



# Heterogeneity of hydrodynamic properties and groundwater circulation of a coastal andesitic volcanic aquifer controlled by tectonic induced faults and rock fracturing – Martinique island (Lesser Antilles – FWI)



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## SUMMARY

We conducted a multidisciplinary study to analyze the structure and the hydrogeological functioning of an andesitic coastal aquifer and to highlight the importance of faults and associated rock fracturing on groundwater flow. A helicopter-borne geophysical survey with an unprecedented resolution (SkyTEM) was flown over this aquifer in 2013. TDEM resistivity, total magnetic intensity, geological and hydrogeological data from 30 boreholes and two pumping tests were correlated, including one which lasted an exceptional 15 months. We demonstrate that heterogeneous hydrodynamic properties and channelized flows result from tectonically-controlled aquifer compartmentalization along the structural directions of successive tectonic phases. Significant fracturing of the central compartment results in enhanced hydrodynamic properties of the aquifer and an inverse relationship between electrical resistivity and transmissivity. Basalts within the fractured compartment have lower resistivity and higher permeability than basalts outside the compartment. Pumping tests demonstrate that the key factor is the hydraulic conductivity contrast between compartments rather than the hydrodynamic properties of the fault structure. In addition, compartmentalization and associated transmissivity contrasts protect the aquifer from seawater intrusion. Finally, unlike basaltic volcanic islands, the age of the volcanic formations is not the key factor that determines hydrodynamic properties of andesitic islands. Basalts that are several million years old (15 Ma here) have favorable hydrodynamic properties that are generated or maintained by earthquakes/faulting that result from active subduction beneath these islands, which is superimposed on their primary permeability.

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## 1. Introduction

Drinking water supply for growing populations on volcanic islands, such as Martinique, is a recurring concern (Peterson, 1972; Falkland and Custodio, 1991; Cabrera and Custodio, 2004; Custodio, 2005; Won et al., 2006; Cruz et al., 2011). Water was historically supplied to these islands by means of dams located on rivers, by tapping springs located at high elevations, by digging or constructing channels and tunnels that permitted “gravity”

distribution of water, and by drilling wells located in valley bottoms and coastal zones (Ecker, 1976; Falkland and Custodio, 1991; Custodio, 2005). In many cases, these surface resources are no longer sufficient, particularly during the dry season; for this reason, authorities are searching for alternative solutions (Falkland and Custodio, 1991; Custodio, 2005; Vittecoq et al., 2007b, 2015; Violette et al., 2014). Recourse to underground resources, which is an obvious solution for hydrogeologists, must be justified and explained. The sectors to be explored must be based on the most detailed conceptual models possible. In this way, appropriate and sustainable management of water resources can be achieved. However, geologic, hydrologic, or hydrogeologic data on which to build these conceptual models are often lacking or insufficient in terms of the complexity encountered in volcanic areas.

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Volcanic islands can be categorized into two groups on the basis of their magmatic composition: islands of predominantly basaltic volcanism and islands of predominantly andesitic volcanism. Conceptual models were developed for basaltic islands in the 1970s and 1980s: the Hawaiian model (Peterson, 1972; Macdonald et al., 1983); and the Canarian model (Custodio, 1975; Custodio et al., 1988). Violette et al. (2014) recently proposed a relationship between these two models: recent islands (<1 Ma) that function as the Hawaiian type may evolve toward Canarian-type behavior after several million years of weathering. The Mahorais model was proposed by Vittecoq et al. (2014) for an old basaltic island in an advanced stage of erosion and weathering. This model, characterized by the existence of several juxtaposed volcanic edifices and a succession of construction phases, shows that groundwater flow is constrained by geologic and geomorphologic structures. These structures result from successive phases of building and erosion of volcanic edifices and heterogeneity of the associated formations (lava and pyroclastic flows, volcanoclastic formations, breccias, lahars, etc.). As in the Canarian model (Custodio, 2005), the older the formation, the lower the hydraulic conductivity. However, no regional watertable (compared to the Canaries islands described by Cabrera and Custodio (2004) and Custodio (2005)) or aquifer of significant extent exists on Mayotte. The associated model is notable due to the “discontinuous” nature of aquifers with highly variable dimensions (from several tens of meters to several kilometers), some perched and others deep, flowing into the sea. This model also shows the ambivalent role of volcanoclastic formations, little-studied formations (Vittecoq et al., 2014; Izquierdo, 2014; Selles, 2014) that at times play the role of aquifer and at other times the role of a semi-permeable horizon.

Although groundwater flow is relatively well described in basaltic volcanic islands, much less work has been done on andesitic-type volcanic islands (Falkland and Custodio, 1991; Vittecoq et al., 2009, 2010; Gourcy et al., 2009; Lachassagne et al., 2011; Charlier et al., 2011). These islands, generally located in island arcs that overlie subduction zones (back-arc basins), are characterized by a high degree of lithologic variability resulting from the superposition of formations produced by distinct eruptive episodes of relatively limited lateral extent (from several tens of meters to several hundreds of meters); in addition, these formations commonly show heterogeneity both laterally and vertically, which gives rise to high lateral and vertical variability of the hydrodynamic properties of the aquifers (Vittecoq et al., 2007b; Gourcy et al., 2009; Charlier et al., 2011; Selles, 2014). This variability is accentuated by chemical weathering and mechanical erosion processes (Audru et al., 2010 and references therein; Rad et al., 2011, 2013) that affect geological formations in different ways, particularly in terms of their nature and porosity (pumice, ash, nuées ardentes, andesites, hyaloclastites, lahars, breccias, conglomerates, etc.), their mineralogy, and their ages. Rainfall, temperature, and the alternation of dry and rainy periods, which are extremely important parameters in humid tropical environments, stimulate these processes.

The hydrogeological functioning of andesitic volcanic islands, and also certain basaltic islands such as Mayotte (Vittecoq et al., 2014) may be difficult to explain on the island scale because of these heterogeneities. It is thus necessary to be able to identify aquifers that have some lateral continuity, and structures that control groundwater flow. The most suitable research scale may be that of the geological formation and its associated aquifer. Investigation at this finer scale, for both predominantly basaltic and andesitic islands, appears to be more relevant because some local or small-size structures (paleovalleys, dykes, weathered and argillized volcanic formations, paleosols, weathering thicknesses, lava tunnels, etc.) have been revealed on the few islands that have been studied in detail (Ecker, 1976; Takasaki and Mink, 1983;

d'Ozouville et al., 2008; Coppo et al., 2010; Vittecoq et al., 2014). These structures may affect the hydrogeological functioning by acting as hydraulic drains channeling groundwater flow or impermeable barriers compartmentalizing supposedly homogeneous aquifers.

In this study we focus on the Lamentin aquifer, a strategic aquifer on the island of Martinique, a predominantly andesitic island (Westercamp, 1982; Westercamp et al., 1989) located in the archipelago of the Lesser Antilles (Fig. 1). This strategic aquifer is located at the center of the island in immediate proximity to the cities of Fort-de-France and Lamentin where half of the island's population lives (total population of island: 395,000 inhabitants in 2012). This aquifer, composed of 15 Ma old fissured and fractured basalts, is both coastal and located at low altitude (<25 m); the risk of saline intrusion related to its exploitation must be considered. The multi-disciplinary approach we propose is based on the correlation of geological, geophysical, and hydrogeological data. The available data set is unprecedented for a volcanic island of the andesitic type: a helicopter-borne geophysical survey with high resolution (SkyTEM – Sørensen and Auken, 2004) was flown over this aquifer in 2013 (Deparis et al., 2014); TDEM resistivity, total magnetic intensity, geological and hydrogeological data from 30 boreholes and two pumping tests were correlated, including one which lasted an exceptional 15 months.

The goal of our study is thus to (i) characterize the structure and hydrogeologic functioning of a coastal andesitic-type aquifer, (ii) show the influence of structure on aquifer compartmentalization, groundwater flow, and saline intrusion, and (iii) show that the key hydrogeologic factor is inter-compartmental hydraulic property contrasts resulting from faulting.

## 2. Martinique island and the Lamentin aquifer

### 2.1. Site location and climate

Martinique (Fig. 1) is an island located in the Lesser Antilles archipelago. With its 1080 km<sup>2</sup> surface, Martinique is the largest volcanic island in the archipelago. It has a maximum length of 65 km along the NNW–SSE axis and a maximum width of 30 km, reducing to 12 km at indentations that constitute the bays of Fort-de-France, Robert, and François (Fig. 1). Its relief is highly variable. The northern and western parts are mountainous in the vicinity of large recent volcanoes (Mount Pelée: 1397 m, last eruption less than a century ago; Piton Lacroix: 1196 m, recently dated at –330 ka by Germa et al., 2011 and Morne Jacob: 884 m, 2.2 to 5.5 Ma). Toward the east and south, the relief is gentle near old volcanic and volcano-sedimentary complexes (from 6.5 Ma to 24.5 Ma) where the hills and small mountains do not exceed 500 m in altitude. The “plain” of Lamentin and Rivière Salée is located along the continuation of the bay of Fort-de-France. The plain is composed of recent sedimentary formations associated with the development of “mangrove” type vegetation along the shore of the Caribbean Sea. The Lamentin plain is the only flat zone (altitudes range from 1 to 20 m above sea level) of significant extent (≈70 km<sup>2</sup>) on the island; it is located at the intersection of numerous volcanic edifices that have built up the center and the southern part of the island, and constitutes the low valley of one of the most important rivers of the island, the Lézarde River.

Martinique has a humid tropical trade-wind climate (Guiscadre et al., 1976). The rainfall regime is characterized by a dry or “lenten” season centered on the months of February to April (inter-annual monthly average of 65 mm in February in Fort-de-France) and a humid or “rainy” season centered on the months of July to October (interannual monthly average of 255 mm in September in Fort-de-France) coinciding with the cyclone season. The trade

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