PAPER

Review: Andesitic aquifers—hydrogeological conceptual models and insights relevant to applied hydrogeology

B. Baud[1] · P. Lachassagne[1] · M. Dumont[2] · A. Toulier[3] · Heru Hendrayana[4] · Arif Fadillah[5] · N. Dorfliger[6]

Abstract

Research on the hydrogeology of andesitic volcanic aquifers in subduction areas is reviewed. Andesitic aquifers are of high interest in volcanic arc islands and subduction zones, where they constitute a strategic water resource. This review gathers a compilation of worldwide results and case studies to propose a generic hydrogeological conceptual model (GHCM). It is based on the geological conceptual model splitting the volcanic edifice, from upstream to downstream, into central, proximal, medial and distal zones. In this geological structure, the GHCM identifies where the main aquifer types (fractured lava, pyroclastic flows, and the volcano-sedimentary basins downstream) and the typical aquitards (lahars, fine pyroclastic falls and surges, indurated pyroclastic flow, and weathered rocks) are structured and organized. To integrate the evolution of volcanoes and some specific volcanic activities, a specific GHCM for old andesitic volcanoes or andesitic shield volcanoes is detailed. The paper also describes how the GHCM results are of use to hydrogeologists in terms of scale (from the lithological units to the regional scale), to effectively site water wells, and to sustainably manage groundwater resources in such aquifers. Among these various scales, the volcanic "flank continuum" is presented as the most adapted to support groundwater resources management. Several ways to improve this GHCM are suggested, notably to better consider the geological complexity of these aquifers.

Keywords Hydrodynamic properties · Pyroclastic rocks · Springs · Volcanic aquifer · Wells

Introduction

Volcanic areas constitute 7–8% of the rock exposed on the emerged Earth, and also 21–23% of the exposed crystalline rocks (Amiotte Suchet et al. 2003). In some such areas of the world, volcanic rocks are the dominant rock type (Cabrera and Custodio 2004), such as in volcanic islands. Volcanic aquifers are distributed across all kinds of climate regions, from arid to humid, equatorial and tropical to boreal, and, for instance, in oceanic islands—Indonesia, Philippines, Japan, the Caribbean, Iceland, Hawaii (USA), Canary Islands (Spain), Réunion (France), Comoros, Faroes (Denmark), etc.—or in volcanic ranges in continental settings—from Alaska in North America to Patagonia in South America, and in Russia (Fig. 1). In volcanic areas, groundwater is widely used because it is available during all seasons, and it is often abundant and of good quality. In both islands and continental areas, groundwater sustains the livelihoods of large populations, agriculture, economic activities, and ecosystems. Nevertheless, groundwater is a resource at risk, both in terms of quantity (overexploitation) and quality degradation (de Marsily 2009; de Marsily and Besbes 2017). Consequently, defining the structure and functioning of volcanic hydrogeological systems is fundamental for surveying, developing (e.g. water well siting), managing and protecting their groundwater resources.

✉ B. Baud
benjamin.baud@umontpellier.fr

[1] HSM, Univ. Montpellier, CNRS, IRD, IMT Mines Alès, Montpellier, France

[2] Geology and Geological Engineering, Colorado School of Mines, Golden, CO, USA

[3] Water Resources Research Center, University of Hawaiʻi at Mānoa, Honolulu, HI 96848, USA

[4] Geological Engineering Department, Universitas Gadjah Mada, Yogyakarta, Indonesia

[5] AQUA Danone, Jakarta, Indonesia

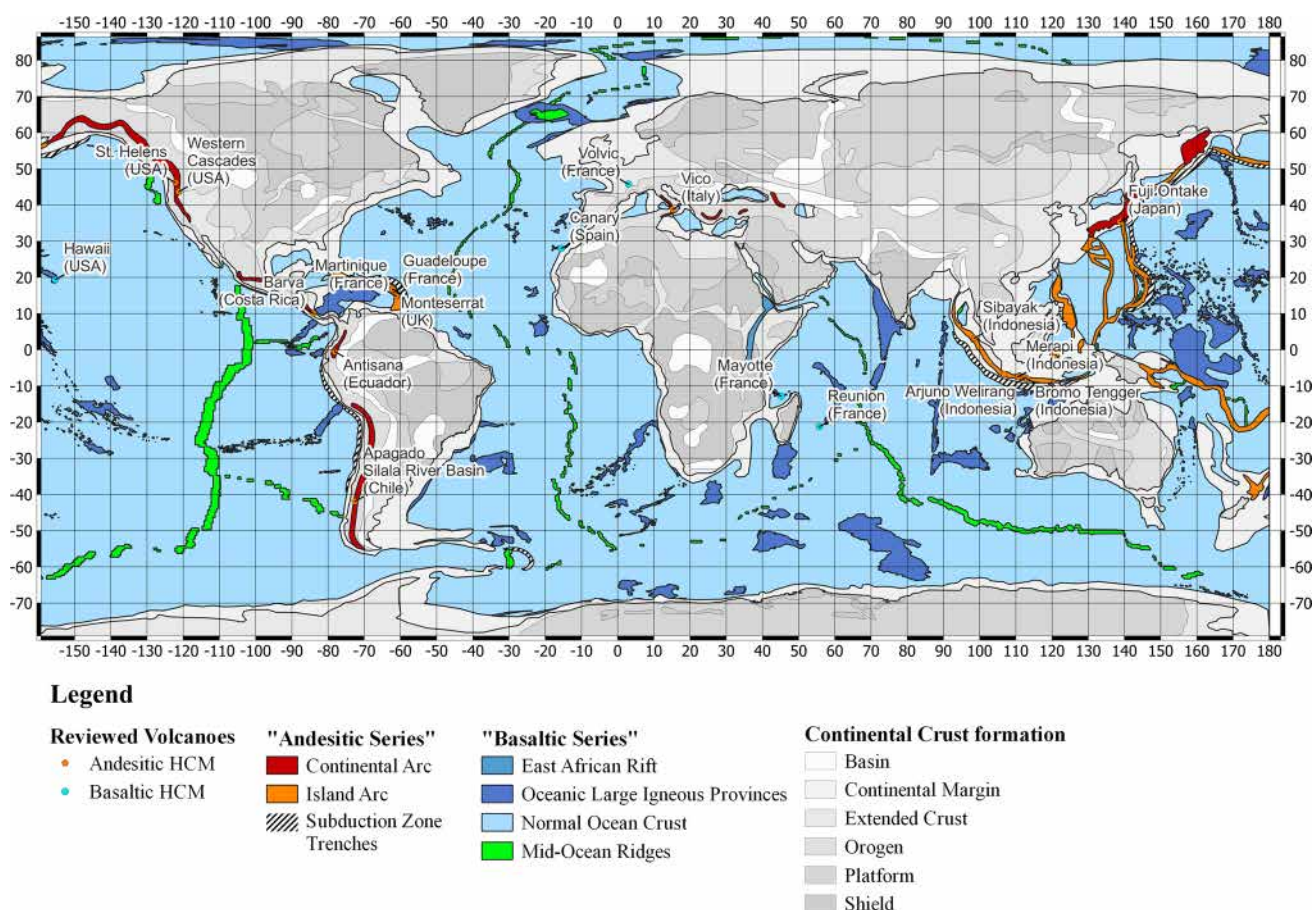[6] DANONE WATERS, Water Institute By Evian, Évian-les-Bains, France

Fig. 1 Main volcanic settings on a simplified geological map of the world. Modified after (Mooney et al. 2023). Resolution 1°×1°

Two main geodynamic contexts are at the origin of volcanic rocks on Earth (Sigurdsson et al 2015; Fig. 2):

1. Below the continental crust or oceanic plates, mantle convection gives rise to the "mantle plume" volcanic rock series, also referred as "basaltic" (e.g., Lachassagne et al. 2014).

2. In subduction areas, the partial melting of the mantle over the subducted slab gives rise to the "volcanic arc" rock series, also referred as "andesitic", from the
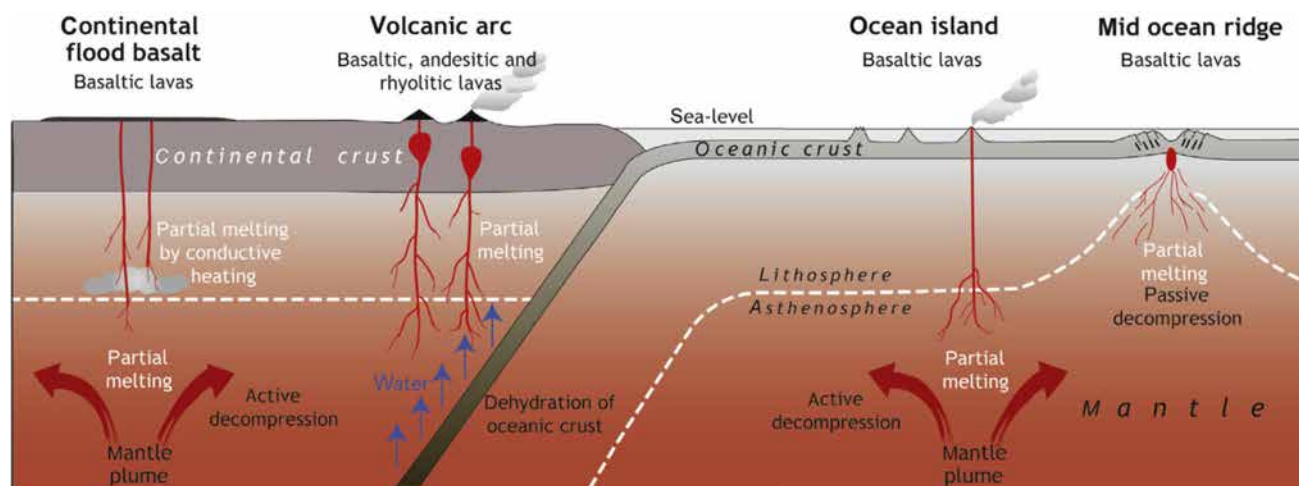

Fig. 2 Geodynamic context of the two main types of volcanism: "mantle plumes" and "volcanic arcs" (Sigurdsson et al. 2015)

"Andes" mountain range (Charlier et al. 2011; Hall et al. 2017; Vittecoq et al. 2019a, b).

The "volcanic arc" rock series represents 2–4% of the exposed rocks on Earth, against 4–5% for the "mantle plume" rock series (Amiotte Suchet et al. 2003); however, andesitic volcanic rocks are much more represented on emerged surfaces. Given the lower volumes of volcanic rocks produced during andesitic eruptions, they represent about 7/8 of all historical eruptions censed on the emerged Earth (Sigurdsson et al. 2015).

The difference between basalt and andesite is the silicon dioxide (SiO_2) content, with basalts $SiO_2 < 51\%$, andesites $SiO_2 > 51\%$, and the rocks following in their rock series as dacites ($SiO_2 > 63\%$) and rhyolites ($SiO_2 > 77\%$) according to the TAS (total alkali versus silica) classification (Gibson 2003). Basaltic lavas are fluidal, and the eruption style is generally nonexplosive to weakly explosive (Tilling 1989). Andesitic magmas are more viscous, with also a higher gas content than the basaltic, and the eruption style is therefore generally explosive (Tilling 1989). In both geodynamic contexts, basaltic and andesitic rocks can be produced depending notably on the magma differentiation (Famin et al. 2022). Both types of rocks can produce several different lithologies (lava flows, pyroclastic flows, etc.), depending of the volcanic event (effusive eruption, explosive eruption, collapse, etc.).

Basaltic aquifers have been studied and conceptualized for more than 50 years (e.g. Peterson 1972, for Hawaii), and have been the subject of continuing interest to the hydrogeological community since then. Volcano/island-scale hydrogeological conceptual models (HCMs) were developed (see section 'Hydrogeological conceptual models (HCMs): definitions') and organized into two families of models to explain the hydrogeological structure and functioning of most basaltic islands/volcanoes like Réunion, Hawaii, Canary Islands, Easter Island, Mayotte (France), Polynesia, etc. (Attias et al. 2020; Cabrera and Custodio 2004; Cruz-Fuentes et al. 2014; Custodio 2007; Gingerich and Voss 2005; Herrera and Custodio 2008; Ingebritsen and Scholl 1993; Izquierdo 2014; Izuka and Gingerich 2003; Join et al. 2005, 1997; Lachassagne et al. 2014; Paris et al. 2005; Pryet et al. 2012; Rodriguez-Gonzalez et al. 2012; Violette et al. 2014, 1997): *the Hawaiian model* (e.g. Gingerich et al. 2000) and *the Canary Islands model* (e.g. Custodio 1989). Consequently, in such a basaltic context, most published HCMs describe large hydrogeological systems, at the island/volcano scale; however, other authors have shown with higher resolution approaches (field geology, geophysics) that most basaltic volcanoes have a much more complex geological structure (Dumont et al. 2021; Izquierdo 2014; Lachassagne et al. 2014). Consequently, Lachassagne et al. (2014) show that the island-scale HCMs can hardly support a relevant framework for solving applied hydrogeology issues. Although this does not necessarily undermine the pursuit of an HCM, its relevance will be addressed and discussed in this paper.

Conversely, the hydrogeological literature on andesitic aquifers is less abundant than that for the basaltic ones, despite their growing socio-economic interest. The development of high-growth countries such as Indonesia induced a recent increase in interest in these andesitic aquifers, with research being conducted in particular in the Caribbean (e.g., Charlier et al. 2011; Lachassagne et al. 2006a; Vittecoq et al. 2019a) and in Indonesia (e.g. Selles 2014; Toulier 2019). Nevertheless, even though some attempts were made, there are yet no unanimously recognized HCMs for andesitic aquifers. In this review (see section 'Hydrogeological conceptual models of andesitic aquifers'), 17 different HCMs are listed, from the Lesser Antilles in the Caribbean (5), Indonesia (4), Ecuador (2), Japan (2), USA (2), Bolivia-Chile (1), and Costa Rica (1), and also several other sites with significant hydrogeological information in the Lesser Antilles, Sumatra (Indonesia), USA, Japan, and Italy.

Consequently, the main objectives of this research are:

1. To establish a survey to critique and synthesize the hydrogeological literature dealing with andesitic aquifers and to highlight the most relevant results
2. To propose one or more HCMs describing the structure and functioning of andesitic aquifers
3. To outline future research perspectives to fill the main knowledge gaps

After presenting the methodology used for selecting the bibliography (section 'Methodology: documentary method used for selecting the bibliography'), the paper describes the hydrogeological characteristics of andesitic lithologies. In section 'Hydrogeological conceptual models of andesitic aquifers', there is a discussion on the functioning of andesitic volcanic aquifers described as HCMs. The section first defines what is an HCM, and then it lists, critiques and synthesizes the available data on HCMs for andesitic aquifers. Finally, three generic andesitic HCMs are proposed, with recommendations for addressing applied hydrogeology stakes in such a context. The last section of the paper discusses these results and outlines future research perspectives to tackle the main challenges identified in this review.

Methodology: documentary method used for selecting the bibliography

A classical documentation method was implemented to identify references on the hydrogeology of andesitic volcanic aquifers, on their HCMs, and more largely on volcanic aquifers:

1. The co-authors of this paper have previously published on this topic and consequently had a primary database of relevant papers and books.
2. Additional (most recent) papers were extensively searched with two complementary methods on Scopus, Web of Science, and Google Scholar: (1) with selected keywords dealing with hydrogeology (volcanic, andesitic, pyroclastic, lava, hyaloclastite, lahars, conceptual model), and (2) with specific regions of the world (Caribbean/Lesser Antilles/West Indies, Indonesia, Philippines, Japan, USA, Canada, Central and Latin America countries – but excluding Brazil, Guyana, Uruguay, Paraguay, Surinam, The Andes mountain range, New Zealand, Russia). This enabled the first large database of papers.
3. These papers were read, and references out of topic (like on basaltic aquifers) or without a significant added value were removed from the list.
4. Additional (older) papers were identified from the reference lists of the papers identified at the previous steps, and the ones with the most significant content were added to the database, as well as additional references provided by the reviewers.

Some key outputs from this documentation process are worth mentioning:

1. A large amount of literature is available on volcanology, but most papers have no link to hydrogeology.
2. The published HCMs in volcanic areas mostly deal with the basaltic context.
3. Most HCMs for the andesitic context are quite recent, and lots deal with volcanic islands (Lesser Antilles, Indonesia, Japan, etc.). This was expected, as volcanic arc islands are one of the main occurrences of andesitic volcanoes. Nevertheless, some of these islands are rather large, such as Java (Indonesia, 128,000 km^2), Hokkaido (Japan, 83,000 km^2), and consequently their geological context can be very similar to that found on continents. Another explanation is linked to the fact that groundwater resources are of higher importance on islands than in the andesitic mountain ranges, such as the Andes or the Cascades, because alternative water resources are often available in mountain ranges (surface water, some being fed by snowpack or glacier, nonvolcanic rock aquifers, etc.).

Hydrogeological characteristics of andesitic rock lithologies

As for any geological context, Custodio (2007) highlights the importance of the geological structure, as a key driver of the structure and functioning of volcanic aquifers. This includes the lithology, the geometry of the lithological units and the other processes (weathering). Given the importance of this geological structure, notably in the volcanic context, this section reviews the literature dealing with the lithologies present in the andesitic volcanic context, their structure, the mode of emplacement and geometry, their hydrodynamical properties, whether they constitute aquifers or aquitards. It also describes the factors, such as weathering, that can modify these initial properties.

General properties of andesitic rocks and composite volcanoes

In the andesite type context, the higher viscosity and gas content of the magma than in the basaltic context lead to:

– Effusive events producing lava flows of generally lower extension from the effusive center, and higher thickness than for basaltic lavas (Sigurdsson et al. 2015). The typical length of lava flows is less than 15 km for andesites, dacites and trachytes (e.g. in Chile, Greece, Philippines, Alaska), whereas it can reach 50 km for basalts (e.g. in Hawaii, Italy, Iceland, Réunion, Canary Islands), with main thicknesses of 20–300 m for the former compared to 3–20 m for the latter (Sigurdsson et al. 2015). This general rule faces exceptions as some volcanoes with a low SiO$_2$ content magma are reported in the subduction context with long periods of highly effusive production, such as on the northern flank of the Bromo-Tengger, Indonesia (Toulier 2019), on the Fuji volcano, Japan (Tsuchi 2017), or the Morne Jacob shield volcano, Martinique in the French Lesser Antilles (FLA) (Germa et al. 2010).
– Very frequent explosive events in the andesitic context, due for instance to a gas overpressure linked to a lava dome at the top of the volcano, the partial or total collapse of the magmatic chamber on itself, or
– Phreatomagmatic and phreatic eruptions that produce explosive events much larger volumes of pyroclastic rocks than in the basaltic context (Sigurdsson et al. 2015).

In the andesitic context, the alternation of eruptive events and destruction events, and the migration of the effusive vents, creates highly accidented, elevated, and often sharp reliefs, also known as "composite volcanoes"/stratovolcanoes (Sigurdsson et al. 2015; Table 1). Although several basaltic volcanoes have a complex structure (e.g. Lachassagne et al. 2014), such alternation is more likely to occur in the andesitic context than in the basaltic one, creating more complex structures at the surface or buried, well documented worldwide (Table 1).

Hydrogeological properties of andesitic lithologies

The volcanic andesitic products comprise two main types of lithologies, lava flows and pyroclastic deposits, with some specificities linked notably to their emplacement mode (e.g. underwater) and/or the physical properties of the rock type (e.g. viscosity). Sigurdsson et al. (2015) distinguish these volcanic products from the epiclasts. The latter result from the remobilization or deposition of the volcanic products by water or into water. Below, all lithologies are described with a general progress from the sample/outcrop/borehole scale to the lithological unit one:

1. Description of the volcanic/geological context where such lithologies are produced
2. First assessment of whether the considered lithology constitutes aquifers, or rather semi-pervious or bodies of very low permeability (aquitards)
3. Structure of the rock, and type of hydraulic conductivity (porous, fractured), as well as other factors, such as weathering, that can modify the initial properties of the rock
4. At the scale of the lithological unit, emplacement mode of the rock

A synthesis of hydrodynamic properties is proposed in Table 2.

Lava flows

Among the volcanic lithologies, lava flows have the highest permeability (Custodio 2007; Lachassagne et al. 2014, 2006a; Selles 2014; Selles et al. 2015; Toulier 2019). Lava flows have a very low matrix primary permeability, even where they exhibit bubbles as these voids are not interconnected. Lava flows' hydrodynamic properties are therefore closely related to the conditions of their emplacement, with (Westercamp 1972) the following:

– *The presence (or not) of breccia layers (also named "autobreccia") at the top and/or bottom of the lava flow*

Table 1 Summary of morphological types among composite volcanoes (Sigurdsson et al. 2015)

Morphological Type	Description	Example	Monogenic/Composite
Simple cone	Classic "textbook" radially symmetric shape; tend to be young	Fuji (Japan), Klyuchevskoy (Kamchatka, Russia), Mount Mayon (Philippines), Osorno (southern Chile), Shishaldin (Aleutians, USA), Taranaki (New Zealand), Cotopaxi (Ecuador)	Monogenic
Shield like	Shallow-sloped flanks, common craters/calderas in the summit region, greater diversity of magmas (include evolved types such as dacite/rhyolite)	Newberry (Cascades, United States), Okmok (Aleutians, United States), Gorely (Kamchatka)	Monogenic or composite depending on the migration of the active vent
Compounds	Limited vent migration—typically resulting in an elongate ridge, more occasionally a large equant massif	Ruapehu (New Zealand), Zhupinovsjy (Kamchatka), Lascar and Irruputuncu (northern Chile), Tatara–San Pedro (southern Chile)	Monogenic or composite depending on the migration of the active vent
Twins	Distinct neighboring volcanoes, considerably closer together than average volcano spacing along an arc; typically, there is an age difference between the two edifices (a younger active and an older cone)	Avachinsky-Koryaksky (Kamchatka), Parinacota-Pomerape and San Pedro-San Pablo (northern Chile), Colima (Mexico)	Composite
Clusters	Groups of more than two distinct polygenetic edifices	Tongariro (New Zealand), Bromo (Java)	Composite
Collapse-scarred	Severe recent modification of morphology by sector collapse, resulting in large summit bowl or amphitheater	Mount St Helens (Cascades, United States), Bezymianny (Kamchatka), White Island (New Zealand)	Monogenic or composite depending of the migration of the active vent

Table 2 Lithologies: synthesis of the hydrodynamic properties

Lithology	Type of porosity	Hydrodynamic properties	Aquifer hydraulic conductivity [K] (m s^{-1})	Aquitard
Lava flows	Fractured	Aquifer/aquitard	[$2 \cdot 10^{-7}$–$1 \cdot 10^{-3}$]	-
Ignimbrite (flow + fall + surge)	Porous/fractured	Aquifer/aquitard	[$2 \cdot 10^{-7}$–$1 \cdot 10^{-2}$]	-
Epiclastites	Porous	Aquifer	-	-
Lahars	Porous	Aquitard	-	[$5.3 \cdot 10^{-8}$–$1.9 \cdot 10^{-7}$]
Dome	Fractured	Aquifer	$7 \cdot 10^{-5}$	-
Scoria cone	Porous	Aquifer	$> 10^{-6}$	-
Hyaloclastites and interstratified lava	Porous/fractured	Aquifer	$3 \cdot 10^{-4}$	-
Cooked paleosoil	Fractured locally	Aquitard	-	-
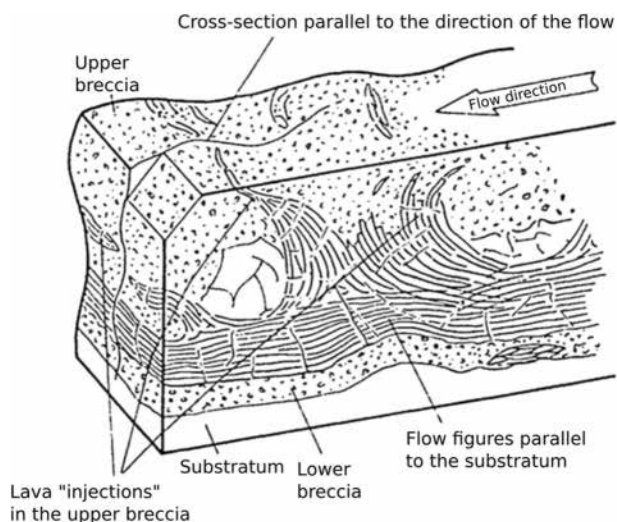
Fig. 3 Typical sketch of an andesitic lava flow from observations performed in Martinique (French Lesser Antilles) from Westercamp (1972)

that exhibits an interstices permeability. The presence and thickness of the autobreccia is controlled by the lava viscosity. Consequently, in the andesitic context, the size of the breccia blocks can be much larger, and the breccia layer thicker, than for basalts. For instance, the thickness of the breccia associated with the Madeleine lava flows (Guadeloupe, FLA) can reach several meters. The blocks are decimetric to metric, leading to a high "intergranular" porosity and give birth to several 10s of L s^{-1} flow at each spring at the end of the lava flows (Lachassagne et al. 2006a; Vittecoq et al. 2008).

– *The presence (or not) of cooling fractures within the lava flow body, which provide its fracture permeability*. Andesitic lava flows can comprise two types of cooling fractures (Lachassagne et al. 2006a): (1) classical prismatic columnar joints, as in basaltic lavas, which develop perpendicular to the cooling surface, and (2) discrete shear surfaces (Fig. 3) that develop parallel to the lava

flow lines/surfaces and are at the origin of flow figures which frequently result, after cooling, in a cracking of the rock. Their spacing gets down to the centimeter scale. Most are parallel to the paleosurface/substratum on which the lava was flowing (in the flow, near the paleosurface); some exhibit irregular complex shapes, such as a "cauliflower shape" (Westercamp 1972).

Without these structures, massive lava flows act as a local aquitard that can confine an underlying aquifer. Lava flows thus present a strong variability of their hydrodynamic properties even within the same flow with the alternance of impervious rocks (massive lava) and permeable sections, fractured or with interstitial permeability.

Because of their high viscosity, andesitic lavas cover a shorter distance than the basaltic ones while flowing and are much thicker (see also section 'General properties of andesitic rocks and composite volcanoes'). They flow along the maximum slope, filling the pre-existing valleys if any, or just cover the topography. Decametric andesitic lava flows are not rare, notably in narrow paleovalleys where their thickness can exceptionally reach a few hundred meters (Sigurdsson et al. 2015). Due to the thickness of andesitic lava flows, the number of autobreccia layers is less in the andesitic context than in the basaltic one.

As river erosion processes generally create a new incision at a place where the lithology is less competent/indurated than the newly deposited andesitic lava flow, new valleys generally dig themselves along the boundary of the previously emplaced lava flow (Sigurdsson et al. 2015). This new valley may be filled with another lava flow, and so on. It is important on the field to determine whether the river took place over a unique paleovalley filled with volcanic rocks, or if it developed at the limit between two adjacent paleovalleys. This can be detected by the observations of different lithologies on the right and left banks of the current river/valley. As aquifers are hosted in the paleovalley, is it important to locate its limit to site a borehole within the paleovalley and not at the boundary.

As for all other volcanic formations, the degree of weathering of lava flows also plays an important hydrodynamic role. In volcanic settings, the weathering or hydrothermal alteration results in partial or total transformation of their constituents (minerals, glass) into clay (notably smectites-type clays in andesitic and basaltic lavas), which obliterates, in part or totally, any permeability. The weathering of lava flows (and more generally of volcanic rocks) is faster for similar climatic conditions than for plutonic rocks (Eggleton et al. 1987; Lachassagne et al. 2021). The edge facies (breccias of the walls, roof and sides of the flow) are more likely to weather rapidly than the core of the flow due to their initial porosity and permeability. Thus, a single lithological flow can still comprise pervious levels in the fractured unweathered massive but fractured part of the lava flow, and impervious ones in the case its breccia levels were totally transformed into clay (see section 'Lesser Antilles', which describes such weathered lava flows).

Lava domes, dome-flows, screes, scoria cones

In the andesitic context, most lava domes, especially those located near the top of the volcanic edifice, are destroyed by explosions because of the gas-richness of the magma (see section 'General properties of andesitic rocks and composite volcanoes'). However, some of them, less rich in gases, can develop and even give rise to dome-flows, especially on flat slopes (e.g. caldera bottom), on gently dipping slopes, or in paleovalleys. Such domes are highly fractured, with metric to decametric scale blocks separated by large cracks that exhibit a very high hydraulic conductivity (Vittecoq et al. 2023, 2019a, b). These large cracks and blocky facies are related first to the very high viscosity of the rock, and second to cooling fractures. Vittecoq et al. (2019a, b) report hydraulic conductivity values of ~$7 \cdot 10^{-5}$ m s^{-1} in a 1 million year (Ma) old dacitic dome from Martinique (FLA).

Where the morphology of their substratum favors the concentration of groundwater flow, domes and dome-flows give birth to high hydraulic conductivity aquifers with high-discharge springs. Their discharge is proportional to the recharge rate and surface area. Such aquifers are generally of low inertia due to their high hydraulic conductivity (high diffusivity) resulting from fractures—for example, such (several tens of m^3 h^{-1}) low-stage discharge springs are flowing out from the "Piton du Carbet", Martinique (FLA) dacitic domes and dome-flows, notably around the Champflore basin, where they fill gently dipping paleovalleys and around the Pitons du Carbet dacitic domes (Lachassagne et al. 2006b).

In contrast, where the morphology and/or the high permeability of their substratum does not favor the concentration of groundwater flow, such domes and/or dome-flows do not give birth to significant discharge springs, as for example

the recent (1902, 1929) andesitic domes of the Montagne Pelée (Vittecoq et al. 2023). In this context, the piezometric level is very low, and the domes are largely or totally unsaturated (Vittecoq et al. 2023)—an example is the Soufrière volcano dome in Guadeloupe (FLA) (Lesparre et al. 2012), where, the groundwater transit time in the dome is only a few months (25 days to 3.5 months).

Such domes are surrounded by scree slopes resulting from rock falls from the dome. The scree slopes are of very high permeability, can be of significant volume, and can also extend to the foot of the steepest part of the volcanic edifice, such as at Montagne Pelée (Vittecoq et al. 2023).

Lava domes may not have been preserved, and/or have been destroyed by further explosions or eroded, in which case, the volcano's conduit may be exposed at the surface, and also the contact of the intrusive lava body and its enclosing rocks. This is notably the case of the Pitons du Carbet andesitic "domes", ~0.9 Ma (Westercamp 1972), that are surrounded by several tens of m^3 h^{-1} low-stage discharge springs. There, the intrusive lava in the palaeoconduct act as the aquifer, and the enclosing (weathered) rocks as the aquitard.

Scoria cones or strombolian cones are represented both in the basaltic and andesitic contexts. Their hydrogeological properties are notably described by (Lachassagne et al. 2014 and Rouquet et al. 2012) in the basaltic context. The easy weathering of volcanic ejecta from strombolian cones results in a rapid reduction of their hydraulic conductivity (K, below 10^{-6} m s^{-1}) after even a short (a few thousand years) exposure at the surface. This may however not be the case (slower weathering) in cold climates such as the mountainous climate of Volvic, France (Lachassagne et al. 2006a; Rouquet et al. 2012) where several thousands to tens of thousands of years old scoria cones play a capacitive role at the aquifer's scale.

Hyaloclastites

As explained in Sigurdsson et al. (2015), hyaloclastites literally means "a rock composed from glass-fragments". Such lithologies are produced during eruptions involving water (subaerial, more or less deep marine-floor, or under glaciers and lakes). Such lithologies include small glassy elements produced during explosive events (most being due to the presence of water), but also small glassy elements produced by the very fast cooling of a lava/magma that is fragmenting it. Therefore, hyaloclastites are characterized by their high glass content and the small size of their elements (mostly <1 mm), whatever the initial magma composition (basaltic to dacitic). The hyaloclastites can stay in their place of production (primary hyaloclastites) or be remobilized by gravitational processes (aerial or submarine debris flow,

current, etc.; secondary hyaloclastites). These formations are often associated with interbedded lava flows.

Hyaloclastites have a low matrix permeability (Lachassagne 2006). The presence, particularly within the primary facies, of interbedded lava flows (which means not totally brecciated lavas) and the fracturing of these lava flows (cooling fractures, pillows) can nevertheless give them the character of local aquifers (Lachassagne et al. 2006a; Vittecoq et al. 2008). In fact, one can observe, in the same hyaloclastite body, the continuum between an unbrecciated lava and secondary hyaloclastites, and even some lahars (Westercamp 1972). Some aquifers in interstratified lavas are reported in 12−14 Ma hyaloclastites in the localities of Le Marin and Le François, in Martinique (FLA) (Lachassagne et al. 2006a; Vittecoq et al. 2008). Transmissivity values up to $8 \cdot 10^{-3}$ $m^2 s^{-1}$ for a 30-m-thick screened interval are reported in Le Marin ($K \sim 3 \cdot 10^{-4}$ m s^{-1}).
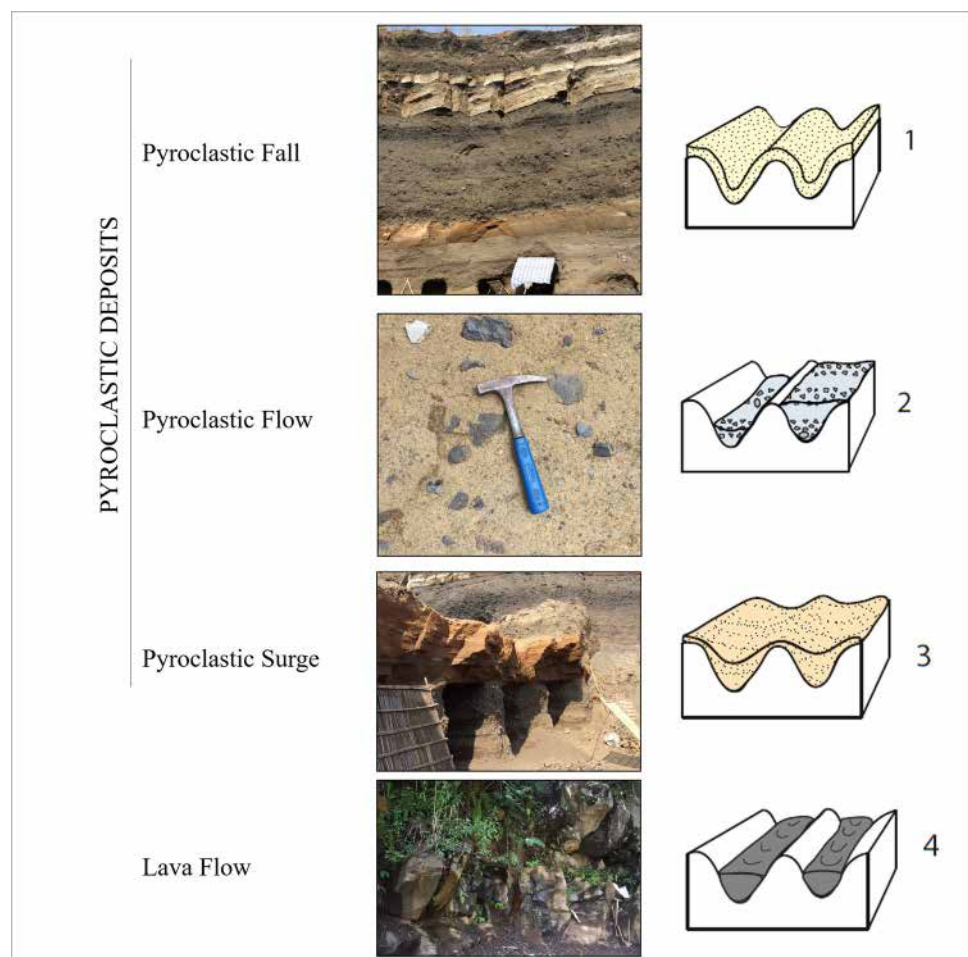
Pyroclastic materials

Pyroclastic materials are produced during explosive eruptions, regularly destructing the top of the volcano, destabilizing its flank, or even creating a large caldera (Selles 2014; Sigurdsson et al. 2015; Walker 1971). If these products are remobilized by water or deposited into water, they are considered as epiclasts (see section 'Epiclastic lithologies'). Pyroclastic materials are of tree main types (Sigurdsson et al. 2015) (Fig. 4):

– Pyroclastic falls: materials ejected into a cloud and falling down on the emerged ground
– Pyroclastic flows: materials "flowing" down the topography
– Pyroclastic surges: very hot material flowing at high speed

The vertical deposition and succession of all these deposits are called "ignimbrites" (Sigurdsson et al. 2015). Generally, from bottom to top, they comprise, for a unique eruption, (1) surge, (2) flow and (3) fall deposits. However, ignimbrites are often the result of several successive eruptions with local erosion of some levels, notably due to the surges and/or the absence of some of these main types.

Fig. 4 Summary of the facies distribution and cover on the topography from (Selles 2014). *1* pyroclastic fall, *2* pyroclastic flow, *3* pyroclastic surge, and *4* lava flows emplaced in paleovalleys

The *pyroclastic falls* are also named tephra or tuffs (Selles 2014; Sigurdsson et al. 2015; Toulier 2019). These deposits are produced during explosive or phreatomagmatic events. A large quantity of small materials is ejected into the air, covering the preexisting topography with parallel beds, good sorting, and juvenile and reworked clasts with angular shapes. This material, according to its granulometry, is sorted into ash (including sand; <2 mm), lapilli (2–64 mm), and blocs and bombs (>64 mm, angular). This type of deposit is characterized by a very strong heterogeneity and is generally not or poorly sorted. The distance to the volcanic vent may allow graded bedding. Usually, the further the deposits are, the greater the amount/proportion of fine grains, and vice versa. These deposits can have a large spreading from the volcanic vent—up to more than 20 km from the origin with a significant, at least centimetric, thickness (Selles 2014)—and its thickness is influenced by the volume of the ejected material, the grains size, the violence of the eruption, and the wind. Depending on their granulometry, sorting and, above all, degree of weathering, these products can range from a very low hydraulic conductivity to a low to medium one. Thus, they are the origin of very local aquifers, developing at the scale of a hillslope (or part of a hillslope), that give rise to low discharge (<1 L s^{-1}) springs, such as on the upper slopes of the Bromo-Tengger volcano (Toulier 2019). The internal molds of fossil trees, lying, may play the role of a natural local drain and then explain the location of these low-discharge springs, for instance in Martinique (FLA) (Lachassagne 2006; Vittecoq et al. 2008).

Pyroclastic flow extent depends on the slope, the viscosity, and the density of the material. Usually, these deposits follow the topography and fill up paleovalleys (Sigurdsson et al. 2015), if any. Pyroclastic flows are composed of angular and heterogeneous blocs, heterometric in size (from sand to pluri-metric blocks), resulting from the brecciation of preexisting rocks. Pyroclastic-flows formations have been described as major aquifers in several andesitic volcanoes in Indonesia, Bolivia and FLA (De Roever 1965; Lachassagne 2006; Peach and Taylor 2023).

The axial zones of the pyroclastic flows are poorer in fine elements (ash) and they exhibit the highest hydraulic conductivity (Lachassagne et al. 2006b). As the axial zone has also a higher thickness, it exhibits the highest transmissivity zone into such aquifers. In this axial zone, decimetric voids can increase the permeability, and can be evidenced by observations during drilling in which the drilling tool falls unexpectedly quickly, such as in Martinique (FLA). Similar "loose material" is reported in Sumatra (Indonesia) by De Roever (1965), and in Italy (Allocca et al. 2022). It is not clear whether these "voids" are contemporaneous from the deposit of the pyroclastic flows (voids in between blocks) or if they developed later, for instance due to the entrainment of fine particles

as a result of the groundwater flow, as also hypothesized by De Roever (1965). In Martinique (FLA), the synthesis proposed by (Vittecoq et al. 2008)—with pumping tests performed on 25 boreholes sited in pyroclastics, and with discharges ranging from 1 to 113 m^3 h^{-1}—shows a median transmissivity of $2 \cdot 10^{-3}$ m^2 s^{-1} and a range of 10^{-2}–10^{-4} m^2 s^{-1}.

Welded pyroclastic flows are reported (e.g., Allocca et al. 2022; Smyth and Sharp 2006) to have a dual porosity (matrix, and cooling fractures). Their matrix effective porosity is reported to be widely varying (2–60%; Foster et al. 1985), with welding leading to its decrease. The hydrodynamic properties of welded ignimbrites are then controlled by the density of cooling fractures (Allocca et al. 2022). Welded ignimbrites without cooling fractures are then considered as aquitard. In contrast, nonwelded ignimbrites would mostly owe their hydraulic conductivity to their previously described basal loose/coarse facies. Winograd (1971) and De Roever (1965) respectively describe in Sumatra, Indonesia, dozens of 10–50 L s^{-1} springs emerging from the base of the columnar jointing of welded ignimbrites, and springs and highly productive wells (several 100 m^3 h^{-1}) in similar formations in Idaho, USA.

Pyroclastic surges are mostly composed of very fine materials, transported by turbulent wind-transfer and by saltation (for the coarser elements). Such deposits are discontinuous (Fujinawa et al. 2008; Selles 2014). Due to the very thin granulometry (and possibly weathering), the deposits usually constitute low-permeability layers. The deposits have three origins (Sigurdsson et al. 2015):

– *Ground surge deposits* result from the collapse of an eruptive cone. They deposit just before, and thus under, a pyroclastic flow. They can then act as its low-permeability substrata;
– *Base surge deposits* are due to the collapse of a phreatomagmatic cone. They are thus not associated with a pyroclastic flow and are thus localized along the axis of the thalwegs.
– *Ash cloud deposits* result from the sedimentation, by gravity, of an ash cloud created by the segregation of thin material in a pyroclastic flow. The cloud can deposit independently of the pyroclastic flow or not.

The alternation of pyroclastic flows (with pervious layers, either pumice or nonvesiculated lava) with pyroclastic surges (and also pyroclastic falls) produces multilayered aquifers. On the eastern flank of Montagne Pelée (Martinique), they give rise to tens of 1–10 L s^{-1} springs, spread along the volcano's flank, and borewells tap one or several superimposed layers. Each aquifer has a transmissivity of ~10^{-3} m^2 s^{-1} for a 15-m-thick aquifer, thus with a hydraulic conductivity of ~$7 \cdot 10^{-5}$ m s^{-1} (Lachassagne 2006; Vittecoq et al. 2008).

Cooked-formations, paleosoils, weathering profiles

These formations are paleosoil or paleo tuffs/tephra, which have either been cooked by a hot material deposited above, such as a lava flow or a pyroclastic surge, or have been weathered during their exposition at the surface. Cooking and/or weathering change the mineralogy and the physical properties of the former soil/tephra, and produce a very low hydraulic conductivity layer. Its lateral extent is limited by the extent of the heat source, and the availably of a former "cookable/weatherable" formation. Its thickness can vary from a few centimeters to tens of meters in the case of well-developed weathering profiles. Such decametric weathering profiles are notably known in the central part of Martinique, FLA, within old (Miocene) lava and hyaloclastites formations (Westercamp et al. 1990). These formations are considered as aquitard.

Epiclastic lithologies

The epiclastic andesitic volcanic deposits, resulting from the remobilization of the volcanic products by water, comprise two main types of lithologies: lahars and conglomerates. Volcano-sedimentary deposits are not described in detail in this section as they are more parented to sedimentary deposits than to volcanic ones, but they are described in section 'Hydrogeological conceptual models of andesitic aquifers'.

Lahars

The term "lahar" is an Indonesian word to designate a flow composed of rocks, mud and water. Geologists characterize the lahars according to several schemes of classification (Baumann Traine 2018; Sigurdsson et al. 2015). Primary lahars are generated directly during an eruption if a large volume of water (aquifer, lake, glacier) mobilizes or remobilizes loose materials (pyroclastic flow/fall, etc.). Secondary lahars are generated by heavy rainfall remobilizing loose materials (pyroclastic falls and flows notably). They generally induce smaller volumes than the primary ones and are more frequent. Another classification is linked to the granulometry of the lahars, with a continuous evolution from debris flow constituted by big blocks (>1 m), and hyperconcentrated flows constituted by fine-grained materials (Selles 2014). Moreover, the hyperconcentrated flow is composed of 20–50% of solid materials—blocks and mud, the rest being water (at the time of their deposition)—and 50–60% of solid materials for debris flow. Depending on the topographic morphology before their deposition, these deposits can be channelized

(Ono et al. 2019) or deposited as flat sheets of several meters to tens of meters thickness (Dumont et al. 2023; Fadillah et al. 2023).

Debris flow could theoretically show good hydrodynamic properties notably in the case were the proportion of fine elements within the deposit would be very low. However, this study did not find any references describing aquifers constituted by debris flows (nor lahars) in the volcanic context; only papers on mostly risk assessment were found, or geotechnical oriented papers (Baumann Traine 2018; Lavigne et al. 2000; Pallares et al. 2015). Lahars have a high fine elements content and are systematically described as aquitards (De Roever 1965; Lachassagne 2006; Ono et al. 2019; Pallares et al. 2015). Hyperconcentrated flows are composed of nonjointing blocks in a very low permeability muddy (sandy, silty, clayey) matrix. Such deposits are described either as aquitards, as an impervious substratum to an aquifer (Ono et al. 2019), or confining an underlying aquifer (Dumont et al. 2023; Fadillah et al. 2023).

Lahars, or series of lahars, can also result from the partial collapse of the volcanic edifice, with huge blocks or even hummocks, and vertical and lateral extensions of several tens of meters, and kilometers respectively, and are named debris avalanches (Fig. 5). These formations are also reported to be impervious as a whole, constituting the impervious substratum of overlying aquifers, such as pyroclastic flows from the south-western flank of the Montagne Pelée, Martinique (FLA) (Vittecoq et al. 2023).

Conglomerates

On active volcanoes, therefore with steep slopes, theoretically the alluvium do not accumulate in great thicknesses. However, in Martinique (FLA), several significant such formations are identified with ages ranging between 15 and 1 Ma (Westercamp et al. 1990), with kilometric longitudinal and lateral extensions. Alluviums (and their conglomerates) are very prone to weathering and, notably under tropical climate, they weather fast. Consequently, they fast lose their hydraulic conductivity (Lachassagne 2006; Lachassagne et al. 2014; Vittecoq et al. 2008). In Martinique, these "old" conglomerates are thus not reported as aquifers, but as aquitards. Conversely, on the nearby island of Montserrat (Lesser Antilles, similar climate), an artesian aquifer is sited in surely rather recent, not yet weathered, "reworked gravels and alluvial deposits" (Hemmings et al. 2015b). Where unweathered, notably in temperate countries, e.g. Volvic, France (Lachassagne et al. 2006b; Rouquet et al. 2012), conglomerates (paleo-alluviums in fact) are often found at the bottom of or interstratified within paleovalleys, when rest phases allow their deposition, and can constitute local aquifers.
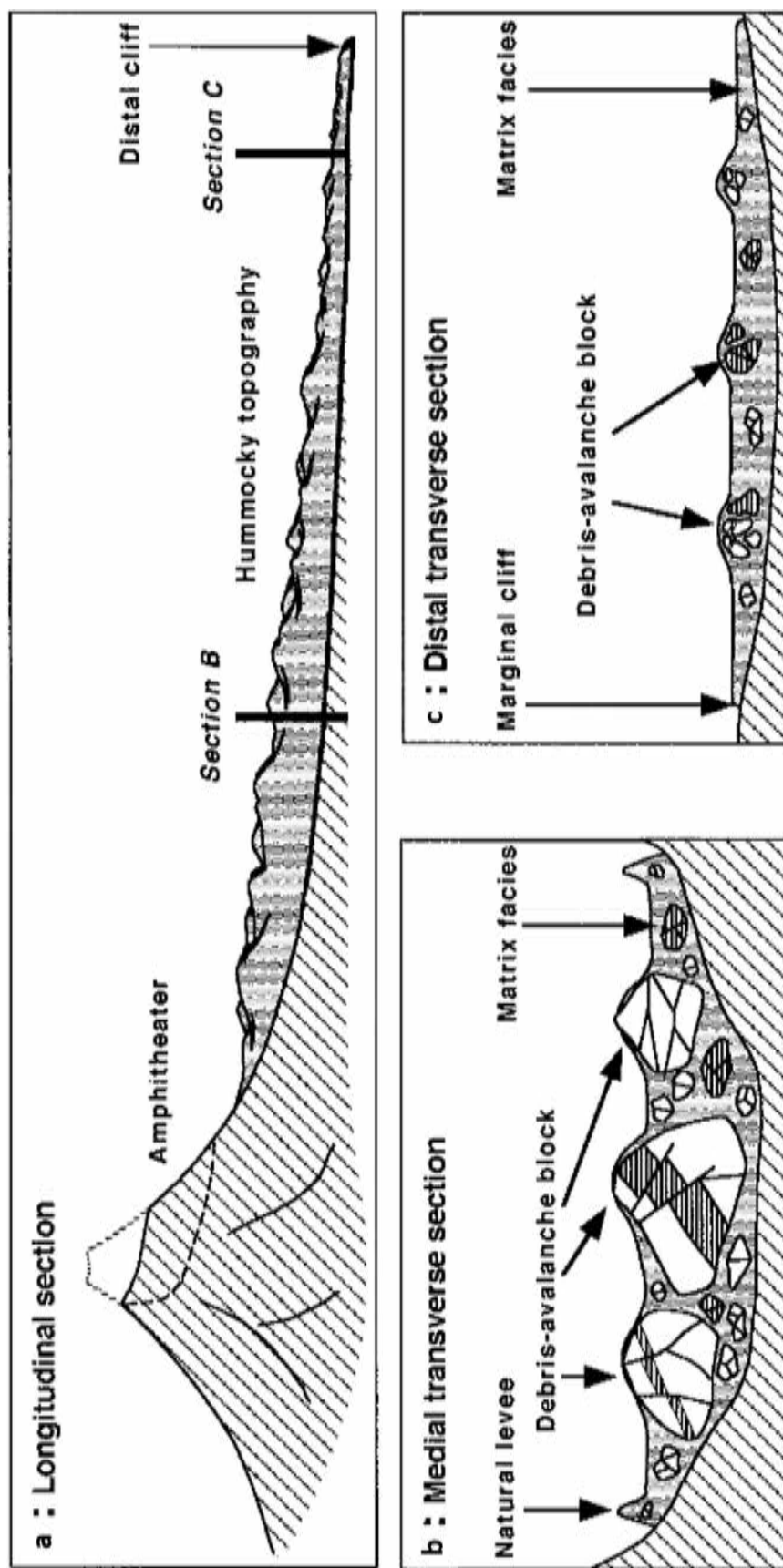
Fig. 5 Schematic cross section of a debris avalanche deposit (Sigurdsson et al. 2015): **a** longitudinal section, up to several kilometers long, **b** transverse section of the medial region, **c** transverse section for the distal region

Structural aspect: polyphased edifices

Andesitic volcano-building alternates constructive eruptive phases and dismantling events (Sigurdsson et al. 2015). The large eruption at Mt St Helens, Cascades range (USA), in 1980 (Brantley and Waitt 1988; Clynne et al. 2008; Criswell 1987; Fisher 1990; Mellors et al. 1988; Waitt 1989; Walker and McBroome 1983) is a perfect example. The volcano stood at about 3,000 m above mean sea level (masl). The entire north face of the volcanic edifice collapsed in a gigantic debris avalanche. Afterwards, a new lava dome grew inside the collapsed structure.

Such destructive events have strong implications on hydrogeological structure and functioning. This has been demonstrated in several studies, and not only on andesitic volcanoes:

– On the andesitic Merapi volcano, Indonesia, major springs are located at the foothill of the volcano, at the bottom of a massive collapsed body that is now filled up by recent deposits (Selles (2014). The groundwater is "channelized" by the paleo-valley created by the collapse event.
– Dumont et al. (2021) show a similar pattern on the basaltic Piton des Neiges volcano (Réunion, Indian Ocean). Large flank collapses are evidenced, now filled with basaltic lavas. The long lifespan of the edifice (several hundred thousand years) allowed for a buildup of such structures (now hidden), which have a strong hydrogeological impact.
– Hildenbrand et al. (2005) show similar patterns on the basaltic Tahiti Nui Island (French Polynesia), even though the important weathering of the volcano (high rainfall, old structures) does not allow the development of large productive aquifers.
– Izquierdo (2014) and Paris et al. (2005) observed the same patterns in the basaltic Canary Islands. High-discharge springs lead to hypothesize a "channelized" groundwater flow, most probably into a hidden/filled collapse structure.

The previously cited studies all demonstrate the importance of the volcano geological structure in the organization of aquifers; therefore, it is essential to reconstruct the volcanological history of the studied sites in order to identify the main construction/destruction phases. This will simplify the identification of the significant hydrogeological features.

Hydrogeological conceptual models of andesitic aquifers

Principally as regards basaltic aquifers, there is a long history to the conceptualization of volcanic aquifers (e.g. Baud et al. 2021; Custodio 2007; Dumont et al. 2023; Herrera and Custodio 2008; Izquierdo 2014; Join et al. 2005; Lachassagne et al. 2014; Selles 2014; Toulier et al. 2019; Violette et al. 1997; Vittecoq et al. 2019a, b).

Hydrogeological conceptual models (HCMs): definitions

White (2003) defines HCMs for karst aquifers:

> The conceptual model is usually physical—an interconnected sequence of recharge areas, permeability distributions, and geologic substrates that collectively provide a visualization of the way in which water is added to the system, stored in the system, transmitted through the system, and discharged from the system. […] a well-structured conceptual model should be translatable into mathematics—the physical picture replaced by a set of coupled differential equations that describe the transport processes along with the boundary conditions imposed by the geologic setting.

From a complementary methodological view, Enemark et al. (2019) define the HCM as a "collection of hypotheses describing the understanding of groundwater systems". Those authors also state that HCMs "are considered one of the major sources of uncertainty in groundwater flow and transport modelling." In the opinion of the authors of this article, an HCM also describes the current knowledge about a given hydrogeological system and it should also describe the main remaining deficits of knowledge and uncertainties. Thus, during the lifespan of a project, the HCM of a given hydrogeological system should evolve and improve. Anderson et al. (2015); Brassington and Younger (2010); Bredehoeft (2005); and Enemark et al. (2019) propose several techniques and tools to build up and validate HCMs.

For clarification, it is important to distinguish between the HCM of a given hydrogeological system, as described in the preceding, and what is defined here as the "generic hydrogeological conceptual model" (GHCM) of a given type of hydrogeological systems, such as hard-rock aquifers (see for instance Lachassagne et al. 2021, 2011), karst aquifers (Hartmann et al. 2014; Mangin 1975; White 2003), and basaltic aquifers (see section 'Introduction'). As no GHCM has yet been proposed for andesitic systems, to the authors' knowledge, the aim of this section is to identify, critique and synthesize the HCMs available for andesitic aquifers and to propose one or several GHCMs.

Existing HCMs in andesitic context

Most HCMs for andesitic areas are site-specific. Several of these HCMs rely on a geological conceptual

model inspired by Bogie and Mackenzie (1998), Riggs and Busby-Spera (1991), Smith (1988), and Vessel and Davis (1981), in which the geology is considered as the main driver of the hydrogeological structure, hydrodynamical parameters and functioning of the volcano (see section 'Hydrogeological characteristics of andesitic rock lithologies'). This geological conceptual model outlines the idealized geological facies distribution in andesitic volcanoes. Even if it is a geological conceptual model that is presented in the next section, and not a *hydro*geological conceptual model (HCM), from the outputs of section 'Hydrogeological characteristics of andesitic rock lithologies', it is already easy to identify the main aquifers and aquitards involved.

Idealized (hydro)geological facies distribution in andesitic volcanoes

The geological conceptual model of andesitic volcanoes is based on a radial (proximal to distal) lithological distribution along the volcano's slope, divided into four main zones (Fig. 6):

1. The *central zone* shows interstratified proximal pyroclastic materials, andesitic lava/domes/breccia, and intrusive rocks subject to hydrothermal alteration. As this part of the volcano is subject to frequent explosions, only small volumes of volcanic products are preserved. This zone shows primary slopes of 30° (Sigurdsson et al. 2015);

Fig. 6 **a** Lithological facies distribution in an andesitic volcano, from Sigurdsson et al. (2015); **b** Same facies distribution with the definition of central, proximal, medial, and distal zones, from Selles (2014) for Merapi Volcano, Indonesia
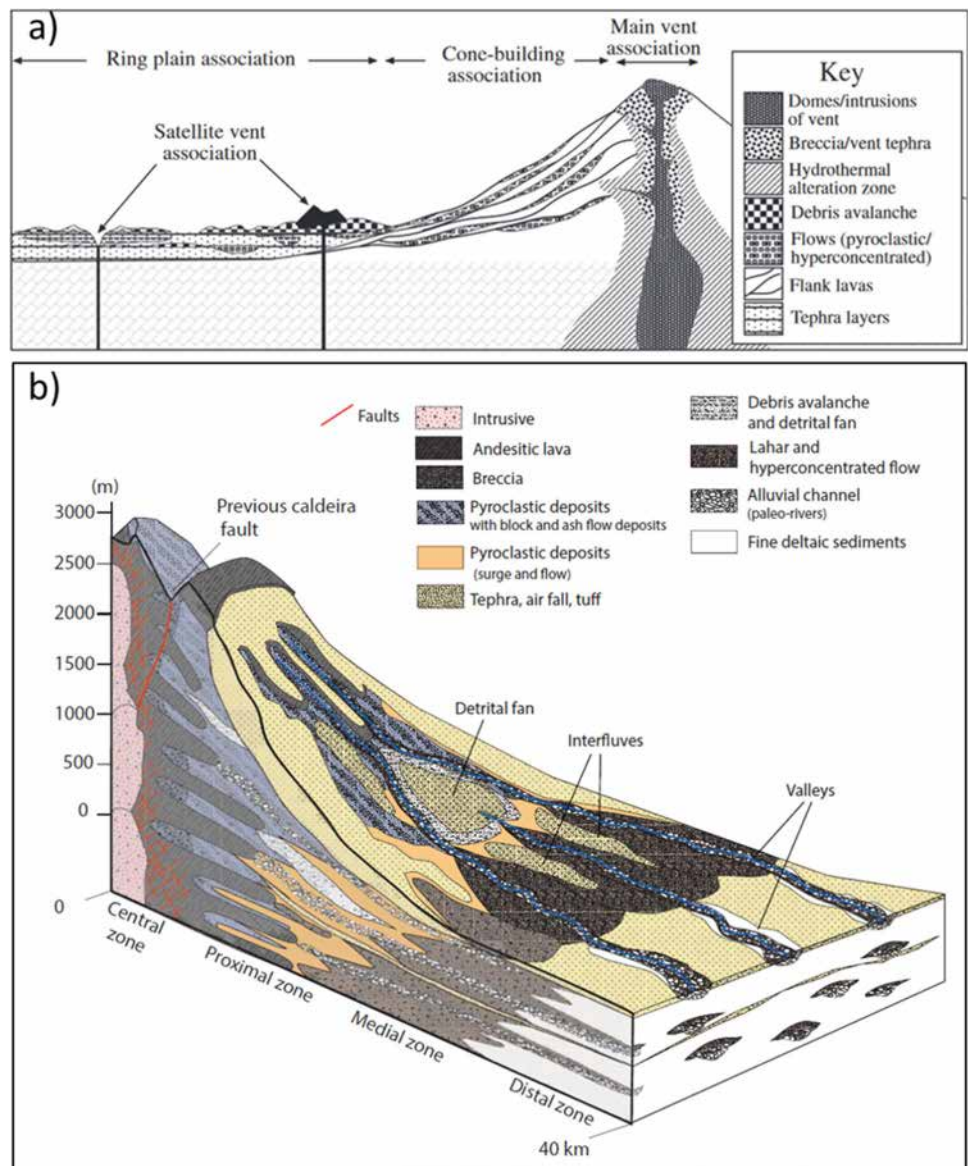
2. The *proximal zone* has slopes decreasing from 15 to ~5° (Dumont et al. 2023). The relative proportion/thickness of lava flows and ignimbrites depends on the eruptive style of the volcano. Lahars are rare in that zone as it is the origin of the materials transported by the lahars (pyroclastic falls, flows, weathered/brecciated lava, etc.), and not the lahars deposition area.

3. The *medial zone*, with slopes below 5° (Dumont et al. 2023), is primarily composed of ignimbrites, exceptional lava flows, as well as lahars deposited either in paleovalleys or, more frequently, in fans.

4. The *distal zone* is a detritic depositional area. Compared to other depositional areas (not linked to volcanoes), it is characterized by a high sediment inflow (due to the production of the volcano and its erosion) and is fed by epiclastic volcanic products.

A volcanic edifice experiences periods of volcanic activity during which volcanic products predominantly deposit in the proximal and medial zones. These periods alternate with volcanic rest periods (lasting decades to centuries, or more) during which erosion processes dominate and dig valleys in the proximal and the medial zones, and the distal zone to a lesser extent, notably by regressive erosion. The eroded products accumulate in the distal zone. Due to the volcano's growth, these zones progressively migrate downwards (laterally). The volcano can also be subject to partial/flank collapses that totally rework such a volcanic succession (see section 'Structural aspect: polyphased edifices').

The Merapi, Central Java, Indonesia

Selles (2014) proposes a HCM for the eastern flank of the Merapi volcano, central Java, Indonesia. This HCM is multilayered and divided into three parts. The upper part, above 800 masl, is constituted by small perched pyroclastic aquifers outflowing into temporary rivers, and reinfiltrating/reemerging there due to the alternation of impervious (pyroclastic surges) and pervious (pyroclastic flows) layers. Selles (2014) suggests, notably from groundwater temperature and isotopic data, that this elevation range (from 1,200 to 800 masl) supplies water to these perched aquifers but, above all, it also recharges deeper aquifers, notably the two main aquifers, giving birth to two "spring belts" (SB, Fig. 7). The SB1 spring belt ranges from 800 to 400 masl and is constituted by a large detritic fan, which disturbs the surface drainage network radial alignment. Selles (2014) considers that this fan lies on several paleo river channels, and is a recharge area supplying SB1 at the downstream extremity of the fan. The aquifer is semiconfined and shallow, limited to the extent of the detritic fan. The author suggests also deep infiltration below this detritic fan, supplying the aquifer that gives rise to the SB2 spring belt. SB2 ranges from 200 to 283 masl and, given the springs' discharge (up to several 100 L s^{-1}), is the main spring belt. The author suggests that their location is driven by a fault (Opak fault), perpendicular to the main slope of the edifice. The contributing recharge area would be 37–50% from an elevation ~1,200 masl, and 63–50% from the 800–400 masl recharge zone located under the fan. SB2 does not represent 100% of the total discharge of the aquifers, as a multilayered pyroclastic system is also present downstream. Selles (2014) considers that alluvial paleochannels (Fig. 7) are continuous and then extend from the proximal to the distal zone, and may play a major hydrogeological role. This point may be disputed, notably as such a geological continuity was not demonstrated in the previously cited existing geological conceptual models.

The Salak and the Arjuno-Welirang, West and East Java, Indonesia

This upstream–downstream geological conceptual model was also used to describe several Indonesian andesitic volcanic aquifers. Dumont et al. (2023) well characterized a medial-to-proximal zone aquifer system in West Java (Indonesia) by a multidisciplinary approach: field geology, geophysics, location, springs' discharge and hydrochemistry (major ions and stable isotopes), lumped modeling of the aquifer's discharge, etc. The aquifer consists of more than 50-m thick pyroclastic breccias, probably pyroclastic flows, produced by the Salak Volcano, overlain and confined in the lower part of the study area by 30–50-m-thick laharic deposits. The substratum of the aquifer is unknown: it was not reached either by drillings, or by geophysical measurements whose depth of investigation is ~130 m maximum. The aquifer is ~3 km wide (perpendicular to the main slope), and ~5–6 km long. In the lowest part of the study area, several 15–30 L s^{-1} artesian springs outflow at an elevation of ~450 masl. The total artesian aquifer discharge varies yearly between 150 and 190 L s^{-1}. The springs' outlets are located in recent valleys, where the thickness of the laharic cover was reduced by the rivers' incisions to less than 30 m, and only 200–300 m upstream of the termination of the aquifer, below the impervious cover. There, the laharic cover joins an underlying a priori impervious lithological body, and consequently the aquifer disappears where the pyroclastic layer ends. The recharge surface area is ~17 km^2 and is centered from the isotopic data around a mean elevation of ~800 masl. The authors interpret from the geophysical measurements that the pyroclastic aquifer is recharged where it outcrops, at elevations above 700 masl (above where the laharic cover ends) and consequently does not prevent diffuse infiltration or localized recharge from rivers. The pyroclastic aquifer may also be fed by groundwater inflows from the lava
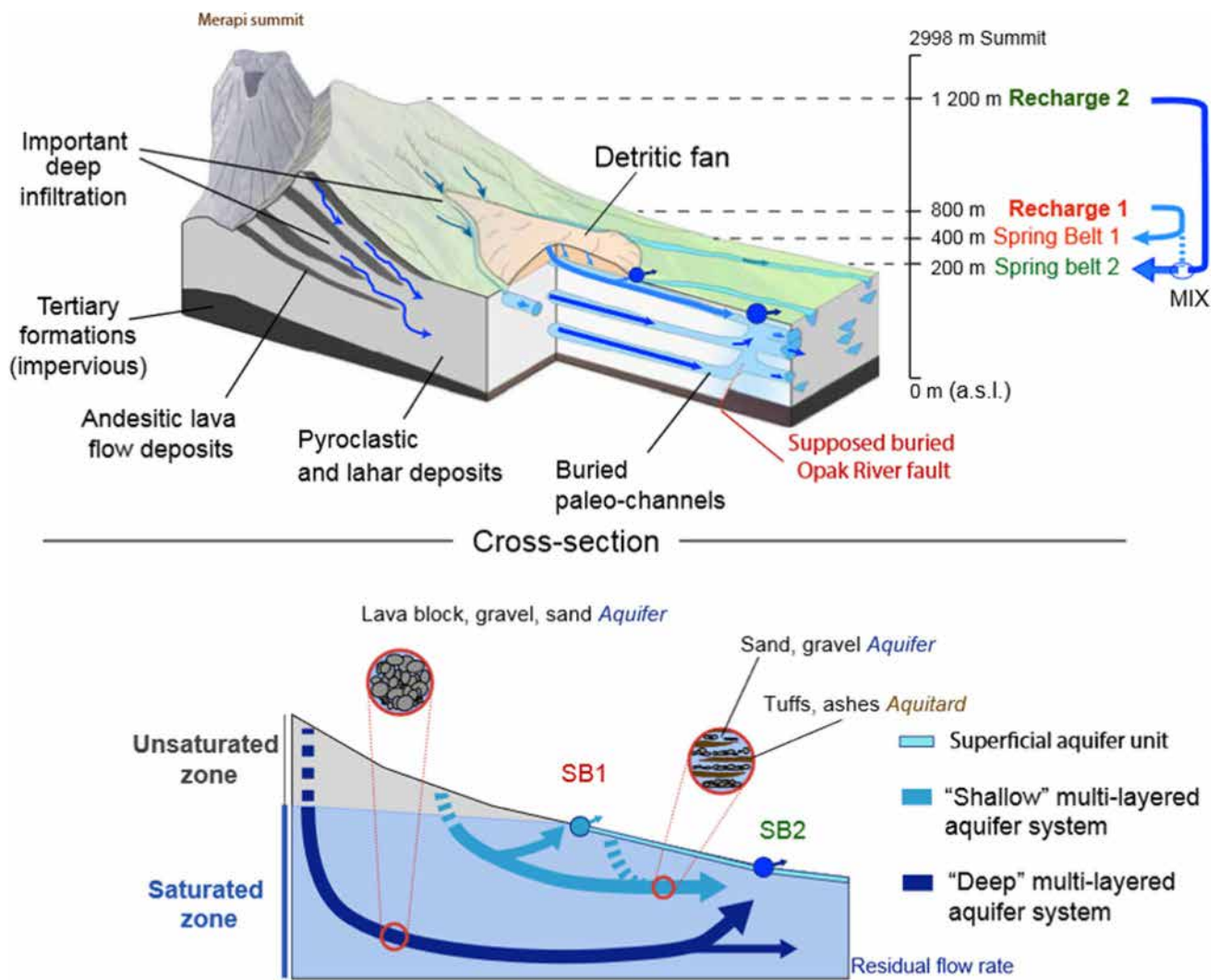
Fig. 7 Hydrogeological conceptual model of the eastern flank of the Merapi volcano, Indonesia (Selles 2014)

flows that outcrop at elevations above 820 masl as well as by the infiltration of surface water from rivers (also at elevations above 700 masl). Thus, this research characterizes in detail such a medial-to-proximal zones pyroclastic aquifer system, and proposes a very consistent and robust local HCM.

Baud et al. (2021) and Fadillah et al. (2023) used the same geological conceptual model to propose the first versions of a HCM for the Arjuno-Welirang volcanic complex (East Java, Indonesia). They divided the hydro-systems into medial-to-proximal zones aquifer systems from geological, hydrogeological and geophysical measurements. Again, recent surface lahars cover volcaniclastic deposits (pyroclastic falls and flows, some alluviums, etc.), interstratified with andesitic lava flows in the upstream part of the aquifer system. The main difference with the HCM from Dumont et al. (2023) is that this aquifer system comprises several

springs at various elevations, suggesting juxtaposed and/or superimposed aquifers.

The Bromo-Tengger, Indonesia

The HCM of Toulier et al. (2019) addresses the Northern Flank of the Bromo-Tengger volcano, Java Island, Indonesia (Fig. 8). This HCM is complete thanks to the implementation of a multidisciplinary approach: geological, geophysical, hydrodynamic, hydrogeochemical (major ions and stable isotopes of the water) data, as well as numerical modelling described in Toulier (2019). This HCM integrates the geological and hydrogeological structure of the volcanic edifice, the hydrodynamic parameters of the aquifers, the location of the recharge area, its elevation, a quantification of the recharge, the pathways of groundwater, its relationships with surface water, and the
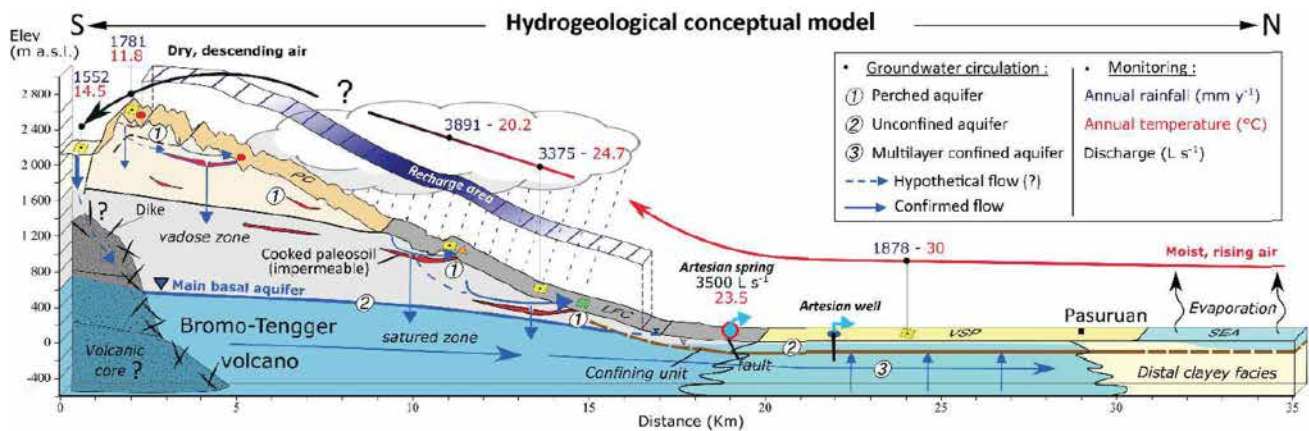
Fig. 8 A hydrogeological conceptual model of Bromo Tengger, Indonesia (Toulier et al. 2019)

location and quantification of the discharge areas (springs and borewells). Two main points are worth highlighting from this HCM (Fig. 8):

– Unexpectedly in the andesitic context, the northern side of the Bromo-Tengger region consists of the accumulation of high-permeability andesitic to basaltic lava flows (from 822 to 152 ka), with a total thickness of ~2 km (Mulyadi 1992; Toulier 2019). In this unit, the piezometric gradient is very low, and, consequently, the vadose zone is very thick (low-lying basal aquifer). Perched aquifers are few and linked to a few local impervious layers intercalated in the lavas' series. With the exception of the proximal area of the current active volcanic vent, which is covered by a thick pyroclastic unit, the northern flank of the Bromo-Tengger looks like a "classic" basaltic shield volcano (Fig. 8). The Bromo-Tengger northern flank has similarities with Hawaiian volcanoes (e.g. Mont Haleakala, in Maui), with the typical low-lying basal aquifer, but without the dyke impounded perched aquifers. Consequently, the previously described proximal-to-medial zones model does not apply to this slope of the Bromo-Tengger edifice. Toulier et al. (2019) show that the aquifer recharge occurs on most of the northern flank of the Bromo-Tengger; its pattern (Fig. 8) is mostly driven by the effective rainfall distribution that peaks at elevation ~1,000–1,200 masl.

– The Bromo-Tengger HCM comprises a volcano-sedimentary plain, which can be assimilated to the distal zone of the previously described HCMs, connected to the upstream volcanic formations. This plain is mainly formed by remobilized volcanic materials (lahars, pyroclastics, tephras, etc.) reworked into sandy sediments including alluvium. Under a low-permeability layer at the subsurface, the sandy sediments constitute an at least 200-m-thick confined aquifer, with transmissiv-

ity ranging between $1 \cdot 10^{-4}$ and $4 \cdot 10^{-4}$ m^2 s^{-1} (Toulier et al. 2022). For most oceanic island basaltic shield volcanoes, such volcano-sedimentary units are located far offshore (or deep below the current edifice), the volcano having grown on a several-kilometers-deep ocean floor and being potentially submitted to subsidence processes (note however that the Honolulu, Hawaii, volcano-sedimentary plain is located on-shore; (Nichols et al. 1996)). In contrast, most andesitic volcanoes grew on an older substratum that was either emerged (for instance in mountain ranges) or at shallow depth at the beginning of the edification of the volcano. On the northern flank of the Bromo-Tengger, as the volcanic aquifer's unsaturated zone is very thick, this aquifer is not drilled. Indeed, it would be very costly and technically difficult to reach this aquifer (and also costly to pump it). Also, as the wells drilled in the volcano-sedimentary aquifer are free flowing (artesian), this volcano-sedimentary aquifer is the main locally used aquifer. This high-quality groundwater is used for various purposes (agriculture, potable water, industries), with more than 600 productive free-flowing already drilled wells with a median discharge of ~4.1 L s^{-1}. Consequently, the discharge of the natural springs (Fig. 8) is strongly decreasing proportionally to the discharge of the newly drilled wells. These high-discharge springs (up to 4 m^3 s^{-1}), recharged at high elevation, have the particularity to exhibit a much lower than normal temperature (~23 °C where 27–28 °C would be expected). Such a feature is also observed in lava flow aquifers from the Cascades Range (USA; Jefferson et al. 2006; Manga 1998).

It is also worth highlighting that numerous major springs (with discharges up to 4 m^3 s^{-1}) outflow all around the Semeru-Tengger complex, at the foothill of this relief, and not only on its northern flank (Toulier 2019). The

Semeru-Tengger complex, with a diameter of ~50 km, comprises the Bromo-Tengger in its northern part, and the Semeru edifice in its southern part. The locations and hydrogeochemistry of these springs show that they outflow from aquifers that are not connected to the Bromo-Tengger northern flank HCM. These other aquifers certainly have a different structure and functioning than those on the Bromo-Tengger northern flank. Therefore, this last HCM is representative only of this specific studied area, not of the entire Tengger-Semeru volcanic complex, which belongs to other geological structures, and consequently to other HCMs.

Japan

Aoki et al. (2019) synthesized the geological knowledge about the Mount Fuji volcano, Japan, known as the water mountain (Schilling et al. 2023). The Mt. Fuji volcano represents a huge groundwater reservoir that sustains the livelihoods of a large area, including the Japan capital, Tokyo, located 100 km to the east. As for the Bromo-Tengger in Indonesia, the Fuji is a composite volcano, with low SiO_2 content products in its last stage of activity. The first stage of activity built up the Komitake volcano (>270–100 ka), which has a basaltic-andesitic to dacitic edifice (Yoshimoto et al. 2010). The second stage of activity built up the Older Fuji, or Ko-Fuji (100–10 ka), and the Younger Fuji, or Shin-Fuji (10 ka to present); this second stage of activity covered the Komitake Volcano (Fig. 9). The lavas from this second stage are 50–52 wt% SiO_2; they are thus mostly basaltic. During the last century, the Mt. Fuji HCM has been developed and improved from the first one built by Kambara (1929; cited in Yasuhara et al. 2020) to render the current one (Adikari 2015; Ono et al. 2019; Schilling et al. 2023; Tsuchi 2017; Yasuhara et al. 2020).

Several aquifers have been characterized within the Young Fuji, predominantly within lava flows (Schilling et al. 2023). Schilling et al. (2023) use a multidisciplinary approach combined with unconventional tracers (microbial environmental DNA, vanadium and helium, along with the classical stable isotopes of the water, noble gas, and major ions analysis) to highlight deep transfers. The recharge occurs mainly at high elevation, partly through snow melt. It is estimated that 90% of the precipitation there (average 2,500 mm year^{-1}) contributes to the recharge (Schilling et al. 2023); it is however probable that this percentage refers to effective rainfall (rainfall minus evapotranspiration) and not to rainfall, as Toulier et al. (2019) obtained the same order of magnitude on Bromo-Tengger (90%); however, that was based on effective rainfall, not on rainfall, and it is noted that less than 10% evapotranspiration is a very low amount. This water infiltrates and flows within the Young Fuji deposits. Part of it flows through the Older Fuji (Ko-Fuji) formations too, and then flows up, back to the Younger Fuji aquifer in the lowest part of the volcanic edifice in the Suruga Bay area, south west of the volcano (Fig. 9). Another part of the groundwater body, especially the one from the Older Fuji aquifer, outflows directly into the five Fuji lakes (north of the volcano) and into the Suruga Bay. The groundwater outflows 15–40 years after rainfall infiltration (Schilling et al. 2023). Schilling et al. (2023) also showed that groundwater is flowing through the Misaka-Tenshu mountain range (the bedrock of the Fuji complex), contributing there to sustaining the local shallow aquifers. The deep and shallow groundwater mixing and outflowing is related to the impervious Fujikawa Kako Fault System (Schilling et al. 2023). Also, as in all coastal contexts, close to the coast, high Cl, Na, and SO_4 content in groundwater highlights seawater intrusion.
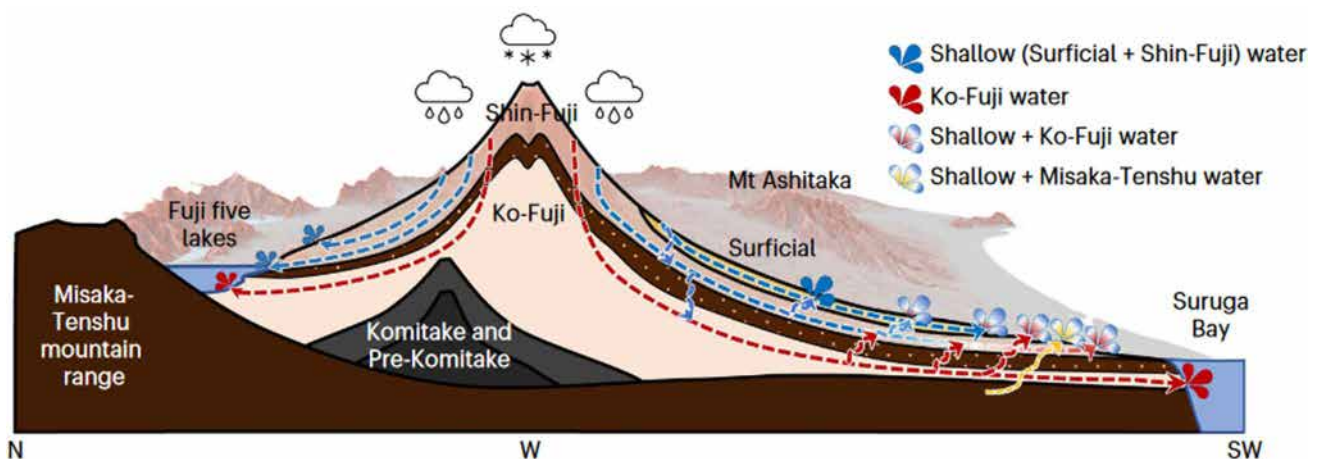

Fig. 9 A hydrogeological conceptual model of Mt. Fuji, Japan, from Schilling et al. (2023)

This recent study from Schilling et al. (2023) confirms vertical exchanges between aquifers in such an edifice, downwards near the top of the volcano, and upwards at its foot, and confirms a rather simple HCM for this volcano. The resulting general scheme (Fig. 9) is much more complex when one gets down to the lithological units scale (e.g. Ono et al. 2019), for instance, to explain the locations of springs and hydrogeochemical variations from one borewell to another.

Asai et al. (2009) note, on the Ontake stratovolcano (central Japan), that most high-discharge springs (>50 L s^{-1}) outflow from the "inner or lower parts of andesite lava flows". They also propose schematic representations of groundwater flow directions, and recharge elevation and relationships between the age (the youngest) of parts of the volcano and springs discharge (the highest), but give no comprehensive HCM of the volcano.

Lesser Antilles

Charlier et al. (2011) proposed a multidisciplinary approach to characterize a watershed (Féfé) in Guadeloupe Island (FLA), using fine-scale field geological characterization, piezometric data, pumping tests, and hydrochemistry (major ions and trace elements). Their HCM highlights two superimposed aquifers. The subsurface aquifer is in "lapilli" (surely pyroclastic falls), of low hydraulic conductivity (10^{-5} m s^{-1}), above a less permeable surge (10^{-6} m s^{-1}). Below this surge, the second aquifer is a succession of fractured lava flows and surges or falls ($5 \cdot 10^{-4}$ to $2 \cdot 10^{-3}$ m s^{-1}),

for which the low-K substratum is a "weathered breccia" (10^{-7} m s^{-1}). This study also highlights, as with Rouquet et al. (2012) in a basaltic setting, the hydrogeological role of paleovalleys. The paleovalleys system (Charlier et al. 2011) was incised during a period with no, or low, volcanic activity, and was then filled up by the lavas and surges during a period of high volcanic activity.

Hemmings et al. (2015a) propose a case study about the island of Montserrat (LA) that had the particularity, at the date of the writing of their paper, to undergo an eruption in progress for 15 years. They mostly propose a dataset about this island, including groundwater recharge estimates, and try to apply the Canary Islands' and the Hawaiian HCMs to explain spring locations and alluvial artesian coastal aquifers from the "Centre Hills" of the island. This HCM for Montserrat was refined from water dating and stable isotope studies (Hemmings et al. 2015b). It shows contrasted hydrogeological behaviors between the "Centre Hills" of the island, with rapid recharge through high-permeability fractured and jointed dome lavas, breccia and screes, and older (~45 years old) groundwaters in peripheral low-elevation pyroclastic flows and epiclastic aquifers.

Based on a heliborne time domain electro magnetic (TDEM) survey calibrated on 51 boreholes and 24 springs, Vittecoq et al. (2019a) aim at providing a HCM of andesitic aquifers from the western-central part of the Martinique island (FLA). Compared to other andesitic areas, the geology of this area is old. The volcanoes have not been active for a million years, and are weathered and dissected by erosion. The area comprises, from bottom to top (Fig. 10):

Fig. 10 A hydrogeological conceptual model of the northwestern part of the Martinique island (FLA) (Vittecoq et al. 2019a, b). Note that the compartmentation of the aquifers, as well as the sharing between the saturated and unsaturated zones, is very schematic and not consistent with the springs' locations
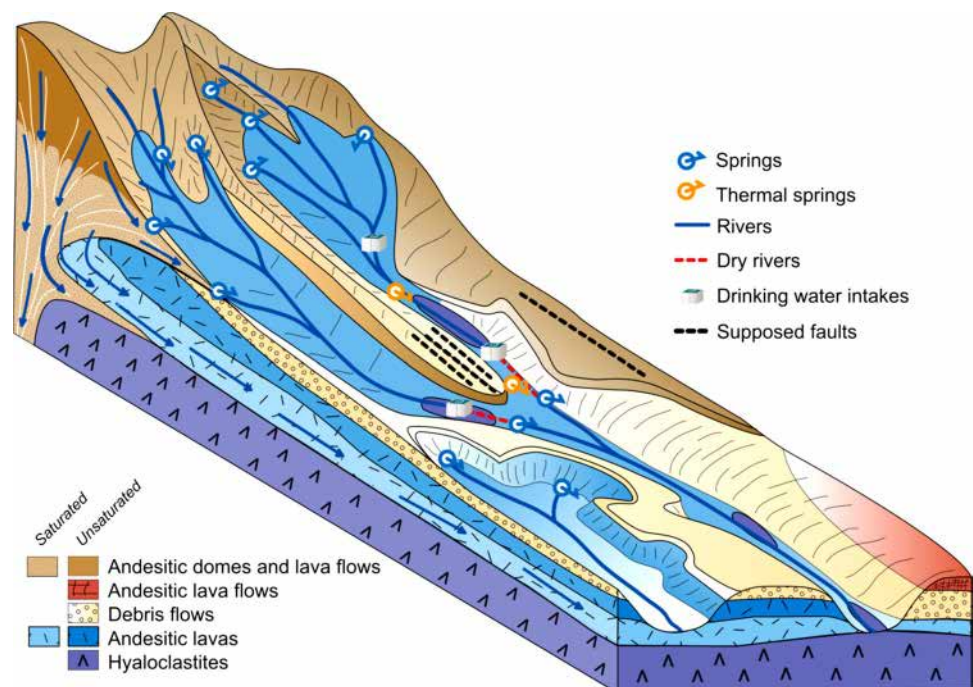
(1) the "Morne Jacob" shield volcano (Germa et al. 2010), emplaced between 5.5 and 2.2 Ma, and constituted by a hyaloclastite substratum covered by a several-hundred-meters to ~1,000-m-thick basaltic to andesitic lava flows series, weathered and eroded, and (2) the "Pitons du Carbet" volcanic series, emplaced between 2.1 and 0.3 Ma, and comprising an alternation of pumice and pyroclastic flows, and andesitic lava flows, as well as conglomerates, and lahars, resulting from the remobilization of the primary products. The "Pitons du Carbet" volcanic series now appears as largely eroded domes in its central upstream area (from the last volcanic phase, 0.3–0.9 Ma), and, downstream, as up to 3-km large paleovalleys filled with all the previously described "Pitons du Carbet" products. These paleovalleys are deeply eroded, and most of them show inverted reliefs.

All piezometric level measurements show shallow piezometric levels (Vittecoq et al. 2019a, b). Consequently, and unlike the recent Bromo-Tengger shield volcano (Toulier 2019; Toulier et al. 2019), the older "Morne Jacob" shield volcano does not constitute a large and unique aquifer. The hydraulic conductivity of its lavas is highly variable spatially and vertically (from less than $2 \cdot 10^{-7}$ to $3 \cdot 10^{-5}$ m s^{-1}; Vittecoq et al. 2019a, b), and the highest values are about one order of magnitude lower than the highest values reported for lavas ($5 \cdot 10^{-4}$ m s^{-1}). This overall lower hydraulic conductivity and high spatial variability explain the absence of a large uniform aquifer in this area. The groundwater is divided into small (a few to several hundred meters in extension) compartmented aquifers within this old shield volcano. This spatial variability is mostly due to the partial weathering of the lava flows, as well as both (1) the internal structure of the lava flows (see section 'Lava Flows'), and (2) the superposition of such lava flows with variably permeable levels. As a result, the "Morne Jacob" shield volcano hosts numerous low-extension aquifers that give rise to several low-discharge springs—several 0.1 L s^{-1} to several (max) 1 L s^{-1} scale discharges—and borewells with, at max, 1–3 L s^{-1} long-term discharge; their instantaneous discharge can reach 10–30 L s^{-1}, but it cannot be sustained due to the low extension of the aquifers. The deepest of these aquifers are surely badly connected to the surface and thus are poorly recharged.

The underlying hyaloclastites are considered by Vittecoq et al. (2019a) as a regional aquitard, partly due to their weathering, but also as a consequence of their low intrinsic porosity and hydraulic conductivity (see section 'Hyaloclastites'). (Vittecoq et al. 2019a, b) show that the andesitic "domes" exhibit a high recharge rate (~85% of the effective rainfall) and have a high hydraulic conductivity. They also suggest, without water balance validation, that part of their groundwater may also seep at depth and recharge the nearby peripheral aquifers. Since they show significant overflow springs and the piezometric level of nearby peripheral

aquifers is high, these leaks, if any, may be minor compared to the overflow.

Thus, with the exception of the rather recent andesitic "domes", the study from Vittecoq et al. (2019a, b) of quite old lavas and pyroclastics only shows local-scale aquifers, due to the weathering and small extension of the lithological formations. This HCM is consistent with previous HCMs of old basaltic volcanoes from Lachassagne et al. (2014) demonstrating the importance of volcanic rock weathering on groundwater behavior. However, Vittecoq et al. (2019a, b) do not provide large-scale HCMs at the scale of the "Morne Jacob" or "Pitons du Carbet" volcanic edifices, nor at the scale of part of these edifices, with the exception possibly of the "domes".

A similar pattern to that observed for the "Morne Jacob" shield volcano is evidenced in other areas of Martinique, notably in the 4–19 Ma andesites, basalts, and hyaloclastites in a flat graben-type plain from central Martinique (Vittecoq et al. 2015). This study also combines a heliborne geophysical survey constrained by hydrogeological data from 30 boreholes and long-duration pumping tests. Vittecoq et al. (2015) show that these old lava formations host, at depths between 30 and ~150 m, compartmented confined aquifers. Through the pumping tests, they characterize two close compartments, ~1–1.5 km^2 each, one with a transmissivity in the range of 4–$8 \cdot 10^{-3}$ m^2 s^{-1} and the second in the 3–$9 \cdot 10^{-4}$ m^2 s^{-1} range—for well-screen lengths of 15–30 m; (Lachassagne et al. 2006a). The two aquifers are hosted by 15 Ma basalts (the "Vert Pré" basalts) known in all central Martinique for their rather high hydraulic conductivity due to flow cooling fractures and breccias at the base of the flows. The compartmentalization of the aquifer seems to be induced by the two families of faults that shape the graben, although the resolution of the geophysical data does not allow one to exclude the influence of the geometry of the different lithological units. Both hypotheses may also be combined. As these aquifers are covered with aquitards and are not connected to other aquifers, the leakage to the pumped borewells is limited, restricting groundwater abstraction to ~10 L s^{-1} in each compartment.

This research was mainly focused on the aquifers' geological structure, and not much on their functioning—shape of groundwater flow, recharge and discharge zones, etc. (see Fig. 13 in Vittecoq et al. 2015). It however shows that lavas of several million years in age can still comprise pervious compartments, enabling groundwater abstraction. This study and the one dealing with the "Morne Jacob" shield volcano (Vittecoq et al. 2019a, b) also show that aquifers in such rather old lava formations are highly compartmented and of an extension limited to specific lithological units (with areas of ~1 km^2 at max), eventually bounded by faults.

The Vittecoq et al. (2023) work, dealing with the Montagne Pelée (FLA) active volcano, is based notably on the

results of a heliborne geophysical survey. It provides valuable information on the hydrogeological properties of some andesitic lithologies (lava domes and their screes, pyroclastic flows, debris avalanches). Vittecoq et al. (2023) also provide a HCM at the volcano scale. Their approach is based on the geological conceptual model presented in section 'Idealized (hydro)geological facies distribution in andesitic volcanoes'. It describes the central to medial zones of the volcanic edifice. Their approach is intermediate, between a low-resolution approach, that would encompass the volcano as a whole, and a high-resolution one that would propose the precise mapping of the aquifers/aquitards. They illustrate the emerging context of springs peripheral to the summital lava domes, and describe the structural hydrogeological asymmetry between the eastern and southwestern flanks of the volcano. The latter has been subjected to several flank collapses, which reworked formations acting as the impervious substratum of the overlying recent pyroclastic flows aquifer. On the eastern flank of the volcano, small perched aquifers are hosted within pyroclastic deposits. They are lying above a second pyroclastic aquifer named the "basal aquifer" in its northern part, where it is mainly flowing to the sea. In its southern part, it is drained by deeply incised rivers that locally reach the low-K substratum of the Montagne Pelée.

Furthermore, Vittecoq et al. (2019a, b) hypothesize that the frequent earthquakes in the subduction context would regularly increase the rocks' hydraulic conductivity, notably in the lava flows. Thus, contrary to the basaltic context where the oldest rocks have the lowest hydraulic conductivity due to weathering (Cabrera and Custodio 2004; Join et al. 2005; Lachassagne et al. 2014), in the andesitic context, the hydraulic conductivity would be cumulative and would increase with rocks ageing (between 1–2 and 4–5.5 Ma in that case study). This theory is still discussed, although it is only based on one data set (Martinique, FLA)—for example, in the Kumamoto region (Japan) or in Martinique, Hosono et al. (2020) and Lachassagne et al. (2011) demonstrate that the hydraulic increase due to seismic activity (as the earthquake "shakes" the aquifer) is limited in time and that the aquifer quickly recovers its previous steady state. Hosono et al. (2020) and Lachassagne et al. (2011) and their cited literature also show that the hydraulic conductivity increase is not spatially generalized. As this debate was only initiated on Martinique, the international scientific community should explore both hypotheses on the basis of their datasets in subduction areas.

Continental Americas

Peach and Taylor (2023) elaborate a local HCM for a transboundary (Bolivia-Chile) 100–150-km^2 andesitic aquifer in Bolivia. The HCM is rather simple with a ~200-m-thick unconfined subhorizontal 1.61-Ma "ignimbrites" aquifer lying on an old Miocene volcanics aquitard. The outflow from this aquifer (on the one hand springs, and on the other hand groundwater-sustaining surface-water discharge and wetlands) is due to a dam effect provoked by the outcropping of the low-permeability substratum. In South America, Favier et al. (2008) also found evidence of "deep-circulations" on the Antizana ice-covered volcano, Ecuador, but they do not detail the structure of the aquifer.

In the Cascade Range in Oregon, USA, Tague and Grant (2004) contrasts the low-permeability Western Cascades (400–1,800 m amsl), composed of deeply weathered and eroded Miocene lavas and pyroclastic flows, and the much younger high-permeability Plio-Pleistocene High Cascades composed of "recent constructional volcanism". The latter exhibit high discharge springs.

Genereux et al. (2009) propose, from hydrochemistry, isotopes and water dating data, a schematic HCM for the typical andesitic Quaternary Barva volcano, Costa Rica. It is mostly composed of lava and pyroclastic flows, and lahars, highlighting a layered anisotropic behavior of the Barva south flank. From that, they suggest a "lateral downslope flow" in lavas, which are the main aquifers, and downwards vertical leakage between lavas in the lower hydraulic conductivity "ignimbrites". They also show a large transfer of groundwater (and carbon) from the volcano (summit at 2,906 masl) to the lowlands located at its foot. Groundwater age data are interesting as they reveal "old water" (2,400–4,000 years) in the bedrock (Cordillera Central volcanic rocks), and "young" water (<55 years) in the local aquifers (volcanic rocks).

Synthesis

This review about andesitic volcano HCMs shows the contrast between (1) old andesitic edifices/formations (e.g. in Martinique, FLA, Bolivia-Chile, or the Cascades range (USA) with ages of about or greater than 1 Ma and up to 15 Ma) that, due to their erosion and weathering state, show only local aquifers disseminated within globally low hydraulic conductivity formations, and (2) much recent edifices (a few thousands to hundred thousand years) exhibiting aquifers of one or several kilometers in length, mostly within lava flows and/or pyroclastic deposits, which are the main geological formations hosting the aquifers. More generally, no GHCM is yet proposed for andesitic aquifers, but only local HCMs resulting from case studies. Nevertheless, the geological model of andesitic volcanoes with central to distal zones seems to be able to serve as a good support to describe aquifer systems in recent andesitic volcanic edifices. It is however not well suited for (andesitic) shield volcanoes (e.g. Bromo-Tengger, Fuji) where the shield volcano (a combination of the proximal and medial zones) is directly connected to the distal zone.

GHCM for Andesitic hydrosystems

The previous section of this paper showed that there is yet no unique GHCM for andesitic aquifers, and that the HCMs proposed from several case studies by the various authors are not fully consistent or transposable to all andesitic contexts. Moreover, these HCMs encompass various study scales, from the scale of the lithological unit (see section 'Hydrogeological characteristics of andesitic rock lithologies') to the regional scale, or at least that of a large volcanic edifice. There is thus a need to build a comprehensive view of andesitic volcanic aquifer HCMs. This review about andesitic volcano HCMs also shows the contrast between (1) old andesitic formations, and (2) much recent edifices. Both show very different hydrogeological behaviors.

Generic hydrogeological conceptual model for old andesitic formations

Old andesitic edifices (older than 1 Ma), due to their erosion and weathering state, show only local aquifers disseminated within globally low hydraulic conductivity formations and, consequently, with low discharge springs (<10 L s^{-1}) and also a modest possible abstraction rate (a few 10 L s^{-1} at max per hydrogeological compartment). Consequently, conceptualizing such hydrosystems at a scale above that of a lithological unit, or the piling-up of lithological units, is hardly feasible. In such a context of old andesitic formations, the volcanic edifices lost most of their primary morphology; the current morphology can hardly serve as a guide for the hydrogeological conceptualization, which explains why, among other factors, no convincing GHCM was proposed as of yet for such a context.

Nevertheless, in this geological context, given the limited extension of the aquifer bodies, most groundwater flows are guided by the current morphology. Consequently, current groundwater watersheds coincide well with topographic watersheds. The HCM for such old andesitic formations thus shows large similarities with the one proposed in Mayotte Island (Lachassagne et al. 2014) with, however, lower hydraulic conductivity in andesitic aquifers, consequently with no or few river losses, and few springs. The picture is that of several low-extension low-productivity aquifers disseminated within very low hydraulic conductivity formations, badly connected or not interconnected with the others. Such aquifers are difficult to localize from the surface, even with geophysical methods, which do not decipher whether a high-resistivity (unweathered) target is pervious (cooling fractures) or not (massive lava body). Conversely, as these formations are globally of low hydraulic conductivity, and highly compartmented, they have the advantage of not being prone to seawater intrusion.

Generic hydrogeological conceptual model for recent andesitic formations

The bibliographical review shows that the geological model of andesitic volcanoes with (central to distal) zones (Sigurdsson et al. 2015; Fig. 6) is a good aid for describing aquifer systems in recent andesitic volcanic edifices (younger than 1 Ma). Consequently, it is possible to define a GHCM by gathering the information from the different HCMs with the knowledge gained from the bibliographical review, identifying aquifers and aquitards, locating springs, drawing piezometric levels, etc. (Fig. 11).

In the andesitic volcanic context, the lithology is the main driver that controls the hydrogeological structure and functioning. Therefore, as with the previous geological studies (Bogie and Mackenzie 1998; Selles 2014; Sigurdsson 2015b; Vessel and Davis 1981), this paper considers four zones in the developed HCM (Fig. 11), namely the central, proximal, medial and distal ones.

The *central zone* extends laterally a few hundred meters to a few kilometers from the summit of the volcano. It is dominated by intrusive rocks, dome and dome flow lavas (and their screes), tephras (including some proximal facies of pyroclastic flows, surges and falls), and autoclastic breccia. This area may contain small-extension perched aquifers in the previously cited lithologies, where they are pervious and if an impervious "substratum" enables the accumulation of groundwater. Such groundwater may be associated with hydrothermalism processes due to proximity with the volcanic vent—fumaroles, hot and/or high electrical conductivity (EC) springs, summit/near-summit lake with low pH waters, etc.—and may also contribute to the vapor produced at the top of the volcano.

The *proximal zone* (Fig. 11) extends laterally up to several kilometres from the summit of the volcano. It is dominated by the piling-up of pervious lithologies such as the fractured facies of lava flows, and their associated breccia, pyroclastic falls, and, to a lesser extent, pyroclastic flows. These pervious rocks are interstratified with impervious lithologies such as surges and lahars, and weathered lithologies. This zone is characterized by perched aquifers of small extent in the previously described pervious lithologies, for which extent and discharge depend on the extension and shape of the impervious layer (and on the climate). This proximal area also allows the recharge of larger-extension aquifers which also continue in the medial and distal zones. The discharge of the proximal-zone perched aquifers is more likely low, and their groundwater have a low mineralization due to the short time of residence of the groundwater.

The *medial zone* (Fig. 11) extends laterally up to more than 10–15 kms from the summit of the volcano. It is dominated by ignimbrites, epiclasts, and by lava flows
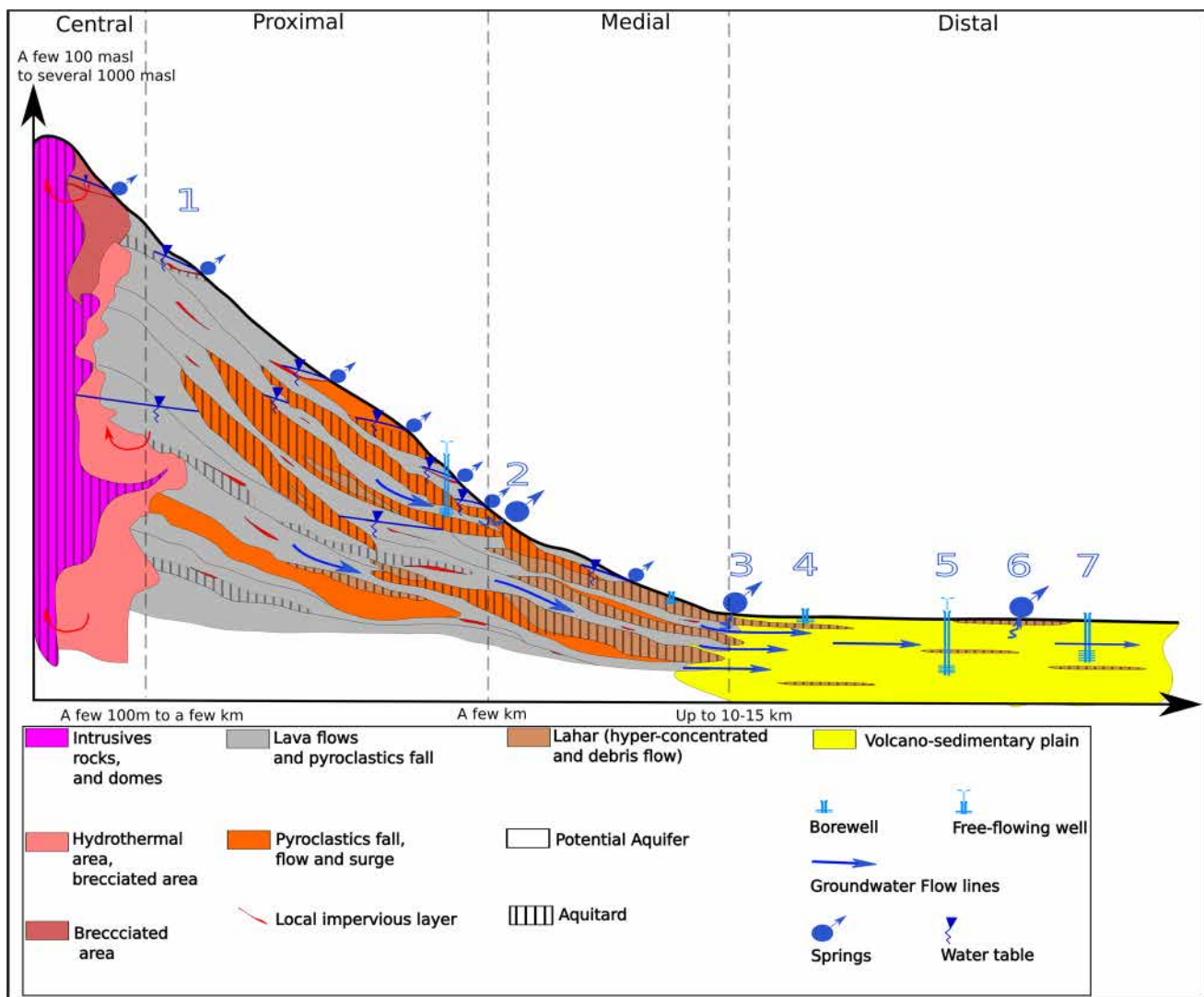
Fig. 11 A generic hydrogeological conceptual model (GHCM) for recent andesitic formations with seven hydrogeological features: (1) local perched aquifer, contact springs; (2) medium elevation springs, outflowing through weakness zones of aquitards; (3) piedmont springs, at the transition area between the volcanic aquifers from the medial zone and the volcano-sedimentary aquifers from the distal zone; (4) shallow wells (dug wells) in unconfined aquifers; (5) deep wells in confined aquifers; (6) low-elevations springs outflowing through weakness zones of aquitards; (7) deep wells in unconfined aquifers

to a much lesser extent. Consequently, the medial zone shows multilayered dominantly porous aquifer systems due to the alternation of pervious ignimbrites (reworked if any) deposits, and potentially fractured lava flows and their breccia where lava flows reach this zone, and impervious epiclasts. Each aquifer is meters to tens of meters thick, hundreds of meters to kilometers wide (perpendicularly to the main slope), and often several kilometers long, and then often beginning in the proximal zone. Their substratum is also of similar thickness and extension. The hydrogeological systems of this medial zone have either of the following structures:

- *Pyroclastic flows (and lava flows, but which are less present than pyroclastic flows) that fill pre-existing (paleo) valleys*. The resulting pyroclastic aquifers have a narrow lateral extent as they are bounded by the walls of the paleovalley(s). Vertically, they are bounded by interstratified impervious lahars and/or pyroclastic surges and falls;
- *Pyroclastic flows (and lahars and surges) that deposit on a flat surface, as the pre-existing paleovalleys were totally filled*. They deposit radially from the eruptive center, as detritic fans. Then the resulting pyroclastic aquifers have a large lateral extent (up to a few kilometers), as well as their impervious laharic cover if any,

and surges and falls to a lesser extent. These lahars, if any, well confine these aquifers, which are nevertheless multilayered (alternation of pyroclastic and lahar fans).

During an eruptive cycle, channelized aquifers develop first and are then "covered" by fan aquifers.

Two kinds of springs are observed in the medial zone: springs issuing from locally recharged unconfined aquifers, and springs flowing out from confined aquifers, recharged at a higher elevation, notably in the proximal zone. Springs from unconfined aquifers are mostly localized in the valleys, and canyons, if any, where the piezometric level reaches the topographic surface. It is worth noting that springs outflowing from confined aquifers are not necessarily located in current valleys. Some of them are located above the most downstream part of the related confined aquifer which may not coincide with a current valley. Borewells in such confined aquifers can be free-flowing or not, depending on the topography/piezometry relationships.

The *distal zone* (Fig. 11) extends laterally up to 15 km and much more from the summit of the volcano. It is exclusively composed of volcano-sedimentary multilayered porous aquifers composed of detritic materials. The subsidence explains the thickness of such aquifers when it reaches or exceeds several hundreds of meters (Roberts et al. 1994). Their thickness is about 120–140 m max for coastal aquifers in the case of glacial/interglacial eustatic variations without subsidence (Neal and Abreu 2009). At high elevations (Favier et al. 2008; Hall et al. 2017) and/or latitudes (e.g. Jefferson et al. 2006; Tague and Grant 2004), this distal zone can also comprise glacial-fluvial sediments.

HCMs at various scales: insights for applied hydrogeology

The previously described GHCM was built in consideration of several scales of interpretation, as done in the literature, depending on the object of interest. A HCM can also be defined at the scales listed in the following:

1. *Pervious lithological unit*. This constitutes an aquifer such as a single lava flow or a pyroclastic flow. It can also be part of a pervious lithological unit such as the fractured part of a lava flow, and/or it's breccia, which can be an aquifer. This HCM scale is notably required to define the emerging context of a spring, interpret the lithological log of a borewell, design the borewell technical log, interpret a pumping test, etc. The location of the point of interest within the GHCM zones may give a preliminary idea of the results—for instance, to decipher whether one deals with a local perched aquifer, a paleovalley aquifer, or a more "regional" one.

2. *Hydrogeological formation*. This refers to an aquifer constituted by the thick piling-up of lava flows, for instance, or an aquitard. Working at this HCM scale is notably required for mapping hydrogeological potentialities, and for providing the (ideally 3D) contours (top, bottom, lateral extent) of potential aquifers (e.g. lava flows, pyroclastic flows). These hydrogeological potentialities maps can notably be used in the early phase of siting projects for one or several water wells. It may also be used to identify the recharge area of an aquifer formation, and where it outcrops.

3. "*Continuum*". The flank of a recent volcano, as idealized in Fig. 11, is a volcanic "continuum", and is defined as a morphologically coherent ensemble, generally comprising several lithological formations, superimposed and/or juxtaposed. It has well-defined underground boundaries (preferably no-flow). Its coherent morphology enables upstream–downstream ground- and surface-water coherent flow computation, within and/or on adjacent lithological formations that exchange flows with each other. As a water budget can be computed at this HCM scale, such a HCM can be used for sustainable water resources management, particularly to avoid overexploitation of the continuum or of a given lithological formation within the continuum.

4. *Volcanic edifice*. This refers to a scale such as that described by Vittecoq et al. (2023) for the Montagne Pelée. Such an HCM is mostly the combination of several "continuum" HCMs. It can be useful to have a complete view of the volcanic edifice, although the flanks of the edifice may show different patterns from one to another. A symmetrical pattern on all sides of the volcano is very unlikely. A volcanic-edifice-scale HCM can also be used for water resources management;

5. *Stratovolcanoes*. Most andesitic volcanoes are organized as stratovolcanoes, with a well-identified morphological shape. Hydrogeologically, most stratovolcanoes are composed of several adjacent volcanic edifices that constitute a *volcanic complex*, such as the Bromo-Tengger Semeru (Toulier et al. 2019). In each volcanic complex, surface water and groundwater generally flow radially, from the top of the volcanic complex to its foot. It may be of interest to work at the volcanic complexes scale, for instance to compute their water budget, notably to study the hydrogeological interactions between volcanic edifices, and to encompass the whole system in order to define a water-resources-management strategy and water policy.

6. *Regional scale*. Volcano-sedimentary aquifers at a regional scale are located downstream of volcanic complexes/edifices and can be supplied by the surrounding volcanic edifices. If their peripheral boundaries and recharge areas are well defined, these regional volcanic complexes can be used to manage water resources. At the scale of a volcanic complex or a *regional volcanic*

complex, several configurations and delimitations are possible depending on (1) the purpose, and the perimeter, of the study area (application-dependent contour), and (2) its (hydro)geological configuration, notably the contours of the volcanic complexes.

Discussion and perspectives

The literature reviewed here, about andesitic volcano hydrogeological context, showed the absence of a recognized GHCM. This paper presents several site-specific HCMs elaborated at several scales, from the lithological units to the regional scale. From the analysis of these HCMs, this paper proposes a GHCM for andesitic hydrosystems; however, this GHCM still mostly relies on a two-dimensional (2D) approach, and there are some comments on how to tackle three-dimensional (3D) issues. Further research should focus on progressing from a 2D to a real 3D GHCM. There are still some questions about the lateral distribution of aquifers (and aquitards), notably in a same "continuum". The investigation of new case studies, or the deepening of the investigation of already investigated ones, should focus on this issue.

Like in most studies, this paper considers the "continuum scale" as the best scale for sustainable groundwater resource management. Indeed, it is at this scale that one can identify aquifers, their mutual relationships and their functioning, and their relationships with surface water, etc. In the andesitic context, due to the relatively high frequency of volcanic-edifice construction/destruction events, at the timescale of the lifespan of a volcano, the construction of an accurate HCM relies on high-resolution investigations (Lachassagne et al. 2014). This is consistent with the fact that the geological structure is the main driver governing the functioning of the hydrogeological systems. The facies distribution evolution along a volcanic transect is therefore a key parameter to define the GHCM, as proposed in Fig. 11. It is suggested here that it would be better to partly adopt the terminology from Schumm (1977), which better describes the geological and hydrogeological processes involved in each zone. Then, the upstream–downstream succession would be: (1) central zone, (2) proximal zone, (3) transfer zone, and (4) depositional zone. As already proposed for other complex hydrogeological systems (Dewandel et al. 2017; Maréchal et al. 2014), a multidisciplinary approach is required to elaborate a robust HCM. The geological approach can be completed by geophysical investigations as well as with hydrodynamic parameters measurement (pumping tests for instance), location, quantification and definition of the emerging context of springs, characterization of water inflows in existing wells, of surface-water/groundwater relationships, of the hydrochemistry (major ions and stable isotopes of the water) in the various compartments of the hydrosystem, etc. These investigations may be completed/interpreted with water budgeting, and various types of models and data processing tools.

In andesitic volcanoes, most authors do not consider the existence of a basal aquifer flowing through the whole volcanic edifice, although it may exist in andesitic shield volcanoes, such as in the Bromo-Tengger. To highlight the differences between this "andesitic shield" volcano HCM and the one for recent andesitic formations, this paper (Fig. 11) proposes hypothetical piezometric levels in each aquifer, based on an example of aquifer and aquitard distribution. It is proposed that there is not a unique basal aquifer, but several flow paths through the volcanic edifice, some of them supplying the volcano-sedimentary plain aquifers in the distal zone. The piezometric levels shown in Fig. 11 are hypothetical, as they depend on the real aquifer and aquitard distribution. A better characterization of piezometric levels (from observations at springs, wells, rivers) from several case studies may help improve this part of the developed GHCM. The proposed GHCM for andesitic aquifers largely relies on the geological conceptual model sharing the volcanic edifice into central to distal zones.

Conclusion

This review, compiling worldwide case studies, is a first in the field of study on the hydrogeology of andesitic volcanic aquifers. It identifies the main aquifer types, namely lava flows and pyroclastic flows, and the processes that may decrease their hydrodynamic properties such as weathering. It also identifies the main aquitards, namely lahars. Due to the complexity of their geological structures, no generic hydrogeological conceptual model (GHCM) has yet been proposed for such andesitic volcanic formations. Although the authors agree that each volcanic edifice is unique, this paper provides a GHCM that highlights the main hydrogeological features of this type of volcanism. This GHCM largely relies on the geological conceptual model sharing the volcanic edifice, from upstream to downstream, into central, proximal, medial and distal zones that have contrasted hydrogeological structures and functioning. This review also enables one to propose a specific GHCM for old andesitic formations, where this "zones HCM" cannot be applied, and for the particular case of shield volcanoes in the andesitic context. Additionally, this paper describes how applied hydrogeology can benefit from these results, at various spatial scales, from the scale of the lithological unit to the scale of regional volcanic complexes, notably to sustainably manage such aquifers. Among these various

scales, the "flank continuum" is the most adapted scale to achieve effective groundwater resource management. Further improvements to this GHCM are proposed, notably to better consider the 3D structure of such aquifers. All these results have strong socio-economic implications, as the piedmont of such andesitic volcanic edifices is often densely inhabited, and as the groundwater resources of such andesitic aquifers are at high risk in numerous areas of the world.

Declarations

Conflict of Interest The authors declare that they have no conflict of interest.

References

Adikari DP (2015) Hydrogeological features of Mount Fuji and the surrounding area, central Japan: an overview. J Inst Sci Technol 19:96–105. https://doi.org/10.3126/jist.v19i1.13834

Allocca V, Colantuono P, Colella A, Piacentini SM, Piscopo V (2022) Hydraulic properties of ignimbrites: matrix and fracture permeabilities in two pyroclastic flow deposits from Cimino-Vico volcanoes (Italy). Bull Eng Geol Environ 81:221. https://doi.org/10.1007/s10064-022-02712-0

Amiotte Suchet P, Probst J-L, Ludwig W (2003) Worldwide distribution of continental rock lithology: implications for the atmospheric/soil CO_2 uptake by continental weathering and alkalinity river transport to the oceans: world wide distribution of continental rock lithology. Glob Biogeochem Cycles 17. https://doi.org/10.1029/2002GB001891

Anderson MP, Woessner WW, Hunt RJ (2015) Modeling purpose and conceptual mdel. In: Applied groundwater modeling. Elsevier, Amsterdam, pp 27–67. https://doi.org/10.1016/B978-0-08-091638-5.00002-X

Aoki Y, Tsunematsu K, Yoshimoto M (2019) Recent progress of geophysical and geological studies of Mt. Fuji Volcano, Japan. Earth-Sci Rev 194:264–282. https://doi.org/10.1016/j.earscirev.2019.05.003

Asai K, Satake H, Tsujimura M (2009) Isotopic approach to understanding the groundwater flow system within an andesitic stratovolcano in a temperate humid region: case study of Ontake volcano, central Japan. Hydrol Process 23:559–571. https://doi.org/10.1002/hyp.7185

Attias E, Thomas D, Sherman D, Ismail K, Constable S (2020) Marine electrical imaging reveals novel freshwater transport mechanism in Hawai'i. Sci Adv 6:eabd4866. https://doi.org/10.1126/sciadv.abd4866

Baud B, Lachassagne P, Jourde H, De Montety V, Fadillah A, Dörfliger N, Hendrayana H, Rachmansyah A (2021) Preliminary conceptual model of the Arjuno Welirang hydrogeological system, and comparison with the Bromo Tengger: an illustration of the hydrogeological systems diversity in volcanic areas. IOP Conf Ser Earth Environ Sci 851:012016. https://doi.org/10.1088/1755-1315/851/1/012016

Baumann Traine V (2018) Rain-triggered lahar initiation in volcanic areas. Université de Genève, France. https://doi.org/10.13097/ARCHIVE-OUVERTE/UNIGE:117083

Bogie I, Mackenzie KM (1998) The application of a volcanic facies model to an andesitic stratovolcano hosted geothermal, system at Wayang Windu, Java, Indonesia. Proceedings 20th NZ Geothermal Workshop, Auckland, New Zealand, January 1998

Brantley SR, Waitt RB (1988) Interrelations among pyroclastic surge, pyroclastic flow, and lahars in Smith Creek valley during first minutes of 18 May 1980 eruption of Mount St. Helens, USA. Bull Volcanol 50:304–326. https://doi.org/10.1007/BF01073588

Brassington FC, Younger PL (2010) A proposed framework for hydrogeological conceptual modelling: a proposed framework for hydrogeological conceptual modelling. Water Environ J 24:261–273. https://doi.org/10.1111/j.1747-6593.2009.00173.x

Bredehoeft J (2005) The conceptualization model problem-surprise. Hydrogeol J 13:37–46. https://doi.org/10.1007/s10040-004-0430-5

Cabrera MC, Custodio E (2004) Groundwater flow in a volcanic sedimentary coastal aquifer: Telde area, Gran Canaria, Canary Islands, Spain. Hydrogeol J 12. https://doi.org/10.1007/s10040-003-0316-y

Charlier J-B, Lachassagne P, Ladouche B, Cattan P, Moussa R, Voltz M (2011) Structure and hydrogeological functioning of an insular tropical humid andesitic volcanic watershed: a multi-disciplinary experimental approach. J Hydrol 398:155–170. https://doi.org/10.1016/j.jhydrol.2010.10.006

Clynne MA, Calvert AT, Wolfe EW, Evarts RC, Fleck RJ, Lanphere MA (2008) The pleistocene eruptive history of Mount St. Helens, Washington, from 300,000 to 12,800 years before present 35. US Geol Surv Prof Pap 1750-28

Criswell CW (1987) Chronology and pyroclastic stratigraphy of the May 18, 1980, eruption of Mount St. Helens, Washington. J Geophys Res Solid Earth 92:10237–10266. https://doi.org/10.1029/JB092iB10p10237

Cruz-Fuentes T, Cabrera M del C, Heredia J, Custodio E (2014) Groundwater salinity and hydrochemical processes in the volcano-sedimentary aquifer of La Aldea, Gran Canaria, Canary Islands, Spain. Sci Total Environ 484:154–166. https://doi.org/10.1016/j.scitotenv.2014.03.041

Custodio E (2007) Groundwater in volcanic hard rocks. In: Groundwater in fractured rocks. CRC, Boca Raton, FL

Custodio E (1989) Groundwater characteristics and problems in volcanic rock terrains. International Atomic Energy Agency, Vienna, pp 87–137

Custodio E, Guerra JA, Jiménez J, Medina JA, Soler C (1983) The effects of agriculture on the volcanic aquifers of the Canary Islands. Environ Geol 5:225–231. https://doi.org/10.1007/BF02414868

Custodio E, Lopez Garciz L, Amigo E (1988) Simulation par modèle mathématique de l'île volcanique de Ténériffe (Canaries, Espagne) [Mathematical model simulation of the volcanic island of Tenerife (Canary Islands, Spain)]. Simul. Par Modè

Mathématique Lî Volcanique Ténériffe Canar. Esp. Hydrogéologie 2:153–167

de Marsily G (2009) 'L'eau, un trésor en partage', de Ghislain de Marsily [Water, a shared treasure]. Dunod, Paris

de Marsily G, Besbes M (2017) Les eaux souterraines [Groundwaters]. Ann Mines - Responsab Environ 86:25–30. https://doi.org/10.3917/re1.086.0025

De Roever WP (1965) Dacitic ignimbrites with upwards increasing compactness near Sibolangit (NE Sumatra, Indonesia) and their peculiar hydrology. Bull Volcanol 29:105–111. https://doi.org/10.1007/BF02597147

Dewandel B, Alazard M, Lachassagne P, Bailly-Comte V, Couëffé R, Grataloup S, Ladouche B, Lanini S, Maréchal J-C, Wyns R (2017) Respective roles of the weathering profile and the tectonic fractures in the structure and functioning of crystalline thermo-mineral carbo-gaseous aquifers. J Hydrol 547:690–707. https://doi.org/10.1016/j.jhydrol.2017.02.028

Dumont M, Plagnes V, Lachassagne P, Guérin R, Nugraha B, Mohamad F, Oudin L, Fadillah A, Valdès D, Brocard G, Bonjour J-L, Saadi M, Esneu A-S, Muhammad A, Hendarmawan Dörfliger N (2023) Water cycle modelling strengthened by probabilistic integration of field data for groundwater management of a quite unknown tropical volcanic hydrosystem. C R Géosci 355:1–23. https://doi.org/10.5802/crgeos.192

Dumont M, Reninger PA, Aunay B, Pryet A, Jougnot D, Join JL, Michon L, Martelet G (2021) Hydrogeophysical characterization in a volcanic context from local to regional scales combining airborne electromagnetism and magnetism. Geophys Res Lett 48:e2020GL092000. https://doi.org/10.1029/2020GL092000

Eggleton R, Foudoulis C, Varkevisser D (1987) Weathering of basalt; changes in rock chemistry and mineralogy. Clays Min 35:161–169

Enemark T, Peeters LJM, Mallants D, Batelaan O (2019) Hydrogeological conceptual model building and testing: a review. J Hydrol 569:310–329. https://doi.org/10.1016/j.jhydrol.2018.12.007

Fadillah A, Harijoko A, Hendrayana H, Edi Wibowo H, Baud B, Lachassagne P, Satrya Muhammad A, Dörfliger N (2023) Hydrogeological interpretation using electrical resistivity tomography: methodology and conceptual model in andesitic volcanic context. Int J GEOMATE 24. https://doi.org/10.21660/2023.106.3728

Famin V, Paquez C, Danišík M, Gardiner NJ, Michon L, Kirkland CL, Berthod C, Friedrichs B, Schmitt AK, Monié P (2022) Multitechnique geochronology of intrusive and explosive activity on Piton des Neiges Volcano, Réunion Island. Geochem Geophys Geosyst 23:e2021GC010214. https://doi.org/10.1029/2021GC010214

Favier V, Coudrain A, Cadier E, Francou B, Ayabaca E, Maisincho L, Praderio E, Villacis M, Wagnon P (2008) Evidence of groundwater flow on Antizana ice-covered volcano, Ecuador/Mise en évidence d'écoulements souterrains sur le volcan englacé Antizana. Equateur Hydrol Sci J 53:278–291.https://doi.org/10.1623/hysj.53.1.278

Fisher RV (1990) Transport and deposition of a pyroclastic surge across an area of high relief: the 18 May 1980 eruption of Mount St. Helens, Washington. Geol Soc Am Bull 102:1038–1054. https://doi.org/10.1130/0016-7606(1990)102<1038:TADOAP>2.3.CO;2

Foster SSD, Ellis AT, Losilla-Penon M, Rodriguez-Estrada HV (1985) Role of volanic tuffs in groundwater Regime of Valle Central, Costa Rica. Ground Water 23:795–801

Characterization of low-temperature pyroclastic surges that occurred in the northeastern Japan arc during the late 19th century, dynamics of volcanic explosions: field observations, experimental constraints and integrated modelling of volcanic explosions: field observations, experimental constraints and integrated modelling. J Volcanol Geotherm Res 178:113–130. https://doi.org/10.1016/j.jvolgeores.2008.07.004

Genereux DP, Webb M, Solomon DK (2009) Chemical and isotopic signature of old groundwater and magmatic solutes in a Costa Rican rain forest: evidence from carbon, helium, and chlorine. Water Resour Res 45:2008WR007630. https://doi.org/10.1029/2008WR007630

Germa A, Quidelleur X, Labanieh S, Lahitte P, Chauvel C (2010) The eruptive history of Morne Jacob volcano (Martinique Island, French West Indies): geochronology, geomorphology and geochemistry of the earliest volcanism in the recent Lesser Antilles arc. J Volcanol Geotherm Res 198:297–310. https://doi.org/10.1016/j.jvolgeores.2010.09.013

Gibson S (2003) In: Le Maitre R W (ed) (2002) Igneous rocks: a classification and glossary of terms. Recommendations of the International Union of Geological Sciences subcommission on the systematics of igneous rocks. Cambridge, New York, Geol Mag 140:367–367. https://doi.org/10.1017/S0016756803388028

Gingerich SB, Oki DS (2000) Ground water in Hawaii. US Geological Survey, Reston, VA

Gingerich SB, Voss CI (2005) Three-dimensional variable-density flow simulation of a coastal aquifer in southern Oahu, Hawaii, USA. Hydrogeol J 13:436–450. https://doi.org/10.1007/s10040-004-0371-z

Hall ML, Mothes PA, Samaniego P, Militzer A, Beate B, Ramón P, Robin C (2017) Antisana volcano: A representative andesitic volcano of the eastern cordillera of Ecuador: petrography, chemistry, tephra and glacial stratigraphy. J South Am Earth Sci 73:50–64. https://doi.org/10.1016/j.jsames.2016.11.005

Hartmann A, Goldscheider N, Wagener T, Lange J, Weiler M (2014) Karst water resources in a changing world: review of hydrological modeling approaches. Rev Geophys 52:218–242. https://doi.org/10.1002/2013RG000443

Hemmings B, Gooddy D, Whitaker F, George Darling W, Jasim A, Gottsmann J (2015a) Groundwater recharge and flow on Montserrat, West Indies: insights from groundwater dating. J Hydrol Reg Stud 4:611–622. https://doi.org/10.1016/j.ejrh.2015.08.003

Hemmings B, Whitaker F, Gottsmann J, Hughes A (2015b) Hydrogeology of Montserrat review and new insights. J Hydrol Reg Stud 3:1–30. https://doi.org/10.1016/j.ejrh.2014.08.008

Herrera C, Custodio E (2008) Conceptual hydrogeological model of volcanic Easter Island (Chile) after chemical and isotopic surveys. Hydrogeol J 16:1329–1348. https://doi.org/10.1007/s10040-008-0316-z

Hildenbrand A, Marlin C, Conroy A, Gillot P-Y, Filly A, Massault M (2005) Isotopic approach of rainfall and groundwater circulation in the volcanic structure of Tahiti-Nui (French Polynesia). J Hydrol 302:187–208. https://doi.org/10.1016/j.jhydrol.2004.07.006

Hosono T, Yamada C, Manga M, Wang C-Y, Tanimizu M (2020) Stable isotopes show that earthquakes enhance permeability and release water from mountains. Nat Commun 11:2776. https://doi.org/10.1038/s41467-020-16604-y

Ingebritsen SE, Scholl MA (1993) The hydrogeology of Kilauea volcano. Geothermics 22:255–270. https://doi.org/10.1016/0375-6505(93)90003-6

Izquierdo T (2014) Conceptual hydrogeological model and aquifer system classification of a small volcanic island (La Gomera; Canary Islands). CATENA 114:119–128. https://doi.org/10.1016/j.catena.2013.11.006

Izuka SK, Gingerich SB (2003) A thick lens of fresh groundwater in the southern Lihue Basin, Kauai, Hawaii, USA. Hydrogeol J 11:240–248. https://doi.org/10.1007/s10040-002-0233-5

Jefferson A, Grant G, Rose T (2006) Influence of volcanic history on groundwater patterns on the west slope of the Oregon High Cascades. Water Resour Res 42. https://doi.org/10.1029/2005WR004812

Join J-L, Coudray J, Longworth K (1997) Using principal components analysis and Na/Cl ratios to trace groundwater circulation in a volcanic island: the example of Reunion. J Hydrol 190:1–18. https://doi.org/10.1016/S0022-1694(96)03070-3

Join J-L, Folio J-L, Robineau B (2005) Aquifers and groundwater within active shield volcanoes: evolution of conceptual models in the Piton de la Fournaise volcano. J Volcanol Geotherm Res 147:187–201. https://doi.org/10.1016/j.jvolgeores.2005.03.013

Lachassagne P (2006) Martinique, chap XIII. In: Aquifères et eaux souterraines en France, tome 1 [Aquifers and groundwater in France, vol 1]. BRGM, Orleans, France, pp 768–781

Lachassagne P, Adin T, Cruchet M, Lebon D (2006a) chap 5. In: Aquifères et eaux souterraines en France, tome 1 [Aquifers and groundwater in France, vol 1]. BRGM, Orleans, France, pp 816–822

Lachassagne P, Adin T, Cruchet M, Lebon D (2006b) Généralités sur les eaux souterraines, chap 5 [General information on groundwater, chap 5]. In: Aquifères volcaniques [Volcanic aquifers]. BRGM, Orleans, France, pp 52–58

Lachassagne P, Léonardi V, Vittecoq B, Henriot A (2011) Interpretation of the piezometric fluctuations and precursors associated with the November 29, 2007, magnitude 7.4 earthquake in Martinique (Lesser Antilles). C R Geosci 343:760–776. https://doi.org/10.1016/j.crte.2011.09.002

Lachassagne P, Aunay B, Frissant N, Guilbert M, Malard A (2014) High-resolution conceptual hydrogeological model of complex basaltic volcanic islands: a Mayotte, Comoros, case study. Terra Nova 26:307–321. https://doi.org/10.1111/ter.12102

Lachassagne P, Dewandel B, Wyns R (2021) Review: Hydrogeology of weathered crystalline/hard-rock aquifers—guidelines for the operational survey and management of their groundwater resources. Hydrogeol J 29:2561–2594. https://doi.org/10.1007/s10040-021-02339-7

Lavigne F, Thouret JC, Voight B, Suwa H, Sumaryono A (2000) Lahars at Merapi volcano, Central Java: an overview. J Volcanol Geotherm Res 100:423–456. https://doi.org/10.1016/S0377-0273(00)00150-5

Lesparre N, Gibert D, Marteau J, Komorowski J-C, Nicollin F, Coutant O (2012) Density muon radiography of La Soufrière of Guadeloupe volcano: comparison with geological, electrical resistivity and gravity data. Geophys J Int 190:1008–1019. https://doi.org/10.1111/j.1365-246X.2012.05546.x

Macdonald GA, Abbott AT, Peterson FL (1983) Volcanoes in the sea. UH Press, Honolulu, HI

Manga M (1998) Advective heat transport by low-temperature discharge in the Oregon Cascades. Geology 26:799–802. https://doi.org/10.1130/0091-7613(1998)026<0799:AHTBLT>2.3.CO;2

Mangin A (1975) Insights into hydrodynamic behaviour of karst aquifers. PhD Thesis, Université de Dijon, France

Maréchal J-C, Lachassagne P, Ladouche B, Dewandel B, Lanini S, Strat PL, Petelet-Giraud E (2014) Structure and hydrogeochemical functioning of a sparkling natural mineral water system from a multidisciplinary approach: a case study from southern France. Hydrogeol J 22:47. https://doi.org/10.1007/s10040-013-1073-1

Mellors RA, Waitt RB, Swanson DA (1988) Generation of pyroclastic flows and surges by hot-rock avalanches from the dome of Mount St. Helens volcano. USA Bull Volcanol 50:14–25. https://doi.org/10.1007/BF01047505

Mooney WD, Barrera-Lopez C, Suárez MG, Castelblanco MA (2023) Earth crustal model 1 (ECM1): A 1° x 1° global seismic and density model. Earth-Sci Rev 243:104493. https://doi.org/10.1016/j.earscirev.2023.104493

Mulyadi (1992) Le complexe de Bromo-Tengger Est Java, Indonésie Etude structurale et volcanologique [The Bromo-Tengger complex in East Java, Indonesia Structural and volcanological study]. PhD Thesis, Université Blaise Pascal, France

Neal J, Abreu V (2009) Sequence stratigraphy hierarchy and the accommodation succession method. Geology 37:779–782. https://doi.org/10.1130/G25722A.1

Nichols WD, Shade PJ, Hunt (Jr) (1996) Summary of the Oahu, Hawaii, regional aquifer-system analysis. US Geol Surv Prof Pap 1412-A

Ono M, Machida I, Ikawa R, Kamitani T, Oyama K, Muranaka Y, Ito A, Marui A (2019) Regional groundwater flow system in a stratovolcano adjacent to a coastal area: a case study of Mt. Fuji and Suruga Bay, Japan. Hydrogeol J 27:717–730. https://doi.org/10.1007/s10040-018-1889-9

Pallares C, Fabre D, Thouret J-C, Bacconnet C, Charca-Chura JA, Martelli K, Talon A, Yanqui-Murillo C (2015) Geological and geotechnical characteristics of recent lahar deposits from El Misti volcano in the city area of Arequipa, South Peru. Geotech Geol Eng 33:641–660. https://doi.org/10.1007/s10706-015-9848-x

Paris R, Guillou H, Carracedo JC, Torrado FJP (2005) Volcanic and morphological evolution of La Gomera (Canary Islands), based on new K-Ar ages and magnetic stratigraphy: implications for oceanic island evolution. J Geol Soc 162:501–512. https://doi.org/10.1144/0016-764904-055

Peach D, Taylor A (2023) The development of a hydrogeological conceptual model of groundwater and surface water flows in the Silala River Basin. WIREs Water e1676. https://doi.org/10.1002/wat2.1676

Peterson FL (1972) Water development on tropic volcanic islands: type example—Hawaii. Groundwater 10:18–23. https://doi.org/10.1111/j.1745-6584.1972.tb03586.x

Pryet A, d'Ozouville N, Violette S, Deffontaines B, Auken E (2012) Hydrogeological settings of a volcanic island (San Cristóbal, Galapagos) from joint interpretation of airborne electromagnetics and geomorphological observations. Hydrol Earth Syst Sci 16:4571–4579. https://doi.org/10.5194/hess-16-4571-2012

Riggs NR, Busby-Spera CJ (1991) Facies analysis of an ancient, dismembered, large caldera complex and implications for intra-arc subsidence: Middle Jurassic strata of Cobre Ridge, southern Arizona. USA Sediment Geol 74:39–68. https://doi.org/10.1016/0037-0738(91)90034-B

Roberts HH, Bailey A, Kuecher GJ (1994) Subsidence in the Mississippi River Delta: important influences of valley filling by cyclic deposition, primary consolidation phenomena, and early diagenesis. GCAGS Trans 44:619–629

Rodriguez-Gonzalez A, Fernandez-Turiel JL, Perez-Torrado FJ, Paris R, Gimeno D, Carracedo JC, Aulinas M (2012) Factors controlling the morphology of monogenetic basaltic volcanoes: the Holocene volcanism of Gran Canaria (Canary Islands, Spain). Geomorphology 136:31–44. https://doi.org/10.1016/j.geomorph.2011.08.023

Rouquet S, Boivin P, Lachassagne P, Ledoux E (2012) A 3-D genetic approach to high-resolution geological modelling of the volcanic infill of a paleovalley system: application to the Volvic catchment (Chaîne des Puys, France). Bull Soc Géol Fr 183:395–407. https://doi.org/10.2113/gssgfbull.183.5.395

Schilling OS, Nagaosa K, Schilling TU, Brennwald MS, Sohrin R, Tomonaga Y, Brunner P, Kipfer R, Kato K (2023) Revisiting Mt Fuji's groundwater origins with helium, vanadium and environmental DNA tracers. Nat Water 1:60–73. https://doi.org/10.1038/s44221-022-00001-4

Schumm SA (1977) Geomorphic thresholds and complex response of drainage systems. Department of Earth Resources, Colorado State University, Fort Collins, CO

Selles A (2014) Multi-Disciplinary study on the hydrogeological behavior of the eastern flank of the Merapi Volcano, Central Java, Indonesia (Hydrology). Université Paris VI, Paris

Selles A, Deffontaines B, Hendrayana H, Violette S (2015) The eastern flank of the Merapi volcano (Central Java, Indonesia): architecture and implications of volcaniclastic deposits. J Asian Earth Sci 108:33–47. https://doi.org/10.1016/j.jseaes.2015.04.026

Sigurdsson H (ed) (2015a) The encyclopedia of volcanoes, 2nd edn. Academic, San Diego

Sigurdsson H (ed) (2015b) Preface. In: The Encyclopedia of Volcanoes, 2nd edn. Academic, Amsterdam, pp xvii–xviii. https://doi.org/10.1016/B978-0-12-385938-9.05001-X

Sigurdsson H, Houghton BF, McNutt SR, Rymer H, Stix J (eds) (2015) The encyclopedia of volcanoes, 2nd edn. Elsevier, Amsterdam

Smith GA (1988) Sedimentology of proximal to distal volcaniclastics dispersed across an active foldbelt: Ellensburg Formation (late Miocene), central Washington. Sedimentology 35:953–977. https://doi.org/10.1111/j.1365-3091.1988.tb01740.x

Smyth RC, Sharp JM Jr (2006) Chapter 4.1 The hydrology of tuffs. In: Heiken G (ed) Tuffs: their properties, uses, hydrology, and resources. GSA, Boulder, CO. https://doi.org/10.1130/2006.2408(4.1)

Tague C, Grant GE (2004) A geological framework for interpreting the low-flow regimes of Cascade streams, Willamette River Basin, Oregon. Water Resour Res 40. https://doi.org/10.1029/2003WR002629

Tilling RI (1989) Voclanic hazards. American Geophysical Union, Washington, DC

Toulier A (2019) Multidisciplinary study for the characterization of volcanic aquifers hydrogeological functioning: case of Bromo-Tengger volcano (East Java, Indonesia) (Hydrology). Université de Montpellier, Montpellier, France

Toulier A, Baud B, de Montety V, Lachassagne P, Leonardi V, Pistre S, Dautria J-M, Hendrayana H, Miftakhul Fajar MH, Satrya Muhammad A, Beon O, Jourde H (2019) Multidisciplinary study with quantitative analysis of isotopic data for the assessment of recharge and functioning of volcanic aquifers: case of Bromo-Tengger volcano, Indonesia. J Hydrol Reg Stud 26:100634. https://doi.org/10.1016/j.ejrh.2019.100634

Toulier A, Lachassagne P, Hendrayana H, Fadillah A, Jourde H (2022) A cost-effective device and methodology to compute aquifer transmissivity and piezometry from free-flowing artesian wells. Hydrogeol J 30:1917–1931. https://doi.org/10.1007/s10040-022-02505-5

Tsuchi R (2017) Geology and Groundwater of Mt. Fuji, Japan. J Geogr Chigaku Zasshi 126:33–42. https://doi.org/10.5026/jgeography.126.33

Vessel RD, Davis DK (1981) Nonmarine sedimentation in an active fore arc basin. Hridge FG, Flores RM (eds) Recent and ancient nonmarine depositional environments: models for exploration. Society of Economic Paleontologists and Mineralogists, Tulsa, OK, pp 31–45

Violette S, Ledoux E, Goblet P, Carbonnel J-P (1997) Hydrologic and thermal modeling of an active volcano: the Piton de la Fournaise, Reunion. J Hydrol 191:37–63. https://doi.org/10.1016/S0022-1694(96)03071-5

Violette S, d'Ozouville N, Pryet A, Deffontaines B, Fortin J, Adelinet M (2014) Hydrogeology of the Galápagos Archipelago: an integrated and comparative approach between islands. In: Harpp KS, Mittelstaedt E, d'Ozouville N, Graham DW (eds) Geophysical Monograph Series. Wiley , Hoboken, NJ, pp 167–183. https://doi.org/10.1002/9781118852538.ch9

Vittecoq B, Brugeron A, Dewandel B, Gourcy L, Ollagnier S (2008) Étude réalisée dans le cadre des projets de Service public du BRGM 2007 EAUK14 [Study carried out as part of BRGM's public service projects 2007 EAUK14]. BRGM, Orleans, France

Vittecoq B, Reninger PA, Violette S, Martelet G, Dewandel B, Audru JC (2015) 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). J Hydrol 529:1041–1059. https://doi.org/10.1016/j.jhydrol.2015.09.022

Vittecoq B, Reninger P-A, Lacquement F, Martelet G, Violette S (2019a) Hydrogeological conceptual model of andesitic watersheds revealed by high-resolution heliborne geophysics. Hydrol Earth Syst Sci 23:2321–2338. https://doi.org/10.5194/hess-23-2321-2019

Vittecoq B, Reninger P-A, Lacquement F, Martelet G, Violette S (2019b) Hydrogeological conceptual model of andesitic watersheds revealed by high-resolution geophysics (preprint). Groundwater Hydrol/Instruments Observ Tech. https://doi.org/10.5194/hess-2018-637

Vittecoq B, Reninger P-A, Bellier V, Taïlamé A-L, Nacimento L, Gros E, Violette S (2023) Montagne Pelée volcano (Martinique, in the French Lesser Antilles) hydrogeological system revealed by high-resolution helicopter-borne electromagnetic imagery. Hydrogeol J. https://doi.org/10.1007/s10040-023-02642-5

Waitt RB (1989) Swift snowmelt and floods (lahars) caused by great pyroclastic surge at Mount St Helens volcano, Washington, 18 May 1980. Bull Volcanol 52:138–157. https://doi.org/10.1007/BF00301553

Walker GPL (1971) Grain-size characteristics of pyroclastic deposits. J Geol 79:696–714. https://doi.org/10.1086/627699

Walker GPL, McBroome LA (1983) Mount St. Helens 1980 and Mount Pelee 1902: flow or surge? Geology 11:571. https://doi.org/10.1130/0091-7613(1983)11<571:MSHAMP>2.0.CO;2

Westercamp D, Demians d'Archimbaud J, de Lapparent AF, Marinelli G, Tazief H (1972) Contribution à l'étude du volcanisme en Martinique [Contribution to the study of volcanism in Martinique]

Westercamp D, Pelletier B, Thibaut PM, Traineau H (1990) Carte Géol France (1/50 000), feuille Martinique - Orléans : Bureau de Recherches Géologiques et Minières. Notice explicative [Contribution to the study of volcanism in Martinique Geological Map], Bureau de Recherches Géologiques et Minières, NA

White WB (2003) Conceptual models for karstic aquifers. Re-Publ. Permis. Palmer MV, Sasowsky ID (eds) Karst model. Spec. Publ. 5, Karst Waters Institute, Charles Town, WVA, pp 11–16

Winograd I (1971) Hydrogeology of ash flow tuff: a preliminary statement. Water Resour Res 7

Yasuhara M, Hayashi T, Asai K, Uchiyama M, Nakamura T (2020) Overview of the special issue "Groundwater in Mt. Fuji (Part 2)." J Geogr Chigaku Zasshi 129:657–660. https://doi.org/10.5026/jgeography.129.657

Yoshimoto M, Fujii T, Kaneko T, Yasuda A, Nakada S, Matsumoto A (2010) Evolution of Mount Fuji, Japan: Inference from drilling into the subaerial oldest volcano, pre-Komitake: evolution of Mount Fuji. Isl Arc 19:470–488. https://doi.org/10.1111/j.1440-1738.2010.00722.x