

Hydrogeological Characteristics and Geophysical Study of Base Aquifers in the Island of Grande Comore: Implications for Water Resources and Saline Intrusion

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Abstract The Electrical Resistivity Tomography (ERT) and Vertical Electrical Sounding (VES) methods surveys were employed to conduct hydrogeological investigations within the three massifs of Grande Comore. The geometric arrangement of Grande Comore can be subdivided into three distinct segments: A layer exhibiting very high resistivity values ranging from 1000 to over 6000 $\Omega\cdot m$, characterising historical, recent, sub-recent, and even ancient phases; Structures with resistivity values ranging from 100 to over 200 $\Omega\cdot m$, depicting freshwater aquifers; Layers with lower resistivity values ranging from 1 to 100 $\Omega\cdot m$, indicating interfaces between freshwater and saltwater. The island has heterogeneous sub-surface lava formations, with compact, relatively fractured layers that can channel preferential flows. These aspects are visualised through ERT panels, highlighting strong fault zones along the profiles. The perched aquifers, whose resistivity varies from 20 to 90 $\Omega\cdot m$, are exploited in the form of galleries, mainly in the two massifs located at the extremities of the island. These analyses are supported by various data, including lithological profiles, groundwater table levels, groundwater quality, as well as data from VES. The aquifer porosity (ϕ) shows a variation ranging from 0.01 to 0.34, with an average of 0.124, and is closely related to hydraulic conductivity (K_s), fluctuating from 5.68×10^{-8} to 8×10^{-6} m/s following the application of the Kozeny equation. The Badjini massif stands out as a unique area with extensive alteration of volcanic aquifers and intercalated slag basalts. The coastal zones show low electrical resistivity values 20 to 100 $\Omega\cdot m$, indicating a substantial contribution from saltwater intrusion.

Keywords: Electrical resistivity tomography (ERT), vertical electrical soundings (VES), Hydrogeological investigations, Aquifers bases, hydraulic conductivity, Grande Comore

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1. Introduction

Water scarcity and saline intrusion have profound effects on island communities, particularly in the Comoros republic where access to safe drinking water is severely limited. According to the [1], a staggering 85% of the population in the volcanic islands of the Comoros lacks access to safe drinking water. The deficiency in water supply poses significant challenges to the well-being and health of the population. Additionally, climate change intensifies the vulnerability of coastal areas to erosive processes, flooding, and the intrusion of saline water into freshwater aquifers, exacerbating the impact on groundwater resources [2]. Rising sea levels and increased

coastal erosion further compromise the availability of freshwater sources, causing ongoing stress on the already limited resources. Water scarcity not only poses health risks to individuals but also has far-reaching implications for the local economy. Insufficient access to drinking water hampers agricultural productivity, as farmers struggle to sustain irrigation systems necessary for crop cultivation. In addition, the intrusion of saline water into freshwater aquifers exacerbates the problem, further reducing the supply of safe drinking water for the community. It is imperative to address these challenges and develop effective strategies to ensure water security on the islands.

Hydrogeological studies play a vital role in addressing the above challenges. Various research conducted on other volcanic islands provide valuable insights into water

availability and quality in island settings including the hydrogeology, aquifer structures, and saline intrusion.

In Stromboli in the Aeolian Island (Italy), [3] used a combination of self-potential data, large scale DC-resistivity tomography, and measurements of soil temperature and soil CO₂ concentrations and fluxes to characterise the hydrogeological properties of the island. Their findings provided valuable information on aquifer structures and hydrogeological formations on volcanic islands.

Studies have also examined the impact of saltwater intrusion on island groundwater quality. [4] explored freshwater transport mechanism in Hawaii, specifically focusing on the multilayer formation of water saturated layered basalts. Their research highlighted the movement of water through volcanic formations and improved the understanding of saline intrusion in island hydrogeological systems.

Studies on the hydrogeological properties of aquifers on volcanic islands provide important insights into the behaviour of groundwater resources and the challenges associated with addressing water scarcity and saline intrusion. The results of these studies emphasize the need for a sustainable water management plan and continuous monitoring to maintain the quality and availability of groundwater. In hydrogeology, detecting aquifers typically involves the utilization of drilling techniques. However, drilling boreholes in volcanic formations presents significant challenges due to factors such as steep topography and the mechanical resistance of certain volcanic rocks [5]. Moreover, this process can be financially burdensome [6].

To address these challenges, geophysical methods have emerged as non-intrusive alternatives that can provide important insights for ensuring sustainable access to water resources.

The use of geophysical methods, such as Time Domain Electromagnetic (TDEM), electrical resistivity tomography (ERT) and vertical electrical sounding (VES), has proven effective in addressing the limitations of drilling in volcanic formations. For example, [7] conducted a study on the Island of Ischia in Southern Italy, utilizing ERT and VES techniques to examine the relationship between aquifer pumping response and water quality in an active hydrothermal system. Their findings provided insights into the intricate workings of aquifers in volcanic island settings. [8], conducted a high-resolution helicopter TDEM survey over Martinique, an andesitic-type volcanic island, to gather detailed information on the subsurface hydrogeological features. Their study focused on identifying the location and properties of aquifers, as well as their connection to surface water and overall groundwater resources on the island. Through their research, they provided valuable insights into the hydrogeological functioning of aquifers in volcanic islands, which are known for their complex geological formations.

In a recent study conducted on Grande Comore, we utilized DC-resistivity methods such as electrical resistivity tomography (ERT) and vertical electrical sounding (VES) techniques. The purpose of this investigation is to analyze the geology and determine the availability of water resources that can satisfy the needs of the local community. Within this investigation, the study aims to

achieve two objectives. Firstly, it aims to pinpoint appropriate locations for the installation of hydraulic structures such as borehole wells and pumping stations. This information is crucial for optimizing the extraction and distribution of water resources. Secondly, the study intends to identify areas on the island that exhibit substantial groundwater potential. By doing so, decision-makers can allocate resources and plan interventions in areas where the groundwater supply is expected to be accessible. By employing these geophysical methods, the study focuses on overcoming the challenges associated with drilling in volcanic formations and provides valuable information to support the sustainable management and utilization of water resources on the island. "To estimate the hydraulic conductivity of aquifers, pumping or slug tests as well as hydraulic tomography techniques have been commonly employed as suggested by the works of [9] and [10]. It has been demonstrated that electrical conductivity measurements can be used to infer hydraulic conductivity in soils, where soils with high electrical conductivity and hydraulic conductivity generally have higher moisture contents and better pore structure, allowing for better water movement and electrical current flow. Therefore, measuring electrical conductivity can be a useful indirect tool to estimate the hydraulic conductivity of aquifers, providing valuable information about groundwater flow characteristics. DC-resistivity methods, such as ERT and VES, can provide detailed information about the subsurface structures and help in identifying potential aquifer locations, which can then be further investigated using pumping or slug tests to estimate the hydraulic conductivity of the targeted aquifers.

2. Study Area

The Comoros archipelago is situated in the Mozambique Channel, between latitude 10-13°S and longitude 43-46°E as shown in the top left of Figure 1. Known for its humid tropical climate, the archipelago comprises several islands with Ngazidja also known as Grande Comore being the largest, covering a surface area of approximately 1021.38 km². The island's terrain consists of two shield volcanoes, with Mount Karthala being the highest point at 2361 meters above sea level. Moreover, the region is influenced by the movements of the Intertropical wind masses and the semi-permanent oceanic cell, a component of the subtropical anticyclonic belt. Due to its significant size and location, Grande Comore experiences a galloping population growth with approximately half of the population living within 5 km of the coast. The island is thus densely populated, with high but unevenly distributed rainfall. More than 62% of the island's inhabitants depend on rainwater, while the remaining 38% rely on groundwater. Several initiatives have been launched to improve access to drinking water, such as the GECAU (Pilot project for the management of public water services in rural areas on the island of Grande Comore) pilot programme and the GEF (Green Climate Fund: securing a climate-resilient water supply in the Comoros) project. However, much remains to be done in terms of drinking water supply.

However, access to safe drinking water is a persistent

problem in the region [11]. To address this issue, the study focused on examining the basal and perched aquifer segments using a database consisting of 29 sites, 31

electrical boreholes for Vertical (VES), and 93 panels of (ERT) (Figure 1).

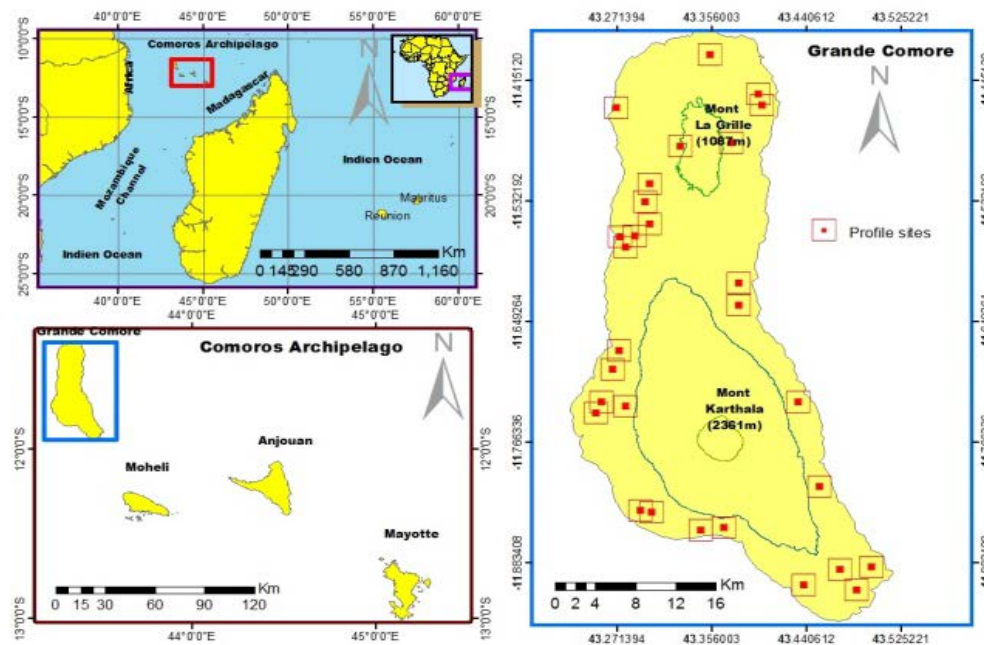


Figure 1. Situation of the Grande Comore (Ngazidja) and study areas

3. Geological and Hydrological Characteristics of Grande Comore Island in the Comoros Archipelago

The Comoros archipelago is situated on an ancient oceanic domain known as the Comoros Basin, which is believed to have originated in the Middle Jurassic period [12]. However, in Grande Comore, there are indications of significant continental material [13,14]. These islands rise above a deep abyssal plain that reaches depths of 3,000 – 3,400 m [15]. Although the nature of Grande Comore's offshore formations is not fully understood, the island itself has an elongated shape with a length of approximately 65 km and a width of about 20 km. It is a relatively young island, with geological estimates placing its formation between 0.01 million years and 1 million years ago [16,17,18] and [19]. Grande Comore is composed of two primary shields, known locally as "Badjini"; "La Grille" and "Karthala." These shields are further classified based on their age, with "La Grille" referred to as Pleistocene, "Karthala" as Quaternary, and the older formation associated with the Badjini massif as Miocene [11,16,20] and [21].

"La Grille" is the remnant of a large caldera, entirely covered by pyroclastic deposits, silicates undersaturated basanites, and occasional alkaline basalts and nephelinites (recent volcanism basanites, alkaline olivine basalts, Oceanites and ancient volcanism of undifferentiated age basanites, alkaline olivine basalts and ankaramites and undifferentiated recent and ancient flows [22] and [23]. "Karthala" makes up the majority of the island and encompasses three units: (i) the younger Karthala (aphyric basalts and hawaiites), which is characterized by "aa" and "pahoehoe" type flows and dominates the active volcanic edifice (Aphyric basalts, olivine basalt,

oceanites and hawaiites), (ii) the historical with a well-preserved volcanic surface (aa" and *Pahoehoe*) and features like summit projectiles, ringed bombs, pyroclastics, slag, and lava, and (iii) the Badjini or ancient Karthala (aphyric basalts, plagioclase basalts, ankaramites, oceanites, hawaiites), which are only visible on the eastern flank of the Karthala volcano and consist of paleo-relief defined by landslides and basalt and basanite collapses. It is added the intermediate rock formations, alluvium and colluvium and Lahar are the volcanism of unspecified origin (intercalated flow, alluvium and colluvium, pyroclastites and slag cones [16,20] and [21]. Grande Comore is made up of "aa" and "pahoehoe" flows and massive vesicular and non-vesicular porphyritic to aphyritic basalt flows [23].

In Grande Comore, the soil has a high infiltration rate of 57 to 63% and a low runoff rate of 5% [11,24,25]. This allows for the formation of deep aquifers at the freshwater/seawater boundary. Despite the absence of hydrographic networks on the island, it's highly permeable soil enables high infiltration potential, resulting in a significant volume of water (approximately 0.5 to 2.109 m³ per hydrological year) within its territory.

The hydrogeological model of Grande Comore has similarities with the Hawaiian model presented by [26]. The groundwater resources of other islands such as the Canary Islands, Cape Verde and Madeleine have been extensively studied, although with different interpretations there are indeed relationships between "high-altitude groundwater" and "basal groundwater" [27] and [28]. The salinity of groundwater and the intrusion of saltwater pose significant challenges to water quality in Grande Comore's aquifers. The shallow hydraulic gradient of 1‰ in the Ngazidja island environment indicates a broad and shallow mixing zone of freshwater resting on saltwater along the coastline, with the zone deepening towards the interior [11]. This increase in density can range from 2 to

5% [29]. A hydrogeological model on the west bank of Karthala confirmed the presence of deep piezometric levels in the form of dome, composed of basaltic flows dipping slightly towards the sea and covering the island's interior. These deep aquifers are primarily known on the shoreline up to 2 km from the coast [11] and [30]. The highly porous and anisotropic nature of these formations, with preferential water flow in the beds, contributes to their hydraulic behavior.

4. Field Survey

The Schlumberger and Wenner-Schlumberger configurations were applied to the difference between injected current and produced potential to calculate apparent resistivity values (ρ_a). Schlumberger and Wenner-Schlumberger configurations were applied to the difference between injected current and produced potential to calculate apparent resistivity values (ρ_a). The SEV results are plotted on a bi-logarithmic graph giving the variation of apparent resistivity as a function of electrode spacing. The ERT device is a variant of the Wenner device in which the distances AM and NB are equal to (a) times the spacing between the measuring electrodes M and N. These are fully automated, robust and fast methods, which depend on obtaining interpreted depths from data received by a PC. The process of [31] is adjusted to change the values of (AB/2) and (ρ_a) in a multilayer model. The maximum distance AB/2 of VES is 800 m.

The electrode array used to conduct ERT is the Wenner-Schlumberger-alpha with 16 to 32 consecutive electrodes spaced 11 to 12 m apart, and the maximum target depth of investigation is 150 m based on the calculation by [32]. The data were processed using RES2DINV [33]. The ERT profiles that emerge following inversion construct a 2D model of the subsurface [34] and [35]. The ρ_a is expressed as a function of potential difference and current intensity [36], in any case derived from Ohm's law.

$$\rho_a = K \left(\frac{V}{I} \right) [\Omega.m] \quad (1)$$

Where K is the geometric factor which depends on the electrode arrays configuration used;

V is the electric potential expressed in millivolts (mV) and I is the injected current expressed in (mA).

4.1. Characterisation of Volcanic Aquifers

Archie's equation [37] is commonly used in geophysics to determine the porosity of a rock from electrical resistivity measurements. The formation factor F_i , values were derived from the resistivity of the aquifer and its groundwater at the VES and nearby hydraulic structures. These values were then used to estimate three sets of hydraulic conductivities (Ks) based on the resistivity values. Consequently, the values of α is the Archies factor and cementation factor (m), were chosen to be 1.01 and 22 respectively. To determine the porosity and hydraulic conductivity (Ks) of volcanic aquifers, borehole resistivity values (VES) and median values of α and maximum (m) can be used.

$$\rho_a = \alpha * \rho_w * \varphi^{(-m)} [\Omega.m] \quad (2)$$

Where φ is the porosity of the rock (expressed as a fraction or percentage). α is the Archies factor, which depends on the electrical properties of the rock and the fluid. m is the cementing exponent, which measures the compactness of the rock. ρ_w is the resistivity of the fluid in the pores of the rock.

α : alpha parameter is the coefficient of void space in rock formations. The value of α was chosen to be 1.01 based on the study of [38]. In addition, in ρ_w is the resistivity of the water in the pore ($\Omega.m$) obtained from the water sample collected at each borehole location using a conductimeter (HI 98192 portable conductivity meter). The other symbols are φ and m the porosity and the cementation factor, respectively. The roots of this trinomial equation are two complex numbers and one real number considered.

$$\ln \alpha = \ln F_i + m * \ln \varphi \quad (3)$$

Where F_i is the formation factor expressed as:

$$F_i = \frac{\rho_a}{\rho_w} \quad (4)$$

Deriving the porosity from Eq. 3, we obtained:

$$\varphi = e^{\frac{1}{m} \ln(\alpha) + \frac{1}{m} \ln\left(\frac{1}{F_i}\right)} \quad (5)$$

Archie law's formula [37] is commonly used to calculate the cementation factor (m), which is related to F_i , ρ_w , and φ . During the survey, we did not carry detail petrophysical studies and laboratory measurements on core samples. The cementation factor varies between 1.01 and 2.2 for clean sands, gravels, alluvium and pyroclastic contained in aquifer layers [39]. In the case of consolidated sandstones and basalts, the m is comprised between 1 and 2.20 [40]. This article, which studies the basal aquifer, assumes that $m = 2.20$, which means that these are consolidated formations such as basalt that contain water in their fractures. Therefore, the value of m is assumed to be 2.20 which is typical for fracture aquifers in volcanic formation. Equation 3 is used to deduce the porosity and hydraulic conductivity (Ks) [41] in a fractured volcanic and hard rock aquifer.

The F_i values were derived from the resistivity of the aquifer and its groundwater at the sites of the various structures and nearby structures. These values were then used to estimate their hydraulic conductivities (Ks) in the three sets based on the resistivity values. These constants (α and m,) which will be used to calculate the porosity of the aquifer was estimated for the remaining geoelectric measurement sites using the modified Archie's law [37], from [41] Eq.2 and its transformation Eq. 5. The hydraulic conductivity Ks is calculated following [38].

$$K_S = 1,91 * 10^{-4} e^{-0,0492 \rho_a} (m / s) \quad (6)$$

4.2. Salinity Determination by Geophysical Methods

The apparent resistivity of water-bearing rock in

volcanic environments, denoted as ρ_w , can be influenced by various factors. These factors include the presence of weathered and fractured volcanic material, hot geothermal fluids, and saline intrusion [3] and [42] have shown that the presence of hot geothermal fluids can affect apparent resistivity measurements in volcanic environments.

The electrical conductivity (EC) is a key parameter in understanding the characteristics of water in such environments. EC is measured in Siemens per meter (S/m), where 1 S/m is equivalent to 10 dS/m. The values of Total Dissolved Solids (TDS), which are expressed in parts per million (ppm) or milligrams per liter (mg/L), are defined in relation with ρ_w ($\Omega.m$):

$$\rho_w = \frac{1}{EC} (\Omega.m) \quad (7)$$

$$TDS = 640 * CE (dS.m^{-1}) \quad (8)$$

This volcanic context seems to define zones favourable to electric resistivity and conductivity moderately marked in the Figure 2 by [44]. However, Table 1 below shows borehole resistivity values VES in volcanic aquifers on the volcanic-stratigraphic lithological profiles that define the thickness of the aquifer, which will enable us to determine porosity and hydraulic conductivity using [45] Kozeny's equation (6), establishing the relationship between the aquifer's hydraulic conductivity and resistivity. Geophysical data acquisition methods, such as VES and

ERT are used to characterize aquifers and map their geometric configuration. The study conducted ERTs and VES surveys across different locations on the island to verify the presence of volcanic aquifers. The specific locations (VES₅, VES₆, VES₂₀, VES₂₁, VES₈, (Table 2) were surveyed to gather data and assess the characteristics of the aquifers in those areas. A synthetic model 1, in which the RMS error was not a discriminating statistical criterion for judging the quality of the models reconstructed by cooperative inversion. In this case, the evolution of the RMS error, normalised to an average of 10% over the iterations of the inversion process for all the E-R-T scans performed, also allows the inclusion of one or more additional a priori structural information to complement the VES.

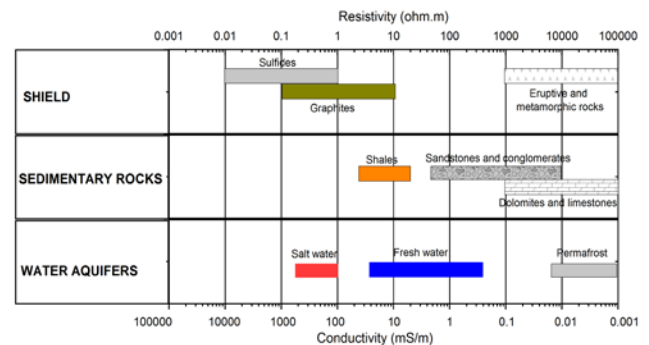


Figure 2. Resistivity and conductivity

Table 1. Summary table of the hydraulic parameters of the aquifers of the island of Grande Comore

VES points	Aquifer resistivity measured (ohm.m)	Hydraulic tools	CE (dS/Cm)	Estim Resistivity ated water	Estimated Porosity ϕ	Estimated Hydraulic conductivity (mg/L)	Estimated Salinity TDS	Quality of water
Massif de Badjini								
VES ₁₉	55	ONU10	2.15	0.465	0.030	$1.28 \cdot 10^{-5}$	1376	Salt water
VES ₂₀	200	ONU17	0.308	3.247	0.049	$1.02 \cdot 10^{-8}$	197.12	fresh water
VES ₂₇	155	F7-MDJ	0.524	1.908	0.04	$9.31 \cdot 10^{-8}$	335.36	fresh water
SE ₂₉	32	ONU42	1.53	0.654	0.058	$3.96 \cdot 10^{-5}$	979.2	brackish water
VES ₃₀	100	F11-MID	0.623	1.605	0.048	$1.39 \cdot 10^{-6}$	398.72	fresh water
VES ₃₁	167	F10-MOH	0.972	1.029	0.024	$5.16 \cdot 10^{-8}$	622.08	fresh water
VES ₃₂	150	S3	0.19	5.263	0.086	$1.19 \cdot 10^{-7}$	121.6	fresh water
Massif du Karthala								
VES ₁	55	-	-	-	-	$1.28 \cdot 10^{-5}$	-	-
VES ₂	90	-	-	-	-	$2.28 \cdot 10^{-6}$	-	-
VES ₃	211	-	-	-	-	$5.92 \cdot 10^{-9}$	-	-
VES ₉	122	-	-	-	-	$4.72 \cdot 10^{-7}$	-	-
VES ₁₀	122	SHA	1.828	0.547	0.019	$4.72 \cdot 10^{-7}$	1169.92	salt water
VES ₁₁	103					$1.2 \cdot 10^{-6}$		
VES ₁₂	148	ONU19	3.77	0.265	0.01	$1.31 \cdot 10^{-7}$	2412.8	salt water
VES ₁₃	50	ONU24	9.63	0.104	0.011	$1.63 \cdot 10^{-5}$	6163.2	salt water
VES ₁₆	50	ONU40	3.06	0.327	0.025	$1.63 \cdot 10^{-5}$	1958.4	salt water
VES ₁₇	47	-	-	-	-	$1.89 \cdot 10^{-5}$	-	Interface water
VES ₁₈	55	F8-MIT	0.13	7.692	0.237	$1.28 \cdot 10^{-5}$	83.2	fresh water
VES ₂₁	100	TP5	0.434	2.304	0.063	$1.39 \cdot 10^{-6}$	277.76	fresh water
VES ₂₃	55	ONU9	1.49	0.671	0.039	$1.28 \cdot 10^{-5}$	953.6	Interface water
VES ₂₆	67	-	-	-	-	$7.07 \cdot 10^{-6}$	-	-
VES ₂₈	650	ONU 14	9.13	0.11	0.002	-	5843.2	Interface water
Massif de la Grille								
VES ₄	40	ONU33	5.29	0.189	0.02	$2.67 \cdot 10^{-5}$	3385.6	salt water

VES ₅	120	F5-CHZ	1.302	0.768	0.025	5.21*10 ⁻⁷	833.28	fresh water
VES ₆	12	F12-CHM	1.074	0.931	0.154	1.06*10 ⁻⁴	687.36	brackish water
VES ₇	3806	ONU2	2.13	0.469	0.001	-	1363.2	salt water
VES ₁₅	35	S1	0.19	5.263	0.25	3.41*10 ⁻⁵	121.6	fresh water
VES ₁₆	84	S2	0.234	4.274	0.113	3.06*10 ⁻⁶	149.76	fresh water
VES ₂₀	56	F4-WEL	0.338	2.959	0.116	1.21*10 ⁻⁵	216.32	fresh water
VES ₂₂	26	S3	0.193	5.181	0.308	5.31*10 ⁻⁵	123.52	fresh water
VES ₂₄	55	ONU28	1.533	0.652	0.039	1.28*10 ⁻⁵	981.12	saltwater

5. Aquifer structure on the Island of Grande Comore (Ngazidja)

5.1. Aquifer structure at La Grille

The Grille is characterized by the presence of superimposed volcanic formations whose geoelectrical characteristics are indistinguishable from those of the Karthala and Badjini. These features indicate intermittent periods of geological rest and weathering, evidenced by the intercalation of resilient layers within the massif. These different geoelectric levels marked by ERT revealed resistivity values ranging from 600 to 6 600 $\Omega\cdot\text{m}$. This suggests relatively low moisture levels compared with the heterogeneous terrain, where resistivity values range from 300 to 600 $\Omega\cdot\text{m}$.

On the other hand, this information is taken from both ERT and VES techniques of La Grille, in the following Figure 3(1a, 1b et 1c) (VES₂₀; VES₅ and VES₆) and Figure 4 (2a, 2b et 2c) (VES₄; VES₁₆ and VES₂₂). Some formations show higher levels of resistance, reflected by resistivity superior like these values 3806 $\Omega\cdot\text{m}$. These resistant levels outcrop from less than 6m down to depths to more than 55 m. The lower resistivity values observed in this region may be indicative of less-resistant formation zones or mixed water sources. Such occurrences are commonly observed in fissured basalts with intercalations of slag and weakly clayey gravel, which are influenced by seawater intrusion.

Moving to the central flank, which is bordered by a number of pyroclastic scoriaceous cones, resistivity values range from 200 to 6600 $\Omega\cdot\text{m}$. These values signify the presence of unsaturated zones in this area. Notably, in the Helendje, Ivembeni, and Dimadjou sectors, high hydraulic conductivity formations are observed at greater depths, characterized by laterites and pyroclastic materials. In this region, thin horizons with resistivity values ranging from 30 to 200 $\Omega\cdot\text{m}$ marked in ERTs and much less in VES, extending over tens of metres are observed. These horizons comprise heterogeneous formations containing fines and/or boulders, thus suggesting the potential for the formation of high-altitude aquifers.

5.2. Structure of Karthala Aquifers

The volcanic flows of Karthala, originating from the island's active volcano, exhibit notable variations in resistivity values as shown in Figure 5(3a, 3b et 3c) highlighting their heterogeneity. The island experiences continuous seismic activity, which has shaped its evolving and well-preserved topography. This topography is characterized by the presence of faults resulting from a

folding phase. Erosion features such as "neo-ravines," are predominantly found on the south-western flank of the massif. The dominant geological composition of the massif includes historical basalts, sub-recent, and, at times, older volcanic rocks. These formations are influenced by areas of diacase, resulting in spatial variations throughout the field. Radial flows, preferential flow paths, and notable anomalies are observed within these formations, contributing to the heterogeneity of the area. Altitude measurements provide insights into the presence of a continuous deep aquifer, with resistivity values of 200 $\Omega\cdot\text{m}$ observed at a depth of 313 meters as determined by VES₈. This observation is accompanied by the identification of a bell-shaped piezometric level, representing the presence of groundwater in the region. Consequently, the western flank areas exhibit geoelectric characteristics indicative of excellent freshwater aquifers. In contrast, the eastern slope presents challenges, with variable water quality. The aquifers within the Karthala region predominantly consist of fractured hard basalt, ancient basalt, and formations with continuous or intermittent water flow.

5.3. Badjini Aquifer Structure

The Badjini massif, often referred to as the "ancient Karthala," is of great significance in understanding its structural characteristics using electrical resistivity analysis. It is located beneath the "recent Karthala", which comprises altered clay layers that impact the depth of the salt wedge. As depth increases, conductivity also increases, indicating the transition from deep saline to brackish water, with resistivity values ranging from less than 1 to 100 $\Omega\cdot\text{m}$.

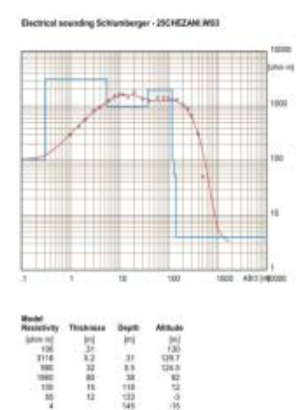
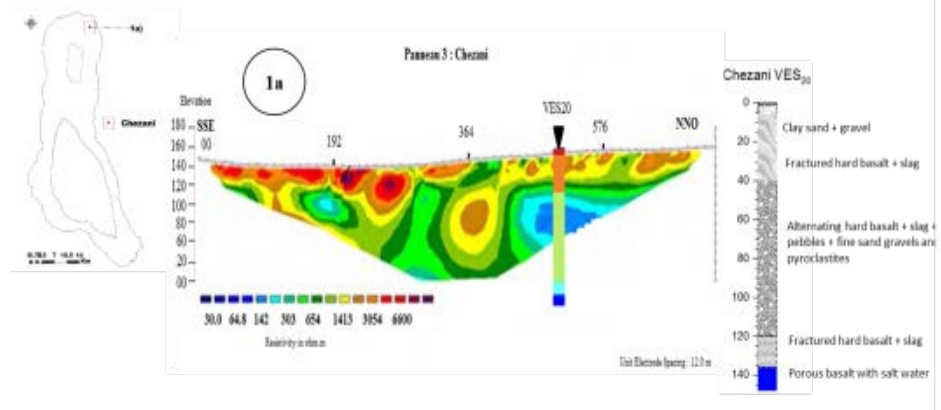
Within the ancient massif, surveys such as ERT and VES outcropped volcanic sedimentary formations resistivity values ranging from 100 to 200 $\Omega\cdot\text{m}$ at various depths. This suggests zones containing materials like pyroclastic slag, porous basalt, and basaltic gravels. Additionally, studying past seismic activities (paleoseismic) assists in determining fault movement directions, while ERT helps identify active Quaternary faults that contribute to the geological characteristics of the recent sector [46]. Similar geological features can be observed in the southwest to southeast sectors of the island, where piezometric levels respond to tidal retreat. At higher altitudes, spring points in the Inane sector suggest the presence of perched aquifers. These aquifers are characterized by varying resistivity values, indicating a mix of highly altered formations, consolidated clays, laterites, and pyroclastites. Overall, the Badjini massif exhibits a wide range of resistivity values, reflecting complex hydrogeological conditions, including the potential for saline intrusion Figure 6(4a, 4b et 4c). The

aquifer structure on the island of Grande Comore (Ngazidja) varies in different locations due to the different formations and characteristics present. The variation of the

aquifers in the three massifs in terms of resistivity is even less clear, and we try to highlight and show this marked dissimilarity in Table 2

Table 2. Different massif structures of aquifer waters of La Grille, Karthala and Badjini

	Resistivity values ($\Omega.m$)	La Grille	Karthala	Badjini
Water from different hydrogeological zones				
Muddy water	< 10	(+++...)	(+++...)	(+++...)
Seawater	< 50	(+++...)	(+++...)	(+++...)
Interface water	50 – 100	(+++...)	(+++...)	(+++...)
Fresh water	100 –1.000	(+++...)	(+++...)	(+++...)
Wet geological formations				
Clay lenses	< 30	(+++...)	($\pm$...)	(+++...)
Altered slag	< 30	(+++...)	($\pm$...)	(+++...)
Altered tuffs	< 30	(+++...)	($\pm$...)	(+++...)
Altered ash	< 30	(+++...)	($\pm$...)	(+++...)
Altered pyroclastics	< 30	(+++...)	($\pm$...)	(+++...)
Slightly weathere	< 30	($\pm$...)	(+++...)	(+++...)
Highly weathered	< 30	($\pm$...)	(+++...)	(+++...)
Massive wet formation				
Massive fractured basalt	10–100	(+++...)	(+++...)	(+++...)
Fractured basalt	> 1.000	(+++...)	(+++...)	(+++...)
Old massive basalt	> 1.000	(+++...)	(+++...)	(+++...)
Slag intercalated with basalt	100 –1.000	(+++...)	(+++...)	(+++...)
Ash	< 30	($\pm$...)	(+++...)	($\pm$...)
Pyroclastites	< 30	($\pm$...)	(+++...)	($\pm$...)
Altered formation	< 30	(+++...)	(+++...)	(+++...)
Unsaturated geological formation				
Unsaturated zone	> 1.000	(+++...)	(+++...)	(+++...)
Artefacts	> 1.000	(+++...)	(+++...)	(+++...)



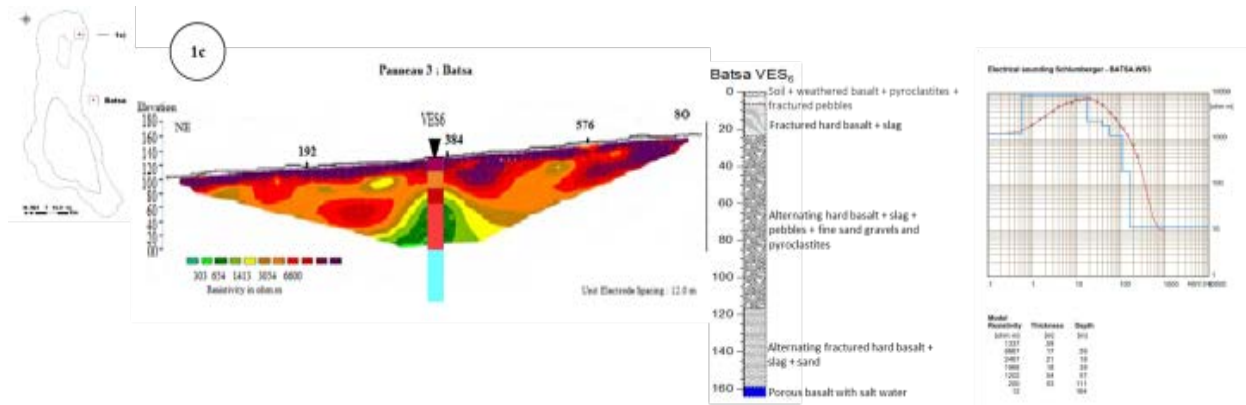


Figure 3. La Grille relief profiles showing the ERTs and boreholes (Chezani ERT (1a) and VES₂₀; Wella ERT (1b) and VES₅ and Batsa ERT (1c) and VES₆. These profiles show alternating basalt and the sub-surface strata are disturbed and show clear contrasts of various faults visible in the panels, which also show disturbed strata cut by local faults

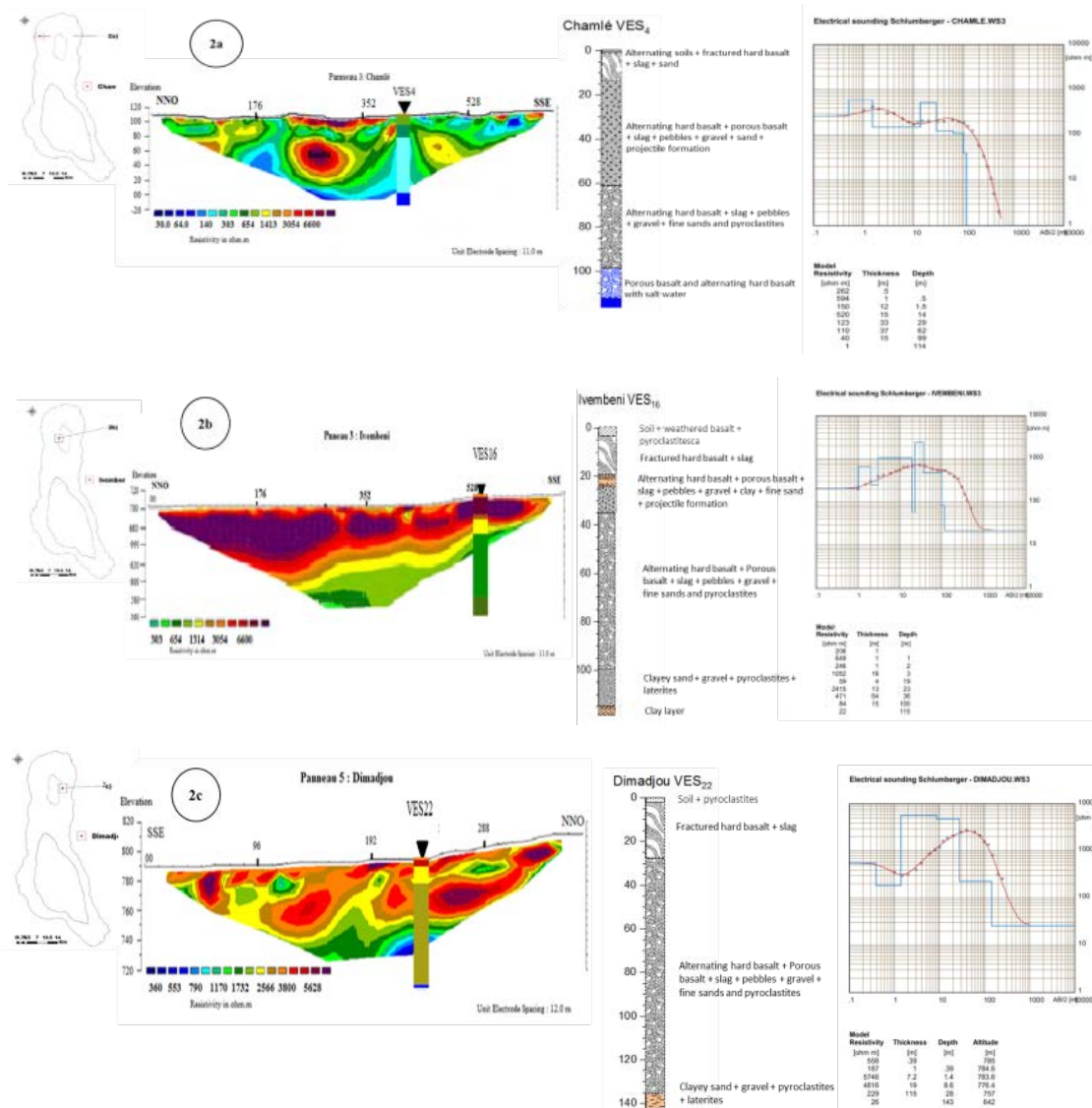


Figure 4. The relief profiles of La Grille representing the ERTs and VES₄; Chamlé (2a) and VES₄; Ivembeni (ERT) (2b) and VES₁₆ and Dimadjou ERT (2c) and VES₂₂, show very heterogeneous values at altitude and at the base, with often thick basalt layers at sub-surface and sub-recent levels

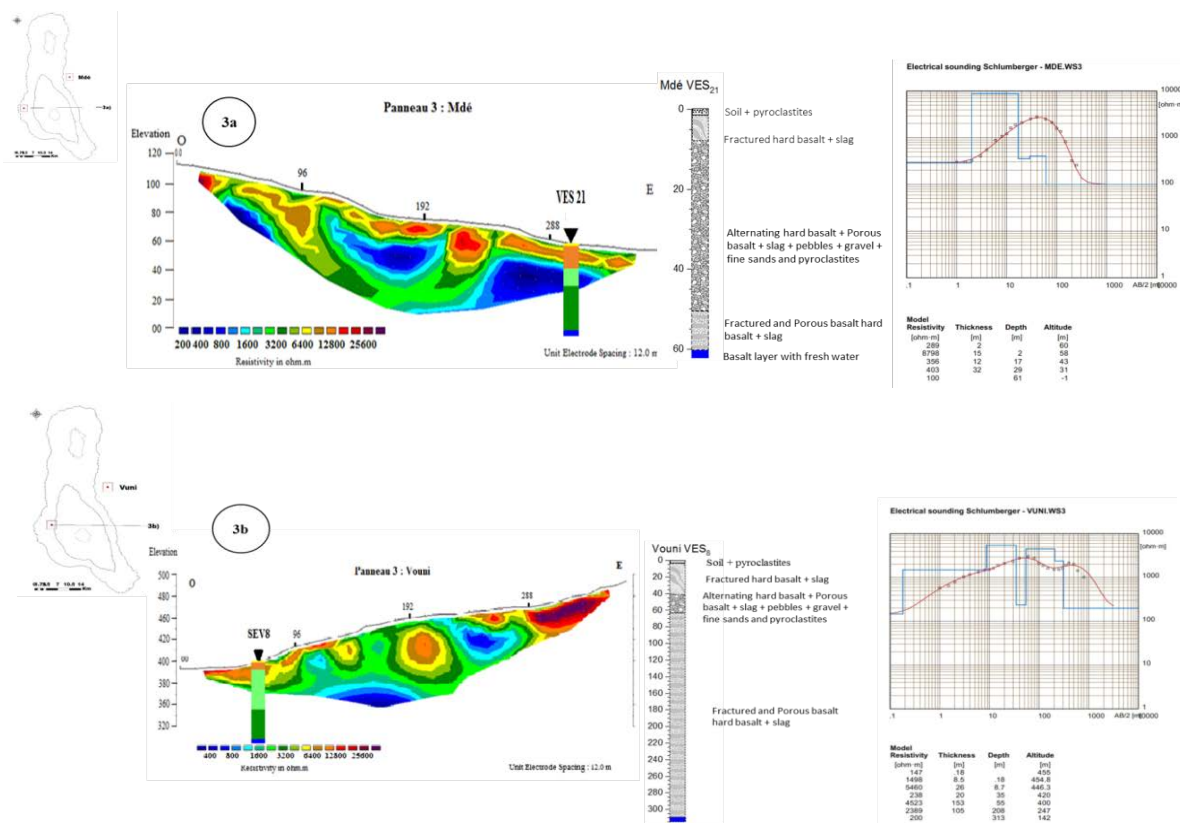
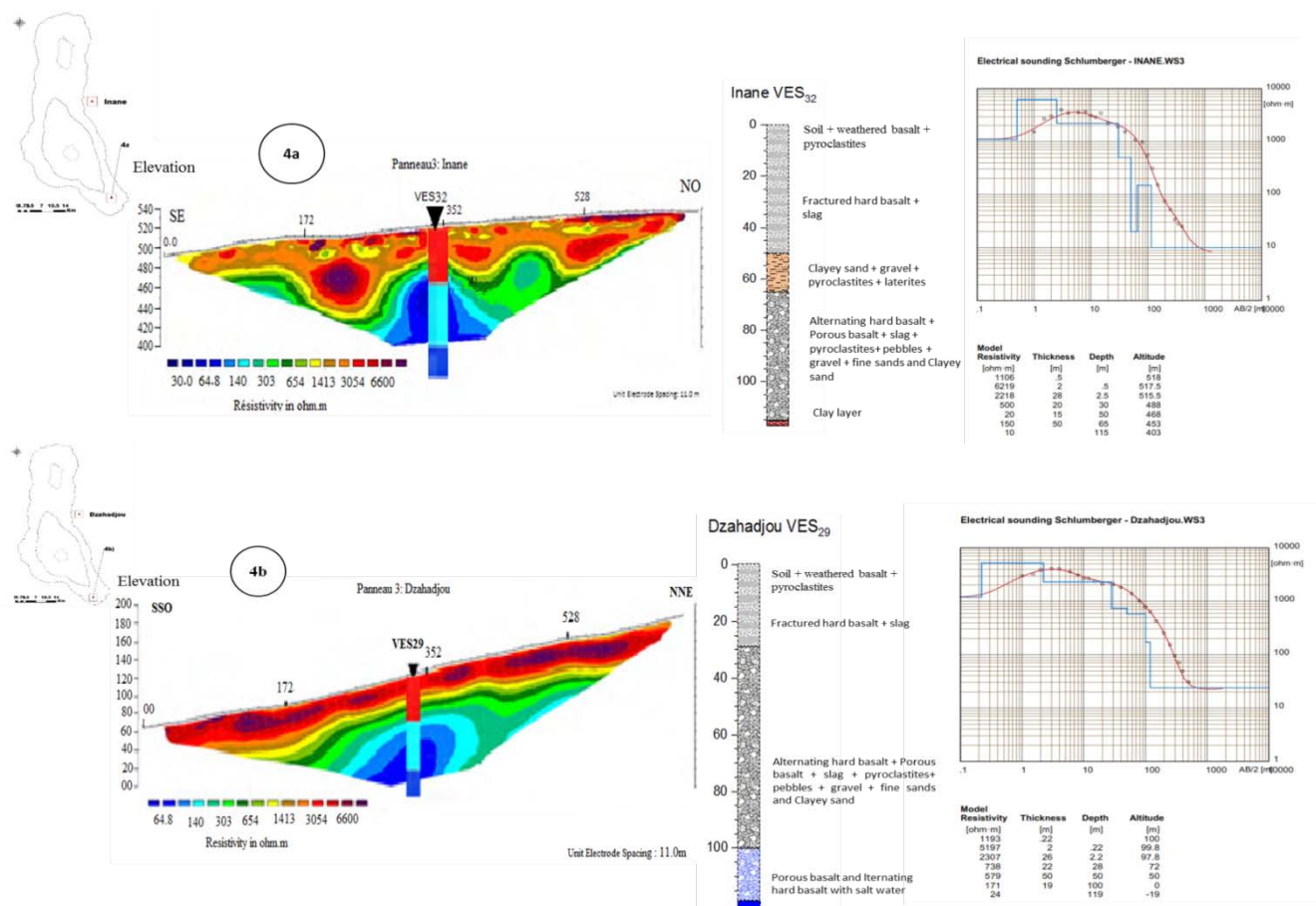


Figure 5. The Karthala relief profiles show ERT (3a) and VES21, the ERT (3b) panel and VES8 Vouni. These profiles show alternating basalts and sub-superficial strata, marking contrasts and various visible faults. The panels also show disturbed strata, trenches and through local faults



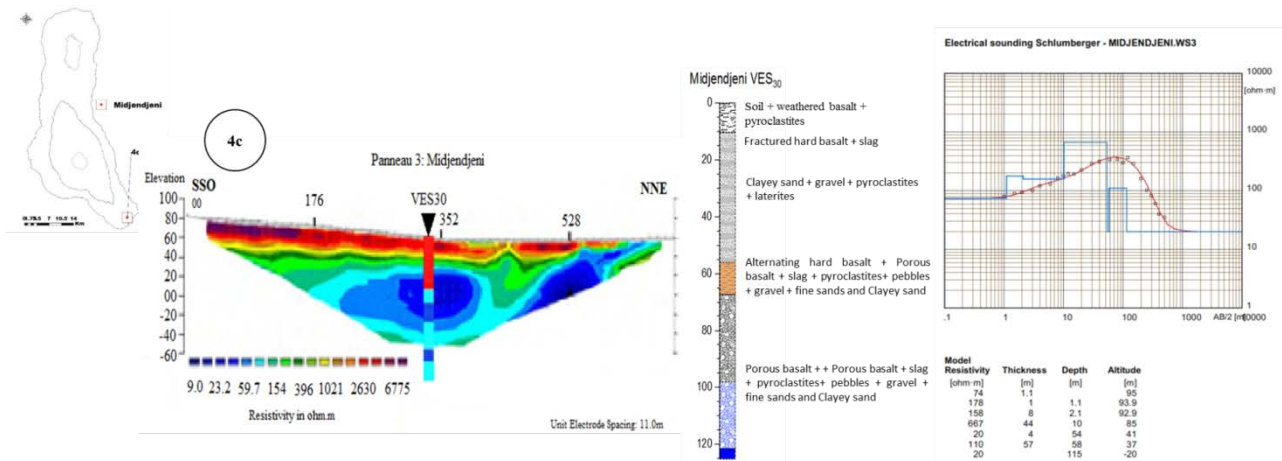


Figure 6. Badjini panels ERT (4a) VES₃₂ from Inane and ERT (4b) and VES₂₉ from Dzahadjou and panel ERT (4c) and VES₃₀ from Midjendjeni. These profiles indicate the alternating basalts and altered strata of Midjendjeni, Mohoro, Oupheni and Madjoma and Inane along the respective slopes in this Badjini massif. The data show aquifer continuity in the same massif from upstream to downstream

6. Discussion

To give an overview of the Table 1 and Table 2, it should be noted that volcanic rocks, mainly flow basalts and associated rocks, are characterised by their inherent porosity. Permeability, sometimes referred to as hydraulic conductivity, is the measure or expression of the ease with which a fluid can pass through a porous material. It should be noted that this porosity property varies considerably within the volcanic environment and can reach values such that basalt flows constitute some of the most permeable aquifer formations known. These include the aquifers in the volcanic formations of Grande Comore (such as scoria, pyroclastic, alluvium, ash and intrusive rocks), which have porosities ranging from 10 to over 31%, with permeabilities of at least 1.92×10^{-4} m/s. Basalts (dense, porous, fissured intermediates, and above all, falling into the categories of massive lava basalts) also have low permeability and a low to average porosity of 1 to 10%. However, in island environments, formations with porosities of between 1 and 2% and permeabilities of less than 4.72×10^{-6} m/s are considered aquicludes. These include intrusive rocks of the dyke and sill type, massive basalts, ancient rocks, tuffs and zoolitic materials. In this volcanic environment, anisotropy affects over permeability about the thickness and slope of the lava. In this case, the hydraulic conductivities defined in the wells tapping the basal aquifer in the coastal zone of Grande Comore showed values of 1.6×10^{-3} to 2.7×10^{-1} m/s according to [24,43]. Grande Comore is an island whose hydrogeological characteristics show ranges of resistivity that decrease with depth, as shown by [47].

The island experiences lateral movements of lava and phreatomagmatic projectiles, setting up faults after the folding phase. The impotent strata were accommodated by textural and shear slippage, while the competent rock units subsequently underwent the erosion, sedimentation and alluviation that led to the current landform are less than ten meters high in some areas. The results of the ERT and VES studies of the trenches reveal that, at times, the sites have undergone shearing or faulting of movements. Moreover, the spatial distribution of the older lithology suggests a Badjini (Karthala Ancien) location, and extends

northwards along the central fault, setting up La Grille. Next come the Quaternary deposits of sub-recent and recent Karthala and its intermediate phase. The ERT and VES surveys do not allow us to follow the age extensions of the state of the rock of the three massifs, but rather of its contribution of water, its alteration and the salinity of the coastal regions of the island, which are a function of the electrical transitivity. However, the lava flows, which have undergone periods of rest and alteration, acquired their current size and shape during these phases. In addition, there was significant explosive activity in these massifs, marked by in-situ observations of pyroclastic products and projections. Analysis of geoelectrical panels ERT and vertical electrical boreholes (VES) revealed resistivity values ranging from 1,000 to over 6,000 Ω .m, showing unsaturated thicknesses in all three massifs.

The Kathala exhibits resistivity values ranging from 1 to 400 Ω .m. However, these formations which are considered to be conductive in well-differentiated soils, may constitute potential aquifers. These hydrogeological characteristics are derived from lava flows Figure 4 and Figure 5. The upper phase is ubiquitous, with significant thicknesses observed on the Diboini plateau, a wide depression between Grille and Karthala. The Karthala is highly heterogeneous, and the ERT also reveals the limits of the alluvial fan deposits on the western and eastern slopes. In this massif, historical or recent and intermediate flows are the source. These represent the unsaturated basalts above the basal aquifer. Sub-surface geological formations are characterised by very high resistivity. Interpreting the paleoseismic survey, for example, could determine the direction of movement along faults and identify preferential flows towards the basal aquifers that bear the groundwater. These are of good quality, with resistivity values ranging from 100 to plus 400 Ω .m. This type of aquifer is well marked by the sections (Mkazi, Mdé, Mitsudjé, Madjoma and Koimbani). On the whole, the island has a very slightly eroded embryonic relief. The central-western sector, represented by the site panels, receives more rainfall. This erosion results in "new gullies", dissection forms of all sizes that break the lateral continuity of the volcano flanks and contribute to the general organisation of the relief with their radial layout. The geophysical surveys carried out on this massif have

also provided information on the structure of the island, which is made up of volcanic rocks, mainly basalts, resting on a continental basement that has now collapsed.

In the La Grille massif, the phases interspersed with periods of rest and alteration represent the intermediate phase. The Grille, which underwent periods of rest and alteration, took on its present size and shape during the recent, sub-recent and intermediate phases. The explosive activity of this massif produced well-preserved pyroclastic formations and cone projections. These phases have resistivity values ranging from 20 to 400 $\Omega\cdot\text{m}$ at altitude. On the other hand, the base aquifers are subject to oceanic forcing, with highly conductive formations similar to those found in other massifs. However, most of the hydrogeological characteristics are masked by the less consolidated and less differentiated conductive formations, which may constitute the base aquifers. Whatever the nature of the soil invaded by the frankly salty water, its resistivity values fall to less than 50 $\Omega\cdot\text{m}$ or are very rarely $< 3 \Omega\cdot\text{m}$, in the drillings and ERT carried out. It is therefore more challenging to gain an understanding of the formations based on these resistivity values in these heavily mixed zones. Boreholes drilled less than 1 km from the coast only show seawater intrusion, and the western slope is the most sensitive aquifer in Figure 3 and Figure 4. On the eastern slope at Gnomamilima, the same type of aquifer is characterised by resistant formations assumed to be non-productive. These saline or mixed waters are represented in formations with low apparent resistivity ranging from 1 to 100 $\Omega\cdot\text{m}$ in the VES boreholes and ERT. Volcanic activity probably began in the Tertiary with the so-called lower phase and was probably confined to the southern part of the island. The southern part of the Badjini massif is below present-day Karthala. In this southern part of the island, clayey alteration layers are observed of Figure 6. The geophysical cross-section obtained shows the boundary of the highly resistant horizons, which are well differentiated as long as we remain in the dry part and neglect the perched aquifers. Below the static level, resistivity is no longer or rarely characteristic of the nature of the terrain. The base aquifer representing the groundwater that is likely to be of excellent quality in this massif has resistivity values of 100 to 400 $\Omega\cdot\text{m}$. The inflexion of the salt interface boundary at the well is suspected on the geophysical profile of this zone. The profiles (Midjendjeni, Mohoro and Oupoveni) are examples of this. However, the groundwater in the recognised mixing water aquifer appears with resistivity ranging from 1 to 100 $\Omega\cdot\text{m}$. This aquifer with resistivity of 1 to 50 $\Omega\cdot\text{m}$, indicates a significant saline intrusion, made by the structures of (Dzahadjou, Malé and Mohoro).

The high altitude areas are forested where they are exceptionally altered: Grille and Badjini are located at the extremities and Karthala is the island's currently active volcano. In the perched areas of the Grille, resistivity values ranging from 20 to 90 $\Omega\cdot\text{m}$ can be found at depths of 100 to 200 m with very low mineralisation. The presence of springs such as Souwu, Bondé, Hamoindze and Mkoudoussi is a clear indication of this. To the South (Badjini), the electrical conductivity values show horizons in the order of 20 to 100 $\Omega\cdot\text{m}$. The clay thicknesses here are significant. This contribution allows us to associate the

presence of springs (Gnambeni and Mrotso) and a prolonged period of hydrographic flow. In the centre of the Karthala slopes in contrast, the ERT survey interpreted palaeoseismic features, which mark the various directions of movement along the faults without the presence of any identified springs in these areas. The thicknesses of the freshwater spotted below sea level at distances of 1.2 km to 3km from the coastline and 75m inland, can be coupled to weathered media as defined by the model and local structures (La Grille and Badjini) at altitude are contrasted and could of course, be exploitable as indicated by [11] and [48]. The hypothesis of saline intrusion is shown by geophysics linked to volcanic units. The grid is weakly altered and intrusion is significant. In all three massifs, there are differences in hydraulic gradient. The geo-resistivity values of the contrasting formations of the three massifs make it possible to visualise the geometry of the base aquifers spatialised in Figure 7. They show that for this study VES and ERT supported by defined resistivity models, contribute to the understanding of the 2D structure established by measured values of georesistivity and EC ($\mu\text{S}/\text{cm}$) of water. However, the taste of water depends on TDS and EC and three (03) classes have been defined based on freshwater (600 mg/l and 500 $\mu\text{S}/\text{cm}$), mineralised water (600 to 1000 mg/l and 500 to 1,000 $\mu\text{S}/\text{cm}$) and saltwater each with a range above (1000 of TDS or EC) (WHO, 2017). These waters are observed in all three massifs (Table 3). The latter make it possible to distinguish the different aquifer structures and their potential, from the saline intrusion in Grande Comore as previously described by Figure 7.

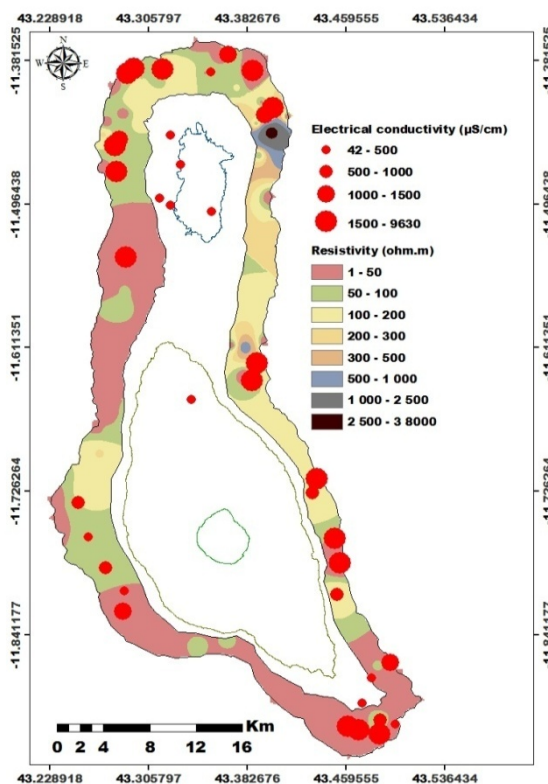


Figure 7. IDW-Spatialization of electrical conductivity of basal aquifers on Grande Comore Island

The comprehensive understanding of the hydrogeological characteristics of the aquifers of the

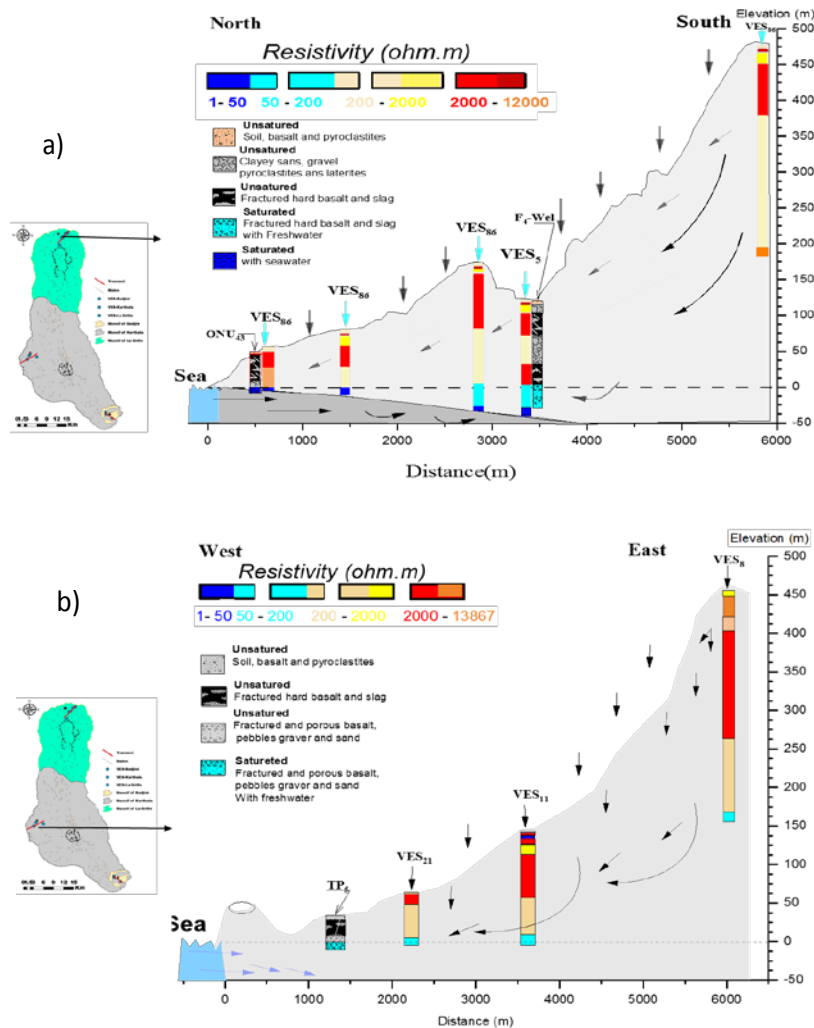
Grande Comore Island based on the data from this study and the 1986 PNUD (VES₈₆) geophysical studies, has been systematically elucidated through detailed profiles of the three massifs. These specific results obtained for each study considered together with morphological and geological features such as anisotropy, faults and facies changes, make it imperative to delineate hydrogeological zones with similar hydraulic characteristics (Figure 8a, Figure 8b, and Figure 8c). It should be noted that in the southern and southwestern sectors of the Grande Comore, it is possible to detect groundwater of acceptable quality. This is due to the presence of impervious clay layers between the basaltic pebbles and the slag in the South. The Karthala (Figure 8b) stands out from the potential catchment areas of the basal aquifer due to its good recharge and significant orographic effects. Similarly, due to its sub-recent and recent formations, part of the high-altitude water flows directly into the base aquifers and towards the sea. The northern base aquifers are very sensitive to marine intrusions, requiring a distance from the coast to ensure good quality. The perched aquifers of La Grille (Figure 8a) may simply serve as a rapid passage of water to the basal aquifer.

Certainly, the steady-state model of the basal aquifers approximated a low piezometry to the north (Figure 8a),

similar to the Hawaiian model. The bell-shaped piezometer also illustrated by [47] (Figure 8b and Figure 8c) is displayed at Karthala and characterizes them as close to the Canarian model. Consequently, the existence of upper aquifers at the Badjini level follows a logical pattern. But despite the presence of clay accumulations at altitude, surface water is only temporary. The dikes of these base aquifers can also act as barriers to marine waters (Figure 8b).

Table 3. The delineated base aquifer potential zones using different ranges of hydraulic conductivity and salinity of boreholes water

Aquifer potential	Estimated Hydraulic conductivity (m/s)	Estimated Salinity of water TDS (mg/L)	WHO (2017) mg/L
High potential base aquifer	1.92×10^{-4}	687.36	600 <
Medium potential aquifer	3.01×10^{-5}	83.2 to 6163.2	< 600 and 1000 >
Low potential aquifer	4.72×10^{-6}	121.6 to 2412.8	< 600 and 1000 >



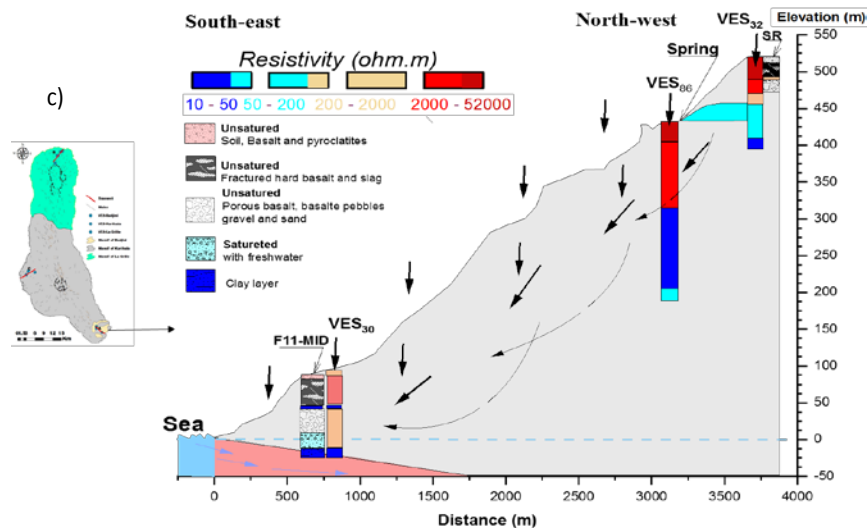


Figure 8. Interpretation of hydrogeological models a) La Grille, b) Karthala and c) Badjini

7. Conclusion

Volcanic rocks, particularly basalt flows, are characterized by inherent porosity. Permeability, also known as hydraulic conductivity, measures the ease with which fluids can pass through porous materials. Porosity and permeability vary within the volcanic environment, with basalt flows being some of the most permeable aquifer formations known. Aquifers in volcanic formations of the Grande Comore have porosities ranging from 0.1 to over 0.31 and permeability of at least $> 1.92 \times 10^{-5}$ m/s. Basalts have low permeability and a low to average porosity of < 0.1 . However, the hydraulic conductivity values obtained by pumping tests in a small number of hydraulic structures exploiting the basal aquifer in the coastal zone of the Grande Comore are between 1.6×10^{-3} and 2.7×10^{-1} m/s. The island experiences lateral movements of lava and phreato-magmatic projectiles, setting up faults after the folding phase. The hydrogeological characteristics of the island show ranges of resistivity that decrease with depth. The island has volcanic rocks, mainly basalts, resting on a continental basement that has now collapsed. The aquifers in the three massifs of the island (Grande Comore, La Grille, and Badjini) have different resistivity values and hydraulic gradients. Saline intrusion is a hypothesis supported by geophysics linked to volcanic units. Geoelectrical methods like ERT and VES can provide valuable information on hydrogeological structures and hydraulic parameters. However, further studies and comprehensive descriptions of aquifer parameters are needed. Overall, the hydrogeological characteristics of the island of Grande Comore are complex and varied, with different aquifer structures and saline intrusion being important factors to consider. Geophysical methods like ERT and VES can help in understanding the structures and impacts on aquifers.

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