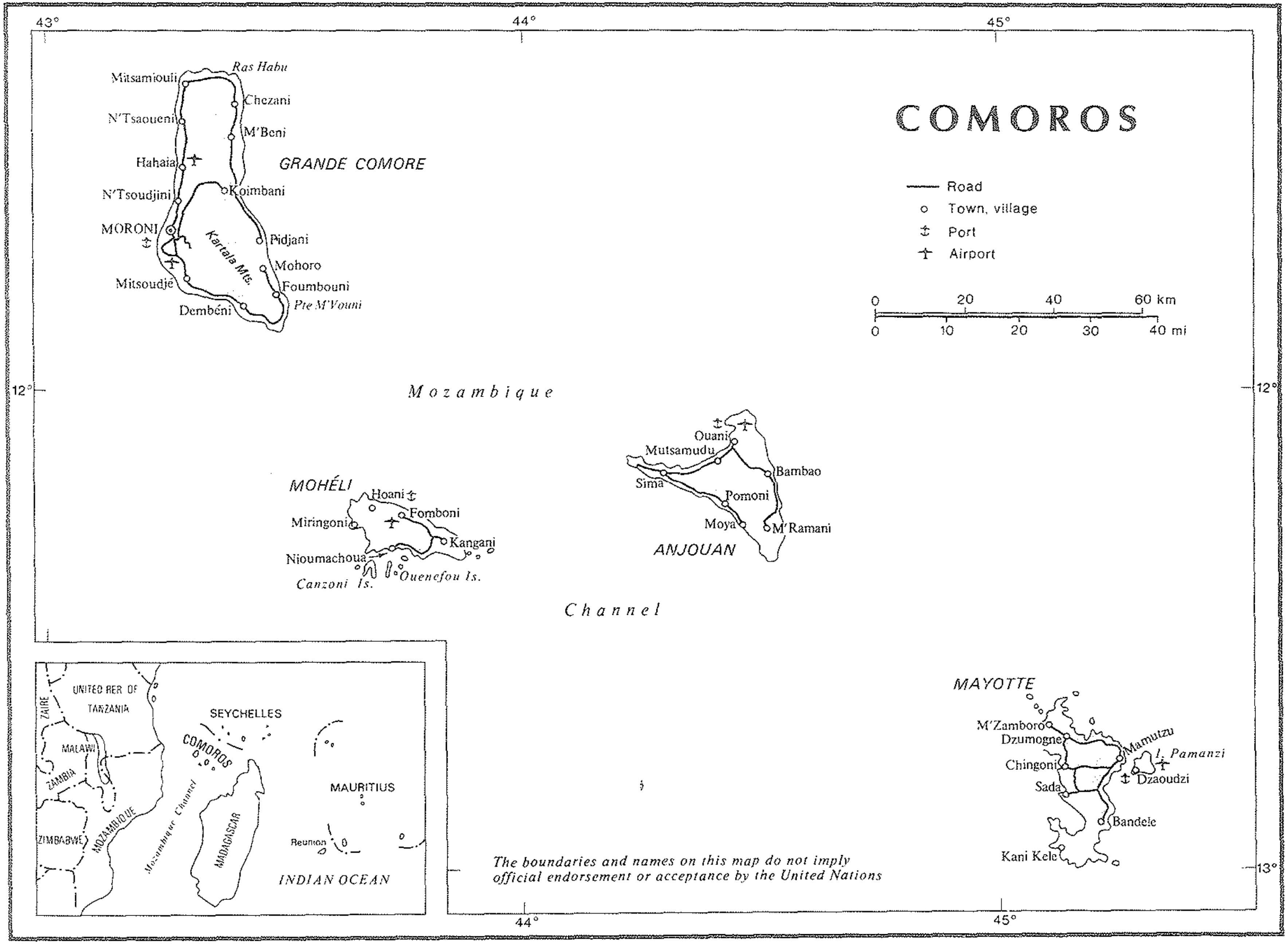
MAP 4. COMOROS — GENERAL MAP



MAP NO.2957 Rev.1 UNITED NATIONS
MARCH 1989

COMOROS

Area: 2,171 km^2
Population: 360,000

I. BACKGROUND

The Comoros archipelago is equidistant (300 km) from the African mainland and the northern part of Madagascar. Ngazidja (Grande Comore), Ndzuani (Anjouan) and Mwali (Mohéli) form the Federal Islamic Republic of the Comoros. Moroni, the capital of the Republic, is on Ngazidja, the largest (1,025 km^2) and westernmost island of the archipelago (the island of Mayotte is under French administration).

The Comoros are volcanic basalt islands, the tips of a submerged range.

Ngazidja has a massive shape and runs north-south, with a swollen central part formed by the volcano Karthala which is the island's highest point (2,361 m); in the north the island is flanked by a massive appendage 30 km long and 15 km wide (the massif of La Grille), and in the south by a smaller appendage, 15 km long and 10 km wide (the massif of Badjini). Viewed from the south, the island has the shape of a dome falling steeply towards the sea. Viewed from the east or west, the enormous dome of Karthala is prolonged northwards by a second, less pronounced swelling, the massif of La Grille, with a high point of 1,087 m. These three units, the massifs of Karthala, La Grille and Badjini, are the island's three fundamental divisions, from the standpoint of both relief and geology. Half of the 200,000 inhabitants are concentrated in the narrow coastal strip which circles the island.

Ndzuani island is triangular in shape and 35 km wide at its largest point. Its highest point is 1,518 m. It has about 140,000 inhabitants.

Lastly, Mwali island has an elongated shape, with a length of 28 km and a maximum width of 12 km. Its highest point is 810 m. It has 20,000 inhabitants.

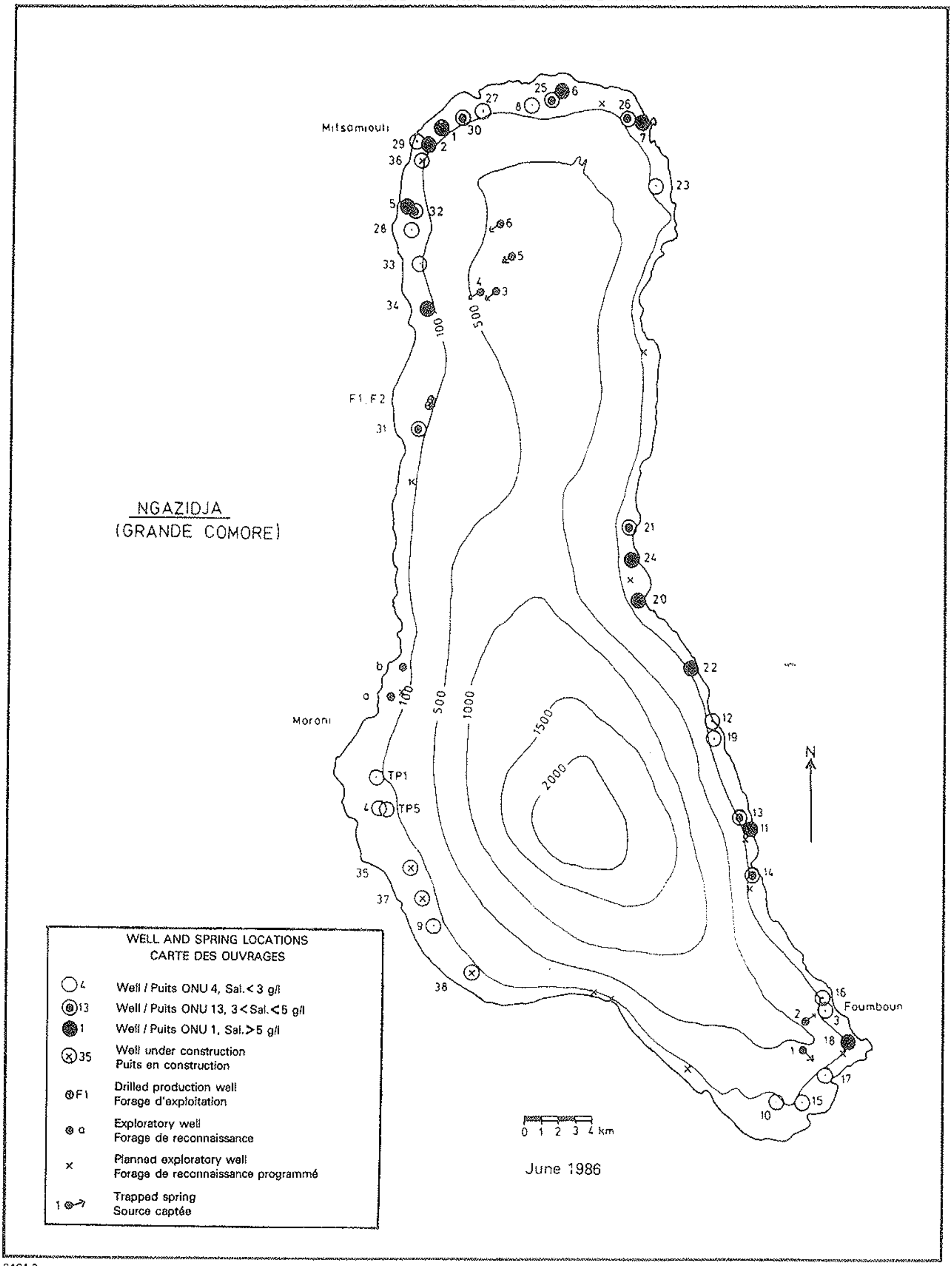
Most of the population subsists on food products for own-consumption. Attempts are being made to develop the cultivation of maize in order to reduce imports of rice, a highly valued food. There is little livestock-raising. Export products consist mainly of vanilla, copra, perfume oil (ilang-ilang) and various spices (cloves).

The Comoros archipelago has a tropical climate, with a warm season which is also the rainy season during the southern-hemisphere summer (November to April), and a "cool" season from May to October.

A feature of this latter season is the cool air flowing from the south/south-east, which is partially dried by its passage over Madagascar. During the warm season the islands are subject to the monsoon blowing from the north-east/north-west.

This tropical climate sometimes changes in a few kilometres, depending on exposure and altitude. There can be sharp contrasts in rainfall between the windward and lee slopes. Altitude also plays a role in the distribution and amount of rainfall and in the geographical distribution of temperatures.

MAP 5. COMOROS NGAZIDJA ISLAND — MAP OF WELLS AND SPRINGS



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On Ngazidja, for example, there is a clear contrast between the poorly watered lee slope (1,398 mm at Foumbouni) and the windward slope where the rainfall, already considerable on the coast (2,695 mm at Moroni), increases sharply with altitude (5,888 mm at Nioumbadjou). Mitsamiouli, at the extremity of the peninsula, receives only 1,884 mm a year. It rains more everywhere during the southern summer, but the dry season is not really very different except on the lee side (five dry months at Foumbouni) and at Mitsamiouli (three dry months). The average annual temperature on the coast is around 25 °C. It declines with altitude. The annual range is small, in the order of 4 °C.

The winds, measured only at Moroni, can be considered gentle, blowing mainly from the south. The average wind speed is 3.1 m/s at Moroni, with a maximum of 4.5 m/s in June and July and a minimum of 2.3 m/s in March and October.

The average humidity is around 85 %. The annual range is small, in the order of 5 %, with a maximum in January and February and minimum in July and August.

Evaporation measured in the Piche evaporometer ranges from 600 to 800 mm a year along the coast.

The surface-water resources are sufficient on Ndzuani and Mwali. On Ngazidja, in contrast, the water problem is acute owing to the island's relief, the dense concentration of its population in the coastal strip and the lack of suitable sites for dams. This island has been the subject of almost all the hydrogeological studies, the results of which are presented below.

II. GEOLOGY

The first geological study of the whole of the Comoros archipelago was carried out in 1960; it revealed three main phases of volcanic activity, separated by phases of rest and alteration. Almost the whole of Ngazidja island is covered with volcanic materials of the most recent upper phase. This is the case of the massifs of La Grille and Karthala; the massif of Badjini dates from on earlier phase. These outcrops are surrounded by lavas of the intermediate phase. The massif itself also contains layers of red clay several metres thick, indicating advanced laterization of the early phases.

The lavas of the upper volcanic phase are compact or finely vesicular grey-black or iron-grey rocks, especially andesitic basalts, labradoric basalts, basanitoids and limburgites. The lavas of the intermediate phase are of a very common type; their mineralogical differentiation from the lavas of the upper phase is not always very clear.

As a rule, these are basaltic lavas of different periods together with their alteration products, scoria, pyroclastic materials, and poorly developed alluviums in places. Little soil has been able to develop on any of these formations (except on the products of the early outcropping volcanism).

Ngazidja island can be described, at least in its upper part, as a pile of lava flows produced by Hawaiian eruptions. Very recent flows are found almost everywhere. Very poor vegetation (lichens and scolopendria) begin to develop here only after 30 to 50 years, so that these past flows are very easily visible. Their surface consists of a jumble of scoria and raised slabs resulting from the consolidation of superficial crusts constantly broken up and carried downhill by the movement of the lava. "Lava galleries" are also common in the recent flows on Ngazidja. These cavities were formed when the still-liquid lava at the heart of the flow continued its downward course, leaving behind a crust solidified by external cooling. Their cross-section shows a somewhat elliptical ogival arch with a large horizontal axis. Very short false stalactites formed by the dripping of still-liquid lava are common here. When the vault collapses, examples of a kind of ravine with parallel and vertical sides are formed.

Scoria are often also found at the base of a flow; the middle part of a flow is more compact but fissured. The lava are sometimes extremely vesicular, as a result of cooling in the open air.

Alteration of the basalts can produce clay strata several metres thick (massif of Badjini).

Strombolian volcanism is found in the form of very numerous scoria cones, sometimes in the shape of ancient craters, consisting of very vesicular elements of different shapes, up to tens of centimetres in size, either piled up or loosely bound by a argillaceous cement. These elements are light and can easily be mixed with basalt blocks of varied facies. Some of these cones have a fine and homogeneous granulometry (a few centimetres in size) and are used as pozzolana. The scoria formations of lapilli and ashes can be of considerable thickness in the massif of La Grille. It is not unusual for fairly thin argillaceous crusts to be found on these materials.

The Vulcanian volcanic activity is characterized by stratified accumulations of cinereous tufa consisting of elements from one millimetre to several centimetres in size, bonded by an argillaceous or ferruginous cement. Facies of explosion breccias are often found here: angular blocks of various basaltic rocks scattered within a fine and stratified material. These tufas are found close to the sea (craters of Lac Salé, Ouémani, N'Gouni, Moindzaza) but they seem to be totally absent from the interior of the island; this indicates that the extremely explosive volcanic activity which produced them was the result of interaction between the incandescent magma and sea water.

Small alluviums, the result of sporadic surface flows, are found in the form of fine materials produced by the recapture of pyroclastic materials or very coarse materials shaped by the action of torrents.

The distribution of the various lithological types has been presented on a geological map on scale 1:100,000 prepared under the UNDP/United Nations project COI/86/001 "Water research and development". This map indicates dykes and fissures, and their direction, visible on aerial photographs on scale 1:10,000.

These are lava-emitting fissures running out of craters of different sizes. Two main directions of fissuration from Karthala can be distinguished: north-south from Karthala towards Badjini; and to the north of La Grille the main directions range from N-W/S-E to N-E/S-W and may represent radial fissuration from the volcano of La Grille; this can also be seen around Karthala.

It is probable that the north-south fissuration to the north and the N-W/S-E fissuration to the south of Karthala have provided and still provide feeder channels for the recent flows which cover most of the island. It is possible that the central chimney of Karthala was blocked and the magma sought other outlets through fissures in the lava.

Geophysical prospecting has been carried out by the quadripole Schlumberger method.

Generally speaking, the whole of the "dry" part of the volcanic formations above the water-bearing stratum acts as a very resistant layer. The part of the formations situated below the water table, i.e. all of the strata impregnated with salt water, or fresh water mixed with salt water, acts as a conductor with respect to the resistant higher formations. However, in this case it is difficult in geophysics to detect the layer of fresh water which in principle overlies the salt water, for the resistivity of the formations impregnated with fresh water lies within the resistivities of the resistant formations and the salt water. A constantly decreasing apparent resistivity curve is this obtained, in which it is not easy to distinguish the intermediate resistivity of the fresh-water formations.

Owing to the problems of making and interpreting electrical soundings in the coastal zone, the activities are concentrated instead in the upper and middle parts of the island, with a view to studying their structure. Fifty-eight soundings have been made.

On the basis of these electrical soundings, the following resistivity table can be established for all the formation known on the island:

(Resistivity of the various formations)

(Dry formations: above the aquifer)

Formation	Resistivity in ohm-m
Lava:	
- Ancient	Approx. 10,000 or higher
- Recent	Approx. 5,000
- Sub-recent	Approx. 2,000
- Intermediate phase	Approx. 550 to 600
- Lower phase	Approx. 150
Alteration zones	Approx. 20
Non-basaltic formations	Approx. 200

These formations are clearly differentiated and, as long as the exercise is restricted to the dry part (disregarding any possible thin perched aquifers) above the water table, it is relatively easy to establish the section of the formations in depth.

In contrast, once below the water table, the resistivity is less characteristic of the nature of the formation and varies more with the salt content of the soakage water. For formations of any kind invaded by salt water the values fall to

1-10 ohm-m. It is more difficult to obtain an idea of the resistivity of the fresh-water formations themselves, for it is rarely possible to determine the absolute resistivity of this layer owing to the thinness of the fresh-water lense. It was not possible with the equipment available to the project to make accurate measurements of the saturated formations in the coastal zone but, in view of the salt content of the wells which were drilled, it is no doubt below 20 ohm-m. The resistivity cannot be estimated for any possible thin formations saturated with extremely soft water in possible perched aquifers.

The geo-electric sections show that the lower phase has been reached only in the southern part of the island. Layers of argillaceous alteration observed on the surface of the massif of Badjini have also been found at depth.

Lavas of the intermediate phase have been found in the massif of Badjini, where they overlie the products of the lower phase, and in the northern part of the island. Basalts of the intermediate phase seem to form the core of the massif of La Grille.

Lavas of the upper phase are found everywhere and can be extremely thick; the thickest are found on the plateau of Djiboini. This slab-shaped plateau seems to be a large depression between La Grille and Karthala, partly covered with lavas of the upper phase.

Lastly, there are the non-basaltic formations, mainly pyroclastic, which are of considerable thickness north of La Grille. These explosion products seem to date from the sub-recent upper phase.

The geological and geophysical studies summarized above indicate certain conclusions about the formation and structure of Ngazidja island.

The island consists entirely of volcanic rocks, mainly basalts, resting on a subsided continental base. Volcanic activity probably began in the tertiary with the lower phase and was probably confined to the southern part of the island: the southern part of the massif of Badjini and a massif under the present Karthala were established.

After a period of rest and alteration, the volcanic activity of the intermediate phase shifted northwards and established the cores of the massifs of Karthala and La Grille, separated by a depression at the level of the plateau of Djiboini. Flows dating from this phase also cover part of the massif of Badjini, which is older.

After a period of rest and alteration, the island acquired its present size and shape during the upper phase. At the beginning of this phase, volcanic activity seems to have occurred in the central and northern parts of the island and, especially in the north, it consisted of basaltic flows with major explosion activity, producing very thick pyroclastic formations north of La Grille, perhaps as a result of interaction between the incandescent magma and sea water. The depression of Djiboini was partially filled by sub-recent flows. The most recent periods seem to have originated only on Karthala. Karthala's central eruptions and fissuration covered almost the whole of the island with early or recent flows. It is probable that Karthala's central chimney was blocked and that the magma sought other outlets through fissures in the lava, especially north-south to the north and north-west/south-east to the south of the volcano. This recent phase is continuing and the island can be said to be still "under construction". Its relief is embryonic and over large areas the vegetation and soil have not yet been able to constitute themselves.

III. GROUND WATER

Hydrogeological studies, projects COI/79/005 and COI/86/001

The first hydrogeological observations on Ngazidja island were presented in 1953 and 1960 by de Saint-Ours who, as there were no wells or boreholes in existence, drew entirely on surface observations. Nevertheless, his reports can be considered the basis of the hydrogeological study of Ngazidja island. No other study covering the whole of the island was made before the start-up of project COI/79/005 in 1980.

Between 1960 and 1972 some parts of the island were studied with a view to the installation of wells. In 1960, the General Geophysical Company (CGG) carried out electrical geophysical prospecting in the areas of Moroni, Mitsamiouli and Foumbouni, with a view to identifying favourable sites for the installation of wells. This study was followed up in the area of Moroni with a series of hydrogeological studies carried out by BRGM which led to the drilling of two wells south of Moroni: TP5 used at present to supply Moroni with drinking water; and TP1 which has not yet been used. There has been no follow-up to the geophysical prospecting in the areas of Mitsamiouli and Foumbouni.

In 1972, during the construction of Hahaia international airport, BRGM carried out a geophysical study (electrical and electromagnetic) followed by reconnaissance drilling, which led to the installation of two exploitation boreholes to supply the airport with water.

Project COI/79/005, entitled "Water research and development", which began in June 1980, was designed with a view to improving the drinking-water supply on Ngazidja by means of ground-water research and development and specifically through the installation of large-diameter wells in the coastal zones. The project was financed by the United Nations Development Programme and implemented by the United Nations Department of Technical Co-operation for Development.

Project COI/79/005, which was completed at the end of 1985, was followed without interruption by project COI/86/001, the main goal of which, in addition to the installation of wells to tap the fresh water of the island's "base aquifer", is to determine the geometry of the aquifers and their hydraulic behaviour, in order to be able subsequently to estimate as precisely as possible the safe exploitation potential in each of the various sectors of the island and the possibility of exploiting any aquifers "perched" above the "base aquifer". For this purpose, the project has a light diamond-coring reconnaissance rig (capacity: depth - about 85 m; maximum diameter - 75 mm), a geophysical array (electric resistivity), and pumps for the test pumping.

Porosity/permeability

The fundamental hydrological characteristic of the whole island is the almost total lack of surface runoff, despite average rainfall in excess of 6 m, even during the wettest months from January to April. Only a few torrents can be observed, during heavy rainfall, in the south-west, the wettest area of the island. Small intermittent streams can also be found in the north of the island and in the south, where layers of argillaceous alteration outcrop and the streams are fed by small springs.

This shows that the lavas covering almost the whole of the island are extremely permeable. This high permeability of the lavas is due to their intense fissuration and the presence of almost continuous cavities and tunnels. The diaclases in the lavas are mainly contraction fissures which developed during the cooling of the lava. The fact that the lavas are very often vesicular certainly facilitates the absorption of rainfall, but heavy rain can infiltrate only through the fissures. The layers of scoria covering the lavas form a rough surface and facilitate the almost complete infiltration of rainwater. The infiltration coefficients for the lavas this come close to 100 %. Thanks to the fissures, cavities and galleries, the infiltration water usually percolates rapidly towards sea level. This is demonstrated by the lack of large springs on the island.

The permeability of the pyroclastic formations, of much smaller volume on the island, is determined by their granulometry. These formations usually consist of fairly homogeneous and well-sorted lapilli and ashes; their permeability can still be considered fairly high, yet clearly lower than that of the lavas. The explosion material forming parasitic cones, the result of Strombolian and Vulcanian activity, is less permeable: small springs are often found here (0.1 l/s), almost always intermittent, within or beside these cones, representing the "overflow" of the rainwater infiltration system.

The beach alluviums and sediments, especially the sand dunes at Mitsamiouli, are mostly well sorted and of average to high permeability.

The island's only formations with low permeability consist of the alteration strata of the volcanic formations. Advanced alteration of these formations leads to the creation of argillaceous strata, as demonstrated in the massif of Badjini, where these strata can be several metres thick and where the two perennial springs are the direct result of these impermeable strata.

It can thus be concluded that the permeability of the volcanic rocks, in their fresh, very permeable state, diminishes as they age and are exposed to alteration, i.e. to the atmosphere.

The free porosity of the volcanic formations is very variable, as is the free-flow capacity or specific yield, which depend on the fineness of the pores and the porosity of the rock. The following figures are given by way of example:

Compact or vesicular basalt:	0 to 5 %
Scoriaceous basalt and scoria:	5 to 30 % and more
Pyroclastic formations:	10 to 30 % and more

Ground-water flows

In view of the extremely high permeability of the basaltic rocks (the other formations, of interstitial porosity, are really of little hydrogeological interest owing to their poor development), there is every reason for believing that the infiltration water does not encounter any major obstacles in its vertical downward movement and that it reaches the base aquifer situated roughly at sea level. However, it is impossible to exclude the possibility of local disruptions of the underground flow of infiltration water, which would facilitate the creation of perched aquifers. For example:

- Impermeable vertical dykes (columns of dense recent lava) may slow down the horizontal flow;
- Alteration of the ancient basalts at depth.

As the degree of alteration of the volcanic rocks and therefore their permeability is in direct proportion to their age, the flow of infiltration water is no doubt influenced by the spatial distribution of the ancient volcanic materials, i.e. the paleo-relief. The ground-water flows tend to be concentrated in the ancient valleys occupied by recent flows which are more permeable that the surrounding older rocks and thus represent preferred underground flow paths.

The only known discharge of fresh water into the sea in the northern part of the island (Trou du Prophète) seems to be directly connected to a major fissuration of the volcanic rocks running S-S-E/N-N-W and ending at Trou du Prophète.

It can be concluded that the ground-water flow paths are complex and influenced by the considerable heterogeneity of the formations (alterations of the different volcanic products, fissuration) and that the formation of temporary or permanent perched aquifers during the movement of the infiltration water towards the base aquifer cannot be excluded (although few surface observations indicate the presence of major perched aquifers). Once it reaches the base aquifer the fresh water mixes with sea water, then penetrates the aquifers over considerable distances (from 2.5 to 3 km at least); this process is determined by the dynamic equilibrium between the pressure of the sea water and the pressure of the fresh water, and the fresh water finally flows into the sea.

Springs and discharges into the sea

There are few springs on Ngazidja island and they all have a low yield. Small intermittent discharges are often found beside and within parasitic cones; in such cases, the water flows over fairly thin argillaceous crusts. Three springs of this kind (M'Koudoussi, Hamoindzé and Souou) are perennial and have been harnessed under project COI/79/005. Their yield varies from 0.5 m^3/h in the dry season to 50 m^3/h in the rainy season.

The three perennial springs with larger yields are probably connected to alteration strata of low permeability covering the volcanic rocks of the early volcanic phases: these springs are N'Gnambéni and M'Rotso in the massif of Badjini and Bondé in the massif of La Grille. Their yield varies between 1.5 and 2.5 m^3/h in the dry season and 30 to over 100 m^3/h in the rainy season. These springs have also been developed under project COI/79/005.

Along the coast, there are a few discharges of brackish water which flow at low tide. Fisherman report the existence of currents of cold water flowing from fissures in the shoreline which perturb the sea water in places. Owing to their location, these springs yield only brackish or salt water, because the fissures from which they emerge are invaded by the sea with every tide. There is no doubt a large number of them, but only the biggest can be recognized:

- Moroni (airfield);
- Trou du Prophète (4 km NE of Mitsamiouli);
- Foumboudzivouni (beach);
- Bandamadji;
- Foumbouni (near the south gate of the village);

- Itsoundzou (1 km west of the village);

- M'Bachilé (south of the village).

These discharges indicate the existence of preferred flow paths through the aquifer.

Hydrochemistry

The infiltration rainwater has a very low mineral content, in the order of 100 mg/l with a Cl content of 10 to 20 mg/l; it is mainly of the Ca-Mg-HCO_3 type when measured in the island's interior springs. Na and Cl are prevalent in all the water tapped in the coastal zone, owing to the influence of sea water, even in the water with lowest mineral content (200 mg/l). The ground water of the coastal zones can therefore be considered essentially diluted sea water, the mineral content of which is determined by the degree of sea water intrusion.

Balance

Not all of the elements for the establishment of an accurate water balance for Ngazidja island are available, but an attempt can be made to indicate approximate values.

In the absence of precise information concerning precipitation and temperature for the whole island, the following values are accepted:

Average rainfall: 2,500 mm/year

Average temperature: 23 °C

Using the Turc formula:

Real evaporation Er = 670 mm/year (measured in the Piche evaporometer)

Runoff coefficient R = 5 % of 2,500 mm/year = 125 mm/year

By inference, the infiltration is therefor I = 1,705 mm/year

Approximately 68 % of the rainfall infiltrates the soil and finally flows into the sea. As the island has an area of 1,025 km^2 and a perimeter of about 170 km, the nominal continuous flow of fresh water into the sea will be on average about 1.2 m^3/h per metre of shoreline. This flow varies around the island, depending on the characteristics of the "upstream" catchment basin.

The values given above are only indicative and do not represent orders of magnitude. However, they are sufficient for the rational exploitation of the fresh-water stratum balanced on the salt water to be envisaged.

Coastal aquifers

During the installation of wells and boreholes, water was found in all cases close to sea level. In no case was a raised (perched) aquifer found. Except in the southern part of the island, the tides, which can exceed 3 m, produce very clear variations in the water level in the wells. The tidal flows spread into the aquifers and are absorbed, causing periodic oscillations in the piezometric level. In some wells the size of these oscillations is roughly equal to one third of the height of the tide, and the maximum levels occur about two hours after high tide. The piezometric level of the stratum located above sea level also varies in step with the oscillations in the water and tide levels. The maximum heights of the piezometric level correspond to low tides and the minimum (or even negative) levels correspond to high tides. The average piezometric level is about 0.60 m above the average level of the sea, giving an average gradient of 0.60 m for 2 km or 0.00030. Other measurements indicate that the seasons have little impact on the level, in the order of 0.10 m.

The salinity of the well water varies little with the tides, but marked seasonal variations can be observed in all the wells in the coastal zones: the salinity can double during the dry season.

The depth of the interface between the fresh water and salt water at a given place is very difficult to assess, owing to lack of boreholes penetrating the whole of the fresh-water lense. The Ghyben-Herzberg principle (the depth of the interface below the average level of the sea is equal to about 40 times - depending on the density of the water - the height of the fresh water above the average level of the sea) is valid only for a homogeneous and static situation. On Ngazidja, however, the fluctuations in the base aquifer due to tides and the aquifer's own flow cause expansion of the interface through dispersion, and the depth of the interface can vary considerably.

IV. EXPLOITATION OF WATER

Storage tanks

Overall water requirements are satisfied mainly (about 75 %) by means of a very large number of individual and communal storage tanks. A census carried out in 1976 by the Ministry of Health and the World Health Organization (WHO) counted 10,927 storage tanks, with capacities ranging between 10 and 200 m^3 (mainly between 20 and 60 m^3). This type of resource has a number of problems:

- Water with a very low mineral content, and therefore decalcifying;

- Exhaustion of the tanks in the dry season.

This latter point requires special attention. The long dry season in 1981, in particular, caused the people considerable suffering, including loss of human life, especially among children.

The other experimental works designed to tap atmospheric water, such as the development of craters for water storage by covering them with impermeable materials, have not produced any truly conclusive results.

Despite these problems, the storage of water in tanks is and will remain essential.

Wells and boreholes

The first wells dug on the island were rudimentary holes, often making use of natural depressions, close to the sea. These "wells" usually yield brackish to salt water, but in some cases, when they are located on a preferred flow path, a slightly brackish water is found (Foumbouni, Foumboudzivouni, Tsangadjou).

Other wells have been dug further from the sea in relatively easy formations, especially in cinereous tufa (south of Moroni and north-east of Mitsamiouli) and in sand dunes (Mitsamiouli). These wells have supplied the two towns in periods of drought. A common feature of this kind of well is that its salinity, low in static situations, increases rapidly during exploitation of the aquifer. A test pumping carried out in a well situated between Iconi and M'Bachilé, for 15 minutes at a flow of 0.78 l/s, demonstrated this increased salinity, for the rate rose rapidly from 0.4 to 1.5 g/l. Similar results have been obtained at Mitsamiouli. It seems that the aquifers in these formations of interstitial porosity are recharged directly by infiltration of atmospheric water and contain only very limited stocks.

The first large-diameter wells drilled through basaltic formations were installed by BRGM in 1967 south of Moroni (TP5 and TP1), following geophysical prospecting carried out by the CGG in 1960 and reconnaissance drilling. These wells indicated a base aquifer subject to sea water intrusion and lying at approximately sea level. The salinity and water levels of the wells are influenced by the penetration of sea water in the basaltic aquifer and by the tides. The reconnaissance wells and boreholes drilled under projects COI/79/005 and COI/86/001 have demonstrated that this base aquifer is widespread around the island. Their location is indicated in annex 7, and the data which they have furnished will be found in annex 8.

The test pumping in wells TP5 and TP1 have demonstrated that the basaltic aquifer is extremely permeable. The pumped yields of 80 m^3/h (TP5) and 70 m^3/h (TP1) were accompanied by drawdowns of only 3 and 6 cm respectively without affecting the water quality.

The quality of the rainwater is usually strongly influenced by sea water intrusion, as is demonstrated by the sometimes very high salinity found in the wells. The sinusoidal oscillations of the tides produce, with some time-lag, similar but less marked oscillations in the water levels in the wells. The hydrogeological conditions of the coastal zone will be described in greater detail in section D.

Very little drilling has so far been attempted at altitude. Two boreholes were drilled by the SIF company in 1961/62 at 141 and 126 m above sea level east of Moroni. According to a BRGM report, the holes penetrated perched aquifers with very low yields (about 300 l/h) at a depth of about 100 m. Total loss of the water occurred in one of the boreholes. These perched aquifers seem to be connected to strata of black loamy sands, perhaps paleo-soils over which the ground water can flow (in small quantities). The information provided by the BRGM report does not lead to any important conclusions owing to the vagueness of the reconnaissance reports on the massif of Badjini for the purpose of verifying the presence of a perched aquifer. The borehole did in fact indicate such an aquifer at between 34 and 40 m, lying on the relatively impermeable alteration stratum of the inferior-phase lavas. This aquifer certainly feeds the two springs in the same sector.

In summary, the supply systems are the following:

- The system for Moroni and its vicinity (40,000 inhabitants), which includes some 450 private connections and 50 public standpipes. The construction of this system was financed by the European Development Fund (EDF) and it came into service in 1977. It is managed by a public body responsible to the Ministry of Supply and Equipment: Eau et électricité des Comores (EEDC). The system is supplied by well TP5, which is 35 m deep and located 7 km south of Moroni; it was drilled in 1967 by BRGM. Two pumps were installed in the well, delivering 300 m^3/h for five to six hours and 120 m^3/h for the rest of the day. The drawdowns are very small, in the order of a few centimetres.

The water has a very low mineral content (200 mg/l). It should be noted that the safe yield was estimated by BRGM at 165 m^3/h, from which it can be concluded that the well's maximum capacity has almost been reached and that in the near future it will no longer be able to satisfy Moroni's water needs. Works are under way to develop well ONU4 which was installed under project COI/79/005 in the same sector, in order to supplement the supply to the system;

- The provision of water for Hahaia international airport from two boreholes (depth - 90 m; mineral content - 1,000 mg/l);

- In the north (Mitsamiouli), a coastal aquifer in coral sands; 1,000 m long and 200 m wide was formerly exploited by two wells (depth - 6 to 7 m) feeding a small delivery network, since dismantled. The available discharge was small (20 m^3/day) owing to the rapid rise of saline ground water;

- A few springs with low yields (in the order of 5 m^3/day during low-water discharge), six of which have been developed under project COI/79/005;

- About 10 discharges of brackish water at the coast which are occasionally used;

- A few shallow traditional wells close to the coast, yielding more or less brackish water;

- 36 wells installed under projects COI/79/005 and COI/86/001, of which 10 are equipped with hand pumps and two with wind pumps. Two of these wells, at Foumbouni and Mitsamiouli, will be developed to supply the networks to be built in these two towns (UNICEF financing). Other donors have been contacted with a view to financing additional supply networks.

The situation with respect to drinking-water supplies can be summed up as far from satisfactory.

A report prepared under project COI/86/001 included proposals for improving drinking-water supplies by using the existing wells.

V. CONCLUSION

On the basis of a schematic and approximate water balance of Ngazidja island which indicates that the nominal continuous flow of ground water into the sea is on average in the order of 1.2 m^3/h per metre of shoreline, it can be concluded that in principle this resource, if properly tapped, could satisfy the needs of the population of Ngazidja.

Base aquifer

Exploitation of the base aquifer seems to be limited mainly by intrusion of sea water than by the yield of the wells. The lack of test pumping has so far prevented any assessment of the safe yields of the existing water points. An overall estimate based on the salinity of the well water indicates, however, that the existing wells give water of an acceptable quality and could be used to supply the population in their vicinity.

However, the fresh-water aquifer in contact with the salt water will have to be exploited with great care in order not to disrupt the delicate balance between the fresh and salt water. It should be noted in this respect that the encouraging experiments in the coastal zone south of Moroni, where the base aquifer can be exploited with high yields (up to 300 m^3/h in well TP5) without affecting the water quality, are not representative of the other coastal zones. This zone is by far the most favourable for exploitation of the base aquifer, owing mainly to the width of the coastal plain, which means that wells can be drilled at more than 2 km from the shoreline, and also to the heavy rainfall in the upstream catchment basin. The much higher salinity rates found in the water points in other coastal zones indicate that the hydrogeological situation there is considerably less favourable for large-scale exploitation of the base aquifer.

The limits to the exploitation of the base aquifer will be determined only by test pumping and reconnaissance boreholes and additional boreholes to exploit the base aquifer.

With respect to the establishment of additional water points to exploit the base aquifer, it should be noted that the results of the drilling of wells have shown that as a rule a distance of at least 1 to 1.5 km from the shoreline must be allowed, if ground water of an acceptable quality is to be found. Ground water with low salinity can be found close to the sea only in the preferred flow paths of fresh water or in impermeable formations (in the extreme south of the island). These preferred flow paths seem to be linked to the paleo-relief (southern part of the island) and to areas of intensive fissuration (northern part): the ground-water flows tend to be concentrated in the ancient valleys at present occupied by recent lava flows which are more permeable than the surrounding rocks, and in areas of intensive fissuration. These flows will have to be studied by means of reconnaissance boreholes and, if the results are positive, followed up by the drilling of wells to establish additional water points, from which it will be possible to exploit the base aquifer on a large scale.

Perched aquifers

Three solutions are in principle envisaged for the provision of drinking water in higher areas:

- The tapping and storage of atmospheric water;

- The piping uphill of ground water from the base aquifer;

- The exploitation of perched aquifers.

The tapping and storage of atmospheric water, the method used up to now, does have problems, in particular a water shortage in the dry season.

The piping of water from the coastal zones involves very high investment and operating costs. This solution is probably practicable only for the satellite villages above Moroni, because there is a large population to be served (about 20,000 persons).

The exploitation of perched aquifers would no doubt be the most appropriate and economical solution. It would be particularly beneficial because these aquifers are protected against any marine pollution and the water taken from them could be distributed by gravity. However, it is doubtful whether these perched aquifers, whose intermittent presence is demonstrated by small discharges of water at altitude and by a reconnaissance borehole, can supply enough water. Reconnaissance drilling is the only means of studying ground-water resources at altitude. It seems that the alteration strata of the basalts and the pyroclastic formations offer the most favourable conditions for the formation of perched aquifers. The geophysical prospecting carried out under the project mentioned above has led to the proposal of four locations for additional drilling to study the perched aquifers.

Lastly, the following are the minimum goals with respect to acquisition of the knowledge required for assessing as accurately as possible the safe exploitation potential in each of the different sectors of the island:

- Test pumping for existing and future water points;

- Reconnaissance drilling, possibly followed by the construction of wells in coastal zones which have not yet been studied and supplied;

- Drilling to observe the intrusion of salt water through the fresh-water lense, beside the exploitation wells;

- Reconnaissance drilling to study the perched aquifers, possibly followed by the installation of wells.

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