GROUNDWATER CONDITIONS IN THE CHACO BOREAL OF PARAGUAY

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SUMMARY

The hydrogeological situation in the area of the Chaco Boreal of Paraguay was the subject of comprehensive investigations carried out in 1959 by a team of experts. A hydrogeological field survey (analyses on about 200 water samples, drillings and analyses on soil samples) together with supplementary soil scientific investigations was followed by a large-scaled geoelectrical survey (160 resistivity soundings by the four-point-method) which provided indications about hydrogeological conditions down to 200 m depth by utilizing the different electrical conductivities of the underground layers.

By these combined investigations the decisive regulating factors for the groundwater balance could be determined. In particular the problems concerning the water salinity have fargoing been solved. Interesting recognitions were thus achieved about the groundwater conditions in a region which in spite of an annual precipitation of 800 to 1000 mm displays an arid character.

RÉSUMÉ

La situation hydrogeologique dans la région du Chaco Boréal du Paraguay a été l'objet de recherches effectuées en 1959 par un groupe d'experts. Une campagne de recherches hydrogéologiques (analyses d'environ 200 échantillons d'eau, sondages et analyses d'échantillons du sol) exécutée en même temps que des recherches complémentaires de spécialistes du sol a été suivie par une recherche géoélectrique à grande échelle (160 sondages de résistivité par la méthode des quatre points) qui a fourni des indications sur les conditions hydrogéologiques jusqu'à des profondeurs de 200 m en utilisant les différentes conductivités électriques des couches souterraines.

1. INTRODUCTION. WORKING METHODS

Hydrogeologic conditions in the Chaco Boreal of Paraguay were the subject of research work carried out by a commission of experts from May to October 1959. The commision consisted of a hydrogeologic working group which was followed, after a period of 4 to 6 weeks, by a team of geophysicists with geoelectric measuring equipment. (*)

Since in the Chaco Boreal of Paraguay no systematical hydrogeologic research had been made so far and therefore no basis existed for own work, the hydrogeologic working team had to begin by comprehensively registering and classifying all water occurrences attainable according to their geologic origin and development, and by determining the position in the depth as well as the physical and chemical properties.

An electrical drilling rig was used for drilling down to a depth of 14 m in order to ascertain the composition of the quaternary sediments. Sections from uncased dug wells, from loam pits and at the banks of periodically flowing rivers served the same purpose in this region otherwise completely devoid of exposures.

A small field laboratory was established in the area for determination of the specific electrical conductivity of the water, the pH-values, the total hardness, the contents of Ca-, Mg-, Fe-, SO_4 and of Cl.

(*) The team was sent off on commission of the Federal Republic of Germany by the BUNDESANSTALT FÜR BODENFORSCHUNG, Hannover, within the frame of TECHNICAL ASSISTANCE. Additionally to the hydrogeological investigations also soil-scientific prospection was carried through which here, however, is not dealt with.

The hydrogeologic data thus obtained were the basis for establishing the program of the geoelectric survey. They helped as well to interpret the geophysical measuring data. Geoelectric investigations concerned a regional survey as well as a prospection in detail.

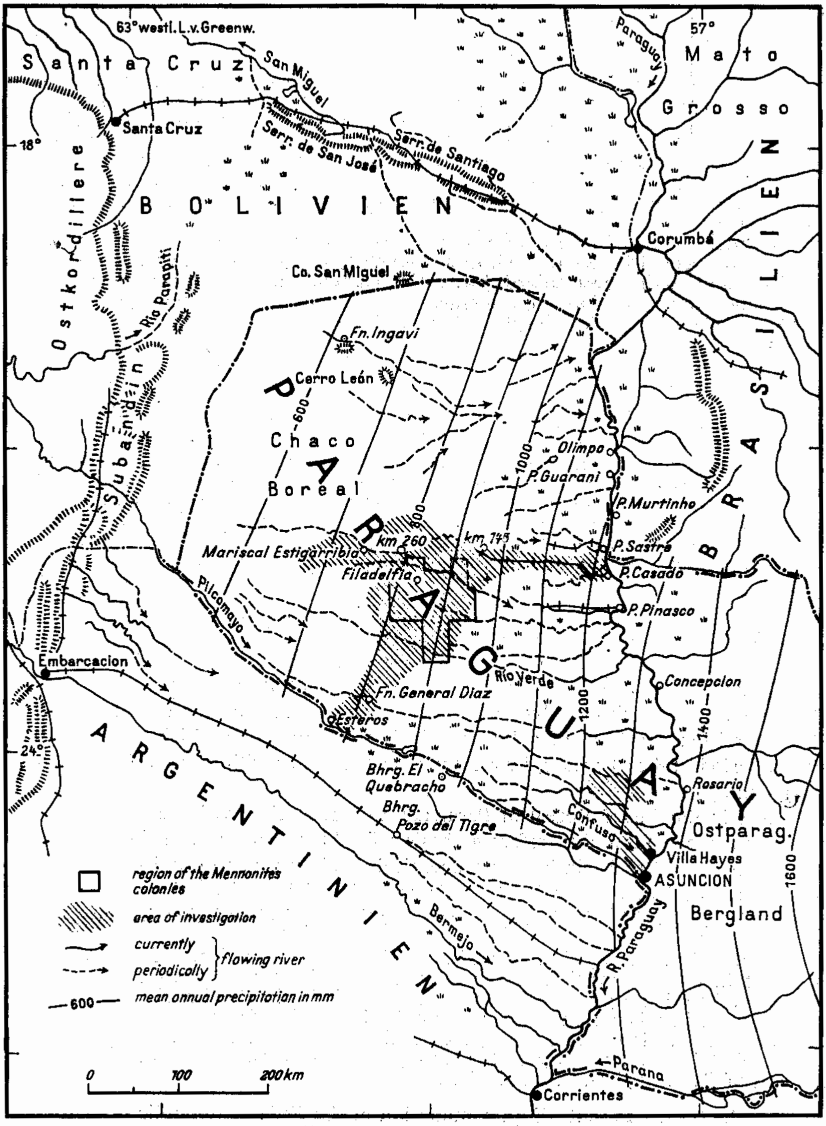

Fig. 1 — *Map of survey*

The electrical resistivities of the underground layers were measured according to the four-point-method using direct current (Schlumberger arrangement). These depth soundings made it possible to recognize underground conditions down to a depth of 200 m. Above all they provided indications about the presence of fresh and salty groundwater in the deeper underground that had not been explored by boreholes and wells. A modern tropic-proof transistor-based apparatus (DC-amplifier) of own development was used.

The location of the surveyed area is represented on Fig. 1. The main region of investigation is adjoining the zone of settlement of the Mennonites. It extends from the Rio Pilcomayo via the central part of the Chaco Boreal to the Rio Paraguay.

2. Geology, orography, climate and vegetation of the Chaco Boreal

2.1. *Geology*:

The Chaco Boreal has an extension of about 250 000 km² and generally consists of quaternary and tertiary(?) loose masses with thicknesses unknown. Exceptions are some single isolated hills of outcropping lower paleozoic and triassic rocks in the river zone of the Rio Paraguay and the northern part of West-Paraguay. The loose masses of the Chaco Boreal are materials of denudation from the Andes regionally arranged according to their grain size. This does not apply to the river sediments of the Rio Paraguay.

In the West, the plain of debris of the Chaco Boreal borders on the Subandin folded in the upper Tertiary and containing continental sediments of the Paleozoic, the Triassic and the Tertiary. In the North, the plain of debris is delineated by lower paleozoic rocks and the crystalline bedrock of the Serras of San José and Santiago. The natural eastern boundary is formed by cretaceous volcanics, lower paleozoic limestones, rocks of the Gondwana-series and triassic sandstones which all crop out in the course of the Rio Paraguay. Towards the South, the quaternary loose masses of the plain of debris continue to the Chaco of Argentine.

2.2. *Orography*:

In the central Chaco, the plain slopes towards the East with approximately 30 m for every 100 km. A hardly pronounced and only locally distinguishable relief is

Fig. 2 — A «Kamp» consisting of fluviatile fine sands (older river system) and overgrown with grass and single trees crosses the dense scrubs growing on clayey soil (west of FILADELFIA, central Chaco)

preserved on the plain: The loess-like impermeable sediments show superficial flat basins which often appear only during the rainy season in the form of water-filled illuvial depressions with diameters from a few 100 meters to several kilometers. Evidences for an older river generation are given by the fluviatile deposits of fine sand which the settlers call «Kämpe». These «Kämpe» force their way through regions with sediments rich in clay (Fig. 2). Clear traces for a younger river generation are to be seen by the shallow dry channel meanders which cross the winter-dry scrubs growing on the clayey sediments as well as the so-called «Kämpe» overgrown with bushes of grass and single trees. A third and youngest river system with ESE-directed flow are, finally, the periodically flowing Riachos with mostly steep banks of up to 5 m in height (Fig. 3, 4).

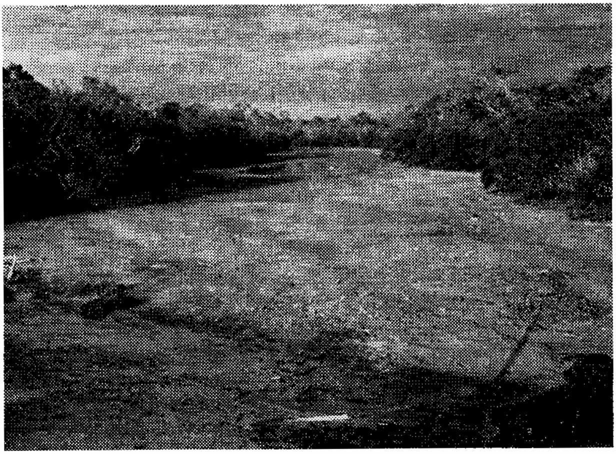

Fig. 3 — Periodically flowing river (youngest river system) during the dry season with rest waters of high grade salinity (RIO MOSQUITO in the north-east section of the Mennonites' colonies, August 1959)

Fig. 4 — Periodically flowing Chaco-river (Riacho) near the Rio Paraguay, till waterbearing in July (about 100 km south of PUERTO CASADO)

2.3. *Climate*:

The climate of the whole Chaco Boreal is influenced by warm air masses from the North and cold air masses from the South. The mostly abrupt change of winds from the North or the South causes heavy rainfalls especially during the summer months from October to March (see climatogram Fig. 5). The average amount of

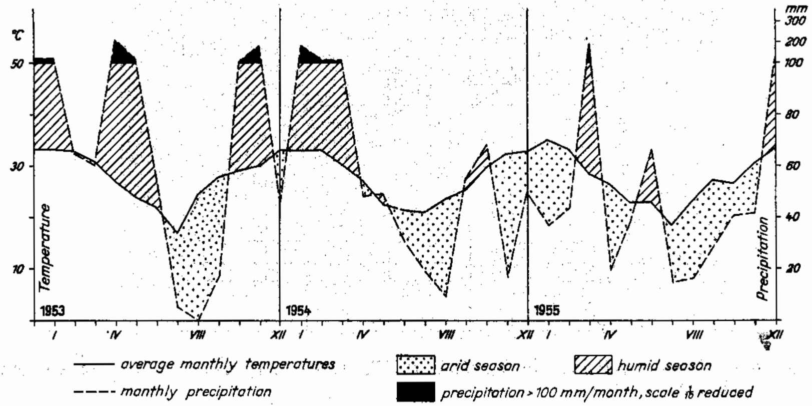

Fig. 5 — *Climatogram of Filadelfia, 1953-55*

	1953	*1954*	*1955*
Mean annual temperatures (°C):	27,8	27,7	27,4
Annual precipitation (mm):	983,7	761,6	622,8

rain of 600 mm in the West increases to 1200 mm in the East (Fig. 1). The actual precipitations of the various years deviate, however, considerably from the average rate determined over many years (up to 40%). High temperatures (annual average ~26°C), almost continuous air movement and low relative air moisture (annual average ~55%) cause a high potential evaporation. The comparative high rates of precipitation falling mostly on impermeable soil cause also a very high effective evaporation.

3. Results of hydrogeologic and geoelectric research.

The actual objective of the commission has been to explore groundwater to be used for a seasonal water supply (irrigation during dry periods) and for a continuous supply of a future industry (working agricultural products). The survey as a whole, however, has enabled experts to form a concept about the groundwater balance in a region that despite its relatively high quantities of precipitation displays an arid character. It shall now be tried to represent briefly the working results obtained by a combination of hydrogeological and geophysical methods.

The area under investigation in the central Chaco is situated already east of all coarser clastic sediments from the Andes. The quaternary sediments of fluviatile and aeolian origin are characterized here by their fine granulation (in general grain sizes below 1 mm in diameter, see Fig. 6). and by their locally changing contents of finely distributed salts.

On the surface impermeable to semipermeable sediments of the type of loess and sand loess prevail over fluviatile and aeolian fills of fine sand. The upper part of the fine sands is laterally indented with loess-like sediments. The lower part, however,

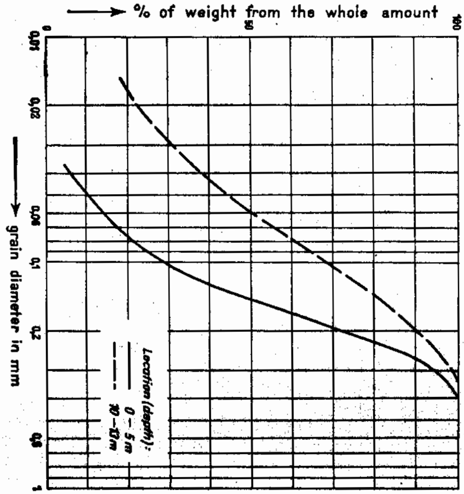

Fig. 6 — *Grain distribution in borehole B, FILADELFIA, central Chaco* (evaluated by H. SINDOWSKI)

belongs to an aeolian fine sand horizon which is obviously widely spread in the central Chaco. Thicknesses of the loess-like sediments and the fills of fine sand decrease from the West to the East and Southeast. Towards the Rio Verde and the Rio Pilcomayo these sediments mentioned above disappear and are partly replaced by sediments of periodically flowing rivers respectively by the clayey and humous river mud on the large region of inundation of the Rio Paraguay.

The continuous horizon of fine sand is underlain by an impermeable bed of loess-like compounds or clay, which resemble the impermeable sediments of the soil crust. This impermeable bed has been found in the whole surveyed area of the central Chaco. It generally separates two groundwater storeys from each other. The surface of this layer, that is at the base of the first groundwater storey, shows flat basins, pockets and channel-like deepenings. They are interpreted as remnants of hollow beds of former drainage systems which later have been filled up and covered by the hanging aeolian fine sands.

The substratum of this impermeable horizon consists of fine and medium-grained sands of unknown thickness which form a second groundwater storey.

3.1. *Superficial waters*:

Due to the hardly pronounced field relief and the very small gradient of the Riachos towards the East to the Rio Paraguay the superficial runoff is low, and in the central Chaco it ceases completely during the dry months. The larger part of the central Chaco must be considered as having no runoff, even in the rainy season. The rainwater remains on the impermeable soils, it possibly collects in the flat depressions of illuviation and in the tied off meanders of the younger and youngest river systems. It largely remains subject to complete evaporation, whereby salts taken up from the soil become concentrated and may finally cover the centre of the evaporation pans in form of salt crusts (Fig. 7). The rare superficial freshwater occurrences on soils that are primarily poor in salt have mostly a close cover of waterplants. Their transpiration is obviously less than the effective evaporation at the free water surface, for

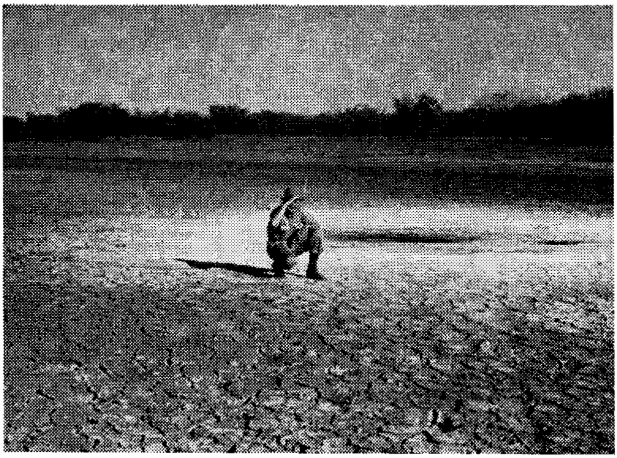

Fig. 7 — Salt crust in an evaporation pan (near Estancia EATON, central Chaco, July 1959)

such water occurrences may mostly overcome the dry periods (Fig. 8). An afflux of surface waters for instance from the Andes in the West does not take place during the whole year.

Fig. 8 — Superficial freshwater occurrence with a close cover of waterplants (near Estancia RIO VERDE, central Chaco, July 1959)

3.2. *First groundwater storey*:

The proportion of precipitation which enters the soil is low because in the central Chaco, the top layer of the soil is mostly impermeable. The water which infiltrates locally reaches the base of the first aquifer, where it collects in the channel and basin-like depression mentioned above. The sizes of these basins of accumulation range from 50 to 600 m in diameter and may attain depths down to 7 m. In the West and Northwest of Filadelfia, geoelectric survey determined unknown deeper channels filled with sand on the bottom of the first aquifer. These channels attain depths of 35 m below surface and carry fresh water. Since the cover has a small thickness and is semi-permeable, rainfalls can here infiltrate quickly (for example at km 260 at the road Mariscal Estigarribia-Casado rail, compare figures 10 and 11) Although here the most important fresh water occurrences determined up to the present in the central Chaco may be concerned, their waters are also regenerated only locally and are not sufficient for a large system of irrigation.

Many water analyses demonstrate the great chemical differences of the waters in the individual basins of accumulations. In Filadelfia, in a region of only approximately 1 km², the variation is for the contents of:

$$CE' = 10 - 1900 \text{ mg/1}$$
$$SO_4'' = 5 - 1700 \text{ mg/1.}$$

The total hardness varies between 2 and 105 dH, the specific electric resistivity of the waters between 0,85 and 75 Ω m.

Waters were taken here from wells, the floor of which is situated between 10 and 14 m below surface (groundwater table at 9-10 m depth). The great chemical differences attested by a number of shallow wells, and the geoelectric survey disclose that there is no continuous groundwater body in the first groundwater storey. Conditions are explained on Fig. 9, which shows a number of detail investigations in Filadelfia. The vertical section represented may be considered as being typical for the central Chaco.

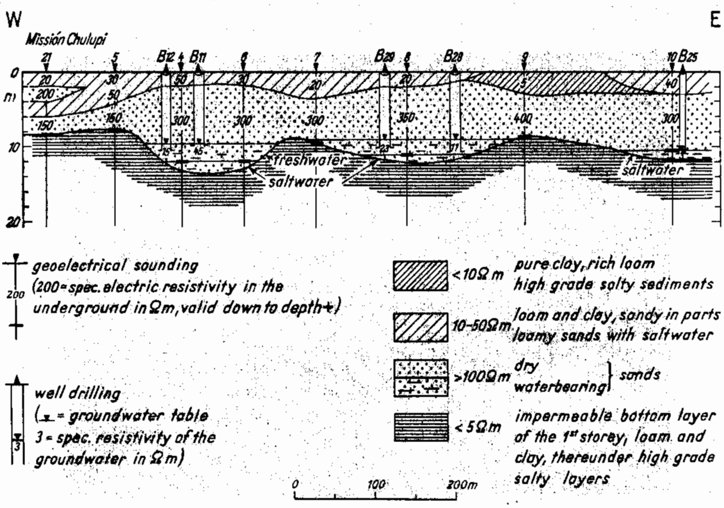

Fig. 9 — Vertical section from FILADELFIA, central Chaco. The spec. electric resistivities calculated from the sounding graphs are marked for the sands of the 1st storey as well as for the impermeable and semipermeable covering. A decrease of the electric resistivity indicates a decrease of permeability for water caused by loamy and clayey components which are good electric conductors. In the region of wells 11 and 12 the sands are well permeable (300 Ω m) and the relatively thin cover is semipermeable (50 Ω m). The basin at the bottom of the 1st storey contains freshwater underlain by saltwater. Geoelectrically the fresh/saltwater interface was determined here. The difference in the Cl'-contents of the waters from wells 11 and 12, reflected in the spec. electric resistivities of the waters (45 Ω m and 15 Ω m), results from the different depths of the wells. The same is valid for wells 28 and 29.

The isolated water occurrences do not seem to follow a main direction. This cannot be expected if it is assumed that these hollow beds are part of a former drainage system covered now by aeolian sediments. Also the Riacho systems of the present time are characterized by numerous confuse meanders which have no main direction in a limited region (Fig. 4). The waterfilled basins at the base of the first groundwater storey are not indicated on the surface.

The groundwater balance of the first storey depends, according to the investigation results described, decisively on the rains that fall in the same region. Since there is no continuous groundwater current following the general slope from the West towards the East, there is also no ingress of groundwater, if so, only during short periods with an extremely high rate of rainfall, which then causes a refill and overflowing of the groundwaters into the hollow beds. The yields of the isolated water occurrences at the base of the first storey depend, therefore, on the size of the basins of accumulation, on the permeability of the covering soil and on the local ratio of rainfall to evaporation. These decisive factors change quite considerably from place to place. However, they make the presence of large non-salty groundwater bodies improbable.

A water-bearing basin with dimensions of 600 × 400 m and an average depth of 3 m, which is large for Chaco-conditions, would have a total content of approximately 700.000 m^3. The pore volume of fine sand filling the basin amounts, according to the grain sizes determined, to 30%, that is, a maximal amount of 200.000 m^3 of water could be contained in the basin.

Since it is assumed that the infiltration water ingresses not only vertically but partly also laterally, the catchment area for the water occurrence can be stipulated with approximately 300.000 m^2 of plain field surface. On the basis of observations it has been determined that approximately 80% of the ground are covered with impermeable soils where the precipitation waters collect in shallow depressions of illuviation until they are completely evaporated. Only 20% of the soil = 600.000 m^2 are permeable or semi-permeable. At an annual rate of precipitation of 800 mm, approximately 48000 m^3 of rainwater fall on these grounds. Since most rains fall during months of very high potential evaporation (see climatogram, Fig. 5), it is suggested that a 10% estimate for the amount of water reaching the groundwater is a rather high one. In this case, waters in the order of approximately 5000 m^3 would be available for regenerating annually in a suchlike isolated water occurrence at the base of the first groundwater storey.

3.3. *Second groundwater storey*:

Shallow bore-holes, deeper dug wells and results of geoelectric deep-soundings over a total length of profile of almost 800 km have shown that a high-grade salty groundwater is to be expected in the sands below the first impermeable bottom layer. It is assumed that this second groundwater storey contains a groundwater body which is closed and large. Additionally it has been ascertained geoelectrically that the content of salt of the waters in the second storey increases towards the East and Southeast, surpassing the amount of 5000 mg Cl/1 east and southeast of the Mennonites colonies.

Some of the results of the geoelectric survey are represented on figures 10 and 11. The vertical section on Fig. 10 is a greatly simplified representation. The diagram does not interpret correctly the complicated structure of the first groundwater storey, for here an interpolation over kilometer distance is not admissible. Valid are the data on the single measuring points. This section shall merely impart a rough concept of the hydrogeologic conditions along a West-East-profile of 300 km length through the Chaco. The decrease of thickness of the first groundwater storey is clearly noticeable as well as the increasing salt content towards the East in the deeper underground which is reflected by a continuous decrease of the specific electric resistivity in the direction towards the Rio Paraguay. Some characteristic sounding graphs from the regional survey are given in figure 6.

Regeneration of the saltwater in the second groundwater storey is not elucidated. It is therefore difficult to judge the groundwater balance. The following interpreta-

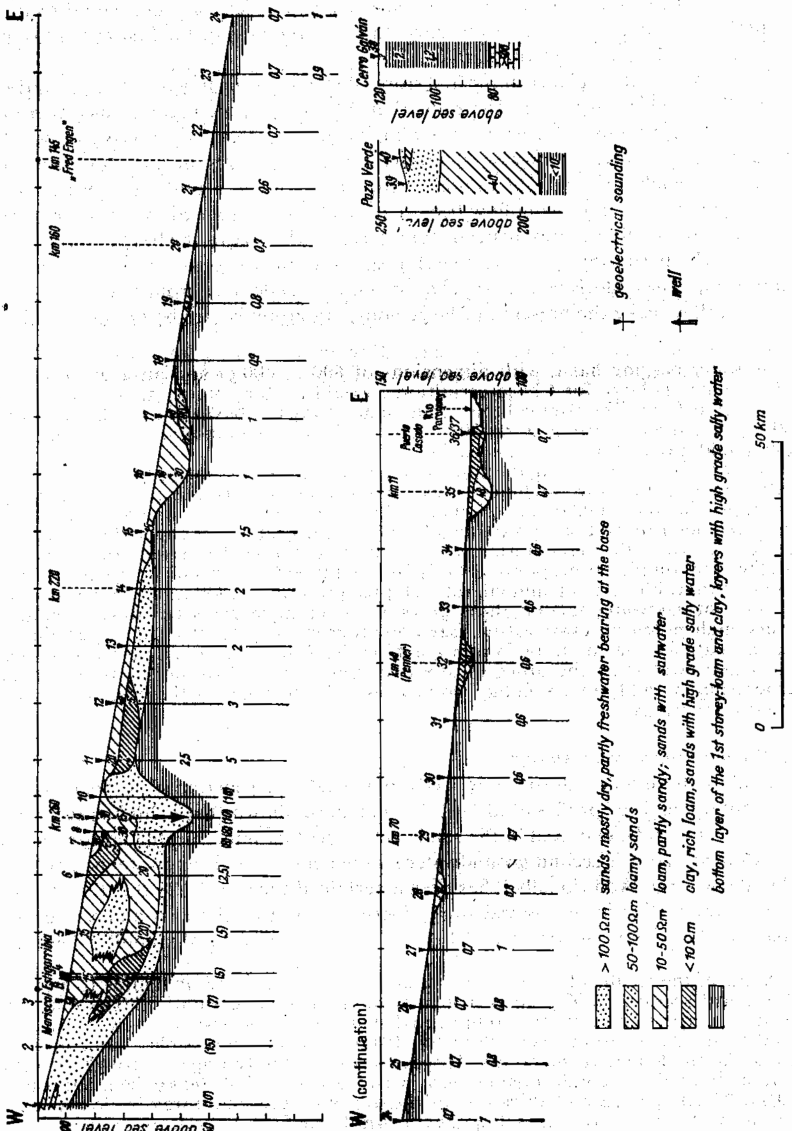

Fig. 10 — W-E vertical section from Mariscal Estigarribia to Puerto Casado according to geoelectrical investigations. (The numbers in the section indicate the spec. electric resistivities calculated from the sounding graphs).

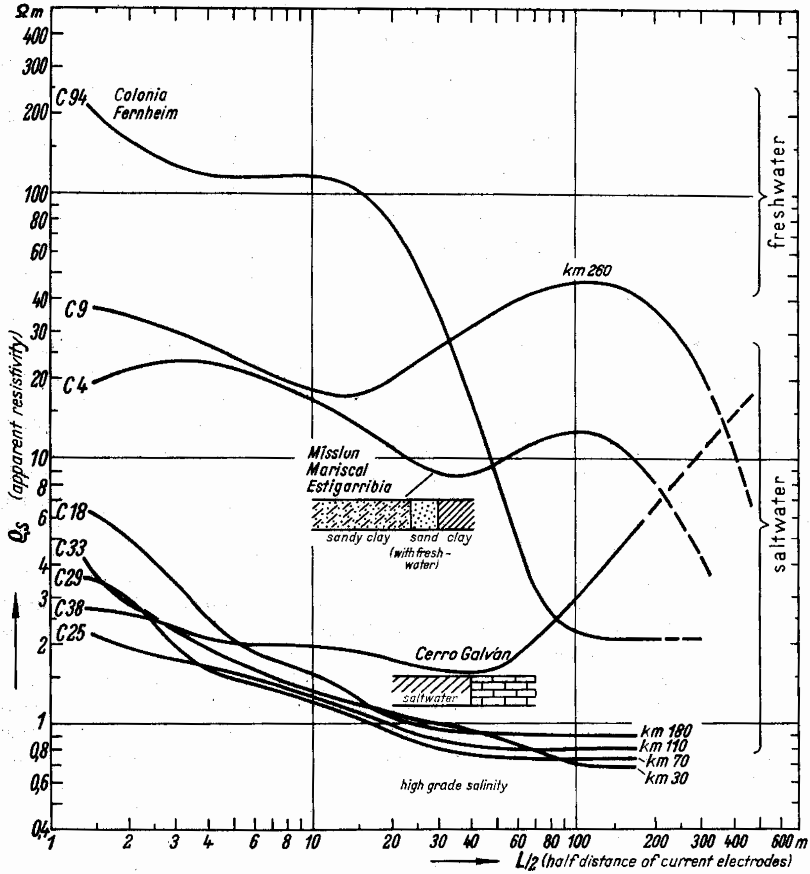

Fig. 11 — Sounding graphs of the regional geoelectric survey (see Fig.10).
C 94 is a typical sounding graph from a «Kamp» near Filadelfia: 10 m fine sands of the 1st storey (120 Ωm) underlain by impermeable clay and saltwater-bearing sands (2 Ωm). Sands with freshwater in deeper basins at the bottom of the 1st storey are indicated by a maximum in the end branch of the graphs C4 and C9. C18, 25, 29, 33 are typical for the eastern part of the profile Mariscal Estigarribia — Puerto Casado. They show the increase of salinity in eastern direction. Sounding C38 measured at the Cerro Galvan near Puerto Casado reached the paleozoic bedrocks of high electric resistivity in a depth of 40m. (For the representation of the two vertical profiles given under C4 and C38 the logarithmical L/2-scale is used as depth scale simultaneously.)

tions are possible: It can be deferred from the descriptions of H. KANTER (1936, p. 129-151) that there is a zone along the eastern margin of the Andes where the sum of the ingressing waters from the precipitation on the Andes rivers is surpassing the amount of evaporation. The development of fresh-water bearing groundwater storeys has obviously taken place here. Farther in the East, however, the waters supplied superficially run dry in the extended briny swamps and pans of evaporation, provided they are not joining the Rio Pilcomayo, the only river which traverses the whole Chaco from NNW to ESE. Under these circumstances, an accumulation of brine by evaporation is a normal phenomenon which takes place in the swamps and pans, even though there may be little soluble matter in the fresh water ingressing at times. After closing by sedimentation of the matter in the influxes or also during the occasional periods rich in rain when the concentrated solutions in the evaporation pans are slushed out, sediments rich in salts and briny solutions come farther to the East into the Chaco plain where they form ingredients of the plain of debris and where saltwater may possibly join the second groundwater storey. This saltwater then migrates below the central Chaco to the East, until it is cut by the lower courses of the Riachos joining the Rio Paraguay which may cause the high salt content of these rivers.

3.4. *Origin and distribution of the salts:*

It may be concluded from the nature of the upper quaternary layers that the climate during their formation was dry to periodically dry, like the present one, and that the region of formation was a large plain. It can therefore be assumed that during the dry period in the central Chaco precipitation was balanced out by evaporation like nowadays, that no runoff was possible, whereas in the rainy season precipitation surpassed the rate of evaporation, a runoff however could not take place because of the unpronounced relief and the small gradient over vast plains. Farther towards the West evaporation seemed to have surpassed precipitation plus the influx coming from the Andes during the whole year. Under these circumstances the western and central Chaco must have served as plain of catchment and enrichment for matters suspended and solved in the rivers coming from the West. As far as we can see there has obviously never been a humid climate such as to wash out completely from the upper quaternary sediments the salts transported to the Chaco, and to remove them towards the East to the Rio Paraguay.

The further way of the salts on the plain and in its sediments has been directed by the change of solution and local washing out during the rainy season and concentration with local precipitation in river meanders, basins of illuviation etc. during the dry season, as well as by the normal capillar rise of salty waters in the soil and precipitation of dissolved matter near to the surface by means of evaporation.

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