MOUNTAIN RESEARCH AND DEVELOPMENT, VOL. 13, NO. 2, 1993, PP. 117-127

CLIMATE CHANGE AND NATURAL RESOURCE DYNAMICS OF THE ATACAMA ALTIPLANO DURING THE LAST 18,000 YEARS: A PRELIMINARY SYNTHESIS

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ABSTRACT Interaction between anticyclonic air masses, the effect of the cold Humboldt current, and the moisture barrier of the mountain chain results in extremely dry environmental conditions on the western slope of the Atacama Andes. Even the highest peaks above 6,700 m in the continuous permafrost belt are currently free of glaciers, and modern recharge of the water cycle is restricted to small catchments at high altitude. The vegetation between 3,100 and 4,800 m is too sparse to initiate any soil formation.

The temperatures of the last cold maximum (18 kyr B.P.) were probably 7°C lower than today. The late-glacial period (17-11 kyr B.P.) was characterized by 5-10 m higher lake levels, indicating a large increase in precipitation at latitude 23-24° South. The early Holocene (11-7 kyr B.P.) experienced wetter conditions and summer temperatures 3.5°C higher than today, together with significant groundwater recharge. This provided favorable conditions for an early hunter-gatherer economy. After about 3000 B.P. conditions became drier; intensive pastoralism may have added to the impacts on vegetation cover, and groundwater recharge was curtailed.

Natural resource management policies must take into account the dynamics of a changing environment. Present-day reliance on groundwater for mining, urbanization, and agriculture cannot be sustained, for supplies are believed to be fossil water, or else the recharge rate is so slow that actual use may far exceed replenishment.

RÉSUMÉ *Synthèse préliminaire du changement climatique et de le dynamique des ressources naturelles dans l'Altiplano d'Atacama au cours des 18,000 dernières années.* L'interaction entre masses d'air anticycloniques, l'effet du courant froid de Humboldt et la barrière à l'humidité constituée par la chaîne de montagnes produisent des conditions extrêmement sèches sur le versant ouest des Andes d'Atacama. Même les pics les plus élevés (au-dessus de 6,700 m), à l'étage du pergélisol permanent, n'ont pas de glaciers et l'alimentation du cycle hydrologique se limite à de petits bassins hydrographiques de haute altitude. La végétation présente entre 3,100 et 4,800 m est trop clairsemée pour contribuer à la formation du sol.

La période glaciaire (18,000 B.P.) était caracterisée par une température annuelle moyenne probablement 7°C plus basse qu'aujourd'hui. Dans le tardi-glaciaire (17-11,000 yr B.P.) les niveaux lacustres étaient 5 à 10 m plus élevés, se traduisant par un accroissement fort des précipitations dans les latitudes 23-24° Sud. Le début de l'Holocène (11,000 à 7,000 ans avant l'époque actuelle) était caractérisé par des conditions plus humides et des températures estivales 3.5°C plus élevées qu'aujourd'hui, avec une alimentation importante des nappes souterraines. Ces conditions ont favorisé très tôt le développement d'une économie basée sur la chasse et la cueillette. Environ 3,000 ans avant l'époque actuelle, les conditions sont devenues plus sèches, le pastoralisme intensif a probablement contribué aux impacts sur la couverture végétale, et l'alimentation des nappes souterraines a beaucoup diminué.

La politique de gestion des ressources naturelles doit tenir compte de la dynamique d'un environnement en pleine évolution. L'utilisation présente de la nappe phréatique pour l'exploitation des mines, l'urbanisation et l'agriculture ne peut pas continuer de cette manière, du fait que l'eau utilisée est probablement de l'eau fossile et que la vitesse d'alimentation est tellement faible que l'utilisation actuelle est probablement beaucoup plus élevée que le réapprovisionnement.

ZUSAMMENFASSUNG *Klimaveränderung und die Dynamik der natürlichen Ressourcen im Atacama Altiplano während der vergangenen 18.000 Jahre. Eine vorläufige Synthese.* Die Kombination von südost-pazifischem Hochdruckgebiet, kaltem Humboldtstrom und der N-S verlaufenden Hochgebirgskette der Anden führt in der Atacamawüste zu extrem ariden Bedingungen von der Meeresküste bis 6.700 m ü. M. So fehlen heute Gletscher selbst im kontinuierlichen Permafrostgürtel oberhalb 5.600 m, eine Erneuerung des Wasserkreislaufs kann nur in lokalen Einzugsgebieten im Altiplano beobachtet werden, und die Vegetation zwischen 3.100-4.800 m ist zu schwach, um zu einer Bodenbildung beizutragen.

Terrestrische und limnische Ökosysteme oberhalb 4.000 m zeigen starke Veränderungen seit der letzten Kaltzeit (18.000 B.P.) Auf kalt-trockene Bedingungen (bis 200 mm Jahresniederschlag) folgte im Spätglazial ein kalt-feuchtes Klima mit mindestens

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400 mm Jahresniederschlag, was zu großen Seen im Altiplano geführt hat. Für das frühe Holozän zeigen Paläoböden mit der maximalen Ausbildung zwischen 4.500–4.700 m warm-feuchte Klimabedingungen mit Sommerregen an. Pollenanalysen weisen auf höhere Temperaturen im Holozän hin. Die heutigen warm-trockenen Bedingungen (bis 200 mm Jahresniederschlag) stellten sich ab ungefähr 3.000 B.P. ein.

Für die nachhaltige Nutzung der natürlichen Ressourcen ist unter heutigen Klimabedingungen der große Bedarf an Wasser (Bergbau, Städte, traditionelle Landwirtschaft in Oasen) besonders problematisch, weil es sich zum Teil um fossiles Wasser handelt.

INTRODUCTION

Sustainable management of natural resources under today's socioeconomic and political conditions will be achieved only if it is based upon a full understanding of the sensitivity and dynamics of present and former processes that contributed to the formation and maintenance of these resources. This implies that adequate information must be available concerning the quantitative and qualitative potential of natural resources and the manner of their development, including such factors as water recharge, soils, and vegetation. It also implies that natural resource renewability, or non-renewability, that is dependent upon environmental conditions which themselves may change through time must be carefully assessed. Rapid changes that must be taken into account, and which can occur on both local or regional scales, include natural processes, such as volcanism, climatic conditions, and oceanic circulation, and anthropogenic processes, such as industrial production of carbon dioxide and methane, and deforestation. Such changes in environmental controls can best be studied in dry and cold ecosystems, such as deserts, polar regions, and high mountains. These ecosystems have comparatively low potential for formation of resources or for their replenishment. Even slight changes in the environmental controls may provoke major fluctuations in the structure and functioning of biotic and abiotic systems.

The extremely dry Atacama Altiplano of northern Chile (Figure 1) provides an outstanding natural labo-

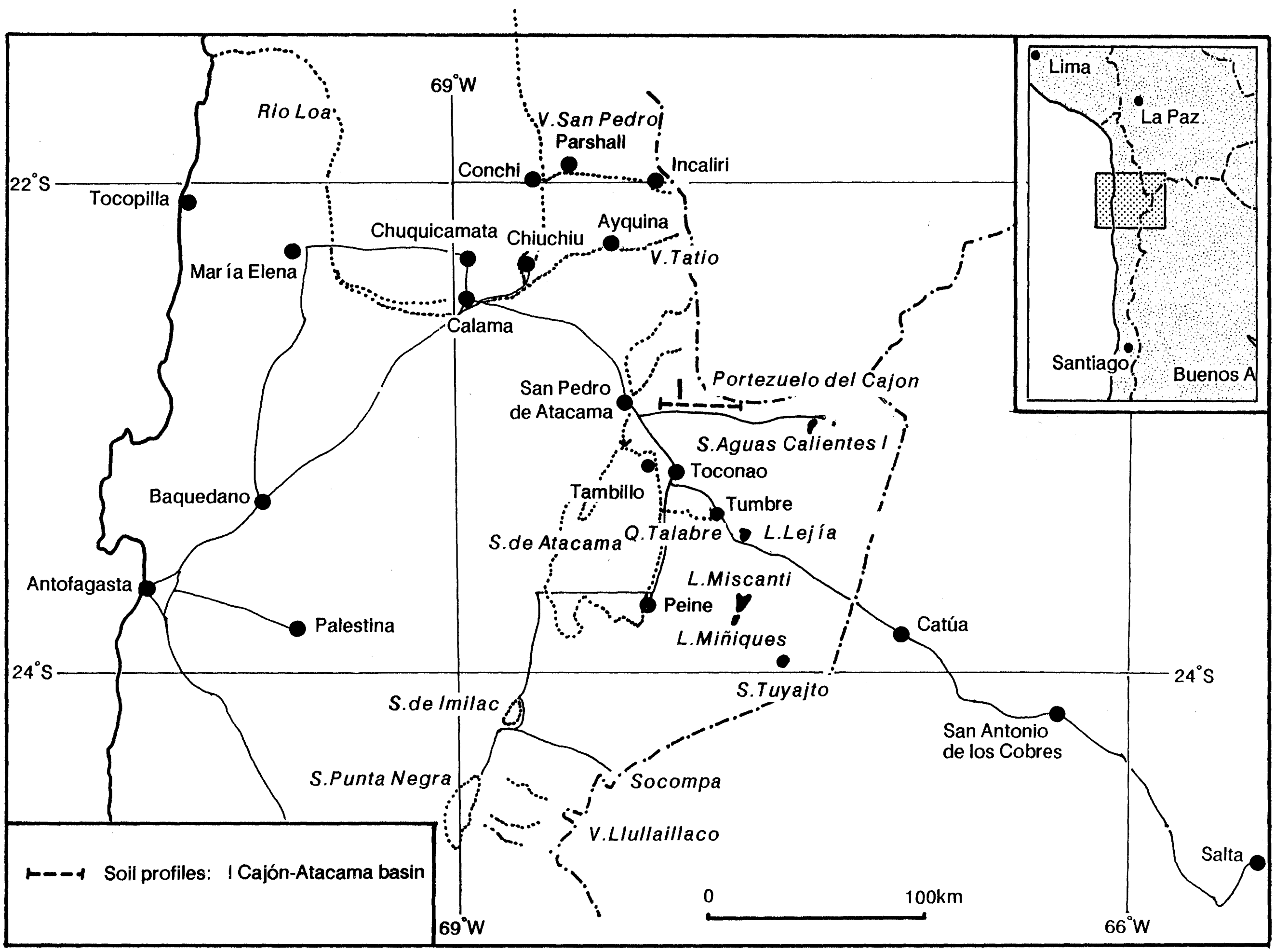

FIGURE 1. The location of the research area.

ratory for the study of past climatic changes and their impacts on natural resources which were the basis for the first hunting and gathering cultures from about 10,800 B.P. onward (Nuñez and Santoro, 1988; Lynch, 1990). The time interval from late Pleistocene to early Holocene is especially significant and its long-term changes are indicated by the shorelines and sediments of former lakes, paleosols, pollen profiles, and glacial and periglacial features. It has become increasingly important that an understanding of the manner in which natural resources have been created in the past is achieved if optimum management polices are to be developed. Modern agriculture, mining, and urbanization in this region seem to depend extensively on access to fossil water with a slow rate of recharge. The large groundwater bodies were formed under climatic conditions very different from those prevailing today. It follows, therefore, that human behavior in the past, and present-day economic activities, must be reconsidered in the context of the environmental changes and their implications for long-term use of natural resources.

The above considerations led to a multidisciplinery approach involving the calibration of a wide range of proxidata. The present paper is a preliminary synthesis of the results of the first three years of this paleoecological research in the Andes of northern Chile between latitudes 22° and 25° South (Figure 1). The methodological aspects of the various disciplines are not discussed. The findings are compared with the results of somewhat similar work on environmental evolution in adjacent areas of Bolivia (Lauer and Frankenberg, 1983; Lauer and Rafiqpoor, 1986; Graf, 1989; Wright *et al.*, 1989; Seltzer, 1990), of Argentina (Markgraf, 1984, 1989), and of Chile at 30° South (Veit, 1990).

PRESENT-DAY CONDITIONS

Today, the Atacama desert is situated in the transition zone between tropical summer and extra tropical winter precipitation (Figure 2a and b). Extremely dry conditions on the western slope of the Andes result from the synergistic interaction between subsiding anticyclonic air masses of the southeast Pacific High Pressure Belt, the drying effects of the cold Humboldt current, and the moisture barrier of the mountain chain. This extreme arid zone (*Trockendiagonale*) crosses the Andes exactly through our research area. Miller (1976), Romero (1985), and others have noted that the winter cyclonic precipitation connected with *Invierno Chileno* is normally blocked north of La Serena at 30° South, and the tropical convective summer precipitation of the *Invierno Boliviano* is restricted mainly to the eastern slope of the Andes. Studies on the evolution of the isotopic composition of rainfall (Aravena *et al.*, 1989) and on the synoptic situation of precipitation events in 1984 (Fuenzalida and Rutllant, 1986) indicate that for both summer and winter precipitation the water molecules were of Amazonian origin. Summer precipitation was linked with an anticyclonic flow pattern in the upper troposphere over the eastern Altiplano, whereas winter precipitation originated from the collision of wet and warm tropical and cold

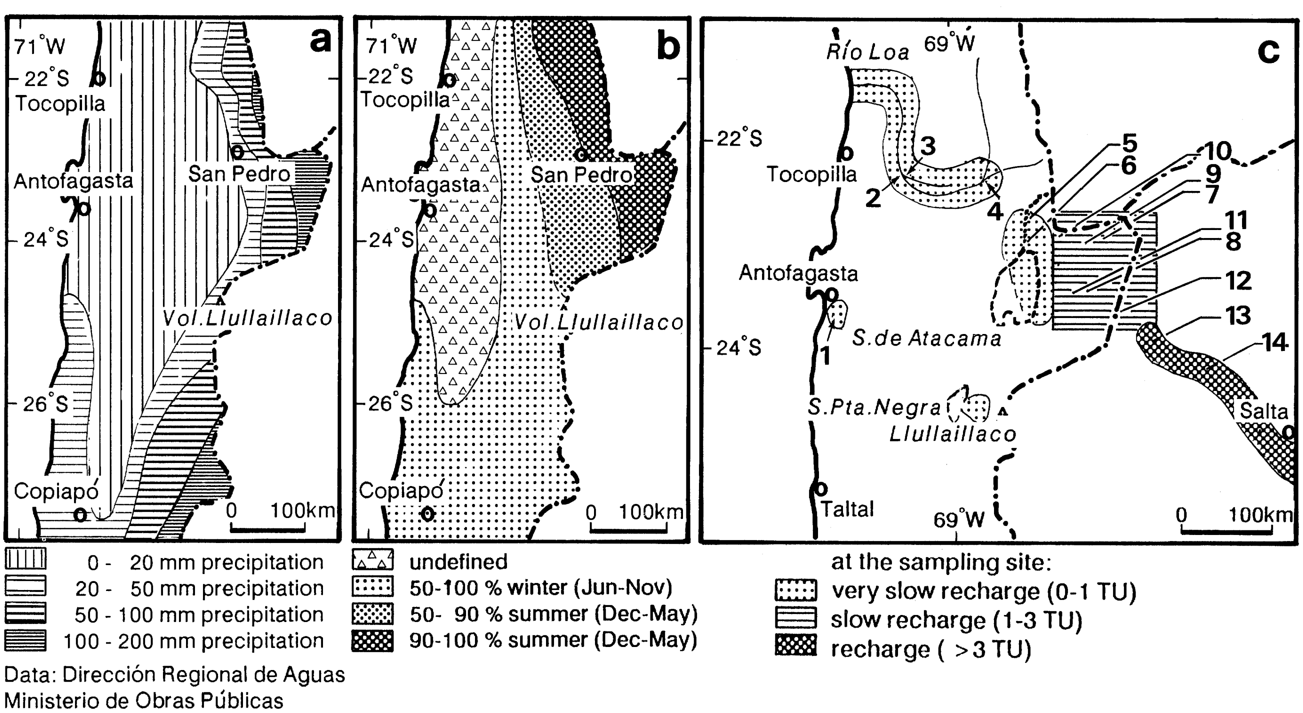

FIGURE 2. The water cycle in northern Chile showing: a) mean annual precipitation; b) seasonal distribution; and c) present recharge of the water cycle (based on tritium measurements).

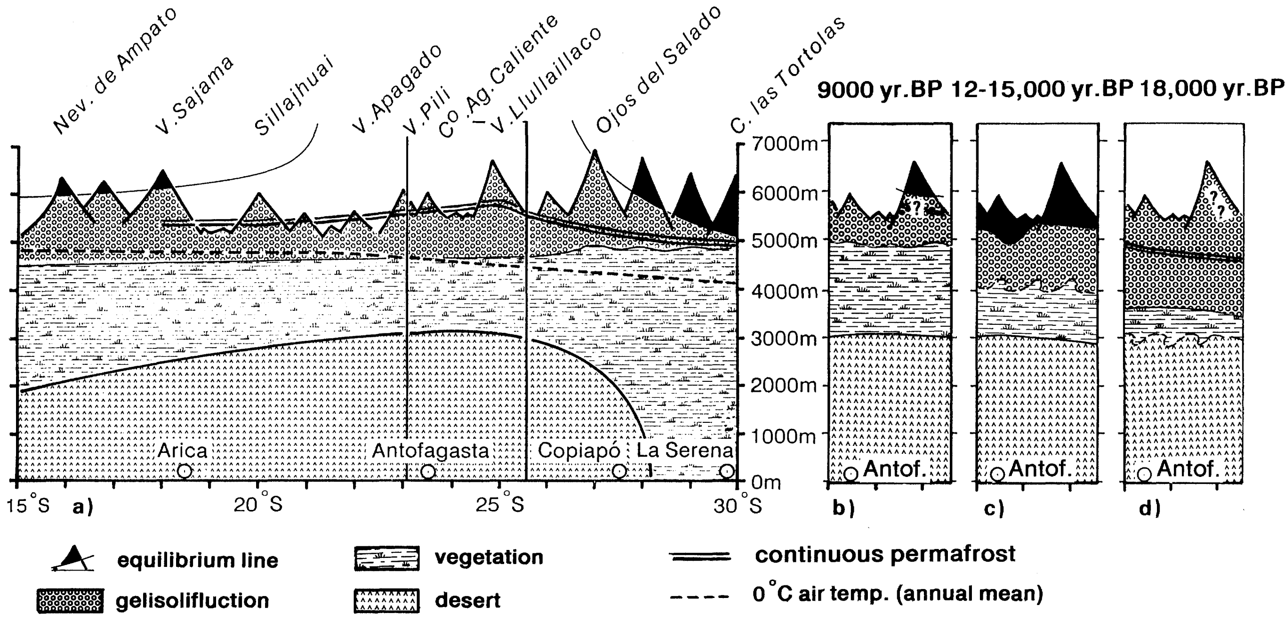

FIGURE 3. Altitudinal belts on the western slope of the Andes: a) between 15° and 30° South at the present time; and between 23° and 25° 30' S at b) 9,000 yr B.P.; c) 12–15,000 yr B.P.; and d) at 18,000 yr B.P.

extra tropical air masses. Furthermore, when ground station data were compared with sequential LANDSAT-TM and -MSS images for the case-study period of 1983–1984 they showed that winter precipitation on the Altiplano (Figure 2b) is highly underestimated because of its solid form (Vuille, 1991). At El Laco (23° 45' South; 67° 20' West; altitude 4,500 m) in the central Altiplano, 380 cm of snow in six events was recorded between May and August, 1990, and 300 cm in three events between June and October, 1991. Monitoring of the snow cover, including melting, sublimation, and infiltration processes, is planned for the future; this will provide information on the snow cover as a resource potential under different climatic conditions. Furthermore, the transition in precipitation regime at 24° South is found in the hydrological response of lakes and salars; this was investigated by analysis of sequential LANDSAT images for 1983–1984. The salars north of 24° South showed an increasing water surface area and volume during the period of summer precipitation, whereas south of 24° South the salars were not affected by summer rainfall; their water surface area increased due to winter precipitation (Vuille, 1991).

Modern recharge of water resources in the west-east transect, Antofagasta–Salta, was investigated by means of ^{3}H (tritium) measurements taken in open water bodies, springs, and subsurface groundwater. Figure 2c indicates that the regional discharge of the Río Loa (Figure 2c, Site 2), the Río Salvador (Site 3), the Río Salado (4), and the Salar de Atacama basin (Puritama 5, San Pedro 6) does not contain any measureable tritium (detection limit 0.3 TU) during the dry season. From this it follows that there is no component of modern water younger than about 40 years and/or that recharge is extremely slow. Partial recharge in the water cycle becomes more frequent in local catchments above 4,200 m on the Altiplano at Aguas Calientes (Site 7), Peña Blanca (9), Cajón (10); groundwater Lejía (11), Paso Guaitiquina (12); snowfield Volcán Pili (8), and especially towards Catúa (13) and San Antonio (14) on the Argentinian side. Therefore, water from regional discharge below 4,000 m does not contain a meteoric water component from about the last 40 years. This is interpreted as evidence for very slow recharge and long residence time of the water molecules in the groundwater body.

These preliminary results imply that groundwater, the major water source for economic activity in northern Chile, must be considered as non-renewable, or a resource which has a very slow long-term rate of renewability. Dissolved inorganic carbon extracted from surface and groundwater samples has been radiocarbon dated (Fritz *et al.*, 1979; Grosjean, 1992). This also indicates that the groundwater bodies were formed as long ago as late-Pleistocene and early Holocene, a conclusion supported by the research program reported here.

The extremely dry northern Chilean environment of today (Figure 3a) is characterized by a very few open, and mostly saline, water bodies (conductivity 5->> 50 mS/cm) above 4,000 m, by very limited groundwater recharge, and by the absence of glaciers, even in the continuous permafrost belt above 5,600 m. The absence of glaciers, even on Volcan Llullaillaco (24° 43' South; 6,739 m; Figure 4), is astonishing and a globally unique phenomenon. It demonstrates the extreme aridity from sea level up to and within the continuous permafrost belt in the *Trockenachse*. The vegetation is so sparse in all altitudinal belts that no soil formation process is occurring. In addition to mining, human activity is restricted to stable oases along the foot of the mountains, with agriculture and rare, seasonal pasturing on the Altiplano.

FIGURE 4. The northern slope of Volcan Llullaillaco (6,739 m); there are no glaciers but there is a permanent firn patch in the summit area; the area is covered by light volcanic material and moraines, probably of a late-glacial stage, reached the outwash plains at an altitude of about 4,900 m.

ENVIRONMENT OF THE LAST COLD MAXIMUM

Reconstruction of the environment that prevailed during the last cold maximum (18,000 yr. B.P.; Figure 3d) is extremely difficult. Glacial, periglacial, and lacustrine features suggest that temperatures were probably 7°C lower than those of today, accompanied by arid to semiarid conditions. The widespread valley glaciation, which is reported from the southern Andes (Clapperton, 1990; and others) ends abruptly north of the latitude of La Serena (Figure 3) and may not have affected the high volcanoes on the adjacent Altiplano to the north in a comparable way. This means that the climatic gradients and the zonal components of the atmospheric circulation might have been stronger than those of today. Rainfall was associated with the westerlies and was more intensive in mid-latitudes (Lauer and Frankenberg, 1983) but their influence did not shift as far north as Copiapó (Figure 3); this suggests the occurrence of extreme temperature and precipitation gradients between the tropics and the extratropics at about 28–30° South. This situtation is shown in the very strong poleward descent of the lower limits of glacial features on the western slope of the Andes at 30° South. This topic requires more extensive research.

LATE-GLACIAL ENVIRONMENT

The late-glacial environment between 17 and 11 kyr B.P. (Figure 3c) is best reconstructed from the stratigraphic sequence of Laguna Lejía (23° 47' South; 4,300 m; Figure 5). The paleohydrologic evolution of this basin is typical of other small catchments above 4,000 m such as Salar Aguas Calientes, Salar de Tuyajto, Laguna Miñiques, and Laguna Miscanti (Figure 1). The absolute chronology, based on radiocarbon ages of lake sediments (organic fraction, dated by AMS technique at ETH, Zurich) and thermo-luminescence TL dates (fine-grain technique on polymineral fractions 4–12 µm; Bürgi, 1992) is consistent; the ^{14}C age inversions at the base of the profiles are interpreted as contamination with young humic acid during more recent lake-level changes. White, brown, and grey/blue bentonite layers indicate volcanic activity and ash deposition in the shallow lake between 17 and 15 kyr B.P. These sediments correspond to a lake level about 5–10 m higher than today, as observed from facies correlation in a sediment section. From the chronological point of view, the radiocarbon age of 15.5 kyr B.P. (organic fraction of lake sediment), and the TL age of 16.7 kyr B.P. (volcanic hard pan; Bürgi, 1992) are reliable. Initially, biological activity in the lake was low and some long-distance arboreal pollen of *Alnus, Podocarpus,* and *Polylepis* in the bentonite layers of the Lejía and Tuyajto basins suggests strengthened and probably regular tropical influence. No pollen from local plant species was found, emphasizing sparse vegetation cover of the Altiplano. Results of a water and energy budget model for the Laguna Lejía catchment show that a summer precipitation regime with 300 mm/yr, representing an increase of 120 mm, or 60–70%, is a possible scenario to establish the lake level 5 m above the current level (Grosjean, 1992). Temporarily, the lake level might have been 10 m higher than today, corresponding to 400 mm/yr summer rainfall. This more humid, but still cold, environment led to groundwater recharge in the Atacama basin, as reported from Tambillo groundwater southeast of San Pedro with 3 pMC (percent modern carbon; Fritz, *et al.*, 1979:541). But absolute ^{14}C (dissolved inorganic carbon) age determination of groundwater may be difficult due to geochemical exchange in the reservoir

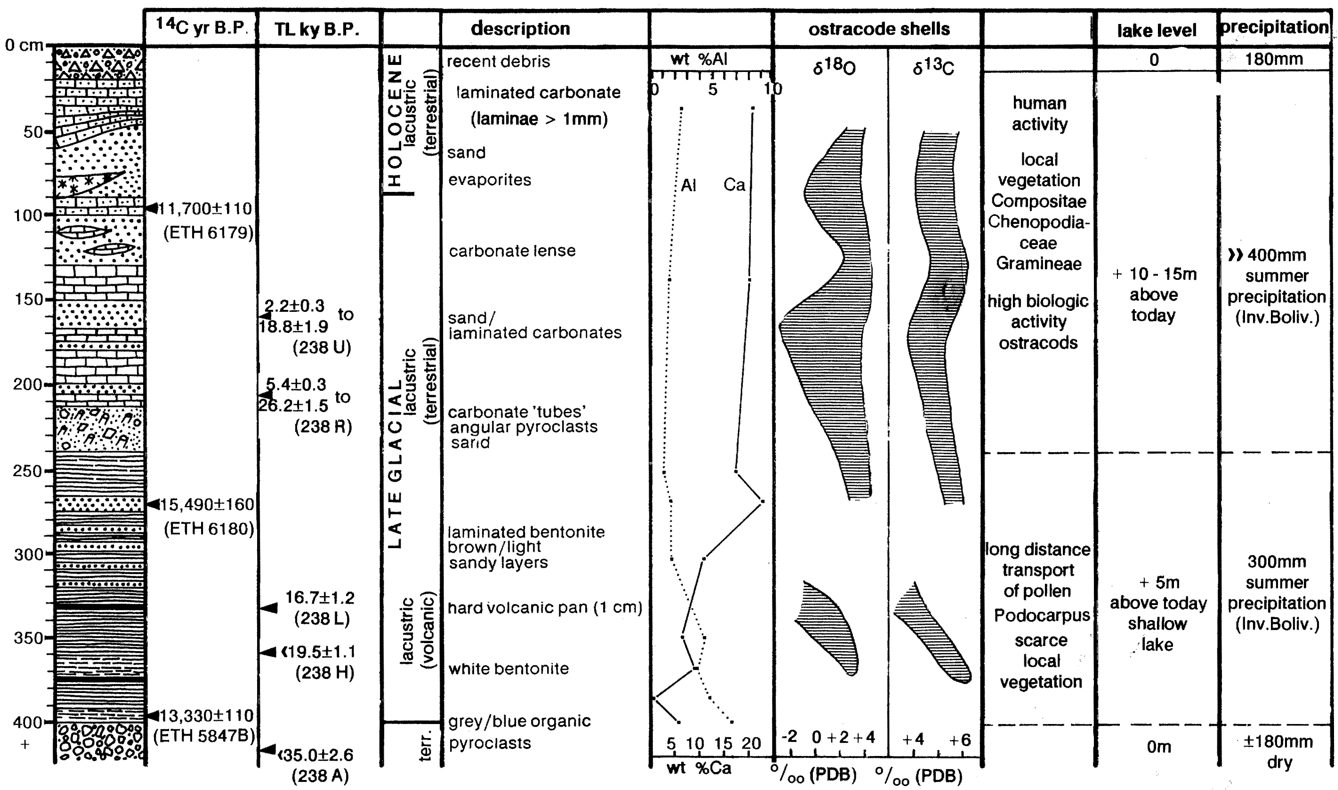

FIGURE 5. Section at Laguna Lejia showing the stratigraphic sequence, ^{14}C (organic fraction) and TL dates, Ca/Al distribution, $\partial\,^{18}O$ and $\partial\,^{13}C$ of ostracod shells, and paleohydrologic and paleoclimatic conditions.

("reservoir effect"). After about 15 kyr B.P., a distinct shift to higher lake levels took place, indicating wetter, and probably warmer conditions. Diatoms, ostracods, and biogenic silica-rich layers formed very fine laminated sediments which corresponded to a lake level 10–15 m higher than today. A probably short-to-medium-term maximum of the lake was reached at 25 m above present lake level. The water surface increased to 10.8 km^2, compared to 1.9 km^2 today. In terms of a possible climatic scenario, this means a minimum of 400 mm/yr summer precipitation (increase of 220 mm/yr or 120%; Grosjean, 1992), temporarily >500 mm/yr. The cloud cover was probably more extensive, maybe twice that of today.

These late-glacial high lake levels are synchronous with the Lake Tauca phase in the Salar de Uyuni basin (13–10,000 yr B.P.) and were made possible due to a precipitation increase in this basin of 180–200 mm/yr, or 30–50% (Kessler, 1985; Hastenrath and Kutzbach, 1985). Kessler (1985, 1991) emphasizes the importance of a summer rainfall pattern. Such a scenario is supported by long-distance transport of tree pollen from Bolivia to the research area (the Tuyajto and Lejía basins), by increased local vegetation cover on the Altiplano, and by the poleward shift of the tropical circulation belts at this time period (Markgraf, 1989:20, 21).

The laminated sediments of Laguna Lejía do not contain significant amounts of clastic sediments and this is interpreted as an indication of dense vegetation This conclusion is supported by the local pollen count (Figure 5), with natural erosion control on the slopes and a certain regularity in the annual distribution of precipitation events. However, the wide range in the $\partial^{13}C$ and $\partial^{18}O$ isotopic composition of ostracod shells in the laminated upper part of the stratigraphic column suggests major short-term fluctuations in the water body of Laguna Lejía (Figure 6). For the time period between 16 and 14 kyr B.P., groundwater recharge is reported for Tumbre (7.3 pMC). The ^{14}C ages are $\partial^{13}C$-corrected (Fritz *et al.*, 1979: 541).

Advection of humidity must have resulted in the extension of glaciers which probably formed the widespread moraine features above 4,250 m at 22° 23' South (Cerro Deslinde; Figure 7) and above 4,900 m at 25° South (Volcán Llullaillaco; Grosjean *et al.*, 1991: 105). The late-Pleistocene equilibrium line—if this term is transferable to the type of glacier found in this dry permafrost environment—must have been depressed to about 4,650 m, as seen at Cerro Pajonal (22° 27' S, 67° 53' W: 4,930 m). Attempts at absolute dating of these moraines using TL fine-grain technique (polymineral fraction 4–12 µm) have been unsuccessful so far. The six TL ages that were obtained appear to be too young (7,400–3,900 yr B.P.; Bürgi, 1992). A plausible explanation is that the fine-grain fraction 4–12 µm was transported from the soil surface to the pedon due to heavy rainfall during postglacial pedogenesis or due to cryoturbation

FIGURE 6. Shorelines on the lava beds indicate higher late-glacial lake levels of Laguna Lejia; see Figure 1.

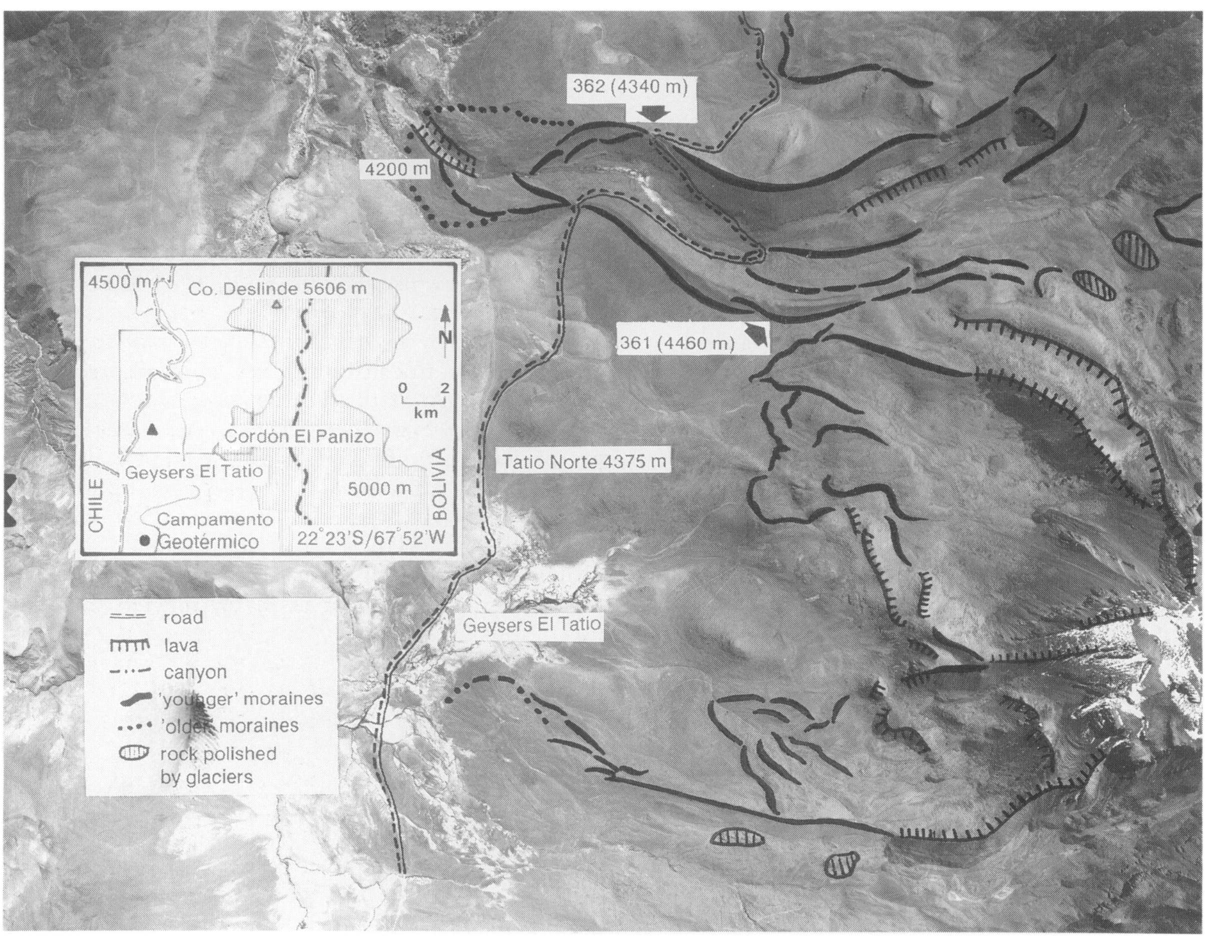

FIGURE 7. Cerro Deslinde showing probable late-glacial moraines and sites of thermoluminescence dating (361, 362); see Figure 1.

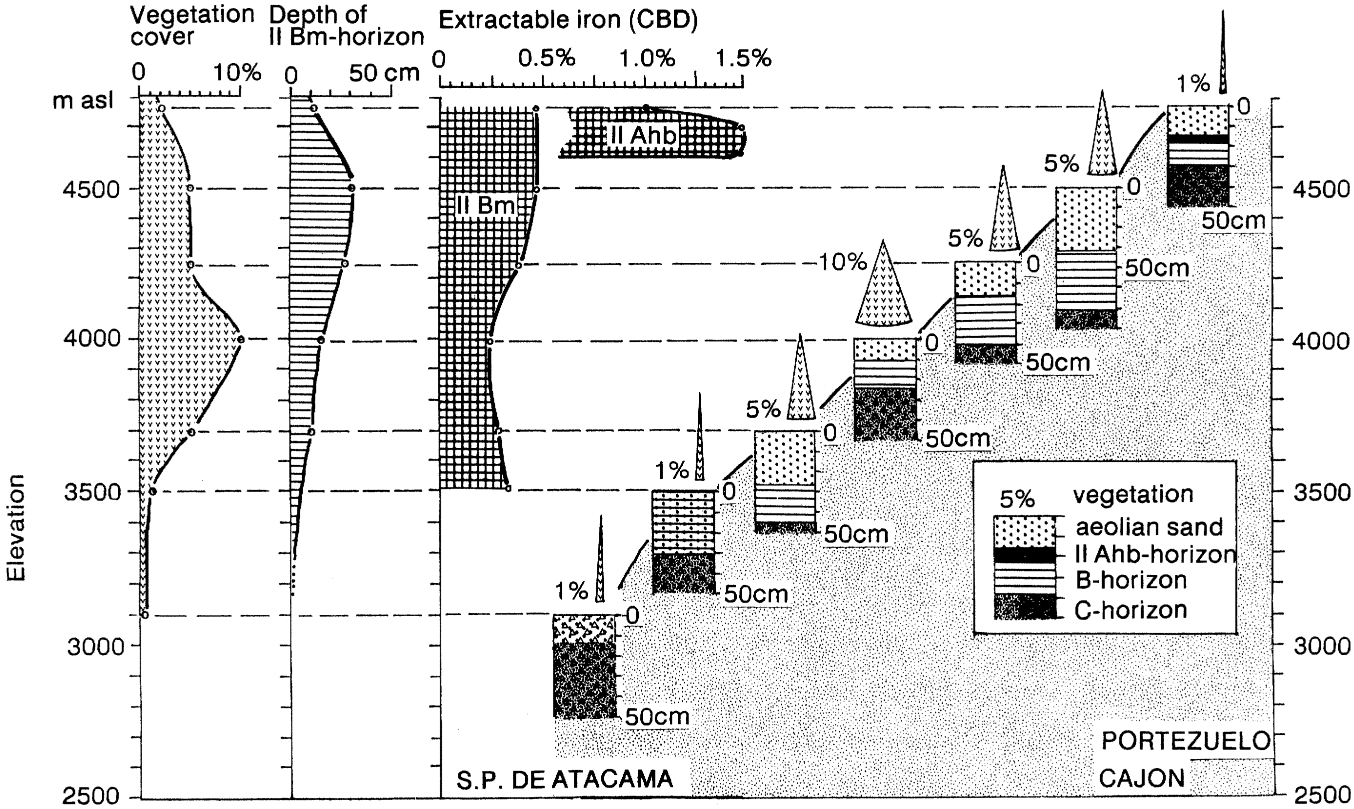

FIGURE 8. Present vegetation cover and paleosols along the western slope of the Altiplano at 23° South between 2,500 and 4,800 m.

and gelisolifluction. The equator-ward descent of the lowest moraines from 25° (4,900 m) to 22° S (4,300 m), the distribution and extent of the glacial and periglacial forms, and the lack of any comparable glacial features at Ojos del Salado (28° S) can best be explained by a southward shift of an intensified tropical summer rainfall pattern. This event was probably synchronous with Huancané II and III in the Cordillera Vilcanota, as well as with Choqueyapu II in the Cordillera Real and Chacabaya A and B (Lauer and Rafiqpoor, 1986; Clapperton, 1990; Seltzer, 1990).

Dense vegetation, animal life, and water resources were the basis for the first hunting and gathering cultures which probably arrived in the Atacama Altiplano at the very end of the Pleistocene at about 10,800 yr B.P. (Nuñez, 1983; Nuñez and Santoro, 1988).

EARLY HOLOCENE ENVIRONMENT

Fossilized soils indicate not only wetter but also warmer conditions with a denser vegetation cover during the early Holocene (Figure 8). The soil profiles were exposed along the western slope of the Altiplano between San Pedro (2,500 m) and Portezuelo del Cajón (4,800 m), with geological parent material, exposition, and slope angle being kept as constant as possible. The soil samples were analyzed for total element composition (HF-digestion), extractable iron (CBD), CEC, organic carbon, and carbonate content. Soil depth, as well as extractable iron content of the ll B_m horizon, show distinctly better soil development some 500 m above the actual vegetation maximum. Six profiles every 100 m were examined and the results are significant. Profiles along two other slopes (Quebrada Tumbre and Catúa) were also checked (Grosjean *et al.*, 1991). A discontinuous dark 1 cm-thick llA_{hb} horizon was found in well-protected sites, at the top of moraines, at 4,600–4,800 m. Direct dating of the paleosol has not yet been successful. The soils are found on top of the moraines at 4,600 m, showing that the weak llA_{hb} is of postglacial age. The period of the soil formation is bracketed by 8.4 kyr B.P. as indicated by the decrease of the lake level in the Salar Aguas Calientes 1 (Figure 1), and by 7.4 kyr B.P. at the lower limit, as shown by a TL-dated periglacial block whose creeping track is free of paleosols.

The chronology remains inconclusive. However, based on the available data, we assume an early Holocene age for soil formation. In terms of climatic information, it appears that wetter conditions and plant-relevant summer

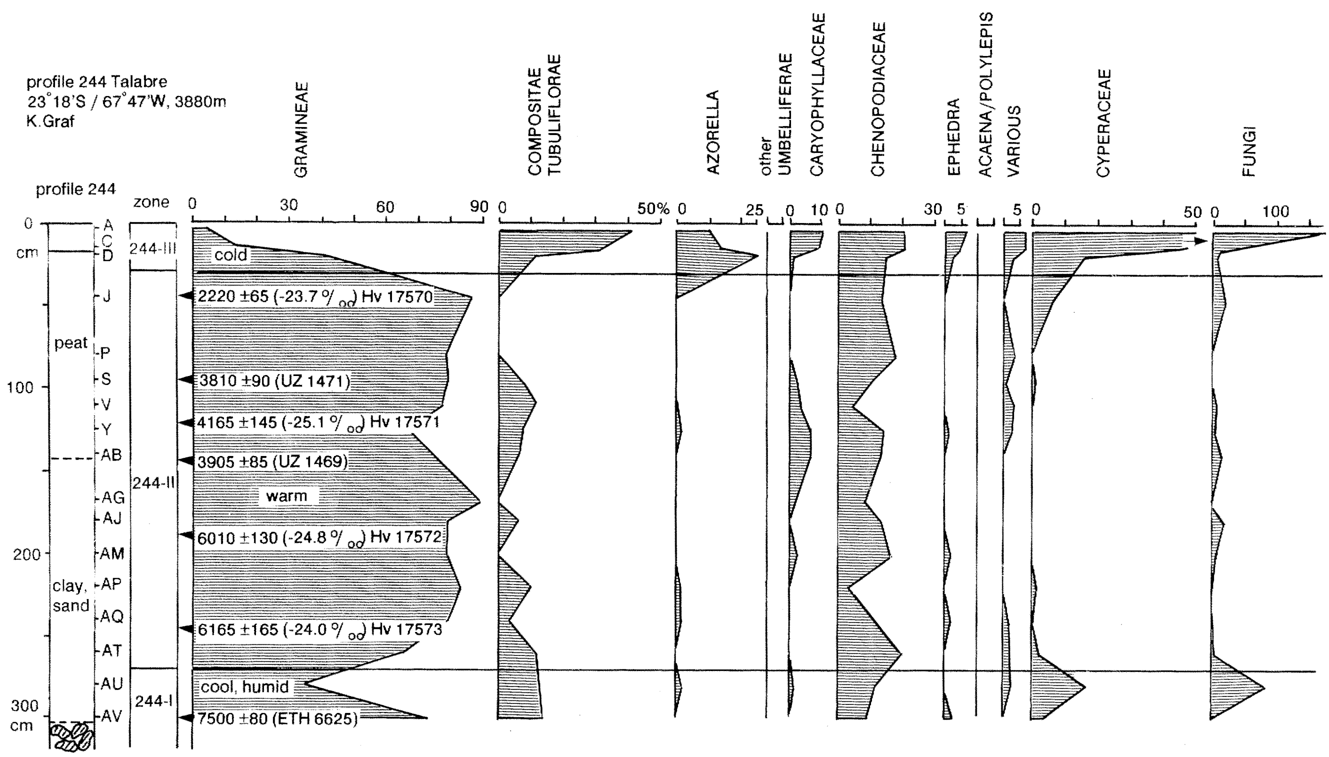

FIGURE 9. Pollen diagram of the Talabre core at 23° South; 3,880 m.

temperatures approximately 3.5°C higher than today prevailed at that time; this assumes a temperature gradient of 0.7°C/100 m. The higher lake levels may have lasted, but absolute dating of early Holocene lake sediments has not yet been successful. Recharge of the groundwater bodies is reported for San Pedro (borehole water, 11-12 pMC; Fritz *et al.*, 1979: 540) between 9 and 10 kyr B.P., depending on the model assumptions for reservoir effect.

Such favorable environmental conditions provided the basis for widespread hunting and gathering cultures during the first period of settlement (10,800–8,500 yr B.P.) in the Atacama highlands (Nuñez, 1983).

THE LATE HOLOCENE ENVIRONMENT

The environmental evolution since 7.5 kyr B.P. is best demonstrated by the pollen profile from Tumbre in the Quebrada Talabre at 3,880 m (Figures 1 and 9). Wet conditions (Figure 9, zone 244-I) were followed by a period with higher temperatures (approx. 6,000–3,000 yr B.P., zone 244-II), but tree growth was still restricted to Quebradas below 3,500 m and to the Atacama basin where there was groundwater available. In view of the favorable environment during the early Holocene, the scarcity of archaeological evidence ("silencio arqueológico," Nuñez, unpubl.) between 8,500 and 4,800 yr B.P. is an important topic for future investigation.

The second phase of extended human settlement occurred after 4,800 yr B.P., when the domestication of camelids occurred (Nuñez, 1983) and after 3,000 yr B.P. when agropastoral cultures were established (Nuñez, unpubl.). However, the increasing practice of irrigation at selected and restricted locations could be interpreted as the result of a slow degradation of natural resources on the open Altiplano. After 2,200 yr B.P., a fundamental change in environmental conditions is evident from the Talabre pollen profile (Figure 9; zone 244-III). The effect of intensive pastoralism on the abrupt change in vegetation is not yet clear, but is confirmed for the adjacent areas in Bolivia and Argentina (Ruthsatz and Fisel, 1984). Arid conditions with only partial groundwater recharge and sparse vegetation cover came to prevail throughout Northern Chile.

CONCLUSIONS AND OUTLOOK

The evolution of environmental conditions in the northern Chilean Altiplano since late-glacial time shows that changes in water, animal, soil, and vegetation resources have been considerable (Figure 3). Several biotic and abiotic systems were affected, and the water cycle, vegetation cover, and consequently animal and human activities responsed rapidly to climate change. The paleoecological findings indicate that environmental conditions during the last 17,000 yr have never been as dry as those of today.

If it is assumed that tropical summer rainfall from the north and northeast was mainly responsible for the more humid conditions on the Altiplano during late-glacial and early Holocene times, the western side of the Andes below 3,500 m must have remained extremely dry, even during the more favorable periods. By inference, strengthened tropical summer rainfall provided only the Altiplano with water resources while arid conditions have prevailed below 3,500 m since late-glacial time.

The water recharge during the late-glacial and early Holocene periods is of great significance even for the present time. The water samples of regional flow systems below 4,000 m do not contain any tritium at the end of the dry season. Hence, the groundwater has a long turnover time and/or is fossil, as indicated by several ^{14}C (DIC) dates. These factors are extremely significant for the expanding mining activities, the growth of Calama and Antofagasta, and the development of agricultural production in the oases along the Salar de Atacama and the Río Loa river system. The prospects for sustainable development could face very serious problems in the near future.

The paleoecological findings show that the tropical rainfall zone was reinforced during late-glacial and early Holocene times from the Sajama region at 18° S as far as the Ojos del Salado area at 27° South. It could be surmised that the tropical zone shifted southward by about 9-12 degrees latitude (Figure 3). In contrast, the westerlies were relatively stable. Today they extend to the region of La Serena (30° South) and it seems that they had no regular influence on the massif of the Ojos del Salado (27° South), even during the last glacial period.

This evident difference between summer and winter precipitation patterns becomes increasingly critical. Too much precipitation, especially snowfall, is observed in the transitional seasons of spring and autumn. This implies that collisions between cold air masses from the westerlies and warm tropical humid air masses would produce precipitation; this occurrence must be analyzed more precisely with remote sensing methods as part of our future research program. A better understanding of these processes could be applied to general circulation models.

The beginning of the cold-water upwelling in the eastern Pacific is reported for the time period subsequent to 5,000 yr B.P. (Enfield, 1989). The El Niño/Southern Oscillation (ENSO) phenomenon has become a climatic anomaly of the first order and has had dramatic impacts, such as the disastrous precipitation events in the Atacama region, at Antofagasta in June 1991, and heavy snowfall in Calama in May 1992. These events are most significant for geomorphic processes, such as landslides and debris flows, and probably also for water recharge in lower-lying areas.

Three high-resolution general circulation models (GCM), produced by the Canadian Climate Center, the Geophysical Fluid Dynamics Laboratory, and the United Kingdom Meteorological Office indicate that the high sensitivity of the most important summer precipitation in the subtropical Andes is due to global warming (WMO/UNEP/IPCC, 1990). Moreover, the models show uncertainties for the area between the tropical and extra tropical circulation and precipitation zones. Although regional interpretation of the GCMs must be used with discretion, major changes are to be expected; for the regional prediction of future conditions, the models must be verified and calibrated with field data. In this sense, an understanding of environmental conditions of the past is the basis for analysis of the most sensitive ecosytems of the present, and for more careful investigation of possible changes in the unique Atacama region in the future.

In conclusion, the Atacama region, as one of the most arid areas in the world, shows a dramatic conflict between rapid growth in economic activity and a weak and sensitive natural resource base. In addition, desert pollution can be irreversible and the groundwater recharge and the water storage capacity are still unknown. Understanding the past is the key to the present and the future: politicians, planners, and economists must be aware of these problems and mindful of these processes if they are to make long-term sustainable, rather than short-term destructive, decisions.

ACKNOWLEDGEMENTS

This study is part of the project "Climate Change in the Arid Andes" financed by the Swiss National Science Foundation (NF 21-27 824:89). We greatly appreciate the help of Willi Egli (Colegio Suizo, Santiago) and Marcela Espinoza (DIFROL, research permission). We owe thanks to Lautaro Nuñez for discussing the archaeological aspect of this paper.

REFERENCES

Aravena, R., Peña, H., Grilli, A., Suzuki, O., and Mordeckai, M., 1989: Evolución isotópica de las lluvias y origen de las masas de aire en el Altiplano chileno. IAEA-TECDOC-502, *Isotope Hydrology Investigations in Latin American*, 129-142.

Bürgi, A., 1992: Aufbau und Betrieb eines Thermolumineszenz-Labors zur Datierung quartärgeschichtlicher Proben. Dissertation Univ. Bern.

Clapperton, C. M., 1983: The glaciation of the Andes. *Quaternary Science Reviews*, 2: 83-155.

———, 1990: Quaternary glaciations in the southern hemisphere. *Quaternary Science Reviews*, 9: 121-304.

Enfield, D. B., 1989: El Niño, Past and Present. *Review of Geophysics*, 27: 159-187.

Fritz, P., Silva, C. H., Suzuki, O., and Salati, E., 1979: Isotope Hydrology in Northern Chile. IAEA-SM. 228, 26: 525-543.

Fuenzalida, H. and Rutllant, J., 1986: Estudio sobre el origen del vapor de agua que precipita en el invierno altiplánico. Informe final, Universidad de Chile. 51 pp.

Graf, K., 1989: Palinología del cuaternario reciente en los Andes del Ecuador, del Perú y de Bolivia. *Boletín del Servicio Geológico de Bolivia,* Serie A, IV/1: 69-91.

Grosjean, M., 1992: Zur Klimatologie und Paläoökologie des nordchilenischen Altiplano seit dem letzten Kaltzeitmaximum. Geographisches Institut Bern, 111 pp.

Grosjean, M., Messerli, B., and Schreier H., 1991: Seenhochstände, Bodenbildung und Vergletscherung im Altiplano Nordchiles: Ein interdisziplinärer Forschungsbeitrag zur Klimageschichte der Atacama. Erste Resultate. *Bamberger Geographische Schriften,* 11: 99-108.

Hastenrath, S. and Kutzbach, J., 1985: Late Pleistocene Climate and Water Budget of the South American Altiplano. *Quaternary Research,* 24: 249-256.

Kessler, A., 1985: Zur Rekonstruktion von spätglazialem Klima und Wasserhaushalt auf dem perusanisch-bolivianischen Altiplano. *Zeitschrift für Gletscherkunde und Glazialgeologie,* 21: 107-114.

______, 1991: Zur Klimaentwicklung auf dem Altiplano seit dem letzten Pluvial. *Freiburger Geogr.* Hefte, 32: 141-148.

Lauer, W. and Frankenberg, P., 1983: Late Glacial glaciation and the development of climate in southern South America. Proc. SASQUA International Symposium, pp. 103-114.

Lauer, W. and Rafiqpoor, M. D., 1986: Die jungpleistozäne Vergletscherung im Vorland der Apolobamba-Kordillere (Bolivien). *Erdkunde,* 40: 125-145.

Lynch, T., 1990: Quaternary Climate, Environment, and the Human Occupation of the South-Central Andes. *Geoarchaeology: An International Journal,* 5/3: 199-228.

Markgraf, V., 1984: Palaeoenvironmental history of the last 10,000 years in northwestern Argentina. Zbl. *Geol. Paläont.* Teil, 11/12: 1739-1749.

______, 1989: Palaeoclimates in Central and South America since 18,000 B.P. based on pollen and lake-level records. *Quaternary Science Reviews,* 8: 1-24.

Miller, A., 1976: The climate of Chile. In Schwerdtfeger, W. (ed.), *The Climates of Central and South America,. World Survey of Climatology,* 12: 113-129.

Nuñez, L., 1983: Paleoindian and archaic cultural periods in the arid and semiarid regions of Northern Chile. *Adv. in World Archaeology,* ll: 161-203.

Nuñez, L. and Santoro, C. M., 1988: Cazadores de la puna seca y salada del área centro-sur Andina (Norte de Chile). *Estudios Atacameños,* 9: 161-203.

Romero, H., 1985: Geografia de los Climas. *Geografia de Chile,* 12: 243.

Ruthsatz, B. and Fisel U., 1984: The utilization of natural resources by a small community on the Highlands of Bolivia and its effect on vegetation cover and site conditions. *Erdwissenschaftliche Forschung,* 18: 211-234.

Seltzer, G. O., 1990: Recent glacial history and palaeoclimate of the Peruvian-Bolivian Andes. *Quaternary Science Reviews,* 9: 137-15.

Veit, H., 1990: Jungquartäre Relief-und Bodenentwicklung in der Hochkordillere im Einzugsgebeit des Río Elqui (Nordchile, 30°S). *Bamberger Geographische Schriften,* 11: 81-97.

Vuille, M., 1991: Die Seen und Salare im nordchilenischen Altiplano. Eine hydrologische Untersuchung mit LANDSAT/TM-und LANDSAT/MSS-Daten. Geographisches Institut, Universität Bern, 99pp.

Vuille, M. and Grosjean, M., 1991: Monitoreo de cambios recientes en el balance del agua en algunos Lagos y Salares del Altiplano chileno utilzando datos LANDSAT-MSS y-TM. lll Encuentro nacional en percepción remota SELPER Chile, 118-132.

WMO/UNEP/IPCC, 1990: *Climate Change: The IPCC Scientific Assessment.* Cambridge Univ. Press, 365 pp.

Wright, H. E., Seltzer, G. O., and Hansen, B. C. S., 1989: Glacial and climatic history of the Central Peruvian Andes. *National Geographic Research,* 5(4): 439-445.