PROJECT SUMMARY

The ultimate goal of this collaborative study is to determine how Holocene climate variability affected landscape evolution in tributary valleys of the western Lake Titicaca basin and how Holocene landscape evolution in those tributaries influenced human activities. To meet this goal we will work at the intersection of three disciplines: paleoclimatology, fluvial sedimentology, and archaeology. We will create a proxy-based, high-resolution (decadal), properly interpreted paleoclimate time series for the western Lake Titicaca basin by collecting and analyzing sediment cores from small, high-sedimentation-rate lakes. We will generate new sedimentologic and geomorphic data, from three river valleys in the same region, and use those data to create a basinwide model of fluvial evolution in the context of regional climate change and base level. And, we will generate new archaeological data that will begin to fill the gaps in our knowledge of the early prehistory (especially the record of the Archaic Period, *ca.* 10,000 to 3500 cal BP) of the basin. These data will address important questions about the character of the initial occupation of the basin, the dynamics of the sedentarization process, and the expansion of agropastoral settlements following sedentarization.

In this study we aim to produce the best-dated and best-understood reconstruction of Holocene precipitation in tropical South America. This record is needed to answer important paleoclimate questions (such as the nature of the sea-surface temperature forcing of the tropical atmosphere), but it also essential to our ultimate research goal. Once climate variability is securely known, we can address questions concerning the evolution of fluvial landscapes within the proper climatological context. Holocene fluvial sedimentology in the western Titicaca basin is largely controlled by precipitation variability, which affects both riverine discharge and base level (the level of Lake Titicaca). Few studies of fluvial evolution have been done with the complete knowledge of the relevant records of both climate and base level, so this is an unusual opportunity to increase our understanding of both the rates and processes of sediment aggradation and downcutting, as well as possible non-linearities in the fluvial response to climate and base-level variability. Because fluvial variability is a key factor in both landscape evolution and the lives of both modern and ancient occupants of the basin, a secure knowledge of climate and landscape variability will allow us to address serious issues relating climate change and human activities. The new archaeological data we will collect will complement ongoing work elsewhere in the basin and the data, gathered within a highly resolved paleoclimatic context accompanied by a well-constrained reconstruction of natural landscape evolution, unrivaled in many other research settings, will allow us to document the relative timing of environmental and cultural change.
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NOTE TO REVIEWERS

This proposal is a thorough revision of one we originally submitted to the Geology and Paleontology Program one year ago. The first version was generally positively reviewed. The comments and suggested revisions by mail reviewers and panelists mostly focused on three issues that we address more fully in this version: (1) dating resolution and potential chronology problems, (2) a perceived lack of integration between the three related portions of the project, and (3) our attribution of certain environmental changes to natural processes, as opposed to anthropogenic forcing.

To address the first point we have added a small budgetary request for ^{210}Pb dating (although, overall, we decreased the three budgets by more than $40,000) of the upper portion of each lacustrine core – the utility of this technique in several Andean lakes from northern Chile has been demonstrated by Valero Garcés (2002). The lakes that we propose to study are moderately alkaline and saline, enough to allow preservation of calcareous microfossils (needed for stable isotopic analysis), yet not require large ^{14}C reservoir corrections. As one reviewer noted, any single ^{14}C date may only have 50-year *accuracy*, but that does not preclude decadal *resolution* in an uninterrupted sedimentary time series. We recognize that dating issues are always critical and we have considerable experience with these issues. Other reviewers added (as we ourselves stated) that the potential resolution of the fluvial and archaeological records is lower than that of the lacustrine records. We have requested 70 ^{14}C dates for the fluvial chronology, but reiterate our contention that it is essential that the fluvial and archaeological records be examined in the context of a securely determined paleoclimatic record, no matter what the resolution of the former.

Our whole proposal is motivated by our overarching desire to integrate paleoclimatic, fluvial, and human histories. Although we believe that each of the three subsections of the proposal could stand alone as viable, independent, fundable projects, we also feel that there is value-added by their integration and our cross-fertilization. All three PIs have worked closely together in pilot field and interpretive studies and we will continue to work together in this study. Another major motivation for the proposal is to educate each of our students in all three sub-disciplines – providing them with a unique set of skills and education. A puzzling comment was made by one reviewer that our field sites do not coincide. The archaeological studies will cover a large survey area in the Ramis valley; this survey area will also be totally covered by the considerably larger fluvial study areas. The lakes that will be cored are not all in the Ramis, Ilave, or Huancane watersheds, but are all in the western Lake Titicaca drainage; we believe that adjacent watersheds have had nearly identical climate histories (and will test this belief with cores from more than one lake).

The third point, made by one reviewer and echoed by the panel, refers specifically to our hypothesis that precipitation variability was the major cause of fluvial aggradation and downcutting. We clearly stated this in the form of a hypothesis (see Figure 10). We believe that it is impossible that the extensive (up to 30 m high; tens of km in extent) early and middle Holocene terraces of the Rio Ilave were significantly manipulated by the low density human populations that lived in the area at that time. We are certainly aware of the cultural landscapes (qochas, raised fields, etc.) constructed in some regions of the Titicaca basin in the late Holocene, therefore we keep an open mind to the possibility of human impact on the much smaller, late Holocene terraces.

PROJECT DESCRIPTION

RESULTS from PREVIOUS NSF SUPPORT

Results from each PI's previous NSF-funded research are summarized in the following sections. Publications resulting from the discussed research are cited in the text and included in the references cited list.

Results from Previous NSF Support -- Catherine A. Rigsby

"Quaternary fluvial sedimentology of the Rio Desaguadero, Bolivian Altiplano," NSF-ATM-9709035, awarded for the period 5/97 to 5/99, $32,850.

"Drilling the Bolivian Altiplano to obtain a paleoclimate record of tropical South America," NSF-ESH-9975161, awarded for the period 6/99 to 5/02, $306,124.

Rigsby and students have investigated the Quaternary fluvial history of Lake Titicaca's outlet, the Rio Desaguadero (Baucom 1997, Baucom and Rigsby 1999, Grove *et al.* 2002), and other rivers on the Bolivian Altiplano by examining both outcropping (terrace exposures) and subcropping (drill core) strata. Terrace strata in the northern Rio Desaguadero valley record two high-water intervals -- one between 4500 and 3900 cal BP and another between 2200 and 2000 cal BP -- that were interrupted by three (drier) periods of fluvial downcutting centered at approximately 4000, 3600, and after 2000 cal BP. These depositional and downcutting episodes were controlled by changes in effective moisture correlative with Holocene water-level fluctuations of Lake Titicaca. Braided river sediments preserved in a single terrace level in the southern (downstream) Rio Desaguadero valley recorded a history of nearly continuous fluvial sedimentation from at least 7000 cal BP until approximately 3200 cal BP that was followed by a single episode (post-3200 cal BP) of downcutting and lateral migration. This sequence of events was primarily controlled by base-level change (lake level of the great paleolakes of the central Altiplano).

In May/June, 1999 we drilled and cored 8 sites in the region where the modern Rio Desaguadero enters the vestigial paleolake (modern Lago Poopo). The purpose of this study was to identify, date, and map the elevation and lateral extent of the youngest generations of paleolakes, and to understand their climatic significance. We are completing detailed sedimentology, geochemistry, and diatom studies on these cores and have identified 9 wet (lake) phases in the cored strata (Rollins 2001, Rigsby *et al*. 2002b). These lacustrine intervals are interbedded with fluvial, deltaic, and glaciogenic sediments. We are able to distinguish shoreline and lake margin sediments from open-water lacustrine and fluvial sediments and are in the process of mapping the extent of the paleolakes. The dated lacustrine intervals are mostly correlative with wet periods recorded in Lake Titicaca (Baker *et al.,* 2001b) and in the Salar de Uyuni (Baker *et al.,* 2001a) and are also apparently correlative with equatorial and high-latitude North Atlantic cold events (such as the LGM, the Younger Dryas, and Heinrich events).

Three M.S. theses and two senior theses have resulted from this work.

Results from Previous NSF Support -- Paul A. Baker

"Quaternary paleoclimatic record from tropical South America: Lake Titicaca," NSF-ATM-9619672, $159,429, awarded for period 4/97-4/00.

"Quaternary paleoclimatic record from tropical South America: drilling the Salar de Uyuni," NSF-ATM-9809612, $297,729, awarded for the period 1/99-12/00.

For the past several years I have been working with colleagues and students on the late Quaternary paleoclimatic history of tropical South America as recorded in the sedimentary records of Lake Titicaca and the Salar de Uyuni. This work is being extended by deeper drilling in Lake Titicaca that was successfully completed in April and May, 2001.

We have shown that large climatic variations in tropical South America are forced by orbitally controlled variations of insolation (Seltzer *et al.* 1998, D'Agostino *et al.* 2001, Grove *et al.* 2002). Maximum summertime insolation in the southern tropics at 20,000 cal BP and at present produces a maximum South American summer "monsoon" and maximum Altiplano or Amazonian precipitation (*e.g.* Cross *et al.* 2000, 2001). Superimposed upon this orbital-scale variability of climate, during both the Holocene (Baker *et al.* 2001b, Tapia *et al.* 2002, Paduano *et al.* 2002) and the late Pleistocene (Baker *et al.* 2001a, Fritz *et al.* 2002, Seltzer *et al.* 2002), were millennially paced, large-amplitude and rapid fluctuations in precipitation in tropical South America. These millennial fluctuations are correlated with, and likely forced by, SST changes in the equatorial and high-latitude North Atlantic: North Atlantic Heinrich events of the late Pleistocene, including the Younger Dryas, and "Bond" events of the Holocene are manifested as wet periods on the Altiplano and in Amazonia. Reinterpretation of the stable isotopic record of South American tropical ice cores demonstrates that precipitation variability, again correlated with equatorial Atlantic SST variability, is also persistent at multi-decadal and quasi-decadal frequencies (Baker 2002).

Two doctoral dissertations, 2 M.S. theses, and 2 M.E.M. theses have resulted from this work.

Results from Previous NSF Support -- Mark S. Aldenderfer

"Sedentarization and Economic Intensification in the Southwestern Lake Titicaca Basin, 5000-3200 BP," NSF-BCS-9816313, $186,536, awarded for the period 1/99-6/99.

"Digital Field Instrumentation for Archaeological Excavation and Mapping," NSF-BCS-9978006, $58,576, awarded for the period 7/99-6/00.

Aldenderfer has one current and one recently completed award for archaeological research in the Lake Titicaca basin. "Sedentarization and Economic Intensification in the Southwestern Lake Titicaca Basin, 5000-3200 BP" supports a two-year project designed to investigate the emergence of early village life in this region through the archaeological analysis of settlement patterns, diet, and social organization. We have completed two field seasons with excavations at two sites—Jiskairumoko and Kaillachuro. Although the data are still under analysis, it is clear that pre-4000 cal BP land use was characterized by some residential mobility. Residential structures are circular in form and are relatively small (Alderderfer 2002, Craig and Aldenderfer 2002). Such structures tend to signal temporary habitation. Diet consisted of wild variants of important plants such as *Chenopodium* and *Solanum* as well as hunted fauna, including deer and camelids. Little or no evidence of social differentiation can be seen in the materials discovered with the human remains found at the sites. Post-4000 cal BP settlement is significantly different: residential structures are larger and more complex, and reflect a more structured use of space within them, a strong indicator of more permanent habitation. Diet likewise changes, with the appearance of cultivated types of *Chenopodium*, and there is a strong possibility that camelids are being herded or penned on site. Finally, there is strong evidence for social differentiation; gold objects and obsidian, imported from considerable distances in the central Andes, are found in very limited quantities and restricted to a very small number of individuals. Continued work at the sites will examine the relationship of these social transformations to environmental change, establish with certainty the timing of the appearance of the cultivated plants and herded animals, and more fully define population size and residential use of the excavated sites. The final field season of the project was completed from July-September 2001. The second award, "Digital Field Instrumentation for Archaeological Excavation and Mapping", was an equipment grant for the purchase of pen computers and specialized software used to implement a fully digital approach to basic archaeological data collection procedures for the field project described above. The equipment was used successfully during the first field season (Craig 2000, Craig and Aldenderfer 2001). Digital cameras were used to photograph archaeological features, and these were georeferenced in the field using ArcView GIS software; this product also served as the data management tool for the project. A description of the experience using this equipment and software has been placed on the WWW at http://titicaca.ucsb.edu/chamak_pacha.

INTRODUCTION

Humans entered the Titicaca basin by 10,000 cal BP (Aldenderfer and Klink 1996; Aldenderfer 1998a; Klink in press). By the eve of the Spanish Conquest, the basin was the scene of one of the densest populations in the Andean world. Even though a constant reality of the human occupation of the Altiplano, during the past and into the foreseeable future, is the close dependence of agropastoral return on the state of climate and the natural environment, the role of climatic variation in the cultural history of the Titicaca basin is poorly understood. For example, although it has been suggested that the collapse of Tiwanaku after AD 1000 was associated with long-term drought (Binford *et al.* 1997), we know little about how climate affected many critical processes in prehistory, such as the domestication of indigenous plants and animals. How populations grew and thrived in a harsh and apparently unpredictable climate is a major research issue in the anthropological study of highland peoples in general and in the Titicaca basin in particular. How the landscapes occupied by those people changed in response to climate forcing is the major focus of this proposal.

Because riparian resources formed the basis for the subsistence economy of the early inhabitants of the basin, the fluvial history of watersheds is particularly important. Although it has been suggested that humans are the major modifiers of the landscape in the Lake Titicaca basin (*e.g.,* Erickson 1999, 2000), this is not true in the western tributaries to Lake Titicaca where human alterations are small (agricultural enhancement of soil erosion, for example) in comparison to natural landscape evolution. In most of the watersheds of the Lake Titicaca basin, landscape evolution is primarily controlled by fluvial processes, as evidenced by the high – commonly >25m high – fluvial terraces. Preliminary studies indicate that these fluvial processes are largely shaped by changing climatic conditions. Hence, in the western Lake Titicaca basin climate, landscape evolution, and human occupation are intimately related. In this project, we propose to examine climate/landscape/land-use questions of both regional and far-reaching concern: *how did Holocene climate variability affect landscape evolution in tributary valleys of the western Lake Titicaca basin and how did Holocene landscape evolution in those tributaries influence human activities*?

Objectives and Rationale

We will examine these important questions by working at the intersection of three disciplines: paleoclimatology, fluvial sedimentology, and archaeology. Although this is not an entirely new endeavor, even in the Lake Titicaca basin (*e.g.*, Seltzer and Hastorf 1990, Binford *et al.* 1997), we believe that with the new data we will acquire, and with our collective expertise, we will be able to better address these fundamental interdisciplinary scientific problems.

Our pilot studies in the Rio Ilave valley (Rigsby *et al.* 2002a) suggest that human occupation of these drainage basins does vary with fluvial and climatic variability and that fluvial terraces are affected by regional climate variability. From a landscape evolution perspective, we are at a big advantage in this region because we can determine both precipitation variability and changes in base level (the level of Lake Titicaca). On a coarse scale, Holocene climate change on the Altiplano has already been documented. Early Holocene precipitation was about 40% less than modern (Cross *et al.* 2001). This aridity caused the level of Lake Titicaca to drop as low as 85 m below its present level at about 6000 cal BP (Seltzer *et al.* 1998; Cross *et al.* 2000) and caused the salinity of Lake Titicaca to increase to perhaps 1/3 of seawater values by 4000 cal BP (Cross *et al.* 2001). The aridity was enduring, but punctuated by millennially paced wetter periods (Baker *et al.* 2001a). As summertime insolation increased throughout the southern tropics, Early Holocene aridity gave way to generally wetter conditions after 5000 cal BP. The late Holocene, wet "climatic optimum" of the Altiplano was also marked by millennially paced wetter periods (Abbott *et al.* 1997a, Baker *et al.* 2001a; Rigsby *et al.* 2002b), the most recent of which coincided with the Little Ice Age of northern high latitudes (Thompson *et al.* 1986; Baker, 2002). Although these Holocene wet/dry periods are now known, their timing and amplitudes are not at all well known – we propose to study smaller, and more sensitive, lake basins in the western Lake Titicaca watershed to greatly improve the knowledge of this climate history.

With an improved Holocene climate record in hand we can investigate the role of climate change in fluvial landscapes. Although it is generally agreed that climate is important in the evolution of fluvial systems (Porter *et al.* 1992, Bridgland 2000, Freeman 2000, and many others), much controversy exists as to how much, and on what time-scales, it is important. While Vandenberghe (1995) suggests that climate is most significant on orbital time-scales, studies by Nanson (1968) and Erksin and Warner (1988) caution against regarding short-term climate changes as minor in relation to orbital-scale changes. Most workers do agree that major changes in the fluvial environment occur during times of climatic transition (*e.g.* Knox 1972, Rose and Boardman 1983, Bull 1991, Vandenberghe 1995, Bridgland 2000, Reneau 2000). And, it has been suggested that the main climatic control on river systems is discharge variability (Schumm 1993, Miall 1996, Jones *et al.* 2001). In systems with minimal vegetation (and, typically, low sediment cohesion), such as the Rios Ilave, Ramis, and Huancane of this study, increases in runoff lead to increases in sediment load, delivery of large amounts of sediment to either the local or the absolute base-level, and to valley aggradation (*e.g*. Rose *et al.* 1980, Rose and Boardman 1983, Bull 1991, Sugai 1993, Allen and Breshears 1998).

Because the Ilave and Ramis tributaries drain the Cordillera Occidental – an active volcanic arc – a large portion of the source sediment is composed of easily eroded pyroclastic deposits. But, although late Pleistocene glaciation in the Cordillera Occidental accelerated the supply of these pyroclastic sediments to fluvial systems and to Lake Titicaca (Baker *et al.* 2001a, Seltzer *et al.* 2002), active volcanism has played no other discernible role in Holocene fluvial evolution of the western Lake Titicaca basin. The youngest macroscopic ash found in sediments from Lake Titicaca cores dates to 27,000 cal BP (Baker *et al.* 2001a). The Huancane drains less easily eroded Mesozoic strata of the Cordillera Vilcanota. For all three tributaries, there was apparently no time in the Holocene when vegetative cover in the basin was so great that sediment cohesion would have been dramatically altered (Paduano *et al.* 2002). Knowledge of these complicating factors simplifies the task of trying to deduce the most important relationships among the histories of precipitation, base level (Lake Titicaca level), and fluvial aggradation versus incision in these river valleys. Understanding these natural fluvial/climate relationships will allow us to take the next step, examining the relationship between environmental change and changes in land use.

A detailed knowledge of the history of landscape evolution in these river valleys will provide a baseline for addressing serious issues relating climate change and human activities. The role that climatic variation has played in the social and political evolution of the peoples of the Titicaca basin as well as peoples across the Andes, has been hotly debated for more than 30 years. Erickson (1999, 2000), for example, argues that many explanations of cultural change and process in the Andes are dominated by what he calls neo-environmental determinism. He is specifically critical of the suggestion that the collapse of Tiwanaku was directly caused by a long-term drought (Kolata and Ortloff 1996, Binford *et al.* 1997). While some of his interpretations of the existing paleoenvironmental record are inaccurate, his major tenet is reasonable: over-reliance on gross characterizations of external forces, such as climatic variation, relegates humans to a strictly passive role. Explanations based on such forces fail to capture the creativity of humans during potentially difficult periods of environmental change. Our viewpoint is straightforward: we believe that it is currently impossible to evaluate arguments about the ways humans responded to past climate variations from any theoretical perspective without sufficiently fine-scale, properly interpreted environmental data. Until we can more confidently place human activities in a secure environmental context, we cannot evaluate causal models of cultural change. The new archaeological data we collect will elucidate the Holocene history of land-use history in the western Lake Titicaca basin. We will use those data (along with similar, previously collected, data and the new paleoclimate and fluvial data) to document the relative timing of environmental and cultural change.

Toward these ends, we address fundamental research questions in paleoclimatology, fluvial landscape evolution, and Andean archaeology with three specific, interrelated, objectives:

(1) <u>Determine the Holocene climatic (with emphasis on precipitation) history of the western Lake Titicaca watershed at high temporal resolution</u>. The nature of climatic variability on the Altiplano at multidecadal- to centennial- to millennial-timescales is a major question. We *hypothesize* that Altiplano precipitation does vary at such time scales. Documentation, however, is currently non-existent to poor. Modern climatological studies, based on the short instrumental record, largely suggest that Pacific sea-surface temperature (SST) variability (ENSO) forces most of the interannual precipitation variability on the Altiplano and in central Andes (*e.g.* Vuille *et al.* 2000, Garreaud *et al*. 2002). However, longer-term indirect proxy records of precipitation, such as water-level measurements of Lake Titicaca, ice-core isotopic measurements, and geological records, point toward an additional equatorial and high-latitude Atlantic SST control of precipitation variability at decadal and longer timescales. New, well-dated high-resolution records of paleoclimate from small lakes in the region are essential for resolving this issue. Such records will make it possible for us to more critically examine the connections between precipitation

variability on the Altiplano and North Atlantic SST variability at decadal to millennial timescales and the strength of the known Altiplano-Pacific SST teleconnection on these longer timescales.

(2) Determine how this precipitation variability, along with base-level change (determined from the lake-level history of Lake Titicaca), affected the aggradation and downcutting of fluvial sediments in the three major tributaries in this part of the basin (the Ilave, Ramis, and Huancane). We *hypothesize* that aggradation in western Titicaca river valleys is associated with increased rainfall and that downcutting is associated with decreased or flashy rainfall. Once precipitation variability is securely known (at the very least in relative magnitude), we can test this hypothesis. Also, with a more detailed record of water level changes in Lake Titicaca we can address questions concerning the relationship between sediment aggradation or downcutting and base level, as well as the possible existence of non-linearities in the fluvial response to climate and base-level variability (such as amplified responses of discharge to precipitation; thresholds on transport and erosional velocities; and extreme responses to extreme climate events).

(3) Determine the relationship between early human occupation/land-use of these river valleys and changes in precipitation and the land surface. Once climate and landscape history are known, we will be in a position to address major questions regarding ecological and human responses. We *hypothesize* that there is a relationship between natural climate and landscape changes and human land-use in the river valleys. We can address this hypothesis by posing four questions of great interest: 1) How do settlement patterns change during the Archaic in relation to variation in precipitation and lake-level rise and fall from cal 10,000 BP to 3400 BP? In particular, when does use of near-lake environments begin? 2) What is the correlation between climate variation and the period of agricultural expansion from cal 3500-2500 BP? 3) How did the northern basin polities respond to the supposed periods of drought during the Middle Horizon, especially from AD 650-730 and AD 1000-1100, and how did the responses differ from what transpired in the southern basin? 4) Is the emphasis on pastoralism and terrace agriculture that is interpreted in the southern basin as a response to increased aridity between AD 1100-1300 (Stanish in press) also apparent in the northern basin? Is there a significant difference between northern and southern basin strategies?

BACKGROUND STUDIES

Setting and Modern Climatology

Lake Titicaca (Figure 1), at an elevation of 3810 m, is the highest large lake in the world and the largest lake in South America. The lake occupies an endorheic basin that extends from about 14° to 17° S and from about 68° to 71° W. This basin, the northern part of the Bolivian and Peruvian Altiplano, is bordered by the non-glaciated Cordillera Occidental on the west, and the glaciated Cordilleras Oriental on the east and Vilcanota on the north. The southern limit of the basin is lower, and the lake overflows periodically (depending on lake level) into the Rio Desaguadero, which discharges into large, shallow, saline Lago Poopo, and the presently dry salars (salt flats) of Coipasa and Uyuni. The Rios Ilave, Ramis, and Huancane are among the five major tributaries to Lake Titicaca (in order of decreasing discharge these tributaries are the Ramis, Ilave, Coata, Huancane, and Suchez). Modern instrumental records illustrate the rapid response of fluvial discharge in the Titicaca basin to the summer precipitation peak, and the rapid response of lake level (base level) to summer discharge peaks (Fig. 2). Changes in lake level are clearly related to seasonal as well as interannual precipitation variability.

The northern Altiplano has a cold, semi-arid climate. Average annual precipitation in the Lake Titicaca watershed is about 800 mm. Precipitation is strongly seasonal with approximately ¾ of the annual precipitation falling in a four-month period from December through March. The annual cycle of precipitation on the Altiplano is highly correlated with the annual cycle of deep convection that develops over most of tropical South America during the austral summer (Aceituno and Montecinos 1993; Aceituno 1996). The Pacific coastal

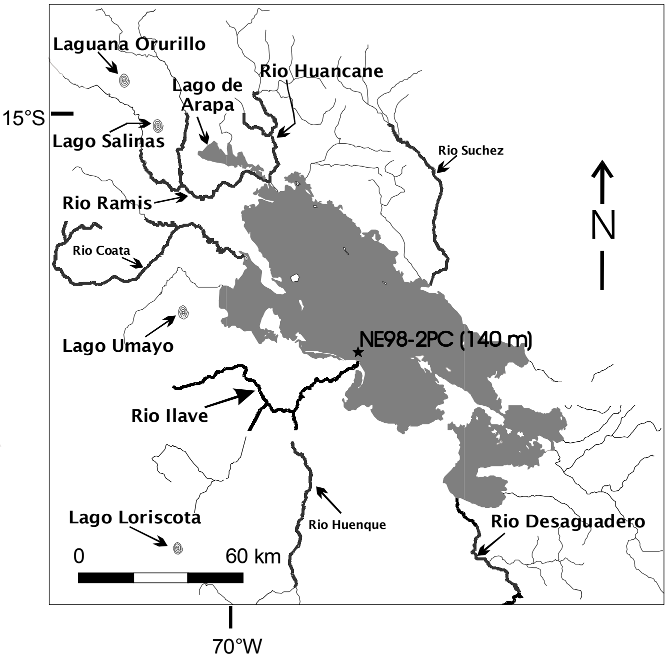

Figure 1. Map of the Lake Titicaca watershed showing the major drainages and proposed study sites.

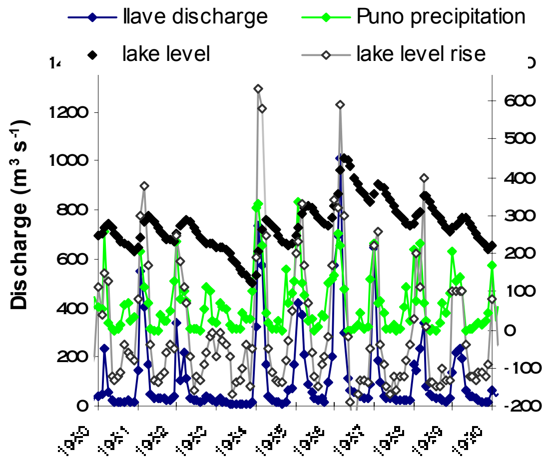

Figure 2. The level of Lake Titicaca has been recorded at Puno, Peru, since 1914. The highly seasonal nature of the rainfall on the Altiplano causes increased input to the lake (as illustrated by the Ilave discharge) and a sharp lake level rise near the end of the wet season. The rise is followed by a slower fall of lake level spread over the remainder of the year due to evaporation and, at high lake stages, discharge via the Rio Desaguadero. As discussed in the text, larger interannual variations of lake level occur as a result of dry or wet years (or multi-year periods). The most recent and largest amplitude event of this century occurred in 1986 when lake level rose more than 4 m above the long-term average, bringing about extensive flooding of lake-shore cities and agricultural fields, and resulting in extensive economic loss (Sztorch *et al.* 1990). This rise was caused by abnormally high rainfalls between 1984 and 1986, coincident with the well-developed La Nina event that occurred in the Pacific Ocean region during this period. The almost total lack of precipitation during the El Nino of 1982-83 led to desiccation of the Rio Ilave; great loss of crops and livestock and abandonment entire villages in the western Lake Titicaca watersheds.

temperature inversion, aided by the relatively steep lapse rate and the Andean orographic barrier, precludes significant moisture fluxes from this source (Garreaud 1999).

Intraseasonal to interannual precipitation variability is attributable to a number of different atmospheric circulation patterns (Lenters and Cook 1997, 1999). Because the position and intensity of the Bolivian high control flow throughout much of the height of the troposphere from the Andean crest upward (above about 600 hPa, Garreaud 1999), they also control the advection of moisture onto the Altiplano from the Amazon basin. Aceituno and Montecitos (1993) and Garreaud *et al.* (2002) demonstrated that the Bolivian high is shifted southward, and easterly moisture flux is enhanced, during wet intraseasonal events on the Altiplano. The major factor identified by Lenters and Cook (1997) as effecting this southward displacement is the low level northwesterly flux of warm moist air along the eastern flank of the Central Andes, the so-called low-level jet. Precipitation on the Altiplano, and elsewhere in central and southern South America, is also strongly regulated by the position and intensity of the transient South Atlantic Convergence Zone (SACZ) (Lenters and Cook 1997, 1999). When the SACZ is located farther to the west, the Bolivian high elongates towards the southeast, upper-level easterly flow is increased, and high precipitation results from the Central Andes south through Argentina. When the SACZ is positioned farther to the east, the Bolivian high shifts northward, and cool and dry conditions prevail in the Central Andes.

Paleoclimatology

As summarized in Melice and Roucou (1998), $\delta^{18}O_{ice}$ from the Quelccaya ice cap (Thompson *et al.* 1986) is inversely correlative with annual lake-level rise in Lake Titicaca, and the ice core isotopic composition can be used as a proxy for regional precipitation amount (Fig. 3). Recently, Vuille and others (2002a, 2002b) have beautifully demonstrated, in observational and modeling studies, the primacy of precipitation amount in control of $\delta^{18}O$ in the tropical South American ice cores. Hoffman and colleagues (2002) have also made this point. In short-duration instrumental records interannual (ENSO) and "quasi-decadal" (QDO) precipitation variabilities (Figs. 4 and 5) are evident, if not statistically significant in spectral analysis. In the longer duration Quelccaya record (Fig. 6) there is a statistically significant, large amplitude, persistent variance with a period of about 13 years (Melice and Roucou 1998). Modern statistical (Vuille *et al.* 2000) and synoptic (*e.g.* Lenters and Cook 1999, Garreaud and Aceituno 2001, Garreaud *et al.* 2002) climatological studies have repeatedly demonstrated the importance of ENSO-controlled precipitation variability in the central Andes and there is evidence that this variability influences modern agricultural yields on the Altiplano (Orlove *et al.* 2000). Surprisingly, however, modern climatological studies have not identified, or convincingly demonstrated the forcing mechanism for, the QDO variability that is so clear in the proxy-based record. We believe that the most likely external control of this large-amplitude atmospheric QDO variability on the northern Altiplano is through the QDO variability of North Atlantic SST (Fig. 7; see also Nobre and Shukla 1996, their Figure 14; Melice and Roucou 1998).

Millennial-scale precipitation variability on the Altiplano, perhaps overprinted by a lower amplitude multi-decadal oscillation, is documented (but, as yet, not totally convincingly so) throughout the Holocene by the Sajama ice core (Thompson *et al.* 1998; Fig. 8) and Lake Titicaca sediment cores (Baker *et al.* 2001b). Baker *et al.* (2001a)

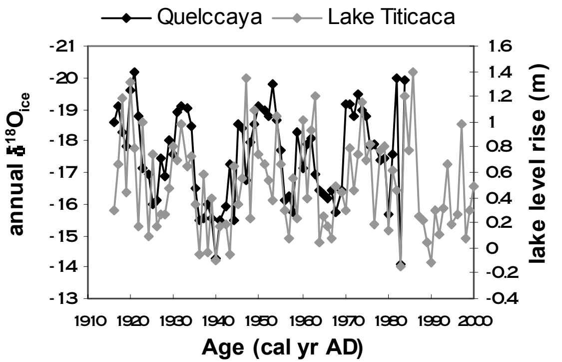

Figure 3. There is a significant correlation between the $\delta^{18}O_{ice}$ from Quelccaya and annual lake level rise ($r^2 = 0.2424$, n = 69, significant at the 99% confidence level), a less significant correlation between layer thickness at Quelccaya and lake level rise ($r^2 = 0.1558$, n = 69), and no significant correlation between $\delta^{18}O_{ice}$ and layer thickness for the period 1500-1984 ($r^2 = 0.0125$, n =485). Thus, $\delta^{18}O_{ice}$ is an excellent proxy for past precipitation amount; ice layer thickness is not.

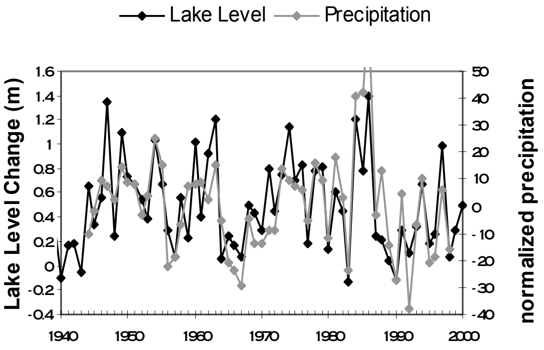

Figure 5. There is a significant correlation between the annual rise of lake level (October through April) and the instrumental record of annual precipitation within the northern Altiplano (normalized rainfall departures from 20 stations in the Lake Titicaca watershed): lake-level rise is a good measure of precipitation integrated throughout the basin. ENSO and quasi-decadal fluctuations of lake level are evident.

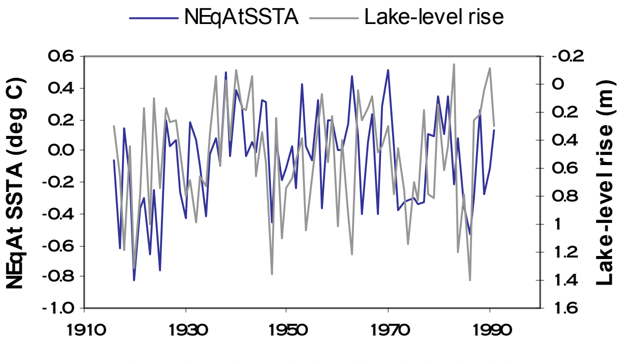

Figure 7. Time series of annual rise of level of Lake Titicaca compared with the time series of DJFM SST anomaly for the northern equatorial Atlantic (7.5º to 22.5ºN, 2.5ºE to 37.5ºW, SST anomaly data from Kaplan, 1997). Colder SST in the northern equatorial Atlantic may bring about wet conditions in much of Amazonia (Nobre and Shukla 1996) and in the northern Altiplano.

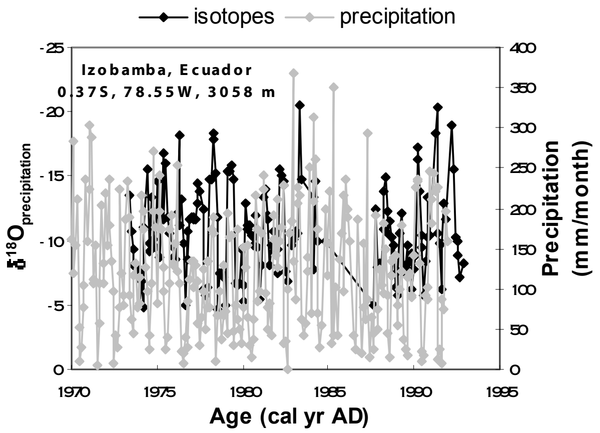

Figure 4. Modern precipitation data from Izobamba, Ecuador (0.37˚S, 78.55˚W, 3058 m, IAEA/WMO 1998). The precipitation undergoes a seasonal $\Delta\delta^{18}O$ of about 8‰, more negative values occur in the wet season. Similar variability exists in Altiplano precipitation, although there are no equally long time series.

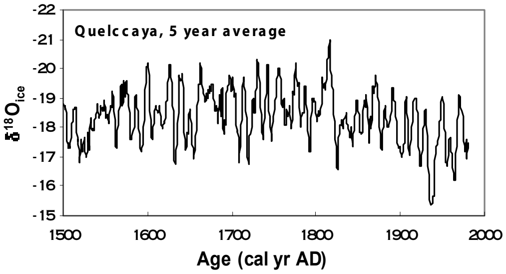

Figure 6. $\delta^{18}O_{ice}$ in Quelccaya ice cap (Thompson *et al*. 1986), 5-year moving average of annual data for the well dated portion of the record. Note the persistent quasi-decadal fluctuations of 2 to 3 ‰, representing significant wet-dry cycles. Melice and Roucou (1998) demonstrated this statistical significance throughout this record.

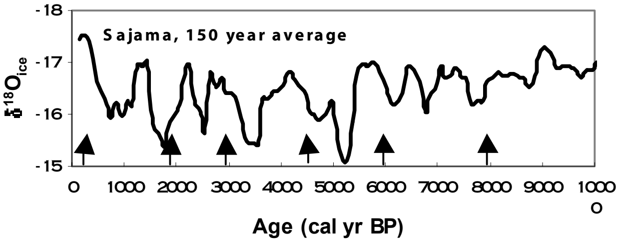

Figure 8. $\delta^{18}O_{ice}$ in the Sajama ice cap (Thompson *et al*. 1998), 3-point moving average of presumed 50 year intervals. Millennial events of 1 to 1.5 ‰ amplitude are persistent throughout the Holocene. Our arrows highlight the millennial cold SST events deduced from sediment cores offshore of West Africa (DeMenocal *et al*. 2000) and synchronous with the "Bond events" of the subpolar North Atlantic (Bond *et al*. 1997). Baker *et al*. (2001b) hypothesized that tropical Atlantic meridional SST gradients force millennial wet-dry cycles in the Lake Titicaca watershed. The Sajama record is not well dated, especially in the early Holocene

proposed that these millennial events are linked in time and, perhaps by forcing mechanism, to the "Bond events" of the North Atlantic (Bond *et al.* 1997, DeMenocal *et al*. 2000, Bond *et al.* 2001).

Insolation control by the precessional cycle has a major impact on the intensity of the South American Summer Monsoon (SASM; Zhou and Lau 1998) and on summertime precipitation amount on the Altiplano. The last two maxima of summertime insolation over tropical South America were at ~21,000 cal BP and at present (Berger and Loutre 1991). Response to this orbital variability is evident in sediments from Lake Titicaca and the Salar de Uyuni. Lake Titicaca was very fresh and overflowing at 21,000 cal BP and is fresh and (barely) overflowing today, but in the early and middle Holocene, the lake level fell to 85 m below its outlet (Seltzer *et al*. 1998). In the Salar de Uyuni insolation maxima are coincident with thick accumulations of lacustrine mud (Fig. 9), however, the presence of lakes during periods of low insolation (*e.g.* 30,000 cal BP), coincident with Heinrich events, suggests that the pattern of cold North Atlantic/wet Altiplano observed in the Holocene record also is found in earlier portions of the record.

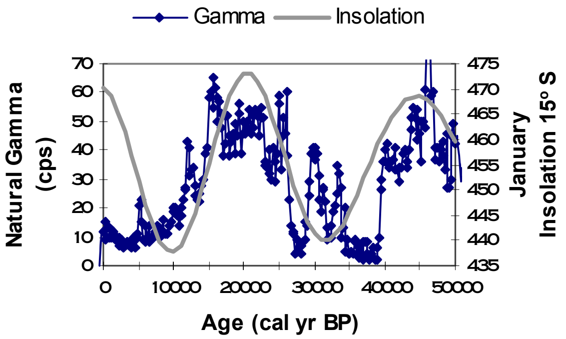

Figure 9. Measurements of natural gamma radiation in a borehole in the Salar de Uyuni (Baker *et al.* 2001a) distinguish between salt (low values of gamma) representing dry periods and lacustrine mud (high values of gamma) representing wet periods. Insolation changes on orbital timescales (from Berger and Loutre 1991) are believed to be responsible for variable intensity of the South American Summer Monsoon bringing about large changes in summertime precipitation. The unexpected presence of lakes during periods of low insolation (*e.g.* 30,000 cal BP), coincident with Heinrich events, suggests to us that a North Atlantic SST-Altiplano precipitation teleconnection persists throughout the record.

Tributaries to Lake Titicaca must respond to these quasi-decadal, multi-decadal, millennial, and orbital variations in precipitation recording their responses in the sediments of the terraced river valleys. Accurately reconstructing a well-dated and highly resolved Holocene precipitation history of the western Lake Titicaca basin will allow us to correlate changes in these fluvial landscapes with changes in Holocene climate.

Pilot Studies in the Rio Ilave Valley

Our pilot study of the fluvial sedimentology and human history of the Rio Ilave valley demonstrated that a more extensive analysis of the sedimentology and geomorphology of this and other Lake Titicaca tributaries, coupled with high-resolution climate data and new archaeological survey data, is justified and necessary.

<u>Fluvial/Climate Relationships</u>. By measuring river cross-sectional and longitudinal profiles and by analyzing depositional environments of terrace strata, we were able to document the existence of 5 terrace tracts in the Rio Ilave valley (T1 through T5; Fig. 10). These tracts occur as both paired and unpaired terrace sets and have average heights from 1.4 m to 24.3 m above the modern river valley. The highest terraces (T4 and 5) are present throughout most of the study area, but are absent in upstream reaches, where the river is marshy and has low relief. These high terraces are generally lens-shaped; they are lowest immediately downstream of bedrock constrictions, highest and broadest in riverine embayments. The lowest terraces (T1 and T2) are only present in the upstream and downstream reaches of the valley, adjacent to bedrock constrictions and in areas of relatively low relief. Sediments that comprise the terraces are fluvial silts, sands, and gravels that occur in two distinct facies associations: thick, gravelly, braided river strata that are present only in the upstream-most terraces and in terraces of a large, upstream tributary (the Rio Uncallane), and volcanogenic silty, sandy, and gravelly meandering river strata that are present throughout the study area. Sediments of terraces T3, 4, and 5 are very ash-rich; terrace T4 is locally capped by a thick soil horizon; and terraces T3 and T4 have thin gravel caps.

Sediments and terraces of the Rio Ilave valley document a history of aggradation and downcutting that we attribute to Holocene regional climate change (Rigsby *et al.,* 2002a). Contrary to comments by one previous reviewer and the panel, there is little evidence supporting the notion that human activities were responsible for either aggradation or downcutting of these massive deposits -- with the possible exception of T1 (we will keep an open mind.) Specifically, periods of aggradation appear to be correlative with periods of increased precipitation (and rapid rise of Lake Titicaca) and periods of downcutting appear to be correlative with periods of decreased precipitation (and falls or still-stands of Lake Titicaca). A first step toward understanding effects of these aggradational and downcutting phases on the human occupants of the river valley is to correlate the terrace history with the moderate-resolution records of climate and base level that are presently available (Baker *et al.* 2001b). Our correlation of the Ilave valley aggradational and degradational history with regional (and perhaps global) climatic events is illustrated in Figure 10. The majority of the fluvial sequence (aggradation of the compound T3-T5 terraces) corresponds to a

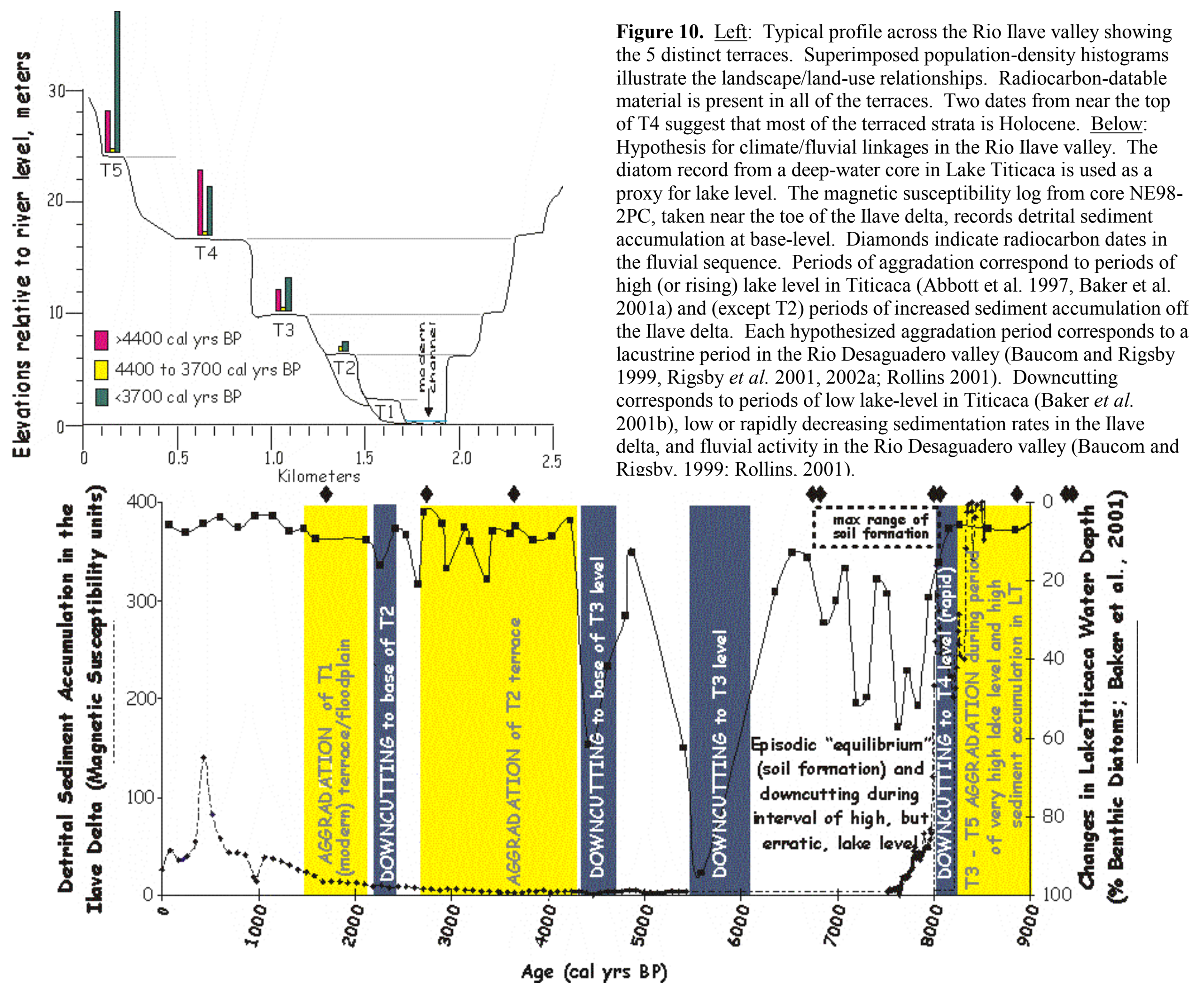

Figure 10. Left: Typical profile across the Rio Ilave valley showing the 5 distinct terraces. Superimposed population-density histograms illustrate the landscape/land-use relationships. Radiocarbon-datable material is present in all of the terraces. Two dates from near the top of T4 suggest that most of the terraced strata is Holocene. Below: Hypothesis for climate/fluvial linkages in the Rio Ilave valley. The diatom record from a deep-water core in Lake Titicaca is used as a proxy for lake level. The magnetic susceptibility log from core NE98-2PC, taken near the toe of the Ilave delta, records detrital sediment accumulation at base-level. Diamonds indicate radiocarbon dates in the fluvial sequence. Periods of aggradation correspond to periods of high (or rising) lake level in Titicaca (Abbott et al. 1997, Baker et al. 2001a) and (except T2) periods of increased sediment accumulation off the Ilave delta. Each hypothesized aggradation period corresponds to a lacustrine period in the Rio Desaguadero valley (Baucom and Rigsby 1999, Rigsby *et al.* 2001, 2002a; Rollins 2001). Downcutting corresponds to periods of low lake-level in Titicaca (Baker *et al.* 2001b), low or rapidly decreasing sedimentation rates in the Ilave delta, and fluvial activity in the Rio Desaguadero valley (Baucom and Rigsby, 1999; Rollins, 2001).

time of high precipitation on the Altiplano and high water level in Lake Titicaca. The maximum age of this aggradation episode is not known, but the oldest reliable dates suggest that it started during the LGM wet period, was ongoing through the Younger Dryas, and may have continued until ~8250 cal BP. Increased fluvioglacial runoff during this time resulted in increased sediment load and high sediment accumulation rates offshore from the Ilave delta (as recorded in sediments from core NE98-PC2; Figs. 1 and 10). With the input of large volumes of easily eroded volcanic-rich sediment from source areas in the Cordillera Occidental, contemporaneous with high base level (Lake Titicaca), sediment load was sufficient to fill the valley and choke the river system. In embayments behind bedrock constrictions, sediments were deposited to heights in excess of 25 meters above the valley floor (compound terraces T3-T5). This aggradation was followed by the downcutting of the T4 and T3 terrace tracts. As documented in other settings (Bull 1991), but not yet documented by detailed chronologies in these strata, the shift from aggradation to downcutting was likely very rapid.

The initial downcutting began immediately after a decrease in precipitation, runoff, and sediment load (as seen in the Ilave Delta sediment accumulation record; Fig. 10) and a drop in base level – probably just prior to ~8000 cal BP. Although the initial downcutting was likely very rapid, the strata document several periods of episodic equilibrium. The longest equilibrium phase was the prolonged period of T4 terrace erosion and soil formation (between ~8250 and 6780 cal BP). The T4 equilibrium phase was followed by the T3 downcutting episode. Downcutting to the base of T3 may have been episodic. It occurred between ~6000 and 4500 cal BP – the major downcutting episodes were likely coincident with a periods of rapidly decreasing levels of Lake Titicaca (Fig. 10) and decreased precipitation on the Altiplano. The thickness of the gravel caps on these terraces and the thick soil at the top of the T4 terrace, suggests that T4 had a longer equilibrium period than T3. Downcutting was followed by two periods of infilling that resulted in deposition of the T2 and T1 terraces sediments. The T2 and T1 aggradational events occurred, respectively, from ~4000 to 2500 cal BP and from ~2200 to 1600 cal BP – during millennial periods of rising water levels in Lake Titicaca, lacustrine sedimentation on the Altiplano (Baucom and Rigsby 1999, Baker *et al.* 2001b, Rigsby *et al.* 2002b), and increased sedimentation off the Ilave delta. They were separated by brief equilibrium stages and brief downcutting events.

Landscape/Land-use Relationships. Archaeological survey data argue strongly for a human presence in the basin by 10,000 cal BP. Small numbers of lower-elevation peoples from the western Andean valleys began to use the Titicaca basin during the Early Archaic (Aldenderfer and Klink 1996, Aldenderfer 1998a, Klink in press). During the earliest human occupation, Lake Titicaca was freshening and the lake was at a highstand from ~9,500 to 8500 cal BP (Baker *et al*. 2001b). Although *Poacea* (grasses) and *Polylepis* (queñua) were probably present around the lake margin (Paduano *et al.* 2002) – suggesting the establishment of habitat for camelids and taruca – data from the Ilave drainage and from the nearby Juli-Pomata region suggest that the near-lake-margin environments were not used extensively during this period (Stanish *et al.* 1997, Klink and Aldenderfer 1996, Aldenderfer and Klink 1996). Instead, the interior drainages were the centers of human activity. Residential bases were established in the mountain valleys along the Altiplano rim, while the main portions of the river valleys were likely explored and utilized only through day-use and longer-distance logistical forays.

Humans occupied the higher terraces of the Ilave (T3, T4, and T5; Fig.10) for at least 5000 years (prior to ~4400 BP). Excavations at Jiskairumoko (at the T5 level in the central Ilave valley) show that a sedentary settlement was in place at the site in the Terminal Archaic (by ~4200 cal BP). Populations in the Ilave drainage increased significantly from the Terminal Archaic (~ 4500-3500 cal BP) to the Early Formative (3500-3000 cal BP) and the lower Ilave terraces (T1 and T2) were not used extensively until after ~4400 to 3700 cal BP (Aldenderfer and Lopez 2000), a trend also seen in data from farther upstream in the Rio Huenque (Klink in press). This increase in population was coincident with a period of increased precipitation, high levels of Lake Titicaca, increased discharge, and the formation of low terrace (T2) in the Ilave valley.

The period 3500-2600 cal BP witnessed the expansion of small, apparently agropastoral, communities across much of the Titicaca basin (Aldenderfer 1998b, Stanish in press). The existing settlement record in the basin suggests that near-lake environments became more important through time. This development presumably took place contemporaneously with the intensified reliance upon agricultural production in the economy and possible freshening of the lake between 3500 and 3200 cal BP, a scenario described by Binford *et al.* (1997). However, according to the data from Lake Titicaca (Baker *et al.* 2001b), this expansion took place in three distinct paleoclimatic regimes. Interestingly, the broad shifts in climate during this time appear to parallel changes in both Ilave terrace morphology and agricultural technology in the southern basin. In the Ilave, Juli-Pomata, and Huenque survey areas, as well as in excavations at Camata (Steadman 1995), andesitic hoes (rare prior to 3200 cal BP) become increasingly common after 3200 cal BP. Households may have used hoe technology as they moved into new settlement niches where soils were harder to manipulate with previous (presumably wooden tool) techniques (Boserup 1965, Stanish in press). This implies a movement into pampas surrounding river terraces and the lake margin and may have been a response to drier conditions and to the downcutting of previously available T2 terrace expanses. The downcutting of the T2 terrace (Fig. 10) was apparently associated with a brief (post ~3000 cal BP) period of variable, but decreased, lake level. After ~2000 cal BP, precipitation increased, lake levels returned to, or slightly above (Abbott *et al.* 1997a, Baucom and Rigsby 1999), modern levels, and the T1 terrace was formed – once again providing fresh fluvial landscapes for agricultural use.

Humans are obviously capable of creatively adapting to even rapid changes in climate. Although climate does not unquestionably determine human life style, people living in already harsh environments (such as Andean valleys) must constantly change life strategies (foraging, agricultural, hunting, etc.) to adjust to changes in basic living conditions. In such environments, changes in precipitation (discharge) are the primary controls on fluvial processes and landscape evolution and, combined, changes in precipitation and landscape are the most important controls on the availability of land for settlement, agriculture, and other human uses. The unique coupling of detailed base level, paleoclimate (precipitation), fluvial sedimentology/geomorphology, and human occupation records that are available in the Lake Titicaca basin is unrivaled in many other settings. Detailed studies of Holocene climate and landscape change (similar to, but at higher resolutions than, our pilot study in the Ilave valley), when coupled with archaeological survey data detailing the history of land-use patterns, will allow us to gain a more complete understanding of the natural forces, as well as any anthropogenic modifications, that shaped landscape evolution. Only with such detailed data sets can we begin to evaluate arguments about causes of changes in land-use.

PROPOSED METHODS for DEDUCING HUMAN/CLIMATE/LANDSCAPE RELATIONSHIPS in the WESTERN LAKE TITICACA BASIN

Our analysis of Holocene-age fluvial and lacustrine sequences and our interpretations of the relationships between climatic change and human activities will be based on paleoclimatological and archaeological data sets and on detailed examination of the geomorphic and sedimentologic character of the river basins. Using the methodologies summarized below, we will (1) core and analyze the sediments of small lake basins in the western Lake Titicaca watershed to construct a paleoclimatic time series that encompasses the entire Holocene epoch and has a resolution of about 10 years, (2) analyze Holocene-age fluvial sedimentary and terrace sequences in three tributary basins (the Ilave, Ramis, and Huancane) to reconstruct the natural landscape evolution, and (3) conduct an archaeological survey of the Ramis drainage (to complement on-going survey work in the Huancane drainage and the completed survey studies in the Ilave drainage) to provide a chronology of human occupation in the three river valleys. All of these studies will be conducted within overlapping field areas.

The sedimentological studies will allow us to reconstruct in detail the depositional environments of the fluvial strata, as well as the geomorphic history of the tributaries, and to use those reconstructions to make interpretations about the impact of Holocene precipitation changes in study areas. The lacustrine studies will include the examination of cores from small lakes within the watersheds of the three tributary basins, as well as the examination of cores from Lake Titicaca. The small-lake studies will provide paleoclimate data that will be a major improvement over the coarse resolution data derived from Lake Titicaca sediments and from the poorly dated, and perhaps improperly interpreted, histories determined from the Sajama and Huascaran ice cores. Unlike lakes in the eastern Cordillera (*e.g.* Abbott *et al.* 1997b, 2001; Wolfe *et al.* 2001) the western basin lakes that we will study are not glaciated, are closed or nearly closed, moderately saline/alkaline, have variable water levels, are sensitive to climate fluctuations, and preserve carbonate in their sediments. The archaeological work will combine new survey data from the Ramis drainage with analysis of excavation and survey data from the Rio Ilave and Huenque drainages (Aldenderfer and Klink 1996; Klink and Aldenderfer 1996; Aldenderfer and de la Vega 1997; Klink in press), and from the Huancane drainage (C. Stanish, UCLA). The analysis will take into account the already understood geographical limits of human occupation during the time period of interest and will provide a compilation of previous and recently acquired data on human occupation of this region. In its entirety, the archaeological data set that we will employ for this project will allow interpretations about human land use throughout the full reach of studied drainages.

With all three data sets in hand, we will put the environmental variability recorded by the lake and river strata into a human context by correlating changes in the fluvial landscape with changes in human occupation/land-use patterns as recorded in archaeological data. This process will allow us to rigorously test hypotheses concerning the influence of climate on the evolution of riparian landscapes and on the history of human occupation and enterprise in the basin. The utility of this approach was demonstrated (albeit at coarse resolution) by our pilot work in the Rio Ilave valley. We expect that the higher resolution data we will gather during this project will allow us to make detailed interpretations concerning human land-use and environmental change in the entire northern and western Lake Titicaca basin.

Lacustrine (paleoclimate) studies – P. A. Baker

The paleoclimatic portion of this project will be done using lacustrine sediments. We plan to collect cores in at least four different lakes in the western portion of the Lake Titicaca basin (Figure 1): Lago Loriscota (elev. ~4600+m), a closed-basin saline lake located in the Cordillera Occidental southwest of the Ilave drainage; Lago Umayo (elev. ~3830 m), a deep, freshwater lake located northwest of Puno at the archaeological site of Sillustani; Lago de Arapa (elev. ~3810 m), a large lake that throughout the Holocene was alternatively flooded and desiccated depending on the level of Lake Titicaca; and Lago Salinas or Laguna Orurillo (elev. ~3840 and ~3880 m, respectively), small lakes in the upper reaches of the Rio Ramis watershed. Contrary to the comments of a previous reviewer, none of these lakes were subjected to glaciation during the Holocene or even during the last glacial maximum. We took 1.0 m-long pilot cores from Lagos Loriscota and Umayo during the summer of 2000. These lakes contain rich records with abundant carbonate shell material, abundant organic matter, and well preserved diatoms. Accumulation rates in similar lakes on the Altiplano average about 1 mm yr^{-1}, thus sampling at 1 cm intervals should provide decadal resolution; bioturbation depths in these lakes is usually less than 1 cm. Because of the large number of samples required for decadal resolution (1000), we will only do the highest resolution work on our best cores (determined by carbonate and diatom preservation and preliminary radiocarbon dating). We also installed a data logger to continuously record air and water temperature in Lago Loriscota and we sampled ground-, river- and lake waters from several sites to help in our eventual construction of chemical and isotopic budgets of the lakes.

One of our doctoral candidates (Ms. Jennifer Garland, Duke University) is analyzing a piston core that we recovered in 1998 from Lake Titicaca near the Ilave delta (core NE-98-2PC, 140 m water depth). That core has a moderate-resolution Holocene section (about 0.5 mm yr^{-1}) that we have sampled continuously at 2 cm intervals. Smear slides have been made from each sample for counts of the percentage of benthic diatoms (the counts will be done by S. Fritz and P. Tapia, University of Nebraska). These counts are the best proxy for reconstruction of lake level and (via its first derivative) precipitation (as in Baker *et al.* 2001b, but at considerably higher resolution). The diatom counts will be supplemented by measurements of carbonate and organic carbon content and stable isotopic determinations on both fractions. The Lake Titicaca core provides the unique opportunity to determine simultaneously paleoclimatic history and, as previously discussed, the base-level history that is critical for constraining the history of fluvial sedimentation. The small lakes have the advantage of greater sensitivity in response to shorter timescale (decadal to centennial) variability of precipitation and temperature.

Our methods will involve duplicate coring with a Russian peat corer or Livingston corer, core description, continuous core logging (magnetic susceptibility), geochemical analysis (stable isotopic and minor element analyses of carbonate shell material and organic matter), and diatom paleoenvironmental analysis. Age dating will utilize AMS ^{14}C analysis of terrestrial organic matter, lacustrine shells, and bulk organic carbon (the most reliable fraction in Lake Titicaca sediments). Reservoir corrections will be made using terrestrial carbon that should be relatively abundant in the lower elevation lakes (dating may be problematic in the more-saline Lago Loriscota (*e.g.* Geyh *et al.* 1999) in which case we will substitute a fresher lake). In addition, we will utilize ^{210}Pb analysis to date the surface sediments of each lake. Paleoclimatic reconstruction will depend mostly on diatom studies and stable oxygen isotopic modeling (as detailed in Cross *et al.* 2001 and Arnold 2002). Isotopic budgets of lakes depend on the balance of inputs (via rivers, groundwater, and direct precipitation) and outputs (via outflow and evaporation) and their respective isotopic compositions. A critical piece of information, almost always missing in isotopic reconstructions, is the isotopic composition of source precipitation. Because of the ice cores from Quelccaya and Sajama (Thompson *et al.* 1986, 1998), we know the isotopic composition of the source precipitation and, very generally, how it has varied through time (the isotopic composition of the modern snow at Quelccaya and Sajama is nearly identical to that of modern precipitation falling on the Lake Titicaca watershed). Our goal in analyzing lacustrine carbonates is to similarly reconstruct the (climatically controlled) isotopic variation of the source precipitation. Our product should resemble Figure 8. The critical difference is that we will have a much more secure chronology than the ice cores, especially in the early and middle Holocene. A similar kind of reconstruction was done recently by Arnold (2002) in her M.S. research on the Late Pleistocene lakes of the Bolivian Altiplano. An important and powerful conclusion is that the oxygen isotope composition of lacustrine carbonates varies mostly due to isotopic variability of source precipitation which, in turn, is a function of precipitation amount (a fairly general rule in the tropics). This point allows us to rather precisely reconstruct precipitation amount, as well as lake levels, evaporation (dictated by hypsometry), and runoff. Temperature variability has a less important impact on the isotopic composition of lacustrine carbonates through its impact on oxygen isotope fractionation (water/carbon) and on evaporation: the independent reconstruction of lake level using planktonic/benthic diatoms will allow us to independently calculate paleotemperatures. In general, we aim to achieve a new level of sophistication in calculation of precipitation and temperature – the most important elements of climate – from lacustrine sediments. These high-resolution, well-dated climatic records are essential to enable us to objectively evaluate both global-scale climatic teleconnections and forcings (for example correlation with SST reconstructions) and local-scale influences on fluvial landscapes and human cultural history.

Sedimentology – C. A. Rigsby

An important goal of our proposed research is to understand the basinwide history of Holocene fluvial development (sediment deposition, terrace formation, and downcutting) and how this landscape evolution articulates with the histories of climatic forcing and human cultural adaptation. Records of millennial-scale precipitation variability should be preserved and readable in the terraces and modern cutbanks of the Rio Ramis and Rio Huancance, as they appear to be in the Rio Ilave valley. The sedimentary and geomorphic records will likely document a history of aggradation and downcutting linked to Holocene climate change on the Altiplano. We will test the hypothesis that periods of aggradation are correlated with periods of increased rainfall and that periods of downcutting are correlated with periods of decreased or flashy rainfall. And, we will investigative the relationship between periods of downcutting and aggradation and changes in human land-use.

Our first mission is to complete our pilot study of the fluvial sediments of the Ilave valley by collecting additional dateable materials from our measured sections to secure the timing of terrace development and erosion. We will then undertake detailed studies in the Ramis and Huancane drainages to determine if our hypothesized history can be generalized basinwide (and perhaps much farther afield, *e.g.* the Amazon headwaters in the Cordillera

Oriental). Our expectation is that local differences (especially in stream gradient and composition of source sediment) will influence river development, but that – as seen in our pilot study of the Rio Ilave valley – climatic variability will dominate the development of the Ramis and Huancane valleys,. Local differences may have resulted in different terrace morphologies that could have influenced patterns of human settlement and utilization of the landscape. Also, differences in density of human occupation and land-use patterns could have altered sedimentation and erosion rates, hence subtly altered the timing of climatically controlled landscape changes.

Terrace and modern cutbank exposures (including the entire archaeological study area described below) will be mapped and measured using standard techniques for sedimentological facies analysis (such as those outlined by Miall 1996 and Reading 1996). Emphasis will be placed on identification and description of lateral and vertical facies changes (facies architecture) utilizing variations in grain size, sedimentary structures, bed morphology and contacts, and the presence of interbedded lacustrine sediments. Sediments comprising the terraces will be described in detail, key elevations and longitudinal profiles will be surveyed, terrace profiles will be constructed (with the aid of total station and differential GPS measurements), and organic material will be sampled for dating by ^{14}C using AMS methods. Based on our experience in the Ilave and Rio Desaguadero valleys, we expect to find scattered, but well-preserved, charcoal and fossil roots in the fluvial strata. The requested seventy ^{14}C dates should be sufficient (more dates would be better but, of course, more expensive) to allow a reasonably high-resolution reconstruction of fluvial processes, as well as correlation among the fluvial terraces and with the paleoclimatic and archaeological records. Absolute dating will be supplemented with sediment accumulation rate models derived from physical properties measurements (grain size and porosity), geochemical analyses (organic and inorganic carbon), and sedimentological data. In addition, we will undertake petrographic analyses, using smear slides and thin sections, and X-ray diffraction analyses to better evaluate the sediment sources and depositional environments. Based on our experience with terrace outcrops and cores in the Rio Desaguadero valley (Baucom and Rigsby 1999; Rigsby *et al.* 2002b) and on our pilot study of strata within the Rio Ilave valley, we expect to be able to differentiate between major depositional environments (braided, meandering, lacustrine), to identify smaller-scale environments (such as channel, point bar, crevasse splay, shallow vs. deep lake, wetland, and floodplain), and to be able to correlate changes in depositional environments, as well as terrace type and age, to changes in climate and to periods of human occupation. All of the sedimentological data (landforms, profiles, sample locations, etc.) will be recorded digitally in the field so that they can be incorporated into the regional GIS database (described below).

Archaeological studies – M. S. Aldenderfer

The archaeological studies for this project will be conducted in three phases: (1) regional survey and site/landscape definition; (2) detailed site mapping, definition, and systematic collection; and (3) compilation of data collected in phases 1 and 2 with data from previous studies in the Ilave and Huenque drainages (Aldenderfer and Klink 1996; Klink and Aldenderfer 1996; Aldenderfer and de la Vega 1997; Klink in press) and from on-going studies in the Huancane valley (C. Stanish, UCLA). Our primary field and analytical approach will use settlement pattern analysis and data derived from that analysis. There are areas on a landscape that have relatively discrete boundaries as defined by artifact scatters and human constructions (sites). There are also larger-scale human modifications of the terrain (raised fields, qochas, canals, and other constructions) that are best conceived of as landscape features (Erickson 2000). As such, we will utilize both a site-focused and a landscape philosophy in our analysis. Also, to carefully distinguish between natural/fluvial (river channels, terraces, etc.) and human (canals, raised fields, etc.) modifications of the landscape, the archaeological work will be done in close concert with the fluvial studies. Given our previous experience in the Ilave survey and subsequent excavations, we believe that settlement pattern studies, within a robust and sophisticated GIS context, will permit us to achieve a balance between site-focused and landscape perspectives.

The new field research for this project will be conducted within the Rio Ramis drainage in the Department of Puno, Peru. The survey zone, defined as a corridor surrounding the Rios Ramis and Pucara, is estimated to be ~360 km^2. It begins at the modern lake margins, continues north within the Rio Ramis and Rio Pucara valleys for ~50 km, and terminates ~10 km south of the major site of Pucara. The zone ranges in elevation along the valley floor from ~3815 m in the south to ~3950 m in the north and includes the following natural landforms: lake margin and associated small hills, river channel and associated terraces; meandering floodplain of the Rio Ramis; wide, relatively flat pampas along the east and west sides of the river above the channel, especially along the Rio Pukara; and a series of low hills and mountains to the west, which reach elevations of ~4300 m. This area contains near-lake margin environments likely to have been open and available in the period 10,000-3500 cal BP (pampas and high ground near the modern town of Caminaca and closer to the lake itself); river terraces that figure as settlement loci for every time period, but which may have been used differentially; pampas that may have been the scene of agricultural expansion during the Formative Period (3500-2500 cal BP) and loci of settlement during the Middle Horizon (*ca.* AD 400-

1100) and Altiplano (*ca.* AD 1100-1450) periods; and high ground on the west side of river valleys that may have figured prominently in the Archaic Period (10,000-3500 cal BP), Middle Horizon, and Altiplano period use of the landscape. Also, the south end of the survey zone has been postulated by Erickson (2000) and others as a potential zone of early raised field agriculture. The total area to be surveyed is comparable to most recent survey projects in the region (360 km^2 in the Juli-Pomata region, *ca*. 400 km^2 in the Tiwanaku valley, *ca*. 100-200 km^2 in the Pampa Koani, *ca.* 50 km^2 in the Ilave, and *ca*. 33 km^2 in the Huenque). A map of the survey zone is available at http://titicaca.ucsb.edu/chamak_pacha/docs/nsf_proposal_2002/.

During the first phase of this work, we will conduct a 100% pedestrian, full coverage survey of the entire zone. Survey teams will systematically walk transects across the survey blocks at intervals ranging from 10-15 m and no greater than 50 m intervals. Low topographic features not visible on the 1:100,000 scale maps will be specifically targeted because low relief mounds of this type are known from previous surveys to be foci of prehistoric habitation (Erickson 1988, 2000). We also expect to encounter larger-scale human landscape features such as raised field systems, terraces, canals, qochas, and other modifications. Our experience in the Ilave/Huenque region suggests that we will have no difficulty distinguishing between these human modifications and natural landforms.

During our field efforts we will use information technologies designed to record infield digital data that can be quickly entered into a regional-scale GIS. We will use satellite photos and digital copies of 1;100,000 and 1:50,000 scale maps as our infield orienting tools. These images will be housed on a set of Fujitsu pentop computers running ArcView 3.2 and will be georeferenced to each other. Each survey team will be able to record data digitally as encountered. We will locate ourselves on these maps with Trimble handheld GPS units. Once sites or landscape features are encountered, they will be evaluated, and boundaries estimated. Following this, they will be mapped using the GPS; these spatial data will be downloaded into the master GIS at the field base camp each evening. Crew chiefs will also fill out digital forms in the field; these will be backed up as well. Digital cameras will be used to record sites, landscape features, and other important aspects of the terrain. Collections will be made of diagnostic ceramics and lithics. Sufficiently large samples of lithic debris and non-diagnostic ceramics will be recovered to allow rough estimates of artifact densities.

During the second phase of our field effort, we will systematically collect samples of sites deemed relevant (by the phase 1 surveys) to the resolution of the research problems outlined in this proposal. Depending on the topographic complexity and the density of artifact scatters on the sites, we will employ a blend of data recovery strategies including point mapping of artifacts using total stations that will be integrated into the master GIS at an intrasite scale (similar to our Jiskairumoko collections), transects, and dog leashes. The goal of this collection will be to develop data sufficient to allow us to distinguish (within the limits of surface data) relevant aspects of site structure (see Aldenderfer 1989: 140-155; Aldenderfer 1998a for details). We will also map important landscape features using total stations and GPS units. Phase 3 is the laboratory and interpretive phase of our work. During this phase we will complete the master GIS, integrate the geomorphology and archaeological survey data from the Ramis, and compare these with data from the Huancane drainage and from our own previous survey work in the Ilave drainage.

The success of this project depends upon dating the surveyed sites at a sufficiently fine resolution. For the ceramic period, we are fortunate that the northern basin has been the focus of extensive and excellent ceramic analyses including those by Steadman (1995), Franquemont (1986), Mohr Chavez (1977), Mujica (1987), and Chavez (1992) for earlier periods, Carlevato (1988), Rowe and Brandel (1971), and Julien (1983) for later time periods. The ceramics recovered by the project will be examined by Cecelia Chavez, who has long experience with materials from this region. For the lithics, we now have a highly detailed and stratigraphically verified projectile point chronology for the south-central Andean highlands (Klink and Aldenderfer in press). This includes four types securely dated to 10,600-8800 cal BP, transitional types covering the period 9600-7800 cal BP, five types that date from 6800-4900 cal BP, two types that date from 4200-3800 cal BP, and ten other types that can be used for other Archaic periods. We have also made progress in dating the ubiquitous small triangular notched base points and can assign most of them to the Early and Middle Formative periods. In sum, these data types should allow us to date sites and their components with sufficient resolution to reconstruct the history of human occupation and land-use in this region.

Relationships with Peru

All three collaborators have extensive experience working in the Altiplano in general and in the Lake Titicaca Basin, in particular. Rigsby and Baker have worked in the region for seven years – under conveñios with ALT (the bi-national, Bolivian and Peruvian, Authoridad de Lago Titcaca) that were recently renewed and amended to include the entire Peruvian watershed of the lake. Aldenderfer has been working in Peru for 19 years. His work is sponsored by the Peruvian INC through the normal permitting process. Our combined experiences in the region make us familiar with the logistical and political considerations necessary for the success of a project of this scale. Our work will be done in collaboration with scientists from Universirad National del Altiplano in Puno, Peru (Edmundo Moreno T. and Edmundo de la Vega) and INC (Rolando Paredes).

SIGNIFICANCE of this RESEARCH

This research will provide new empirical data of three distinct, but closely related, types. (1) We will generate a high-resolution, well-dated, and properly interpreted paleoclimatic time series of the western Lake Titicaca basin for the entire Holocene epoch. These data will allow us to securely understand the nature of precipitation (and possibly temperature) variability on the Altiplano and to relate this variability to potential forcing mechanisms (including Holocene SST patterns, insolation changes, and Atlantic thermohaline circulation changes). They will also provide a background for understanding the Holocene fluvial evolution of the basin and allow us to develop and test more complete contextualized models of past human behavior. (2) We will generate new sedimentologic and geomorphic data that can be used to create a basinwide model of fluvial evolution in the context of regional climate change. This model will be valuable as a case study of landscape evolution in a complex high elevation environment (that may be extended to similar environments in other regions of the world) and will provide archaeologists with a fuller understanding of the natural forces that shaped landscape evolution. (3) We will generate new archaeological data that will begin to fill the very serious gaps in our knowledge of the early prehistory of the western Lake Titicaca basin – knowledge that, until recently, has been almost exclusively based upon excavations at large, late sites. These new data will allow us to test important problems in basin prehistory – such as the character of initial occupation of the region, the dynamics of the sedentarization process, and the expansion of agropastoral settlements following sedentarization – and will provide a record of human activity in river valleys during the periods of climatic change recorded in the fluvial and lacustrine data sets. We will accomplish all of these studies within a highly resolved paleoclimatic context accompanied by a secure reconstruction of landscape evolution, unrivaled in many other research settings.

Integration of Research and Education, Improving Infrastructure for Research

This project will improve U.S. research infrastructure by building new partnerships among universities and disciplines. It will promote the integration of research and education by involving both undergraduate and graduate students in research. Each PI will encourage participating students to work directly with every aspect of the project, enabling them to obtain a richer experience than would be possible by working only within a single discipline. We believe that students who participate in the project will have distinct advantages because of this multidisciplinary focus. Also, we will contribute to technical innovations by working within a GIS framework that will incorporate archaeological, geological, and paleoclimatological data into one regional database.

Integrating Diversity into NSF Activities

We promote diversity directly by being a diverse team (one woman, two men) and through our individual efforts to include and mentor students in our respective universities. All three PIs have excellent records of involving females and undergraduates in both field and laboratory research. We will also continue to work with international collaborators in Peru and Bolivia.

Producing and Archiving Data Relevant to Specific Research Initiatives

The problems we address and the data we produce are directly relevant to research initiatives that aim to understand both natural climate variability and the human impact of global change using the paleo record – goals with direct societal relevance. As is recognized in several white papers to the Geology and Paleontology Division of EAR, the study of the history of Earth's landscapes and the climate to which those landscapes have been subjected provides the context for human existence. Hence, understanding the impact of global change on landscapes is critical to our understanding of human occupation (and modification) of those surfaces. In addition, the U.S. Earth Systems History Program, the NOAA Climate and Global Change Program, and the international Past Global Changes (PAGES), and Climate Variability (CLIVAR) programs all have the study of non-linear changes observed in the paleo record as one of their foci. Records from small lakes and fluvial sediments in the Titicaca basin are a key step to understanding those changes, and records of human occupation/land-use are key to understanding the relationship between human activities and natural climate variability. All data will be archived at the World Data Center for Paleoclimatology, following established protocols, and made available via the Internet.

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