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Climate and Collapse: Agro-Ecological Perspectives on the Decline of the Tiwanaku State

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After approximately 700 years of growth and colonial expansion, the Tiwanaku state disintegrated as a regional political force in the south-central Andes between *c.* AD 1000–1100. This paper examines the collapse of the state of Tiwanaku through the lens of its agricultural history. We argue that the proximate cause of Tiwanaku's decline as a politically integrated, expansive state society was the deterioration and ultimate abandonment of its regional-scale agricultural systems, both in its core area in the Andean *altiplano* and in its economic colonies in the lower-altitude *yungas* zones. We present evidence that the collapse of Tiwanaku intensive agriculture was triggered by regional change in climatic conditions recorded in highly-resolved palaeoenvironmental data derived from the Quelccaya ice cap of southern Peru and in sediment cores from Lake Titicaca. Our analysis of the Quelccaya data documents a radical climate change in the south-central Andes during the post-AD 1000 era in the form of a statistically significant decrease in mean precipitation level that persisted until *c.* AD 1400. By defining vulnerability classes for various agricultural technologies used in different regions of the Tiwanaku state, we then relate this palaeoclimatic data to performance of specific core area and colonial Tiwanaku agricultural systems. We demonstrate that chronic drought conditions led to sequential collapse of these distinct agricultural systems: irrigation-based agriculture in Tiwanaku colonies at lower altitude failed first, followed by groundwater-dependent raised-field systems in the *altiplano*. Agricultural and settlement pattern changes in the post-AD 1000 period are correlated with the palaeoenvironmental data to present an integrated view of the coupling of climate and cultural process. The full implications of the agro-ecological collapse model presented here reach well beyond an explanation for the decline of Tiwanaku alone.

Keywords: LATE HOLOCENE CLIMATE CHANGE, AGRICULTURE, STATE COLLAPSE, ANDES, BOLIVIA, TIWANAKU.

Introduction

There is an undeniable material basis to the political integrity of states (whether archaic or modern), and a large part of any explanation of state collapse resides in the vicissitudes of the production and distribution of wealth. In the case of the pre-industrial state, economic well-being was synonymous with agriculture: wealth was generated primarily by intensive farming of arable land and not by industry or commerce. This essential truth holds even

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more rigorously in the context of the Precolumbian Andean world where markets and mercantile activities were, on the whole, non-existent, or at least, severely restricted in geographic and economic scope. In lieu of unrestricted commerce and free market exchange, there was, in essence, no other source in the ancient Andes for generating substantial wealth beyond the margin of subsistence than intensive agriculture. Not surprisingly, some of the greatest public works of Andean civilization are its monumental agricultural and hydraulic structures which reshaped entire deserts, mountains and high plateaus into economically productive landscapes. When we look for the causes of large-scale political collapse in the Andes, then, we might profit from a close examination of agricultural history. This paper examines the collapse of the native Andean state of Tiwanaku through the lens of its agricultural history. We argue that the direct cause of Tiwanaku's decline as a politically integrated, expansive state society was the deterioration and ultimate abandonment of its regional-scale agricultural systems. We present evidence that the collapse of Tiwanaku intensive agriculture was triggered by regional change in climatic conditions. The full implications of this agro-ecological/climatological collapse model reach well beyond an explanation for the decline of Tiwanaku alone.

Background: The Prelude to Tiwanaku Collapse

After approximately 700 years of growth and colonial expansion, the Tiwanaku state disintegrated as a regional political force in the south-central Andes between AD 1000–1100 (Table 1).* Through progressively complex statecraft and apparent economic opportunism, Tiwanaku expanded from its core territory in the Lake Titicaca basin to establish a dispersed network of cultural and economic centres in diverse ecological settings (Figure 1; Kolata, 1983). Tiwanaku cultural, political and economic presence takes different forms in different geographic zones, both inside and outside of its heartland on the high plateau. In the Lake Titicaca basin, we can isolate the full panoply of Tiwanaku state action: an integrated network of densely populated, internally differentiated settlements distributed strategically across the landscape with the capacity of exploiting a variety of production zones. In the lower *yungas* zones that lie both to the east and west of the *altiplano*, Tiwanaku appears in the form of large-scale colonizing populations which, to judge by the scope and persistence of occupation, were clearly established as permanent residences. The case of the Moquegua Valley of south coastal Peru is a particularly clear example of intense *altiplano* colonization of a *yungas* environment for the purpose of directly controlling lower-altitude, arable land (Goldstein, 1989). This territorial expansion and control of lower altitude zones which began in the latter

*The precise dating of the Tiwanaku collapse is a subject of some controversy. The traditional view is that the (terminal) Tiwanaku V phase persists until AD 1200 at Tiwanaku (Ponce, 1972) as well as in some of its colonial enclaves in the *yungas* zones. A number of radiocarbon dates from Tiwanaku settlements in the Moquegua Valley seem to support this scenario. However, as is evident from Table 1, recent radiocarbon dates from urban centres in the Tiwanaku heartland, specifically Tiwanaku and Lukurmata, suggest a terminal date somewhere between *c.* AD 900–1100. Bermann *et al.* (1989) argue that the Moquegua colonies of Tiwanaku collapsed prior to the decline of the Tiwanaku core area around Lake Titicaca, a view consonant with the argument presented in this paper. They suggest that the Tiwanaku collapse in the Moquegua valley was complete by AD 1000. Since identification of Tiwanaku V in the coastal colonial enclave depends principally on stylistic analysis of ceramics, it is conceivable that there was a persistence of Tiwanaku and Tiwanaku-derived stylistic influences in ceramic traditions on the coast after the political decline of Tiwanaku itself and its colonial enclaves. This scenario is consistent with the recent interpretations of Goldstein (1989) and other investigators of the *Programa Contisuyu* (Rice *et al.*, 1989; Watanabe *et al.*, 1990).

Table 1. Radiocarbon dates for Tiwanaku IV and Tiwanaku V contexts from Tiwanaku, Lukurmata, and selected sites in the Moquegua Valley, Peru

Site	Laboratory designation	Radiocarbon years	Calibrated years	Tiwanaku phase
Tiwanaku	SMU-5639	1170±60 BP	AD 860±80	TIW V
Tiwanaku	ETH-6306	1460±60 BP	AD 590±60	TIW IV
Tiwanaku	SMU-2330	1080±210 BP	AD 950±110	TIW V
Tiwanaku	SMU-2367	1150±80 BP	AD 880±80	TIW V
Tiwanaku	ETH-5680	1170±65 BP	AD 860±85	TIW V
Tiwanaku	SMU-2468	1390±50 BP	AD 640±35	Late TIW IV
Tiwanaku	SMU-2467	1130±60 BP	AD 900±70	TIW V
Tiwanaku	SMU-2472	1200±115 BP	AD 830±130	TIW V
Tiwanaku	SMU-2465	1110±50 BP	AD 930±60	TIW V
Tiwanaku	SMU-2466	1170±60 BP	AD 860±80	TIW V
Tiwanaku	SMU-2289	1185±60 BP	AD 840±80	TIW V
Tiwanaku	SMU-2290	1120±70 BP	AD 910±85	TIW V
Tiwanaku	SMU-2276	1070±60 BP	AD 960±60	TIW V
Tiwanaku	SMU-2277	1130±60 BP	AD 900±70	TIW V
Tiwanaku	SMU-2469	1190±100 BP	AD 830±115	TIW V
Lukurmata	SMU-2165	1000±230 BP	AD 1020±220	TIW V
Lukurmata	ETH-3180	990±95 BP	AD 1045±100	TIW V
Lukurmata	ETH-3179	1180±110 BP	AD 840±115	TIW V
Lukurmata	SMU-1920	1201±96 BP	AD 818±110	TIW V
Lukurmata	ETH-3178	1085±90 BP	AD 950±100	TIW V
Lukurmata	SMU-2117	1090±60 BP	AD 950±70	TIW V
Chen Chen	HV-1076	1040±65 BP	AD 999±32	TIW V
Chen Chen	HV-1077	930±65 BP	AD 1105±78	Late TIW V
Loreto Viejo	HV-1091	980±70 BP	AD 1024±84	TIW V
Omo	Beta-26650	1120±60 BP	AD 897±53	TIW V
Omo	Beta-26649	1170±70 BP	AD 883±93	TIW V

Note in particular the recent suite of dates from household contexts at Tiwanaku and Lukurmata indicating that Tiwanaku V phase occupation at these sites terminates between *c.*AD 900–1100. Radiocarbon dates for Tiwanaku and Lukurmata are corrected and calibrated according to the Stuiver & Pearson (1986) calibration curve. Radiocarbon dates for Chen Chen, Loreto Viejo and Omo are published in Rice *et al.* (1989: 8) and were calibrated using the CALIB radiocarbon program, University of Washington, Quaternary Isotope Laboratory.

portions of the Tiwanaku IV phase (*c.* AD 400–750) qualifies the mature Tiwanaku state as a true imperial system. In the more distant southerly reaches of the Tiwanaku sphere of influence, such as the high Atacama Oasis of Chile, its physical presence appears most prominently in elite mortuary and domestic contexts, suggesting a more specialized, fluid and transactional quality to the relationship between the *altiplano* state and its local counterparts.

Although Tiwanaku colonies exploited *yungas* zones to produce a number of products otherwise unavailable at high altitude, the economic key to the functioning of the state was an integrated agricultural core area in the Lake Titicaca basin that operated by means of regional manipulation of land, labour and most especially, water resources (Kolata, 1991). Local to the capital city of Tiwanaku itself are enormous tracts of (raised) agricultural fields that were farmed by exploitation of available ground, river and springwater through technically sophisticated means (Kolata, 1986, 1991; Kolata & Ortloff, 1989; Ortloff & Kolata, 1989). Secondary state centres and their immediate rural hinterlands in

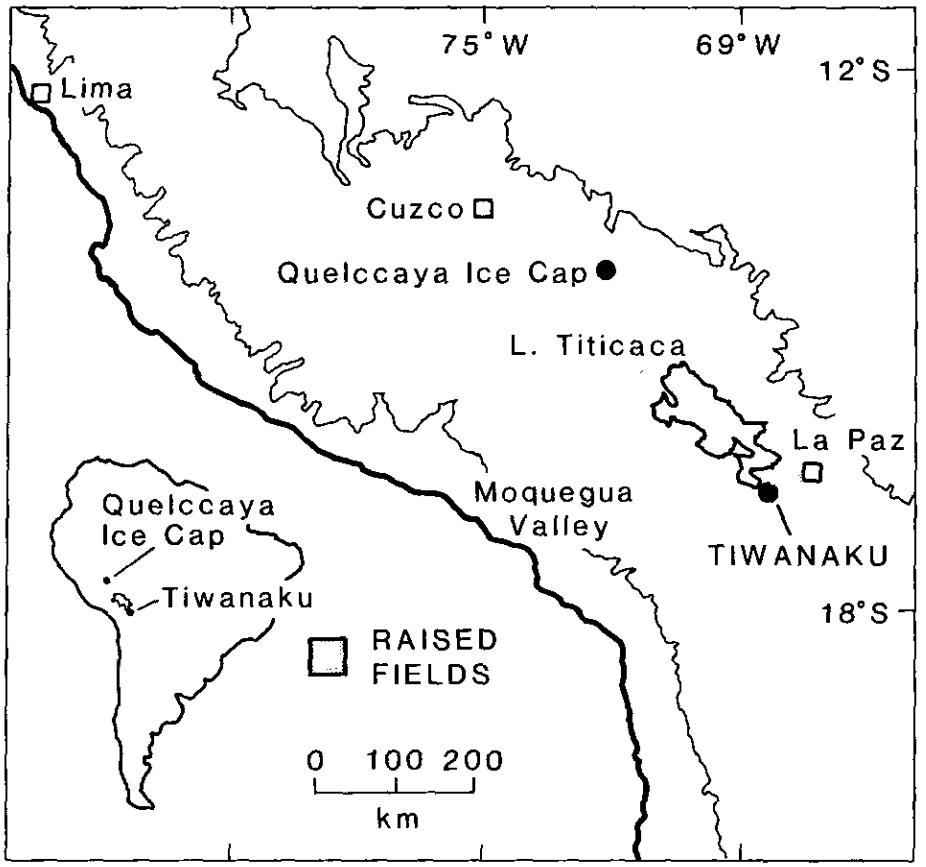

Figure 1. South-central Andean region illustrating the location of principal sites discussed in the text, including the Quelccaya ice cap, Tiwanaku and the Moquegua Valley.

close proximity to Tiwanaku (for example, Lukurmata, Khonko Wankane and Pajchiri) appear to possess both agricultural self-sufficiency and substantial potential for surplus production that could have been funneled into redistributive networks with other colonial and administrative centres of the empire (Kolata, 1991).

Technical expertise stemming from centuries of empirical observation and experiment is evident in the planning, engineering, construction and maintenance of these state agricultural systems. In a previous paper (Ortloff & Kolata, 1989: 53), we concluded that the hydraulic control devices that were essential to the long-term functioning of these systems represent an example of "designed multifunctionality" responsive to severe inundation–drought cycles that are characteristic of the *altiplano* climatic regime. The development of regional administrative centres, each with agricultural field systems under their control that incorporated refined hydrological engineering practices, constituted a near optimal agricultural base for economic and political stability. Consistent with the degree of organizational complexity evidenced in the archaeological record, the administrative resources necessary to co-ordinate this state-level agricultural system, as well as to implement the latest agricultural and after-supply innovations to increase crop yields can be assumed to be in place (Kolata, 1991).

In totality, the Tiwanaku state appears to have constructed an interlocking, redundant and optimum agricultural supply base resistant to collapse and disintegration. Yet, despite an apparently secure basis for continued expansion and economic growth, the empire and its colonies collapsed after at least seven centuries of successful function. As indicated above, the period of collapse comes toward the end of the regional historical period denoted as Tiwanaku V (AD 800–1100). The collapse mechanism of the Tiwanaku state is only now emerging as the result of co-ordinated research into details of the functions and vulnerabilities of the agricultural base of the Tiwanaku heartland and colonies, together with climatological and ecological data from this period. Recent projects concentrating on Tiwanaku colonial outposts (Rice *et al.*, 1989; Watanabe *et al.*, 1990) in the Moquegua Valley as well as at Tiwanaku proper (Kolata, 1986, 1989, 1991) have generated new knowledge that allows for a reconstruction of a general outline of Tiwanaku's history of growth and subsequent decline.

In particular, data on climate variation obtained from the Quelccaya ice cap cores (Thompson *et al.*, 1988) have permitted preliminary correlations of Tiwanaku culture history with changing ecological conditions (especially precipitation patterns). Such correlations form the basis of the collapse model for Tiwanaku and proceed from statistical analysis of the Quelccaya ice cap data. This statistical analysis indicates a radical climate change in the south-central Andes during the post-AD 1000 era. Environmental change in the form of precipitation decreases is shown to lead to a progressive collapse of the agricultural systems of the Tiwanaku colonies followed by the collapse of the raised field systems of the heartland area. Since climate differentially affects the different types of agriculture systems supported in each of the dispersed empire centres, response to climate change is varied yet predictable. The body of existing archaeological data is correlated with the results of a statistical analysis of the Quelccaya ice cap data to present an integrated view of the coupling of climate and cultural process.

Analysis of Climatological Data from the Quelccaya Ice Cap

The most highly resolved record of regional palaeoclimates derives from recent ice coring work at the Quelccaya glacier (Thompson *et al.*, 1985, 1988). The Quelccaya ice cap is located in the Cordillera Oriental mountain range of southern Peru approximately 200 km north-west of Lake Titicaca (Figure 1). Thompson *et al.* (1988) demonstrated that the Quelccaya record is a good proxy for the level of Lake Titicaca in the 20th century by establishing a qualitative correspondence between annual precipitation at the meteorological station of El Alto near La Paz and annual changes of lake elevation.

In overview, during Tiwanaku IV and V times, the Quelccaya record clearly indicates wetter periods from AD 610–650 and 760–1040 and periods of decreased precipitation from AD 650–730. In the post-Tiwanaku period from AD 1245–1310, the region experiences a severe precipitation deficit. High dust concentrations in the ice core with peaks around AD 600 and 920 have been associated with periods of major earth-moving, including raised-field construction, in the *altiplano* around Lake Titicaca (Thompson *et al.*, 1988). Prevailing winds from the *altiplano* transport particles of dust and organic debris toward the Quelccaya glacier where they are deposited in snow layers. These particles serve as dateable boundaries within the accumulated snow layers and as indicators of unusual events such as volcanic eruptions, or, as in this instance, large-scale earth moving with its attendant generation of wind-borne dust.

The proximity of the Quelccaya ice cap to Lake Titicaca and the main urban centres of the Tiwanaku empire is significant in that climate history derived from analysis of ice cap data can be assumed to apply during the historical development of the state. The currently analysed sections of the Quelccaya ice cap are a record of climate variation in the south-

central Andes over the period from AD 400–1980 (Thompson *et al.*, 1979, 1982, 1985, 1987, 1989). The basic data are cumulative measurements of annual snow layer deposits. The thickness of annual layers, measured in cores extracted from the ice cap, are shown in Figures 2–4. These figures present the data for the period AD 800–1400.

In simplest terms, large snow layer thickness is indicative of heavy annual rainfall at lower altitudes; small layer thickness implies an annual period of lower rainfall. While numerous wet periods exist in the record as illustrated in these figures, and severe drought is certainly implied in the period from AD 1245–1310, the data only reveal clear trends through statistical analysis. Over 200-year intervals from AD 800–1400 the mean annual snow layer thickness progressively declines as indicated by the values shown in Figures 2–4. The $\overline{X}$ and $\bar{x}$ values illustrated in Figures 2–4 represent 200-year averages of the snow layer thicknesses above and below the mean layer thickness respectively. Replotting the data in terms of a 3-year (Figure 5) and a 9-year (Figure 6) moving average from AD 800 to AD 1400 more clearly reveals the sequence of change in precipitation levels. While vigorous fluctuations in precipitation certainly exist over decades, there is a statistically significant change in mean moisture level beginning after AD 1000.

If the ice core thickness distributions are integrated to emphasize mean precipitation level changes, a smoothed, time-dependent measure of precipitation can be obtained (Figure 7). The integrated curve illustrated in Figure 7 is obtained by time integration of the ice cap data displayed in the 9-year moving average plot (Figure 6). Initially, the overall mean value of snow layer thicknesses over the entire time range of the plot is found. The area above this mean value is denoted as positive area; the area below this mean value is denoted as negative area. The integration then reveals large-scale changes in mean thickness layers, while small fluctuations are de-emphasized. Note that the integration parameter (y-axis) for the curve in Figure 7 is given as m-yr (metre-year). In this curve, if the precipitation level is constant, for example, a linear rise is expected in the integrated result. Deviations from the linear characteristic then indicate either excessive rainfall or drought periods depending on the position of the integrated curve with respect to the linear result. Figure 7 illustrates a gradual change in precipitation starting around AD 950 indicated by the slope change at that time (marked here as point A), followed by a precipitous change in moisture content commencing with the post-AD 1000 period (marked here as point B). This reflects the statistically significant change in mean levels of precipitation between the pre- and post-AD 1000 time periods. A short uptick in moisture level at AD 1300 in this curve is represented together with a subsequent decline starting from about AD 1350 and extending at least up to AD 1400. The departure of the integrated moisture curve from linear in the time period AD 1050–1200 indicates several excursions of increased rainfall from a lower mean level characterizing the post-AD 1000 time period. Generally this result translates into a much drier climate on average in the post-AD 1000 period than in earlier times (See Appendix A).

Palaeolimnological work by our own research team in Lake Titicaca supports the Quelccaya evidence for climate change (Binford & Brenner, 1989; Leyden, 1989). According to pollen data from a lake sediment core, the lake level was significantly higher than usual between *c.* AD 350–500, implying increased precipitation, decreased evaporation or both. The 98 cm long core (22-VII-86-1) was extracted from 2·5 m deep water approximately 65 m offshore north-west of the site of Lukurmata (Figure 8), and represents *c.* 2000 years of sediment accumulation (Binford *et al.*, 1992). Elevated lake level is marked by a dramatic rise in pollen from aquatic macrophytes, specifically *Ruppia* (widgeon grass), *Myriophyllum* (water milfoil) and *Elodea* (water weed), and from the planktonic alga, *Pediastrum boryanum*, in the mid-core section between 40–60 cm (Figure 9). The sediments from 40–44 cm in this section have been ^{14}C dated to 1445 ± 210 BP, uncorrected. This increase in aquatic macrophytes and planktonic algae co-occurs with a

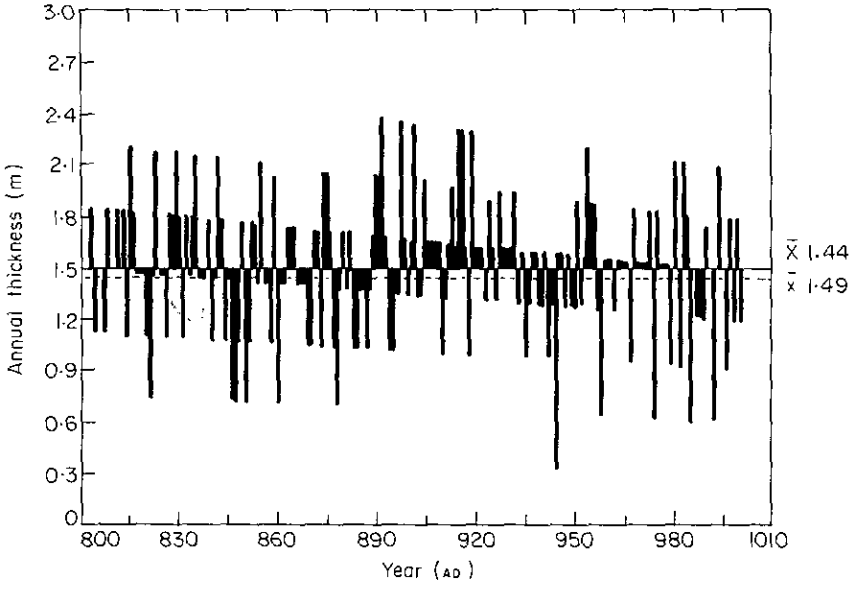

Figure 2. Annual ice cap thickness values at the Quelccaya glacier in the period from AD 800–1000. The figure is based on privileged, unpublished data and reproduced here with the permission of L. G. Thompson.

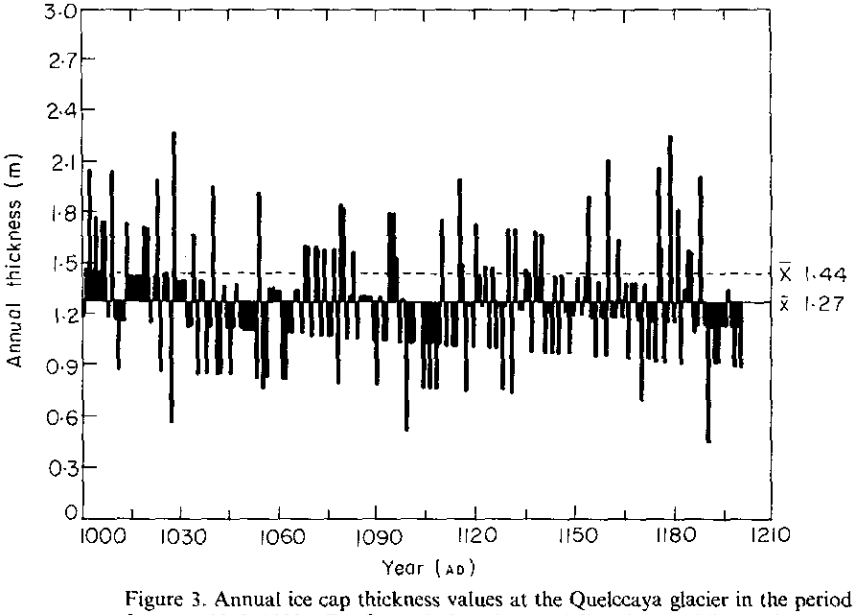

Figure 3. Annual ice cap thickness values at the Quelccaya glacier in the period from AD 1000–1200. The figure is based on privileged, unpublished data and reproduced here with the permission of L. G. Thompson.

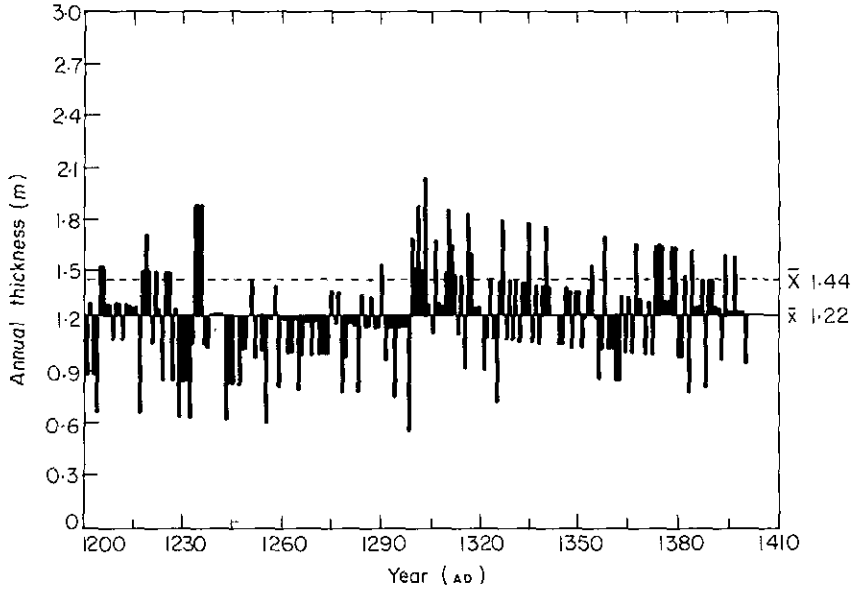

Figure 4. Annual ice cap thickness values at the Quelccaya glacier in the period from AD 1200–1400. The figure is based on privileged, unpublished data and reproduced here with the permission of L. G. Thompson.

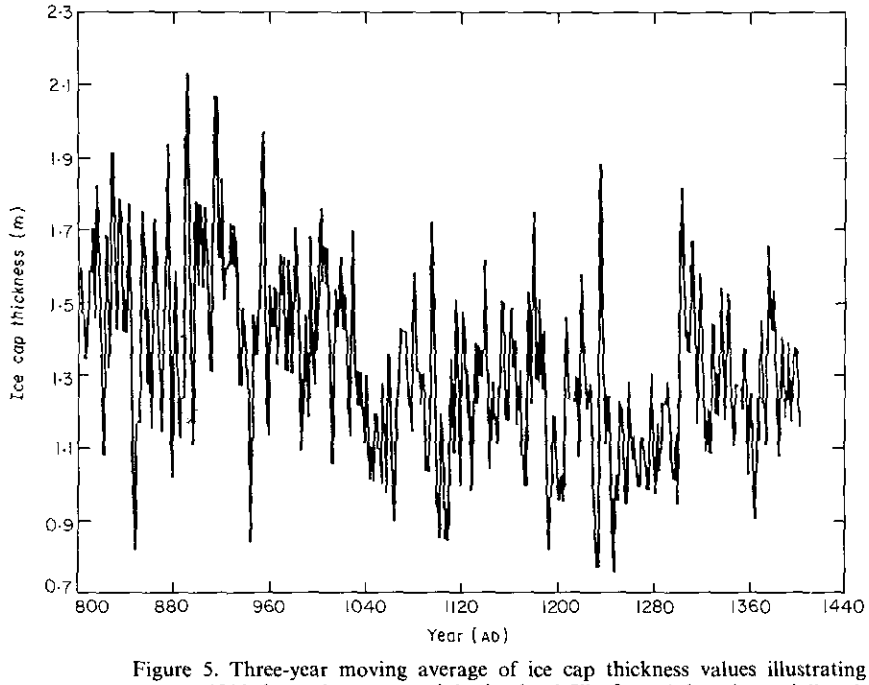

Figure 5. Three-year moving average of ice cap thickness values illustrating post-AD 1000 change in mean precipitation level. The figure is based on privileged, unpublished data courtesy of L. G. Thompson.

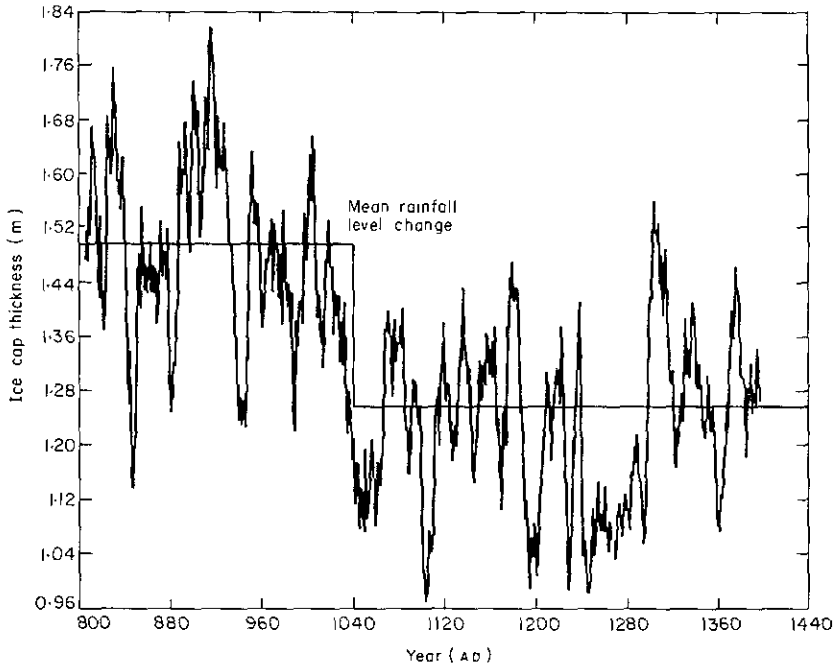

Figure 6. Nine-year moving average of ice cap thickness values. This plot provides an enhanced, graphic display of the post-AD 1000 decline in mean precipitation level. The figure is based on privileged, unpublished data courtesy of L. G. Thompson.

decrease in sedges, almost certainly totora (*Schoenoplectus tatora*). Leyden (1989) interprets this pollen distribution as a result of rising lake levels over the core site drowning the sedges and promoting the expansion of aquatic macrophytes and algae. Subsequently, the sediments in the upper 30 cm of the core exhibit a resumed relative dominance of sedges in the palynological record and a concomitant decline in aquatic macrophytes (Figure 9). The pollen distribution in the upper third of the Lukurmata core reflects a lowering of lake levels and a return to littoral conditions at the coring site (Leyden, 1989). Age-depth estimates on these sediments place this decline in lake level within the post-AD 1000 period of desiccation recorded in the Quelccaya ice cap. In short, the palaeolimnological evidence of lake level fluctuations (and, by inference, changing precipitation) from lake sediment cores is consistent with the Quelccaya ice cap data.

In addition to recording changes in precipitation, a measure of the prevailing temperature at the Quelccaya glacier can be inferred from isotopic ^{18}O measurements (Figure 10) taken coincident with ice layer thicknesses (Thompson *et al.*, 1988). These measurements indicate a rise in mean annual temperature of between 0·5–1 °C beginning around AD 1000 and persisting until at least AD 1400. Of course, this mean temperature rise should be interpreted in a statistical sense given that fluctuations from the mean temperature level of ± 1 °C appear in this time period. The AD 1000–1400 temperature rise has been observed in Europe as a phenomenon designated the Mediaeval Warm Epoch (Lamb, 1965, 1982; Anderson, 1991). Crops normally grown in the southern parts of Europe flourished in the colder climate of the Scandinavian countries leading to a period of economic prosperity throughout Europe. Vineyards and associated wine production peak during this time due

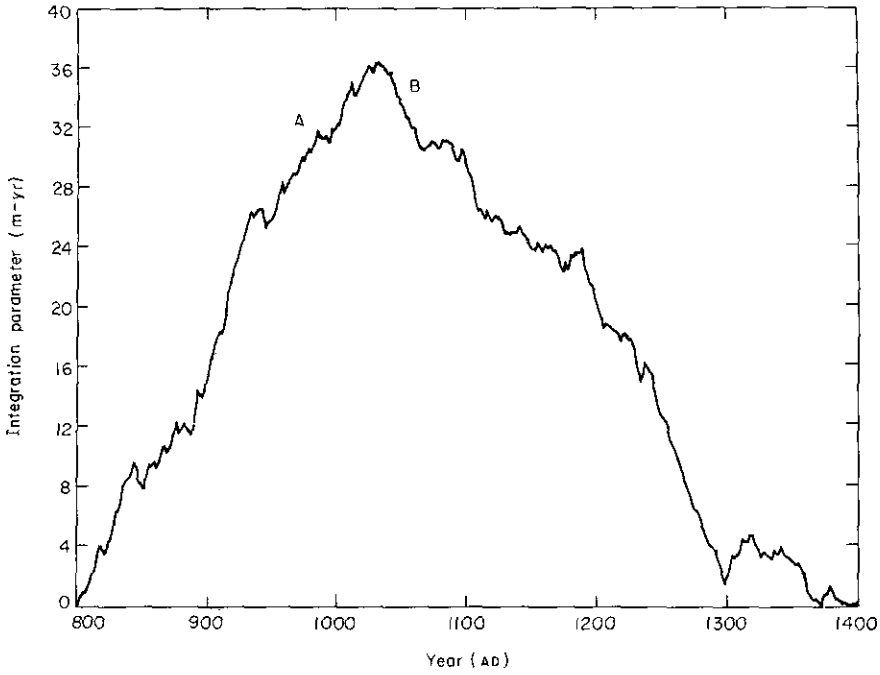

Figure 7. Integrated, time-dependent ice cap thickness curve. This figure illustrates a time integration of the ice cap thickness values from the 9-year moving average plot displayed in Figure 6.

to the mildness of the climate. However, the general rise in temperature was not without negative collateral effects: devastating torrential rains occurred frequently in Europe in the 14th century destroying the gains of earlier periods (Lamb, 1965). As evidenced by the Quelccaya ice cap data, this temperature rise appears to extend into the Western Hemisphere indicating that this climate change was probably a global phenomenon. Subsequently, the post-AD 1500 era is characterized by a mean annual temperature drop of approximately 1·3 °C lasting up to AD 1890. This phenomenon has been denoted as the "Little Ice Age" and again appears to be a global effect (Grove, 1988). For the AD 1000–1400 period in the Quelccaya area, both a temperature rise and a precipitation deficit occur simultaneously. These phenomena may be related but it is problematic to couple these effects. For example, during the Little Ice Age, the first few centuries were characterized by an average precipitation increase of 25% while the later centuries had a 20% decrease in mean precipitation (L. Thompson, pers. comm., 1991).

The climate changes during the post-AD 1000 era documented in the Quelccaya ice cap had an agro-ecological impact on South American civilizations equally as profound as the historically documented effects on western European societies. The specific effects of these changes on Tiwanaku agricultural systems will be examined in detail below. In sparest terms, however, we hypothesize that climate change in the form of persistent lowered precipitation in the post-AD 1000 period was the mechanism that triggered the collapse of Tiwanaku's agricultural base and ultimately the disintegration of the state itself. This is not to say that this "great drought" is a complete explanation for the collapse of Tiwanaku's political system. The process of political collapse in the face of declining agricultural

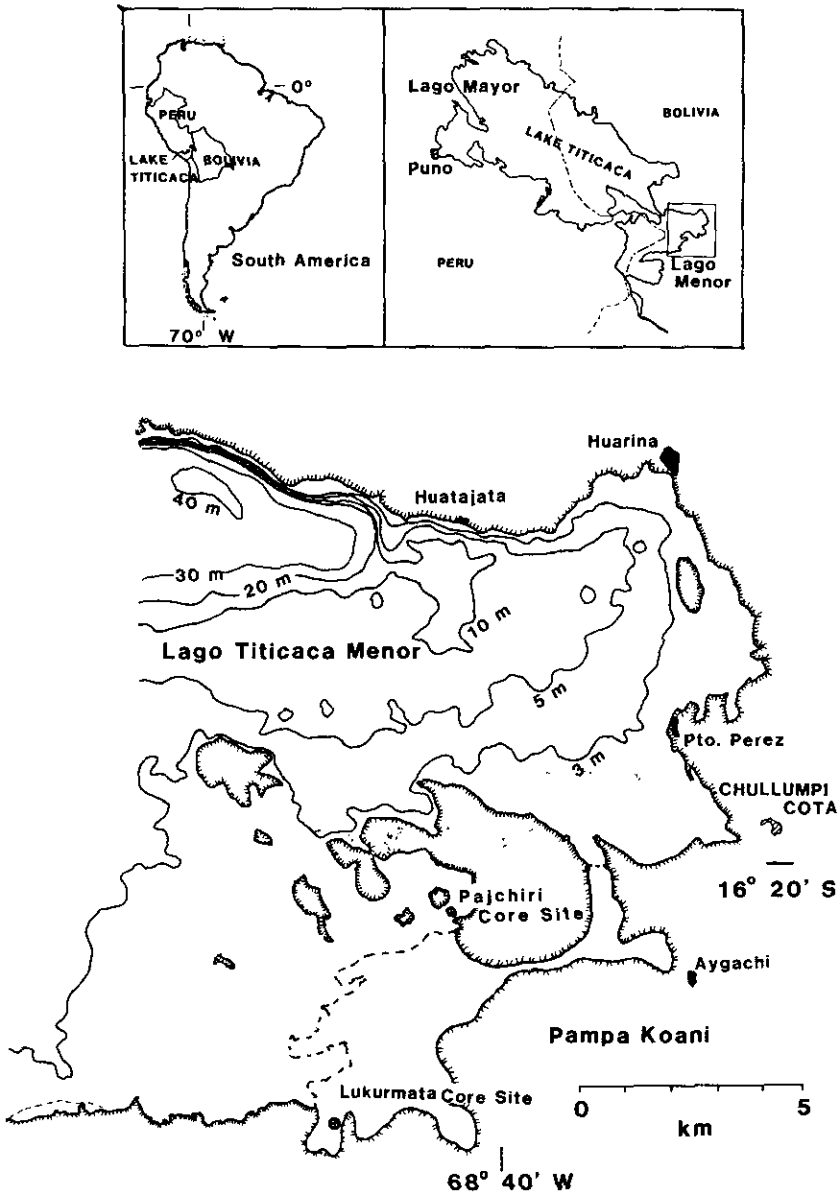

Figure 8. Map illustrating location of lake core sites with respect to the archaeological site of Lukurmata and the raised field zone of the Pampa Koani. Sediment core 22-VIII-86-1 is designated here as the Lukurmata core site. Map courtesy of Michael Binford.

returns undoubtedly required a few generations and, most likely, entailed complex, historically specific instances of social competitition, conflict and re-alignments that are unrecorded in the archaeological record. Nevertheless, within a possible hierarchy of explanations, we propose that the post-AD 1000 climatic shift to chronic drought conditions was the *proximate* cause for the collapse of the Tiwanaku state.

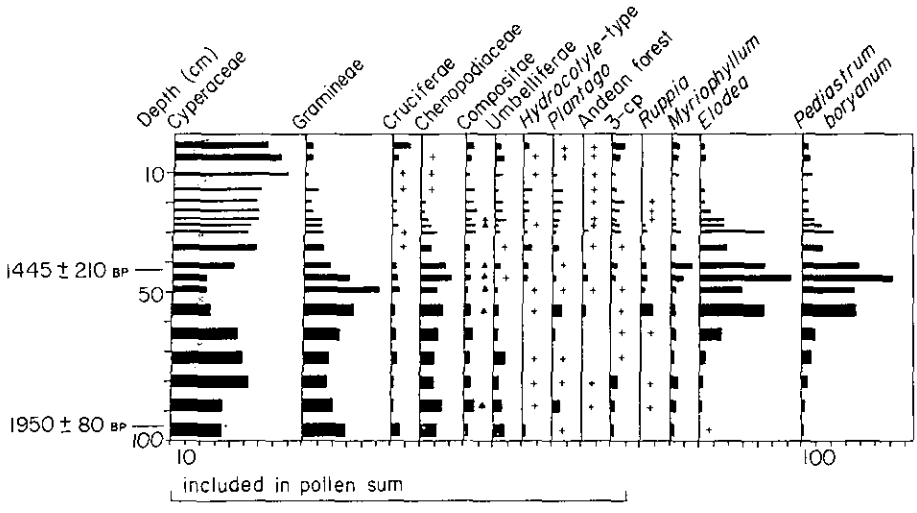

Figure 9. Pollen percentage diagram for Lake Titicaca sediment core 22-VIII-86-1. Pluses represent percentages less than 2%. Triangles indicate levels in which *Ambrosia* is present. Aquatic taxa are excluded from the pollen sum. All profiles are drawn to the same scale except for *Pediastrum boryanum* which is displayed at 1/10-scale. Redrawn from Leyden (1989: 270) with addition of radiocarbon dates on sediments in basal and mid-core sections.

Climate Effects on Tiwanaku Agricultural Systems

In order to relate the foregoing climate data to performance of Tiwanaku agricultural systems, we first define relative vulnerability classes for various agricultural technologies used in different geographic regions of the Tiwanaku state (Table 2). The order of vulnerability ranking of these agricultural technologies directly depends on: (i) the relationship of water source and water redistribution techniques to field systems and, (ii) the effects of drought conditions on the function of a given system. Since the water supply ultimately relates to climate-dependent rainfall, fluvial runoff or groundwater storage, the agricultural systems that depend on these sources will be affected differentially as indicated in Table 2. Here we discuss the type, water source and vulnerability of specific Tiwanaku agricultural technologies in the *altiplano* and in the Peruvian south coast valley of Moquegua (Figure 1).

Altiplano systems

The immediate environs and near hinterland of Tiwanaku are characterized by extensive groundwater and springwater supplied raised-field systems and by *cochas*. *Cochas* are essentially sunken-gardens excavated into the phreatic zone (Flores-Ochoa, 1983) to exploit stored groundwater. We have strong circumstantial, but no incontrovertible evidence that *cochas* were part of the sophisticated repertoire of Tiwanaku farmers, at least during the Tiwanaku IV and V phases.* As noted in Table 2, raised fields and *cochas* possess water source and redistribution attributes that render them resistant to drought conditions, placing them in the lowest vulnerability classes (0 and 1).

Two types of canal fed raised-field systems are also found in the Tiwanaku hinterland. One such irrigation network was discovered in the Pajchiri area to the northwest of the Pampa Koani (Ortloff & Kolata, 1989). This aqueduct-based network is driven by local,

*Footnote on p. 207.

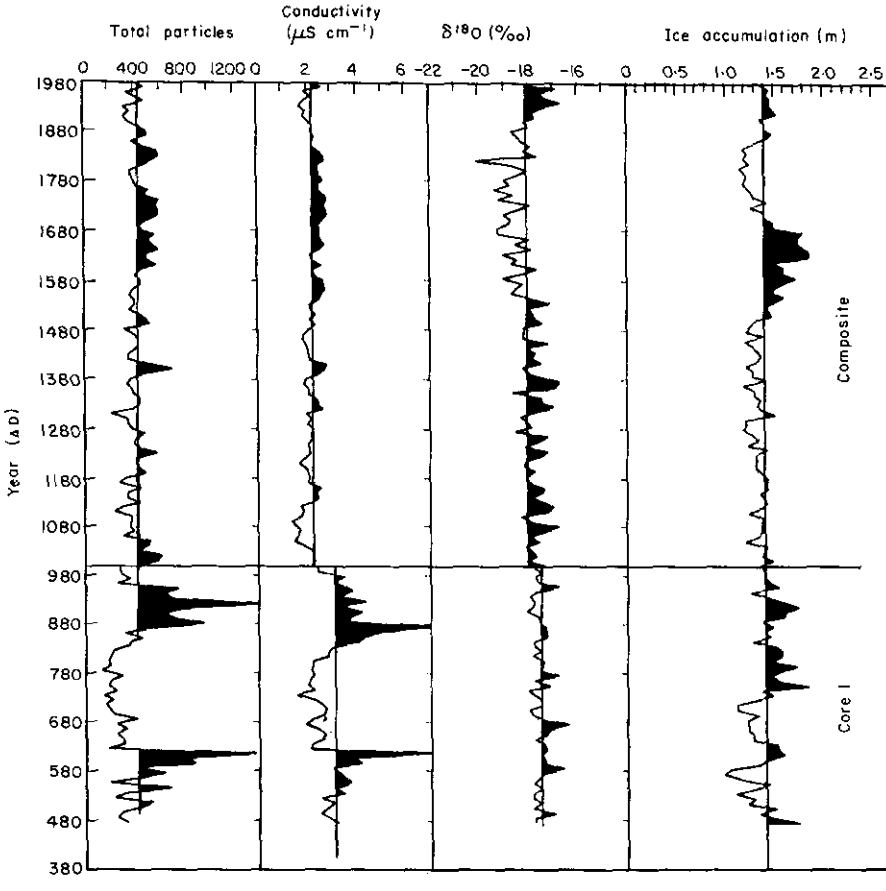

Figure 10. Total particles, conductivity, isotopic oxygen and ice accumulation from the Quelccaya ice cap, AD 400–1980 from Thompson *et al.* (1988). Note particle accumulation peaks at AD 620 and 950, referred to in the text.

*Albarracín-Jordan argues that artificial terraces in the valley of Tiwanaku were also part of the state's repertoire of intensive agricultural techniques (Albarracín-Jordan and Mathews, 1990). However, these "agricultural" terraces possess substantial quantities of cultural material (ceramics, ground stone, projectile points, etc.) suggesting that they were in actuality terraces constructed to accommodate domestic architecture rather than intensive agriculture. Similar domestic terraces have been investigated at the Tiwanaku secondary urban sites of Pajchiri and Lukurmata. Extensive excavations of such terraces at Lukurmata revealed unequivocal evidence that they were employed for domestic architecture, and not for agriculture (Kolata, 1989). It is possible that some form of house gardens were interspersed among the residential architecture on these terraces, but these would not have been of sufficient scale to constitute an intensive, state-managed agricultural system. Given these clear precedents, and the presence of similar surface domestic debris on the terraces in the lower Tiwanaku valley, the preponderance of evidence suggests that the Tiwanaku valley terraces were also designed primarily for residential architecture and not for intensive agriculture. However, we accept Albarracín-Jordan's interpretation of these terraces to the extent that they may have been utilized partly for supplemental, family-based agricultural production. In a previous paper, Kolata (1987: 38–41) argued that the massive agricultural terraces that do exist in the Tiwanaku area, such as on the island of Cumana to the northwest of the Pampa Koani, are primarily a post-Tiwanaku phenomenon. Given the above discussion, we see no compelling evidence to alter that conclusion.

Table 2. Agricultural system vulnerability

Vulnerability class	System type	Water source	Vulnerability
5	Spring-supplied localized systems	Shallow groundwater	Immediate response to rainfall fluctuations
4	Rainfall-supplied terraces	Rainfall	Immediate response to rainfall fluctuations
3	Canal-supplied river plain agriculture	Fluvial/ Surface flow	Immediate response to rainfall fluctuations
2	Canal-supplied terrace agriculture	Snow-melt/ Rainfall	Delayed response to rainfall fluctuations
1	Raised fields	Groundwater/ Springs/Fluvial	Delayed response to rainfall fluctuations
0	Cochas	Deep groundwater	Delayed response to rainfall fluctuations

high-elevation springwater. A second and more extensive system of canal-fed raised fields is found in the valley of Tiwanaku and in the Catari river sub-basin (Figure 11). These raised fields were supplied by canals that drew water from local rivers and streams (see Kolata, 1991: Figure 7). If these canal-fed raised fields had operated with surface runoffs as their *sole* source of water, they would have been highly vulnerable (class 3) to drought conditions. However, these systems were simultaneously supplied by groundwater, and they therefore retain a lower relative vulnerability rank (class 1). One other source of acquifer recharge exists in the Tiwanaku hinterland. Snow-melt from the Cordillera Real channelled water to a network of raised fields in the Pukarani area to the northeast of the Pampa Koani (Figure 11). The Pukarani network of raised fields was dependent upon this remote source of groundwater recharge, and therefore linked directly to the regional precipitation regime.

Moquegua Valley systems

Recent research in the Moquegua Valley has begun to clarify the nature and extent of Tiwanaku state expansion from the *altiplano* to the western Andean slopes and coastal zones of southern-most Peru (Goldstein, 1989; Rice *et al.*, 1989; Stanish, 1989; Watanabe *et al.*, 1990). In many respects, the Moquegua Valley can be considered as a paradigmatic case of Tiwanaku agricultural colonization outside of the *altiplano*. Aridity and broken, difficult terrain severely constrain agriculture in the 140 km long drainage area of the Moquegua Valley. Although this drainage system rises above 5000 m, less than 20% of the catchment area lies within the zone of seasonal rainfall. Consequently, cultivation requires artificial, canal-based irrigation. Not surprisingly, the utilization of scarce runoff is itself subject to topographic constraints which divide Moquegua agriculture into four ascending zones (Moseley *et al.*, 1991; Figure 12). The second zone, which lies at the heart of the mid-valley, contains the largest expanse of arable land, comprised of fertile flatlands formed around the confluence of the three major valley tributaries. This zone was the focus of heavy and long-term Tiwanaku occupation.

The Tiwanaku occupation of the Moquegua Valley was the subject of preliminary work in the 1960s (Disselhoff, 1968). Current studies have identified more than a dozen sites

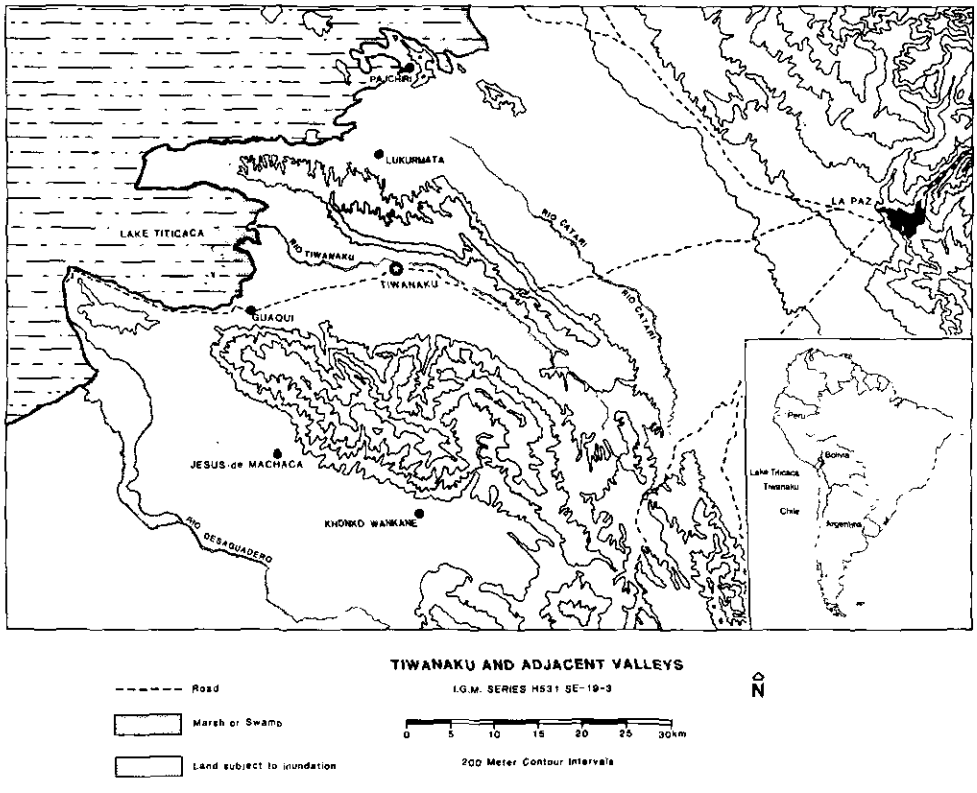

Figure 11. Tiwanaku and adjacent valleys illustrating the location of archaeological sites discussed in the text and the general topographic and hydrological features of the Rio Tiwanaku and Rio Catari (Pampa Koani) sub-basins. The Tiwanaku hinterland illustrated here was the location of approximately 190 km^2 of raised fields incorporated into a regional system of agricultural production (see extended discussion of this point in Kolata, 1991).

(Rice *et al.*, 1989; Moseley *et al.*, 1991). Tiwanaku sites are concentrated in the lower agricultural zones where farming was supported by canal systems that reclaimed relatively flat land (Figure 12). Associated settlements range from multi-room farmsteads or hamlets to nucleated communities of several hundred structures grouped around plazas. There are special purpose sites such as the extensive settlement of Omo, where massive adobe architecture and formal, stepped terrace layout imply an administrative function (Goldstein, 1989). Three 50–150 room Tiwanaku settlements are situated at the base of Cerro Baul immediately adjacent to irrigated bottom lands of the Torata and Tumilaca rivers (Figure 12). However, significantly there appears to be little or no Tiwanaku association with agricultural terraces at higher elevations; these are apparently post-Tiwanaku constructions.

The Moquegua Valley is characterized by a multiplicity of agricultural techniques designed to exploit available water resources in varied forms. These techniques include rain-fed agricultural terraces, canal irrigated field systems in the floodplain of the Moquegua River, high elevation agricultural terraces provisioned with snow-melt derived

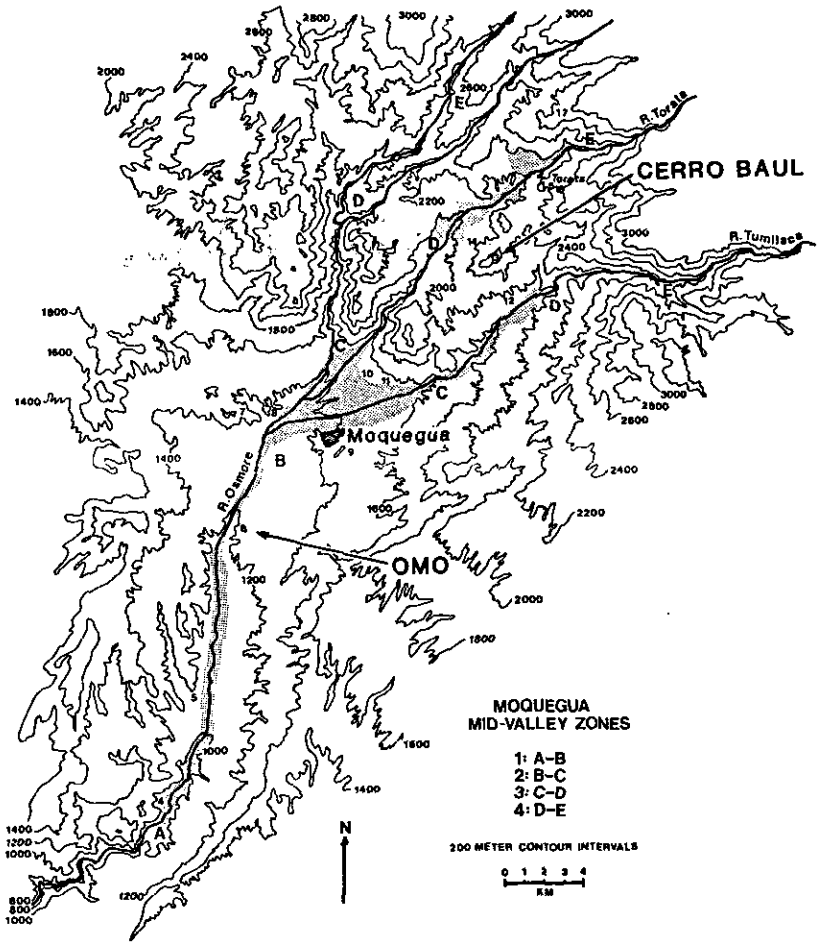

Figure 12. Map of the mid-valley region of the Moquegua Valley illustrating location of the four ascending zones of agricultural production and the Tiwanaku site of Omo referred to in the text. Redrawn from Moseley *et al.* (1991) and Goldstein (1989).

water by means of elaborate ridge-top canal systems, and local wetlands agriculture supplied by seepage from spring and groundwater at coastal sites near Ilo (Clement & Moseley, 1989). The rather unusual snow-melt-driven system of terraced agriculture in the sierra zone of the Moquegua Valley exhibits relatively intense usage from Tiwanaku V into post-Tiwanaku times. Irrigated floodplain agriculture in the Moquegua Valley appears to be earlier and associated with both Tiwanaku phase IV and V colonies.

Vulnerability of Tiwanaku agricultural systems

Tiwanaku agricultural systems in both the *altiplano* core territory and in its coastal colonial outposts reflect consummate skill in conception and construction (Kolata & Ortloff, 1989; Ortloff & Kolata, 1989; Kolata, 1991). Nevertheless, both core and colonial Tiwanaku agricultural systems fail and are abandoned in the immediate post-AD 1000 period. We argue that the proximate cause of this regional failure was the severe and

chronic precipitation deficit recorded in the Quelccaya ice cap. Given the different ecological, technological and organizational characteristics of these various agricultural systems, we further hypothesize that there was a distinct temporal sequence in the extinction of these systems based on their relative vulnerability under extended drought conditions.

Agricultural systems of vulnerability classes 3, 4 and 5 are most directly linked to precipitation levels (Table 2). In the chronic absence of rainfall, agricultural fields dependent upon the water sources that define these vulnerability classes are the first to fail. Such systems do not possess remote or delayed water delivery capacities. In contrast, systems of vulnerability class 2 are dependent upon snow-melt for water supply. Much like slow groundwater seepage, this source features a gradual, delayed release of stored water. Since accumulated snow and ice may represent water storage from past millennia, a rise in regional ambient temperature, such as that which occurred in the post-AD 1000 period, can activate melting at the lower snow boundary, and thereby provide a water source of long duration independent of prevailing moisture conditions. Such systems apparently provided water supply to the Moquegua terrace systems throughout post-Tiwanaku times. The groundwater based raised-field systems of the Tiwanaku hinterland (Pampa Koani, Tiwanaku Valley) are grouped as class 1 systems. Due to the nature of the groundwater reservoir, evaporation through the surface is limited. Seepage rates into the canals of raised field complexes is similarly a slow process further limiting the effects of evaporation. Since the collection zones supplying groundwater to the raised fields in the Tiwanaku hinterlands are immense and since this supply results from the integrated effects of rainfall infiltration and slow groundwater flow toward the field systems, depletion of this resource is minimal under normal drought-like climate variations. In periods of prolonged drought, the groundwater level will ultimately decline as resupply diminishes. Finally, class 0 systems are represented by *cochas*. As noted above, these systems are essentially pits dug into the phreatic zone above the water table that supported crop production on the shallow-angle side walls and pit bottoms. *Cochas* offer a simple technological response to drought conditions: they can be continuously excavated to follow a decreasing water table. Although least vulnerable to drought, by their nature, *cochas* have limited planting surface area and offer a relatively low rate of agricultural return relative to labour invested.

Table 2 then categorizes the vulnerability classes of the multiple types of agricultural systems found within the Tiwanaku heartland and its agricultural colonies located in the Moquegua Valley. Under chronic drought conditions, each of these agricultural systems will ultimately fail, but they will fail sequentially and not simultaneously. The systems that possess delayed delivery characteristics (vulnerability classes 0, 1 and 2) will sustain production longer than those systems directly tied to the precipitation regime (vulnerability classes 3, 4 and 5). In short, in the presence of extended drought conditions, there is a definite temporal sequence of extinction of agricultural systems based on their vulnerability class. Given this sequential extinction effect, one immediate agro-ecological consequence of the climate change documented in the Quelccaya ice cap was shifts in the agricultural supply zones available to the Tiwanaku state. These supply zone shifts, in turn, would have generated grave social problems for a political system experiencing increasing economic stress.

Table 3 summarizes the salient points regarding the historical effects of the climate change model advanced. As precipitation levels begin to decrease gradually after AD 950, class 3 canal-supplied agricultural systems characteristic of the Tiwanaku V colonies in the Moquegua Valley are early casualties of reduced rainfall and reduced river flow rates. The Tiwanaku V colonies in the middle Moquegua Valley (Figure 12) relied almost exclusively on canal-fed irrigation systems to support their populations. Even more vulnerable to minor rainfall and runoff decreases were the small communities dependent

Table 3. Out-of-use history for agricultural system types

Vulnerability class	Time period	Out-of-use history
5	AD 850–950	Spring-supplied agricultural systems on far south Peruvian and north Chilean coast collapse due to receding water table.
4	Post-AD 1000	Limited rainfall-supplied Tiwanaku V terraces fail. Terrace agriculture becomes the dominant mode in the southern Titicaca basin as mean precipitation levels recover after AD 1400.
3	AD 900–1000	River-irrigated agricultural systems in Moquegua mid-valley region fail by AD 900–1000. These systems do not recover in post-AD 1000 environment.
2	Post-AD 1000	Canal-irrigated terraces supplied by snow-melt and available rainfall virtually out-of-use after AD 1000, but continue in limited form.
1	AD 1000–1100	Regionally integrated raised-field systems in Tiwanaku hinterland collapse. Limited use of raised fields in local areas in post-AD 1000 environment. No raised fields cultivated by the time of Inca incursion, *c.* AD 1450.
0	Post-AD 1000	Post-Tiwanaku agriculture centres around localized high groundwater zones using *cocha* technology. After AD 1400 recovery in precipitation levels, intensive agriculture shifts to rainfall-supplied terraces in Titicaca basin.

upon groundwater seepage (class 5) along the Peruvian and Chilean coasts (Clement & Moseley, 1989). As only a small fraction of the river flow supplies the groundwater reservoir, coastal communities depending upon springs and seepage for water supply to field systems are the first to experience minor changes in the water supply. These small spring-based agricultural communities may have gone into decline as early as AD 850–950 (Bermann *et al.*, 1989) with the initial shifts to a drier climatic regime evidenced in the integrated moisture supply curve (Figure 7).

Despite the deterioration of the Tiwanaku V Moquegua colonies' agricultural base, the heartland agricultural system dependent upon raised fields and, to a lesser degree, rainfall supplied terraces (see footnote p. 207) were still relatively viable due to the time lag in groundwater change even under incipient drought conditions. Further, the potential crop supply base from heartland systems far exceeded the demand, leading to excess agricultural capacity (Kolata, 1991). Therefore, even if these fields operated at partial capacity due to gradually changing groundwater conditions, sufficient agricultural supply to sustain the local population was still possible. But the agricultural system as a whole would have lost substantial capacity for surplus production.

Ultimately, chronic drought conditions began to lower the water table height in the raised field complexes in the Tiwanaku heartland, changing the delicate phreatic zone moisture balance derived from canal water and mound surface height difference. Declining availability of fresh water supply caused subtle changes in the heat transfer characteristics of the raised-field systems (Kolata & Ortloff, 1989). The formation of dry soil surface

layers, for example, changes the heat conduction and moisture transport characteristics of the raised fields increasing chances of crop loss from frost damage (Sato *et al.*, 1990). However, the key problem (and the most devastating effect) was the drought-related withdrawal of water supply from the raised field platform root systems as the groundwater level dropped. Given a receding water table, there was no economically feasible method to reconfigure the water supply and reproduce production results similar to those achieved under fully functioning raised-field systems.

The evidence of changing settlement patterns

In this model of climate-induced state collapse, the heartland area is the last survivor, but only in the presence of an observable loss in agricultural capacity from year to year. Given predictable and non-reversible decline in the principal agricultural supply base, regionalization and opportunistic exploitation of declining water resources replaced previous centralized state control of an integrated agricultural landscape (Kolata, 1991). Since available water resources were dispersed and limited, the size of the group deriving sustenance from each water source was commensurate with the source itself. Post-Tiwanaku settlement patterns in the valley of Tiwanaku dramatically reflect this process of population dispersion and disaggregation. In the Tiwanaku IV and early Tiwanaku V phases, the lower and middle valley of Tiwanaku was organized into an integrated agricultural production zone characterized by a distinct settlement hierarchy. Albarracín-Jordan & Mathews (1990) have identified a series of Tiwanaku IV and V phase settlements spaced regularly (approximately 2 km apart) along the colluvial terraces on both the north and south sides of the valley. They classify these as secondary (*c.* 3–10 ha in size) and tertiary (*c.* 1–3 ha in size) sites within the settlement hierarchy and associate them directly with the administration of agricultural production on raised fields in the adjacent alluvial plain of the Tiwanaku river (see Albarracín-Jordan & Mathews, 1990: Map 4 and Map 5). A large number of fourth-order sites in this hierarchical ranking were small mounds and sherd scatters (< 1 ha) directly associated with the raised fields themselves. In sharp contrast, the immediate post-Tiwanaku settlement pattern in the region exhibits a complete disintegration of this settlement hierarchy, and presumably the underlying political and economic structures that were reflected in this hierarchy (see Albarracín-Jordan & Mathews, 1990: Map 6). As Albarracín-Jordan and Mathews (1990: 191–192) note, the immediate post-Tiwanaku period ("Early Pacajes" in their nomenclature) was characterized by

> "a proliferation of small sites which were distributed in a dispersed fashion throughout all of the microenvironments of the valley, including the intermontane zone which had not been occupied previously. The secondary centres that characterized the Tiwanaku IV and V periods disappear as such, converting into small habitation centres. These transformations suggest a change in the social order from a hierarchy of centralized administration to autonomous social groups reduced [in scale]" (our translation).

Although there are still substantial numbers of sites in Tiwanaku's hinterland after AD 1000, they are widely dispersed across the landscape and few exceed 1 ha in size. The upper end of the previously existing settlement hierarchy (in terms of settlement size and presumed political complexity) is clearly truncated. Most dramatic in terms of settlement pattern transformations, the cities of Tiwanaku and Lukurmata themselves are virtually abandoned at this time. Radiocarbon dates on Tiwanaku V phase households in these cities cluster between AD 750–950 and no radiocarbon dates on domestic occupations are associated with these urban centres past AD 1000 (Table 1). There was, in short, a dramatic redistribution of population in the Tiwanaku hinterland characterized by disaggregation

and, more tellingly, complete de-urbanization. If as Saalman (1968: 11) suggests "there is only one criterion of failure for cities: depopulation," then after AD 1000 Tiwanaku and its secondary urban centres were clear failures. As a corollary to this proposition, when cities and urban culture fail, so do the state political systems in which they are embedded.

There is some evidence for localized raised-field cultivation in the post-AD 1000 environment (Albarracín-Jordan & Mathews, 1990; Graffam, 1990). However, despite subsequent periods of relatively higher precipitation that would have again made this form of cultivation technologically feasible, the earlier regional system of large-scale agricultural production was never reactivated. This serves to illustrate that societies possess thresholds of irreversibility. Once fragmented, precarious structures of organizational complexity characteristic of imperial societies never permit a return to the original state.

Stanish's recent settlement pattern survey in the Juli-Pomata area on the north-western margins of Lake Titicaca provides a portrait of agricultural collapse and settlement transformation in that region consistent with the scenario we have outlined for the Tiwanaku hinterland. He reports evidence of intrusive human occupation and tombs in previously productive raised-field complexes in the immediate post-AD 1000 period (Charles Stanish, pers. comm., 1991). Provocatively, Stanish suggests that with the collapse of Tiwanaku raised-field agriculture in the region, there was a shift to increasing emphasis on camelid pastoralism to replace lost food resources. Such a shift would entail dramatic changes in the logistics of subsistence and, correlatively, in the structure of the prevailing social order, toward a more dispersed, mobile (and perhaps aggressive) society.

Relocation and regionalization of populations around increasingly scarce water resources also occurred outside the *altiplano* in the Tiwanaku colonial outposts of the Moquegua Valley. This process of climate-induced, settlement re-organization is directly reflected in the emergence of post-Tiwanaku groups in the upper Moquegua Valley sierra zones. Agriculture in the Moquegua region shifts away from the irrigated cultivation of the mid-valley floodplain characteristic of the Tiwanaku V colonies toward higher elevation agricultural terraces tied to a restricted water supply derived from snow melt and available precipitation (Bermann *et al.*, 1989; Rice *et al.*, 1989). Water supply was now critical to survival and defensive structures appear in profusion in the sierra zone apparently guarding and controlling access to the supply canals (Kolata, 1983; Rice *et al.*, 1989). The water supply from this source was limited, however, given declining precipitation and lack of replenishment of the sierra snow pack in the post-Tiwanaku environment.

Beyond Tiwanaku: Regional Implications of the Climate Change Model in the Post-AD 1000 Period

The implications of this agro-ecological model of state collapse reach beyond the specific case of Tiwanaku. Agricultural system collapse has been noted previously in other areas of the Andes in the immediate post-AD 1000 environment (Ortloff, 1992), and we propose that these instances of system collapse were similarly related to the chronic drought conditions documented here. The history of Chimu land reclamation in the Moche Valley on Peru's north coast offers a particularly intriguing forum for exploring the potential Andean-wide effects of this climatic change on large-scale systems of agricultural production. The Chimu state's intervalley canal between the Moche and Chicama valleys on the Peruvian north coast is a classic example of engineering response to water supply problems (Ortloff *et al.*, 1982). This canal was designed and built at great labour cost to supply fresh water from the Chicama river to existing field systems within the Moche Valley that were clearly experiencing a significant water deficit. Ortloff *et al.* (1982) originally interpreted the source of this water deficit as the result of localized tectonic uplift which physically stranded the intakes of entire canal systems. Despite considerable debate on

this issue (Kus, 1984; Pozorski & Pozorski, 1982), the empirical evidence for uplift and canal stranding is compelling (Ortloff *et al.*, 1983). The climatological data for the extensive drought characterizing this period provides a complementary explanation for the water deficit that stimulated the ultimately ill-fated Chimu attempt to capture water from the Chicama river. Both tectonic and drought effects appear to act simultaneously to decrease the net water supply to the Moche Valley field systems.

Figures 13 and 14 summarize the results of previous, quantitative research by one of the authors into the dynamics of large-scale Chimu canal systems on the north side of the Moche Valley and into the smaller Carrizal spring system in the lower Moquegua Valley respectively (Ortloff, 1992). The decrease in canal flow rates through time in these figures is derived from measurements of changing canal cross-sections and computation of flow rates through different canal configurations. Shown sequentially are the total flow rate of water supply systems, land area in cultivation and the manpower requirement for agricultural system construction.

Inherent to the dynamics of these systems is significant decline in water supply in the post-AD 1000 environment and the consequent struggle for survival by utilization of increasingly more complex engineering practices or alternative agricultural technologies. The Chimu state adapted to the deteriorating environmental circumstances of the post-AD 1000 period by successfully establishing an aggressive tribute economy through territorial expansion and by application of sophisticated canal technologies to reconfigure irrigation systems continuously for optimum production (Kolata, 1990; Ortloff *et al.*, 1985). For the Chimu, reconfiguration of the agricultural supply base to the north of the Moche Valley and conquest of the far northern Lambeyeque polities in the period from AD 1000–1300 was consistent with the drive to secure high flow-rate rivers for irrigation agriculture and to control adjacent valleys to fortify the state's eroding economic base. Other smaller polities, such as that focused around the Carrizal spring system in southern Peru, were incapable of substituting or generating new sources of wealth in the face of declining agricultural returns as did the Chimu. For lack of efficient technical solutions to restore an alternate agricultural supply or the ability to expand their resource base through aggression, these smaller-scale societies simply disappeared.

Summary and Conclusions

The principal conclusions of this paper are summarized in Table 4. The Tiwanaku empire experienced collapse of its agricultural base after AD 1000 due to a dramatic decline in mean annual precipitation commencing around AD 950. Recovery in terms of return to the precipitation levels of the pre-AD 1000 period began only centuries later. Several higher rainfall excursions from the lower mean of the post-AD 1000 environment do occur, but even these brief precipitation pulses were truncated by an intensification of drought conditions in the period from AD 1245–1310. Generally, in environmental terms, the post-Tiwanaku period from AD 1000–1400 was characterized by a significant water deficit that had severe negative impacts on systems of intensive agriculture. Categorization of the vulnerability of diverse types of Tiwanaku agricultural systems in both the *altiplano* and in its dispersed colonial network suggests a sequential extinction of these different systems based on their degree of linkage to the prevailing precipitation regime (Tables 2, 3). We propose that the successive collapse of these systems proceeded chronologically in order of their vulnerability. Heartland agricultural systems, composed primarily of raised fields, exhibited a delayed response to drought conditions and consequently were the last to fail. Since the centre of the empire was still intact as the colonies began to fail, the long-term drought slowly led to an awareness of the imminent failure of the agricultural system. Under such circumstances, an organized technical defense to maximize agricultural

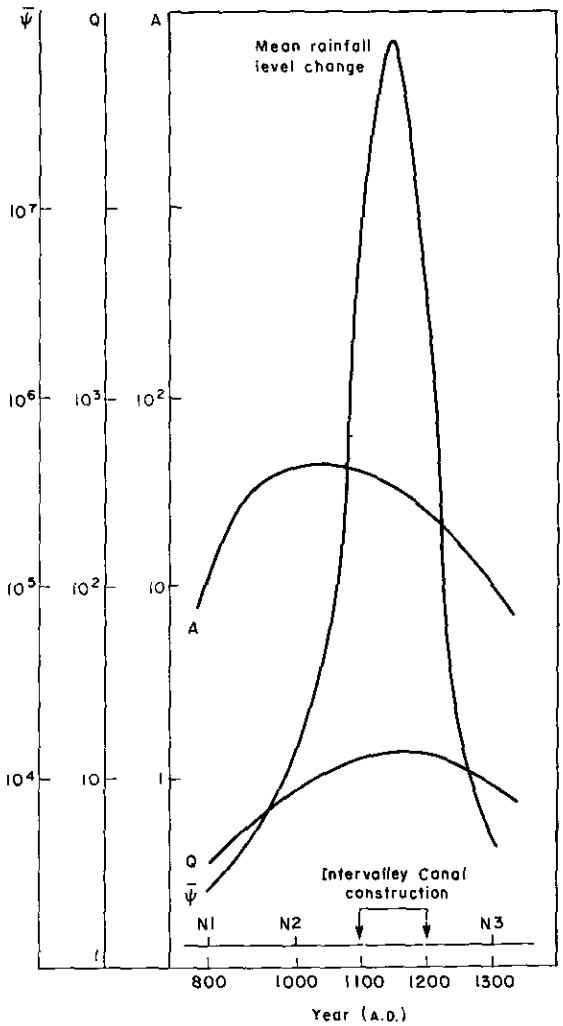

Figure 13. Selected diagnostics of the north side Moche Valley canal system for the period between *c.* AD 800–1300. Diagnostics include labour input (man-hours), canal flow rate (m^3 sec^{-1}) and irrigated land area (km^2). Adapted from Ortloff (1992). N1 = Mochica, N2 = Vichansao, N3 = Moro, A = irrigated land area (km^2), Q = canal flow rate (m^3 s^{-1}), $\bar{\psi}h$ = labour input (man-hours).

production in the heartland was possible, and may have been accomplished by reconfiguring raised-field networks in areas of relatively higher groundwater near the shores of Lake Titicaca. Ultimately, chronic drought resulted in failure of the core raised-field systems as well. With the collapse of this essential agricultural base, the Tiwanaku state's political structure fragmented. This fragmentation is reflected clearly in a dramatic change in settlement patterns that can best be characterized by the terms disaggregation, deurbanization and dispersion of populations. This signal change in settlement and population distributions can be detected in the immediate Tiwanaku hinterland, in the Juli-Pomata region of the Lake Titicaca basin, and in the lower-altitude colonial region of

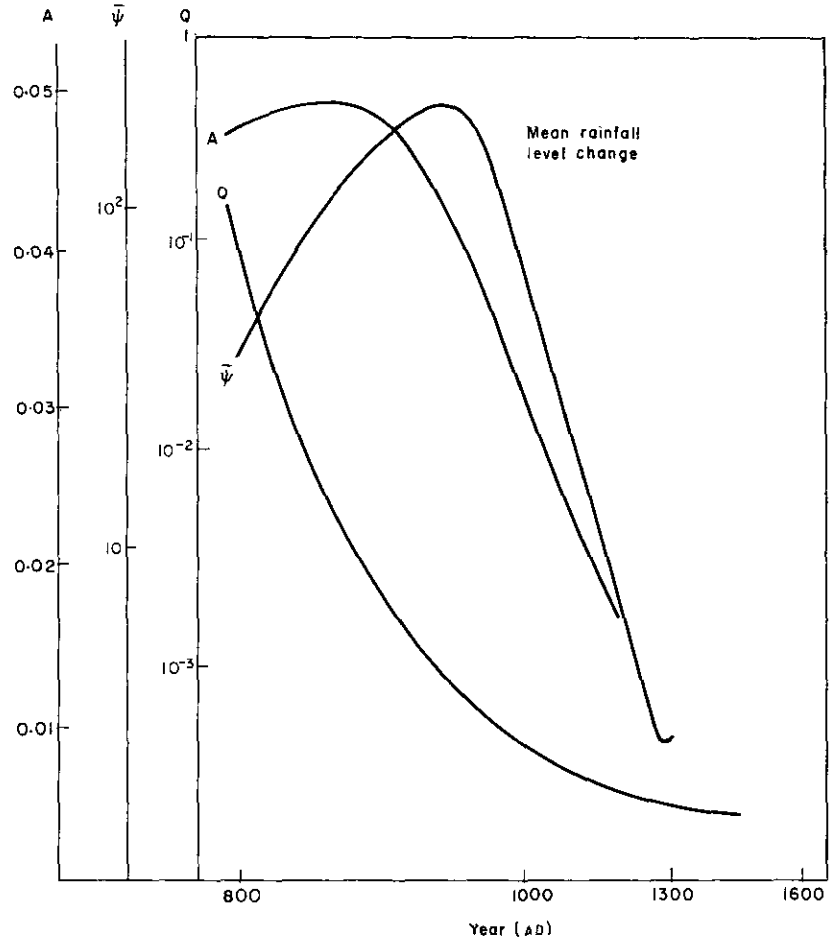

Figure 14. Selected diagnostics of the Carrizal spring system in the lower Moquegua Valley for the period between *c.* AD 800–1300. Diagnostics include labour input (man-hours), spring flow rate (m^3 sec^{-1}) and irrigated land area (km^2). Adapted from Ortloff (1992). A = land under cultivation (km^2), Q = spring flow rate (m^3 s^{-1}), $\bar{\psi}h$ = labour input (man-hours).

the Moquegua Valley. We predict that future intensive settlement pattern surveys in other areas of Tiwanaku hegemony in the south-central Andes will reveal similar shifts in population concentration.

Since the Tiwanaku state was based on a surplus-producing agricultural system that was sustained over a period of at least seven centuries, the intense drought conditions of the post-AD 1000 period can be understood as an extraordinary and catastrophic episode of climate change beyond any experienced during the formation and design of the raised-field system. Over the course of these centuries, Tiwanaku society became dependent upon a system of agricultural production that was well adapted to the rigorous environmental conditions of the *altiplano*; a system that could adjust to normal cycles of drought and inundation characteristic of that environment (Kolata, 1991; Ortloff & Kolata, 1989). The state organized labour on a grand scale to construct raised-field systems in their final

Table 4. Summary of collapse model and principal conclusions

1.	Quelccaya ice cap records statistically significant decrease in rainfall after AD 1000.
2.	Quelccaya ice cap oxygen-18 isotopes record 0·5–1°C temperature rise after AD 1000.
3.	The post-AD 1000 period witnesses sequential collapse of Tiwanaku agricultural systems according to their vulnerability to intensifying drought conditions.
4.	Tiwanaku V Moquegua mid-valley agricultural systems fail early (*c.* AD 900–1000) in the collapse sequence due to their direct, precipitation-dependent water supply systems.
5.	Tiwanaku V raised-field systems driven by groundwater sources in the altiplano exhibit delayed response to intensifying drought conditions and persist in production longer than the Moquegua agricultural colonies.
6.	Altiplano raised-field systems in the core area of the Tiwanaku state eventually fail (*c.* AD 1000–1100) as the duration of the post-AD 1000 drought exceeds the normal recovery time of the field systems to pre-AD 1000 seasonal and periodic precipitation fluctuations.
7.	Post-Tiwanaku settlement patterns in the altiplano reflect human response to chronic drought conditions. Urban settlements are abandoned and the redistribution of populations after AD 1000 can be characterized as a process of disaggregation and dispersion. The political structure and hierarchical modes of production of the Tiwanaku state disintegrate under severe, climate-induced agricultural collapse.
8.	Post-Tiwanaku settlement pattern change in the Moquegua Valley reflects a similar drought-driven response. There is disaggregation of populations and a shift to smaller sites, many of which show evidence of fortification and siting in defensible locations that protect access routes to available water sources. Agriculture reverts to small-scale, localized production, particularly in mid and upper-valley terraces supplied by snow-melt and available precipitation.
9.	Climate change recorded in the Quelccaya ice cap was a pan-Andean (and most likely, hemispheric) phenomenon. A post-AD 1000 agricultural crisis triggered by a significant water deficit can be documented in the Moche Valley. Consequently, climate-induced agricultural collapse and radical transformations in settlement patterns should be detectable during this period in other regions of the Andes.

Tiwanaku phase IV and V configurations. The intricate drainage and water-shunting systems to control groundwater level and intercept runoff are eloquent testimonies to indigenous understanding of the hydrological environment and its manipulation (Kolata & Ortloff, 1989; Ortloff & Kolata, 1989; Kolata, 1991). Nevertheless, despite centuries of sophisticated manipulation of the hydrological regime for the benefit of agricultural production, Tiwanaku agro-engineers were incapable of responding to a drought of unprecedented duration and severity. In the prolonged decades of drought conditions that ensued in the post-AD 1000 era, there was insufficient production and storage capacity to support the urbanized populations that had grown up in the lake district during previous periods of agricultural expansion and prosperity. The end-product of a climate-induced deterioration of the agricultural base was predictable: Tiwanaku cities were abandoned and the surplus-extracting apparatus of state administration lost both its fundamental source of power and its social relevance.

Implicit in this model of drought-induced agricultural crisis and state collapse is the probability that the phenomenon of climate change recorded in the Quelccaya glacier was pan-Andean. The implications of this conclusion for post-AD 1000 Andean prehistory are apparent: climate-induced agricultural crises and potential radical transformations in settlement patterns should be detectable during this period in other regions of the Andes.

We propose that the Chimu history of land reclamation and aggressive territorial expansion on the north coast of Peru (Kolata, 1990), particularly in the period from AD 1000–1300, is one trenchant example of this process of human adjustment to pan-Andean environmental change.

Acknowledgements

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Appendix A

A brief comment on statistical methods employed in this paper is in order. In analysing the degree of dependence and correlation between two normally distributed ice cap thickness populations, we used the *t*-test to examine the hypothesis that mean precipitation levels are significantly different in the pre- and post-AD 1000 environments (Dunn & Clark, 1974). We tested the null hypothesis that the means of the distribution from which each population was drawn is identical. The null hypothesis was rejected, supporting the conclusion of a change to a drier climate in the post-AD 1000 period. From analysis of input data files and use of standard statistical nomenclature, the following table can be constructed:

Group	*N*	Mean	SD
Pre-AD 1000	225	1·487	0·388
Post-AD 1000	376	1·232	0·316
Separate variances	$t = 8{\cdot}4566$	DF = 403·7	$P < 0{\cdot}00001$
Pooled variances	$t = 8{\cdot}7059$	DF = 599	$P < 0{\cdot}00001$

These results indicate that the probability that the ice cap thickness distribution before AD 1000 and that after AD 1000 are from the same population is $< 0{\cdot}00001$. Assuming that the observed correlation between snow layer thickness and intensity of annual rainfall is correct, from a statistical perspective, it is clear that the Quelccaya ice cap data provides firm evidence of a significant climate change in the form of lower precipitation levels in the post-AD 1000 environment (from that existing previously). As indicated in the text, this lowered mean precipitation persists for four centuries (*c.* AD 1000–1400) despite several brief excursions of above average rainfall (Figures 3, 7).