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Fluvial history of the Rio Ilave valley, Peru, and its relationship to climate and human history

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Abstract

Fluvial strata and landforms in the Rio Ilave valley (Peru) document a history of Holocene aggradation and downcutting that is correlative with regional climatic events and provides an environmental context for human occupation of the river valley. Periods of aggradation correspond to periods of high (or rising) level in Lake Titicaca and elsewhere on the Altiplano, and increased sediment accumulation in the Rio Ilave valley. Downcutting episodes correspond to periods of low level in Lake Titicaca and low or rapidly decreasing sedimentation rates in the Ilave delta. There are five terrace tracts (T1 through T5) present in this southwestern Lake Titicaca tributary. These tracts occur as both paired and unpaired terraces and have average heights from 1.4 to 24.3 m above the valley floor. The major part of the fluvial sequence was deposited during the time period from prior to the Last Glacial Maximum until about 8300 calendar years Before Present (cal BP) – a period of generally high (but variable) precipitation on the Altiplano and high water level in Lake Titicaca. Initial deposition (aggradation) was followed by successive downcutting to the T4 and T3 terrace surfaces. Initial downcutting began immediately after precipitation, runoff, and sediment load decreased while base level dropped. It was followed by a period of episodic equilibrium and minor downcutting that included a prolonged period of soil formation between ∼8350 and 6780 cal BP. The major pulses of downcutting likely occurred between ∼6000 and 4500 cal BP and were coincident with periods of decreased precipitation on the Altiplano and decreasing levels of Lake Titicaca. Two final periods of infilling, resulting in deposition of the T2 and T1 terrace sediments ∼4000 to 2500 cal BP and ∼2000 to 1600 cal BP (during periods of rising water level in Lake Titicaca, lacustrine sedimentation in the Rio Desaguadero valley, and increased sedimentation offshore the Ilave delta), were separated by brief equilibrium stages and a brief downcutting event. This fluvial history, when coupled with regional paleoclimatic data, relates to the region's preceramic through Tiwanaku-period archeological records. Archeological evidence indicates that humans occupied the Ilave valley as early as 10 000 cal BP. The higher terraces (T3, T4 and T5) were occupied for at least 5000 years, but humans did not utilize the lower terraces (T1 and T2) until after ∼4400–3700 cal BP. Our results confirm that these lower terraces would not have been available for either occupation or agriculture until after ∼4000 cal BP.

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1. Introduction

Humans entered the Titicaca basin by 10 000 cal BP (Aldenderfer and Klink, 1996; Aldenderfer, 1998a; Klink, in press) and by the eve of the Spanish conquest, the basin was the scene of one of the densest populations in the Andean world. Even though the close dependence of agropastoral return on the state of climate and the natural environment is a constant reality of the human occupation of the Altiplano, during the past and into the foreseeable future, the role of climatic variation in the cultural evolution 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 (Ortloff and Kolata, 1993; Binford et al., 1997), we know little about how climate affected certain 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 and how these changes may have affected the human occupants of the landscape are the major foci of this paper.

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. It has been claimed that humans are the major modifiers of the landscape in the Lake Titicaca basin (e.g. Erickson, 1999, 2000), but in the Rio Ilave valley 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 (Fig. 1), landscape evolution is primarily controlled by fluvial processes. The fluvial data presented here allow us to begin to examine systematically the question of how Holocene climate variability affects the landscape and how landscape variability affects human activities. We are at an advantage in this region, relative to many traditional fluvial geomorphic studies, because we know the history of both climate and base level (the level of Lake Titicaca).

Middle Holocene precipitation on the Altiplano was perhaps 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 (Seltzer et al., 1998; Cross et al., 2000). The aridity was enduring, but punctuated by millennially paced wetter periods (Baker et al., 2001b). As summertime insolation increased throughout the southern tropics, Early Holocene aridity gave way to generally wetter conditions starting after 5000 cal BP. The Late Holocene, wet 'climatic optimum' of the Altiplano was also marked by millennially paced wetter periods (Rigsby et al., 2000; Baker et al., 2001b; Rigsby et al., 2001), the most recent of which coincided with the Little Ice Age of the northern high latitudes (Thompson et al., 1986).

Although it is generally agreed that climate is important in the evolution of fluvial systems (Porter et al., 1992; Brigdland, 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 Erskin 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; Brigdland, 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 Ilave, 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 Rio Ilave drains 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., 2001b; Seltzer et al., 2002), active volcanism has played no other discernible role in Holocene fluvial evolution of the basin. The youngest macroscopic ash found in Lake Titicaca cores dates at 27 000 cal yr BP (Baker et al., 2001b). Also, there was apparently no time in the Holocene when the vegetative cover in the basin was so great that sediment cohesion would have been dramatically altered (Paduano et al., 2002). The relative unimportance 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 vs. incision in the Ilave valley.

2. Geomorphic and climatic setting

Lake Titicaca (Fig. 1), at an elevation of 3810 m, is the highest large lake in the world and the largest lake of 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 Cordillera Occidental to the west, the Cordillera Oriental to the east, and the Cordillera Vilcanota to the north. The southern limit of the basin is lower, and the lake overflows periodically (depending on lake level) into the Rio Desaguadero that discharges into the large, shallow, saline Lago Poopo, and the presently dry salars (salt flats) of Coipasa and Uyuni. The Rio Ilave is one of the five major tributaries to Lake Titicaca; in order of decreasing discharge these tributaries are the Ramis, Ilave, Coata, Huancane, and Suchez.

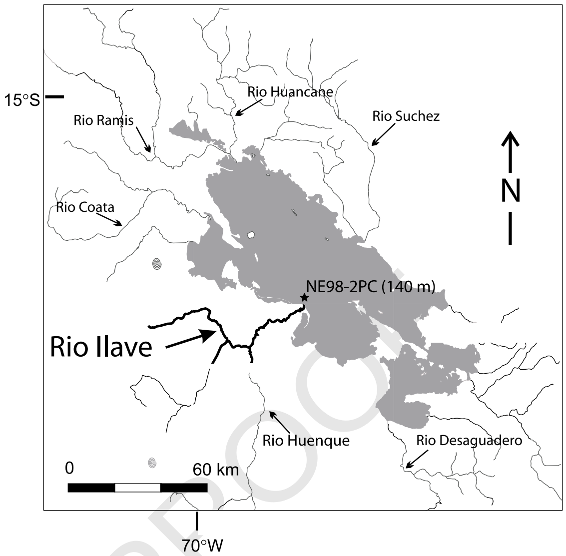


Fig. 1. Map of the Lake Titicaca basin showing the Rio Ilave and other major drainages.

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 3/4 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 temperature inversion, aided by the relatively steep lapse rate and the Andean orographic barrier, precludes significant moisture flux from this source (Garreaud, 1999). Modern instrumental records illustrate the rapid response of fluvial discharge in the Titicaca basin to the summer season 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.

Intraseasonal to interannual precipitation variability on the Altiplano 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, they also

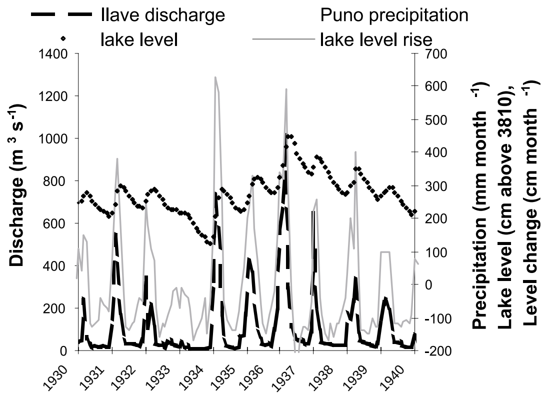


Fig. 2. The level of Lake Titicaca has been recorded at Puno, Peru, since 1914. The highly seasonal nature of the rainfall on the Altiplano causes increased input to the lake (as illustrated by the Ilave discharge) and a sharp lake level rise near the end of the wet season. This rise is followed by a slower, evaporation-driven, fall of lake level spread over the remainder of the year and, at high lake stages, discharge via the Rio Desaguadero.

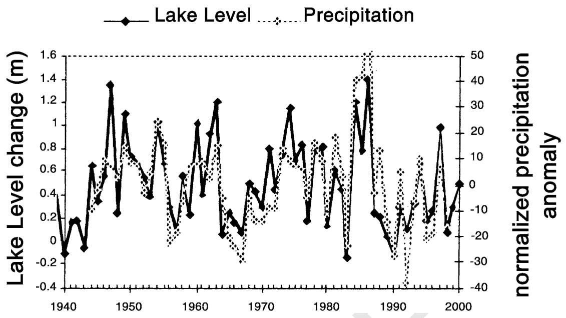


Fig. 3. Annual rise of lake level (October–April) is correlated with the instrumental record of annual precipitation within the northern Altiplano (normalized rainfall departures from 20 stations in the Lake Titicaca watershed): lake level rise is a good measure of precipitation integrated throughout the basin. ENSO and quasi-decadal fluctuations of lake level are evident.

control the advection of moisture onto the Altiplano from the Amazon basin. Aceituno and Montecitos (1993) demonstrated that the Bolivian high is shifted southward, and easterly moisture flux is enhanced, during wet intraseasonal events on the Altiplano. 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 similar controls on interannual precipitation variability in the central Andes that are well correlated with El Niño Southern Oscillation (ENSO) variability. This ENSO-related interannual precipitation variability clearly affects riverine discharge and lake level (Fig. 2); it also influences modern agricultural yields on the Altiplano (Orlove et al., 2000).

There has been little study of the nature and origin of precipitation variability on the Altiplano on decadal to millennial time-scales, yet such variability must play an important role in the fluvial and landscape processes. Two archives of climate information that are relevant to this issue are the Quelccaya ice core (Thompson et al., 1986) and the lake level history of Lake Titicaca, measured at Puno, Peru, since 1914 (Servicio Nacional de Meterologia y Hydrologia del Peru). The annual rise of water level in Lake Titicaca is well correlated with the wet season (and annual) precipitation amount on the northern Altiplano (Fig. 3). Moreover, Melice and Roucou (1998) showed that $\delta^{18}O_{ice}$ from the Quelccaya ice cap (Thompson et al., 1986) is inversely correlated with annual lake level rise in Lake Titicaca, hence the ice core isotopic composition can itself be used as a proxy for regional precipitation (Fig. 4). Melice and Roucou (1998) also demonstrated in the Quelccaya record that there is a statistically sig-

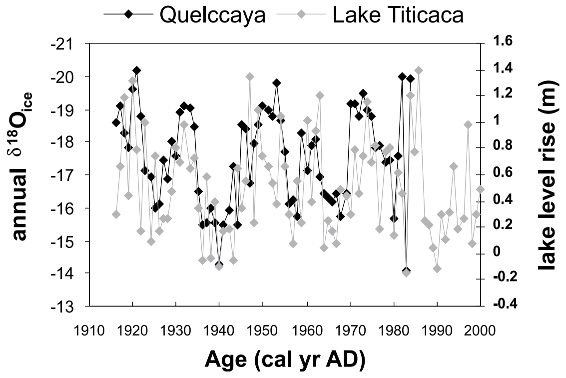


Fig. 4. There is a significant correlation between the $\delta^{18}O_{ice}$ from Quelccaya and annual lake level rise ($r^2 = 0.2424$, $n = 69$, significant at the 99% confidence level), a less significant correlation between layer thickness at Quelccaya and lake level rise ($r^2 = 0.1558$, $n = 69$), 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; ice layer thickness is not.

nificant, large amplitude, persistent variance with a period of about 13 years. We believe that this apparent quasi-decadal variability of precipitation on the northern Altiplano is related to the quasi-decadal variability of northern equatorial Atlantic sea surface temperature (Fig. 5; see also Nobre and Shukla, 1996, their fig. 14)

Millennial-scale precipitation variability on the Altiplano is documented throughout the Holocene by the Sajama ice core (Thompson et al., 1998; Fig. 6) and Lake Titicaca sediment cores (Baker et al., 2001b). Baker et al. (2001b) 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 the summertime precipitation amount on the Altiplano. The last two maxima of summertime insolation over tropical South America were at ∼21 000 cal yr 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 yr 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 the insolation maxima are coincident with thick accumulations of lacustrine muds. However, the presence of lakes during periods of low insolation (e.g. 30 000 yr BP; Baker et al., 2001a), coincident with Heinrich events and cold temperatures in the North Atlantic, suggests that the pattern of cold North Atlantic/wet Altiplano observed in the Holocene record also is found in earlier portions of the record.

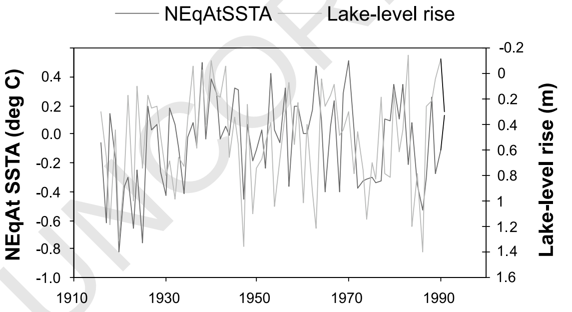


Fig. 5. Time series of annual rise of level of Lake Titicaca compared with the time series of DJFM Sea Surface Temperature (SST) anomaly for the northern equatorial Atlantic (7.5° to 22.5°N, 2.5°E to 37.5°W; SST anomaly data from Kaplan et al., 1997). Colder SSTs in the northern equatorial Atlantic correlate with wet conditions in much of Amazonia (Nobre and Shukla, 1996) and in the northern Altiplano.

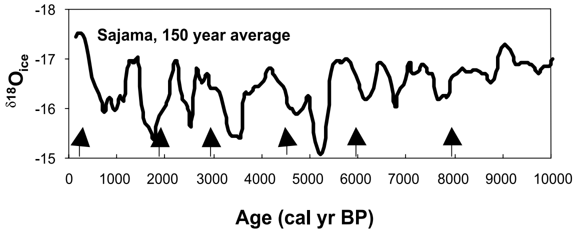


Fig. 6. $\delta^{18}O_{ice}$ in the Sajama ice cap (Thompson et al., 1998), three-point moving average of presumed 50-yr intervals. Millennial events of 1–1.5‰ amplitude are persistent throughout the Holocene. The arrows highlight the millennial cold SST events deduced from sediment cores offshore West Africa (DeMenocal et al., 2000) and synchronous with the 'Bond events' of the subpolar North Atlantic (Bond et al., 2001). Baker et al. (2001b) hypothesized that tropical Atlantic meridional SST gradients force millennial wet–dry cycles in the Lake Titicaca watershed.

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. In the Rio Ilave valley, sediments preserved in terraces and modern cutbanks document a history of aggradation and downcutting that we attribute to regional Holocene climate change. Specifically, as the data reported here show, periods of aggradation are correlative with periods of increased precipitation (and rapid rise of Lake Titicaca) and periods of downcutting are correlative with periods of decreased precipitation (and falls or standstills of Lake Titicaca).

3. Methods

Our analysis of terraced, Holocene-age fluvial sequences in the Rio Ilave valley and our interpretations of their climatic causes and possible human responses are based on archeological and climatological data sets and on detailed examination of the geomorphic and sedimentologic character of the river basin. Terrace and modern cutbank exposures were mapped and measured using standard techniques for sedimentological facies analysis (such as those outlined by Miall, 1996; Reading, 1996). Emphasis was placed on identification and description of lateral and vertical facies changes (facies architecture) utilizing variations in grain size, sedimentary structures, bed morphology, and contacts. Sediments comprising the terraces were described in detail, key elevations and a longitudinal profile surveyed, terraces profiles constructed (with the aid of a total station and Global Positioning System (GPS) equipment), and datable organic material sampled.

Well-preserved, datable organic material is scarce in these strata. Where present it consists of small amounts of disseminated organic detritus (woody material and charcoal) within the slightly sandy mud lithofacies. These samples were subjected to radiocarbon analysis at the National Ocean Sciences Accelerated Mass Spectrometer Facility, Woods Hole Oceanographic Institute. The CU-Boulder INSTAAR Laboratory for AMS Radiocarbon Preparation and Research performed all the preparations. CALIB 4.3 (Stuiver and Braziunas, 1993; Stuiver et al., 1998a,b) was used to convert the radiocarbon ages to calibrated years Before Present (cal BP). Discussion in the text focuses on the 2σ calibrated ages; both calibrated and uncalibrated ages for all samples used in this study are presented in Table 1.

These sedimentologic techniques allow us to differentiate among the major fluvial depositional environments preserved in the terrace sediments, to identify smaller-scale environments (such as channel, point bar, crevasse splay, wetland, and floodplain) in some locations, and to use these distinctions to make interpretations about the impact of Holocene precipitation variability on the fluvial processes in the Ilave valley. We broaden the context of these environmental changes by comparing the fluvial data with archeological data from survey and excavation projects in the Ilave and Huenque drainages (Aldenderfer and Klink, 1996; Klink and Aldenderfer, 1996; Aldenderfer and de la Vega, 1997; Klink, in press) and with climate and lake level (base level) data from Lake Titicaca (Baker et al., 2001b).

4. Terrace sediments

Sediments that comprise the Rio Ilave terraces are fluvial silts, sands, and gravels that occur in

Table 1
Sample numbers, location names, terrace numbers, and radiocarbon and calibrated ages for all the samples used in this study

Sample number	Laboratory number	Location name	Terrace number	Radiocarbon age (yr BP)	Calibrated age (yr BP)
HS-2	CURL-5464	Quinafaja	T1	1660 ± 35	1673 ± 39
HS-1	CURL-5462	Quinafaja	T2	2560 ± 40	2577 ± 93
HS-3	CURL-5465	Quinafaja	T2	3440 ± 50	3702 ± 129
RC1-b	CURL-5457	Rio Uncallane	T2	2460 ± 35	–
CH-3	CURL-5460	Chingani	T3	33 000 ± 27	–
HS2-1	CURL-5461	Quinafaja	T3	29 000 ± 180	–
QP2-1	CURL-5466	Quebrada Pucara	T3	21 700 ± 200	–
QP2-2	CURL-5467	Quebrada Pucara	T3	13 040 ± 70	15 420 ± 735
QP2-3	CURL-5468	Quebrada Pucara	T3	26 980 ± 170	–
Toto 2	CURL-5456	Totorani	T4	7350 ± 50	8837 ± 206
Toto 3	CURL-5455	Totorani	T4	8020 ± 75	8020 ± 75
Toto 5	OS-27588	Totorani	T4	5980 ± 40	6808 ± 86
Toto 5	OS-27587	Totorani	T4	5930 ± 40	6735 ± 70
Toto 5a	OS-27590	Totorani	T4	6080 ± 45	6938 ± 54
Toto 5a	OS-27589	Totorani	T4	5980 ± 45	6813 ± 96
Toto 6	OS-27591	Totorani	T4	7400 ± 45	8262 ± 94

Table 2
Summary of lithofacies used in this study

Facies code	Description	Sedimentary structures	Interpretation
Gm	Gravel, matrix-supported	Crude horizontal bedding	Channel fill; bar
Gmsh	Gravel clast-supported	Horizontal bedding, commonly imbrications	Channel fill; bar
Gp	Gravel, transitional between clast and matrix supported	Planar cross-bedding	Channel fill; bar
Gt	Gravel, clast-supported	Trough cross-bedding	Channel fill; bar
Sh	Sand, very fine to very coarse	Horizontal bedding	Channel fill; bar
Sp	Sand, fine to coarse, locally pebbly	Planar cross-bedding	Channel fill; bar
Spw	Sand, medium to silty sand	Planar, wavy, ripple, to climbing ripple laminations	Point bar; levee
Smg	Sand, fine to very coarse, locally dispersed pebbles and mud rip-ups	Massive	Channel fill; bar
St	Sand medium to very coarse, locally pebbly	Trough cross-bedding	Channel fill; bar
Fm	Mud	Massive	Channel fill; bar
Fml	Mud	Massive or planar laminations	Overbank and/or floodplain; inactive channel
Fprw	Silt, mud, clay; common clay drapes	Planar, wavy, ripple, or climbing ripple laminations; convolute bedding	Levee and/or crevasse splay; overbank and/or floodplain
Fsm	Silt	Massive or planar laminations	Overbank and/or floodplain; inactive channel

three distinct facies associations (FAs): gravelly braided river deposits, sandy braided river deposits, and meandering river deposits. Braided river deposits are more abundant than meandering river deposits, occurring throughout the upper and central reaches of the river valley. Meandering river deposits are confined to the lower reaches of the river valley, in the areas downstream of Totorani (Fig. 7). The lithofacies that constitute these FAs (Table 2) were classified on the basis of grain size, sedimentary structures, biological components, and stratigraphic position, following the procedures of Miall (1996, 1983) and Rust (1978). The lateral and vertical distribution of lithofacies, along with groupings of their characteristics, formed the basis for the FA definitions (Table 3). Descriptions of the FAs and their characteristic lithofacies, as well as interpretations of the depositional environments, are presented below and illustrated in Figs. 8 and 9.

4.1. Gravelly braided river deposits (FA-1)

Gravelly braided river deposits occur only in the terraces of the Rio Uncallane tributary and the lowest (oldest) strata in terraces along the central stretch of the Ilave (between the Rio Uncallane and the Rio Huenque; Fig. 7). This FA,

Table 3
Description, dominant lithofacies, and depositional environment of the FAs preserved in terrace exposures of the Rio Ilave

Facies association	Dominant or characteristic lithofacies	Description	Depositional environment
FA-1	Gm, Gt, Gp, Smg, Sp, Fm	Crudely bedded, fining- and coarsening-upward sequences of cross-bedded and laminated gravels with minor sand and mud	Gravelly braided stream deposits
FA-2	Gnsm, Gm, Smg, St, Sh, Sp, Spw, Fsm, Fml	Complexly cross-bedded, fining-upward sequences of coarse sand with local gravel and minor mud	Sandy braided stream deposits
FA-3	Fml, Fprw, Fsm, Spw, Smg	Planar laminated to cross-laminated to massive muds, silts, and sands in thick fining-upward sequences	Meandering stream deposits

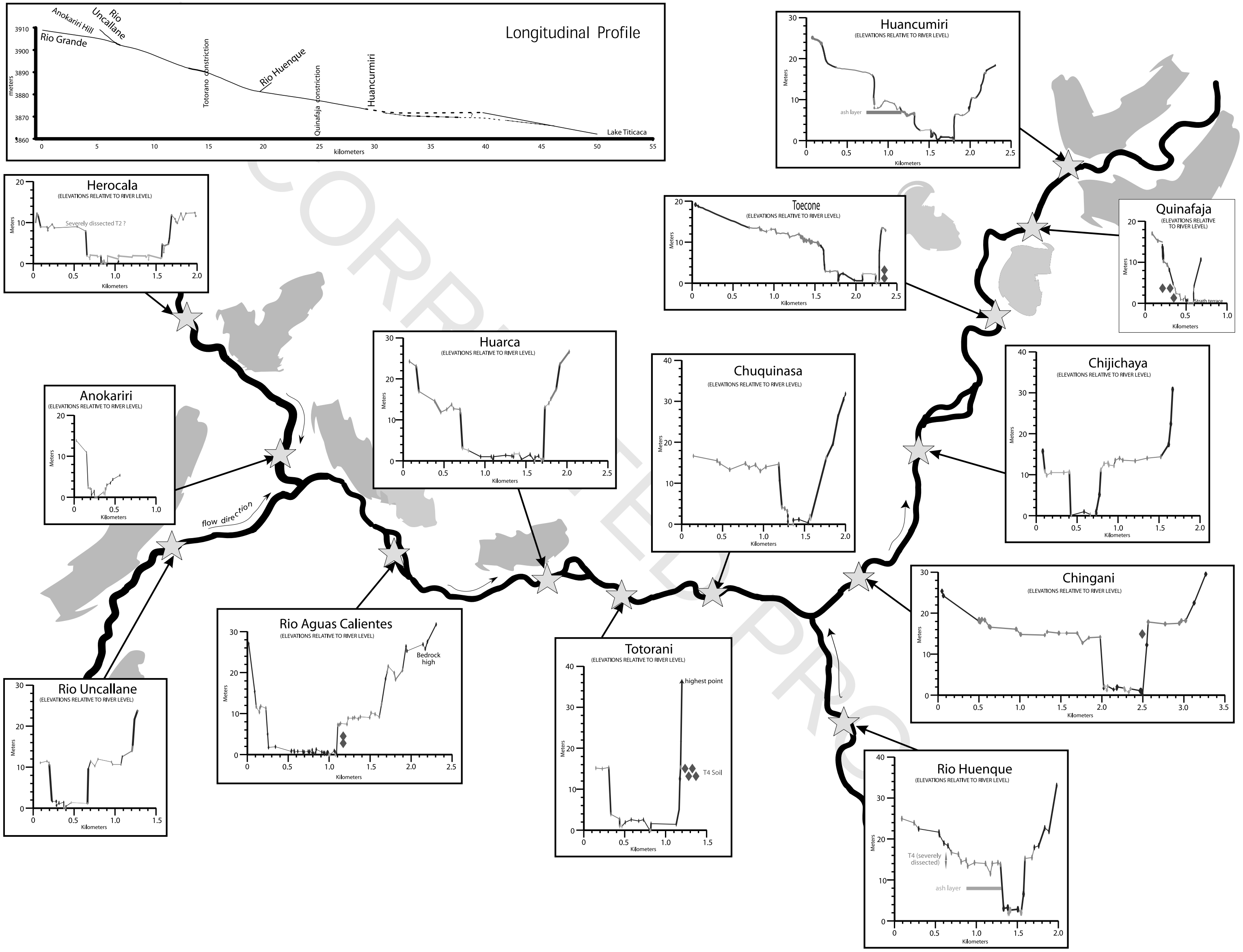


Fig. 7. Rio Ilave terrace profiles and longitudinal profile. Diamonds mark locations of key dates; shaded areas show bedrock highs.

which includes the coarsest grained strata present in the Rio Ilave terraces, is characterized by crudely bedded, fining- and coarsening-upward sequences of gravel, with minor amounts of sand and mud (Fig. 8A).

4.1.1. Description of lithofacies

Fine-grained lithofacies are rare in FA-1. The only fine-grained lithofacies present in FA-1, lithofacies Fm (massive mud), occurs as rare, thin (>0.25 m) beds interspersed between the thick sand and gravel lithofacies. Sandy lithofacies in FA-1 include planar cross-bedded, medium to very coarse sand (Sp) and massive pebbly sand (Smg).

Three coarse-grained lithofacies dominate FA-1: lithofacies Gm, Gt, and Gp. Lithofacies Gm is horizontally bedded, clast-supported, and locally imbricated coarse gravel and gravelly sand. Clast size ranges from pebble to boulder, with cobble-size clasts dominant. Lithofacies Gt and Gp consist of trough and planar cross-bedded gravel, respectively. Lithofacies Gt is a clast-supported cobble to boulder conglomerate. Lithofacies Gp is transitional from clast- to matrix-supported and generally finer grained (containing mainly cobble- and pebble-size clasts) with varying amounts of sand-size matrix material. These gravel lithofacies occur as 1–1.5-m-thick stacked gravel beds or as 0.5–2.5-m-thick, sharp-based units that fine upward and are capped by thin (>0.3 m) beds of lithofacies Smg or Sp.

4.1.2. Interpretation

A gravelly braided river, similar to the braided stretches of the modern Rios Ilave and Uncallane, deposited FA-1. Evidence supporting this interpretation includes the abundance of coarse-grained sediment, the presence of complexly interbedded coarse-grained sediments, the interbedded fining- and coarsening-upward sequences, and the scarcity of fine-grained lithofacies. This FA preserves complexly intercalated bar and channel sequences such as those present in the proximal- and mid-reaches of modern gravelly braided rivers (Reineck and Singh, 1980; Miall 1987).

Braiding results from large and rapid fluctuations in river discharge, abundance of coarse sediments, high rates of sediment supply, and easily eroded banks (Shelton and Noble, 1974; Cant and Walker, 1978; Cant, 1982). Under such conditions, the stream channel is rapidly choked with coarse bedload. Rapid decreases in velocity cause instantaneous deposition, consequently sediments are poorly sorted and the most common lithofacies are channel gravels and low relief bar deposits (Gm, Gp, Gt, and Sp). Such deposits dominate both paraglacial and non-glacially influenced braided systems (Smith, 1974; Boothroyd and Ashley, 1975; Rust, 1978; Smith, 1978).

4.2. Sandy braided river deposits (FA-2)

Sandy braided river deposits of FA-2 are common in the central reaches of the Rio Ilave valley, especially in the Rio Aguas Calientes and Totorani reaches (Figs. 7 and 8B). Stacked, complexly cross-stratified, fining-upward, lapillaceous sands and gravelly sands with thin interbeds of silt and mud characterize these strata. FA-2 is distinguished from FA-1 by an overall lack of gravel, the dominance of sandy distinct, fining-upward sequences, and the common occurrence of interbedded muds.

4.2.1. Description of lithofacies

Sandy lithofacies dominate FA-2. Lithofacies Smg (massive gravelly sand), St (trough cross-bedded coarse to gravelly sand), Sp (planar cross-bedded very coarse to medium sand), and Sh (horizontally stratified coarse to fine sand) occur in 0.5–3-m-thick, fining-upward sequences. Lithofacies St is the most abundant sandy lithofacies in the FA. The sandy sequences are locally interbedded with thin (0.2–0.8 m) beds of parallel to ripple-laminated silt and silty sand (Spw and Fsm) and massive to laminated silt and mud (Fm and Fml). Gravel lithofacies are rare in these strata. Lithofacies Gmsh and Gm occur locally at the base of sandy fining-upward units, but thick gravel beds are not present. Individual gravelly and cross-bedded sand beds of this FA can be traced laterally throughout much of the central portion of the study area.

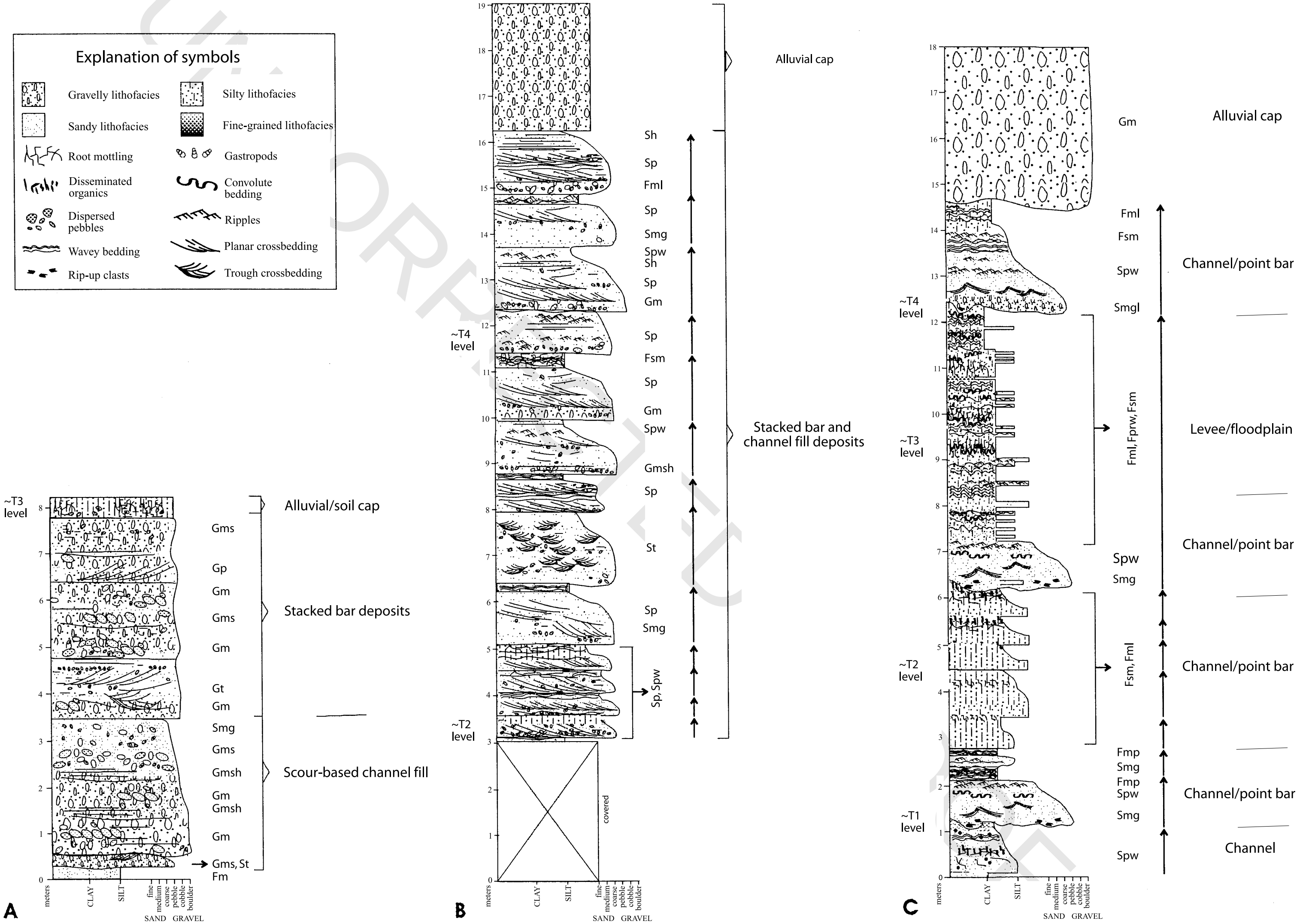


Fig. 8. Typical measured stratigraphic sections from the Rio Ilave terrace exposures. (A) Gravelly braided river strata; composite section from the Rio Uncallane. (B) Sandy braided river strata; composite section from the Totorani area. (C) Meandering river strata; composite section from the Huancumiri–Quinafaja area. Arrows show direction of fining. See Fig. 10 for locations and Table 2 for lithofacies descriptions.

4.2.2. *Interpretation*

FA-2 was deposited by a sandy braided river. Fining-upward sequences are common in sandy braided systems. Fining-upward sequences such as the ones preserved in this FA generally result from sedimentation in braided channels (Miall, 1982; Reineck and Singh, 1980). They also result from waning flow over bars and channels as the result of accretion during active channel migration (Davis, 1983; Kraus, 1984). Such sequences suggest cycles of fluctuating energy regimes. They may record individual flood cycles (Darby et al., 1990) and are probably related to annual to millennial-scale fluctuations of precipitation. Individual coarse units (Gm, Gmsh, Smg) are channel deposits (Miall, 1982). Pebble stringers and channelized gravels more likely represent lags on scour surfaces (Reading, 1996).

4.3. *Meandering river deposits (FA-3)*

Meandering river strata (FA-3) are abundant in the Rio Ilave terraces. They are present in all of the terrace exposures downstream of Huarca (Fig. 7). This FA is characterized by 0.5–6.0-m-thick sedimentary packages dominated by distinct fining-upward sequences of volcanigenic sands and tuffaceous siltstones and mudstones, thick sequences of interbedded silt and mud, and local lenses of sandy gravel, silt, and mud (Fig. 8B). FA-3 occurs both above and laterally adjacent to (grading from) FA-2. It is distinguished from FA-1 and FA-2 by a lack of gravel and the presence of thick sequences of silt and mud.

4.3.1. *Description of lithofacies*

The lithofacies that comprise FA-3 are Fml, Fprw, Fsm, Spw, and Smg. The sandy lithofacies occur at the bases of fining-upward sequences. Lithofacies Smg, a massive sand with locally dispersed pebbles and mud rip-up clasts, commonly exhibits an erosive base and typically grades upward into planar- to wavy- to cross-laminated silty sand (Spw). Lithofacies Fsm consists of massive to laminated silt and silty clay in beds ranging from a few centimeters to 0.5 m in thickness. It occurs as individual fining-upward sequences and as interbeds within finer grained strata. Lithofacies Fml, massive to planar-laminated mud, occurs within fining-upward sequences, typically overlying lithofacies Spw. Lithofacies Fprw is characterized as a planar- to wavy-laminated silt to silty clay to clay, with common mud drapes and soft-sediment deformation features. It occurs locally atop fining-upward sequences and, in the Huancumiri section (Figs. 7 and 8C), as a thick sequence of thinly bedded and complexly laminated, rippled, and climbing rippled very fine sand, silt, and mud.

4.3.2. *Interpretation*

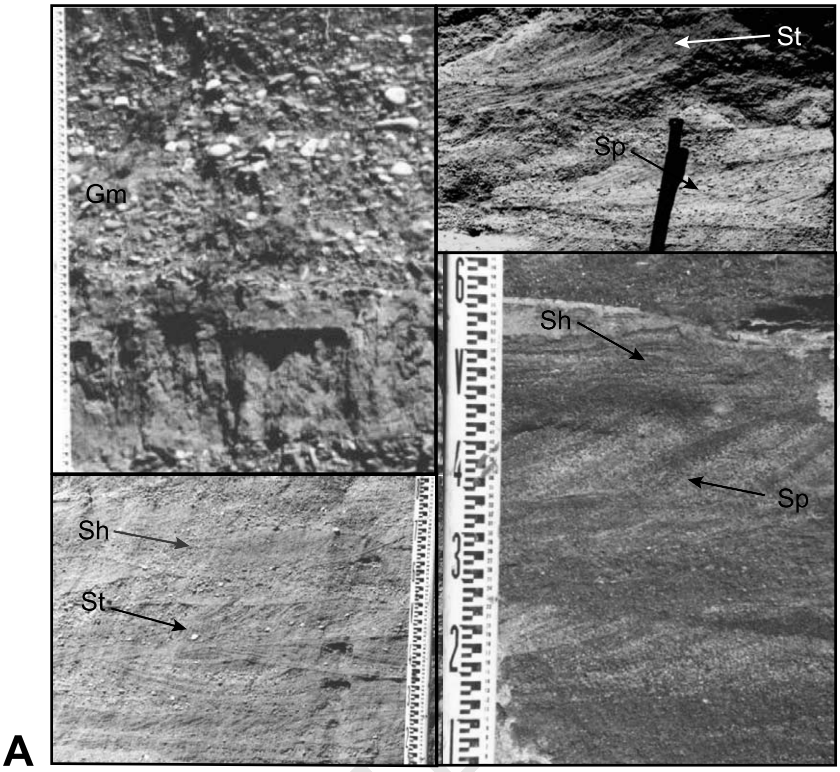
FA-3 records deposition in a meandering river. This FA is dominated by thick (approximately 0.4 to >5 m) overbank or floodplain deposits (lithofacies Fsm, Fml, Fmp, Fpwr) that rest above fining-upward channel and point bar deposits (Smg, Spw, Fsm). Evidence for the meandering river interpretation includes the absence of interbedded channel and bar lithofacies, the overall fine-grained nature of the strata, and the presence of thick overbank deposits and fining-upward sequences. Similar fining-upward meandering river strata have been documented in Holocene terrace (Baucom and Rigsby, 1999) and subsurface (Rollins et al., 2000; Rollins, 2001) strata of the Rio Desaguadero valley, where they are interpreted to coincide with periods of increased effective moisture on the Altiplano.

5. Fluvial history

The meandering and braided river strata of the Rio Ilave valley are exposed in five distinct terrace tracts. The terrace morphology, age, sedimentary characteristics, and history of formation are, as discussed in the following sections, intimately related to the regional climatic (precipitation) variations.

5.1. *Terrace morphology and age*

The five terrace tracts in the Ilave valley (T1–T5) 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 (Fig. 7). The com-


Gm
St
Sp
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Sp
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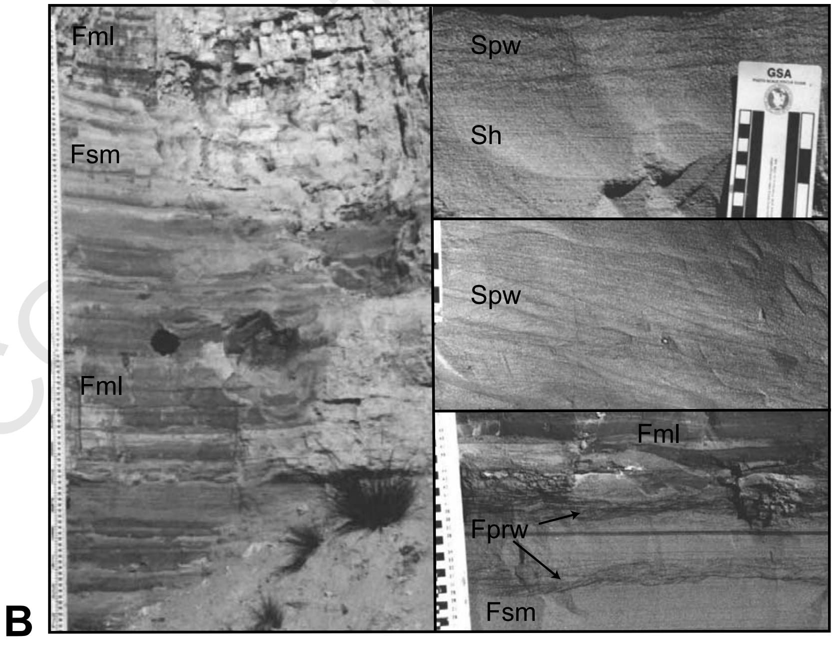
Fml
Fsm
Fml
Spw
Sh
GSA
Spw
Fml
Fprw
Fsm
B

plete suite of terraces is not present in all localities, but each terrace is identifiable by its sedimentary characteristics and its height above the modern river (Fig. 10). In general, the terraces are best formed in the downstream reaches of embayments. At confluences terrace surfaces are well formed in both the downstream and upstream reaches. The upper four terraces occur, locally, as paired terraces. An unpaired strath terrace is present at the lowest terrace level near Quinafaja, but paired strath terraces do not occur. Only the two lowest terraces (T1 and T2) are demonstrably fill terraces; the others are cut-fill terraces (following the terminology of Bull, 1991). All of the terrace surfaces are actively cultivated by modern farmers and have cultivated zones up to 1 m deep.

The highest terraces (T3, T4, and T5) are present throughout most of the study area. They are composed of ash-rich fluvial strata (dominantly lapillaceous gravels and sands, tuffaceous siltstones, and mudstones). T5, the highest terrace surface at 24.3 m above river level, is highly dissected and is present from the Rio Uncallane downstream. It is most prevalent near the Rio Uncallane tributary, present locally downstream of Huarca, and absent in the upstream-most reaches – where the river is marshy and has low relief (see Figs. 7 and 10).

Terrace T4, with an average height of 15.7 m, is the most persistent surface in the river valley and is present in all but the upstream-most, low-gradient, wetland-like sections. In the central part of the Ilave valley, the T4 level is identifiable as either a distinct terrace or as a gravelly sand horizon within the non-dissected stratigraphic section (Fig. 8). Where the T4 terrace surface is well formed, the surface is capped by either a thick (up to 2 m) soil horizon or a gravel cap. Gravels dissect the T4 surface to a depth that reaches 3.5 m above the modern river (more than 3/4 of the ~15 m terrace height) in the downstream reaches of the Totorani embayment. Terrace T3 is present in both upstream and downstream reaches, but absent in the central portion of the river valley (between Rio Aguas Calientes and Chijichaya). Similar to the T4 terrace, T3 is comprised of ash-rich fluvial sediments, is not fully formed (cut) in the upstream reaches (embayments) above bedrock constrictions, but is well formed (cut) in the downstream reaches. Thin gravel caps (< 2 m) are present locally. These highest terraces are generally lens-shaped; they are lowest immediately downstream of bedrock constrictions, highest and broadest in embayments. Samples of organic material from a thick soil horizon near the top of the T4 terrace yielded dates ranging from 8292 ± 34 cal BP at the base of the soil to 6735 ± 70 cal BP at the top. Samples from T3 sediments (from beneath the level of the T3 surface and stratigraphically lower than the T4 strata) range in age from 15 420 ± 735 cal BP to ~33 000 BP (Table 1). These samples suggest (but do not prove) that approximately 25 m of sediment (most of the T3 through T5 stratigraphic section) was deposited in the Ilave valley since the Late Glacial Maximum (LGM). Almost half of that strata was deposited, and subsequently downcut, during the Holocene.

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 (Figs. 7 and 10). Terrace T2 has an average height of 4.83 m and is present only near the Quinafaja bedrock constriction and, possibly, at Herocala (Figs. 7 and 8). Terrace T1, the youngest surface above the modern channel, is the modern floodplain terrace. It is characterized by 1–1.5-m-high, distinct, narrow platforms on the inside of modern mean-

Fig. 9. Lithofacies characteristic of the three FAs present in the Rio Ilave terrace exposures. (A) Sandy and gravelly lithofacies typical of braided stream deposits. Massive gravel (Gm), pebbly trough- and planar cross-bedded very coarse pebbly sand (St, Sp), and horizontally laminated sand (Sh) are common in FA-1 (gravelly braided stream deposits). Interbeds of horizontally laminated and trough and planar cross-bedded medium to very coarse (locally pebbly) sand are common in FA-2 (sandy braided stream deposits). (B) Thick, fining-upward sequences of finer grained strata, such as ripple- and climbing ripple-laminated fine sand and mud (Spw and Fprw), massive to planar laminated silt (Fsm), laminated mud (Fml) and horizontally laminated fine to medium sand (Sh) are common in FA-3 (meandering stream deposits).

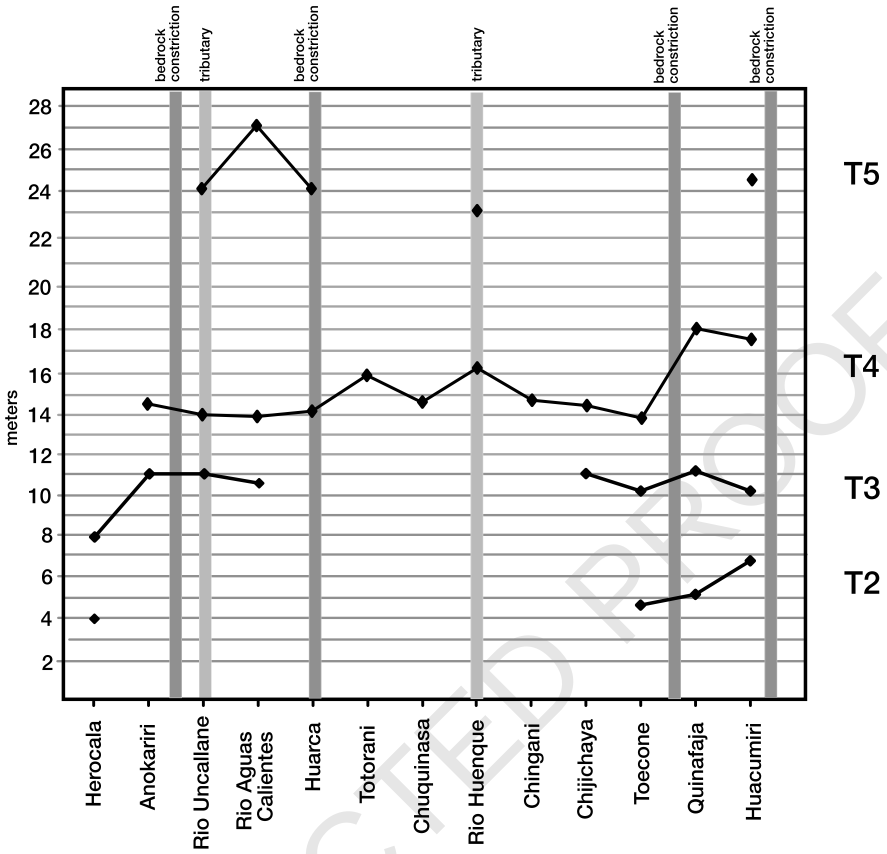

Fig. 10. Graph showing the heights of the four upper Rio Ilave terrace tracts. Terrace height is partially controlled by proximity to bedrock constrictions and tributaries.

ders. Organic material from the T2 and T1 sediments yielded dates of 3702 ± 127 to 2486 ± 62 cal BP and 1673 ± 39 cal BP, respectively (Table 1).

5.2. *History of terrace development*

The sedimentologic and geomorphic characteristics of these terraces, along with the radiocarbon ages from terraces T1 through T4, allow us to develop a history of terrace development for the river valley (Fig. 11). Gullies that dissect the terrace suite near Quinafaja and Huacumiri expose a complex 3-D geometry. The sediments underlying terraces T3 through T5 are vertically continuous through the three-terrace sequences and grade down-gradient from gravelly braided stream deposits (FA-1) to sandy braided deposits (FA-2) to meandering stream (FA-3) deposits. No evidence of major erosional events or of long-term hiatuses is present in the composite 3-terrace stratigraphy (Fig. 8). This suggests that the sediments beneath these terraces were deposited in a continuous or nearly continuous manner. Aggradation of such thick sequences of fluvial strata is common in arid, rocky basins when large amounts of sandy sediment are introduced (Bull, 1991). If stream power is insufficient to handle the increased sediment load, the entire river valley may be choked with thick piles of sediment. Many river systems grade downstream from coarse-grained to fine-grained braided systems and, eventually, to meandering systems. The gradual downstream gradation of the sediments underlying the Rio Ilave terraces from gravelly braided river strata to meandering river strata is likely the result of a progressive downstream decrease in sediment load. This suggests that different reaches of the river valley filled at different rates depending on, for example, the length and gradient of the embayment and the availability and grain size of the source material. The occurrence of braided fluvial strata (FA-1 and FA-2) in the more upstream reaches – but at the same stratigraphic level as meandering strata in downstream reaches – is a result of the presence of bedrock constrictions behind which large volumes of sediment could be trapped, the differing gradients of individual embayments, and the downstream-decreasing availability of coarse-grained source material.

The T4 and T3 surfaces represent equilibrium stages during a progressive downcutting of these sediments. The complex distribution and heights of the T5 through T3 terraces are consistent with the overall basin geometry of alternating embayments and constrictions. As is typical of arid-region mountain streams (Bull, 1991), the Ilave valley terrace heights typically decrease upstream toward constrictions and the terrace widths are generally broader in embayments.

In contrast to the compound T3–T5 terrace set, terraces T1 and T2 are individual, inset, fill terraces. The T2 strata onlap the T3 terrace and the T1 strata onlap the T2 terrace (Fig. 11), indicating that these terraces were formed during two distinct episodes of aggradation.

5.3. Terrace development and climate change

A first step toward understanding the effects of these aggradational and downcutting phases on riparian biota and on the human occupants of the Ilave 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 climatic events is illustrated in Fig. 12. The majority of the fluvial sequence (aggradation of the compound T3–T5 terraces) corresponds to a time of high precipitation on the Altiplano and rising or 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 wet period, and may have continued until ∼8250 cal BP. High 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 12). 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 m above the valley floor

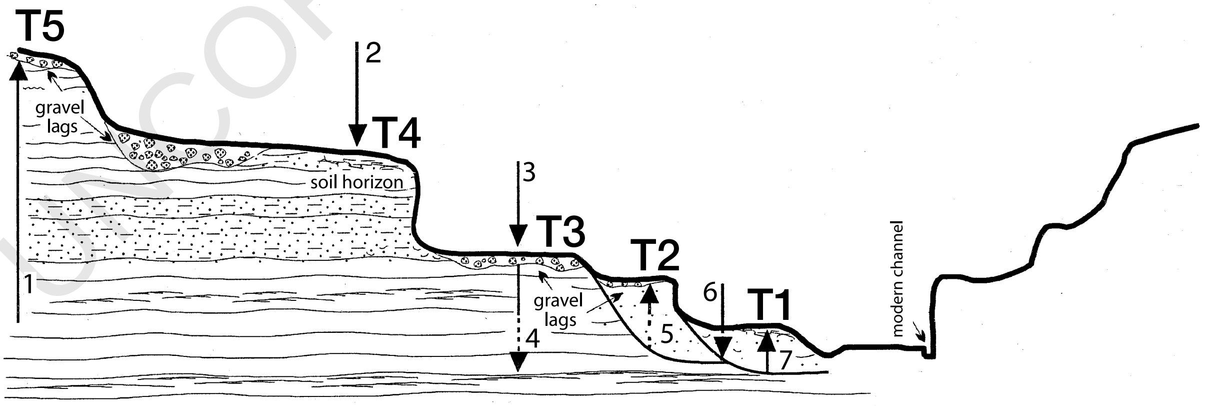

Fig. 11. Model for the aggradation and downcutting of the Rio Ilave terraces. Numbered arrows show sequence and directionality (aggradation or downcutting) of events.

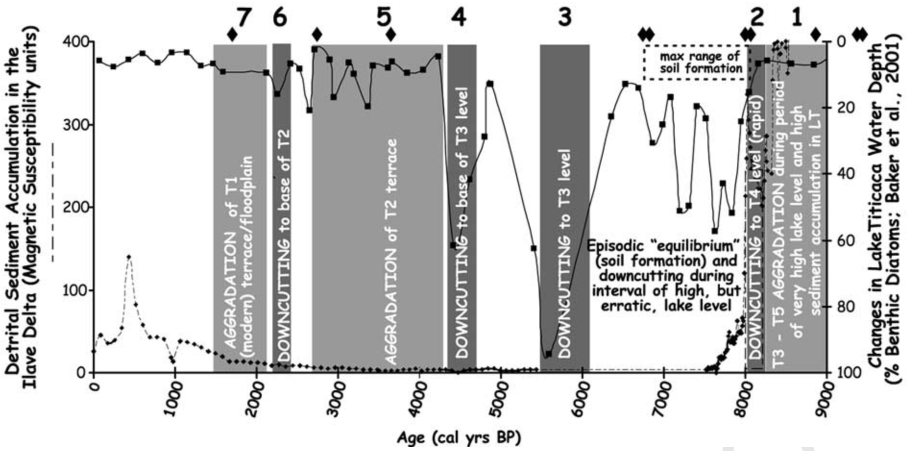

Fig. 12. Relationship between the Rio Ilave terrace development and changes in base level and sediment load. The benthic diatom record from a deep-water core (NE98-2PC) in Lake Titicaca is used as a proxy for lake level (solid line). The magnetic susceptibility log from a core taken at the toe of the Ilave delta records detrital sediment accumulation at base level (dashed line). The diamonds indicate radiocarbon dates in the fluvial sequence and the numbers correspond to the aggradational and downcutting events illustrated in Fig. 11. Note that periods of aggradation correspond to periods of high (or rising) lake level in Lake Titicaca (Abbott et al., 1997; Baker et al., 2001a) and (for all but T2) the periods of increased sediment accumulation in the Ilave delta. Further, each hypothesized aggradation period corresponds to a lacustrine period in the Rio Desaguadero valley (Baucom and Rigsby, 1999; Rigsby et al., 2001; Rollins, 2001). Downcutting episodes, which leave behind no datable strata, are bracketed in age by dates within the aggradational sequences and apparently correspond to periods of low lake level in Lake Titicaca (Baker et al., 2001a), low or rapidly decreasing sedimentation rates in the Ilave delta, and fluvial activity in the Rio Desaguadero valley (Baucom and Rigsby, 1999; Rollins, 2001).

(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), the shift from aggradation to downcutting was likely very rapid.

The initial downcutting probably began immediately after precipitation, runoff, sediment load decreased (as seen in the Ilave delta sediment accumulation record; Fig. 12), and base level dropped – probably just prior to ~8000 cal BP. Although the initial downcutting was likely very rapid, the terraced 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 periods of rapidly decreasing levels of Lake Titicaca (Fig. 12) 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 suggest 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 terrace sediments. The T2 and T1 aggradational events occurred from ~4000 to 2500 cal BP and from ~2200 to 1600 cal BP, respectively – during millennial periods of rising water levels in Lake Titicaca, lacustrine sedimentation in the Rio Desaguadero valley (Baucom and Rigsby, 1999; Rigsby et al., 2001) and the Salar de Uyuni (Baker et al., 2001a, and increased sedimentation off the Ilave delta. They were separated by brief equilibrium stages and brief downcutting events.

6. Discussion

The role that climatic variation has played in the social and political evolution of the peoples of the Titicaca basin as well as the 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; Ortloff and Kolata, 1993; Binford et al., 1997). While some of his interpretations of the existing paleoenvironmental record are inaccurate, his point is clear: 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.

Archeological survey data argue strongly for a human presence in the Titicaca 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 most of the earliest human occupation (10 000–8500 BP), Lake Titicaca was freshening and the lake at a highstand from ~9500 to 8500 cal BP (Baker et al., 2001b). Although *Poaceae* (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 used extensively. 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 through day-use and longer-distance logistical forays.

Humans occupied the higher terraces of the Ilave (T3, T4, and T5) for at least 5000 years (prior to ~4400 cal BP) (Aldenderfer and Klink, 1996). Excavations at Jiskairumoko (at the T5 level in the central Ilave valley) show that a sedentary settlement is 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); the lower Ilave terraces (T1 and T2) were not used extensively until after ~4400–3700 cal BP (Fig. 13), a trend also seen in data from the Rio Huenque (Klink, in press). This increase in population was coincident with a period of increased precipitation, rising levels of Lake Titicaca, and increased discharge and the formation of low terrace (T2) in the Ilave valley (Fig. 12).

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 the near-lake environments became more important through time. This is presumably correlated with the intensified reliance upon agricultural production in the economy and the 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.,

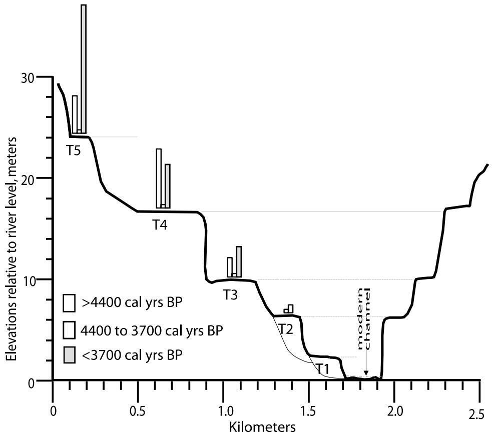

Fig. 13. Typical profile across the Rio Ilave valley showing the five distinct terraces discussed in the text. The superimposed population-density histograms, based on survey and excavation data (Aldenderfer and Klink, 1996; Klink and Aldenderfer, in press), illustrate the human/land-use relationships. Although some sites could have been lost during downcutting events (events 2, 3, 4, and 6 on Figs. 11 and 12), the overall relationship between human land-use and the fluvial landscape is clear: humans occupied the upper terraces (T3–T5) during the Early Archaic (prior to ~4400 BP) and the low terraces (T2 and T1) were not used until the Terminal Archaic (4400–3700).

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 the pampas surrounding river terraces and the lake margin. It may have been a response to drier conditions and the downcutting of previously available T2 terrace expanses. The downcutting of the T2 terrace (Figs. 11 and 12) was associated with a brief (post ∼3000 BP) period of variable, but decreased, lake level. After ∼2000 cal BP, lake levels returned to, or slightly above (Abbott et al., 1997; Baucom and Rigsby, 1999), modern levels, precipitation increased, and the T1 terrace was formed, once again providing fresh fluvial landscapes for agricultural use.

7. Summary

Instrumental records show that, on seasonal to decadal time-scales, changes in the Rio Ilave discharge are related to changes in precipitation as well as changes in the level of Lake Titicaca. Our investigation of the Rio Ilave terraces suggests that the Ilave River also responded to centennial- and millennial-scale events – especially changes in precipitation and consequent changes in sediment load. According to paleoclimatic reconstructions and our history of terrace development, the Ilave valley was relatively wet during the initial human occupation (∼10 000 to sometime prior to ∼4400 cal BP). This was a time of high, but erratic, lake levels and of soil formation on the high terraces of the river valley. Humans occupied the higher terraces (T3, T4, and T5) for at least 5000 years during this time interval. The lower terraces (T1 and T2) were not present, hence not utilized by humans for occupation or agriculture, until after ∼4000 cal BP.

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 the 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 and discharge are the primary controls on the fluvial processes and landscape evolution; changes in precipitation and landscape are the ultimate controls on the availability of land for settlement, agriculture, and other human uses. This coupling of base level, paleoclimatic, and human occupation records in the Rio Ilave valley provides a more complete understanding of the natural forces that shaped landscape evolution and its anthropogenic modifications.

8. Uncited references

Erickson, 1988; Kaplan et al., 1997; Nanson et al., 1993; Seltzer et al., 2000; Shanley and McCabe, 1994; Smith and Smith, 1984

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