Proceedings of the 9th International Clay Conference, Strasbourg, 1989, V.C. FARMER and Y. TARDY (Eds)
Sci. Géol., Mém., 88, p. 53 - 61, Strasbourg, 1990

ENVIRONMENTALLY CONTROLLED VARIATIONS IN CLAY MINERAL ASSEMBLAGES FROM LAKE SEDIMENTS IN THE VENEZUELAN ANDES

Baruch WEINGARTEN*, Richard YURETICH*, Raymond BRADLEY*
and Maria Lea SALGADO-LABOURIAU**

ABSTRACT - X-ray diffraction analysis of the <2µm fraction of near-surface sediments (shallower than 1 m) from lakes in the central Andes of Venezuela reveals distinctive clay mineral assemblages at different elevations. Sediments located in the Tierra Helada climatic zone at elevations of 3,460 to 3,700 m a.s.l. are characterized by illite, chlorite, an illite-chlorite (a mixed-layer) and a degraded Mg-chlorite. Some kaolinite is also present.

At lower elevations (1,620 to 2,380 m a.s.l.), within the Tierra Templada climatic zone, the clay-size fraction of sediments from two lakes in the upper part of the zone is generally amorphous to XRD except for some gypsum. In two other lakes at lower elevations within the zone, the clay fraction is dominated by kaolinite with minor amounts of illite and degraded chlorite. Gibbsite is also present in amounts ranging from a trace to 50%. In the single lake in the Tierra Caliente climatic zone (at 1,100 m a.s.l.) illite dominates the clay assemblage (>90%) with subordinate kaolinite and traces of chlorite.

The clay-mineral assemblages generally reflect altitudinal patterns of temperature and precipitation, although the alkaline water chemistry of the Tierra Caliente lake and local bedrock influences modify the patterns. A long core (6.3 m) retrieved from one lake in the Tierra Templada zone shows the clay minerals before ~10,000 years B.P. to be similar to those in the modern Tierra Helada zone. A climatic change accompanying glacial retreat is inferred.

INTRODUCTION

The Venezuelan Andes extend for over 450 km across northwestern Venezuela. The highest elevations are reached in Sierra Nevada de Mérida, the central part of this mountain range (Fig. 1). One of the notable features at elevations above 3,400 m is the abundance of lakes which occupy cirques, glacially scoured depressions and basins behind terminal moraines. In addition, there are several lakes at lower elevations in basins of various origins.

In this study we report clay mineral data from nine lakes in the Venezuelan Andes (Fig. 1). The selected lakes range in elevation from 1,100 m to 3,700 m a.s.l. and are located in three different altitudinal climatic zones (Lauer, 1979) (Fig. 2).

The four highest lakes, Montón, Saisay (both at 3,700 m), Mucubají (3,540 m) and Negra-A (3,460 m), are located in the Tierra Helada climatic belt (alpine, cold and moist). Except for Lake Mucubají, which is a moraine-dammed lake, the other three occupy cirque basins. These high-elevation lakes are all underlain by the Precambrian Sierra Nevada Formation, consisting primarily of gneisses, with subordinate granites and schists.

Four lakes are located in the Tierra Templada climatic zone (temperate, warm and moist). The two higher lakes, Brava (2,380 m) and Los Lirios (2,300 m), are underlain by phyllites and slates of the Paleozoic Mucuchachí Formation. The two lower lakes, Negra-M (1,700 m) and Blanca (1,620 m) are underlain by the Sierra Nevada Formation. The origin of these basins is not known, although the depressions may have been formed by glacial scour prior to Quaternary(?) tectonic subsidence (C. Schubert, personal communication, 1983).

---

*Department of Geology and Geography
University of Massachusetts, Amherst, MA 01003, USA
**Departamento de Geociencias
Universidade de Brasilia, 70910 Brasilia D.F., BRAZIL

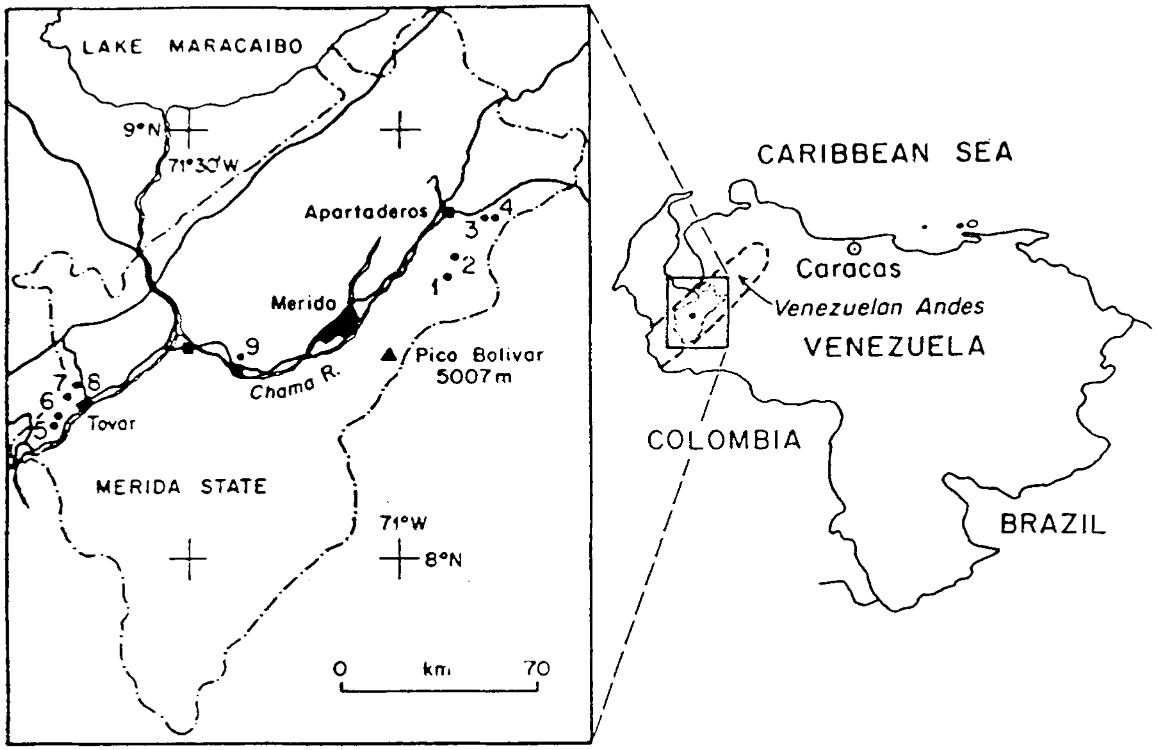

Figure 1 : *The study area and location of the lake basins; Montón (1), Saisay (2), Mucubají (3), Negra-A (4), Brava (5) Los Lirios (6), Negra-M (7), Blanca (8) and Urao (9)*

The lowest lake, Urao (1,100 m) is located in the Tierra Caliente climatic zone (sub-tropical, warm and semi-arid). This lake is situated within a tectonic pull-apart basin related to movement along the Boconó Fault (Schubert, 1982). The rocks around the basin are the Triassic red-beds of the La Quinta Formation. In addition to sporadic rainfall the lake is fed by alkaline spring waters and has no permanent surface outlet.

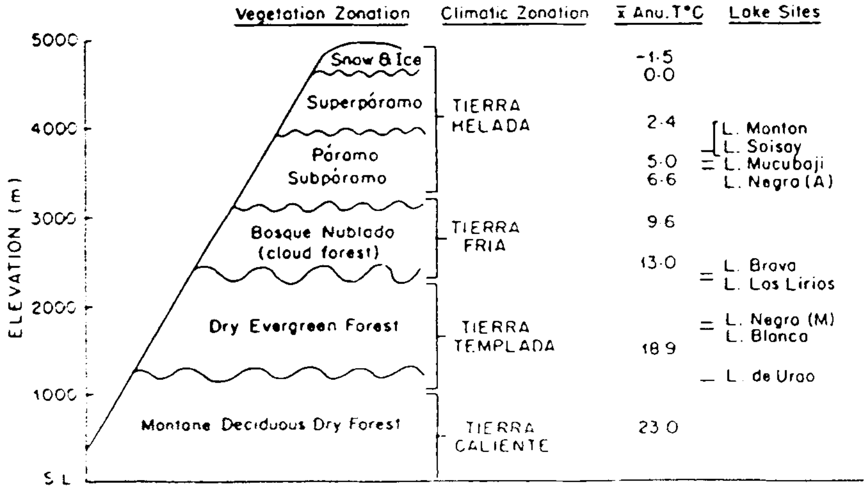

Figure 2 : *Altitudinal distribution of lakes in relation to climatic and vegetation zones*

I - ALTITUDINAL DISTRIBUTION OF CLAY MINERALS

A - METHODS

Clay minerals were determined qualitatively and semi-quantitatively. Qualitative analysis of the clay minerals and gibbsite was performed on oriented samples of the <2 µm fraction of untreated sediments using a Siemens X-ray diffractometer with Cu Kα radiation and a Ni filter. Chlorite is usually identified by a 14 Å peak which neither expands upon glycolation nor collapses heating to 550^{o}C. In this study, none of the samples were affected by glycolation but several showed a collapse of the 14 Å peak (to 10 Å) upon heating. Brindley and Brown (1980) noted that these contradictory responses indicate the presence of a degraded Mg-rich chlorite. Illite was identified by the typical 10 Å (001) reflection which persisted or was enhanced by heating of the sample to 550^{o}C. The presence of kaolinite was established in two stages; by the collapse of the ~7 Å (001) and ~3.5 Å (002) reflections upon heating to 550^{o}C, and by digesting with 1N HCl (Carroll, 1970). The presence of these two reflections, following the acid treatment, was indicative of kaolinite. The reflection peaks for the mixed-layer clay range between 11 Å and 12 Å, suggesting the presence of an illitic component. The lack of swelling upon glycolation excludes the presence of expandable clay mineral component. Mixtures with vermiculite are not likely due to the absence of vermiculite from the sediments. This reduces the likely composition to illite-chlorite. Additional support for the presence of a mixed-layer illite-chlorite comes from soil studies in the Mucubají area where illite-chlorite was identified as the most abundant mixed-layer clay (Malagon, 1982).

Semi-quantitative estimates of clay minerals and gibbsite have been obtained from individual measurements of the area under the (001) reflection of the respective minerals. Subsequently, the relative abundance (%) of the area under each (001) peak was calculated as part of the total area, of all (001) reflections measured within each lake (Table 1). Clay-mineral analyses of 64 samples from nine one-meter long sediment cores (one core from each lake) revealed the presence of chlorite, degraded chlorite (d-chlorite), a mixed-layer clay (an illite-chlorite) (I-Ch), illite and kaolinite (Table 1). Gibbsite and gypsum were also identified in the <2µm fraction of some lakes.

Table 1: *Relative abundance (%) of clay minerals and gibbsite in the clay fraction of sediments from the different lakes*

Lake	Chlorite	I.-Ch.	Illite	Kaolin.	Gibbsite
Montón	19	8	26	47	----
Saisay	12	6	46	36	----
Mucubají	16	9	52	24	----
Negra-A	4	---	72	24	----
Brava				tr. (?)	
		(Mostly X-ray amorphous)			
Lirios				tr. (?)	
Negra-M	3	---	2	76	19
Blanca	1	---	2	89	8
Urao	3	---	83	14	----

Clay minerals in the sediments of the Tierra Helada lakes show similar patterns of abundance and distribution, although there are some specific differences among the basins (Fig. 3). In the Tierra Templada lakes two extremely different results were obtained. Lakes Brava and Los Lirios contain largely X-ray-amorphous material (only traces of gibbsite and kaolinite were detected), whereas in the lower-elevation lakes Negra-M and Blanca, the mineral assemblages consist primarily of kaolinite and gibbsite (Table 1; Fig. 4). The clay minerals in Lake Urao consist of illite and kaolinite (Fig. 5). In general, there appears to be a consistent grouping of clay mineral assemblages according to altitudinal differences among the lakes and this is perhaps related to the climate at these elevations (Lauer, 1979).

B - ENVIRONMENTAL INFLUENCES

An apparent association between climate and clay minerals was initially recognized in deep-sea Atlantic sediments (Biscaye, 1965; Jacobs, 1970). Latitudinal belts of clay minerals coincided reasonably well with known global climatic zones, although some bedrock influences could also be discerned. In general, the deposited clays reflect the weathering environment in the continental source area (Singer, 1984), and early diagenesis in sea water is minimal. This relationship between weathering conditions and deposited clays might also be extended to altitudinal climate zones as observed in the Venezuelan Andes.

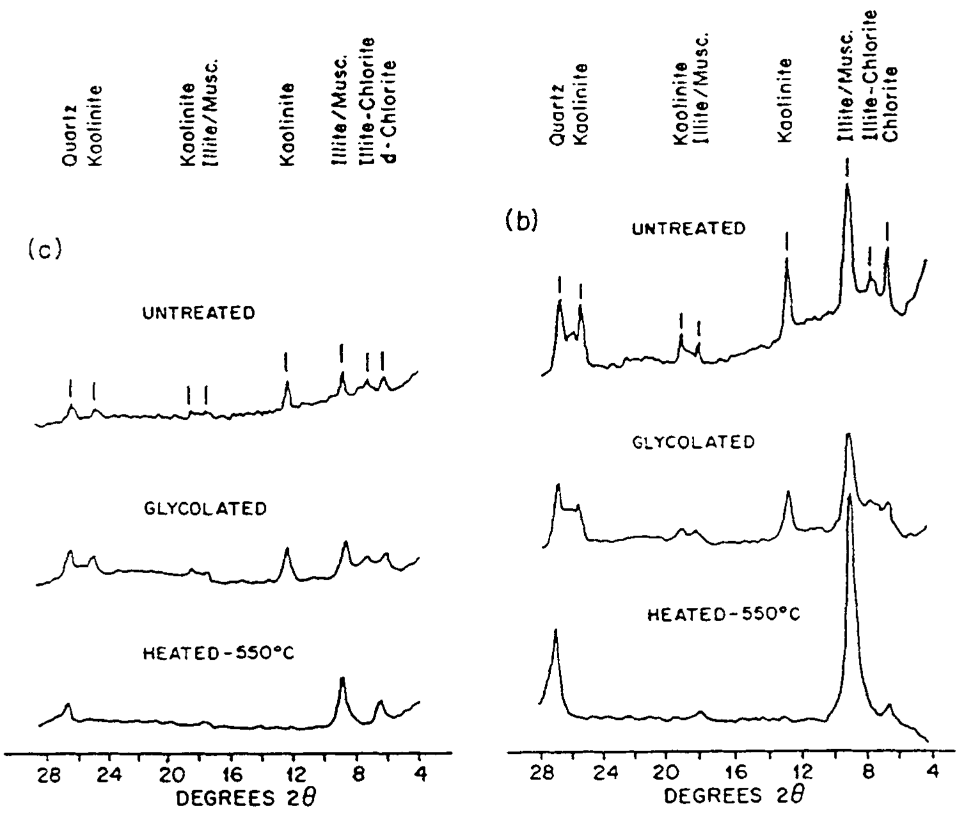

Figure 3 : *Comparison of X-ray diffraction patterns for two of the high-elevation lakes, Saisay (a) and Mucubají (b)*

The prevalence of illite and chlorite in the highest lakes agrees with similar findings in Antarctic soils and sediments (Bockheim, 1982). High abundances of illite and chlorite in Antarctica have been interpreted as indicating weak weathering intensities, typical of cold climatic conditions dominated by mechanical weathering. For these minerals to be very abundant hydrolysis should be minimal, since this process is responsible for the degradation of illite and chlorite (Birkeland, 1984).

Degraded chlorite was identified in the sediments of the two lower lake basins of the Tierra Helada climatic zone, Mucubají and Negra-A (Fig. 3). The greater abundance of d-chlorite may indicate some increase in weathering intensity at these slightly lower elevations (Barshad, 1966).

The presence of kaolinite in the clay assemblages of these high lake basins seems out of place since kaolinite normally forms under warm, wet conditions accompanied by a high leaching rate (Singer, 1980). Malagon (1982) has interpreted kaolinite in some soils around Lake Mucubají as a relict of an older paleosol. Weingarten (1977) also found such paleo-oxisols in other high parts of the Venezuelan Andes. Thus, kaolinite may not be forming in the present Tierra Helada environment.

In the two highest lakes in the Tierra Templada climatic zone (Brava and Los Lirios), the clay-size fraction contains mostly amorphous material, except for prominent diffraction peaks of gypsum. The nature of the amorphous material is unknown, although it is most likely organic in origin since the sediments of both lakes contain about 75% organic matter by weight (Weingarten, 1988). It proved resistant to standard peroxide oxidation, which is not unusual since some types of sedimentary organic matter require boiling and other harsh treatments for effective removal (Ingram, 1971). The source of the gypsum is not known. One possibility is that sulfide minerals in the Mucuchachí Formation are oxidizing to gypsum in the soil and these are subsequently transported to the lake.

Chemical analyses of the lake waters show elevated silica concentrations (>13 ppm) in lakes Brava and Los Lirios (Weingarten, 1988), suggesting a high rate of silicate weathering in the surrounding drainage basin. The source of the amorphous organic material may be from diatoms, which should also thrive in the high-silica environment. Although modern diatoms have not yet been recovered from the lake, the presence of diatomaceous earth in the drainage basin supports their presence (Varga Molner, 1970).

Kaolinite and gibbsite dominate the clay mineral assemblages in the two lower Tierra Templada lakes (Negra-M and Blanca) (Fig. 4). The presence of these minerals reflects the warm temperatures and high humidity at these elevations, which would result in enhanced leaching, intense hydrolysis and deep chemical weathering. The chlorite in these lake sediments is poorly crystalline, degraded variety, in contrast to the type found at higher elevations. This also fits the climatic conditions at these altitudes, where chlorite undergoes more rapid breakdown.

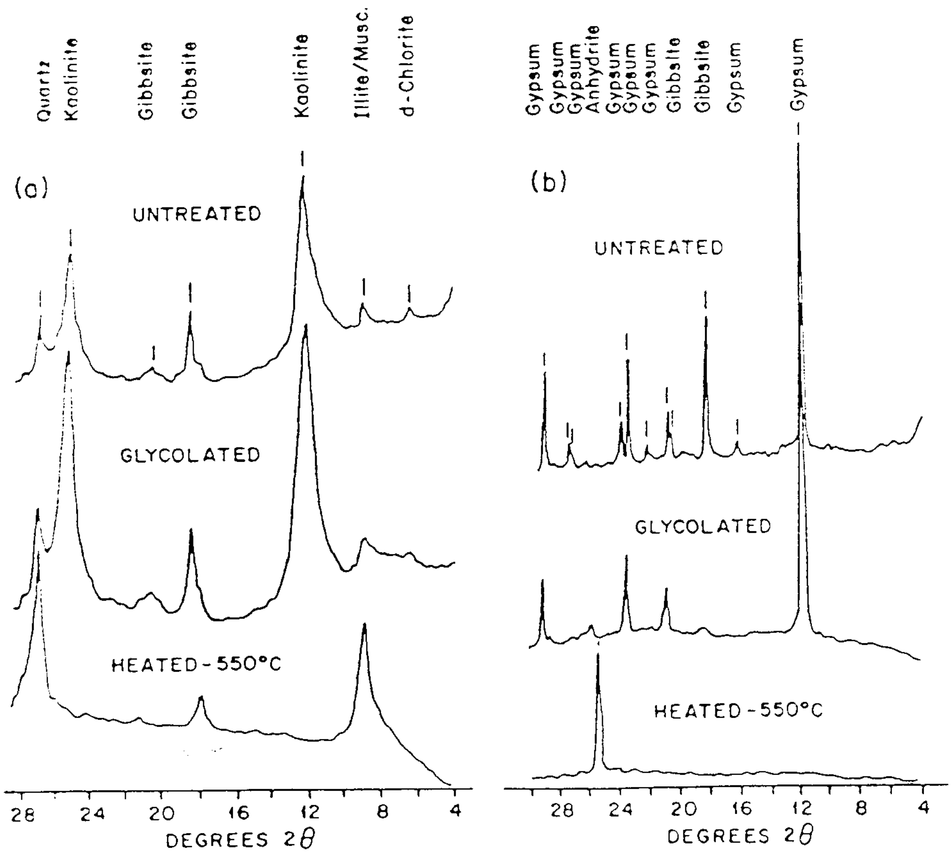

Figure 4 : *X-ray diffraction patterns from lakes Blanca (a) and Los Lirios (b)*

The differences in clay mineral assemblage between these and the upper Tierra Templada lakes may be a function of bedrock differences. The fine-grained phyllites of the Mucuchachí Formation in the Brava and Los Lirios basins may decompose at a faster rate than the granitic gneisses of the Sierra Nevada

Formation. Consequently, gibbsite and dissolved silica will be the primary weathering products delivered to the upper lakes, whereas more diverse clay minerals will survive in the Negra-M and Blanca basins. Further study of the soil clays in these basins is warranted.

The dominant clay in the clay-mineral assemblage of Lake Urao, in the Tierra Caliente climatic zone, is illite (Fig. 5). Although the climate here is warm the accompanying aridity would limit weathering. Furthermore, the surrounding sedimentary rocks in the basin (La Quinta) may contribute detrital illite to the basin. Finally, Lake Urao is an alkaline, saline water body (pH=10; TDS=~1400), and such conditions can favor the preservation of illite (Yuretich and Cerling, 1983).

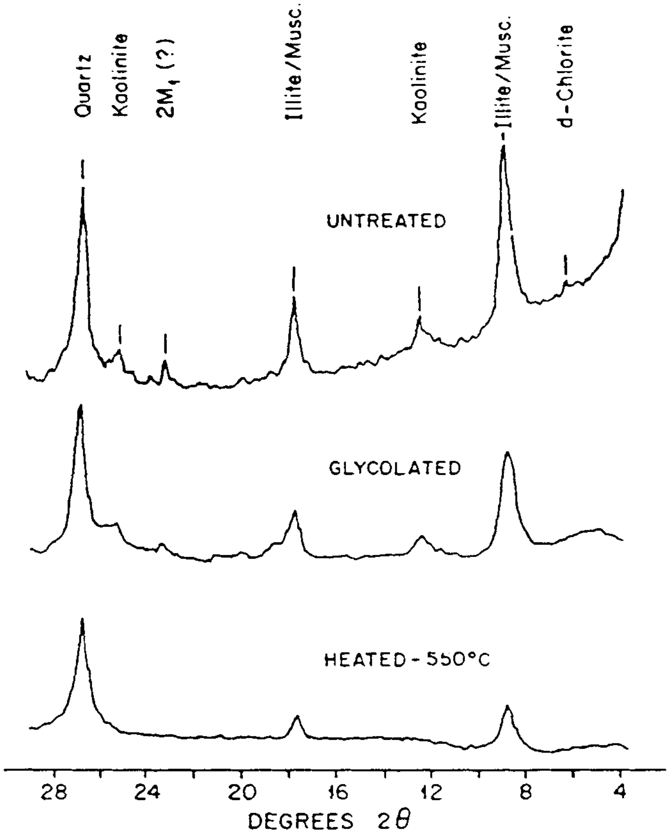

Figure 5 : *X-ray diffraction patterns for sediments in Lake Urao located in the Tierra Caliente*

C - ILLITE CRYSTALLINITY

Since illite is a recognizable component of all the lake groups, measurements of illite crystallinity were undertaken to see if it varied in an regular or systematic fashion. Illite crystallinity was determined by measuring the width of the glycolated illite (001) peak at half its height and dividing this by the peak height ($W_{1/2}/H$). This definition of illite crystallinity is to an extend a combination of the Weaver index (Weaver, 1960) and the Kübler index (Kübler, 1964). It allows to standardize the illite crystallinity measurement which is necessary when illite is present in variable abundances (Fig. 3). The Weaver and Kübler indexes do not compensate for the different intensities in such varied samples. The results show that illite is 3 to 4 orders of magnitude more crystalline in the Tierra Helada lake sediments than in those from the Tierra Templada (Table 2).

The high illite crystallinity in Lake Urao suggests that hydrolysis is less intense here than in the Tierra Helada lakes, and this agrees with the previous clay-mineral data. Because rainfall in the Urao area is intense but sparse and of short duration, only poorly weathered detrital material from the shattered La Quinta Formation reaches the lake.

The elevated alkalinity of Lake Urao may also contribute to the high illite crystallinity. Similar environments have been found to promote the formation of illite, since high concentration of K^+ in the water (20 ppm in Lake Urao) may fully saturate the exchange sites in the illite structure (Singer and Stoffers, 1980).

Table 2 : *Grouping of lakes based on mean values of illite crystallinity*

Lake	Illite crystallinity
Montón	0.12
Saisay	0.15
Mucubají	0.11
Negra-A	0.11
Negra-M	0.21
Blanca	0.30
Urao	0.04

II - PRE-HOLOCENE SEDIMENTS FROM LAKE LOS LIRIOS

A long core (6.3 m) was taken from Lake Los Lirios in the Tierra Templada zone. The upper 4.2 m of sediments in the core exhibit a fine-grained mineralogy similar to the surface sediments, i.e. dominantly an X-ray amorphous material (Fig. 6). However, below this level and

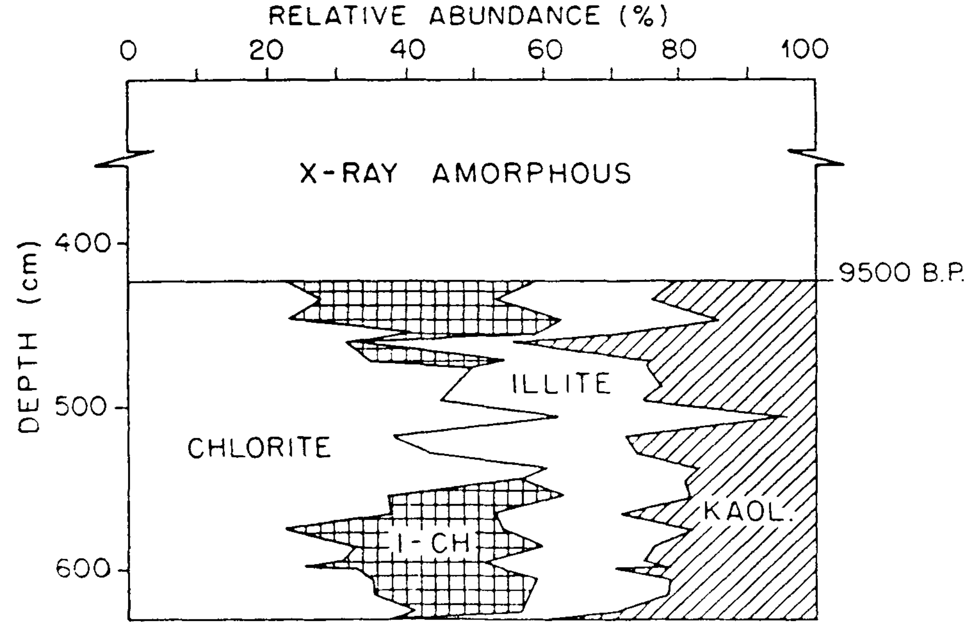

Figure 6 : *Relative abundance of clay minerals in the long (6.3 m) sediment core from Lake Los Lirios.*

continuing to the bottom of the core, the sediments contain the clay minerals illite and chlorite (± kaolinite) in abundances very similar to those now found in the Tierra Helada climatic zone (Fig. 6). ^{14}C dating of the core yields an age of ca. 17,000 years B.P. for the bottom, and a date of 9,500 years B.P. for the clay-mineral transition.

Giegengack and Grauch (1976), Salgado-Labouriau et al. (1977) and Schubert (1987) postulate an age of ca. 13,000 years B.P. for the latest glacial retreat in the Venezuelan Andes. Moraines from this glaciation extend downward to an elevation of 2,900 m. It is conceivable that clay minerals in the lower part of the core were deposited under conditions resembling the modern Tierra Helada, and the environmental conditions surrounding Lake Los Lirios assumed their present conditions some 3,000 years after the glaciers began retreating.

III - CONCLUSIONS

The sediments in the lakes of the Venezuelan Andes form compositional groups which reflect the environmental conditions at their respective locations. The types of clay minerals and their relative abundances in the lake sediments appear to have been strongly influenced by climatic factors. The cold and wet conditions of the Tierra Helada climatic zone afforded strong physical weathering conditions which are reflected in the abundance of illite and chlorite.

The decreased abundance of chlorite at lower elevations is accompanied by a qualitative change within the 14 Å mineral phase, which indicates a relative increase in the proportion of degraded chlorite. An increase in both temperature and precipitation most likely contributed to this change. In the Tierra Templada zone, where kaolinite becomes the dominant clay mineral, warm temperatures, high rainfall and effective leaching promoted an intense degree of chemical weathering.

The dominance of the 10 Å clay-mineral phase in the Lake Urao sediments is more complicated. An arid climate coupled with abundant detrital illite from the surrounding Mesozoic rocks and a strongly alkaline lake water all served to promote the accumulation of crystalline illite.

The influence of bedrock geology in the other basins cannot be ruled out. The observed clay-mineral variability among lake basins within each of the climatic zones most probably reflects divergences in the mineral composition of the bedrock. This is particularly true for the Tierra Templada lakes, where the pronounced differences in the modern sediments coincide with the location of the lakes either in the Mucuchachí or the Sierra Nevada Formations. However, the consistency of clay-mineral signatures in the three altitudinal zones point toward a primary influence of the modern environmental (especially climatic) conditions.

ACKNOWLEDGEMENTS - This study forms part of a Ph.D. dissertation by the senior author and was supported by N.S.F. grant ATM83-03171 and C.O.N.I.C.I.T. (Venezuela) grant SI-1359. We thank Carlos Schubert, Paul Doyle, Marie Litterer and Larry Feldman for their valuable help in various stages of this project. The quality of this manuscript was improved by the reviews of C. Latouche and an anonymous reviewer.

REFERENCES

BARSHAD I. (1966) - The effect of variation in precipitation on the nature of clay mineral formation in soils from acid and basic igneous rocks. Proc. 1st Internat. Clay Conf. Jerusalem, p. 167-173.

BIRKELAND P. W. (1984) - Soils and Geomorphology. Oxford University Press, Paris, 372 p.

BISCAYE B. E. (1965) - Mineralogy and sedimentation of recent deep sea clay in the Atlantic Ocean and adjacent seas and oceans. *Bull. Geol. Soc. Amer.*, 76, p. 803-832.

BOCKHEIM J. G. (1982) - Properties of a chronosequence of ultra-xerus soils in the Trans-Antarctic mountains. *Geoderma*, 28, p. 239-255.

BRINDLEY G. W. and BROWN G. (Eds.) (1980) - Crystal Structure of Clay Minerals and their X-Ray Identification. *London Mineral. Soc.*, Monograph no. 5, 495 p.

CARROLL D. (1970) - Clay minerals: A guide to their X-ray identification. *Bull. Geol. Soc. Amer.*, Spec. Paper no. 126, 80 p.

GIEGENGACK R. F. and GRAUCH R. I. (1976) - Late Cenozoic climatic stratigraphy of the Venezuelan Andes. *Bol. Geol.*, 2, Pub. Esp. no. 7, p. 1187-1200.

INGRAM R. L. (1971) - Sieve analysis. R. E. CARVER, (Ed), Procedures of Sedimentary Petrology, 1971, New York, Wiley, p. 49-67.

JACOBS M. B. (1970) - Clay-mineral investigation of Cretaceous and Quaternary deep-sea sediments of the North American Basin. *Jour. Sed. Pet.*, 40, p. 864-868.

KÜBLER B. (1964) - Les argiles, indicateurs de métamorphisme. *Rev. Inst. Franç. Pétrol.*, 19, p. 1093-1112.

LAUER W. (1979) - La posición de los páramos en la estructura del paisaje de los Andes tropicales. Actas de seminario de Mérida, 1979, L. M. SALGADO-LABOURIAU (Ed), Medio Ambiente Páramo, Mérida, Venezuela, Ediciones Centro de Estudios Avanzados, p. 29-43.

MALAGON D. C. (1982) - Evolución de los suelos en el Páramo Andino (NE del Estado Mérida, Venezuela). Mérida, Venezuela, CIDIAT, 222 p.

SALGADO-LABOURIAU M. L. SCHUBERT C. and VALASTRO S. (1977) - Paleoecologic analysis of a Late Quaternary terrace from Mucubají Venezuelan Andes. *Jour. of Biogeog.*, 4, p. 313-325.

SCHUBERT C. (1982) - Neotectonics of Boconó Fault, western Venezuela. *Tectonophysics*, 85, p. 205-220.

SCHUBERT C. (1987) - Climatic changes during the last glacial maximum in northern South America and the Caribbean: A review. *Interciencia*, 13, p. 128-137.

SINGER A. (1980) - The paleoclimatic interpretation of clay minerals in soils and weathering profiles. *Earth-Science Reviews*, 15, p. 251-293.

SINGER A. (1984) - The paleoclimatic interpretation of clay minerals in sediments - A review. *Earth Science Reviews*, 21, p. 251-293.

SINGER A. and STOFFERS P. (1980) - Clay-mineral diagenesis in two East African lake sediments. *Clay Minerals*, 15, p. 291-307.

VARGA MOLNER L. (1970) - Estudios del sector minero de la región de los Andes. Republica de Venezuela. Corporación de los Andes, no. 2, p. 113-150.

WEAVER C. E. (1960) - Possible uses of clay minerals in search for oil. *Bull. Amer. Assoc. Petrol. Geol.*, 44, p. 1505-1518.

WEINGARTEN B. (1977) - Tectonic and paleoclimatic significance of a Late Cenozoic paleosol from the Central Andes of Venezuela. Unpublished MS thesis, University of Pennsylvania, Philadelphia, Pennsylvania, 68 p.

WEINGARTEN B. (1988) - Geochemical and clay-mineral characteristics of lake sediments from the Venezuelan Andes: Modern climatic relations and paleoclimatic interpretation. Unpublished Ph.D. dissertation, University of Massachusetts, Amherst, Massachusetts, 213 p.

YURETICH R. F. and CERLING T. E. (1983) - Hydrogeochemistry of Lake Turkana, Kenya: Mass balance and mineral reactions in alkaline lake. *Geochimica et Cosmochimica Acta*, 47, p. 1099-1109.