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Discussion of palynological methods and paleoclimatical interpretations in northern Chile and the whole Andes

Discusión de métodos palinológicos e interpretaciones paleoclimáticas en Chile septentrional y en todo Los Andes

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ABSTRACT

The present paper attempts to deal with palynological data with a view to deducing statements about climatic history. The primary data were collected from Quaternary lake sediments and peat bogs during field studies, and from the literature. The methodology will be shown in the example of Northern Chile and in comparison with the Andean region on the whole; however, laboratory methods are not discussed here. In this way, we can obtain secondary data concerning the ancient vegetation cover and the paleoclimate. Two aids were used in achieving this aim, i.e. an interpretation key for Andean pollen diagrams in general, and a table especially for pollen taxa from Northern Chile. This enables paleoclimatic interpretations to be made. Furthermore, several maps focus on the entire Andes in addition to the particularly significant role played by the Atacama region within the paleoclimatic sequences. Four maps illustrate the precipitation at 2000, 5000, 11000 and 19000 yBP, followed by a synthesis chart. Around 35000-25000 yBP, Patagonia and the Andes from Ecuador northwards were more humid than today; however, the cordilleras between 5° S and 37° S were drier. These conditions changed completely in the time lapse from 23000 to 13000 yBP, and since then the Atacama region, for example, has remained somewhat more humid than today; therefore, this extreme desertification took place only during the last 1000 years. Analogous information on the paleotemperature completes the interpretation. The period between 35000 and 25000 yBP suggests interstadial conditions which caused temperatures 3-4°C. lower than today quite uniformly across the whole area of the Andes. This contrasts with the Pleniglacial situation between approximately 23000 and 13000 yBP; the extreme depression took place at 19000-18000 yBP, geographicaly in Tierra del Fuego and Colombia (-8 to -9° C. in comparison with the annual means from today). Somewhat less intense was this last glacial phase in Ecuador (-6° C.). Here and in Middle Chile, the Lateglacial lasted 4000 to 5000 years in total, distinctly longer (as much as twice the duration) than the Lateglacial experienced in Colombia and in the Atacama region. During the Postglacial, the Andes of Chile have suffered no further significant variations in annual temperature (±1°C. in relation to today), except in the extreme South (2° to 3° C. higher) some 5000 years ago during the climatic optimum.

Key words: Paleotemperatures, paleoprecipitations, indicators taxa.

RESUMEN

La base del presente estudio son datos palinológicos provenientes de investigaciones propias de campo sobre sedimentos lacustres y turberas Cuaternarias, además de la bibliografía respectiva. En este trabajo se explica en detalle la extracción de estos datos primarios para el desierto de Atacama. A continuación, se explican métodos para deducir conclusiones sobre la paleo–vegetación y el paleoclima, obteniendose así datos secundarios. Para ello se usa una clave de interpretación de diagramas palinológicos y una tabla especial para los taxa indicadores de Chile septentrional. Se discuten varios mapas de los Andes en general, pero enfocando la situación específica del área de Atacama en la historia del clima. Siguen mapas sobre las precipitaciones en los Andes hace 2000, 5000, 11000 y 19000 años y asímismo una síntesis sobre estos cambios desde hace 35000 años. En el período entre 35000-25000 años (yBP) la Patagonia y los Andes septentrionales presentaban más humedad que hoy, mientras que las cordilleras eran más secas entre aprox. los 5°S y 37°S. Estas condiciones cambiaron completamente entre 23000-13000 yBP. Desde entonces, el área de Atacama quedó algo más húmeda que hoy; su desertificación extrema se dió desde hace unos 1000 años. Mapas correspondientes sobre las paleotemperaturas completan las conclusiones. Entre 35000-25000 años se estiman temperaturas medias anuales de unos 3°C más bajas que las de hoy. Esta situación interestadial cambió en el último Pleniglacial, mostrando variaciones extremas en Tierra del Fuego y en Colombia, con diferencias de -8 hasta -9°C en relación con hoy, mientras que en el Ecuador eran sólo unos -6°C. El Tardiglacial duró unos 4000 o 5000 años en el Ecuador y Chile central, es decir claramente más (quizás aún el doble) que en Colombia y en el area de Atacama. Durante el Postglacial los Andes de Chile sufrieron sólo pequeños cambios de ± 1°C en relación con las temperaturas actuales. Al contrario el extremo Sur tenía con temperaturas 2-3°C más altas que hoy durante el hipsitermal hace 5000 años .

Palabras clave: Paleotemperaturas, paleoprecipitaciones, taxa indicadores.

INTRODUCTION

In the Southern hemisphere, the Andes offer, in a unique way, the opportunity to make observations of geographical, biological and climatological data on a large scale. The present paper attempts to deduce their interrelations, dealing principally with pollen analysis. The methodology will be shown for the example of Northern Chile. The field studies were carried out in 1990 and 1991, together with scientists from the Universities of Berne and Vancouver, supported by the Swiss National Foundation. The computer graphics were designed by Max Maisch, University of Zurich; the datings were provided by laboratories at the Landesamt für Bodenforschung Hannover, at the ETH (AMS spectroscopy) and at the University of Zurich; and the English manuscript has been revised by Colin Thomas, University of Sheffield.

At the beginning it will be useful to give a short overview. The first part deals with primary data which have been collected from various pollen profiles in Northern Chile. During the last 20 years, I have completed analogous studies in other Andean countries, especially Bolivia, Ecuador and Venezuela (GRAF 1992). By comparing these results it is possible to outline some general rules and methods which can be used in such studies. In this way, deducing the ancient vegetation cover and the paleoclimate, one gets diverse secondary data . With this information, we can make important statements about the climatic history of the Atacama desert during the last 35000 years. In this synthesis it will also be interesting to discuss further palynological interpretations for the whole of the Andes.

PRIMARY DATA

Topography

The special study area comprises the Western Cordillera between the Salar de Atacama and the Chilean boundary to Ar-

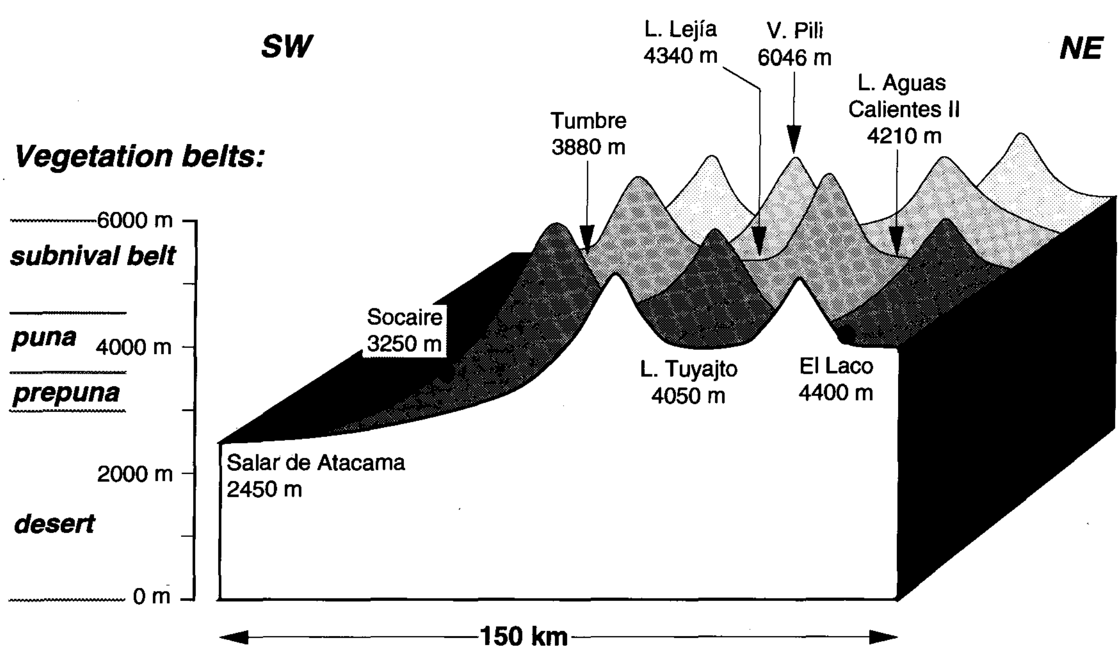

Fig.1: In this volcanic region we find many lakes and salars which sometimes offer excellent profiles for palynological investigations

En esta región volcánica se encuentran muchos lagos y salares que ofrecen a veces perfiles excelentes para investigaciones palinológicas gentina and Bolivia, lying at 2500-6000 m (800-2000 ft.) between 22-24°S. There we find many volcanoes which have previously erupted lava streams into wide basins. Often these interandean basins and valleys are filled with lakes, salars and occasionally with peat bogs. Their sediments have been analysed palynologically between the altitudes of 3850 and 4350 m, for example on the border of the lakes Lejía, Tuyajto and Aguas Calientes II, as well as within the peat bog Tumbre near the village Talabre (see Fig.1). The advance of the glaciers of the last ice age reached a maximum at an altitude of 4200 m, but for the most part they extended only as far as an altitude of 4400 m, and thus they did not reach the locations studied.

Actual vegetation

Along a transect from the volcanic Cordillera to the Salar de Atacama, glaciers are absent today (Fig.1). The subnival belt lies approximately between the altitudes of 4500 and 6000 m and is sparsely covered in the lower region by cushion plants, bunch grasses and rosette plants: Compositae, *Azorella*/Umbelliferae, *Gentiana*, *Oxalis* and *Pycnophyllum*/Caryophyllaceae. At altitudes of 3750-4500 m, the Puna is situated. This is an Andean shrub and grass belt with additional Compositae, and with shrubs of *Ephedra*, Leguminosae and Verbenaceae. The subsequent belt between 3100-3750 m is called Prepuna, which is again dominated by Compositae, but this area also contains typical xerophytic representatives such as *Atriplex*/Chenopodiaceae, *Descurainia*/Cruciferae and *Tephrocactus*. Lower in altitude, the vegetation cover becomes more and more open and changes into desertified sand and salt areas.

The pollen diagram from Laguna Lejía

As an example the pollen diagram Laguna Lejía is presented in Fig.2. It reflects the relatively sparse Andean vegetation, dominated by Gramineae, Compositae or Chenopodiaceae. Of particular interest are those plants shown on the right side of the diagram. There we see Cyperaceae and further plants common to humid locations, which characterize superbly the primary

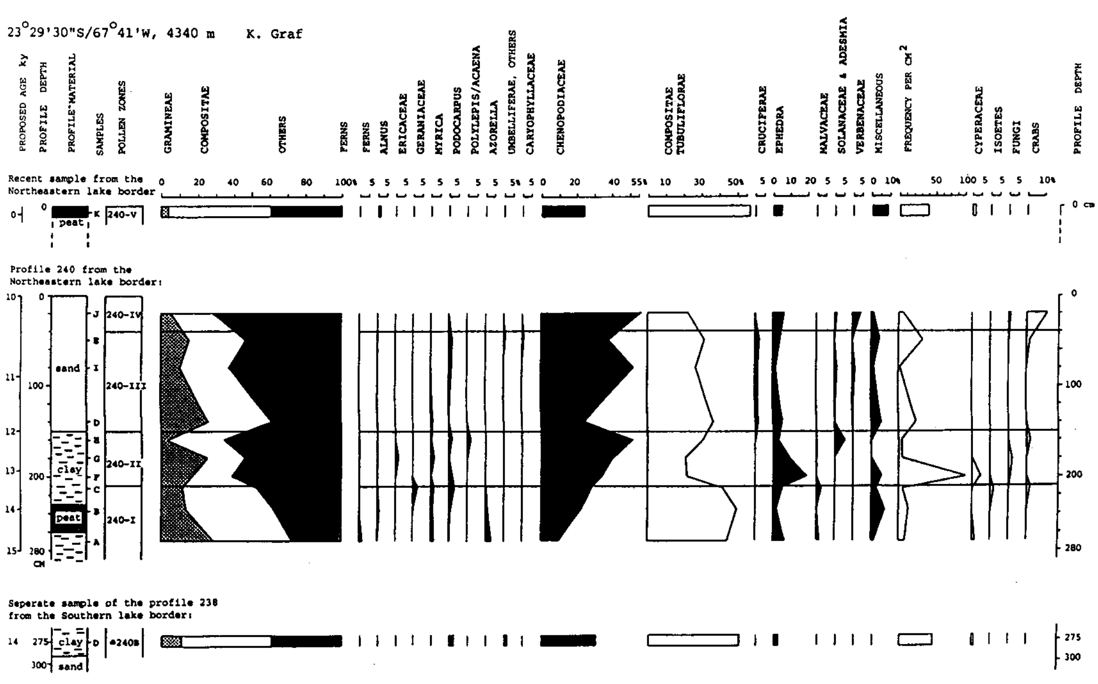

Fig.2: Profile 240, Laguna Lejía

Perfil 240, Laguna Lejía

sedimentation environment. According to this information, *Alnus*, *Podocarpus* and *Polylepis* for example must be classified as arboreal pollen as a result of their long distance transportation by the wind. The expression palynomorphs indicates all pollen grains and spores. In any case, fern spores occur very rarely in these arid regions.

The profile 240 is taken from the Northeastern border of Laguna Lejía. Several datings from the neighbouring profile sites 125 and 238 place it in the Lateglacial between 15000 and 10000 yBP (Messerli et al. 1992, p. 265). For instance, the samples 238D and 240B in Fig.2 correspond with 125N from Laguna Lejía, and this sample has been 14C dated 13330±110 yBP (ETH-5847B). Zone 240-I is characterized by 40-50% Compositae, whereas in the subsequent upper zones the Chenopodiaceae dominate. The long distance transportation of pollen has a tendency to decrease towards the higher levels. Only in zone 240-V are similar conditions to those found at the profile base once again observed.

METHODS TO CLASSIFY POLLEN DIAGRAMS

General interpretation key

A well defined strategy is necessary to interpret the primary pollen data mentioned above. According to my experiences with diverse peat bogs in the entire tropical Andes, I have endeavoured to formalize this procedure with a standardized interpretation key. Principally, it allows one, with the use of a diagram, to decide if conclusions drawn from the pollen percentages are to be made in a direct or indirect manner. Conclusios drawn in a direct manner mean that one equates a frequent pollen type with a high frequency of the corresponding plants. On the contrary, one draws an indirect conclusion if, for example, a large amount of a certain pollen type is estimated to originate from large distance transportation and therefore only a little vegetation has actually grown at the profile site. The points 1-11 in the interpretation key indicate the direct and indirect manner of interpretation, whilst the points 12-15 go further towards the decision as to whether or not the climate was humid. The temperature or the wind regime are not explicitly mentioned. Such conclusions are only to be drawn following comparisons of several diagrams and their geographical distribution.

1. Locations in low latitudes	
1a) situated between 2000-5000 m in the tropics or subtropics (12°N - 32°S)	3
1b) not the case	2
2. Locations in higher latitudes	
2a) in mid latitudes (33-56°S) between 0-2000 m	3
2b) not the case	individual interpretation
3. Restriction by precipitation	
3a) annual mean greater than 1500 mm	Relation:direct
3b) annual mean of maximum 1500 mm	4
4. Judgement of the sample material	
4a) inorganic (marine, lacustrine or glacial) sediments including gyttja	5
4b) organic sediments, peat	10
5. Predominant grain sizes	
5a) clay	6
5b) coarser sediments	indirect/12

6. Judgement of the degree of meteorization	
6a) palynomorfs predominantly meteorized or bleached	indirect/12
6b) palynomorfs predominantly with intact walls (exine, perispore, exospore)	7
7. Sedimentation process	
7a) lacustrine or marine sediments (e.g. loam)	direct
7b) not the case	8
8. Degree of human influence	
8a) clay from a prehistoric cave or cultural horizon	direct
8b) gyttja, hangfood loam, or other fine sediments	9
9. Aquatic plants	
9a) diagram zone with more than 10% *Isoëtes* on averageand at the same time further aquatic indicators(*Botrycoccus*, *Myriophyllum*, *Potamogeton* or *Typha*) indicating peats and shallow water	direct
9c) not the case	10
10. Percentage of plants originating from humid localities	
10a) diagram zone with more than 10% of Cyperaceaeor Juncaceae on average	direct
10b) A maximum of 10%	11
11. Plants from humid locations in other diagram zones	
11a) mean amount of Cyperaceae in the diagram zone less than 1/3 of that in another diagram zone	indirect/12
11b) A minimum of 1/3	direct
12. Dryness of climate estimated from arboreal pollen	
12a the diagram zone contains more than 30% arboreal pollen originating from cloud forests on average	relatively dry
12b) A maximum of 30%	13
13. Dryness of climate estimated from tree ferns	
13a) the diagram zone contains more than 10% Cyatheaceae spores on average	relatively dry
13b) A maximum of 10%	14
14. Dryness of climate estimated by comparing different zones	
14a) the diagram zone contains a minimum of 4 times morepollen from trees and other forest representatives than from the corresponding poorest postglacial millenium	relatively dry
14b) less than 4 times that amount	15
15. Summarized judgement of pollen origin	
15a) the diagram zone contains on an average more than 70% plants possibly originating from the surroundings (excl. those of humid localities)	relatively humid
15b) A maximum of 70%	individual interpretation

Application on the special pollen taxa of Northern Chile

Once the principal interpretation of each diagram zone has been decided upon, we attempt to judge the paleoclimatic importance of particularly characteristic pollen types. For Northern Chile, this is demonstrated in Fig.3. For instance, if arboreal pollen of *Alnus* and *Polylepis* is found and an indirect conclusion is drawn (signature ID), the resulting climate must have been cold and humid. In the same way, *Podocarpus* indicates a cold, dry climate. This is due to the biogeographical fact that *Podocarpus* prefers less humid sites than *Alnus* and *Polylepis*, and therefore we infer a certain dryness of climate. On the contrary, if a direct interpretation mode (signature D) is chosen for the three aforementioned taxa, this indicates a relatively warm climate. A further interesting example is given by *Ephedra*. Pollen of this shrub occurs nearly exclusively in the case of direct interpretation, and the corresponding climate is cold and dry. *Azorella* also reflects this Puna climate by way of a direct conclusion; however, *Descurainia* indicates rather humid conditions.

Of course, the table of Fig.3 is not entirely complete, but it may give an illustration of the observations made in Northern Chile and the state of knowledge today. Effectively, only the typical plants of an entire community would allow a realistic interpretation. However, if the information indicated is based on numerous Andean pollen diagrams, many new fascinating possibilities of climatic interpretation are given.

PALEOCLIMATIC EVALUATION

Maps of former precipitation

As in the preceding text, the aim is now to present the methods used step by step. First, the precipitation in the whole Andes 2000 years ago is illustrated graphically (Fig.4) in a rather more concentrated manner. For each cited profile, it is indicated whether more or less precipitation was falling at that point in time in comparison with the levels of today. Much drier climate is symbolised by (—) and similar humidity conditions to those existing today by (·). The distribution of the data allows one to illustrate regions of surplus and regions of

Climate indication:	humid	dry	independent in relation to humidity
cold	ID Polylepis & Alnus ID Tarasa/Malvaceae D Descurainia/Cruciferae D Chenopodiaceae in lacustrine sediments	ID Podocarpus D Azorella/Umbelliferae D Ephedra D Tarasa D Compositae	category "diverse", e.g. D Scrophulariaceae, D Geraniaceae or D Labiatae
warm	ID Fabiana/Solanaceae ID Adesmia/Leguminosae ID Verbena D Ferns D Polylepis & Alnus	ID Ferns D Podocarpus D Verbena D Amaranthaceae D Cactaceae	D Solanaceae D Malvaceeae
independent in relation to altitude	ID Caryophyllaceae ID Gramineae ID Chenopodiaceae D Cyperaceae D Fungi (spores)	D Chenopodiaceae in peat with a lot of Cyperaceae D Caryophyllaceae	ID Compositae ID Cyperaceae ID Fungi D Gramineae

Fig.3: Interpretation made directly (D) and indirectly (ID) for some important pollen taxa in the Atacama desert. For detailed explanations see text.

Interpretación directa (D) e indirecta (ID) para algunos tipos de polen de la puna de Atacama. Para explicaciones detalladas vea en el texto.

deficit. Approximately 2000 years ago, for example in the Tierra del Fuego region, we note a somewhat drier climate than is seen today; however, in Middle and Northern Chile a more humid climate existed. The coast of Peru is also shown as having had a relatively humid climate and, therefore, the tropical Andes at that time were, on the whole, drier than today.

Using the same method the three maps of Fig.5 have been produced and will be interpreted. The Andes of Northern Chile and Argentina 5000 years ago were characterised by a climate rather more humid than that of today and the Southern Andes experiencing drier conditions. The situation approximately 11000 yBP portrays the Andes from 18°S northwards as a relatively deficient region; however, in absolute terms the Colombian Andes, for example, had nevertheless a humid climate. If we focus on one former situation in particular, namely the last Pleniglacial at 19000-18000 yBP (see also Frenzel 1988, p.210), Chile was characterized by a similar distribution of precipitation to that seen at 5000 yBP, and so too were Colombia and Venezuela. However, quite conversely the conditions of the annual mean temperature were extremely different during these phases.

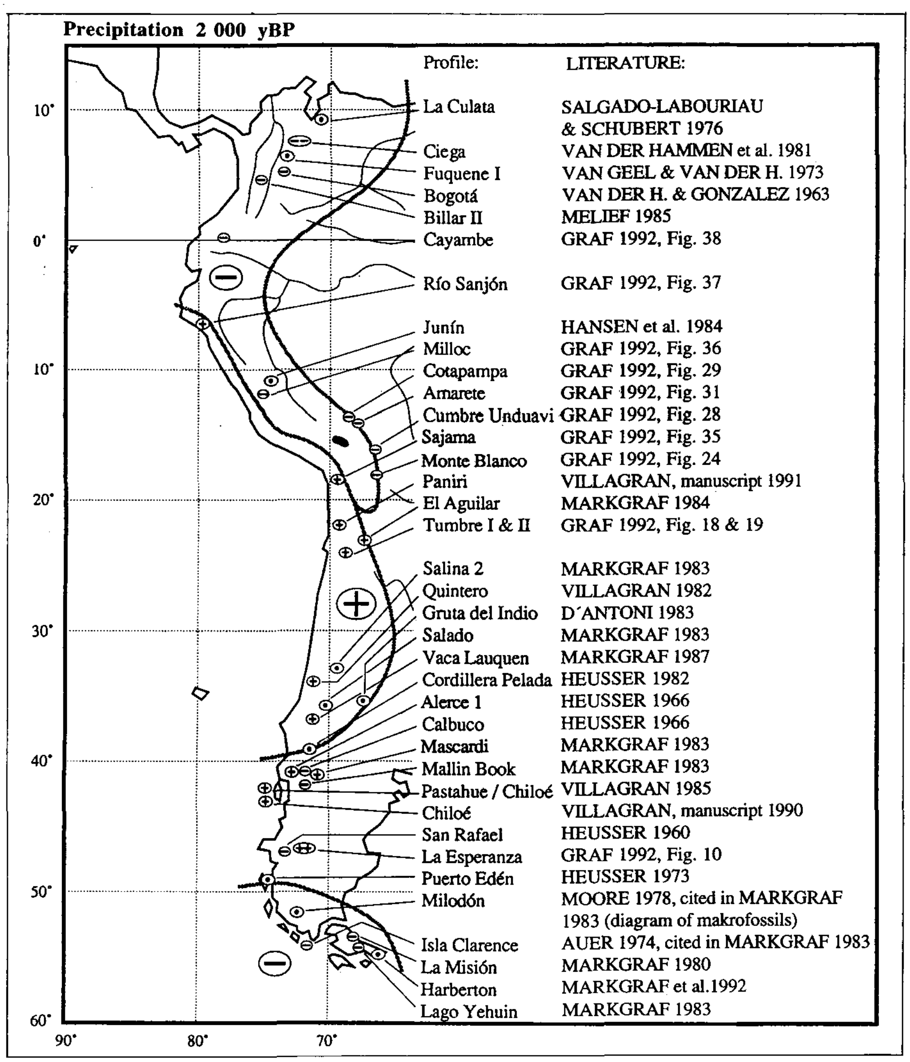

Fig.4: Precipitation in the Andes 2000 years ago, compared qualitatively with today (see text).
Precipitación en los Andes desde 2000 años, en comparación estimada con la situación actual (vea texto).

Maps on paleotemperature

Annual mean temperatures at around 5000 yBP, 11000 yBP and 19000 yBP are illustrated in Fig.6 (for the Northern Hemisphere two analogous maps are given by Frenzel 1988, p.209 & 214). The postglacial optimum lies around 5000 yBP and has produced in the whole Andes a somewhat warmer climate than today. The largest positive values are estimated to occur in Tierra del Fuego, in the Titicaca lake region and in the area of Bogotá. The situation was contrarily inverted at 19000 yBP, with extreme values of -8°C. in Tierra del Fuego, the Sabana de Bogotá and probably the Altiplano region, too. During the Lateglacial, around 11000 yBP, quite similar depression values, namely -5 till -6°C., occur in the three regions already mentioned, whilst values of only -3° C. occur in the intermediate areas.

Synthesis of precipitation and temperature during the last 35000 years

In this continuation the facts noticed are compressed and concentrated even more. In Fig.7 trends towards more humid or more arid climates are simulated, based on the information from Figs. 4 and 5. The data for instance at 5000 yBP are plotted vertically in the rectangular diagram. This gives a climate which is drier than today in the Southern Chilean and Argentine Andes, i.e. south of 37°S, and also in Peru and Colombia. In this context it is notable that Patagonia was more humid than today approximately 35000-25000 years ago, along with the Andes from Ecuador northwards. These conditions changed completely in the time lapse between 23000 and 13000 yBP. Only at the boundary to the Postglacial were both relatively humid regions in the Southern and Northern An-

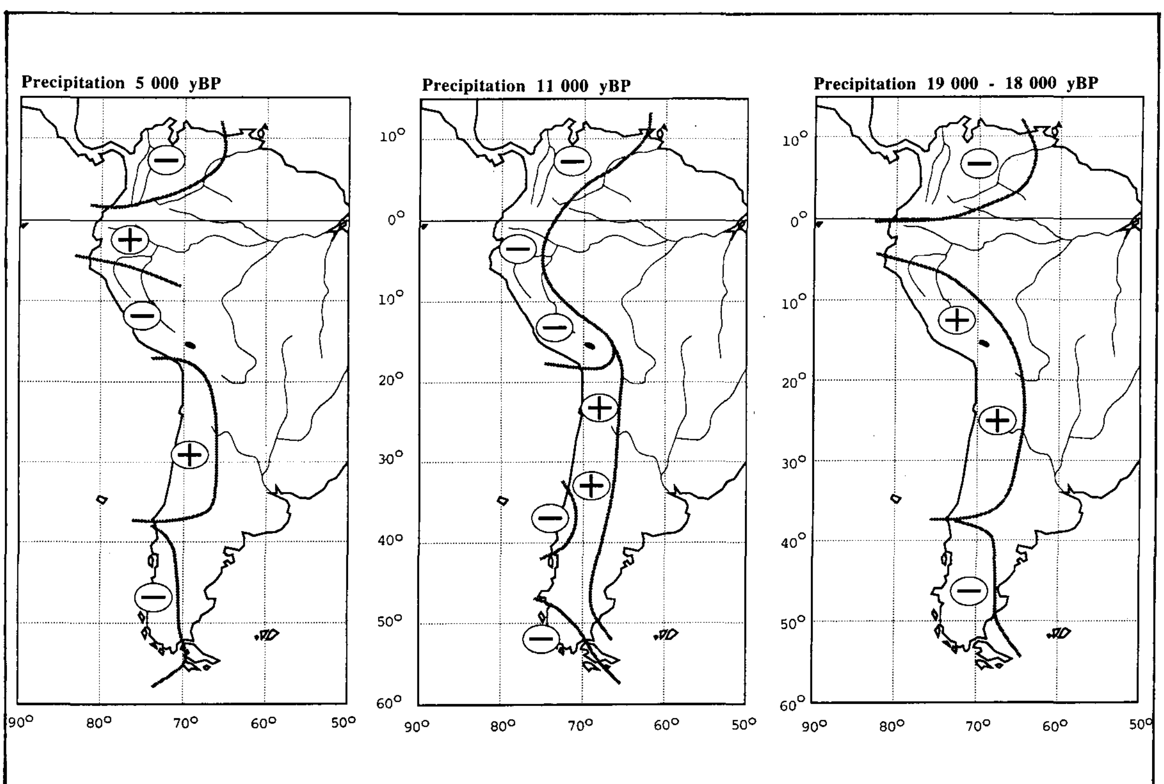

Fig.5: Former precipitation in the Andes.
Precipitación anterior en los Andes.

des once again established. In addition, the Atacama desert situated between 23-27°S was then more humid than today, and this area remained so almost until the present day. Therefore, this extreme desertification only took place during the last 1000 years.

Fig.8 gives analogous information concerning palaeotemperature changes in the Andes. The period between approximately 35000 and 25000 years suggests interstadial conditions which caused temperatures 3-4°C. lower than today quite uniformly in the whole area of the Andes. This contrasts with the Pleniglacial situation between approximately 23000 and 13000 yBP. The extreme depression took place between 19000 and 18000 yBP, i.e. geographically in Tierra del Fuego and Colombia (-8 to -9°C. in comparison with the actual annual means of today). This last glacial phase was somewhat less intense in the region of Ecuador (only -6°C. compared to today). Here, the distinct warming of the Lateglacial began early and lasted about 6000 years; however, this was distinctly longer than the Lateglacial phase experienced in the Atacama region. At the beginning of the Postglacial at 10000 yBP, the temperatures reached similar values to those reached during the Interstadial at 30000 yBP. Temperatures practically identical to today were achieved approximately 9000 yBP, and the Chilean Andes in particular have suffered no further significant variations of annual temperature since that time.

The sequences described may of course be examined in more detail, and many statements are merely hypothetical as yet. For example an exact answer is not given to the question of a possible final glaciation between about 12500 and 8000 yBP in

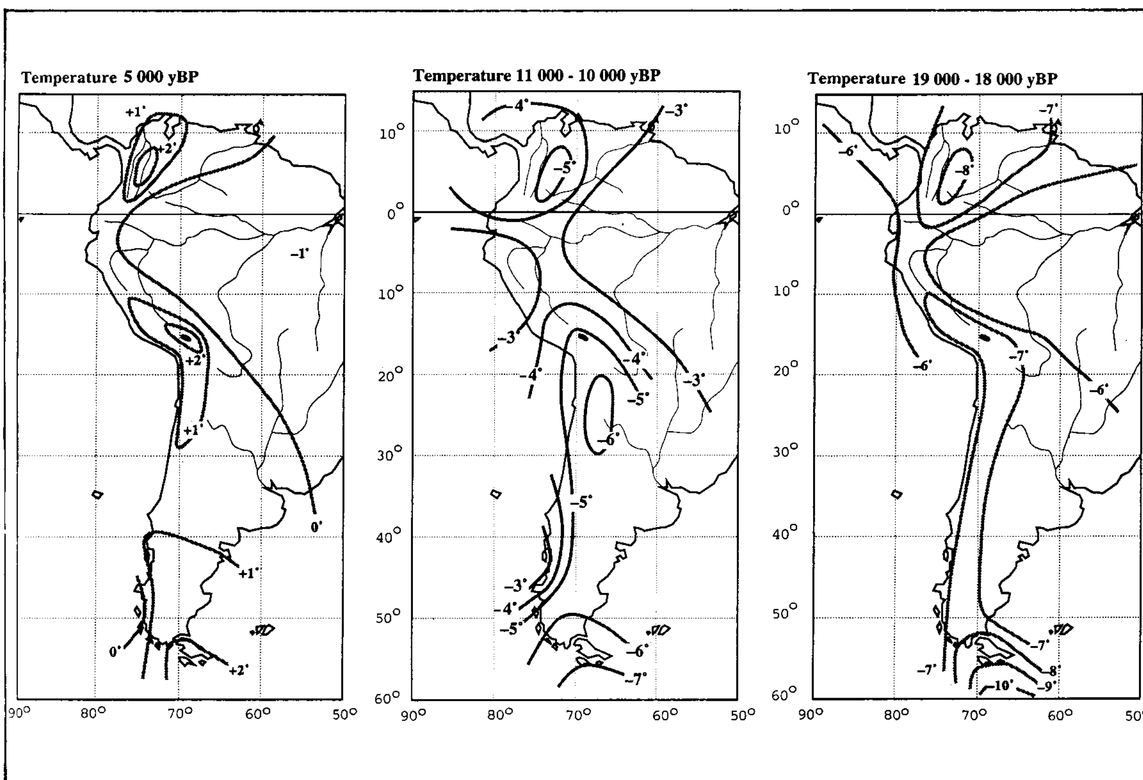

Fig.6: Former temperature in the Andes, compared with the present day.

Paleotemperatura media annual en los Andes, en comparación con hoy .

Tierra del Fuego, (see Markgraf 1983, p.50). Moreover, I agree with Heusser (1984, p.88), when he states that between 14600 and 4500 yBP in the Chilean Lake region (40-42°S) variations in the annual mean temperature did not exceed 2-3°C. when compared to the annual means of the present time. Regretably, we have insufficient information detailing the changing seasonal temperatures (see e.g. Heusser 1984, p.77). The area of the Valdivian rain forest between 40 and 48°S Markgraf (1989, p.20) indicates temperatures 4°C. lower than today immediately before 12000 yBP, which coincides with a peak towards the left of Fig.8. In this sense, future palynological results may be able to refine these figures. Naturally, one could also modify them using glacial historical or other paleoclimatic methods. Nevertheless, the aim of the present study has been delimited methodically, namely to review a great number of palynological data and to interpret them in the context of wide temporal and spatial variations.

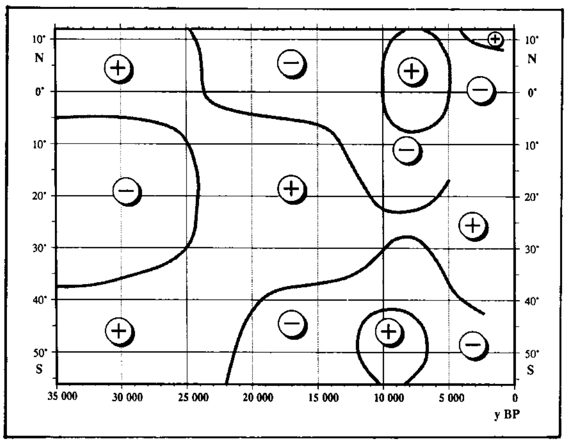

Fig.7: Reconstruction of the former precipitation, compared to the present day.

Reconstrucción de la precipitación pasada, en comparación con hoy.

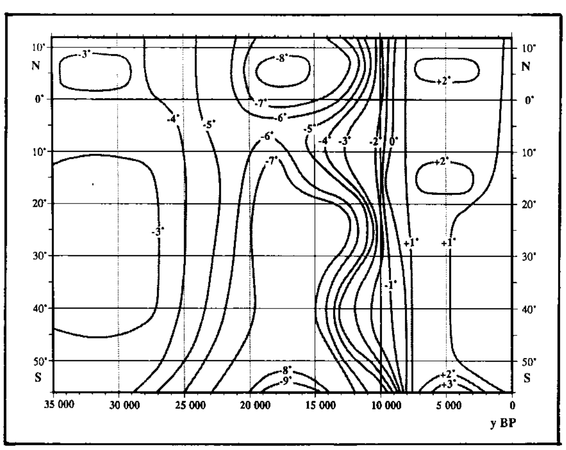

Fig.8: Reconstruction of the former mean annual temperature, compared to the present day and displayed for the Andes without big oceanic influence.

Reconstrucción de la paleotemperatura media annual, en comparación con hoy, para los Andes situados fuera de gran influencia oceánica.

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