Journal of Hydrology 509 (2014) 519–538

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Influence of successive phases of volcanic construction and erosion on Mayotte Island's hydrogeological functioning as determined from a helicopter-borne resistivity survey correlated with borehole geological and permeability data

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ARTICLE INFO

Article history:
Received 11 June 2013
Received in revised form 26 November 2013
Accepted 30 November 2013
Available online 7 December 2013
This manuscript was handled by Corrado Corradini, Editor-in-Chief, with the assistance of Fritz Stauffer, Associate Editor

Keywords:
Island hydrogeology
Volcanic aquifer
Conceptual models
TDEM
Permeability
Resistivity

SUMMARY

The purpose of this study is to show how a multidisciplinary approach that combines geophysics, geology and hydrogeology has made it possible to: (a) significantly improve our understanding of the hydrogeological regime of the volcanic island of Mayotte, and (b) provide a new set of geophysical measurement calibration data. In 2010 a helicopter-borne geophysical survey (SkyTEM) was flown over the entire island (374 km^2) with a measurement density hitherto unheard of in a volcanic environment. In addition, a database was compiled containing the geological logs of 55 boreholes. 52 of these boreholes have hydrogeological information like aquifer position and piezometric level. 21 of the boreholes have transmissivity values. Correlations were made between the inverted resistivities as obtained from the helicopter-borne TDEM profiles and the nature, age and hydrodynamic properties of the formations as obtained from the borehole data.

Five hydrogeological units were mapped. These are characterized by an alternation between phases of dominant volcanic construction, with the emplacement of basaltic lavas, phonolite massifs and pyroclastic deposits, and phases of dominant erosion with the deposition of volcaniclastic material (colluvium, breccias, basaltic lavas and phonolite blocks and all materials resulting from slope slides) along the slopes and in the topographic depressions. It has also been possible to assign resistivity and permeability ranges to four of these units. Ranges that are also dependent on the age of the deposits: the younger the formation is, the greater its resistivity and the higher its permeability.

The hydrogeological regime is marked by the phases of volcanic construction and erosion that succeeded one another during the geological history of Mayotte over the last 10 Ma. A conceptual model adapted to the specific geological context of this island, and differing from the Canarian and Hawaiian models, is also put forward. This model is marked by the island's "fragmented" character resulting from its geological history (several volcanic edifices, several phases of construction and erosion), and is applicable to an old volcanic island in an advanced stage of erosion and weathering, with a volcanic history similar to that of Mayotte, i.e. with climate variations and erosion periods long enough to register volcaniclastic deposits.

1. Introduction

Understanding the hydrogeological regime of volcanic islands is essential if one is to ensure suitable management of their water resources and improve the population's water supply, especially where there has been a severe population increase in recent decades. Nevertheless, geological, hydrological and hydrogeological data are commonly scarce and inadequate given the geological complexity of volcanic zones.

Several methodological approaches based on (1) geological and hydrogeological reconnaissance (Ecker, 1976; Macdonald et al., 1983; Join and Coudray, 1993; Izquierdo, 2011; Izquierdo et al., 2011, 2014), (2) numerical modeling (Custodio et al., 1988; Violette et al., 1997; Join et al., 2005; Vittecoq et al., 2010), (3) geophysics (Lienert, 1991; Descloitres et al., 1997; Albouy et al., 2001; d'Ozouville et al., 2008; Auken et al., 2009; Vittecoq et al., 2011;

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http://dx.doi.org/10.1016/j.jhydrol.2013.11.062

Pryet et al., 2012), and (4) hydrochemistry (Join et al., 1997; Cruz and Silva, 2001; Cruz, 2003; Cruz and Amaral, 2004; Cruz and França, 2006; Koh et al., 2006, 2012 ; Herrera and Custodio, 2008; Gourcy et al., 2009) have been used to define the hydrogeological model of volcanic islands. For basaltic volcanic islands, results can be broken down into two main types, the Hawaiian model and the Canarian model. These models describe hydrosystems at the scale of an entire island, which is often a single edifice. More recently, Violette et al. (in press) define an evolutionary link between these two classical conceptual hydrogeological models based on Santa Cruz and San Cristobal Islands characteristics.

The Hawaiian model (Meinzer, 1930; Peterson, 1972; Macdonald et al., 1983; Tabasaki and Mink, 1983; Jackson and Lénat, 1989; Violette et al., 1997; d'Ozouville et al., 2008; Auken et al., 2009; Pryet et al., 2012) considers firstly the existence of a basal groundwater body with a low hydraulic gradient that is subject to saltwater intrusion, and secondly the presence of perched groundwater bodies conditioned by dykes and/or impervious layers (sills, ash beds, tuffs, annealed paleosoils). The Canarian model (Custodio, 1975; Custodio et al., 1988; Join and Coudray, 1993; Izuka and Gingerich, 2003; Join et al., 2005; Hagedorn et al., 2011) considers the presence of a continuous regional groundwater body whose shallow piezometric level is subparallel to topography. This model assumes that weathering processes have an influence on the progressive permeability decrease of the volcanic formations. Thus the older volcanic formations are less permeable than the more recent ones (Custodio, 2005), and permeability gradually decreases with depth ("aging effect"). The kinetics of this aging effect is complex, poorly constrained, and a function of several parameters. It can vary from a few tens of millions of years to a few thousand years, depending on the nature of the rocks and the intensity of the weathering. Mair and Fares (2011) show that a lithological difference giving a permeability contrast can lead to the same type of hydrogeological behavior.

The internal structure of the volcanic edifices nevertheless remains poorly constrained, and the operating assumptions for these models are generally based on the interpretation of indirect data. Also, most published studies (apart from those concerning the Canaries) deal with young volcanic islands that are at the most a few million years old. Very little has been published on the hydrogeological regime of old volcanic islands resulting from a multiphase volcanic activity under the influence of a wet tropical climate.

Hydrogeological studies in volcanic islands are challenging due to (1) difficulties in accessing the study sites (steep slopes, dense vegetation and a limited number of access tracks), (2) the geological complexity (lateral and vertical lithological variability with superimposed weathering), and (3) the lack of boreholes enabling detailed hydrogeological characterization, which limits detailed validation of the different approaches and methods. Such studies have so far been based mostly on a single approach or methodology each of which, within its own limitations and uncertainties, has helped improve our understanding of the hydrogeological regime of volcanic islands. The combination of these approaches enables us to simplify them and validate indirect observations (geophysics, geochemistry and satellite image analysis) with direct observations (geology, hydrology and hydrogeology).

The use of helicopter-borne geophysical methods allows one to overcome the access problems. For example, d'Ozouville et al. (2008), Auken et al. (2009) and Pryet (2011); Pryet et al. (2011, 2012) used the time-domain electromagnetic (TDEM) system SkyTEM (Sørensen and Auken, 2004) on the volcanic islands of Santa Cruz and San Cristobal in the Galapagos Archipelago. They were able to reveal resistivity variations within the first 300 m depth. However, in the absence of boreholes, the presence of buried perched aquifers could not be validated on the arid island of Santa Cruz.

In this article we study the island of Mayotte, whose volcanic activity ranges from 10 Ma to −7000 years, and propose a conceptual model for its hydrogeological regime. The proposed multidisciplinary approach is based on correlating geophysical, geological and hydrogeological data. The available data at Mayotte are both extensive for an island of this size and of good quality. In 2010, a helicopter-borne geophysical survey (SkyTEM) covered the entire island in a month with a measurement density hitherto unheard of in a volcanic environment. In addition, geological logs from 55 boreholes are available, with hydrogeological data (aquifer identification, water levels) for 52 of them plus, for 21 of them, hydrodynamic characteristics calculated from pumping tests lasting more than 12 h.

The purpose of this article is to: (i) correlate the inverted resistivities from the TDEM profiles with the nature, age and hydrodynamic properties of the formations intersected by the boreholes, (ii) characterize the structure and hydrogeological regime of Mayotte, and (iii) show the relationships between the hydrogeological regime and the phases of construction and erosion of a multiphase volcanic edifice.

2. Mayotte general context

Mayotte is an island of the Comoros Archipelago in the west of the Indian Ocean (Fig. 1). With a population that has grown fourfold in the past 30 years (212,645 inhabitants in 2012), the island is now (2012) densely populated with 570 inhabitants/km^2. Consequently, water requirements are substantial. Current production of 8.2 million m^3 per year corresponds to a consumption of about 106 l/day/capita, but with improvements in public health and living standards, plus economic development, we can expect an increase in water consumption tending, in the coming decades, towards that of the Western countries (150 l/day/capita). Surface water is tapped extensively (mainly directly from permanent rivers and with two dams, whose volumes are 1.5 and 1.95 million cubic meters) and critical situations can occur during the dry season. The groundwater resource is little used at present (15% of supply) owing to a lack of knowledge concerning the island's hydrogeological regime. Mayotte, like many volcanic islands, is difficult of access due to dense tropical vegetation and steep slopes.

2.1. Geography and climate

Mayotte is a French overseas 'département' comprising a main island (362 km^2) rising to an altitude of 660 m and known as Grande Terre, and a smaller island (12 km^2) peaking at 203 m and known as Petite Terre. Some 60% of the island's morphology consists of steep hills with an average altitude of more than 300 m and slopes higher than 15%.

The island's climate is wet tropical maritime (Lapègue, 1999) with a dry season and a wet season separated by two shorter interseasons. The wet season (austral summer) extends from December to March and is characterized by heavy rains and strong winds mainly from the north to northwest. The movement of the air masses in the intertropical convergence zone (ITCZ) can also cause tropical depressions from the northeast. The first interseason occurs during April and May, with lower rainfall and winds from the southeast. The dry season (austral winter) extends from June to September when Mayotte is subjected to regular dry cold winds from Antarctica via the Mozambique Channel separating Africa and Madagascar (to the South and Southwest). This is accompanied by a fall in temperature of 3–4 °C and rainfall. The second interseason runs from October to November with the winds again changing direction and blowing generally from the East and Northeast.