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SUITABILITY OF DAM SITES IN MAURITIUS

by

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INTRODUCTION

Sites where dams/reservoirs have been proposed in Mauritius are listed in Table 1. In many of these places, detailed investigations have been carried out, only to be shelved for some reason or other. Other dams have been constructed, sometimes after a sketchy desk study investigation, simply because of the urgency of water supply or because of lack of appropriate expertise. It is proposed here to look at a few dams (proposed or built), notably because of findings during investigations or during performance afterwards.

GENERAL GEOLOGY AND HYDROGEOLOGY OF MAURITIUS

Geological history

Geological studies on Mauritius have been carried out by several persons including de Chazal *et al.* (1949), Simpson (1951), Walker & Nicolaysen (1953), McDougall & Chamalaun (1969), Baxter (1975), Perroud (1982) and Willaime (1984).

Mauritius is entirely of volcanic origin, with almost all the rocks found on the island being basalts or pyroclastics of various kinds. The only non volcanic formations found on the island are recent raised reefs and beach and dune deposits. These are thin and of very small areal extent.

Table 1: Dam sites proposed in Mauritius

Dam Site	Desk Study	Geophysical	Coring	Feasibility Study	Design	Construction
Mare aux Vacoas	1881					1885-1961
Tamarind Falls						1902
La Ferme	1900				1914	1914
La Nicolière	1895			1914		1924-1929
Réduit						1931
Mare Longue					1953	1953-54
Piton du Milieu					1953	1953-54
Eau Bleue					1961	1961-62
Valetta						1949
Diamamouve	1978		1978	1978	1978	1980-1983
Belle Etoile	1978					
Quatre Soeurs	1978					
Moulin à Poudre	1966	1958-1966	1966			
Montagne Longue	1966	1958-1966				
Mare d'Australia	1940	1959-1966	1991			
Rivière Baptiste	1966	1967	1972	1972-73	1974	
Hermitage	1967	1963-1967				
Côte d'Or	1967	1964-1967		1981		
Mon Vallon	1989					
Chamarel	1962	1962	1966	1968		
Montagne La Terre		1967				
Piton du Milieu extension		1967				
La Nicolière extension	1966	1959-1966	1966-1992			
Midlands	1914	1962-1992	1966-1992	1914-1993		
Calebasses	1966	1959-1966	1992	1988		
Black River	1972			1980		
Astroea	1977			1977		
Bagatelle	1989	1966	1989	1989		
Terre Rouge	1988	1989	1989	1989	1990	
Sorèze	1954		1971	1971		
Guibies	1979	1966	1981	1981		
Rivière du Poste/La Flo	1972		1972	1973		

Table 1. Dam sites proposed in Mauritius

In fact, in the formation of the island, four volcanic phases (Fig. 1) must be considered,

(i) Emergence
(ii) Older Volcanic Series
(iii) Intermediate or Early Volcanic Series
(iv) Younger Volcanic or Late Volcanic Series.

Geology

The Older Volcanics Series rocks are generally massive and any fissures or vesicles are usually filled with secondary zeolite and calcite crystals. The weathering of the older series, which is in general very deep except on the eroded outcrops, produced clayey material which contributed to the blocking of the fissures and cracks of the rocks during about the last 6.8 million years. This explains the general impermeability of these series.

The Younger Volcanics of the second and third phases include highly fissured, vesicular and scoriaceous basalts and fine-grained pyroclastics. All important aquifers are found within the basalts of the Younger Volcanic Series, particularly the Late Volcanics.

The same process appears to have occurred with the early volcanics of the young series, which were more or less deeply weathered during the period of quiescence between 1.9 and 0.7 million years ago. During this long period, fissures were also partly blocked by secondary deposits. This explains why early lavas are in general less permeable than late lavas, which are fresher.

Lava tunnels

Fig. 2 shows the location of known lava tunnels. Cavities may act as collector drains for underground water and thus be quite useful. But they will also channel polluted water with the same ease. The Petite Rivière tunnel is high enough to allow walking during most of its length (some 800m). At the entrance, it is some 6m wide. An examination of the tunnel shows that there are no pools of standing water, indicating that there is an outlet somewhere, probably near the sea. It has been proved recently that there is probably no outlet for human access, but as water does not accumulate anywhere, the effect of having such a lava tunnel on the banks or in the bed of an impounding reservoir may be imagined. The reservoir will never get filled!

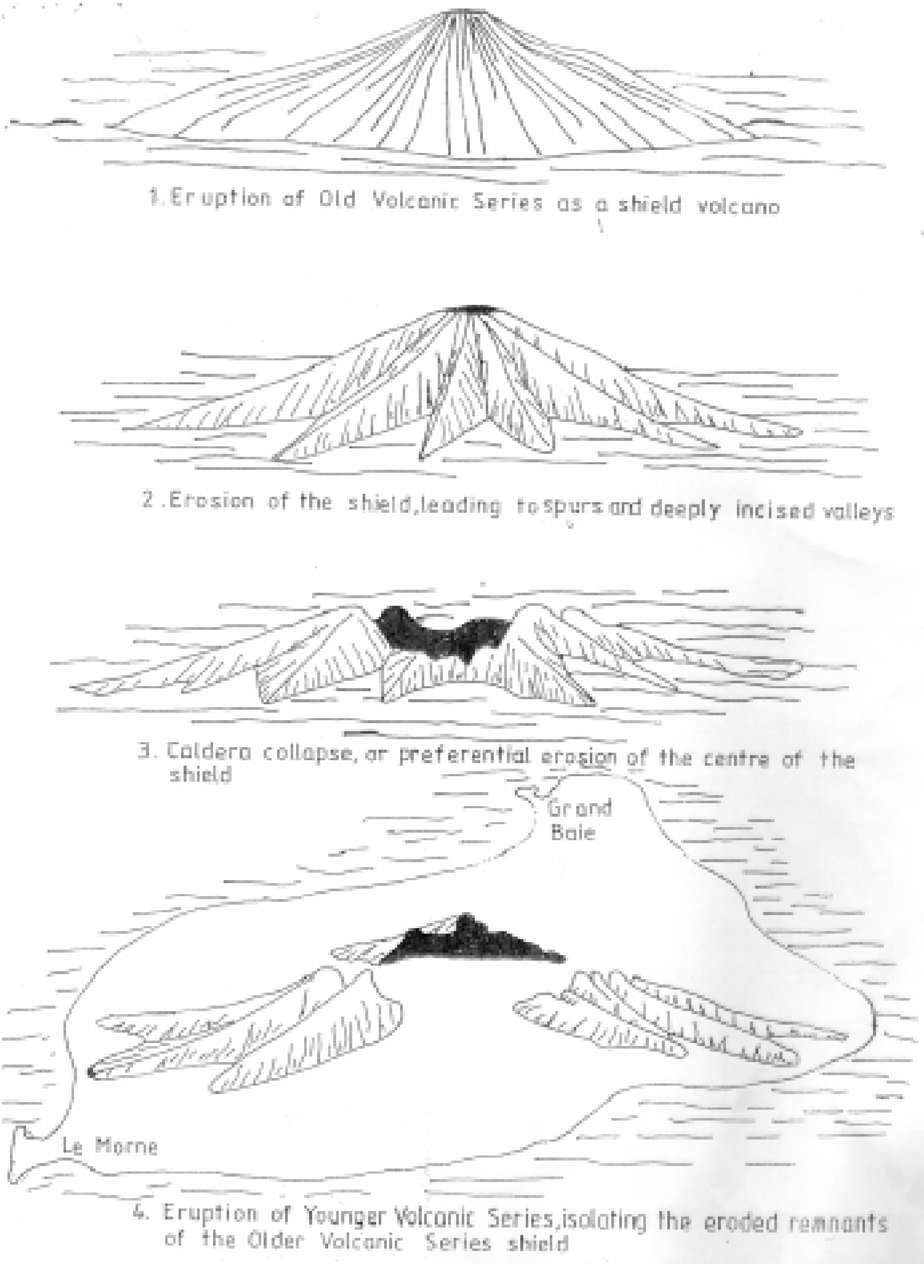

Fig. 1. Formation of the island

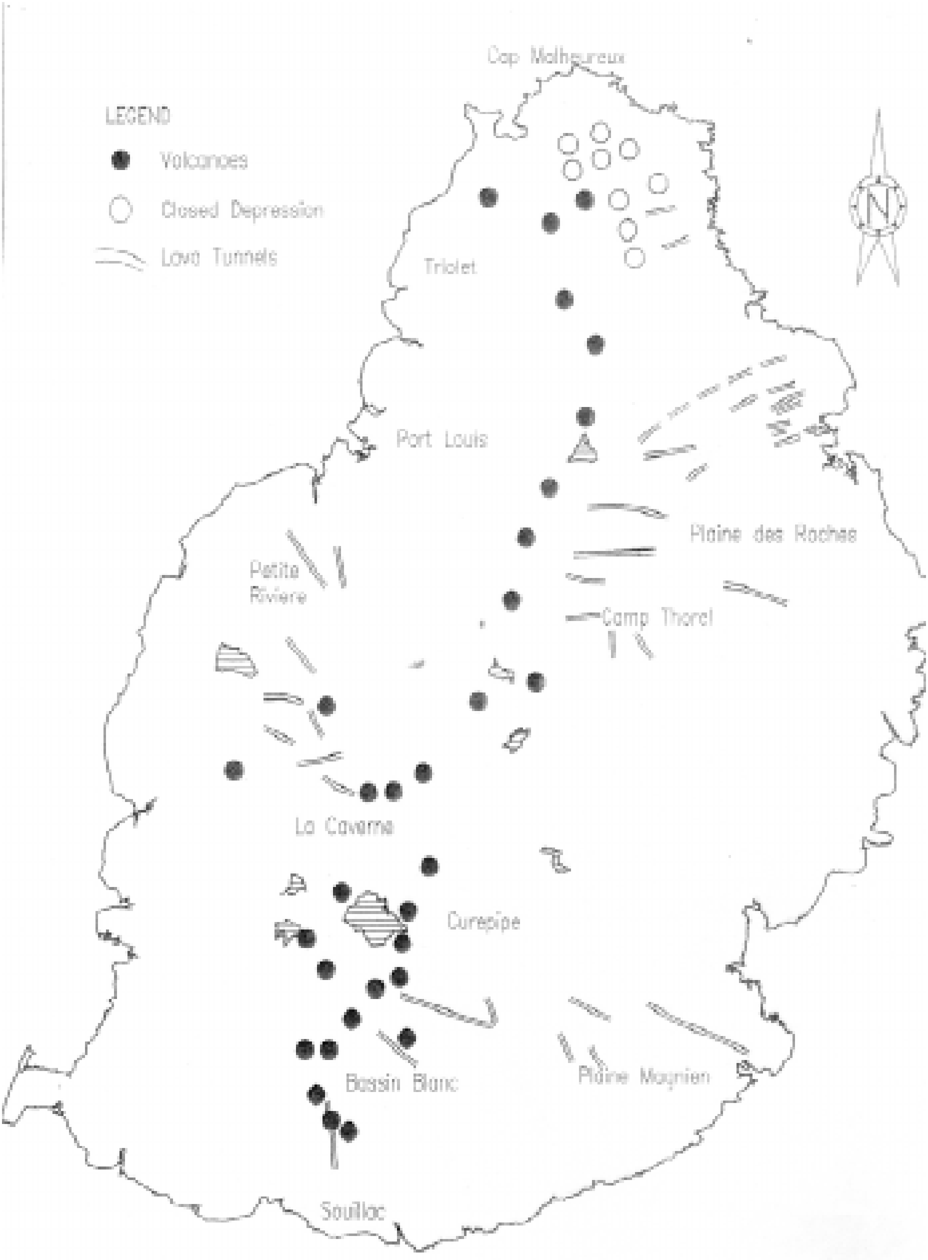

Fig. 2. Location of lava tunnels

INVESTIGATION METHODS USED

The desk study and preliminary reconnaissance

Desk studies have been carried out extensively in recent times as regards investigations relating to Midlands (1973), Guibies (1980), Bagatelle (1989), Midlands (1991).

Aerial photographs for Mauritius have been very useful during the investigations pertaining to Guibies valley (1980), Midlands (1991), and even for locating dam sites on Cascade and Terre Rouge rivers in the neighbourhood of Bagatelle (1988).

Field exploration

Geological mapping frequently forms the initial phase of exploration and should identify potential problems such as permeable lava of the third phase and distinguish them from aquicludes. Tuff represents the most common aquiclude and constitutes hydrogeological barriers. The situation is further complicated where facies changes take place in a horizontal direction. Furthermore, geological mapping should accurately locate igneous intrusions and major faults. Large intrusions can have a notable influence on the pattern of groundwater movement. Fault zones may be either highly permeable or may act as barriers to groundwater flow, depending upon the type of material occupying the fault zone. For example, in the Grand River North West gorge, the geological investigation carried out for the proposed Sorèze dam in 1971 indicated that the presence of a fault was not to be discarded. This could explain water losses that seem to occur in the river. Overburden may perform a confining function in relation to the major aquifers they overlie; or because of their lithology they may play an important role in controlling recharge to major aquifers. The boundaries of the aquifer may not correspond with the stratigraphic units present. Nevertheless detailed lithological descriptions facilitate correlation between borehole logs.

GEOPHYSICAL INVESTIGATIONS IN MAURITIUS

Electrical surveys

Geophysical investigations were performed between 1958 and early 1964 for the Chamber of Agriculture and the Government of Mauritius by the Compagnie

Générale de Géophysique and under the supervision of the Mauritius Sugar Industry Research Institute. They consisted of large-scale electrical (Schlumberger) surveys for which electrical probes were in general spaced apart on a grid with a mesh of about 500m. Only a few small detailed surveys were undertaken during this period, including one at Midlands in 1961, undertaken to ascertain the water-retaining characteristics of the bed of the proposed reservoir.

The objective of the first geophysical surveys was to determine the topography of the impermeable old substratum and in particular to look for buried valleys under the permeable young formations. The investigations started with the deeper surface flows, the base of which would be below the water table throughout the year; later, deeper flows, which would probably be entirely below the water table, were also studied. However, after the first survey, it was quickly realized that the volcanic formations, young as well as old, contain a significant proportion of clayey materials, mainly produced by weathering and decomposition of the lavas. The hydrogeology of the various districts of the island was then considered as being governed by the vertical and lateral juxtapositon of two kinds of formations of different permeabilities:

(i) Impermeable, little fissured compact lavas, clayey weathered scoria and lavas, and clayey tuffs;
(ii) Very permeable lavas, heavily fissured, with vesicular facies and comparatively rare deposits of fresh scoria.

In the coastal regions, all permeable formations in contact with the sea contain salt and brackish waters. The fresh water overlies the brackish water, the interface between the two depending upon the amount of incoming fresh water and the distribution of permeabilities within the strata.Therefore, the boundaries of salt-water invasion had to be surveyed both in clayey and in highly permeable strata. It was found that in these regions sea water has in fact invaded the deep strata, so that the base of the freshwater bearing formations may be considered to be salt water, rather than being determined by geology alone.

The results of these investigations were checked and completed by a drilling and test pumping campaign which started in 1960 while the geophysical work was still in progress. The Mauritius Sugar Industry Research Institute coordinated the work, giving technical and administrative supervision.

Since 1965 and with the advent of the FAO (Food and Agriculture Organisation) team for a Land and Water Resources Survey, the project carried out small detailed surveys for fourteen reservoir and dam studies, one tunnel, and one small

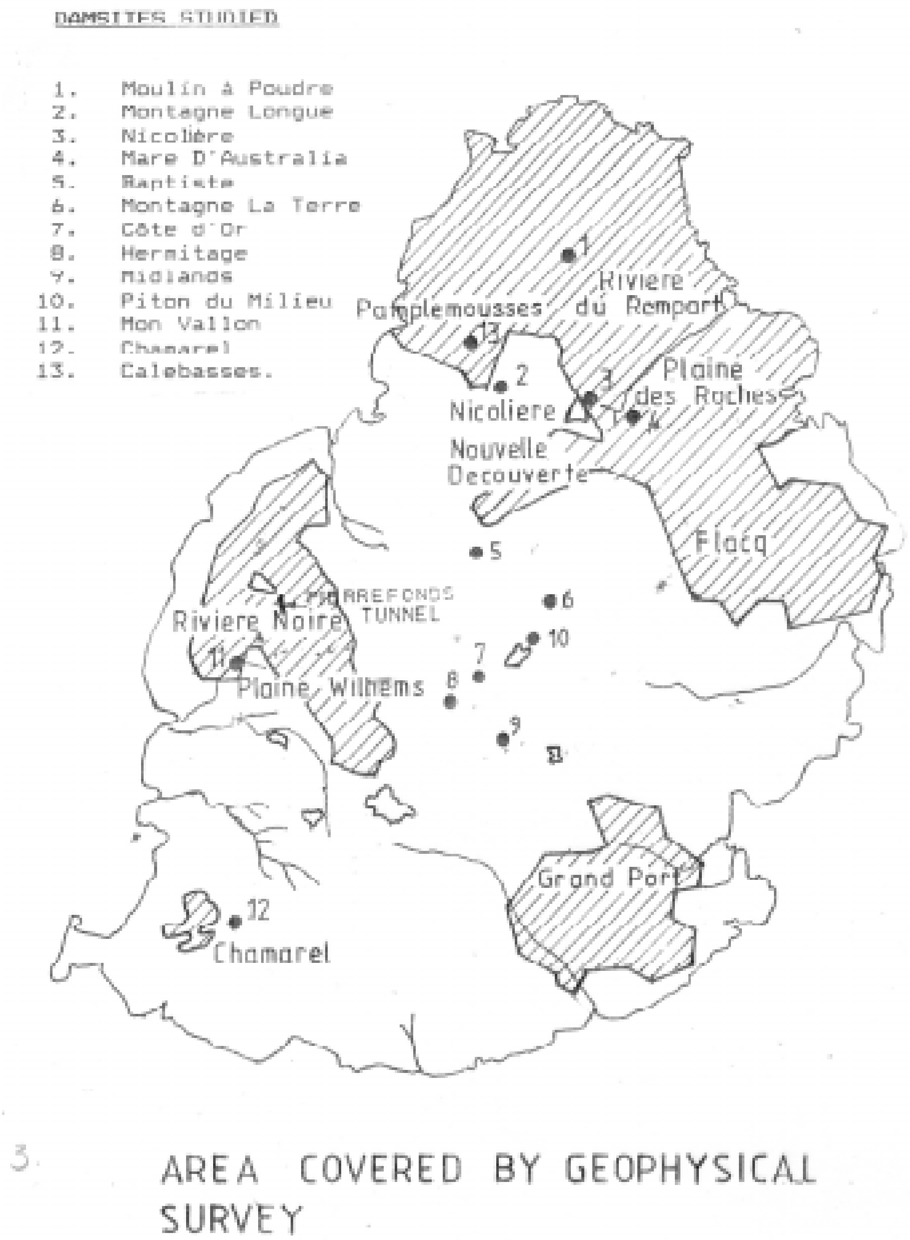

Fig. 3. Location of dam sites surveyed geophysically

groundwater exploitation scheme, the locations of which are also shown on Fig. 3.

Seismic surveys

In 1988, the Japanese team carried out seismic surveys on several sites for the Port Louis water supply project, namely Guibies, Terre Rouge, Bagatelle. In 1991, Coyne et Bellier carried out seismic surveys at Midlands dam site. It may be noted that this led to a new interpretation of resistivity surveys previously carried out.

INVESTIGATIONS AT SOREZE

Findings

In 1971 the Centre d'Etudes du Bâtiment et des Travaux Publics (CEBTP) carried out a geological reconnaissance for the Central Electricity Board (CEB) at Sorèze dam site. This brought out the simultaneous existence of

(i) Natural cavities which may be very large
(ii) Zones of poor drilling recovery, sometimes as low as 10%.

These two types of voids do communicate with each other through a network linked by vertical fracturation.

Fig. 4 shows the location of the investigation coreholes, while Fig. 5 displays the cumulative height of cavities and poor recovery zones.

Cavities and poorly recovered zones under the river bed level in coreholes No. 2, 3, 4, 5 and 6 have been identified, thereby indicating the possibility of water flow under the river bed level.

Furthermore, a sandy layer probably of fluvial origin was observed between elevations 81.1m and 81.4m (above mean sea level) in corehole No. 3. It may be noted that the river bed level is above 90m elevation. On the banks, the upper part of the Late Lavas contains many cavities, so that it might reasonably be thought that a certain number correspond to "lava tunnels".

Fig. 6 shows the results of permeability tests in the core holes. The values displayed are quite high, particularly if it is remembered that above 50 L.U., the Lugeon test

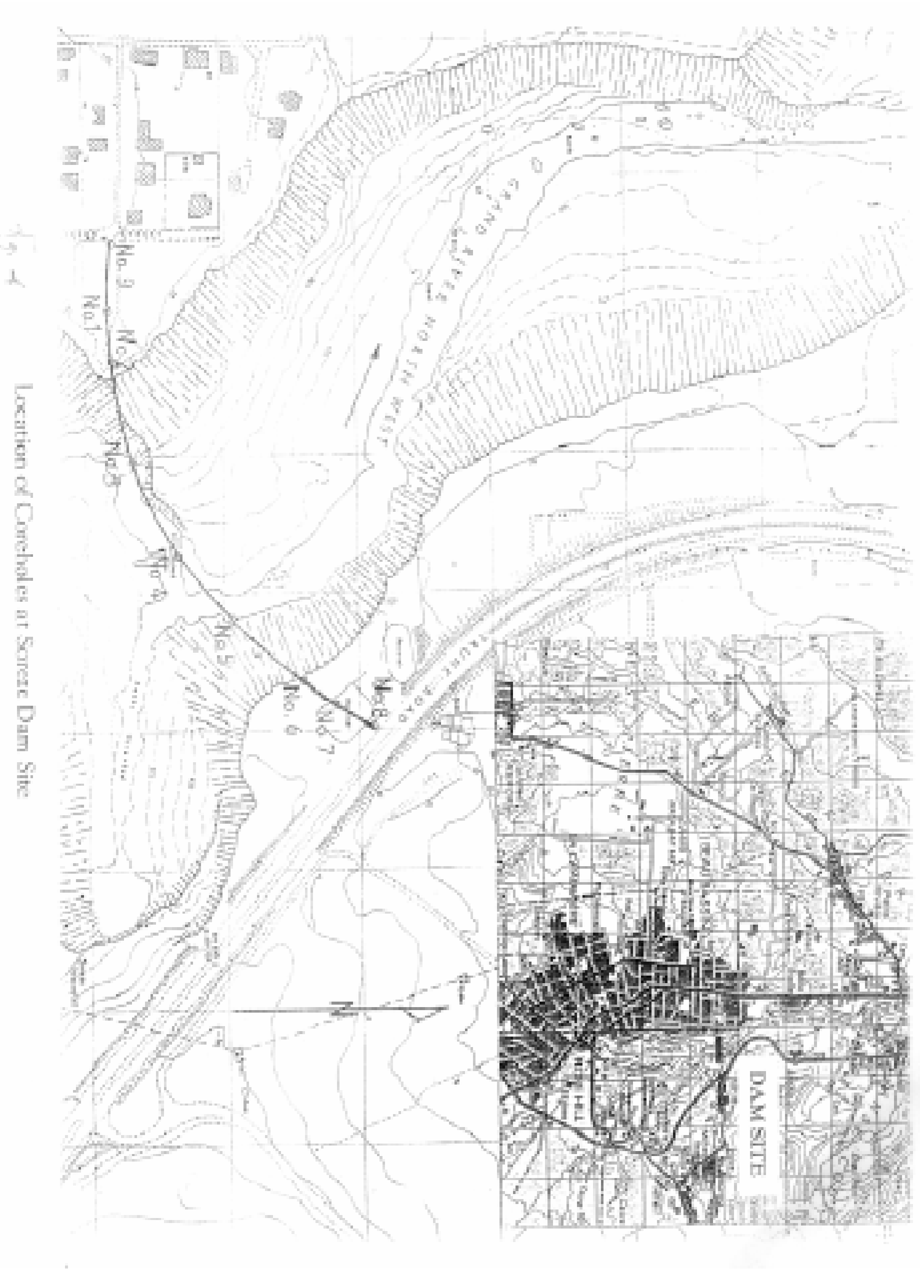

Fig. 4. Location of coreholes at Sorèze

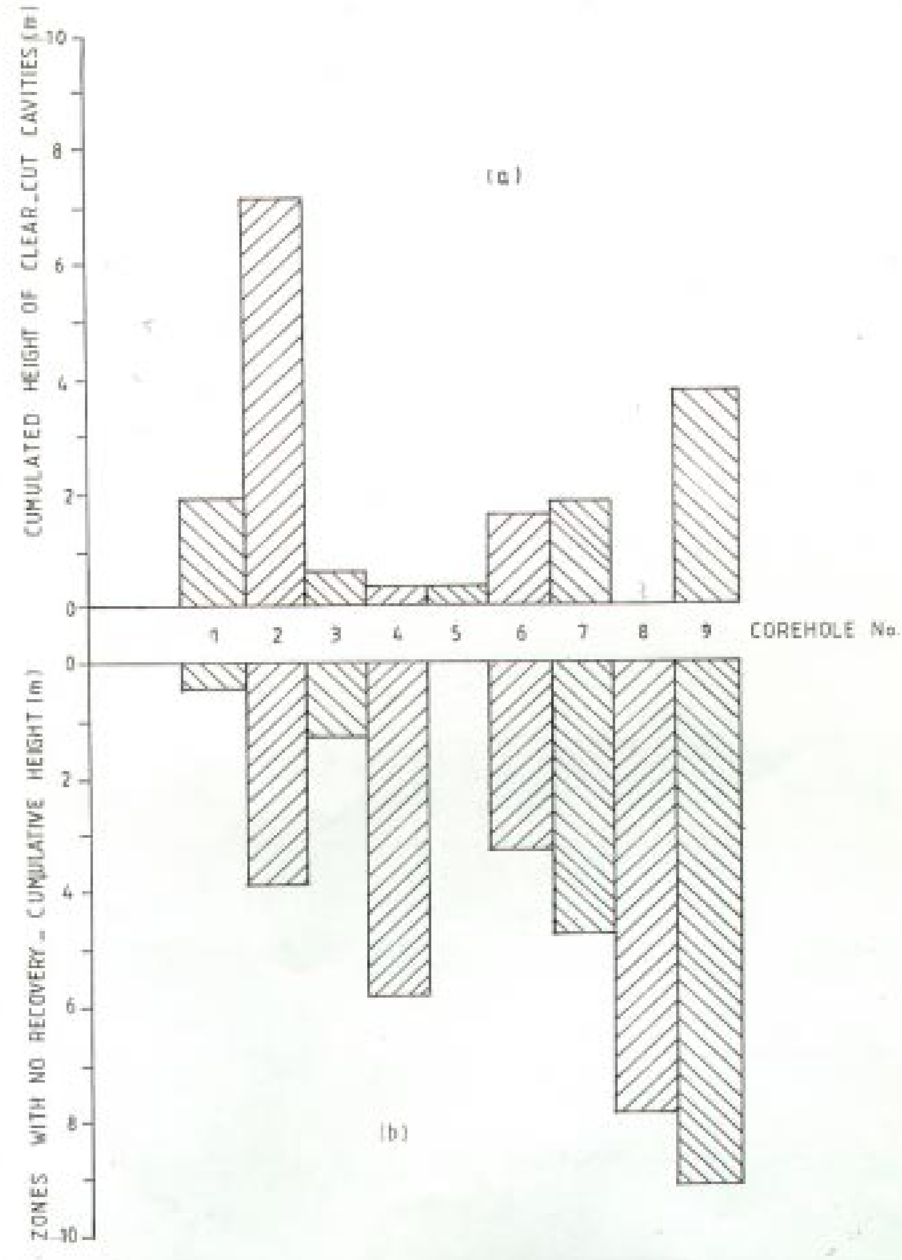

Fig. 5. Cumulative height of cavities at Sorèze

loses its significance.

Thus, it is important in a dam site geological survey to investigate the possible presence of such cavities/tunnels which could render the whole dam construction useless. At Pueblo Viego site (Columbia), a 60000m^3 cavern in karstic terrain was discovered further to investigating a small gallery of only a few metres. Basalt is not karst, but when there are alternating flows of basalt and clinkery lava, the problems are so similar that the term "*karstic volcanic terrain*" is not totally inappropriate.

Seismicity

Seismic effects due to the filling of large reservoirs with water have been reported in several countries. An increasing number of seismic vibration in the vicinity of large reservoirs in the Sudan has been registered, but the question still remains as to whether all these reported vibrations were really caused by the water load in reservoirs or whether they would have occurred anyway.

There are no known active faults on or in the vicinity of Mauritius. Seismic data were investigated during the study of Midlands (1972) and Champagne (1978) dams. The Institute of Geological Science indicated two earthquakes in the region at low depth at a distance of 700-800km. of magnitude 5.7 and 6.2 and of estimated intensity 6.1 and 8.7 (modified Mercalli scale) in the vicinity of the island. The British Geological Survey mentions that Mauritius is a region of little seismicity.

Richter states that between 1896 and 1956 there were two shallow earthquakes of magnitudes 7.9 (latitude 34°S, longitude 58°E) and 8.4 (latitude 49°S, longitude 31°E). The distance between these epicentres and Mauritius are therefore 1600 and 3800km. respectively.

There was an earthquake at Diego Garcia (2080km from Mauritius) in 1968. More recently, on the 30 November 1983, an earthquake of magnitude 7.6 on the Richter scale occurred at Diego Garcia. The vibrations rippled through other islands of the Chagos archipelago. The effects of the earthquake was observed three and a half hours later at Rodrigues (at 1650km.) by a violent succession of tidal waves during 1h. It is likely that there were six complete oscillations. No effect was observed in Mauritius.

In all these cases, the earthquakes were sufficiently far away as to render unnecessary the consideration of earthquake probability in Mauritius and thus classify the island as only slightly seismically active.

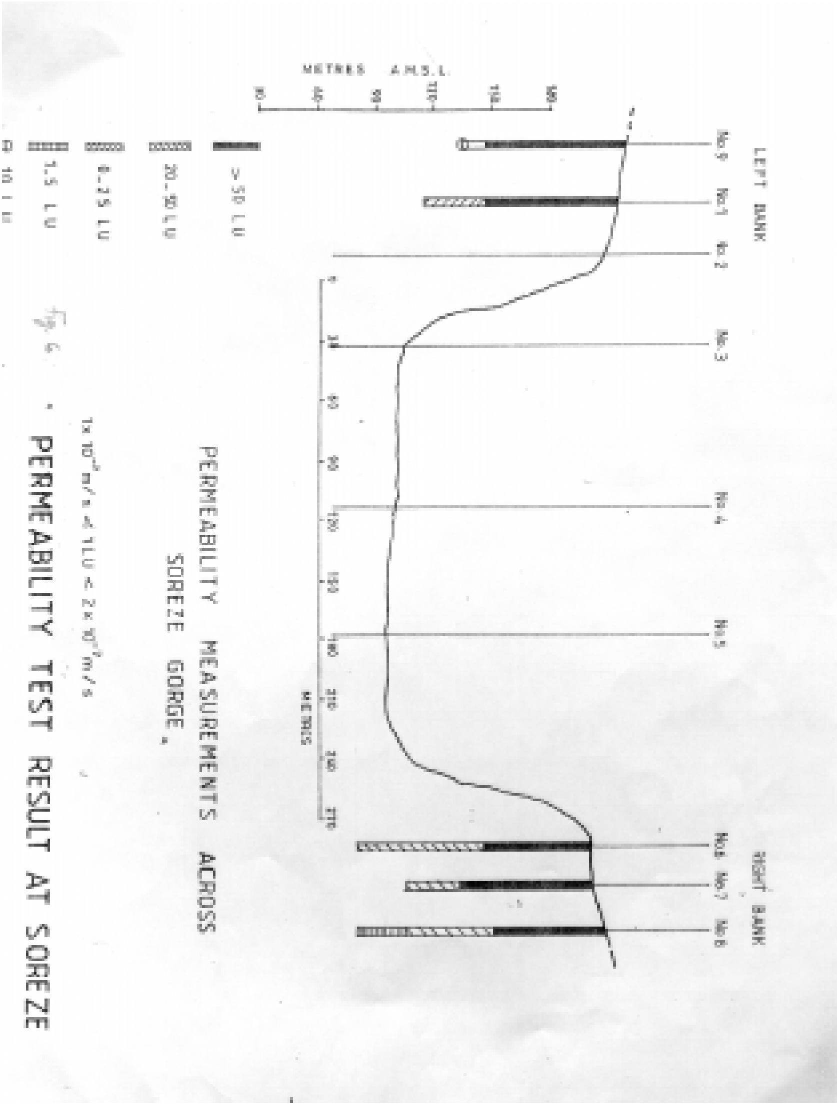

Fig. 6. Permeability test results at Sorèze

It would seem, however, that slight earthquakes have occurred a number of times in Mauritius, the first one being recorded on the night of 3-4 August 1786. An earthquake occurring on 6 January 1863 even damaged a masonry house at Pamplemousses. On 26 July 1925 earth tremors were felt in certain parts of the island, particularly between Port Louis and Beau Bassin. More recently, on 13 February 1992 in the early morning, an earthquake of magnitude 3.5 on the Richter scale occurred in Reunion. This earthquake, apparently, had nothing to do with the earth tremors which were felt in Mauritius on the same day, and also about the same time in Mauritius, in various parts of the island such as Camp de Masque, Plaine Verte, between Port Louis and Beau Bassin, and Mare Gravier. When it is considered that Mare Gravier is about 1km. from the Soreze dam site, and that the geological prefeasibility study report on the project (Arnould, 1971) indicated that the presence of a fault was not to be discarded, the question of building a dam in the vicinity of Soreze should be given serious consideration.

INVESTIGATIONS AT GUIBIES

Work carried out

Work on this site included rotary cored boreholes for the installation of piezometers, rotary percussive drilling, and trial shafts, trial pits and trenches. The trial shafts were of 1.6m diameter, the aim being to examine visually the soil profile. The trial pits were positioned to investigate the variation in superficial geology and the suitability of potential borrow materials. Trenches were positioned across likely boundaries between material types, to investigate the relationships between different materials at their margins. *In situ* hand shear vane tests was carried out in selected horizons in the trenches.

Geomorphological and geological mapping work was carried out, involving identification of the landforms and drainage regime, the inspection of natural exposures of rock and soil and the study of cutting exposures on the sugar estate roads. Laboratory testing of selected disturbed and undisturbed samples were carried out in Johannesburg.

Geology at Guibies

The geological cross section of the valley at the dam axis is shown on Fig. 7. Features of interest include,

(i) The development of colluvium in the base of the valley by erosion of the cliffs

on the flanks of the valley, with subordinate alluvial deposition, accompanied by in situ weathering of the valley floor.
(ii) Flow of the Younger Volcanic Series upstream of the mouth of the valley over the irregular colluvial and alluvial surface.
(iii) Continued development of colluvium and alluvium accompanied by in *situ* weathering of the Younger Volcanic Series.

The transition from a completely weathered rock to a residual soil is normally defined by the disappearance of any evidence of relict rock structure from the material. At Guibies, the residual soil derived from the Older volcanic series is a complex mixture of partially weathered clasts (from fresh to completely weathered) in a matrix of brown, orange and grey mottled clay. The residual soils derived from the Younger series are more distinctive, being a very stiff fissured brown silty clay, stained blue along major fissures.

Colluvium covers a large proportion of the valley and, on the right flank, has travelled up to 1km from its source at the cliffs. This movement, initiated predominantly by gravity, has been partly gradual and partly catastrophic in nature.

Summary of reconnaissance works

The above investigations led to the following conclusions,

(i) The Guibies valley bed was covered by colluvium with clay horizons, which could affect not only the stability of the dam, but that of the valley sides as well
(ii) The hydrogeological conditions are acceptable with a mean permeability of 10^{-6} m/s
(iii) Poor site conditions in the valley point to dam slopes of 1:6 for the upstream and downstream embankments

A second opinion was then sought. While there was general agreement on the conclusions, differences related to permeability and the characteristics of colluvium. If the horizontal permeability is very high compared to the vertical permeability, then seepage losses under the dam could be high.
While the first report indicates that the colluvium will behave as a clayey material thereby needing dam slopes of 1:6, the second report mentions that the colluvium will behave as a granular material, thereby needing dam slopes of 1:3. Needless to say, the financial difference between the two proposals would be enormous!

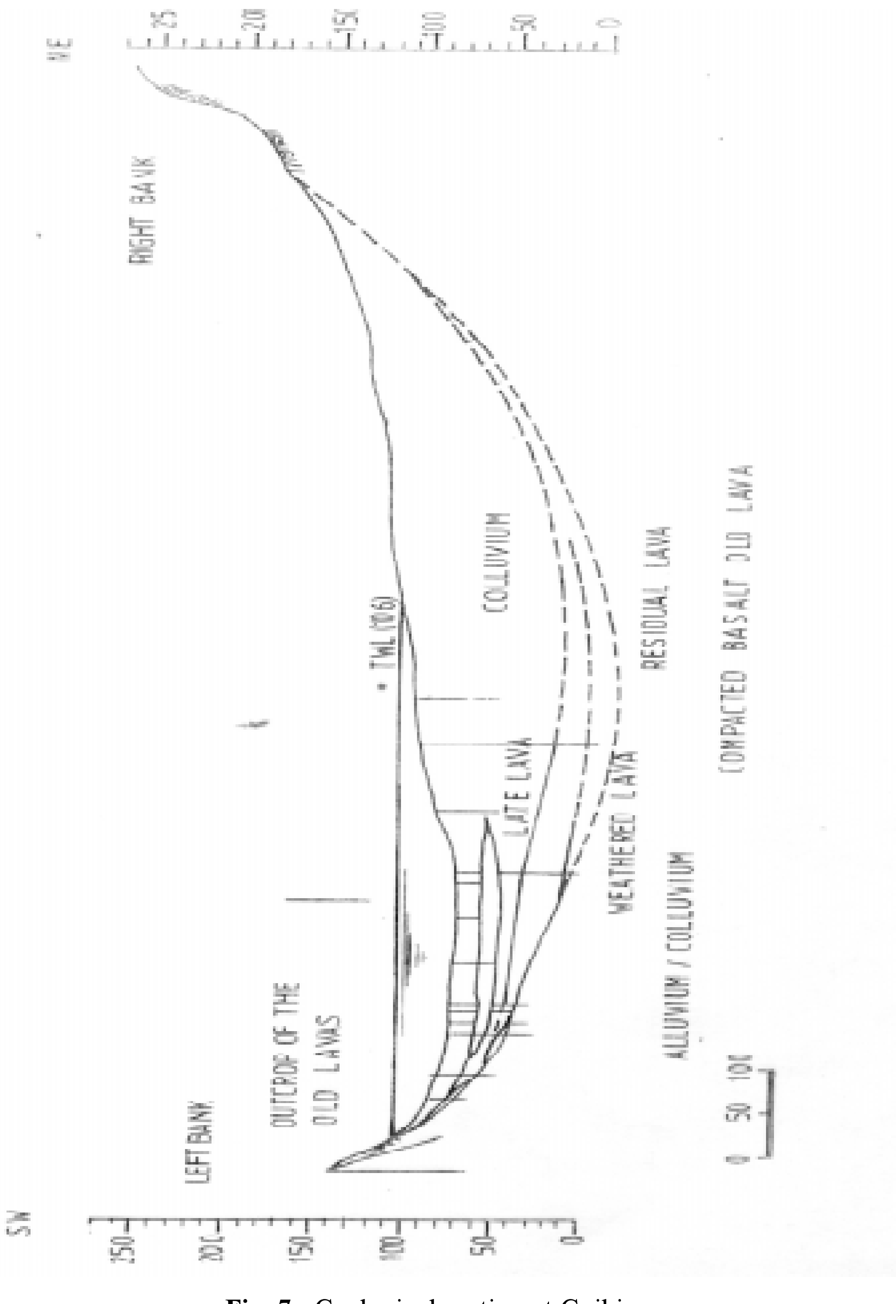

Fig. 7. Geological section at Guibies

INVESTIGATIONS AT MIDLANDS

Previous studies

The geology of the Midlands dam site and reservoir has been investigated and described since the early 1920's, consisting of electrical resistivity, coreholes. As at 1974, at least six persons had studied the project and while there were some major points of difference in the interpretation and findings, there was one point of agreement. Broadly, every investigation concluded that the basal fresh fissured lavas have a potentially high permeability, and that the overburden of the weathered lava/ash/soil has a lower permeability.

The conclusion was that the danger of leakage from the bed of Midlands depends on three factors,

(i) The position of areas of exposed fresh lavas at the surface
(ii) The present permeability of the overburden of weathered lava/ash and soil
(iii) The eventual permeability of overburden if it is totally saturated for a long period of time.

It is recommended that earthfill for the embankment be taken from outside the reservoir area because if it is removed from the floor of the reservoir, it may expose the fresh permeable lavas. Incidentally, this has been the case with Eau Bleue reservoir.

Recent investigations

For cross-checking and completing the previous reconnaissance works and the above conclusions, a program of additional investigations was carried out in 1991. These works were performed specifically along the potential dam axis, just downstream of the existing embankment. Their main objective was to define more accurately the natural conditions of the foundations. They consisted of boreholes with coring and permeability tests, tests pits with samples for laboratory analysis, seismic refraction spreads, and electrical resistivity soundings.

These investigations bring forward favourable findings:

(i) The basaltic bedrock is hard and massive directly below the residual soil layers. The relevant core recovery is entire with an RQD value ranging over 75 and specific seismic velocity greater than 3,800 m/s.
(ii) The vacuolar basalt facies is identified as only thin and scattered beds or lenses

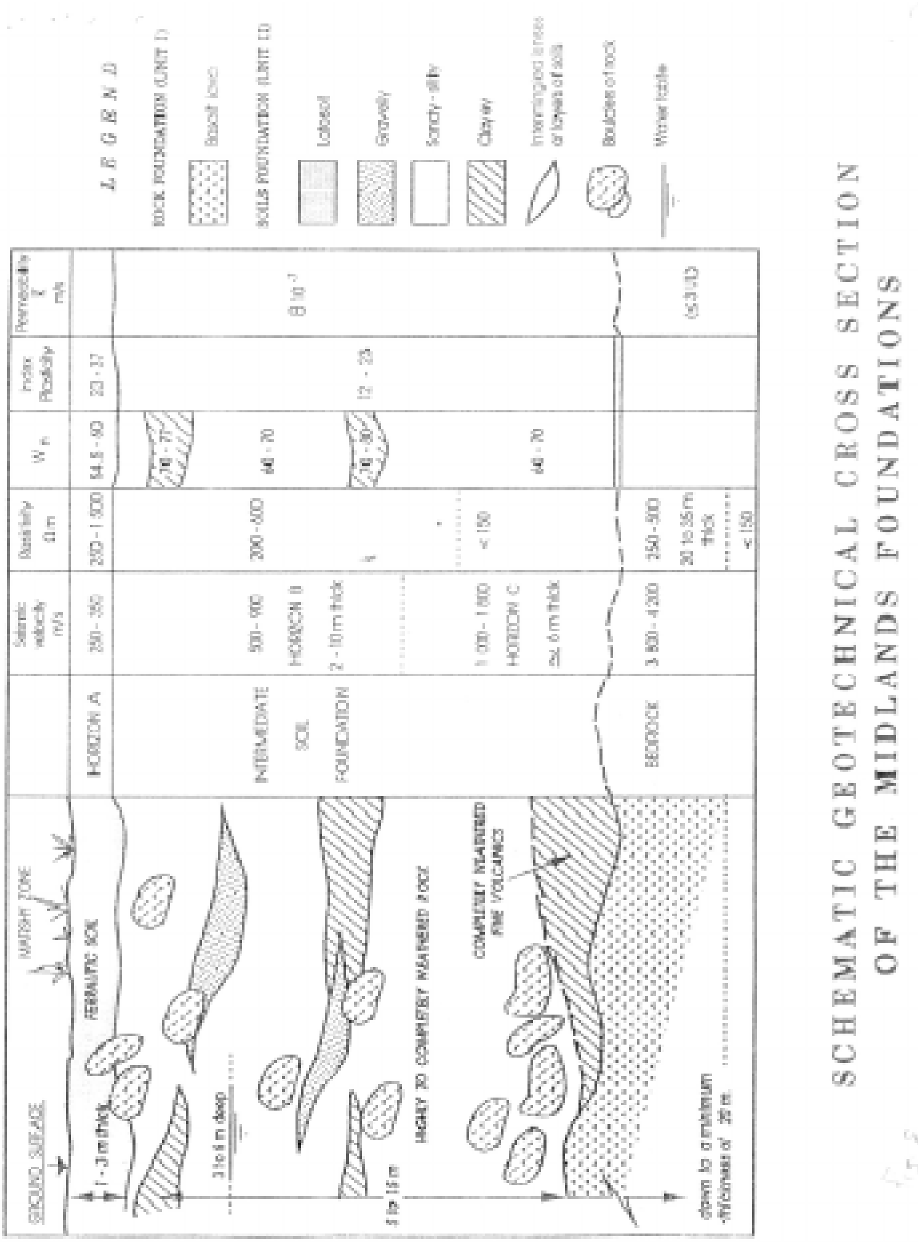

Fig. 8. Lithological cross-section at Midlands

intercalated within the massive lava, with thicknesses of the order of 1m. A schematic lithological cross section of the foundations is given on Fig. 8.

Permeability and hydrogeology

In the light of the recent data calibrated by the results of core drilling, it has been concluded that the previous correlations between the resistivity measurements (1961 and 1966 electrical surveys) and the assumed permeability of the foundations was inadequate and inconclusive.

Table 2 shows resistivity values which have been given to correlate to petrography and to permeability. In fact, some coreholes drilled in 1966 at Midlands did not fit in with this resistivity classification used commonly for Mauritius. This was based on an unchecked theory stating that the resistivity value of 500 Ωm would be the limit above which the strata might be permeable and under which the formations would be clayey and watertight. Fig. 8 shows the actual correlations between lithological features, resistivity ranges and permeability values. While this certainly emphasises that Table 2 is but a guide, it confirms the geologist's contention that a geophysical survey without any correlation to actual lithological features may give the wrong conclusion about a site. In particular here, while previous studies indicated the bed of Midlands dam as being permeable, this present discussion and Fig. 8 show the exact contrary.

EAU BLEUE AND MARE LONGUE RESERVOIRS

Eau Bleue is an earthfill dam which was constructed during the period 1961-1962. As it seemed convenient at that time, the valley bed was excavated to provide some earth material for the dam. After impoundment, it was found, however, that the reservoir was leaking. The explanation was that excavating the clayey bed material

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Table 2: Resistivity Values

dry lava and scoria	500 to 10 000 ohm.m
wet lava and scoria (fresh water)	100 to 300 ohm.m
detrital formation and dry weathered lava	50 to 500 ohm.m
clayey strata	15 to 50 ohm.m
wet formations saturated with brackish or salt water	1 to 20 0hm.m

had laid bare the permeable lavas. More recently, during the period 1992-1994, the reservoir was emptied so as to allow the construction of a new spillway. Places could be observed, in the reservoir bed, where water was slowly oozing out from underground. This also confirms the theory that this reservoir has a good connection with the water table in the area. At about the same time, the Cluny borehole, situated downstream, did experience a dramatic reduction in its yield.

In 1966, as part of the general geophysical survey being carried out, electrical resistivity soundings were taken at a few reservoirs. Fig. 9 shows the clear demarcation of Eau Bleue with respect to the others. It may be observed that even Mare Longue reservoir has some zones of high permeability. In fact, there are several seepage patches downstream of the dam, while on the right abutment the weathered lava flows (observable from inside the reservoir) allow seepage at high water level. It is a credit to the designer that he installed a Vee-notch downstream for measuring this flow. This information, unfortunately, is not shown on any drawing but was obtained while discussing with the gauge reader for the water level in the reservoir.

MATERIALS

Generally, the soils in Mauritius, in terms of plasticity, fall below the "A" line on the standard plasticity chart presented on Fig. 10, and clearly show similarities to the increasingly well-known halloysite-bearing red clays of residual or volcanic origin typical of many of the tropical areas of the world. A detailed study of these materials was carried out in connection with the design of the Sasumua dam in Kenya.(Terzaghi, 1958). In this context, it is important to bear in mind that these soils are good engineering materials, particularly suitable for embankment and earth dam construction despite their very high water content (Wesley, 1973). The high water content of these clays is a result of water being tied up within the halloysite and within a characteristic aggregated clay structure; this water does not influence the plasticity or engineering behaviour of the soil although this moisture is measured by conventional testing procedure.

CONCLUSION

It is well known that no two dam sites are alike, but these few cases should be sufficient to prove that the approach to dam construction in volcanic terrain should be one treated with caution.

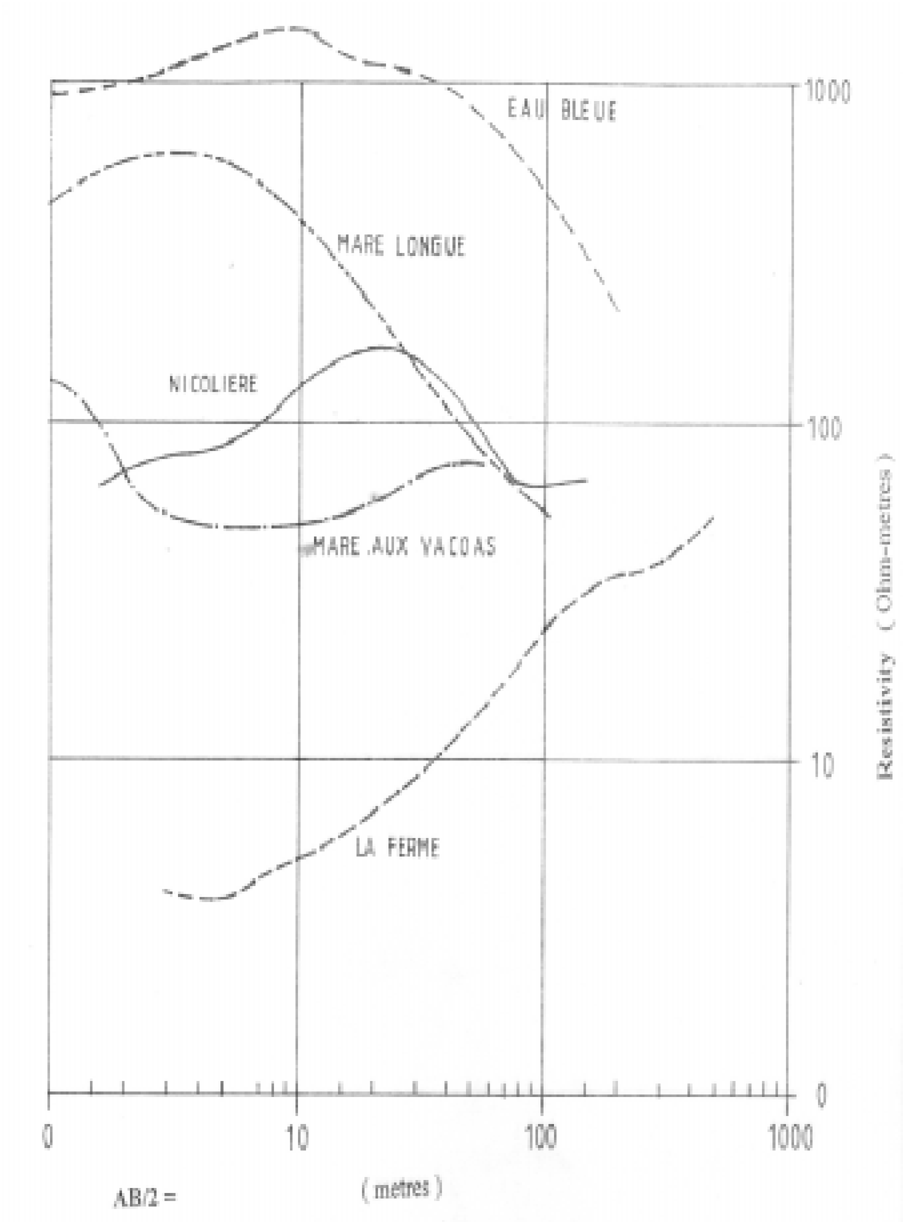

Fig. 9. Geophysical survey curves at a few reservoir sites

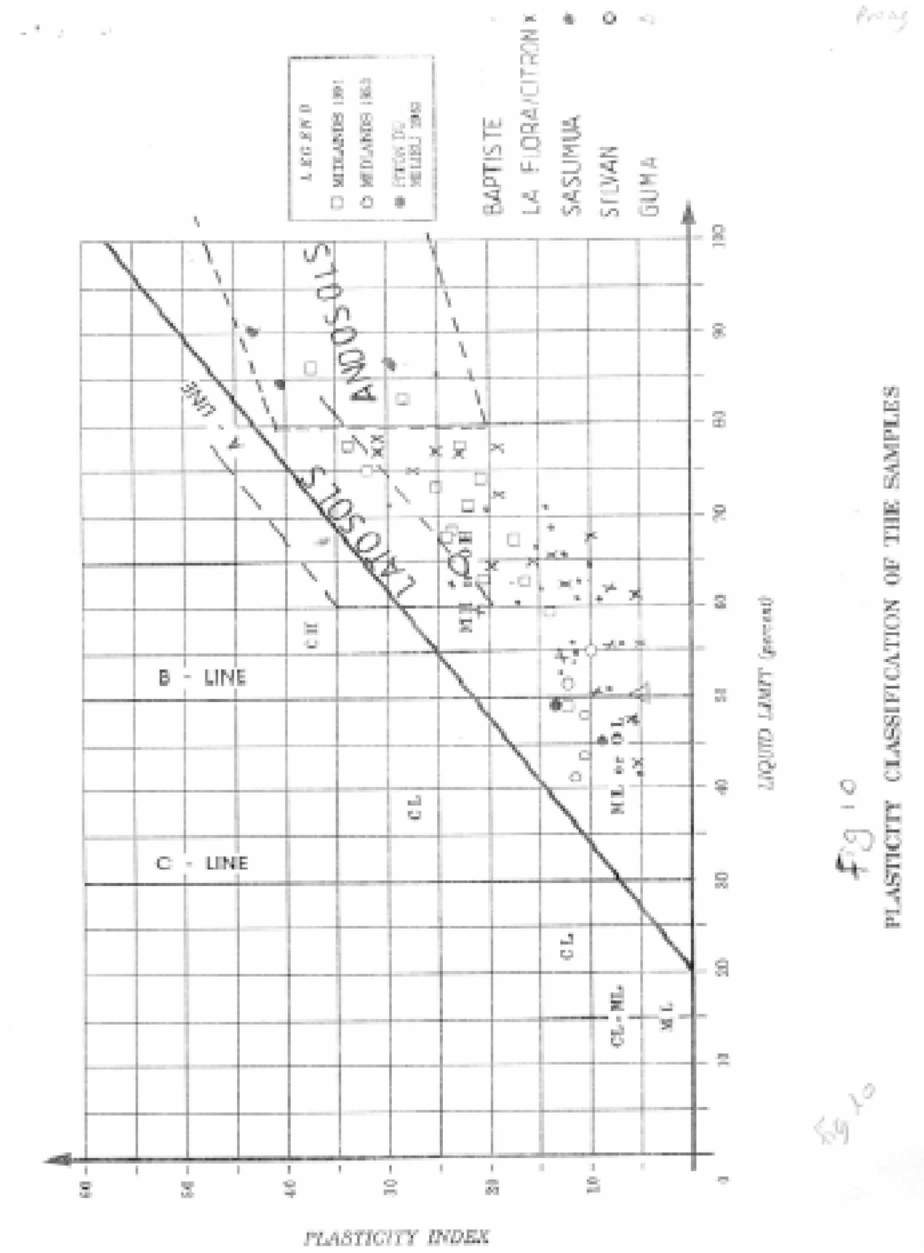

Fig. 10. Plasticity results w.r.t. the A-line

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