COMMISSION INTERNATIONALE
DES GRANDS BARRAGES

Quinzième Congrès
des Grands Barrages
Lausanne, 1985

EXPLORATION, INVESTIGATION AND TREATMENT OF SEEPAGE IN THE BASIN OF THE LA BOLERA DAM (*)

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1. INTRODUCTION

The study and investigation of the impermeability of a dam site and basin is the question of greatest importance after structural stability and strength, as the effectiveness of dam construction depends on this.

There are many cases in which the dam site permeability can have a decisive effect on the dam's stability, either due to the sub-pressure, piping or slippage of the foundation and river banks.

In the La Bolera dam, where permeability problems have arisen in the basin and at the dam site, these do not affect the dam stability at all. The dam is a curve gravity dam, with a radius of 80 m and foundations laid in a deep gorge of very hard cretaceous limestone (Fig. 1 and 2). The dam height above the river bed is 48 m, although it has been necessary to excavate to a depth of 25 m that was filled with clay, sand and gravel, backfilling with concrete throughout the dam foundation base.

The reservoir in the River Guadalentin, (Fig. 3) a tributary of the Rver Guadalquivir, has a capacity of 56×10^6 m^3 and is employed for irrigation purposes and water supply to towns.

Due to the topographical conditions of the dam site, with a crest length of 108 m, the volume of concrete in the dam is only 36 000 m^3 and that of the river bed fill is 10 000 m^3.

(*) *Exploration, investigation et traitement des infiltrations dans le reservoir du barrage de La Bolera.*

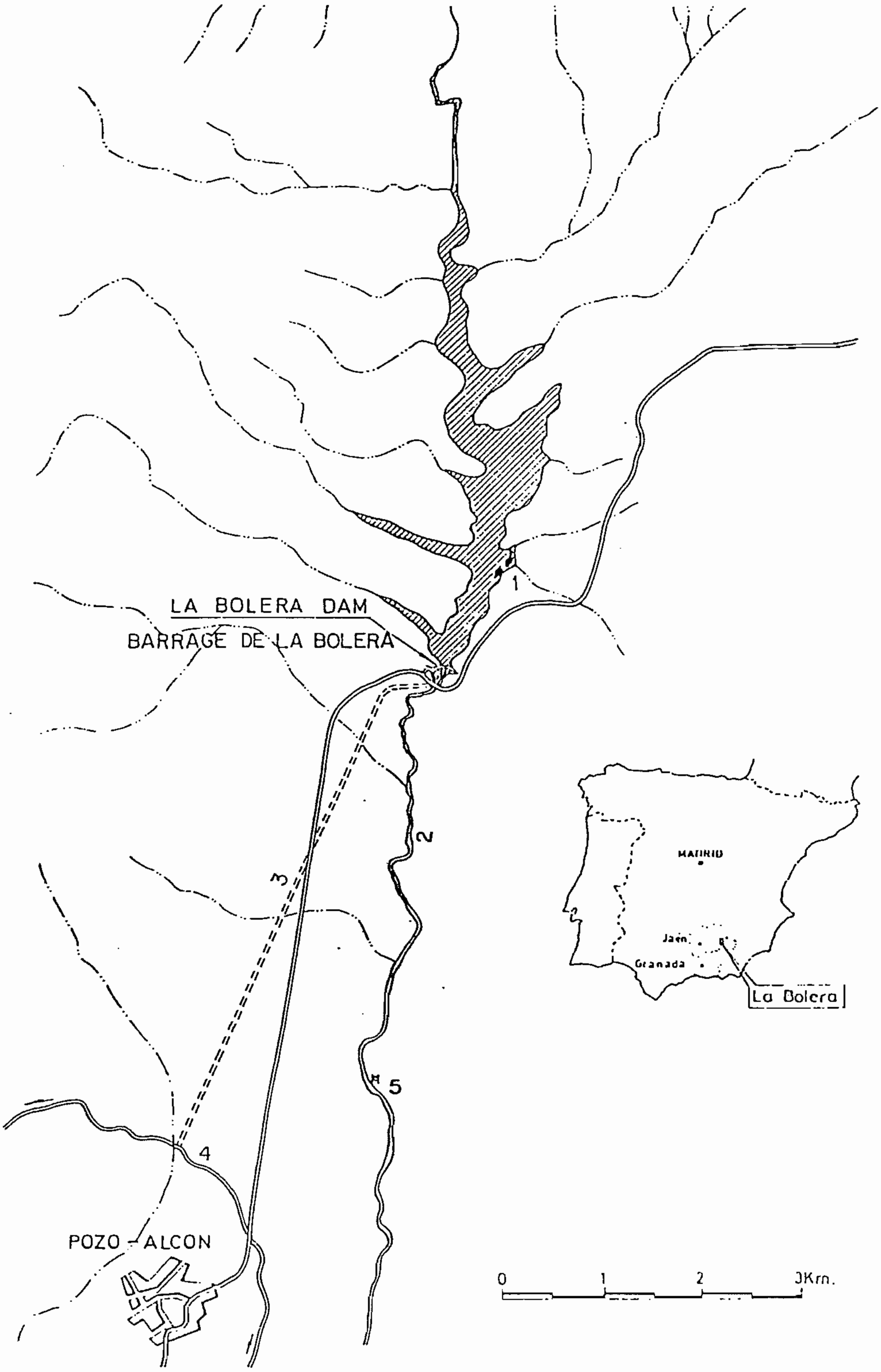

Fig. 1

La Bolera dam, location map

Barrage de La Boléra, plan de situation

1. Karstic zone
2. Guadalentin river
3. Irrigation channel
4. Channel
5. Peralta spring

1. Zone karstique
2. Rivière Guadalentín
3. Canal d'irrigation
4. Canal
5. Source de Peralta

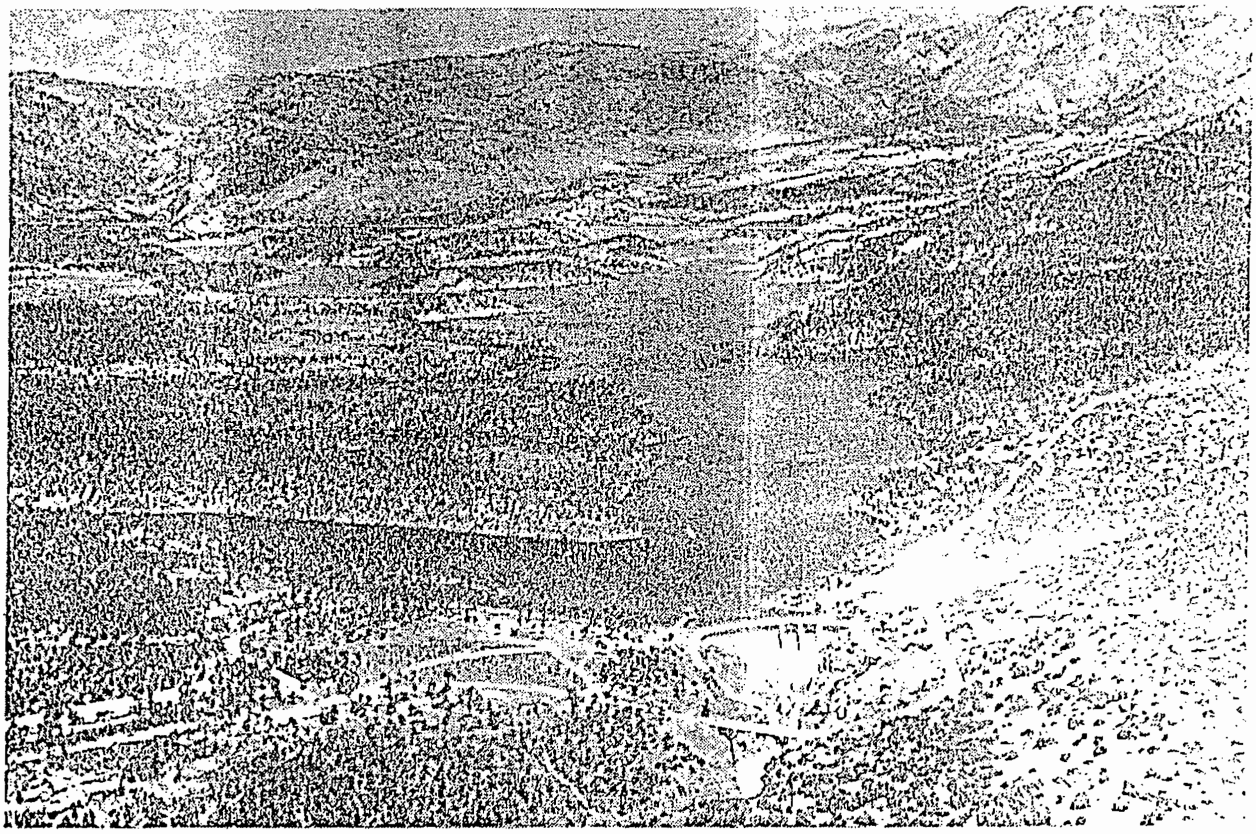

Fig. 2

La Bolera dam, general view
Barrage de La Boléra, vue générale

2. GEOLOGY OF LOCATION

The geological structure of the La Bolera dam site has been the subject of many surveys between 1942 and 1961, the date on which dam construction work started and, later, during the execution of the works between 1961 and 1968, new geological and geotechnical surveys and investigations were completed. Many meters of bore-hole have been sunk, together with geophysical, seismic and electrical surveys, completed with palaentological studies of soil samples, water table measurements, study of spring, etc.

In general terms, the geological structure of the dam site comprise a cretaceous limestone dome that is tangentially cut by the river bed. Above this limestone and concordant with it are the eocene marls on the right bank, with a horizontal conglomerate attributable to the old quaternary crowning them (Fig. 4 and 5).

The reservoir basin comprises conglomerates on the right bank and cretaceous limestones on the left bank of the lower half, with the upper being fundamentally marls and marlish limestones.

Downstream of the dam site the cretaceous limestones continue for some 4 km until they terminate in an impermeable barrier of gypsum clays of the

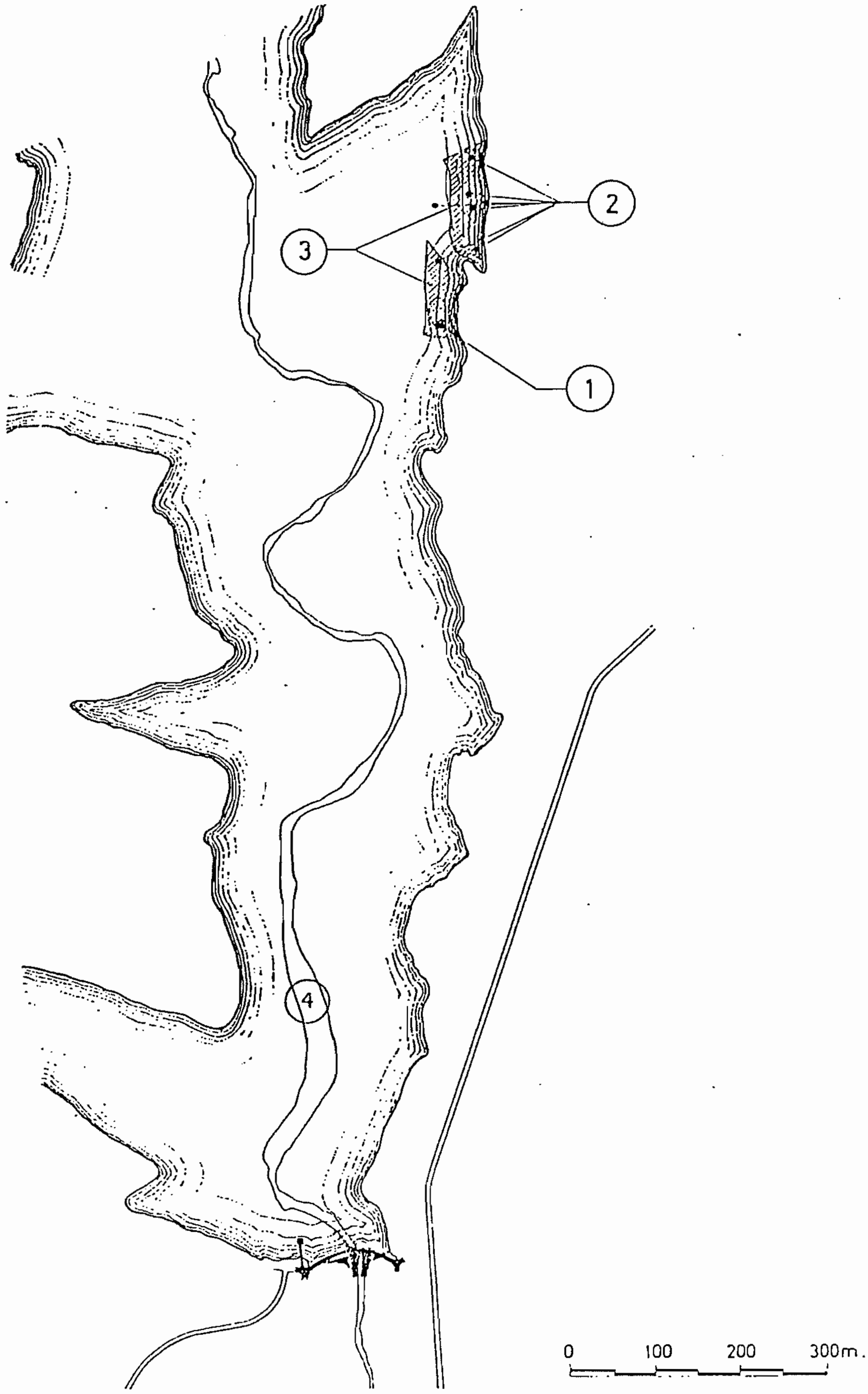

Fig. 3

La Bolera dam, reservoir map

Barrage de La Bolera. Plan du réservoir

1. Cavern No. 1
2. Other caverns
3. Karstic
4. Guadalentín river

1. Caverne n° 1
2. Autres cavernes
3. Zones karstiques
4. Rivière Guadalentín

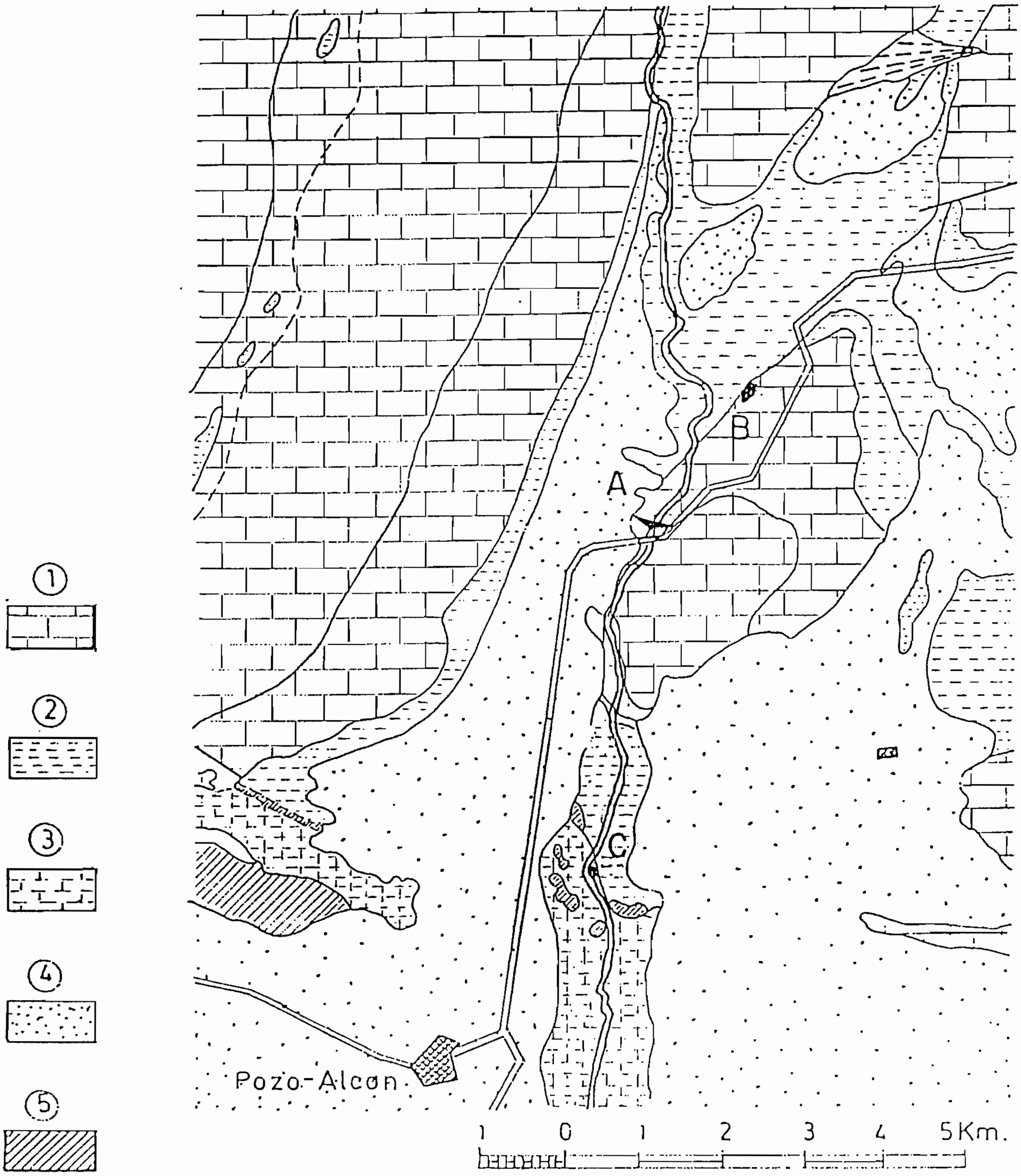

Fig. 4

Geological map

Carte géologique

1. Cretaceous limestone
2. Marl-eocene
3. Cretaceous marl
4. Conglomerate - Quaternary
5. Clay with gypsum — Keuper

A. La Bolera Dam
B. Karstic zone
C. Peralta spring

1. Calcaire - Crétacique
2. Marne - Éocène
3. Marne - Crétacique
4. Conglomerat - Quaternaire
5. Argile avec gypse - Keuper
A. Barrage de La Boléra
B. Zone karstique
C. Source de Peralta

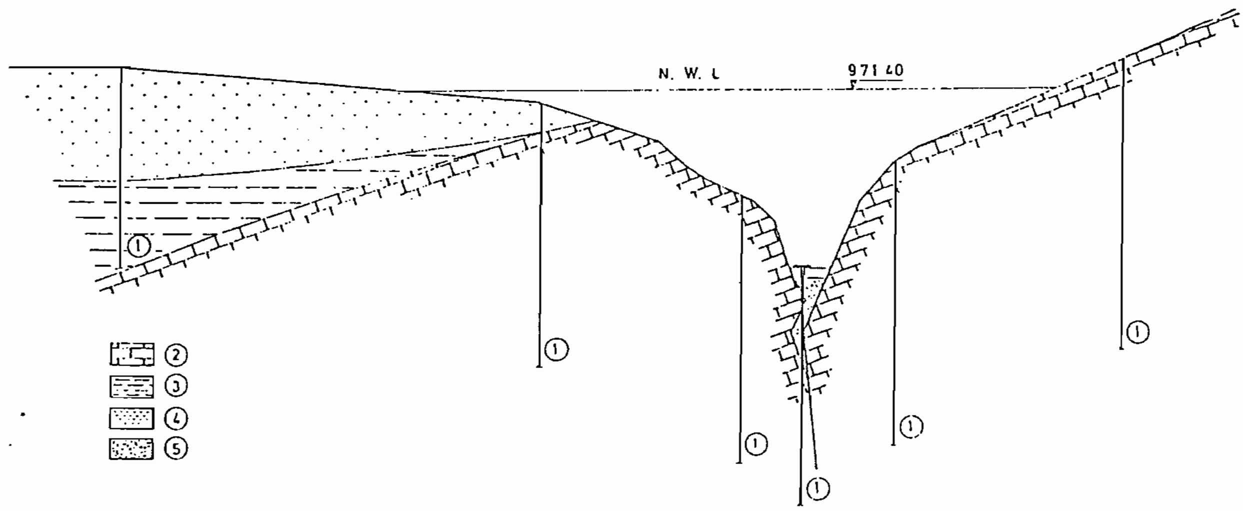

Fig. 5

Geological section of La Bolera Dam site

Coupe géologique de l'emplacement du barrage de La Boléra

1. Investigation bore-hole
2. Limestone
3. Marl
4. Conglomerate
5. Sand, clay and gravel

1. Sondage
2. Calcaire
3. Marne
4. Conglomerat
5. Sable, argile et gravier

triassic (Keuper). Over the last 2 km these limestones are covered in the upper of the valley by eocene marl (Fig. 4).

The whole zone is highly folded by orogenic movements with a great many faults and joints, due to the correspondence to the union between pre-Betic and Sub-Betic facies.

3. THE PROBLEM IN HAND

The only doubt arising in the initial survey was the existence of a drainage point next to the river, upstream and very close to the dam site, that could affect the success of the reservoir, so that a detailed survey was commissioned, sinking bore-holes in order to study the impermeability problem.

The studies came to the conclusion that the underground translocation was limited to a joint in the river bed filled with sand, clay and gravel, so that it was recommended that this joint be cleaned and scale and that the bottom and sides be sealed by grouting. It was estimated that the basin impermeability was assured.

On carrying out the cleaning and excavation of the river bed, it was confirmed that the joint forecast did not exist, but that is was in effect a 25 m deep and 8 m wide palaeo-bed comprising limestone of great hardness and compaction thourghout, perfectly closed with rounded shapes at the bottom. Th palaeo-bed was concreted throughout its depth over a length of 60 m.

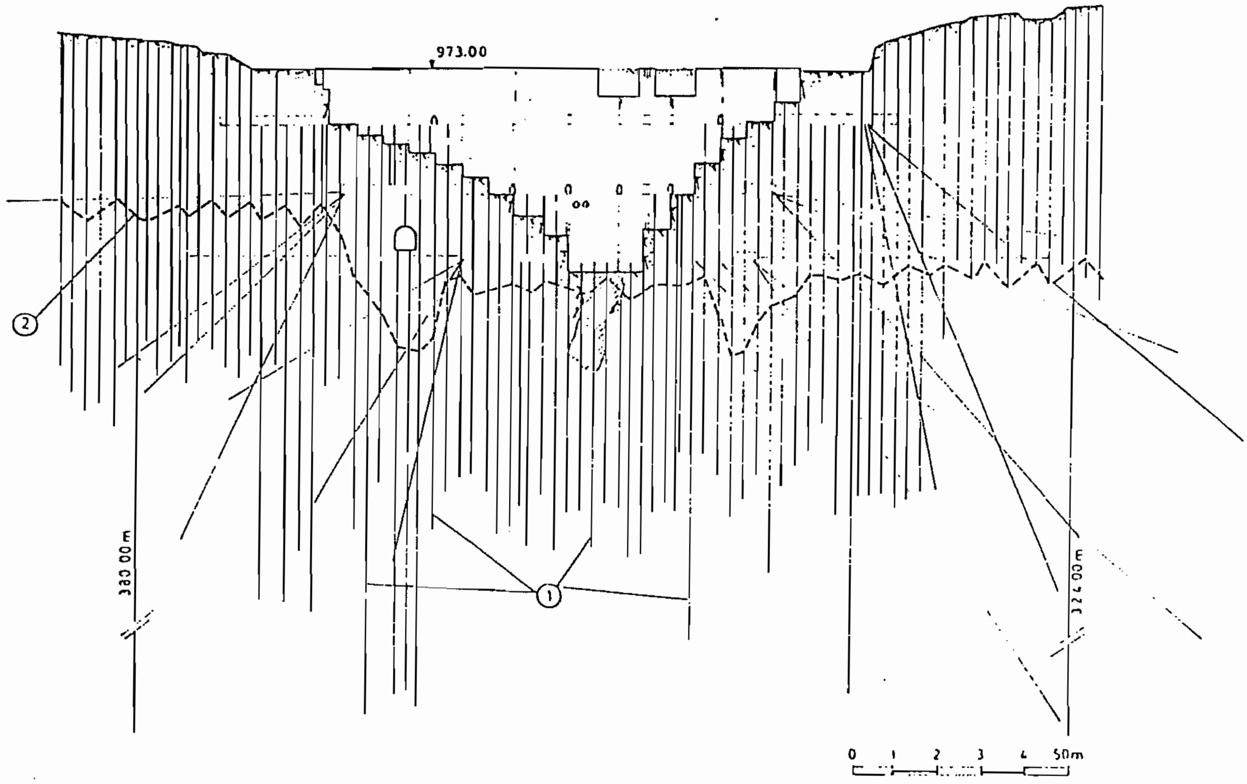

Fig. 6

Grout curtain
Voile d'injection

1. Bore-hole
2. Water table level

1. Sondage
2. Niveau phréatique

The geological studies and surveys carried out during dam construction concluded that the underground translocation was towards the reservoir, with possible passages through both banks, and recommended the execution of grout curtains to seal both banks.

4. GROUT CURTAINS EXECUTED

In accordance with the recommendations of the geological report, grout curtains were executed in the sides and dam site (Fig. 6) in two phases. The first phase covered the dam site itself and 63 mm diameter bore-holes were sunk form the dam galleries. Bore-hole depth was of the order of 60 m at a 3 m spacing. Cement grout admission was highly variable from one bore-hold to another. The zone covered by these bore-holes virtually completely corresponds to the limestone formations and no karstic orifices were observed.

The second grouting phase consisted of widening the screen on both banks and increasing bore-hole density in the dam site zone to a 1.5 m spacing. Limestone continued to appear on the left-hand bank while the right-hand bank is constitued of conglomerates, as observed in Fig. 5. The cement grout

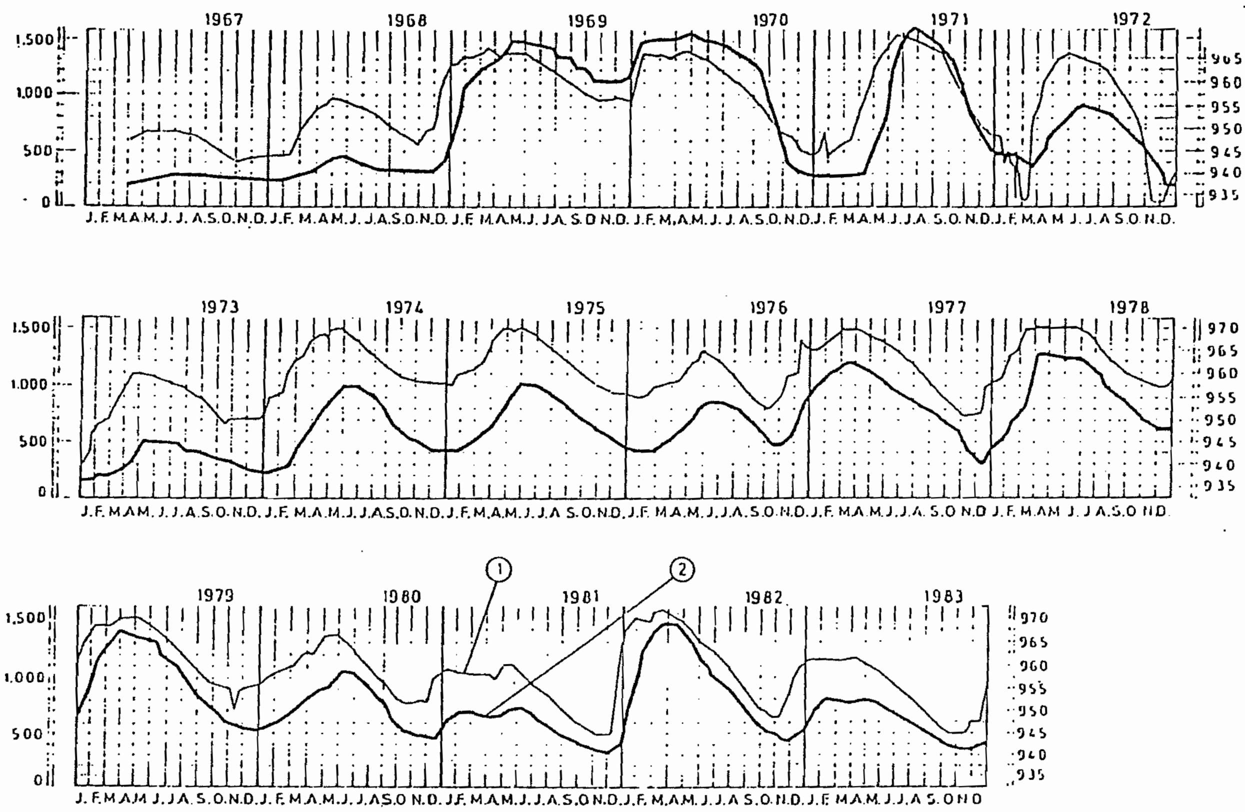

Fig. 7

Graphic, level of reservoir - Discharge of the spring
Graphique, niveau de la retenue - Débit de la source

1. Level of reservoir
2. Discharge of the spring

1. Niveau de la retenue
2. Débit de la source

admission was highly variable from one bore-hole to another in the limestone and much more uniform in the conglomerates.

The water table line (Fig. 6) shows a very irregular distribution always underneath the river level, with two very deep troughs in both dam abutments in the limestone zone. In the conglomerate zone, the water table levels had a more uniform distribution and were a little lower than the reservoir level.

During execution of the first phase of the grout curtain in 1967 and in accordance with the geological surveys that were being carried out, the existence of a source was discovered in the left-bank of the river, some 4 km downstream from the dam site and with a level difference of some 150 m. This source denominated Peralta gave a flow-rate of 250 l/s (Fig. 1).

The cretaceous limestones from the dam site to de peralta source form a series of dolds that are cut in this location by the outcrop of triassic clays (Keuper), that represent the impermeable base level of the zone.

From the start we knew that this source was the natural outlet of the leakage observed in the reservoir basin, so that we installed a weir flow meter to measure the source flow-rates.

On initiating the first partial filling of the reservoir in 1968, the source flow-rate only increased slightly. At the beginning of 1969 the reservoir was filled over in a short period of time, and was discharching through the spillway from January to May. The flow-rates of the Peralta source increased up to 1 400 l/s. As the reservoir level fell, so did the source flow-rate.

In 1970 the reservoir was again completely filled and discharged through the spillway from January to April and the source flow-rate again increased to (over in a short) a similar extent to the year before (Fig. 7 —reservoir level graph— source flowrates).

In the light of the second phase grouting programme that was being carried out at this time, the summer of 1970, which was having no appreciable effect on the leakage, we decided to suspend grouting and lower the reservoir level to observe the basin, suspecting that the leaks were not occurring close to the dam site but, to the contrary, could be taking place in the reservoir basin.

As the level fell, the reservoir basin was carefully inspected, especially the limestone zone, with the result that a cavern of 1,0 × 0,5 m was found at elevation 951,70 where, according to our calculations, some 500 l/s were leaking out.

The reservoir level was reduced below this elevation, but was held between 950 and 945 and it was confirmed that the Peralta source flowrate dropped spectacularly, until it was almost reduced to its original figure, which demonstrated that this cavern and others in this zone were the major cause of leakage observed in the reservoir.

The banks were inspected and the drainage points found were plugged with mortar and clay as described below, but the lack of time did not allow a more detailed survey of the zone to be carried out as the reservoir level was starting to rise again.

When the reservoir level rose again in the spring of 1971, the Peralta source flow-rate increased slightly but, on exceeding the level above the spillway lip with the gates closed (something that had not been done previously) the flow-rate of the Peralta source increased greatly and reached 1 600 l/s (as seen in the graph of Fig. 7).

Wa lowered the reservoir level and carefully inspected the zone, discovering new caverns covered over with scouring from the side located in the high zones of the reservoir, above the spillway lip.

5. CAVERN EXPLORATION AND INVESTIGATION

Fig. 1 and 4 indicate the karstic limestone zone of the basin, located 1,5 km upstream of the dam and the location of the main cavern found is marked on Fig. 3 which we denominate cavern no. 1, together with that of other drainage points close to it (Fig. 8 and 9).

Cavern no. 1, the plan, longidutinal profile and cross-sections of which are shown in Fig. 10, was inspected and explored over a length of 300 m with a

Fig. 8

Karstic zones
Zones karstiques

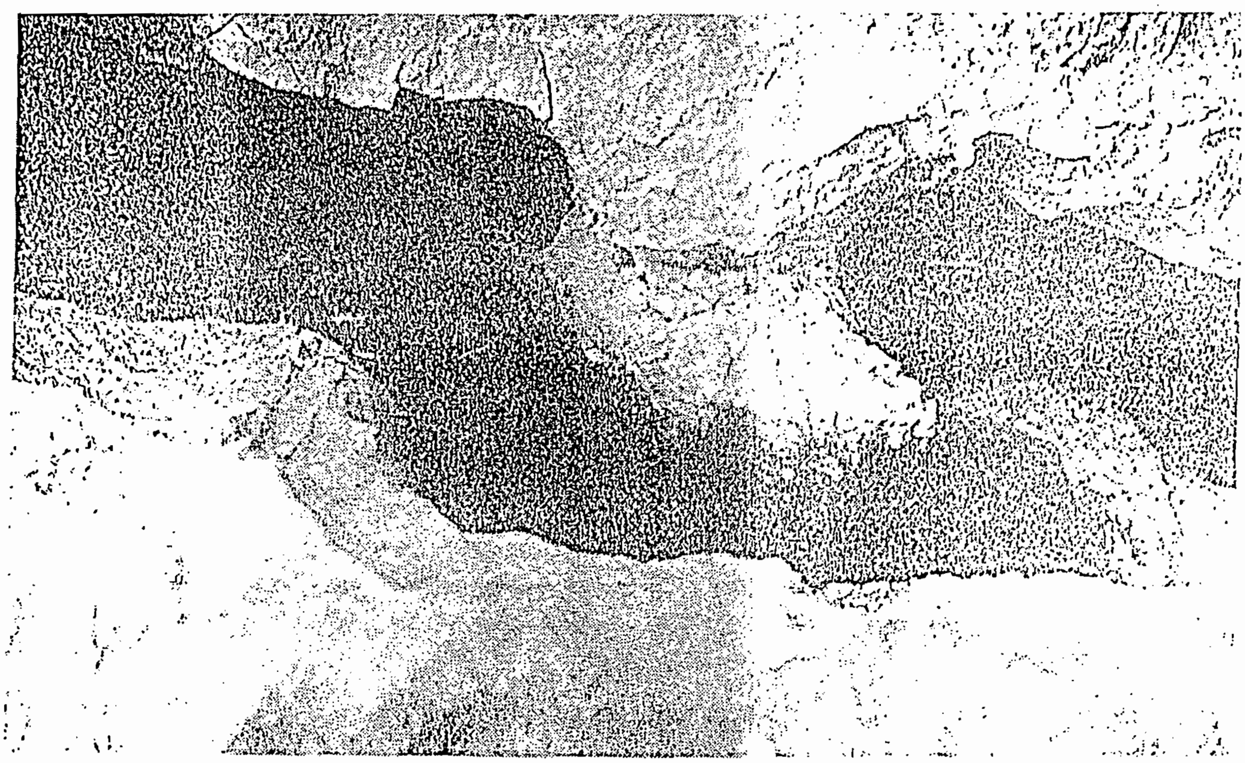

Fig. 9

Karstic zones

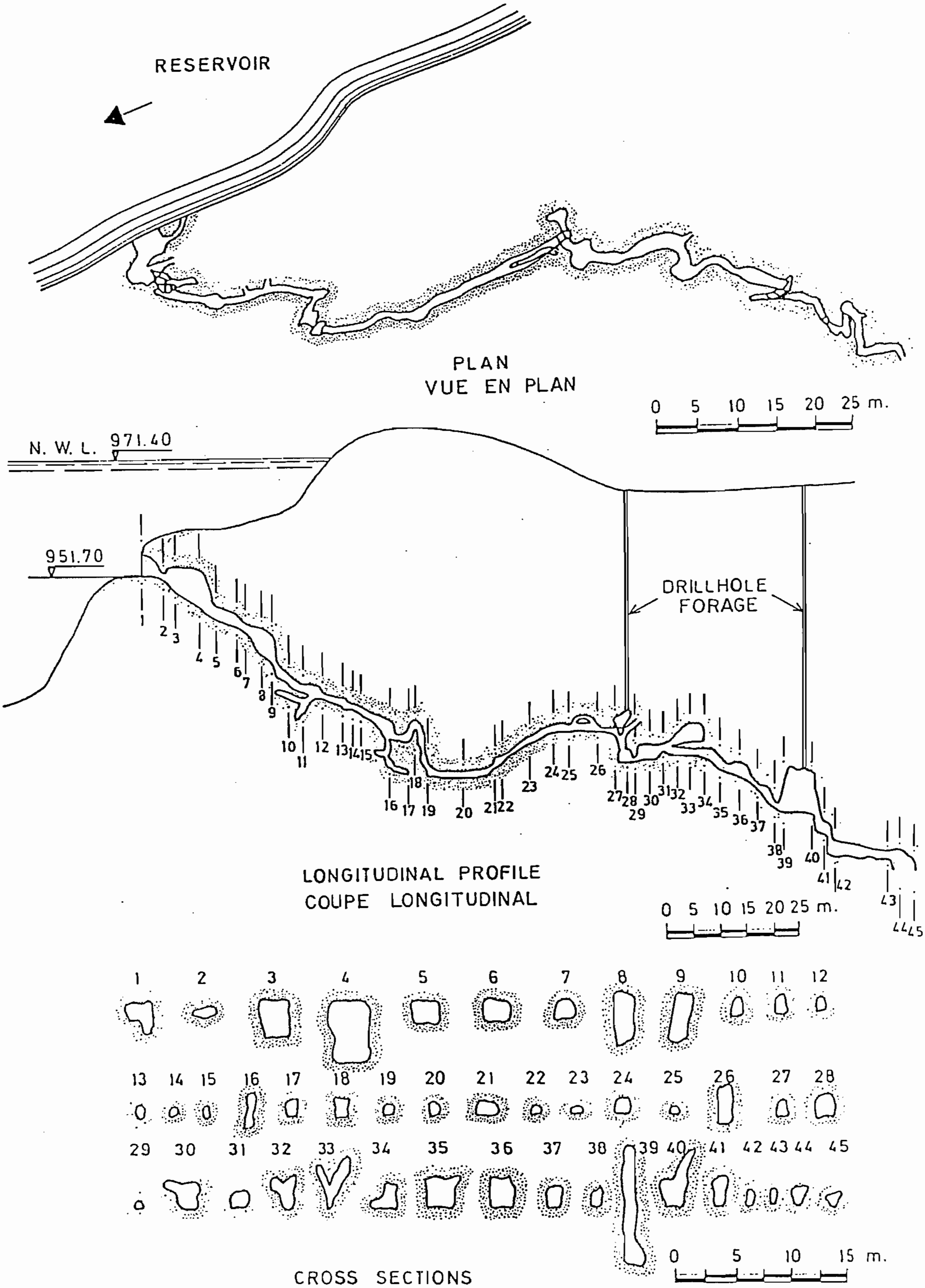

Fig. 10

Cavern No. 1

Caverne n° 1

Fig. 11

Cavern No. 1 - Entrance
Caverne n° 1 - Entrée

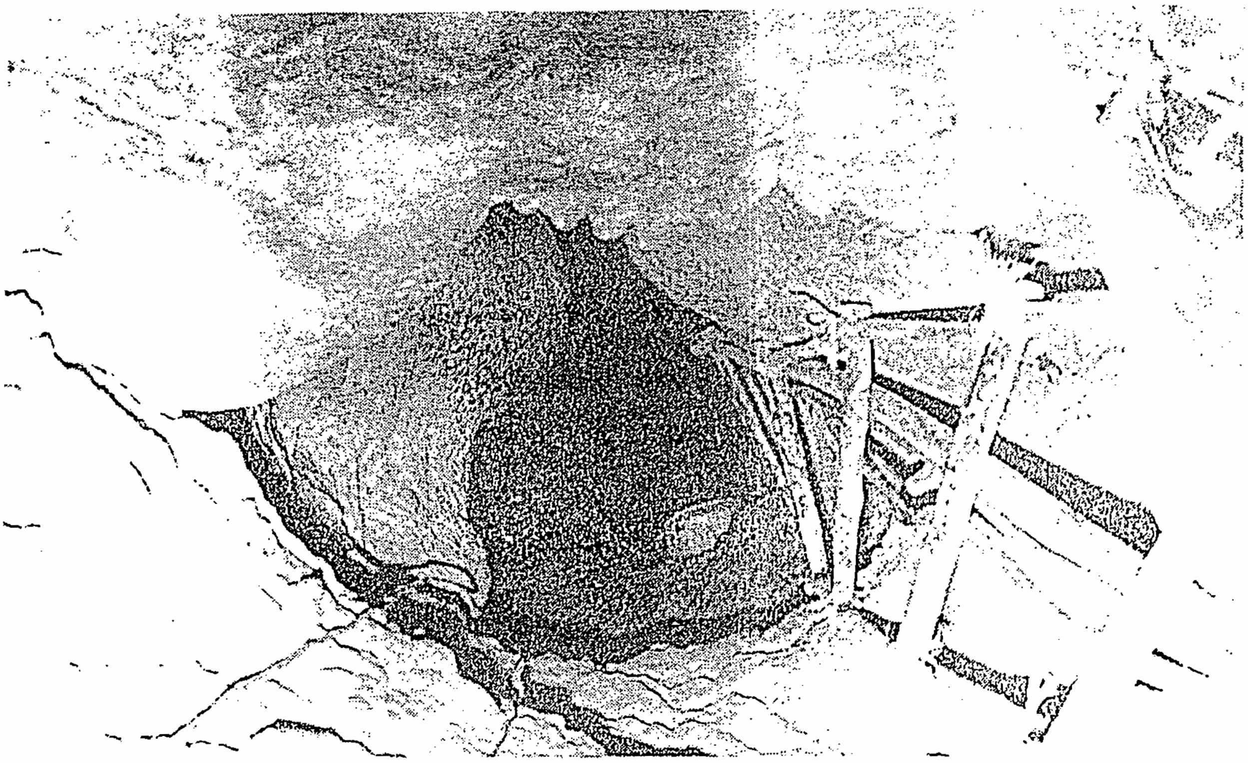

Fig. 12

Cavern No. 1 - Interior
Caverne n° 1 - Intérieur

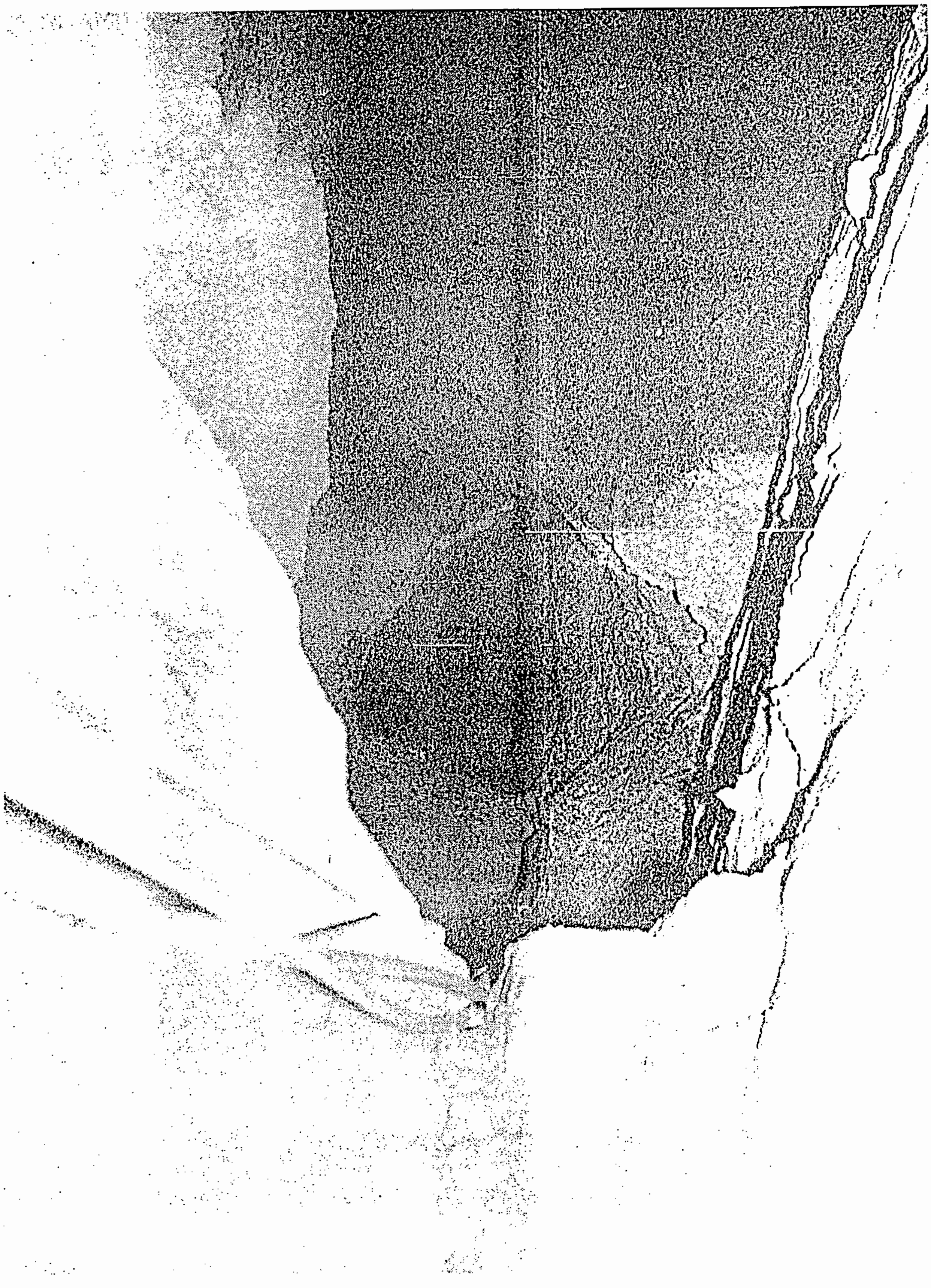

Fig. 13

Cavern No. 1 - Interior

Caverne n° 1 - Intérieur

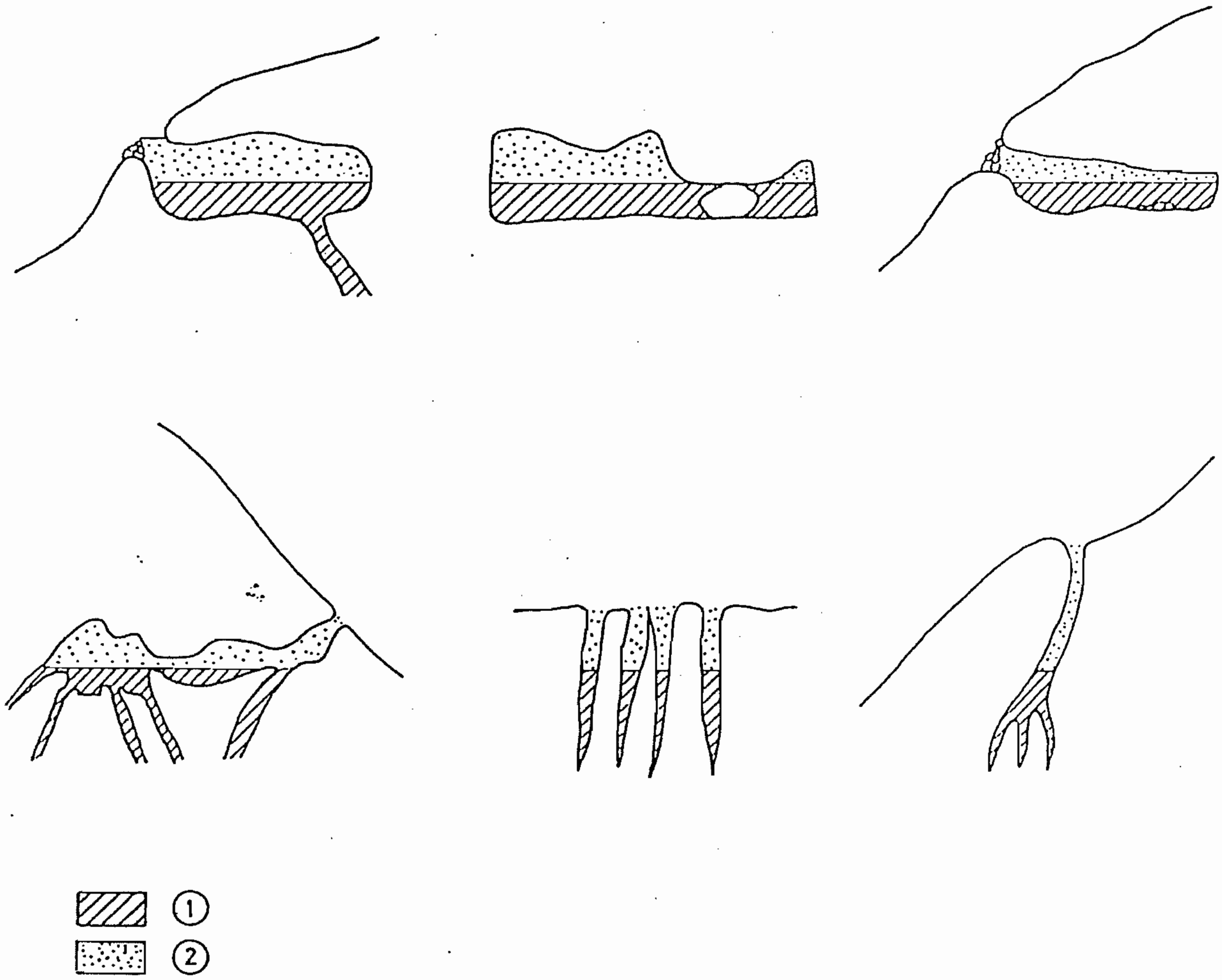

Fig. 14

1. Mortar 2. Clay

1. Mortier 2. Argile

Other caverns - Treatment

Autres cavernes - Traitement

level difference of 80 m. The exploration and survey of this cavern lasted 4 months, was a difficult and risky task given the narrowness of some zones of the duct through which a man could hardly crawl and given the need to remove rubble that was blocking some sections, the continuous ups and downs and the lack of ventilation, so that it could be considered as a speleological investigation (Fig. 10).

This cavern comprises a typical karstic duct of water under pressure that corresponds to the juvenile phase of the karst formation with rounded shapes produced by the erosion of the duct perimeter as the water flows through under pressure.

Fig. 12 and 13 show the rounded shape of the ducts, without reconstruction phenomena and the existence of "terra rosa" decalcification clay alternating with other shapes, generally in fault or joint, of free translocation and limestone reconstruction phenomena.

Close to cavern no. 1 there is a strongly karstified zone covering 300 m lying between elevations 940 and — 971,40 (maximum reservoir level), where

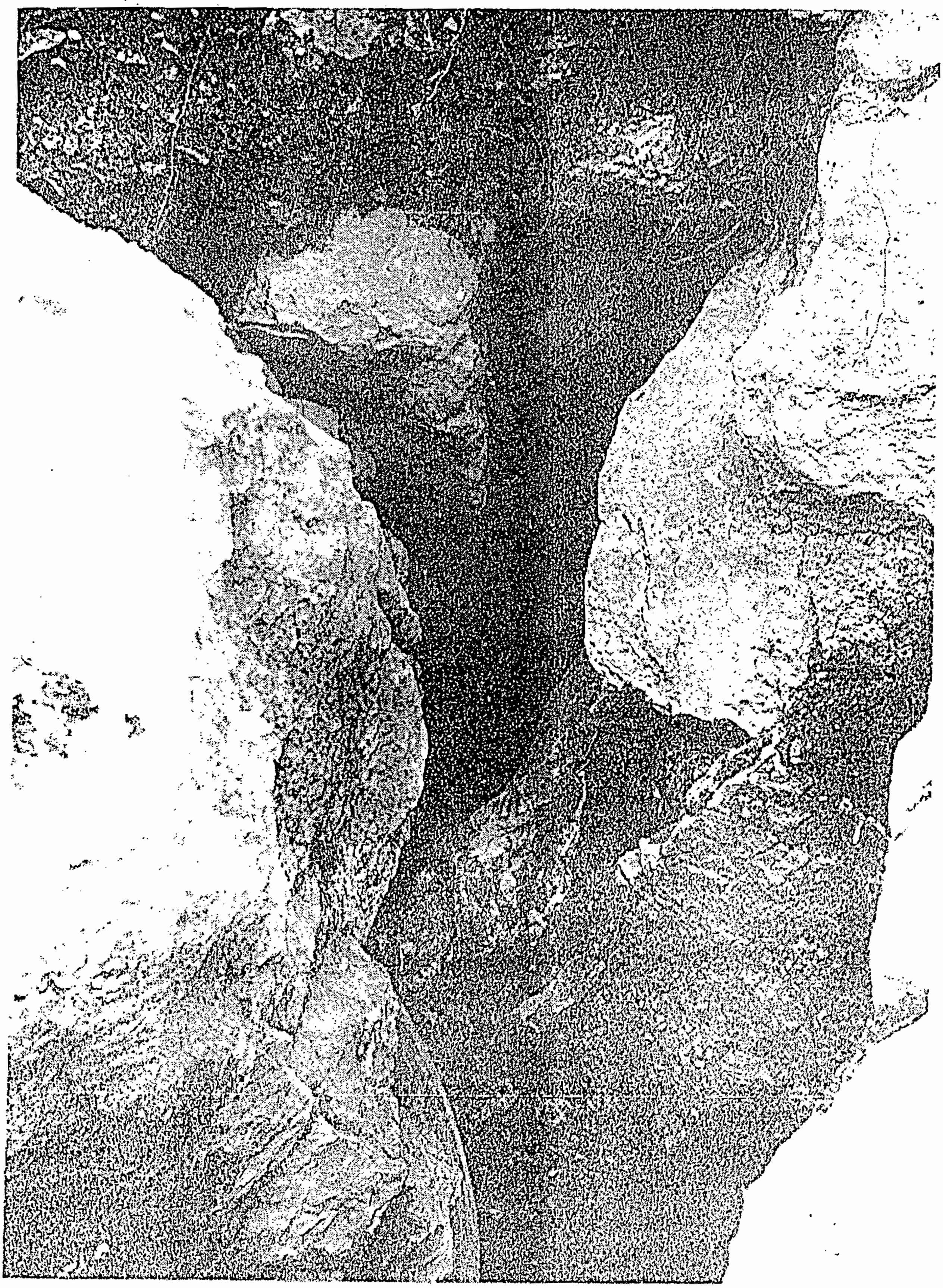

Fig. 15

Other cavern - Entrance

Autre caverne - Entrée

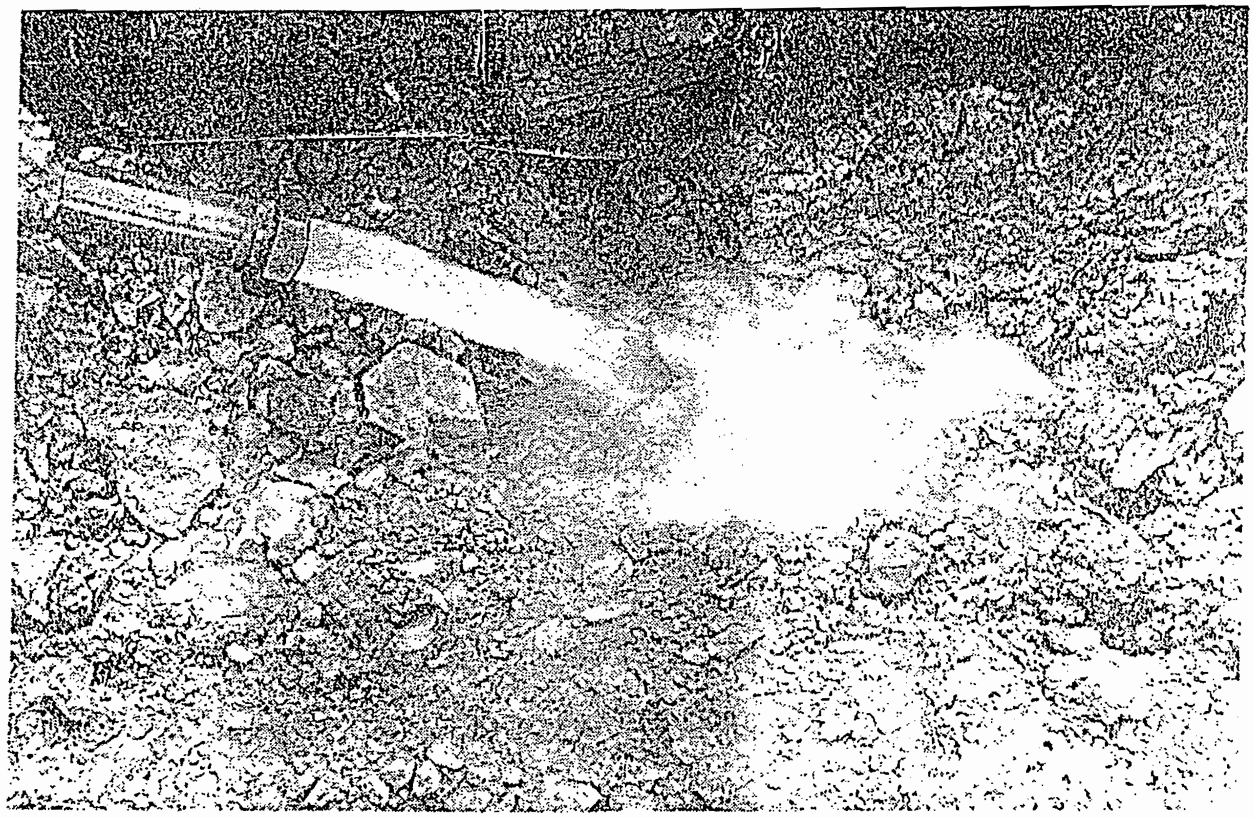

Fig. 16

Permeability test
Essais de perméabilité

various caverns of relative importance (Fig. 14 and Fig. 15) were discovered and investigated to the point that entry is possible, together with small irregularly distributed drainage ducts. For the investigation and surveying of the small drainage points, the rock was cleanded, removing the topsoil and detritus and then testing absorption of the cracks and sink-holes in the limestone with a water hose in order to detect the zones water losses were taking place (Fig. 16).

The discovery of the caverns and drainage points has shown us that the water flow and, consequently, reservoir basin leakage was mainly but not uniquely due to the existence of an old Karst that, on becoming wet due to the reservoir, alowed water to flow.

The existence of the Karst justifies the water table levels observed in the sealing curtain bore-holes being so deep with respect to the river level and so irretularly distributed.

Cavern no. 1 explored to nearly 80 m below the reservoir level was completely dry, which confirms that the limestone is practically impermeable and that the water flow was only through the darstic ducts.

The situation inside the reservoir basin of cavern no. 1, its great depth and its direction in the opposite sense to that of ther river, indicate that the water flow could have great depth and that probably the ducts will pass well away from the dam site zone covered by the grout curtains.

Also the existence of the karst justifies the bore-hole admissions that were so irregular and the filling of cavities that have no communication with the reservoir, explaining the low efficiency of the sealing curtain in cutting off leakage that, however, served to plug small leakage points at the rock-concrete contact zones.

6. TREATMENT OF CAVERNS AND DRAINAGE POINTS

In order to cut off the leakage in the reservoir basin caused by the existence of caverns and drainage points, the main caverns were filled and the small drainage points sealed off.

Cavern no. 1, given its large size, is filled with sections of cement mortar in the narrow zones and clay in the wider zones (Fig. 17). Due to the existence of ducts in the form of a syphon, two bore-holes were sunk from the surface through which a flexible plastic hose was introduced through which the clay or cement and fine sand mortuar grout was pumped. The first section of the duct was filled with flexible hose introduced through the entrance that was removed as the work advanced (Fig. 18).

The remaining visitable caverns (Fig. 14) were filled with the same system, introducing hoses through the entrance. Firstly, they were filled with cement grout to plug the smaller orifices, then with cement and very fine sand mortar and finally with clay grout. We consider it to be very important that the first fill is with cement or mortar grout in order to avoid them being uncovered by water action, with the clay only being to complete the sealing process when the main orifices are already covered.

The treatment of the non-visitable drainage points employed the same system. The production of grout or mortars was in an ordinary cement mixer and was pumped to the point of application through a flexible plastic pipe.

In order to complete the sealing off of the karstic zone after filling the drainage points found, surface layers of sealing concrete without coarse aggregates was executed to cover the whole zone suspected of containing karstic ducts. The concrete was mixed in an ordinary cement mixer and taken to the application zone through gutters and then spread by hand (Fig. 19 and 20).

The cost of all of the surface layer and drainage point filling operations was little more than 12 million pesetas in 1972.

7. RESULTS OBTAINED

The work described above was mainly carried out in 1971 and 1972 although the basin has been surveyed in later years in order to discover new drainage points, fill them in with the same system when any have been found.

No new caverns have been discovered in the basin and the small drainage

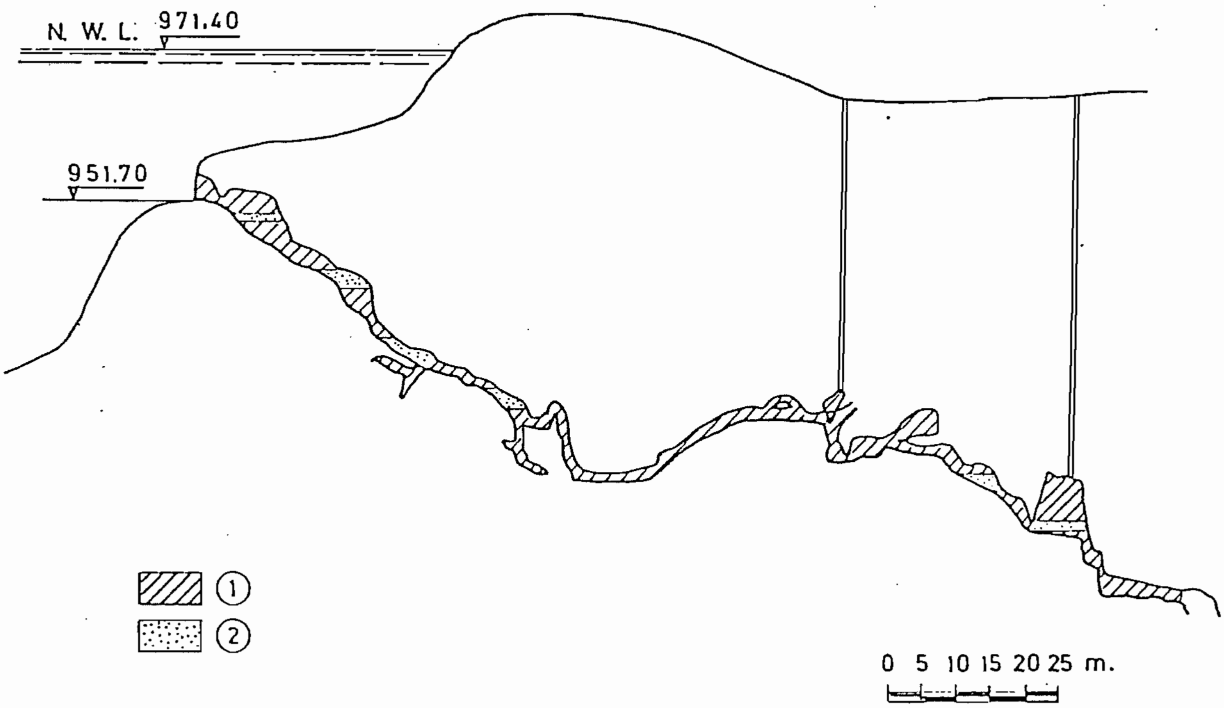

Fig. 17

1. Mortar	*1. Mortier*	Cavern No. 1 - Treatment
2. Clay	*2. Argile*	*Caverne n° 1 - Traitement*

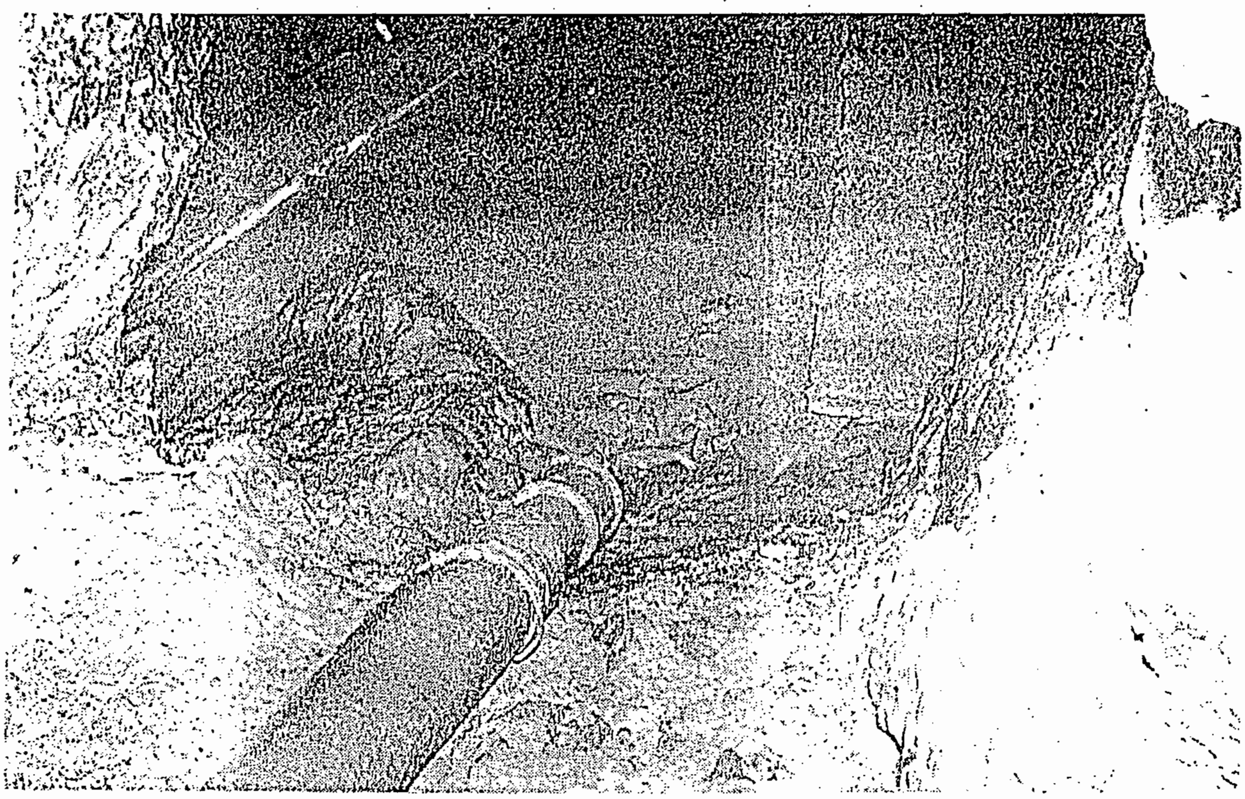

Fig. 18

Filling cavern with clay

Remplissage de la caverne avec argile

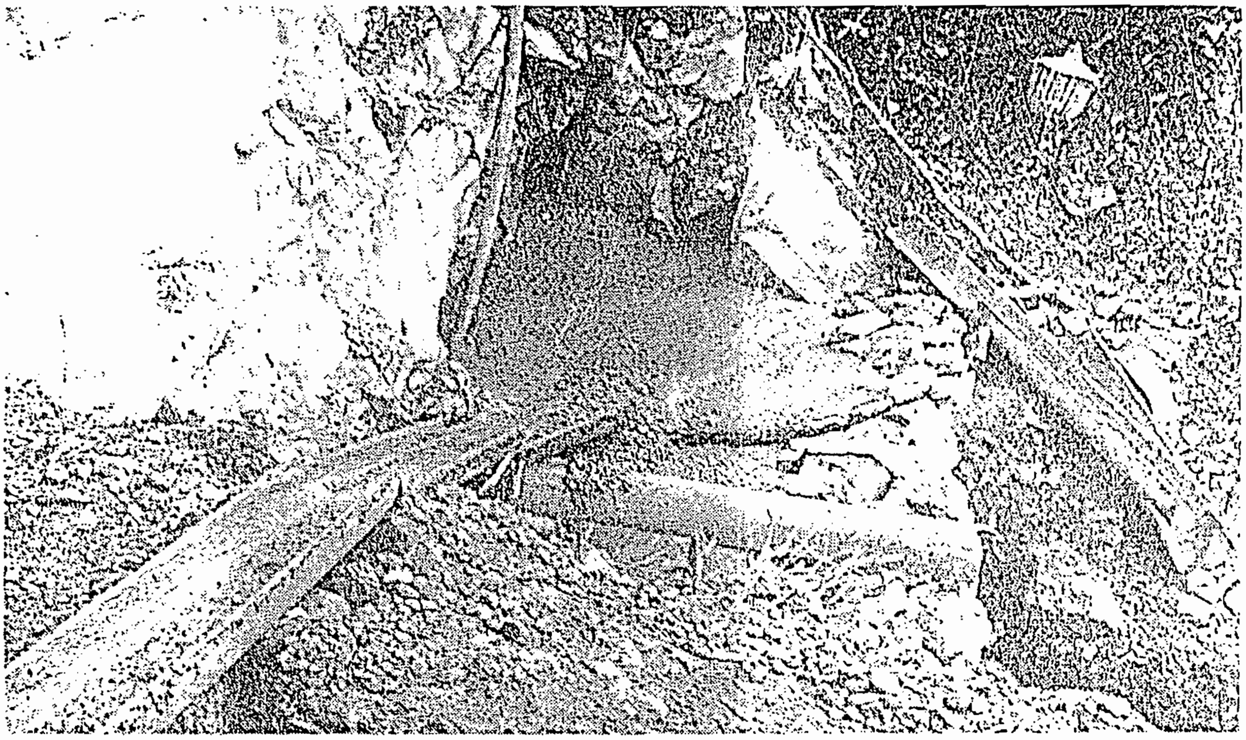

Fig. 19

Superficial layer of concrete
Couche de béton en surface

Fig. 20

Superficial layer of concrete
Couche de béton en surface

points that have been detected at a later date are very close to the karstic zone already treated.

In the graph of source flow rate —reservoir level (Fig. 7)— it can be seen that after carrying out the treatment the leakage in the years 1972, 1973, 1974, 1975, 1976 and 1977 decreased considerably despite the reservoir reaching its maximum level with gates in all of these years. The reduction in leakage can be estimated at 600 l/s which approximately represents one half of the water losses. From 1978 onwards the source flow-rates increase and, consequently, the leakage when the reservoir reaches the highest levels, but is, however, still small when the reservoir is at lower levels. This circumstance seems to indicate the opening of new drainage points in the high zone of the reservoir produced by the water removing the topsoils and rubble that were blocking them and a new drainage point system campaign is scheduled for this year.

We consider that the most important achievment of the work described above is not only the appreciable reduction of existing leakage from the reservoir basin of La Bolera, but that avoided the opening of large-scale leaks that would undoubtedly have occurred if this work had not been carried out, as the water uncovered the many karstic ducts existing in the basin, which would have seriously affected the success of the reservoir.

Since 1968, when the dam entered into service, the reservoir has been completely filled every year, except for 1976, 1981 and 1983, which were extremely dry years, having discharged large volumes of water through the spillway in the remaining years, which confirms that the leakage occurred in the basin, which has been controlled and partly suppressed, has not perturbed the operation of the reservoir that supplies its irrigation zone under completely normal conditions.

8. CONCLUSIONS

From the experience obtained in the investigation and treatment of leakage in the La Bolera reservoir, general conclusions can not be drawn. This is only a specific case that does not necessarily have to repeated anywhere else.

However, with all possible caution, we belive that some lessons can be learned from the treatment of leakage in reservoirs situated in karstic zones.

1) When the reservoir basin has limestone formations, the possible existence of karstic phenomena must be investigated. To do this the limestone surfaces must be carefully surveyed, after cleaning, in order to check for the existence of sink-holes, drainage points etc. or other karst absorption forms.

2) In the event that the existence of karstic phenomena is detected, it is advisable to carry out permeability tests to estimate the possible extent of leakage.

3) The study of sources that may exist in the basin and especially in the river upstream of the dam, is fundamental, measuring their flowrates before and after filling the reservoir.

4) If the existence of a developed karst is confirmed, we belive that the classic grout curtains at the dam site will not be very efficient, so that grout curtains should be limited to the zone close to the dam, without extending it excessively when trying to cut off leakage; it will probably be a more advisable solution to fill in the drainage points and surface layers in the karstic zone, employing procedures similar to those described in this paper.

5) This sealing work should not be carried out until the existence of water leaks has been confirmed, as a fossil karst may be concerned with no communication downstream of the dam. The best sign of the existence of real water leaks is the increase in flowrate of sources located downstream of the dam and the confirmation of the permeability of the zone to be treated.

6) The filling in of drainage points and the execution of sealing layers in karstic zones is slow work that requires great care and workmanship, but we consider that in many cases it will be the most effective and economic system in order to control and reduce water leaks in reservoirs where leaking is caused by karstic phenomena.

SUMMARY

The existence of karstic zones has been observed in the La Bolera dam (Spain), whose dam site and reservoir are located in cretaceous limestone formations, which are responsible for major leakage from the reservoir.

The procedure adopted for the exploration and investigation of this karst is described, which resulted in the discovery of several large caverns, together with other smaller ones and many small drainage points.

The treatment of the caverns and drainage points involved the filling in with clay grout and cement mortar that was manually introduced inside the karstic ducts, completing the sealing of the small drainage points with surface layers of concrete.

An analysis is made of the results obtained that are shown in a graph of leakage flowrates-reservoir height and several conclusions are drawn relating to the treatment of water leaks in reservoirs located in karstic zones.

RÉSUMÉ

L'existence de zones karstiques a été observée au barrage de La Boléra, où la retenue et le barrage sont situés sur des calcaires crétaciques qui donnent lieu à des fuites importantes.

On décrit dans cette communication la méthode adoptée pour les reconnaissances qui ont conduit à la découverte de quelques grandes cavernes ainsi que d'autres plus petites et de nombreux petits conduits d'infiltration.

Les traitements des cavernes et des conduits ont comporté leur remplissage

par injection d'argile et mortier de ciment qui y étaient introduits manuellement. L'imperméabilisation des petits conduits a été complétée par des couches de béton en surface.

La communication présente une analyse des résultats obtenus, représentés sur un graphique, qui donne les débits de filtration en fonction du niveau du réservoir. On tire aussi quelques conclusions sur le traitement des fuites d'eau pour des réservoirs situés en zones karstiques.