and distribution. Intake capability, slope, and channel hydraulic configuration set maximum limits on the volume of water that a canal can supply. However, the maximum limit on the size of the planting area over which this supply can be efficiently distributed is the downslope area included between the river and the canal. This "angle of reach" between river and canal thus establishes the distance of transport relative to area of planting surface (Fig. 5).

If a canal intake feeds from an entrenched river, then its initial lead-off channel must slope downstream at a low angle of reach before it can exit the confines of the downcut floodplain at an elevation suitable for perpendicular course placement. Given water loss in transport, the perpendicular course distance that the canal can supply is thus limited

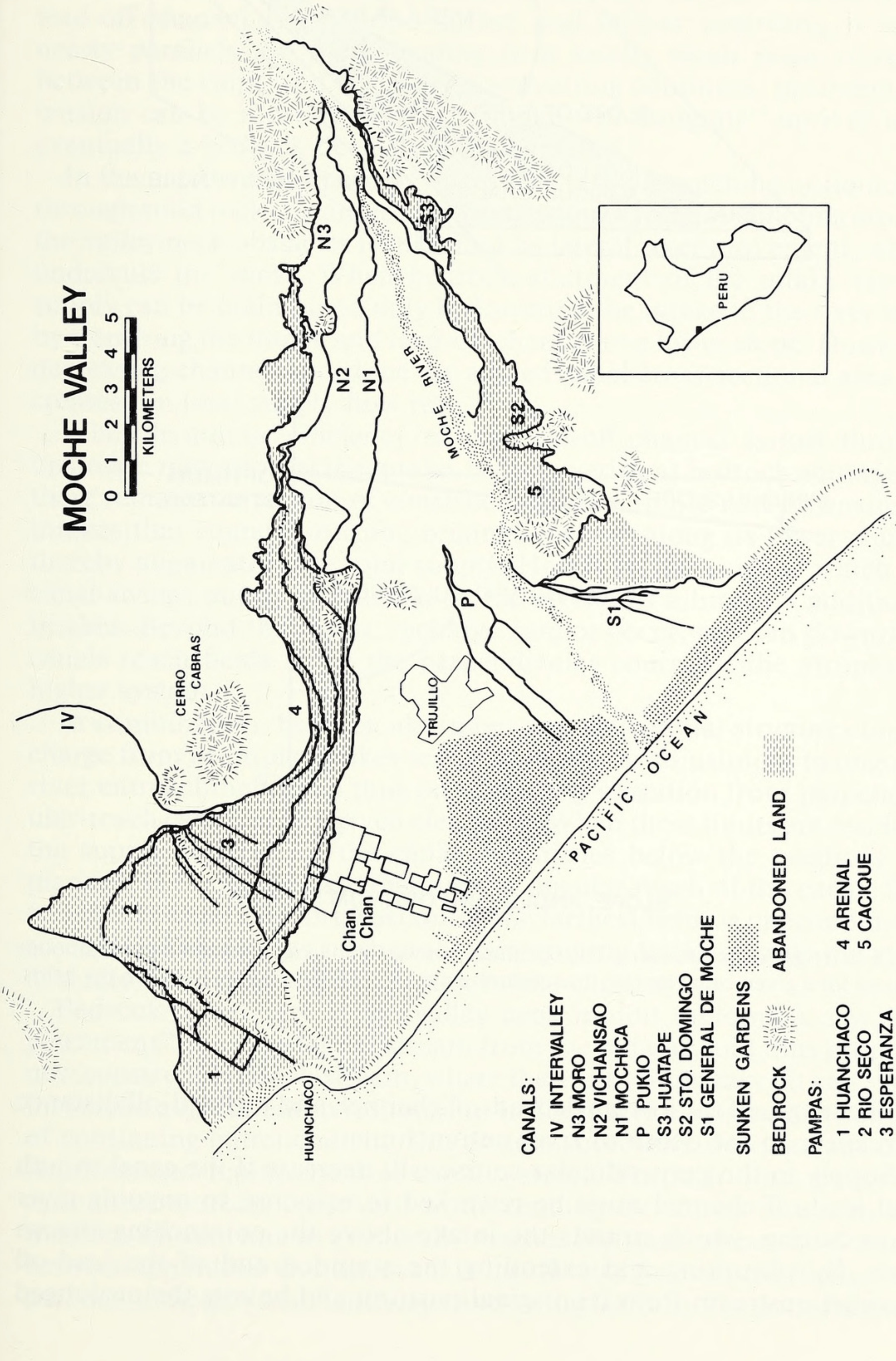

Fig. 4.—Map of the lower Moche Valley showing major canals, pampas, and areas of abandoned fields.

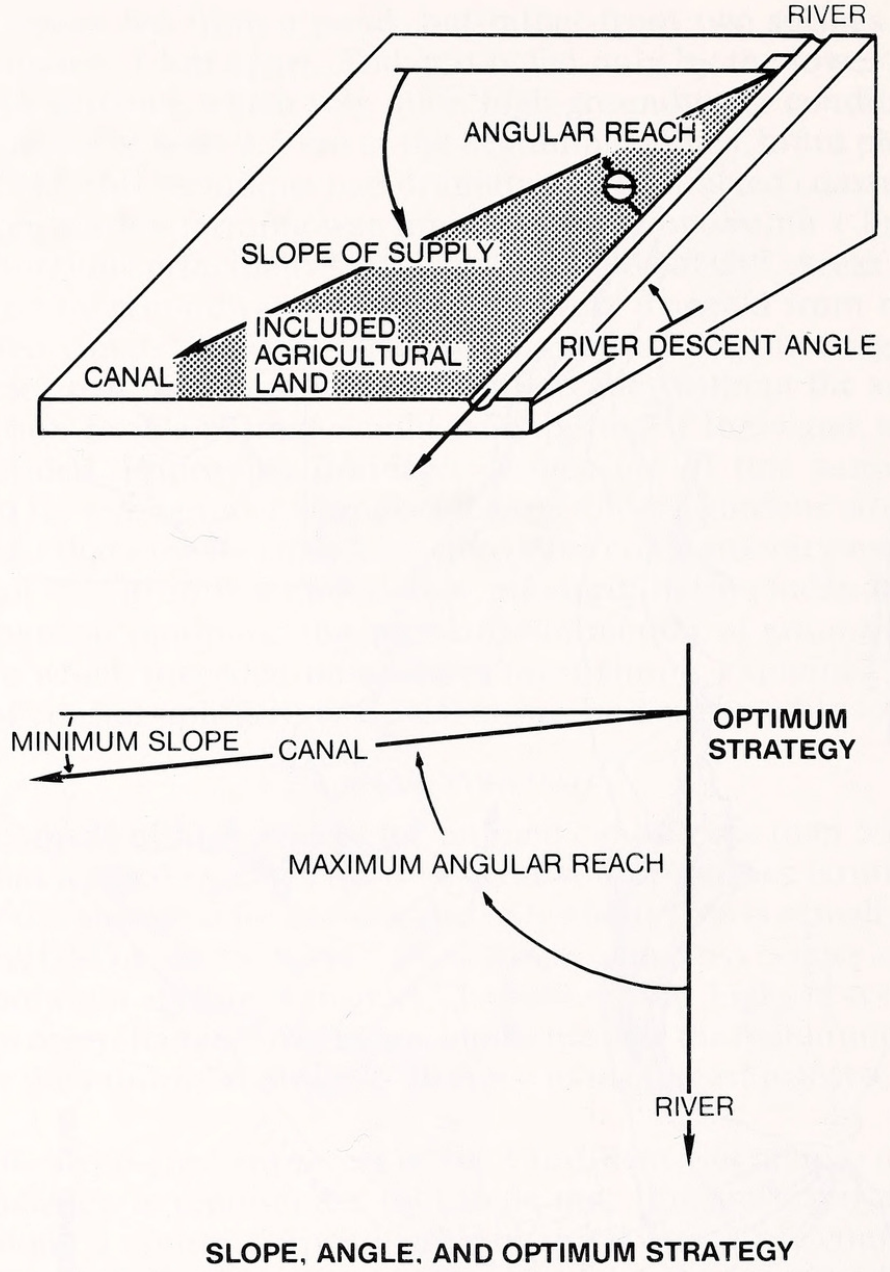

Fig. 5.—Irrigation parameters. The optimum strategy is to irrigate the maximum amount of land for a given canal length, thus minimizing water loss during transport to the fields.

by the length of the low-angle lead-off channel, and the lead-off distance is relative to the depth of river entrenchment.

Supply to the perpendicular course will decrease if the canal mouth and lead-off channel must be reworked in response to ongoing river downcutting, which strands the intake above the entrenching stream flow. By reworking and extending the stranded end of the lead-off channel upstream from its original position and having the prolonged lead-off channel intersect the river at a higher elevation, a new intake can be constructed which maintains the canal supply, but at the expense of increasing low-angle transport distance. In other words, as the lead-off channel is extended farther and farther upstream, it more nearly parallels the river, leading to a locally small angle of reach between the canal and river. As downcutting continues, upstream extension can be repeated, and the intake will "migrate" upriver until eventually a bedrock obstacle is encountered.

In the narrow bedrock valley neck, the task of trenching or tunneling through solid rock curtails lead-off extension, while aqueducting around the valley neck obstacles is inhibited by lateral river movement, which undercuts the canal. When bedrock abutment of the intake occurs, supply can be maintained only by lowering the intake to the river level by trenching the intake and lead-off channel to a lower slope. However, decreasing channel bed slope for a fixed canal cross-sectional area decreases the total supply flow rate.

When hydraulic efficiency of the lead-off channel is lost through upstream migration of the intake, or its lowering at bedrock abutments, there remains an option of constructing one or more new downstream intakes that connect into the original channel along its lower course, thereby augmenting the total supply. However, the point at which the canal swings out perpendicular to the river sets a limit on additional intakes. Beyond this point, recharge cannot occur, nor can downriver canals reach fields along the perpendicular course of the atrophying higher system.

In combination, bedrock abutment and elevational strictures on recharge from multiple intakes set finite limits on adjustment to ongoing river entrenchment, and thus on sustaining irrigation from perpendicular-reach canals at any given elevation. When these limits are reached, the supply capacity of the canal diminishes below the needs of the planting area encompassed within the angular reach of the canal. Due to water loss in transport, sustaining the farthest fields is uneconomical, so cultivation retreats upchannel, constricting back towards the river at a rate relative to the decreasing intake capacity.

Bedrock abutments at the valley neck inhibit building a new "replacement" canal system upstream from the old one, and thus promote new construction downstream, where there is sedimentary fill and room for intake adjustment in response to further river changes. In a context of continuing entrenchment, this fosters successive downstream construction and replacement of canal systems. Through time, irrigation agriculture retreats coastward at descending elevations in a step-like manner. Entrenchment eventually reaches the stage where the distance between the intake and the coast is insufficient for lead-off channels to pull out of the downcut landscape and swing laterally to a perpendicular course placement. Thus, in overview, the angle of reach and area of irrigation agriculture in any given valley are relative to its degree or depth of river entrenchment. The Rio Santa, which has an extraordinarily large discharge volume, supports an extraordinarily small agricultural area because it is the most deeply entrenched river on the north coast.

Historical Perspective

The physical record of how irrigation systems behave through time is not unlike the record of glacial behavior. As ice or agriculture advance over a landscape, evidence of earlier advances or contractions is largely destroyed. However, as the ice melts or agriculture contracts, they leave behind moraines or abandoned fields and canals as evidence of their retreat. While there may have been more than one early agricultural advance in the Moche drainage, most abandoned agrarian structures of easily recognizable form date later than ca. A.D. 500 and pertain to two pre-Hispanic occupations—Moche and Chimu (Table 2). During the later occupation, the large metropolitan center of Chan Chan, north of the river, became the imperial capital of Chimor, a desert polity with political hegemony reaching over the coast from southern Ecuador to central Peru. Agricultural lands surrounding the city were worked and administered as a unified plantation system (Moseley and Deeds, 1982; Keatinge and Day, 1973; Keatinge, 1974). Pre-Hispanic agricultural works survive, in analyzable form, outside the area of contemporary farming, and therefore reflect agrarian collapse at the distal ends of the irrigation system. At the entrenching river, evidence of abandoned intakes and lead-off adjustment has been destroyed by river movement or masked by continuing cultivation.

The Canal Configuration

The river-fed irrigation system of the lower Moche drainage is based on three Primary Maximum Elevation Canals (PMECs) on each side of the river (Fig. 4). Maximum Elevation Canals are channels having the highest elevation in a particular section of the valley, and thus delimit the angular reach and irrigated area. These canals are numbered sequentially upstream and are lettered N or S, indicating whether they are north or south of the river. Although potential for angular reach increases in the upstream direction, the area currently served by each successively higher PMEC decreases (Table 3).

Local farmers indicate that within the span of living memory canal intakes have been a continuing source of problems. The S1 intake, which is bedrock abutted, has both an abandoned cement mouth and a higher, more recent, intake and flow diversion structure of rustic wood and cobble construction. The N2 intake has migrated upstream

Table 3.—*Characteristics of modern and ancient Moche Valley canals.*

Canal	Capacity (m^3)	Modern area served		Ancient maximum area	
		Ha	%	Ha	%
N3 Moro	2.5	700	6.7	1509	8.2
N2 Vichansao	3.0	1363	13.1	5821	31.6
N1 Mochica	10.0	4859	46.6	8992	48.8
Pukios	1.4	1504	14.4	—	—
S3 Huatape	0.6	258	2.5	309	1.7
S2 Santo Domingo	1.5	759	7.3	1793	9.7
S1 General de Moche	2.0	987	9.5	—	—
Totals	21.0	10,430	100.1	18,424	100.0

since the turn of the century and now has merged with the N3 intake at a valley neck bedrock abutment. Although both canals feed off the same intake and have only slightly different maximum capacities (2.5 versus 3.0 m^3/sec), the N3 is subject to silt clogging and irrigates only about half the area of its counterpart (ONERN, 1973). This condition would be expectable if the abutted N3 has experienced slope lowering and thus lost transport efficiency as a result of intake lowering prior to the N2's recent migration to the abutment.

Channel sections of operational PMECs intrude upon archaeological ruins of known antiquity, and therefore must date later than the structures they cut or the deposits they overlie. The S3 overrides Moche phase III deposits, whereas the N3 overlies phase IV materials but is, in part, functionally associated with the site of Galindo, a phase V settlement near the valley neck (Bawden, 1982). The operational N2 transects a ruin dating to the first millennium B.C., and an abandoned section of it cuts through a Moche phase IV mound (Pozorski, 1982). The S2 cuts Moche phase III–IV roads (Beck, 1979). Operational and abandoned sections of the N1 intrude upon Middle Chimu phase architecture at Chan Chan (Kolata, 1982; Lange, 1971), whereas the S1 lead-off channel crosses a surface created by 17th century mining of Huaca del Sol, a huge Moche pyramid, and therefore dates to the Colonial period or later (Topic, 1982; Hastings and Moseley, 1975).

All of the operational PMECs, except the S1, have abandoned courses extending out into what today is desert (Fig. 4). Abandoned extensions and field areas of the N3 and S3 are less well preserved than comparable aspects of the N2 and S2 systems, while abandoned N1 extensions and fields are in the best state of preservation.

Canal courses, such as those of the N3 and N2, converge and cross, and excavations demonstrate that abandoned courses are often occupied by multiple, superimposed channels. This situation may reflect both the resupplying of older courses and the intentional use of the sediments accumulated in beds of older channels as low-permeability linings to inhibit seepage. When such courses cross or merge, the series of superimposed channels may split and recombine in ways that defy surface detection. Much of the excavated information comes from channel transects downstream of unexplored course convergences and therefore does not securely monitor flow routing along potentially alternative paths. Thus, excavated transects must be approached as a series of isolated profiles that: a) establish maximum potential water supply vis-à-vis hydraulic limitations of channel design; and b) monitor realization of supply potentials vis-à-vis bedload sediments and soil oxidation, the presence of which establishes use, but the absence of which does not disprove use.

Canal Classes

Survey, excavation, and analysis of hydraulic design and engineering features allow recognition of three major classes of canal remnants (Ortloff et al., 1983*b*) (Tables 4–6).

Class 1 canals have unlined parabolic channel cross-sections typical of the equilibrium shapes obtained after flow-induced sidewall erosion has occurred in channels dug into loosely consolidated soils. These channels supported subcritical flows and reflect hydraulic design mechanisms cognizant of that flow regime. Canal beds are oxidized from long or intensive use, generally exhibit extensive silt accumulations, and may underlie later canals built in or along the same course. This class includes last-use extensions of the N3 and the S3, and remnants of unconnected oxidized channels that originated higher up than the present N1 or S1 and that pertain either to early phases of the higher extant PMECs or to different, more ancient, systems.

Class 2 canals are generally trapezoidal in cross-section and are masonry lined with cobbles set in adobe mortar. These channels supported either subcritical or critical flows by design manipulations of bed slope, channel cross-section, and sidewall roughness. Oxidation is rare to absent, and while unused courses are present, silt accumulations indicate limited use occurred. This class includes last-use extensions of the N2, as well as the S2, which saw several sequential phases of masonry constructions that often overlie Class 1 channels.

Class 3 canals have unlined earth bank channels with profiles cut to trapezoidal form but eroded to a parabolic shape. Flow is subcritical, channel oxidation may occur, and bed sediment layers indicating use are present. This class includes the last and present phases of the N1 and the operational S1, as well as parts of the N2, N3, S2, and S3 canals.

Table 4.—*Characteristics of the three major classes of canal remnants in the Moche Valley, Peru.*

Canal Class	Description	Strategy	Association	Northside[1]	Southside[1]
1	Northside unlined parabolics with upvalley inlets Southside unlined N3 or N2; S3?	Maximize angular reach Maximize supply with subcritical hydraulics Inlet region rework as river downcuts	Moche/Chimu COASTAL UPLIFT	N3 Moro Phase I N2 Vichansao N2 Huanchaco Esperanza G High level	S2 Cerro Arena 1, 2 S3 Orejas Phase 1 A Canal
2	Stone lined (Inter- and Intravalley) N2; S2	Maximize angular reach Maximize supply with critical/subcritical hydraulics & controls Reduce hydraulic resistance with canal cross-section shaping and canal straightening Inlet region rework as river downcuts	Chimu Major Flood RIVER DOWNCUTTING	B A C D E Phase 1, Phase 2, Phase 3, Phase 4 Phase 1, Phase 2, Phase 3, Phase 4, Ph.5 SUNKEN GARDENS	Phase 2
	Unlined parabolics with downvalley inlets N1; S1	Maximize angular reach Maximize supply with subcritical hydraulics Inlet region rework as river downcuts	Chimu	Intervalley EI, EII, EIII N1 Mochica Pukio Canals Low level	S1 General de Moche

[1] Underlined/slashes denote terminal phases.

Table 5.—*Characteristics of canals on Pampa Huanchaco, Moche Valley, Peru.*

Phase	Canal class	Supply canal	Maximum flow rate (m^3/sec)	Comments/use indications
1	1	N3 and/or	1.8	All branches used.
2	1	N2	4.8	All branches used.
3	2	N2	2.7	Not all constructed branches used.
4	2	N2	1.3	Length of used canals contracting.
5	2	N2	1.1	Far upstream segments used, abandonment of downstream segments.
Present	—	—	0	Total abandonment of Huanchaco system.

The pre-Hispanic water supply to the valley's northwestern plains can be studied in the N2 (Vichansao) profile from the excavation farthest upchannel and closest to the modern N2 (Table 6). Of four superimposed PMEC channels, the earliest is a Class 1 canal which had an estimated flow rate of 9.6 m^3/sec and which shows evidence of substantial use. The first superimposed channel had roughly half this capacity, a change that may reflect short-term alternative routing, as this second channel was replaced by a third, larger, Class 2 masonry channel that had an estimated capacity of 10.2 m^3/sec. After destruction by flash flooding around A.D. 1100 prompted reconstruction of the canal, the final channel was built. Its flow rate was 3.1 m^3/sec, which is essentially the same as the contemporary N2. The greatest present flow capacity is that of the contemporary N1, which can carry 10.0 m^3/sec. Therefore, if the N1 replaced the N2 after flooding and reconstruction, then the long-term PMEC sequence does not reflect, in design

Table 6.—*Characteristics of canals on north side of Rio Moche, Peru.*

Canal/phase	Canal class	Maximum flow rate (m^3/sec)	Comments/use indications
G Canal	1	1.1	Fed by N3; use indicated.
Moro/1	1	2.6	N3; all branches used.
Moro/2	1	5.8	N3; all branches used.
Vichansao/1	1	9.6	N2; Early Class 1 type.
Vichansao/2	2	5.0	N2; A-Complex; all later phases show use.
Vichansao/3	2	10.2(?)	N2; A-Complex; all later phases show use.
Vichansao/4	2	3.1	N2; A-Complex; all later phases show use.
Intervalley	2	4.7	Flow rate theoretical: no indications of use.
Mochica	3	10.0	N1; in use at present.

intent or flow capacity, a lack of water or decline in its availability. However, canal profiles at the distal end of the irrigation system do reflect decreased delivery of water. On Pampa Huanchaco, at the western terminus of irrigated land, the first three channels of a five-phase sequence reflect decreasing flow, whereas in two post-flood channels there was a marked decrease in flow rate (Table 5) (Ortloff et al., 1983*b*).

The Distal Canal Sequence

The largest area and longest reach achieved by well-preserved PMECs north of the river are on the western plains of Pampas Esperanza, Rio Seco, and Huanchaco, on the first of which Chan Chan was located. Past and present N1 courses cut into middle phase Chimu architecture at Chan Chan, including the city's north wall (which crosses and blocks feeders from the uphill Class 2 channels) and a walled road that was functionally compatible with a Class 2 extension of the N2 at the head of Pampa Esperanza. This Class 2 channel overlies a Class 1 canal, and both the wall and walled road override other Class 1 canal remnants (Beck, 1979). From these and other stratigraphic superpositions, it is evident that by Moche phase V times Pampa Esperanza was irrigated via a Class 1 extension of either the N3 or N2 and that the system had achieved an approximate perpendicular reach.

The Chimu inherited and reworked this system using Class 1 extensions of the Esperanza MEC in order to reclaim the two western-most pampas (Fig. 6a), which radiocarbon dates indicate was under irrigation by about A.D. 1050. The entire Class 1 canal system, which shows substantial use, was subsequently remodeled and the earlier earth-bank canals were replaced with Class 2 masonry-lined channels (Figs. 6b, 6c). In some cases, these new channels had a trapezoidal cross-section that minimized flow resistance and thus maximized the flow rate for the cross-sectional area. This Class 2 system, which can be traced intermittently back through the Vichansao's profile to the operational N2, saw little use and may still have been under construction at its distal end on Pampa Huanchaco when massive El Niño flooding—of a magnitude as yet unrepeated—occurred. This event, which transpired around A.D. 1100, eroded away more than a meter of valley floor along the river, washed out irrigation works in all parts of the valley, and adversely affected most of the north coast (Nials et al., 1979; Shimada, 1981).

The destroyed Class 2 system was reconstructed, but with significantly lower flow rates. Throughout the western plains the reconstructed system saw little, then ultimately no, use. When Chan Chan's 8 km-long north wall was built across Pampas Esperanza and Rio Seco, formerly farmed lands north and west of the city were left without

GROWTH OF CHAN CHAN AND ADJACENT AGRICULTURE

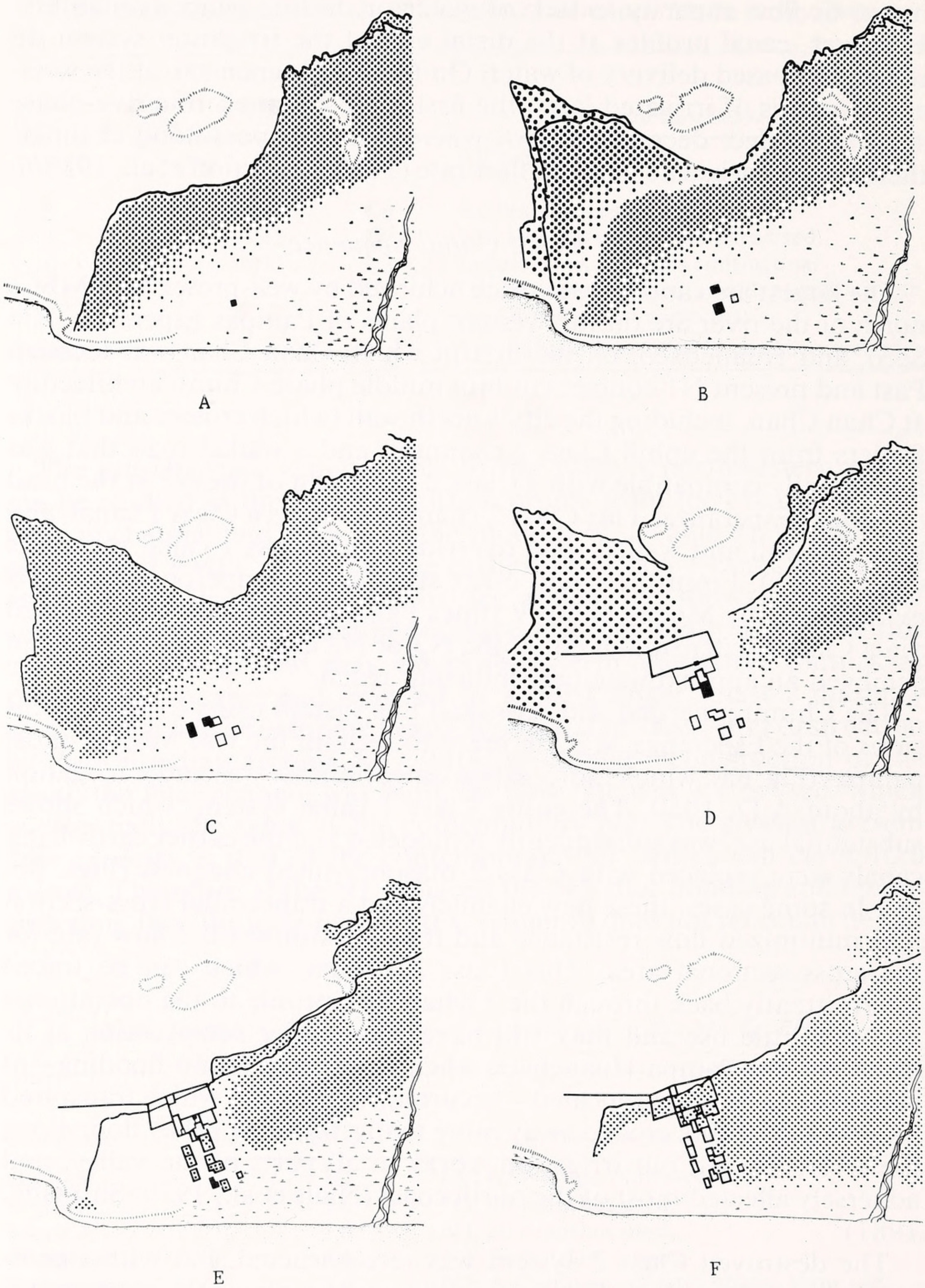

Fig. 6.—Growth of Chan Chan in relation to irrigation on Pampas Esperanza, Rio Seco, and Huanchaco. Dots represent field areas, marsh symbol represents areas of sunken gardens, and the rectangles represent the major compounds at Chan Chan (infilling shows the ones in use at each period). A) First compound was built between irrigated fields and

water. However, a major intervalley Class 2 canal, more than 70 km long, was cut to deliver Rio Chicama water to the head of Pampa Esperanza, and thereby resupply the dry N2 extension (Fig. 6d) (Kus, 1972; Day, 1974; Ortloff et al., 1982). A walled thoroughfare was ceremoniously built from Chan Chan out to the junction of the Intervalley and N2 canals and downstream Class 2 feeders were refurbished in order to distribute the intervalley water. However, masonry lining of the main intervalley course was completed only as far as an active fault north of the intervalley divide. Displacements along this fault, which coincide with a prominent geologic linear, are indicated by disrupted stream drainage patterns. Where the masonry-lined channel approaches the fault, it rests directly atop a bedrock block that has been upthrown at the fault. Today, this final segment of the finished Class 2 Intervalley Canal channel has experienced a 1 degree uphill slope change from its slope at the time of construction (Ortloff et al., 1982).

Radiocarbon dates indicate that significant agricultural activity on the western plains had ended by about A.D. 1350. The inland expansion of Chan Chan ended with the abortive intervalley project, and Late Chimu city construction moved sequentially coastward, back into the old urban core near the beach (Fig. 6e). This retreat is understandable, as the city depended on large, open wells for its potable water. When irrigation ceased to recharge the aquifer that these wells tapped and to mitigate seasonal water table fluctuations, urban growth was forced to reverse itself and follow the declining groundwater levels coastward to more accessible locations, in much the same manner as sunken garden farming retreated coastward (Moseley and Kolata, 1982; Moseley and Feldman, 1982).

The final step in the evolution of irrigation on Pampa Esperanza is represented by Chimu construction of the N1 PMEC and by westward extensions of Class 3 canals across the lower half of the plain. At one point, the N1 watered fields immediately northeast of the city wall, and an unsuccessful attempt was made to channel water along the upslope side of this wall. Next, a viable canal was cut through the wall

←

sunken gardens. B) Expansion of irrigation upslope on Pampa Huanchaco. C) Unification of the irrigation system at its maximum extent. D) Expansion inland of Chan Chan, partial abandonment of the intravalley system, and construction of the Chicama-Moche Intervalley Canal. E) Abandonment of Pampa Huanchaco after failure of the Intervalley project, Moche Valley N1 canal built, and irrigation inside some of the older compounds at Chan Chan. F) Modern system, with areas of former sunken gardens now farmed by pump irrigation.

along a course that is today paralleled—at a lower elevation—by the contemporary N1. Fields and feeders were cut into middle and late phase architecture in the northern part of Chan Chan, but not into its densely occupied coastal sector. Today, some agriculture still goes on among the city's ruins (Fig. 6f).

Parallel events south of the river are understood in less detail. Early remnants of Class 1 systems are crossed by the last-use Class 2 channel of the S2, which apparently was a composite post-flood reconstruction of an earlier operational channel and which saw little use in its final form. There is a hiatus between abandonment of the S2 (by or during the Middle Chimu phase) and the Colonial period construction of the S1. However, this late canal required landscape alterations that would have obfuscated any prior S1 variants that might have been present during the Late Chimu phase.

Limitations on the Data

Data from the Moche Valley support the hypothesis that agrarian collapse is an ongoing process principally related to uplift and ground slope change generated by high rates of tectonic activity along the continental margin, but punctuated by rare but recurrent El Niño flooding. It must be understood that the hypothesis of agrarian collapse has both geological components pertaining to the nature and rates of ground slope change, and hydrological components related to the mechanical consequences of river downcutting. At this stage of investigation, we stress that the latter are better documented and more fully understood than the former.

There is unequivocal evidence of river downcutting and course change in recent millennia. These changes correlate chronologically with both diminution of canal water supplies and contraction of ground water agriculture. Indeed, the latter are expectable hydrological and agro-engineering consequences of the former. River entrenchment can be triggered by a variety of independent processes ranging from deforestation, through minor shifts in precipitation patterns, to coastal uplift. Quaternary terraces and a downcut river profile can be traced through the neck of the Moche Valley downstream to within ca. 6.5 km of the river mouth. In this area the river crosses a pronounced linear (Fig. 1: a–a) associated with the major scarp running between ca. 9° and 6° south latitude. Below this crossing, the river profile has not been successfully traced to the coast. Therefore, river downcutting has yet to be stratigraphically tied to an uplifted beach surface, and alternative triggering mechanisms for entrenchment cannot be ruled out.

It is generally conceded that the present-day north coast marine and meteorological regime, which has communication with the broader tropical Pacific ocean-atmosphere circulation system, has been in place for the last five millennia (Richardson, 1981; Rollins et al., n.d.). El Niño perturbations are an integral feature of this climatic regime, and their occurrence in the archaeological record of recent millennia is well documented (Nials et al., 1979; Shimada, 1981). Thus, we think it questionable that the greater than 30% decrease in irrigated land during the last 1500 years is a product of climatic change or long term alteration of precipitation patterns triggering river entrenchment.

Agrarian abandonment in the rainfall zone of the highlands has yet to be quantified or investigated in detail. Our examination of relevant aerial photographic coverage suggests a disparity between past and present acreage of roughly comparable magnitude to that of the coast. Within the zone of annual precipitation, much—or perhaps most—of this abandoned land was farmed with the use of small canal systems. In theory, if such land supported a more erosion-resistant vegetation cover when under cultivation than when left abandoned, then a corollary of highland irrigation collapse could be "deforestation" and consequent erosion that could exacerbate river downcutting, leading to intake stranding of the coastal canal systems.

We believe that tectonic activity and ground slope alteration provide a much simpler and more unified explanation of coastal and highland agrarian collapse, as well as erosion and river downcutting. As discussed above, the northern watershed of the Cordillera Negra is crossed by a high flexure scarp (Fig. 1). Where this structure emerges from the sea, at 9° south latitude, cumulative coastline displacement securely dated to after ca. 3000 B.C. measures 5 km horizontally and more than 10 m vertically (Sandweiss et al., 1981). In the same area, recent gradual vertical oscillation has averaged 1.8 cm per annum (Wyss, 1978). We suggest that these data constitute a record of structurally unified movement transpiring over the length of the scarp northward to 6° south latitude. From south to north the scarp trends inland and progressively farther back from the sea. There is a corresponding decrease in horizontal separation between the modern littoral and the wave-cut sea cliff (which formed ca. 3000 B.C.), as well as a general vertical decrease in the height of uplifted sea floors and terraces (Cossio and Jaen, 1967). This could reflect a south to north decline in tectonic displacement. Alternatively, as the scarp pulls inland the coastal record of activity along its axis may simply become more indirect. In either case, there is evidence of past—as well as ongoing—tectonic activity in the study area. The same cannot presently be said of potential alternative causes of river downcutting.

In considering these limitations on the data, we should note the growing archaeological documentation of abandoned canal sections that presently run uphill or have gradients that would be inoperable today (Ortloff et al., 1982, 1983*a*; Kus, 1983; Pozorski and Pozorski, n.d.), as well as monumental architecture exhibiting progressive, cumulative slope and orientation alterations transpiring over long periods of occupation (Donnan and Ortloff, 1983). The obvious advantage of the tectonic hypothesis is that it readily accounts for these local phenomena, as well as for the regional contraction of all forms of agriculture.

CONCLUSIONS

Data from the Moche Valley support the hypothesis that agrarian collapse in the Cordillera Negra is closely tied to uplift and tilting of probable fault blocks along the Pacific watershed. The hydrological consequences of the uplift include water table subsidence and river entrenchment. The latter in turn is associated with the breakdown of large scale irrigation systems by loss of canal intake efficiency and eventual stranding of intakes above entrenching stream flow in bedrock canyons.

Within the Moche drainage, the collapse rate registers as roughly a 25% loss of arable land per millennium. The collapse pattern registers as both a "horizontal" contraction of farming toward the river and a "vertical" retreat downslope. As a result, progressively less land can be irrigated. In a like manner, coastal farming supported by groundwater has constricted riverward and seaward, and modern irrigation has moved into areas formerly farmed using groundwater. In the highlands terrace-agriculture has apparently also contracted inward and shifted downslope.

Collapse represents both an ongoing gradual process and one punctuated by radical environmental change. Episodic uplifts such as that suggested by raised coastal terraces and Holocene beach ridges must have extremely negative agricultural consequences. Episodic El Niño flash floods also have had demonstrably negative consequences. Flooding at ca. A.D. 1100 not only destroyed extant canal systems, but also radically changed river erosion and course patterns to such a point that the reconstructed irrigation system could not be effectively brought back into operation, leading to its replacement by new downstream canals that were not capable of supplying all of the land area that was formerly farmed. In turn, these replacement canals have developed chronic intake problems, leading to atrophy at their distal ends.

If agrarian collapse has been correctly analyzed, then future generations are not well served by the present practice of obliviously constructing major reclamation works within the uninvestigated ruins of larger past systems. These ruins both gauge and foreshadow ongoing environmental processes that modern technology is largely unaware of, but to which it is not immune.

ACKNOWLEDGMENTS

The research reported upon here was supported by grants from the National Science Foundation (BNS77-24901), the Frederick Henry Prince Trust, and Soiltest, Inc. Permission to conduct excavations in Peru was granted by the Instituto Nacional de Cultura, Lima. We would like to acknowledge the assistance of Genaro Barr and Miguel Cornejo (of Trujillo); Alan Kolata; James Kus, Fred Nials, and other members of Field Museum's Programa Riego Antiguo; and James Richardson, Thomas Anderson, Jack Donahue, and Harold Rollins (of the University of Pittsburgh).

LITERATURE CITED

BARAZANGI, M., and B. L. ISACKS. 1976. Spatial distribution of earthquakes and subduction of the Nazca plate beneath South America. Geology, 4:686–692.

BAWDEN, G. L. 1982. Galindo: a study in cultural transition during the Middle Horizon. Pp. 285–320, *in* Chan Chan, Andean desert city, (M. E. Moseley and K. C. Day, eds.), Univ. New Mexico Press, Albuquerque.

BECK, C. M. 1979. Ancient roads on the north coast of Peru. Unpublished Ph.D. dissert., Dept. Anthropology, Univ. California, Berkeley, 251 pp.

BIRD, J. B. 1951. South American radiocarbon dates. Mem. Soc. Amer. Archaeology, 8: 37–49.

CARDENAS MARTIN, M. 1977–78. Obtencion de una cronologia del uso de los recursos marinos en el Antiguo Peru. Arqueologia PUC, 19-20:3–26.

COSSIO, A., and H. JAEN. 1967. Geologia de los Cuadrangulos de Puemape, Chocope, Otuzco, Trujillo, Salaverry, y Santa. Bol. Servicio de Geologia y Mineria, Lima, 17: 1–141.

DAY, K. C. 1974. Walk-in-wells and water management at Chan Chan, Peru. Pp. 182–190, *in* The rise and fall of civilizations (J. Sabloff and C. Lamberg-Karlovsky, eds.), Cummings Publ. Co., Menlo Park, California.

DONNAN, C., and C. R. ORTLOFF. 1983. Site tilt at the Chotuna Complex. Paper presented at the 23rd annual meeting of the Institute of Andean Studies, Berkeley, CA, 9 January 1983.

ELING, H. H., JR. 1981. Prehispanic irrigation patterns: monadnocks of the Pampa de Mojucape, Jequetepeque Valley, Peru. Paper presented at the Fourth Andean Archeology Colloquium, University of Texas, Austin, April 1981.

ERICKSEN, G. E., G. PLAFKER, and J. F. CONCHA. 1970. Preliminary report on the geological events associated with the May 31, 1970 earthquake. United States Geological Survey Circular, 639:1–25.

HASTINGS, C. M., and M. E. MOSELEY. 1975. The adobes of Huaca del Sol and Huaca de la Luna. Amer. Antiquity, 40:196–203.

KEATINGE, R. W. 1974. Chimu rural administrative centers in the Moche Valley, Peru. World Archaeology, 6:66–82.

KEATINGE, R. W., and K. C. DAY. 1973. Socio-economic organization of the Moche Valley, Peru, during the Chimu occupation of Chan Chan. J. Anthro. Res., 29:275–295.

KOLATA, A. L. 1982. Chronology and settlement growth at Chan Chan. Pp. 67–86, *in* Chan Chan, Andean desert city (M. E. Moseley and K. C. Day, eds.), Univ. New Mexico Press, Albuquerque.

KOSOK, P. 1965. Life, land and water in ancient Peru. Long Island Univ. Press, New York, 264 pp.

KULM, L. D., W. J. SCHWELLER, A. MOLINA-CRUZ, and V. J. ROSATO. 1976. Lithologic evidence for convergence of the Nazca plate with the South American continent. Pp. 795–801, *in* Initial reports of the Deep Sea Drilling Project, U.S. Government Printing Office, vol. 34.

KUS, J. S. 1972. Selected aspects of irrigated agriculture in the Chimu heartland, Peru. Unpublished Ph.D. dissert., Dept. Geography, Univ. California, Los Angeles, 247 pp.

———. 1983. The Chicama-Moche Canal: failure or success? An alternate explanation for an incomplete canal. Paper presented at the 23rd Annual Meeting of the Institute of Andean Studies, Berkeley, California, 9 January 1983.

LANGE, T. Q. 1971. Preliminary studies of selected field systems, Moche Valley, Peru. Unpublished B.A. dissert., Dept. Anthropology, Harvard Univ., 114 pp.

LETTAU, H. H., and K. LETTAU. 1978. Exploring the world's driest climate. Rept. Institute for Environmental Studies, Univ. Wisconsin, Madison, 101:1–264.

MINSTER, J. B., ET AL. 1974. Numerical modeling of instantaneous plate tectonics. Royal Astronomical Soc. Geophysical J., 36:541–576.

MOSELEY, M. E. n.d. Patterns of settlement and preservation in the Viru and Moche Valleys. In press.

MOSELEY, M. E., and E. E. DEEDS. 1982. The land in front of Chan Chan: agrarian expansion, reform, and collapse in the Moche Valley. Pp. 25–54, *in* Chan Chan, Andean desert city (M. E. Moseley and K. C. Day, eds.), Univ. New Mexico Press, Albuquerque.

MOSELEY, M. E., and R. A. FELDMAN. 1982. Living with crises: a relentless nature stalked Chan Chan's fortunes. Early Man, 4:10–13.

MOSELEY, M. E., R. A. FELDMAN, and C. R. ORTLOFF. 1981. Living with crises: human perception of process and time. Pp. 231–267, *in* Biotic crises in ecological and evolutionary time (M. Nitecki, ed.), Academic Press, New York.

MOSELEY, M. E., and A. L. KOLATA. 1982. Chan Chan: cloistered city . . . the home of god-kings. Early Man, 4:6–9.

NIALS, F. L., E. E. DEEDS, M. E. MOSELEY, S. G. POZORSKI, T. G. POZORSKI, and R. A. FELDMAN. 1979. El Niño: The catastrophic flooding of coastal Peru. Bull. Field Mus. Nat. Hist., 50(7):4–14 (Part I); 50(8):4–10 (Part II).

ONERN. 1973. Inventario, evaluacion y uso racional de los recursos naturales de la Costa: Cuenca del Rio Moche. Oficina Nacional de Evaluacion de Recursos Naturales, Lima, 1:1–493; 2:1–109.

ORTLOFF, C. R., M. E. MOSELEY, and R. A. FELDMAN. 1982. Hydraulic engineering aspects of the Chimu Chicama-Moche Intervalley Canal. Amer. Antiquity, 47:572–595.

———. 1983*a*. The Chicama-Moche Intervalley Canal: social explanations and physical paradigms. Amer. Antiquity 48:376–389.

———. 1983*b*. Hydraulic engineering and historical aspects of the preColumbian intravalley canal systems of the Moche Valley, Peru. J. Field Arch., in press.

PLAFKER, G., G. E. ERICKSEN, and J. F. CONCHA. 1971. Geological aspects of the May 31, 1970 Peru earthquake. Bull. Seismological Soc. Amer., 61:543–578.

POZORSKI, S. G., and T. G. POZORSKI. 1979. Alto Salaverry: A Peruvian coastal preceramic site. Ann. Carnegie Mus. 48:337–375.

———. 1982. Technical report on Programa Riego Antiguo field work. Pp. 68–72, *in* The dynamics of agrarian collapse in coastal Peru, a report to the National Science Foundation on Grant BNS77-24901 (by M. E. Moseley *et al.*).

———. n.d. Preliminary results of investigations in the Casma Valley, Peru. Unpublished manuscript, Section of Man, Carnegie Museum of Natural History, Pittsburgh, 170 pp.

POZORSKI, T. G. 1982. Early social stratification and subsistence systems: the Caballo Muerto complex. Pp. 225–254, *in* Chan Chan, Andean desert city (M. E. Moseley and K. C. Day, eds.), Univ. New Mexico Press, Albuquerque.

RICHARDSON, J. B., III. 1981. Modeling the development of sedentary maritime economies on the coast of Peru: a preliminary statement. Ann. Carnegie Mus. 50:139–150.

ROLLINS, H. B., J. B. RICHARDSON III, and D. H. SANDWEISS. n.d. New evidence and implications of a major change in the structure of the East Pacific water mass about 5000 years B.P. Unpublished manuscript, Dept. Geology, Univ. Pittsburgh.

SANDWEISS, D. H., H. B. ROLLINS, and J. B. RICHARDSON III. 1981. The preceramic occupation of the uplifted Santa Valley coast and evidence for a major El Niño. Unpublished manuscript, Dept. Anthropology, Cornell Univ.

SCHAEDEL, R. P. 1951. The lost cities of Peru. Scientific American, 185(2):18–23.

SHIMADA, I. 1981. The Batan Grande-La Leche archaeological project: the first two seasons. J. Field Archaeology, 8:405–446.

SILLITOE, R. H. 1974. Tectonic segmentation of the Andes: implications for magmatism and metallogeny. Nature, 250:542–545.

TOPIC, T. L. 1982. The early intermediate period and its legacy. Pp. 255–284, *in* Chan Chan, Andean desert city (M. E. Moseley and K. C. Day, eds.), Univ. New Mexico Press, Albuquerque.

USDA. 1955. Water, the yearbook of agriculture, edited by Alfred Stefferud. United States Dept. Agriculture, Washington, D.C., 751 pp.

WEST, M. 1981. Agricultural resource use in an Andean coastal ecosystem. Human Ecology, 9:47–78.

WYSS, M. 1978. Sea level changes before large earthquakes. Earthquake Information Bull., U.S. Geol. Surv., 10:165–168.