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Original Research

The Viterbo Hydrothermal System and Its Sustainable Exploitation, Central Italy

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Abstract

Background: The Regione Lazio-Direzione Regionale dello Sviluppo Economico e delle Attività Produttive (RL–DRSEAP), carrying out its public functions to govern the use of mineral resources (including thermal water), planned the exploitation of the Viterbo hydrothermal system on the basis of a conceptual hydrogeological model (CHM). The CHMs of the Viterbo area and that of the neighboring Tuscany region, characterized by the same geological and hydrogeological setting, are discussed, suggesting the unreliability of the CHM model.

Methods: Research for the CHM for the Viterbo hydrothermal system was carried out on the basis of geological and hydrogeological surveys at a scale of 1:10,000. The equipotential level and temperature of 70 wells was checked and the yield and temperature of 14 springs (10 of thermal water and 4 of cold water) was measured by the volumetric method and use of a digital thermometer in 2017, while the yield of the Bullicame spring has been monitored by the Municipality of Viterbo since March 2001 using an ultrasonic instrument.

Results: The proposed alternative CHM shows that the Viterbo hydrothermal system is experiencing a continuous hydric crisis. This is documented by the decreasing residual yield of springs, boreholes, and wells of thermal water over the last 162 years, due to natural factors and the indiscriminate drilling of many wells over the last 67 years. At present the total yield is 61 L/s, *i.e.* the maximum sustainable yield, and it is very likely that this yield will continue to decrease in the future.

Conclusions: The RL - DRSEAP should avoid using the unreliable CHM for the exploitation of geothermal resources. High resolution reflection seismic prospecting, seismic and geo electric tomography, and the radionuclides of the noble gases ^{39}Ar, ^{81}Kr, and ^{85}Kr could be useful to check the proposed alternative CHM.

Keywords

Conceptual hydrogeological model; hydrothermal system; Viterbo; aquifer; maximum sustainable yield

1. Introduction

The installed capacity for electricity production through geothermal energy and power in geothermal plants in 24 countries worldwide increased from 6,832 MW in 1995, to 8,983 MW in 1995, to 12,635 MW in 2015, and is expected to increase to 21,443 MW in 2020 [1-3]. The top countries according to the 2016 Annual U.S. & Global Geothermal Power Production Report (www.geo-energy.org) are the United States (3,567 MW), the Philippines (1,930 MW), Indonesia (1,375 MW), Mexico (1,069 MW), New Zealand (973 MW), and Italy (944 MW). In Europe the top countries in 2018 were Turkey (1300 MW), Italy (944 MW), and Iceland (750 MW) (https://www.eg ec.org/media-publications/egec-geothermal-market-report-2018/).

According to the International Energy Agency (https://www.iea.org/topics/renewables/geo thermal/), the global geothermal power capacity is expected to rise to just over 17 GW by 2023, with the biggest capacity additions expected in Indonesia, Kenya, the Philippines, and Turkey.

Italy is the first country in the world to cultivate geothermal energy as a renewable resource for industrial uses and for the production of electricity; a former experiment for power generation in Italy was carried out at Larderello in 1904. Studies on geothermal resources have been developed in the last century in central Italy by Terni Company in Conforto [4], the Italian energy provider Enel in Consiglio Nazionale delle Ricerhe, Calamai et al., Cataldi et al. [5-8], Eni - Agip in Ministero dell'Industria, Commercio e Artigianato [9], and Calore et al., Della Vedova et al., and Barbieri et al. [10-15]. Geothermal exploration focused essentially along the peri-Tyrrhenian belt in Latium (Viterbo hydrothermal system) and Tuscany regions with a thin continental crust, where Pliocene-Pleistocene magmatic activity and high heat flow occurred. These areas are characterized by the same geological and hydrogeological settings and by the exploitation of the geothermal resource for the production of electric power [8, 15]. Thus, several conceptual hydrogeological models (CHMs) have been proposed [4, 6, 16-25].

Italy is now experiencing a renewed interest for geothermal energy due to either the growth of energy demand, or the need to reduce CO_2 emissions. In fact, 108 new research permits have been requested by private companies, 34 in Lazio region alone (http://unimig.sviluppoecnom ico.gov.it/unimig/istanze). Furthermore, the 2007-2013 VIGOR Project (Evaluation of the Geothermal Potential of the Regions of Convergence; www.vigor.geotermia.it) proposed by the Ministero dello Sviluppo Economico and Consiglio Nazionale delle Ricerche-Dipartimento Terra e

Ambiente is aimed at the promotion of innovative interventions related to the use of geothermal energy starting from the Calabria, Campania, Puglia, and Sicilia regions of southern Italy.

The Regione Lazio-Direzione Regionale dello Sviluppo Economico e delle Attività Produttive, which according to the law has the public function of governing the use of mineral resources including thermal water, financed with something like 250,000 euros the study on the CHM of Baiocchi et al. [21, 22], to plan the exploitation of the Viterbo hydrothermal resource, actually used for therapeutic purposes at the Spa of Popes and Salus Spa & Resort. As described later, the study of Baiocchi et al. [21, 22] is totally unreliable. Thus, the present study, after examining the proposed conceptual hydrogeological model, proposes an alternative CHM for the sustainable exploitation of the Viterbo hydrothermal system.

2. Materials and Methods

The study operations for the CHM of the hydrothermal system were carried out in three phases. The first phase involved indirect investigation through the acquisition of the following milestones: (1) historical data on the thermal springs, boreholes, and wells from the literature (Conforto, Camponeschi and Nolasco) [4, 26], and (2) the analysis of 70 wells from the data base of the Istituto Superiore per la Protezione e la Ricerca Ambientale (ISPRA) and Provincia di Viterbo. The second phase base allowed the definition of the geological and hydrogeological settings of the hydrothermal system at a scale of 1:10,000 on the base of the surveying carried out since 2001 for sheets 345 "Viterbo"(ISPRA) [27] and 355 "Ronciglione" (ISPRA) [28] of the Geological Map of Italy at scale 1:50,000. The hydrogeological map was surveyed according to the standards of Servizio Geologico d'Italia [29]. During the third phase in 2017 the equipotential level and temperature of groundwater in the 70 wells were checked and the yield and temperature of 14 springs (10 of thermal water and 4 of cold water) were measured by volumetric method and digital thermometer. In particular the Bullicame spring yield is monitored by the Municipality of Viterbo since March 2001 by both an ultrasonic instrument inserted in the pipeline that carries thermal water to Spa of Popes, and a similar instrument inserted at the outlet of the pipeline into the swimming pool of the Spa of Popes. In addition, the measurement is carried out at the entrance of thermal water into the swimming pool of the Spa of Popes by the volumetric method. Pictures of the main thermal springs, dried thermal springs, boreholes, wells, and travertines due to dried thermal springs are provided as Supplementary material.

2.1 Geological and Hydrogeological Setting

The Viterbo geothermal area, about 12 km long and 1.5 - 2 km wide, is located in the western sector of the Cimini Mountains (Figure 1), consisting of volcanic rocks produced by the districts Cimino of lower Pleistocene (1.35 - 0.8 Ma; acid cycle of the Tuscan Magmatic Province) and Vico of middle–upper Pleistocene (0.5 - 0.09 Ma; silica under-saturated k-alkaline cycle of the Roman Magmatic Province; Figure 2). The thickened, folded and thrusted substrate consists from top of the Pliocene-Pleistocene clayey and subordinately sandy shallow marine sediments, the Ligurian units, including the and upper clayey-calcareous member, and the Oligocene Poggio S. Benedetto Sandstone, and Mesozoic carbonate formations of the Tuscan Nappe and Umbria Marche Succession. NW- and NE- striking extensional faults, which affected the peri-Tyrrhenian belt of central Italy during Neogene (Consiglio Nazionale delle Ricerche) [30], formed horst and graben structures. Neogene–Quaternary marine to continental deposits fill the structural lows of the

Mesozoic–Cenozoic substrate [15, 16]. The thinning of the continental crust and the related magmatic cycles, which were active in the peri-Tyrrhenian belt in Pliocene-Pleistocene, generated strong regional heat flow with values of 200 - 300 mW/m^2 up to 450 mW/m^2 in some areas [6, 8, 14]. This belt is also characterized by notable CO_2 emissions which control the travertine deposition, in particular in the Viterbo geothermal area (Minissale et al., Manfra and Masi, and Minissale and Duchi) [17, 31-33].

The Cimino and Vico volcanic rocks make up a shallow aquifer system bounded by the Pliocene–Pleistocene sediments and upper Cretaceous–Eocene Ligurian units. This system consists of a continuous basal aquifer (Boni et al., Baiocchi et al., Capelli et al.) [34-36], which discharges into streams and springs.

The deep aquifer consisting of the Mesozoic–Cenozoic carbonate rocks hosts a geothermal reservoir [6, 16, 20-22]. The shallow and deep aquifers, separated by thick impervious Pliocene and upper Cretaceous–Eocene Ligurian units, are uplifted in the Viterbo area and along with high heat flow cause the upwelling of thermal water via normal faults.

Thus, the Cimino and Vico volcanic districts and the Viterbo area are considered of great geothermal interest (category A1 with temperature > 200 °C) [8]. Furthermore, it should be noted that in the geothermal area of Viterbo there are 4 mining concessions for the exploitation of thermal water issued by the Regione Lazio- Direzione Regionale dello Sviluppo Economico e delle Attività Produttive: Bullicame and Bagnaccio to the Municipality of Viterbo, Paliano to the Free Time Srl, and Oasi to Fenis Immobiliare.

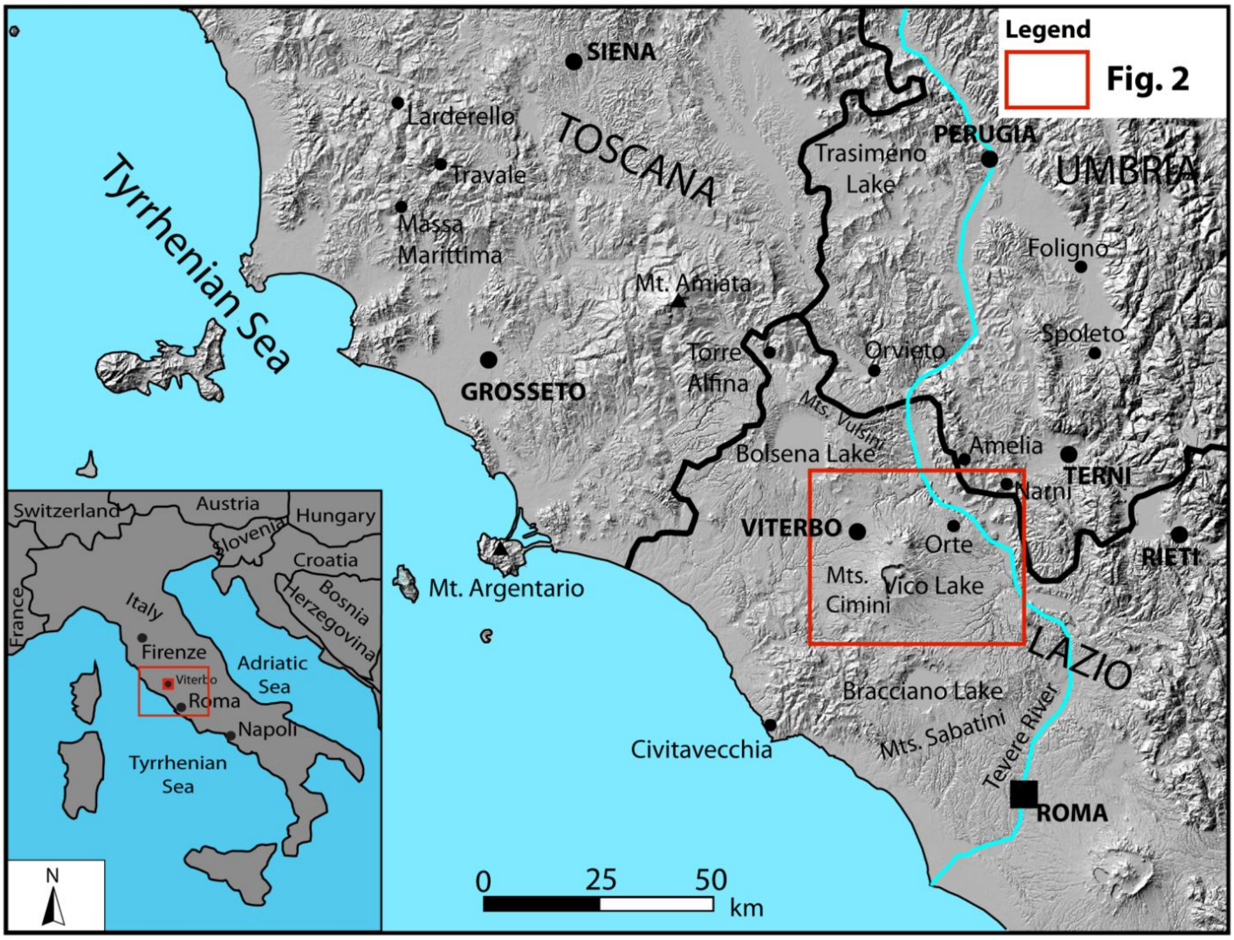


Figure 1 Location of the study area.

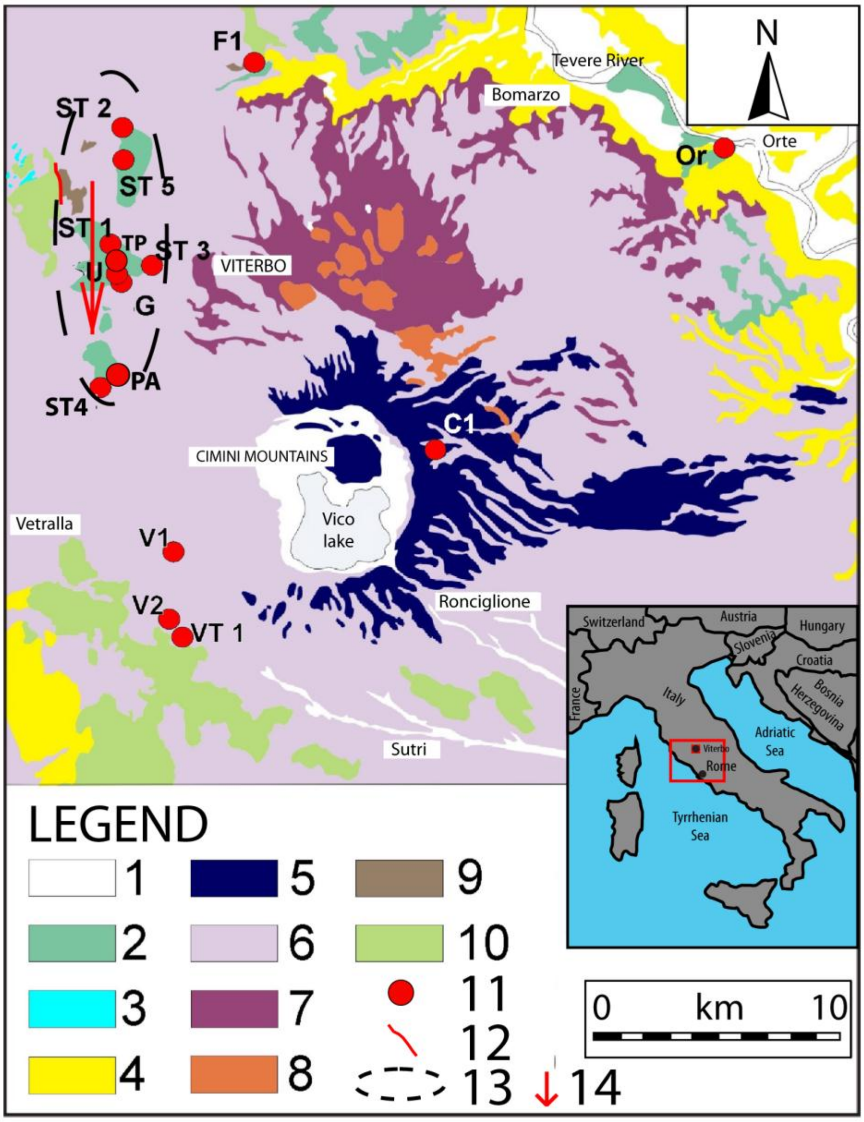


Figure 2 Geological map showing the Cimino and Vico volcanic districts, the Viterbo geothermal area, delimited in the upper left between boreholes ST2 and ST4, and the flow of thermal water from north to south indicating that the recharge area of thermal water cannot be located in the Cimini Mountains. **1,** alluvial deposits (Quaternary); **2,** travertines of the Bullicame Unit (Holocene); **3,** travertines of the Case Castiglione Unit (Holocene); **4,** mainly clayey sediments (impervious complex; upper Pliocene-lower Pleistocene); **5,** post-caldera products of the Vico district (volcanic aquifer; middle-upper Pleistocene); **6,** tuffs and lavas of the pre - caldera activity of the Vico district (volcanic aquifer; middle-upper Pleistocene); **7,** ignimbrites of the latter phase of the Cimino district (volcanic aquifer; lower Pleistocene); **8,** domes of the former phase of the Cimino district (volcanic aquifer; lower Pleistocene); **9,** Poggio S. Benedetto Sandstone (impervious complex; Oligocene); **10,** Tolfa Flysch (impervious complex; upper Cretaceous-Eocene); **11,** borehole: ST1, ST2, ST3, ST4, ST5 of Terni Company; F1, V1, V2, Vt1, C1 of Enel; U and G wells of ex Spa INPS; TP well of Spa of Popes; PA (= Paliano 1 of Figure 4a) and Or wells of private owners; **12,** normal fault; **13,** boundary of geothermal area; **14,** flow of thermal water. Units 4 - 10 are referred to the respective hydrogeological complexes shown in Figure 4.

2.2 The Proposed CHMs

These models are described in chronological order (Figure 3). Conforto [4] built a suitable stratigraphic and tectonic setting of the Viterbo area (Figure 3a) thanks to the geological survey, geophysical prospecting and five boreholes for geothermal research by Terni Company. The Author produced three sections that show (from the top) the Pleistocene pyroclastic rocks, the lower Pliocene clay, and a structural high consisting of the Cretaceous-Oligocene flysch complex overlying the Mesozoic carbonate succession affected, by normal faults, respectively. The pyroclastic rocks host cold water, while thermal water derived from the Mesozoic carbonate rocks "*do not penetrate the flysch complex characterized by minimal permeability,*" flows upwards through the normal faults to the contact between the pyroclastic rocks and flysch complex where it accumulates, penetrating through the discontinuities of the pyroclastic rocks, mixing with the cold water and feeding the thermal springs.

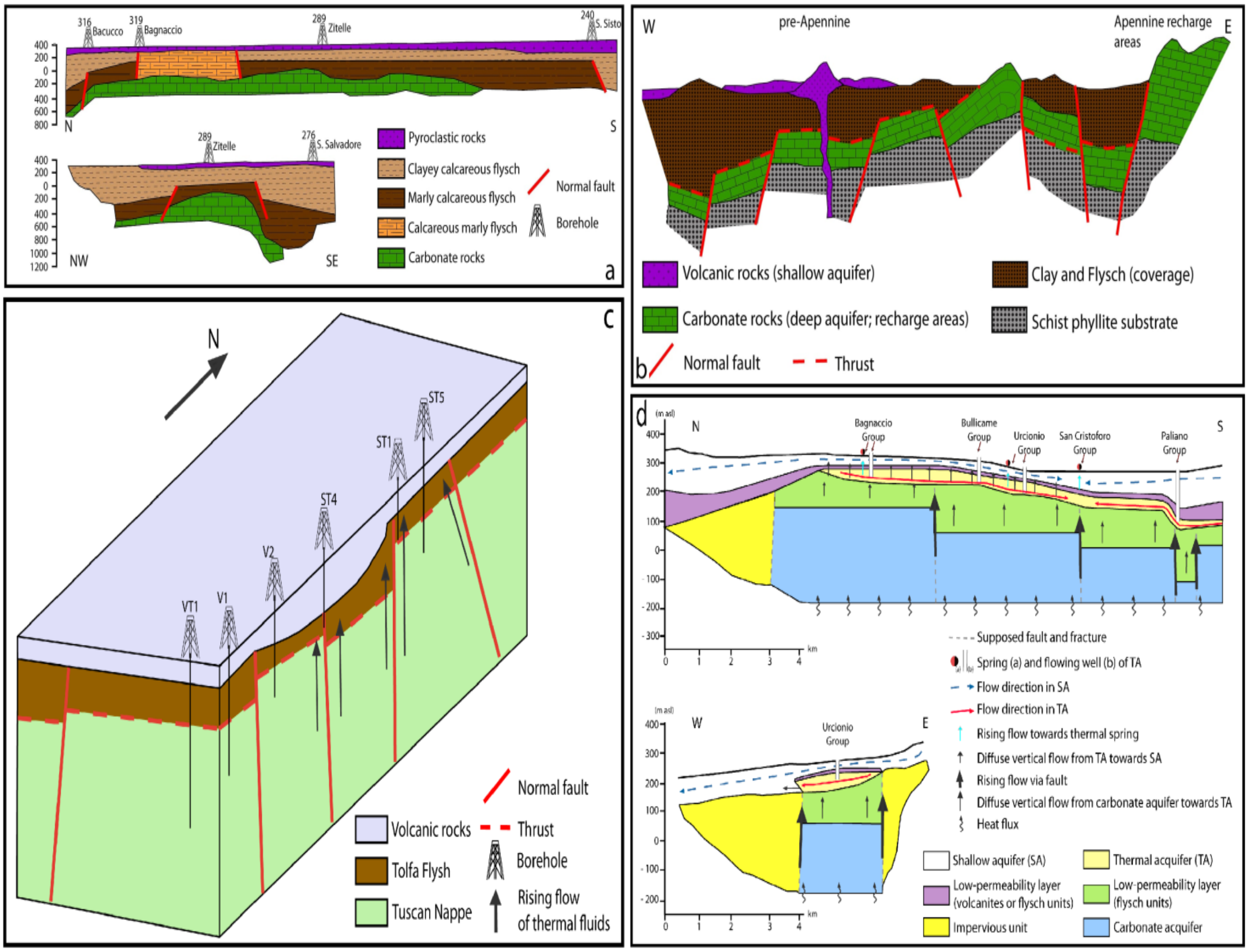


Figure 3 The conceptual hydrogeological models proposed for the Viterbo hydrothermal system. **a)** [4]; **b)** [6]; **c)** [20]; **d)** [21, 22].

Calamai et al. [6] proposed a CHM of the pre - Apennine belt of Tuscany and Latium regions (Figure 3b) including from top the Quaternary volcanic surface aquifer, the "*coverage*" consisting of the Neogene post-orogenic complex, the Paleogene Tuscan and Umbria calcareous marly complex and the Jurassic-Eocene flysch complex, the confined Mesozoic carbonate aquifer and the schist phyllite substrate. The recharge areas or "*absorbing areas*" are made up of the carbonate Mesozoic Umbria Marche Succession of central Apennines.

Buonasorte et al. [16] adopted for the Torre Alfina geothermal area, located about 40 km NW of Viterbo (Latium region; Figure 1), a CHM similar to that of Calamai et al. [6], performing a specific evaluation of the possible supply of water of the flysch complex (the same as Tolfa Flysch) defined "coverage." Considering a leakage toward the carbonate aquifer of Tuscan Nappe and a value of the hydraulic conductivity of 10^{-9} m/s, they showed applying Darcy's law that the contribution of the flysch complex toward the carbonate aquifer was 3.11 L/s, which is an insignificant supply. The recharge area is referred to the carbonate Mesozoic Tuscan Nappe of Mount Cetona (very similar to the coeval Umbria Marche Succession).

According to Minissale et al. [17], the Mesozoic limestone aquifer is recharged in the main area of central Apennines (Umbria and Marche regions; Figure 1) and groundwater flowing westward are conductively heated incorporating large quantities of CO_2 that is discharged in hot springs forming travertines.

Piscopo et al. [18] proposed that the shallow heterogeneous and anisotropic volcanic aquifer of the Cimini Mountains and Viterbo hydrothermal system (Figure 2) is limited at its bottom by the semi - confining low permeability flysch complex and lower Pliocene clay and it is fed from the Cimini Mountains. Thermal water is connected to deep circulation within the carbonate aquifer and have the same recharge area of the volcanic aquifer.

The research of Senarum Universitatis [19] in the Mt. Amiata area (Tuscany region), located about 80 km NW of Viterbo (Figure 1), concluded that the volcanic and carbonate aquifers are hydraulically separated by the impervious flysch complex and the lower Pliocene clay. This interpretation was confirmed by Mannoni et al. and Sbrana et al. [37, 38].

The CHM of the Viterbo hydrothermal system according to [20] (Figure 3c) consists of a volcanic aquifer with cold and mixed waters hydraulically separated by the impervious flysch complex from the deep carbonate aquifer hosting thermal fluids, whose recharge area is located in the carbonate aquifer of the Umbria Marche Succession in central Apennines.

Baiocchi et al. [21, 22], in agreement with Piscopo et al. [18], carried out research on the CHM of the Viterbo hydrothermal system (Figure 3d) including a shallow volcanic aquifer (SA) and a thermal aquifer (TA) which is hosted in the volcanic rocks at the contact with the flysch units or within the upper portion of these units. The two aquifers are separated by a low permeability layer of hydrothermally altered pyroclastic deposits or clayey layers of flysch units with a thickness of a few meters to tens of meters. These aquifers are separated from the carbonate aquifer by a low permeability layer of flysch units with relatively reduced thickness. There is diffuse vertical flow from the carbonate aquifer towards the thermal aquifer (TA) through the flysch units (*i.e.* an aquitard) and from this last one to the volcanic aquifer (SA). The TA has a thickness of 60 m, hydraulic conductivity values of 10^{-4} – 10^{-5} m/s, a yield of 170 L/s, and thermal water flows from N to S and from S to N. The recharge area of the three aquifers is located in the Cimini Mountains. This research on the CHM was adopted also by Comune di Viterbo [39].

Cinti et al. [23, 24] proposed a conceptual hydrogeological model almost identical to that of Baiocchi et al. [21, 22].

Chiocchini and Manna [25], in agreement with the CHM of [20], point out that the total yield of the hydrothermal system is experiencing a hydric crisis over 160 years.

2.3 Difference between the Proposed CHMs

The conceptual hydrogeological models described above are of two types: the first CHM is shown in Figure 3a [4], in Figure 3b (Calamai et al., Buonasorte et al., Minissale et al., Marroni et al., Sbrana et al.) [6, 16, 17, 19, 37, 38] and in Figure 3c [20, 25]; the second CHM is shown in Figure 3d [18, 21-24]. These types of models differ for three fundamental reasons: (1) the hydrogeological role of the flysch units (Tolfa Flysch) between the shallow volcanic aquifer and the deep carbonate aquifer that hosts the thermal fluids; (2) the non-existence of the thermal aquifer (TA); (3) the recharge area of the deep carbonate aquifer. The second CHM (Figure 3d) is totally unreliable due to the following reasons [40]:

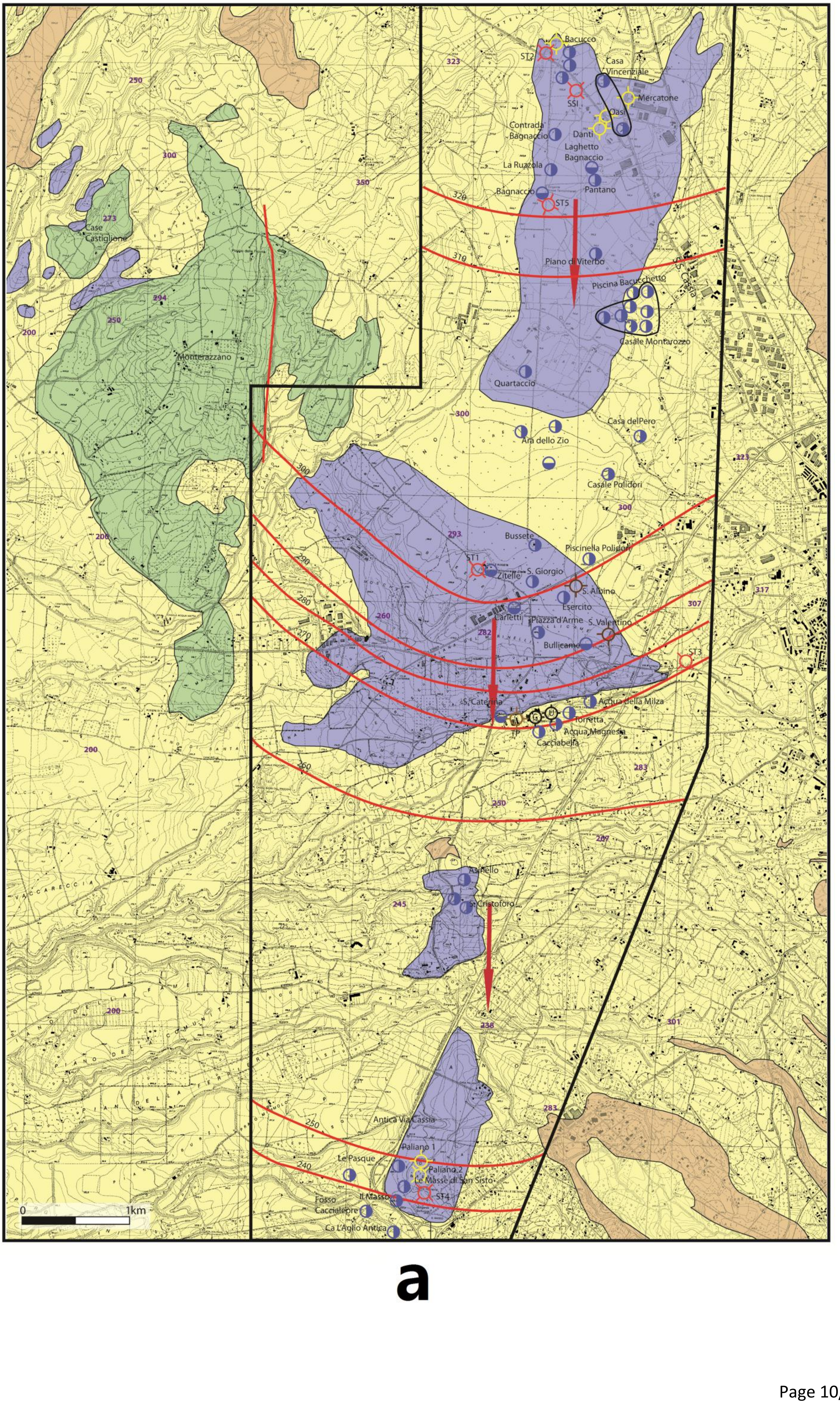
- The longitudinal geological section does not reflect the actual stratigraphic-structural framework of the hydrothermal system.
- The 60 borehole logs, on which the reconstruction of the conceptual hydrogeological model is based, have been improperly manipulated providing a totally incorrect interpretation. In fact, these logs highlight very clearly that: (1) the volcanic rocks (tuffs) are locally impregnated with travertine but are completely devoid of hydrothermal weathering resulting in production of clay; (2) there is no evidence of locally fractured flysch units and of a low-permeability layer made up of isolated clayey layers of the flysch units. Thus, the thermal aquifer (TA) is the artificial invention for a hydrogeological complex scenario that does not exist.
- The flysch units (Tolfa Flysch), with minimal hydraulic conductivity (10^{-9} – 10^{-8} m/s; [18]) and thickness ranging from 120 m and more than 200 m in the Viterbo hydrothermal system to 850 m in Cimini Mountains, are unfit to transfer significant volumes of water. Consequently, the flysch units are not an aquitard and there is no vertical diffused flow through them either from the carbonate aquifer to the volcanic aquifer, nor from the TA to SA.
- The TA, SA, and aquitard cannot be considered homogeneous with respect to their physical properties (hydraulic conductivity, porosity, heat capacity, thermal conductivity). In fact, not only is this assumption strongly in contrast with the former opinion of Piscopo et al. and Baiocchi et al. [18, 35], but the very different lithological and fracturing characteristics of the TA, SA, and aquitard suggest that at least their hydraulic conductivity and porosity cannot be referred to as homogeneous.
- The equipotential lines of the TA oriented NW - SE are wrong because their trend is W – E, and in the southern zone the equipotential line 240 m asl is located north of the equipotential line 250 m asl, but the correct position of this line is south. The wrong position is aimed at demonstrating that thermal water in the southern zone flows from south to north and that the recharge area is located in the Cimini Mountains SE of hydrothermal system.
- The thickness and hydraulic conductivity values of the TA are unrealistic. The potential yield of the TA has been estimated at 250 L/s by [21], and 200 L/s by Baiocchi et al. [22], resulting in a mysterious 50 L/s loss of potential flow from 2012 to 2013. Without taking this inconsistency into account, the value according to Baiocchi et al. [22] (200 L/s) must be considered incorrect because the thermal water flows only from N to S; thus, a TA yield of 170 L/s is unrealistic.
- The recharge area of the hydrothermal system cannot coincide with the Cimini Mountains that are located SE of the Viterbo geothermal area because the thermal water flows from north to south.

3. Results

3.1 The Alternative CHM

Two separate hydrogeological maps of the hydrothermal system, including the complex of travertines, the pyroclastic complex, the pyroclastic-lava complex and the flysch complex (Tolfa Flysch; Figure 4c), have been surveyed to describe the thermal water (Figure 4a) and the volcanic aquifer (Figure 4b), in order to clearly show their equipotential lines. In addition, 3D conceptual hydrogeological models of the hydrothermal system (Figure 5) and the recharge area of central Apennine have been produced (Figure 6), bearing in mind the surface geology, the geophysical data [20] and the borehole logs (Figure 7 and Figure 8). The complex of travertines, consisting of four outcrops of the Bullicame Unit (one in the northern zone, one in the central zone and two in the southern zone; Figure 4) with a thickness between 15 m and 23 m that pinches out laterally, is characterized by a medium-high degree of relative permeability, due to porosity and fracturing. This complex has a very low importance, because almost all rainwater flows vertically to the underlying volcanic aquifer. Despite the medium-high degree of relative permeability due to fracturing, the pyroclastic-lava complex, consisting of the Cimina Ignimbrite and leucitite lavas, has also a low significance, due to its limited outcrops. The pyroclastic complex, consisting of the Vico Red Tuff with Black Scoriae and Vico Varicoloured Bedded Tuffs, dated respectively 0.150 and 0.420 Ma (Laurenzi and Villa) [41], has a medium-high degree of relative permeability due to porosity and fracturing and shows impregnation of travertine either at the contact with the five bodies of Bullicame Unit, or at a depth marked by the boreholes of Terni Company ST1 Zitelle, ST5 Bagnaccio and wells U Uliveto and Paliano 1 (Figure 4a). The overall thickness of the pyroclastic complex inferred by the boreholes of Terni Company [4] ranges from 50 m in borehole ST2 Bacucco in the northern zone up to 165 m in borehole ST4 S. Sisto in the southern zone (Figure 4a). The flysch complex with a thickness of 120 m up to more than 200 m is characterized by the minimal values of hydraulic conductivity, *i.e.* 10^{-8} - 10^{-9} m/s defined by [18, 35], resulting in an impervious complex (Figure 4b). These values are the same as that determined by Buonasorte et al. [16] for the same flysch complex of Torre Alfina.

The pyroclastic complex, whose hydraulic conductivity has a value of the order of 10^{-5} m/s and the transmissivity of the order of 10^{-3} m^2/s [21, 22], forms the volcanic aquifer which is characterized by high heterogeneity and anisotropy, as also recognized by Piscopo et al. and Baiocchi et al. [18, 35], due to its different lithological composition and degree of fracturing. The volcanic aquifer, whose horizontal hydraulic gradient is 0.01, hosts bicarbonate-alkaline-earth water with temperatures ranging from 16.6° to 20°C and mixed water of sulphate-alkaline-earth type with temperatures of 26.5°- 45°C [4, 18, 22-24, 30]. Three springs have a yield of 0.07-2.7 L/s with temperatures of 18°- 19°C, while the Pidocchio spring yield of 10 L/s with temperature of 17°C is tapped for public water supply. 54 wells withdraw cold water with temperatures of 17° - 20°C and 16 wells with mixed waters with temperatures of 26.5° - 45°C, essentially for irrigation in agriculture (Figure 4b). A subsurface divide, consisting of the flysch complex outcropping at Monterazzano, allows groundwater to flow toward the NE in the northern zone and SW in the central-southern zone (Figure 4b and Figure 5a). The recharge area is located in the Cimini Mountains including Viterbo area.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Pantano
ST5
Piano di Viterbo
Piscina Bacucchetto
Casale Montarozzo
Quartaccio
Ara dello Zio
Casa delPero
Casale Polidori
Case Castiglione
Monterazzano
Bussete
Piscinella Polidori
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Zitelle
S. Giorgio
S. Albino
Esercito
Carletti
Piazza d'Arme
S. Valentino
Bullicame
ST3
S. Caterina
Acqua della Milza
Torretta
Acqua Magnesia
Cacciabella
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Asinello
S. Cristoforo
Antica Via Cassia
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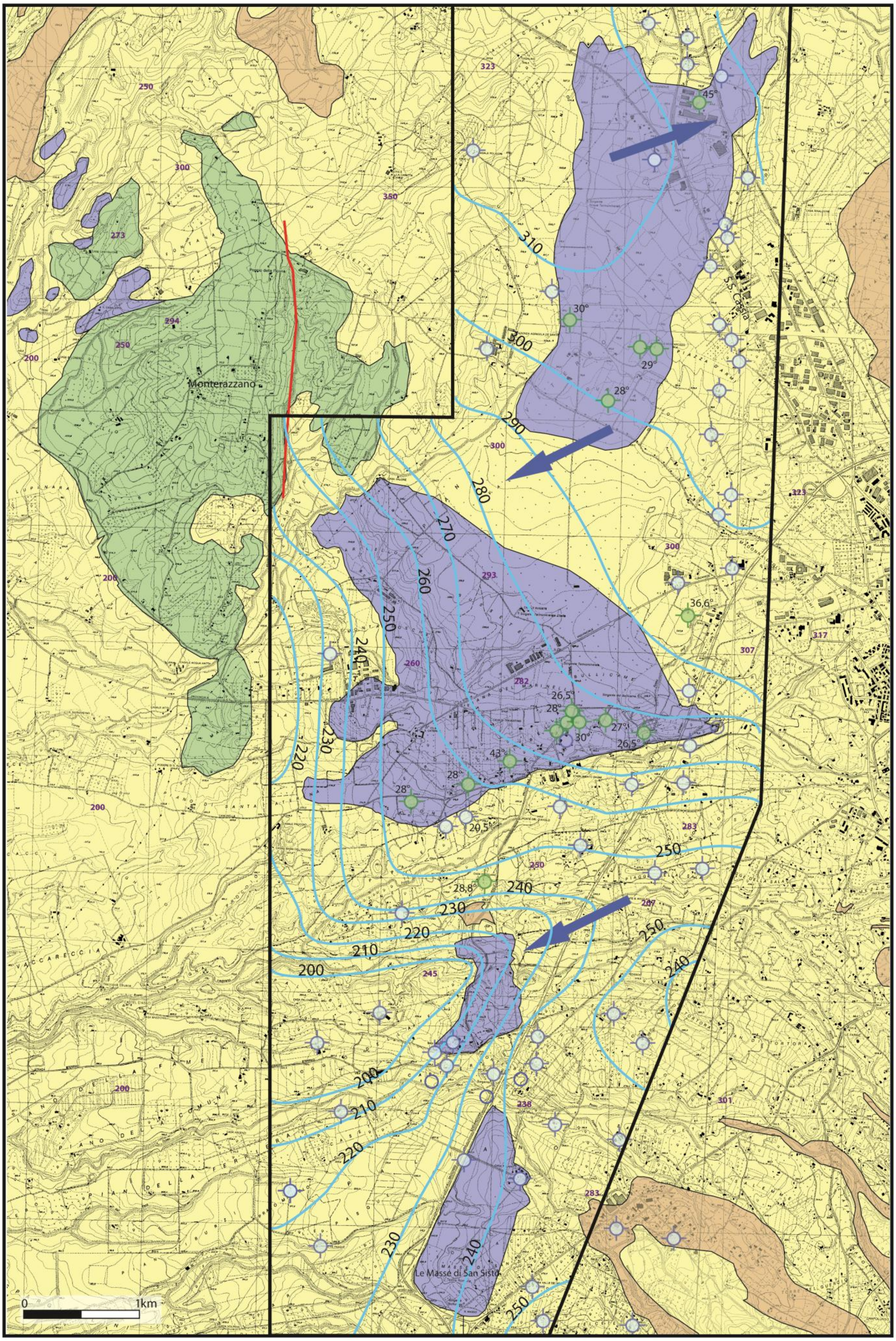
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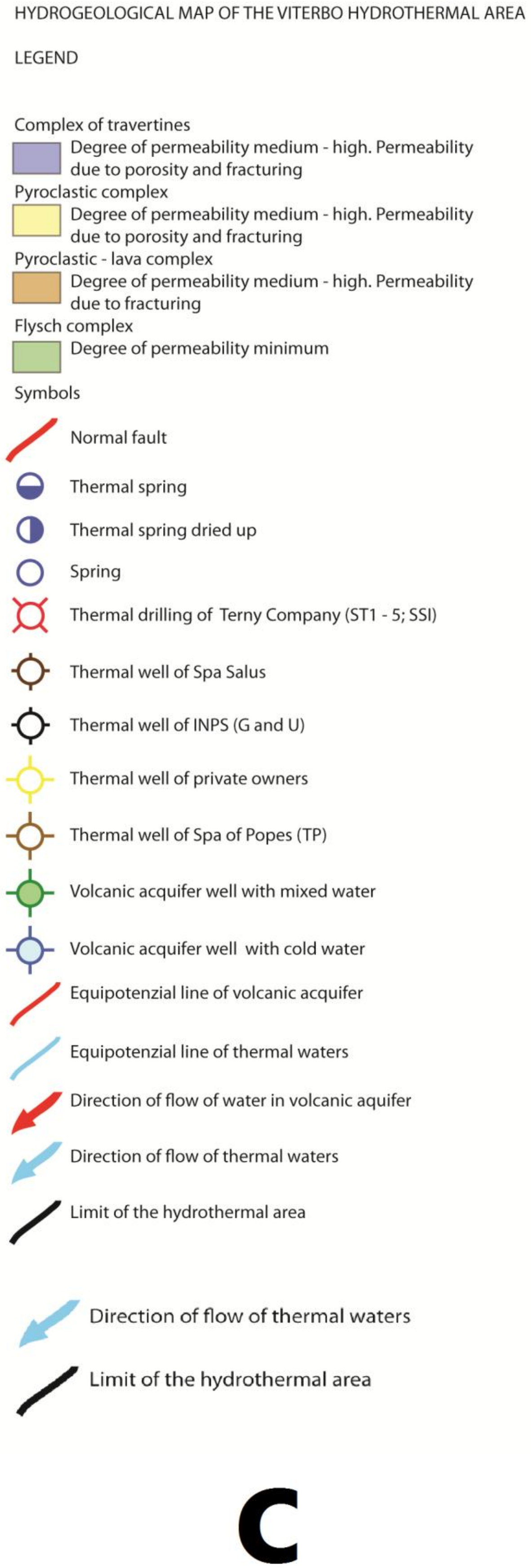

Figure 4 Hydrogeological map of the thermal water (a) and volcanic aquifer (b), and legend (c).

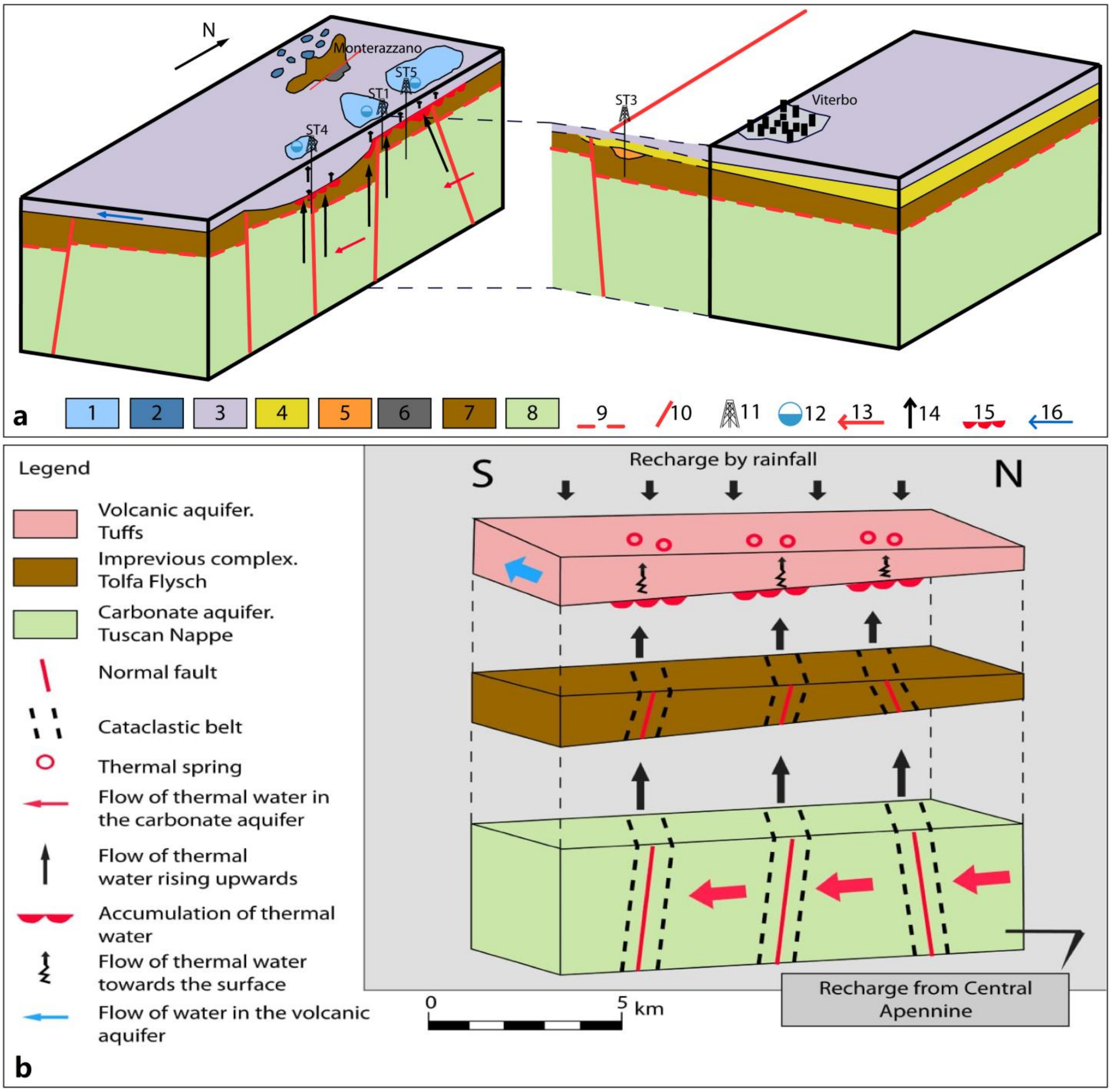

Figure 5 (a) 3D conceptual hydrogeological model of the Viterbo hydrothermal system. **1**, travertines of the Bullicane Unit (Holocene); **2**, travertines of the Case Castiglione Unit (Holocene); **3**, mainly pyroclastic rocks of the Cimino and Vico districts (volcanic aquifer; middle-late Pleistocene); **4**, clay (impervious complex; lower Pliocene); **5**, Manciano Sandstone (upper Messinian); **6**, Poggio S. Benedetto Sandstone (impervious complex; Oligocene); **7**, Tolfa Flysch (impervious complex; upper Cretaceous-Eocene); **8**, Tuscan Nappe (carbonate aquifer; upper Triassic-Paleogene); **9** thrust; **10**, normal fault; **11**, borehole; **12**, spring of thermal water; **13**, direction of flow of thermal water; **14**, flow of thermal water rising upwards; **15**, thermal water accumulated at the base of volcanic aquifer; **16**, flow of groundwater in the volcanic aquifer. **(b)** The simplified 3D conceptual model shows the volcanic aquifer separated from the carbonate aquifer of Tuscan Nappe through the impervious layer of Tolfa Flysch, the recharge of the aquifers, the flow and accumulation of thermal water at the base of volcanic aquifer and rising upwards as far as the surface, and the flow of water in volcanic aquifer.

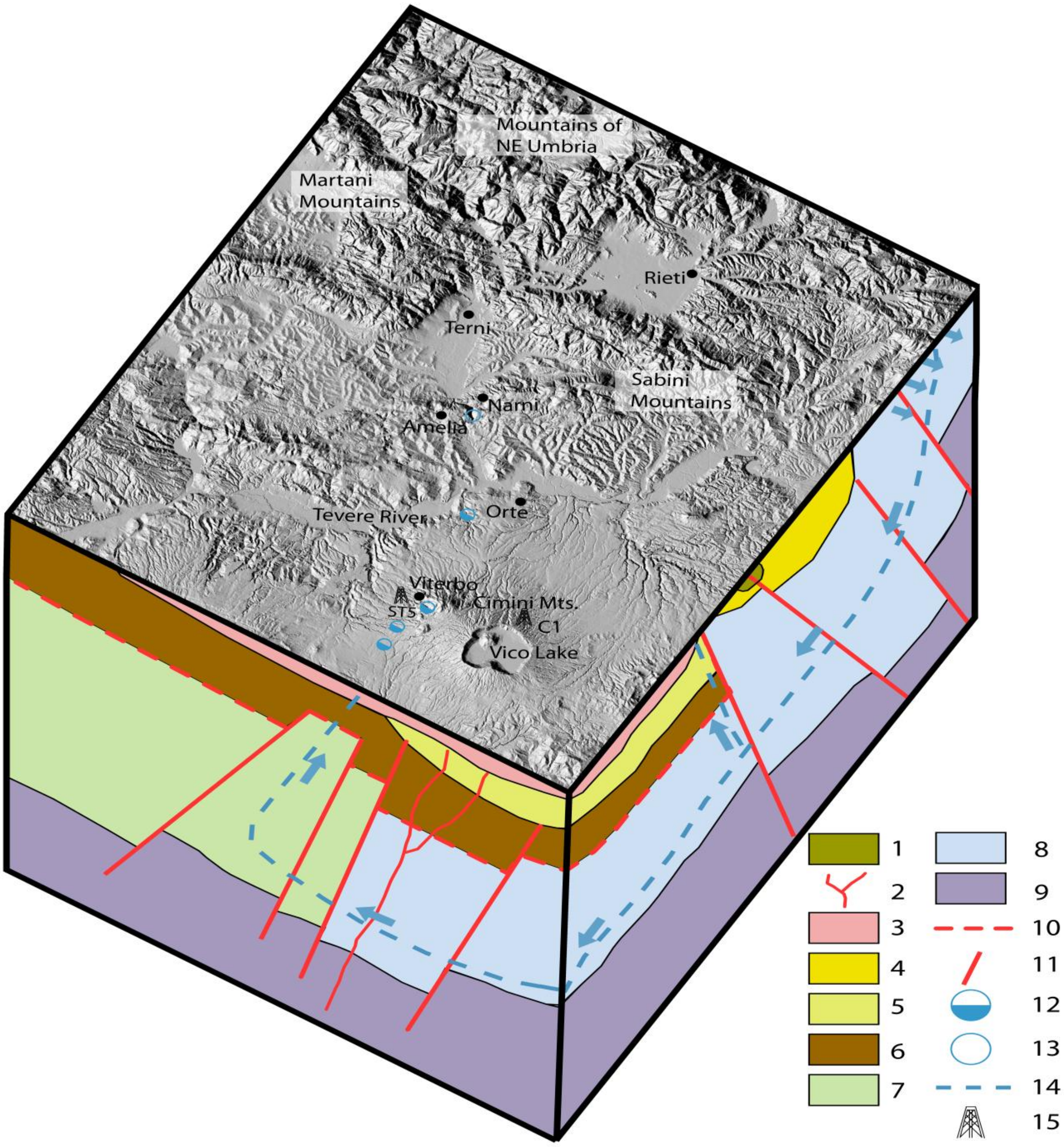

Figure 6 3D overall conceptual hydrogeological model showing the Viterbo hydrothermal system (front section), the recharge area of central Apennine including the mountains of Narni-Amelia, the Sabini Mountains, the Martani Mountains and the mountains of north eastern Umbria with their hydrogeological complexes (symbols 1 - 9), and the circuit that feeds the hydrothermal system (dashed lines in blue). **1,** alluvial sediments (surface aquifer; Quaternary); **2,** magma intrusions of the Cimino and Vico districts (Pleistocene); **3,** volcanic rocks of the Cimino and Vico districts (volcanic aquifer); **4,** clays (impervious complex), sands and gravels (surface aquifer) (Pleistocene); **5,** clayey sediments (impervious complex; lower Pliocene); **6,** Tolfa Flysch (impervious complex; upper Cretaceous-Eocene); **7,** Tuscan Nappe (carbonate aquifer; upper Triassic - Paleogene); **8,** Umbria Marche Succession (carbonate aquifer; upper Triassic-Paleogene); **9,** schist phyllite substrate (impervious complex; Permian); **10,** thrust; **11,** normal fault; **12,** spring of thermal water; **13,** springs of the Nera River; **14,** circuit of groundwater; **15,** borehole: ST5 of Terni Company; C1 of Enel.

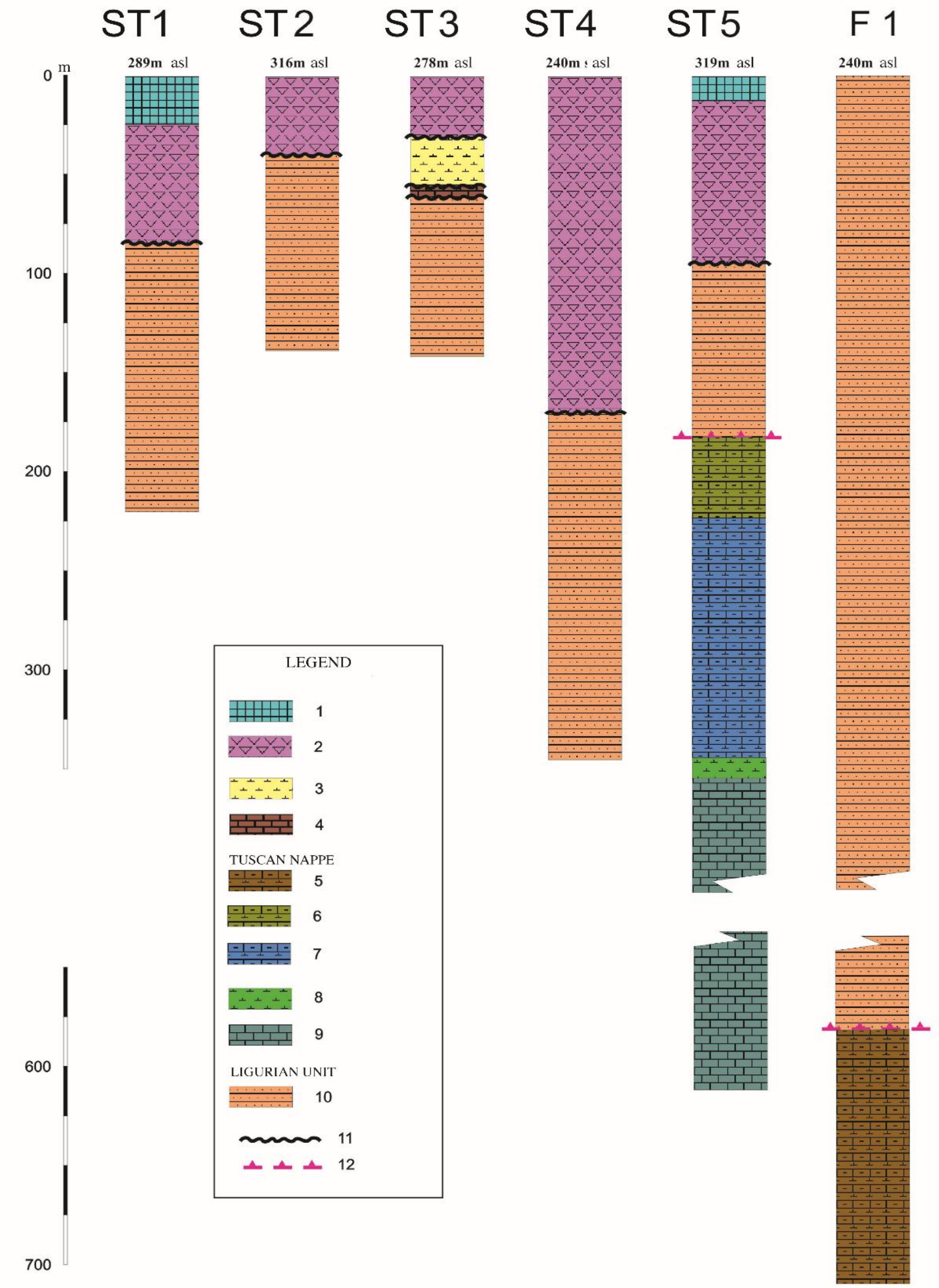

Figure 7 Stratigraphic logs of the Terni Company (ST1 – ST5) and Enel (F1) boreholes. **1,** travertines (Holocene); **2,** pyroclastic rocks of the Vico District (middle-upper Pleistocene); **3,** Fosso di S. Savino unit (clays; lower Pliocene); **4,** Manciano Sandstone (skeletal calcarenites; upper Messinian); **5,** Scaglia (marly limestones; upper Cretaceous–Paleogene); **6,** Diaspri (cherts; Dogger-Malm); **7,** Calcari selciferi (limestones with chert; middle-upper Liassic); **8,** Rosso ammonitico (marls and marly limestones; lower Liassic); **9,** Calcare massiccio (limestones; lower Liassic); **10,** Tolfa Flysch (shales, marls, marly and siliceous limestones, calcarenites; upper Cretaceous-Eocene); **11,** unconformity; **12,** thrust.

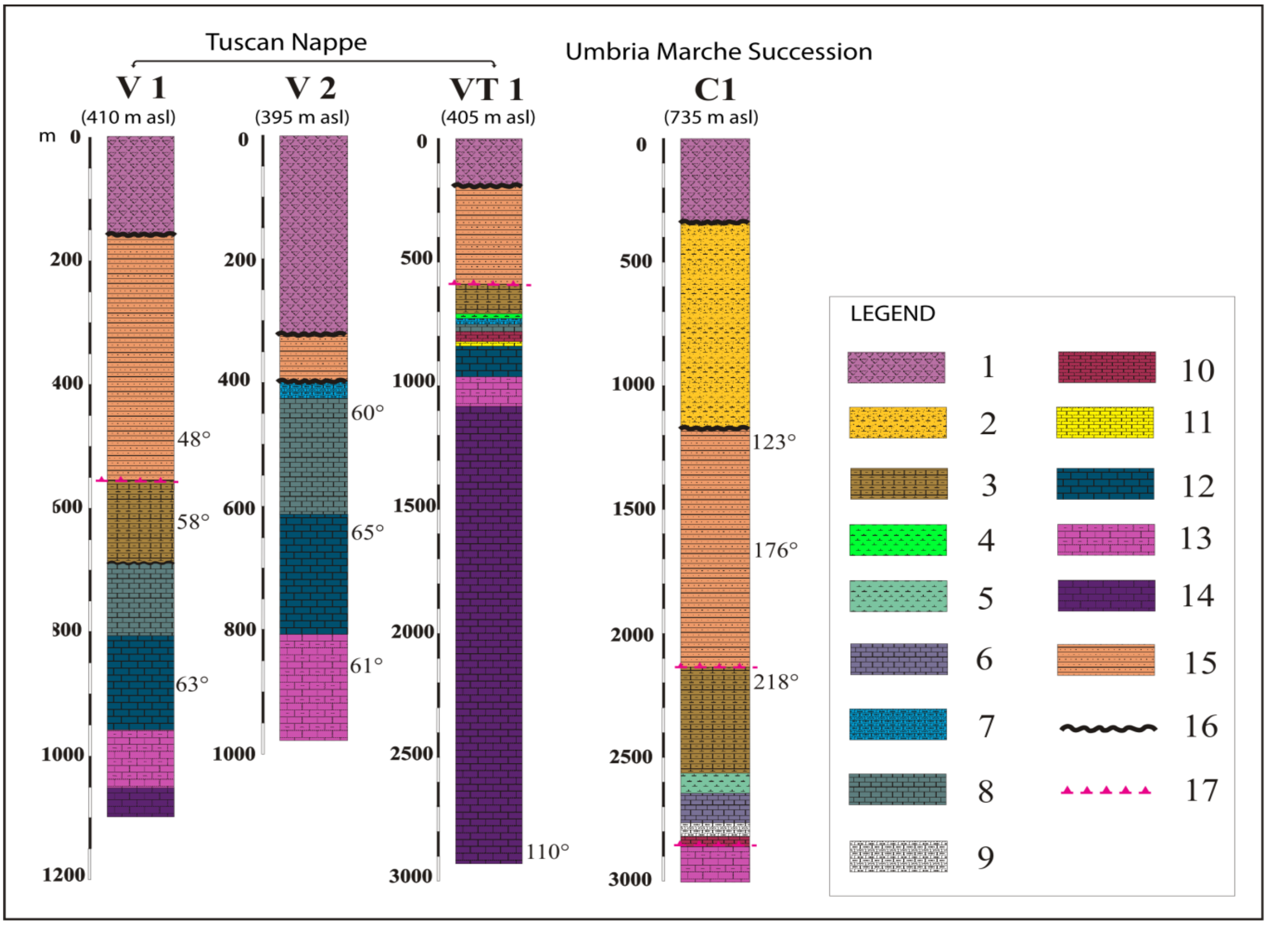

Figure 8 Stratigraphic logs of the Enel boreholes with temperatures measured at different depths. **1,** pyroclastic rocks of the Vico and Cimino Districts (Pleistocene); **2,** mainly clayey sediments (early Pliocene); **3,** Scaglia (marly limestones; upper Cretaceous–Paleogene); **4,** Marne a Fucoidi (marls and marly limestones; lower Cretaceous) - Maiolica (limestones with chert; lower Cretaceous); **5,** Marne a Fucoidi (marls and marly limestones; lower Cretaceous); **6,** Maiolica (limestones with chert; lower Cretaceous); **7,** Diaspri (cherts; Dogger-Malm); **8,** Calcari selciferi (limestones with chert; middle-upper Liassic); **9,** Calcari diasprini (limestones with chert; Dogger); **10,** Rosso ammonitico (marls and marly limestones; lower Liassic); **11,** Corniola (limestones with chert; lower Liassic); **12,** Calcare massiccio (limestones; lower Liassic); **13,** Rhaetavicula contorta Formation (dolomite limestones and marls; upper Triassic); **14,** Calcare cavernoso – Anidriti di Burano Formation (dolomite limestones, dolostones and anhydrite; upper Triassic); **15,** Tolfa Flysch (shales, marls, marly and siliceous limestones, calcarenites; upper Cretaceous-Eocene); **16,** unconformity; **17,** thrust.

The deep carbonate aquifer, recognized in the subsurface, consists of the Tuscan Nappe dissected by three normal faults trending NW - SE, two uplifted and two lowered blocks (Figure 5a), and is completely confined between the impervious complexes of Tolfa Flysch and lower Pliocene clay (either at roof or laterally) and the schist phyllite substrate (Figure 6). No measurement data on the hydraulic conductivity of the deep carbonate aquifer are available, but the high degree of fracturing of carbonate rocks and the development of karst erosion in the Jurassic and Triassic formations of Tuscan Nappe and Umbria Marche Succession in central Apennine (Figure 6) emerged in the Pliocene-Pleistocene [25], suggest that these two complexes are characterized by very high relative permeability. During the drilling of boreholes ST1, ST4, and ST5 of Terni Company (Figure 4a), the thermal water flowed upwards a few meters above the ground level with temperatures of 58°C, 65°C, 68°C, respectively, which increased up to 78°C at the bottom of the borehole ST5 [4]. In addition, a productivity test in the borehole of Enel Vetralla 1 (VT 1; Figure 8) at a depth of 1130-1145 m corresponding to the upper part of the Calcare cavernoso and the Anidriti di Burano Formation provided 8048 m^3 of calcium sulphate water with salinity of about 4 g/l and a maximum yield of 14.7 L/s. Following the 96-hour ascent, a static pressure of about 100 bar and a static temperature of 61.46°C at a depth of 1120 m was extrapolated [25]. The carbonate aquifer hosts the hydrothermal system consisting of sulphate-alkaline-earth-water [18, 20-26, 33, 35, 42-45], steam, and gases (mainly CO_2 and H_2S) that flow upwards due to the following factors:

- the internal pressure of 25-75 bar at 1500 m depth [20] in the carbonate aquifer;
- the pressure of steam and gases which allows the hydrostatic level to be uplifted and the hydrostatic load is lightened resulting in the progressive decrease in density of water;
- the high values of the temperature in the carbonate aquifer with values of 50°C in the roof and 100°C, 150°C, 200°C, respectively, at 1,000, 2,000, and 3,000 m depth [20], that cause the thermal expansion of water, whose role is fundamental.

Most of the steam condenses in the shallow subsurface and the resulting liquid condensate expands laterally or evaporates [46]. Thermal fluids in the carbonate aquifer can penetrate and ascend into the only available spaces, *i.e.* the fractures and above all the permeable cataclastic bands of normal faults and thrusts. This flow agrees with what is reported by Caine et al., Forster et al., Lopez and Smith, Li et al., Underschultz et al. [47-52] who point out that fractures and faults are primary factors for groundwater flow, and high permeability along the faulted areas is crucial for the development of hydrothermal systems. Also, according to Li et al. and Grasby and Hutchinson [51, 53], faults influence the depth of circulation and the consequent temperature, therefore the springs are often aligned along the faults. Thus, the plume of low-density heated dilated water, steam, and gases can flow upwards through the permeable cataclastic bands of normal faults trending NW – SE, expanding laterally and accumulating at the contact between the impervious complex of Tolfa Flysch and the base of the volcanic aquifer (Figure 5). The pressure of steam and gases allows thermal water to penetrate into the heterogeneous and anisotropic volcanic aquifer. Thermal water mixes with cold water in percentages which vary from zone to zone of the volcanic aquifer, resulting in the general decrease in its original temperature. In fact, in the central and northern zones, where the thickness of the volcanic aquifer and groundwater is smaller, the thermal water mixes with a volume of cold water lesser than in the southern zone, where, in contrast, the volume of cold water is larger due to the greater thickness of both the volcanic aquifer and groundwater. This hypothesis is supported both by the temperature of mixed water between 26.5°C and 45°C in the wells of central and northern zones (Figure 4b), and by the concentrations of sulphates and strontium elements, that Baiocchi et al. [21] applied to define the values of the ratio Qt/Qi, in which Qt is the component of thermal water in the volcanic aquifer and Qi is the total flow. The values are higher (0.1 and 0.5) in the central and northern zones and lower (0.1) in the southern zone. Finally, thermal water, after being mixed with cold water, emerges to the surface forming some springs with temperatures ranging actually between 30°C and 62°C. These values are consistent with those of Conforto [4], who measured 35°7 - 63°C in the northern zone, 51° - 61°C in the central zone and 48° - 58° in the southern zone. The thermal water flow is continuous from the north at an altitude of 320 m asl to the south at an altitude of

240 m asl with an horizontal hydraulic gradient of 0.008 [54] (Figure 4a and Figure 9), in accordance with the idea that the recharge area is located north of the Viterbo geothermal area, *i.e.* in the carbonate aquifer of the Umbria Marche Succession including the mountains of Narni - Amelia, the Martani Mountains, the mountains of north eastern Umbria, and the Sabini Mountains in central Apennines [20, 25, 55, 56] (Figure 6). This hydrogeological structure covers an area of 742 km^2, with an average annual precipitation of 1068 mm, an effective average annual infiltration of 637 mm (inputs), corresponding to 472.6 $m^3/y \times 10^6$, and a total yield of springs of 15 m^3/s corresponding to 473 $m^3/y \times 10^6$ (outputs) (Boni et al., Capelli et al.) [34, 57]. Therefore, the hydrological balance is negative, because the inputs are 4×10^5 m^3/y lower than the outputs.

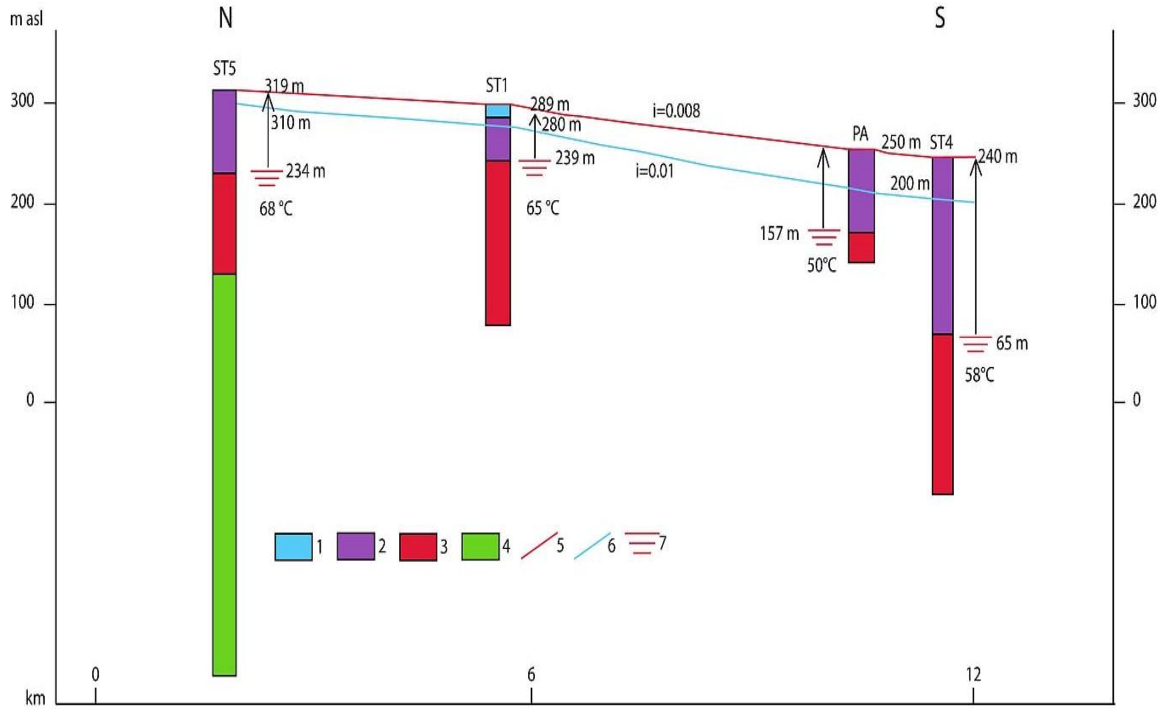

Figure 9 Longitudinal section showing the hydrogeological complexes and the trend of equipotential surfaces of thermal water and volcanic aquifer inferred by boreholes ST5, ST1, ST4 and well PA (= Paliano 1 of Figure 4a). **1,** complex of travertines; **2,** pyroclastic complex (volcanic aquifer); **3,** impervious flysch complex (Tolfa Flysch); **4,** carbonate aquifer (Tuscan Nappe); **5,** equipotential surface of thermal water; **6,** equipotential surface of volcanic aquifer; **7,** equipotential level of thermal water.

The elevation of the recharge area largely located at about 1,200 m asl on average [56] is consistent with the values of the isotopic ratio d $^2H/H$ and d $^{18}O/^{16}O$ of thermal water determined by Piscopo et al. [18]. The high topographic gradient between the very elevated recharge area in central Apennine and the discharge zone of Viterbo at a low altitude (320-240 m asl) results in a high hydraulic head (880-960 m) which acts as one of the main driving forces of the hydrothermal system. The comparison of the equipotential surface of thermal water (Figure 4a and Figure 9) and volcanic aquifer (Figure 4b and Figure 9) highlights that the hydraulic head of thermal water is greater than the volcanic aquifer, resulting in a difference of 10 m (320-310 m asl) in the northern zone and 40 m (240-200 m asl) in the southern zone. Thus, the flow of thermal water from north to south clearly indicates that the recharge area cannot be located in the Cimini Mountains SE of the hydrothermal system (Figure 2 for location).

Ten springs, four boreholes of Terni Company, five wells of official companies (Spa of Popes, Salus Spa & Resort, and ex Spa INPS) and six wells of private owners have been recognized in the geothermal area (Figure 4a).

The springs (Table 1) consist of the Bagnaccio's group at an altitude of 320-309 m asl in the northern zone, the Zitelle and Bullicame groups at an altitude of 298-259 m asl in the central zone, and the Asinello and S. Cristoforo groups at an altitude of 225 m and 230-240 m asl, respectively, in the southern zone.

The boreholes ST1 Zitelle, ST4 S. Sisto, ST5 Bagnaccio, and SS I Seismic I of Terni Company; the wells U Uliveto and G Gigliola of ex Spa INPS, TP of Spa of Popes, S. Valentino and S. Albino of Spa Salus; the wells Danti, Oasi, Mercatone, Bacucco, Paliano 1 and Paliano 2 of private owners (Figure 4a) intercepted thermal water to the contact between the impervious flysch complex and the volcanic aquifer. Although the boreholes of Terni Company have been partially cemented [4], the ST1, SS I, and ST4 are still flowing, while the ST5 has been renovated in 2008 and closed by sluice gates. The wells U and G of ex Spa INPS have been inactive since 1969 due to its closing down, and the wells ST5 Bagnaccio, S. Albino, Bacucco, and Paliano are not flowing. Furthermore, at least 11 privately-owned wells withdraw mixed waters in the area around Bullicame spring and the Spa of Popes (Figure 4b).

Table 1 shows the yield of the springs, boreholes and wells in 1984, according to the fundamental research of Camponechi and Nolasco [26], in 2010 according to Chiocchini and Manna [25] and in 2017 based on new controls. Over a period of 33 years (1984 to 2017), the yield decreased from 123 L/s to 61 L/s (about 50%). The decrease is particularly evident for the Bullicame and Carletti springs: the former spring is famous and emblematic of the city of Viterbo, having been mentioned by Dante Alghieri in Canto XIV of Inferno (verses 76-84). The yield of thermal water, emerging in a large crater known as "caldara," decreased from 30 L/s in 1855 to 20 L/s in 1950 (before drilling the boreholes of Terni Company in 1951; Figure 10). Further decrease occurred, producing a loss of yield of about 10 L/s due to drilling in 1950 of the borehole ST1 of Terni Company (Figure 10) about 1.5 km apart to NW, of the wells of ex Spa INPS in 1960 and 1961 and of the well of the Spa of Popes in 1961 about 550 m apart to SW. Furthermore, the original S. Valentino spring, located about 200 m NE of the Bullicame spring (Figure 4a), was incorrectly converted into a well by the Salus Spa & Resort playing an essential role since both well and spring are fed by the same flow of thermal water. In December 2014 the well underwent a second wrong operation with the removal of the deposits of calcium carbonate that caused an increasing of yield up to 18 L/s, with contemporary decrease in yield of the Bullicame spring. Later the well was partially cemented resulting in a yield of 9 L/s. The yield of the Bullicame spring was 6.5 L/s at the end of December 2014, after the operation on the well S. Valentino, between 4.14 and 2.4 L/s in 2015, and finally 2.8 L/s in 2017 (personal communication of the Municipality of Viterbo). Thus, the total decrease in yield of the Bullicame spring between 1855 and 2017 is 27 L/s (90%) over 162 years, as clearly shown in Figure 10, which also highlights that the yield decreased after the drilling of the wells of ex Spa INPS and the Spa of Popes in 1960-1961 and increased after the closure of the wells of ex Spa INPS in 1969. The yield of Carletti spring, emerging in a small ovoid crater of a travertine dome, decreased from 6 L/s in 1900 to 3.5 L/s in 2004-2010 and to 1.8 L/s in 2017 with a loss of 4.2 L/s, *i.e.* 70% over 117 years. It is also striking that 43 springs, which were discharging in 1984 [26], are currently dry. These springs, shown in Figure 4a, are listed in Table 2, in which 12 springs were necessarily grouped together, therefore the total number is 31. The total loss of yield of the dried springs is 40.0 L/s over a period of 33 years between 1984 and 2017.

Table 3 shows the performance yield of the springs, boreholes and wells of thermal water in 1984 and 2017, the total yield in 1984 and 2017, the total yield of the springs in 1984 and 2017, the total yield of boreholes and wells in 1984 and 2017, and the total yield of the dried springs. Over the period of 33 years between 1984 and 2017 the total yield indicates a constant high loss. Furthermore, several inactive travertines of the Bullicame Unit with dome shapes and the inactive area with the travertines of the Case Castiglione Unit suggest that many springs dried up by a period of many tens to some hundreds of years. The decrease in yield has been detected also in the boreholes of Terni Company ST1 (from 65 L/s in 1951 to 6.5 L/s in 2010 and 5.5 L/s in 2017), ST4 (from 75 L/s in 1951 to 5 L/s in 2010 and 2.2 L/s in 2017), and ST5 (from 100 L/s in 1951 to 40 L/s in 2010) [25] (Figure 10), suggesting that the partial cementation of these boreholes cannot be the sole cause of the decrease in yield.

The current temperature of the springs and boreholes ranges between 30°C and 62°C. Figure 11 illustrates the variations in temperature of the Bullicame and Carletti springs (Figure 4a), in which two periods are highlighted. The former period of Bullicame spring is between 1901 (63°C) and 1953 (55°C) showing a decrease of 8°C over 52 years, while the latter period between 1969 (61°C) and 2017 (55°C) is characterized by a decrease of 6°C over 48 years. The former period of Carletti spring ranges between 1900 (58.5°C) to 1965 (56°C) with a decrease of 2.5°C over 65 years, the latter period between 1974 (59°C) and 2016 (55°C) showing a decrease of 4°C over 42 years. Likewise, the temperature of the boreholes ST5, ST1, and ST4 (Figure 4a) decreased respectively 5°C, 2°C, and 4°C from 1951 to 2010 over 59 years [20, 25]. The decreasing trend of temperature is most probably related to the mixing of thermal water with different volumes of cold water favored by withdrawals from the volcanic aquifer.

The pumping test carried out by Conforto [4] in the boreholes ST1, ST4, and ST 5 resulted in interference with the surrounding springs and for borehole ST1 also with the springs 2 km apart, some of which dried up. These tests lasted a few weeks due to the difficulties with the concessionaries of thermal water, but according to Conforto [4] "*it cannot be ruled out that the duration of the pumping tests were too short for the influence of these test to appear throughout the area*." In other words, the pumping tests should have been carried out for a longer period.

The well G of ex Spa INPS (Figure 4a) was drilled in 1960 with a decreasing yield from 30 to 20 L/s. The thermal water flowed upwards 1 m above the ground level with a temperature of 58°-60°C according to Calamita and Buri [54], who were aware of the possible interference between the boreholes and between the boreholes and the springs. The well U of ex Spa INPS (Figure 4a) was drilled in 1961 with a yield of 22-25 L/s and temperature of thermal water of 54°C, causing the drying up of the wells G and TP Camponeschi and Nolasco [26].

The well TP Spa of Popes, drilled in 1961, caused the drying up of the wells G and U and the lowering of yield of the Bullicame spring. This well was renewed in 1992 with a yield of 20 L/s and temperature of 56°- 57°C (Spa of Popes, personal communication).

Baiocchi et al. [21] carried out pumping tests in well Paliano 1 of a private owner for 68 h, borehole ST5 for 48 h, and well U to analyze the interference between the wells U and TP located 130 m apart. The former two tests are of scarce significance due to their short-term results in a constant drawdown which was not stabilized at the shutdown of test. The tests in the well Paliano 1 and borehole ST5 caused drying up of, respectively, borehole ST4, located 600 m south of well Paliano 1, and the springs located 78 m apart borehole ST5. After closing well TP the recovery has been observed in well U confirming the interference between these wells.

Table 1 Yield of the springs, boreholes and wells of thermal water in 1984 according to [26], in 2010 according to [25] and 2017.

Year	Springs, boreholes and wells	Northern zone Bagnaccio group L/s	Central zone Zitelle and Bullicame groups L/s	Southern zone Asinello and S. Cristoforo groups L/s	Total L/s
1984	Springs	25.7	38	14.85	78.55
	Boreholes and wells	16	22.5	6	44.5
	Total	41.7	60.5	20.85	123
2010	Springs	11.2	24	1.5	36.7
	Boreholes and wells	1.3	26	5	32.3
	Total	12.5	50	6.5	69
2017	Springs	7.4	14.3	0	21.7
	Boreholes and wells	3.5	33.5	2.2	39.2
	Total	10.9	47.8	2.2	60.9

Northern zone

Yield of the springs in 2017: Bagnaccio (0.6), Pool Bagnaccio (6.8), Casale Montarozzo (0); **Yield of the springs in 1984 currently dry:** Casa Vincenzale (0.15), Contrada Bagnaccio (0.5), La Ruzzola (1.5), Pantano (3), Gallinei (2), Piano di Viterbo (1.2), Piscina Bacucchetto (2), Casale Montarozzo (5), Quartaccio (1);

Yield of the boreholes and wells in 2017: Bagnaccio (2), Seismic I (0.10), Danti (1), Oasi (0.4), Mercatone (not available), Bacucco (0)

Central zone

Yield of the springs flowing in 2017: Carletti (1.8), Bullicame (2.8), S. Caterina (5), Bussete (0), Esercito - Piazza d'Arme (0), Zitelle (4.5), Viterbo airport (0.2);

Yield of the springs in 1984 currently dry: Ara dello Zio (0.8), Casa del Pero (0.3), Casale Polidori (3), Capanna Goletti (1), Bussete (1.5), Piscinella Polidori (1.4), San Giorgio (0.5), Esercito (not available), Piazza d'Arme (0.5), Acqua della Milza (0.6), Vesparo (0.2), Torretta (1.2), Acqua Magnesiaca (0.25), Cacciabella (1);

Yield of the boreholes and wells in 2017: Zitelle (5.5), S. Valentino (9), S. Albino (0), Terme dei Papi (19), Gigliola (0), Uliveto (0).

Southern zone

Yield of the springs in 2017: Zero;

Yield of the springs in 1984 currently dry: Asinello (3.5), S. Cristoforo (3.25), Antica Via Cassia (3), Fosso Caccialepre (0.3), Le Pasque (not determined), Ca L'Aglio Antica (0.3), Le Masse (0.25), Il Masso (0.5);

Yield of the boreholes and wells in 2017: S. Sisto (2.2), Paliano 1 (0).

Table 2 Yield of the 43 springs of thermal water active in 1984 according to [26] currently dry. Since it was necessary to group 12 dried springs, their total number in table is 31.

	Spring	Yield L/s
Northern zone Bagnaccio group	Casa Vincenzale	0.15
	Contrada Bagnaccio	0.5
	La Ruzzola	1.5
	Pantano	3
	Gallinei	2
	Piano di Viterbo	1.2
	Piscina Bacucchetto	2
	Casale Montarozzo	5
	Quartaccio	1
	Total	**16.35**
Central zone Zitelle and Bullicame groups	Ara dello Zio	0.8
	Casa del Pero	0.3
	Casale Polidori	3
	Capanna Goletti	1
	Bussete	1.5
	Piscinella Polidori	1.4
	San Giorgio	0.5
	Esercito - Piazza d'Arme	not available
	Piazza d'Arme	0.5
	Acqua della Milza	0.6
	Vesparo	0.2
	Torretta	1.2
	Acqua Magnesiaca	0.25
	Cacciabella	1.3
	Total	**12.55**
Southern zone Asinello and S. Cristoforo groups	Asinello	3.5
	S. Cristoforo	3.25
	Antica Via Cassia	3
	Le Pasque	not determined
	Fosso Caccialepre	0.3
	Ca L'Aglio Antica	0.3
	Le Masse	0.25
	Il Masso	0.5
	Total	**11.1**
	Grand total	**40.0**

Table 3 Total yield of the springs, boreholes and wells in 1984 and 2017; total yield of the springs in 1984 and 2017; total yield of boreholes and wells in 1984 and 2017; difference between the yield of springs in 1984 and in 2017; total yield of the springs active in 1984 currently dry.

Total yield of the springs, boreholes and wells in 1984 L/s	Total yield of the springs, boreholes and wells in 2017 L/s	Difference L/s
123	**61**	**- 62**
Total yield of the springs in 1984 L/s	Total yield of the springs in 2017 L/s	Difference L/s
78.5	**21.7**	**- 56.8**
Total yield of the boreholes and wells in 1984 L/s	Total yield of the boreholes and wells in 2017 L/s	Difference L/s
44.5	**39.2**	**- 5.3**
Difference between the total yield of springs in 1984 and 2017	Total yield of the springs active in 1984 currently dry	Difference L/s
62	**40**	**- 22**

3.2 Geochemical Characters of the Groundwater and Springs

Since there is much data on the geochemical composition of groundwater and springs [18, 20-26, 33, 35, 42-45], it is useful to summarize the main characters of this composition. Three main types of groundwater and springs are recognized. The first group includes thermal water with temperatures of 30°- 60°C (58°- 70°C in the underground), high electrical conductivity and salinity (EC 2900 - 3570 µS) of the sulphate-alkaline-earth-type coming from the carbonate aquifer. This water contains high amounts of CO_2 (235 - 447.2 mg/l) and lower quantity of H_2S (11.48 - 29.54 mg/l). The values of the water/gas ratio recorded in the Terni Company boreholes are 2.1 in the Zitelle borehole, 0.85 in the Bagnaccio borehole and 0.80 in the S. Sisto borehole [4]. The second group of groundwater concerns those of three wells from the southern zone and the Pidocchio spring related to the volcanic aquifer and is characterized by waters with a temperature of 16.6°-20°C, low electrical conductivity and salinity (EC 327-756 µS) with prevalent HCO_3 compared to SO_4, of the bicarbonate-alkaline-earth type. In particular in the urban area of Viterbo, just 1 km from the area with thermal springs, the volcanic aquifer shows temperatures between 15°C and 17°C [58]. Also the third group of water sampled from three wells (the first two in the northern area, the third in the central area) referred to the volcanic aquifer is distinguished by the intermediate characters between the first two groups, with temperatures of 26.5° - 45°C and electrical conductivity and salinity more similar to those of the first group (CE 1450 - 2920 µS) of the sulphate-alkaline-earth type. The water of these wells, enriched with Ca, Mg, SO_2, SO_4, and HCO_3 ions, is due to the mixing of the thermal water with the cold one of the volcanic aquifer. The thermal water is slightly sub-saturated in gypsum and saturated with calcite and dolomite (Piscopo et al., Arnone) [18, 42].

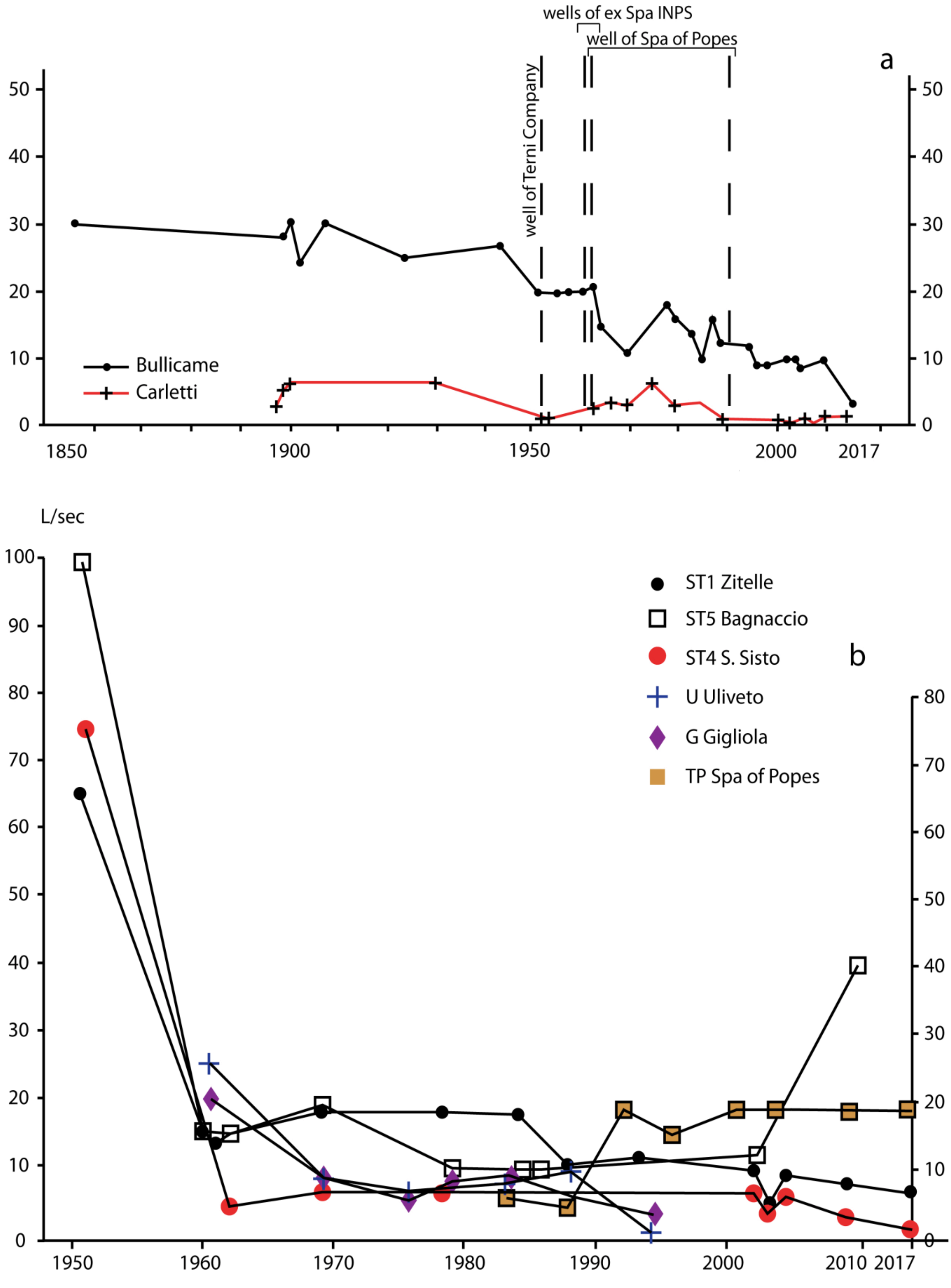

Figure 10 Trend of the yield of the Bullicame and Carletti springs (a); trend of the yield of the boreholes of Terni Company (ST1, ST5, and ST4) and wells of ex Spa INPS (U and G) and Spa of Popes (b).

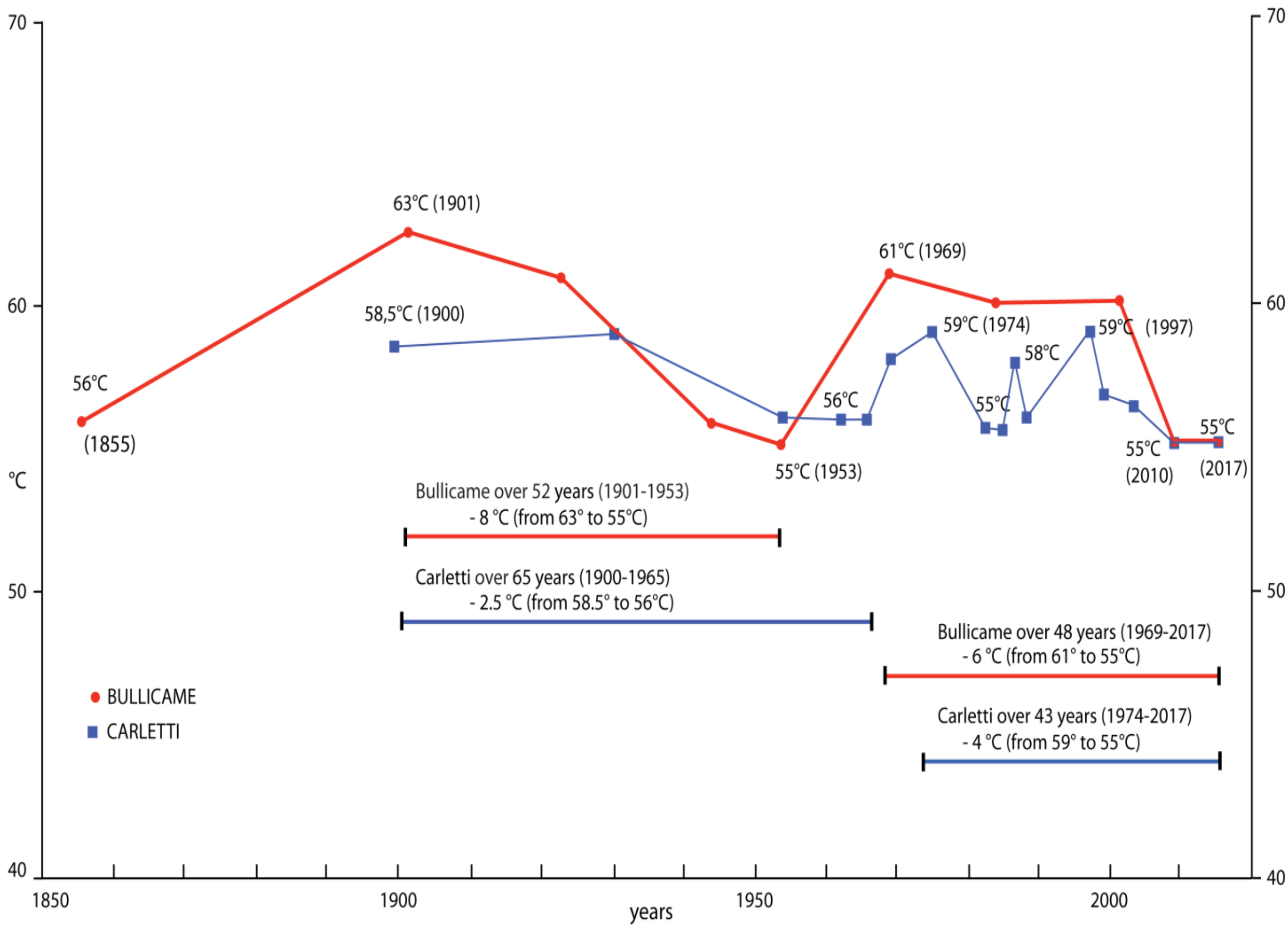

Figure 11 Trend of temperature of the Bullicame and Carletti springs.

The values of the stable isotopes of water $\delta^{18}O$ and δH vary between 6.1 and 6.8 ‰ and between - 39.1 and 39 ‰, respectively, falling on the meteoric water line (Craig) [59]. Based on the study of Longinelli and Selmo [60], which illustrates the relationships between the isotopic composition and the altitudes, it is possible to calculate the altitudes of the recharge area that are between 330 m and 1270 asl.

The values of the isotope ratio $^{87}Sr/^{86}Sr$ are 0.70750 - 0.70850 for thermal waters and 0.70999 - 071043 for the volcanic aquifer (Manna et al.) [58]. Values less than 0.70800 are characteristic of the evaporitic marine rocks of the upper Triassic present in the Calcare cavernoso and in the Anidriti di Burano Formation at the base of the Tuscan Nappe carbonate aquifer, while the values 0.70950 - 0.71100 are typical of the Cimino and Vico volcanic rocks.

Regarding the tritium content of thermal waters and cold waters, Baiocchi et al. [21] indicate that tritium concentrations vary between 2 and 11 TU, which suggests a recent component recharge of waters, *i.e.* post 1952. The thermal waters have lower tritium concentrations (2-5 TU), while those from cold waters show higher concentrations (8-11 TU). If the radioactive half-life of tritium is considered and the same isotopic content of rainwater recharging is taken for both thermal and cold waters, there is a 14-year-difference in the residence time between the two types of waters. However, bearing in mind that thermal water mixes with cold water in percentages varying from zone to zone of volcanic aquifer, these indications have very little meaning.

3.3 The Groundwater Circuit that Powers the Hydrothermal System

The provenance of thermal water is connected to the circulation of groundwater in the carbonate aquifer of Umbria Marche Succession present in central Apennine, *i.e.* in the mountains of Amelia – Narni, the Martani Mountains, the mountains of north eastern Umbria and the Sabini Mountains (Figure 6). The groundwater of this hydrogeological structure, already mentioned in the results, emerges with a chloride-alkaline composition and $^{87}Sr/^{86}Sr$ isotopic ratio identical to that of the thermal waters of Viterbo along the Nera River gorge near Narni (Figure 6) forming a linear spring at the height of 75-65 m asl with a temperature of 15°C and a yield of 13.5 m^3/s. This water, mixed with that of the sands and gravels of the surface aquifer (symbol 4 in Figure 6) superimposed on the carbonate aquifer, flows towards the valley of the Tevere River, begins to warm up and emerges first in Orte forming a thermal spring (30°C), then continues towards the Cimini Mountains – Viterbo area, heating up further on, feeding the carbonate aquifer (Umbria Marche Succession and Tuscan Nappe; Figure 6), and emerges forming the thermal springs of Viterbo.

To explain the difference in altitude between the spring of the Nera River at 75-65 m asl and the thermal springs of Viterbo at 320-240 m asl, *i.e.* 245-175 m, we must consider the paleogeographic setting of the area between the Tyrrhenian Sea and the central Apennines (Figure 12) in lower Pleistocene, *i.e.* about 2.588 Ma (Gibbard et al.) [61] and later when the districts Cimino (1.35-0.8 Ma) and Vico (0.5-0.09 Ma) were active.

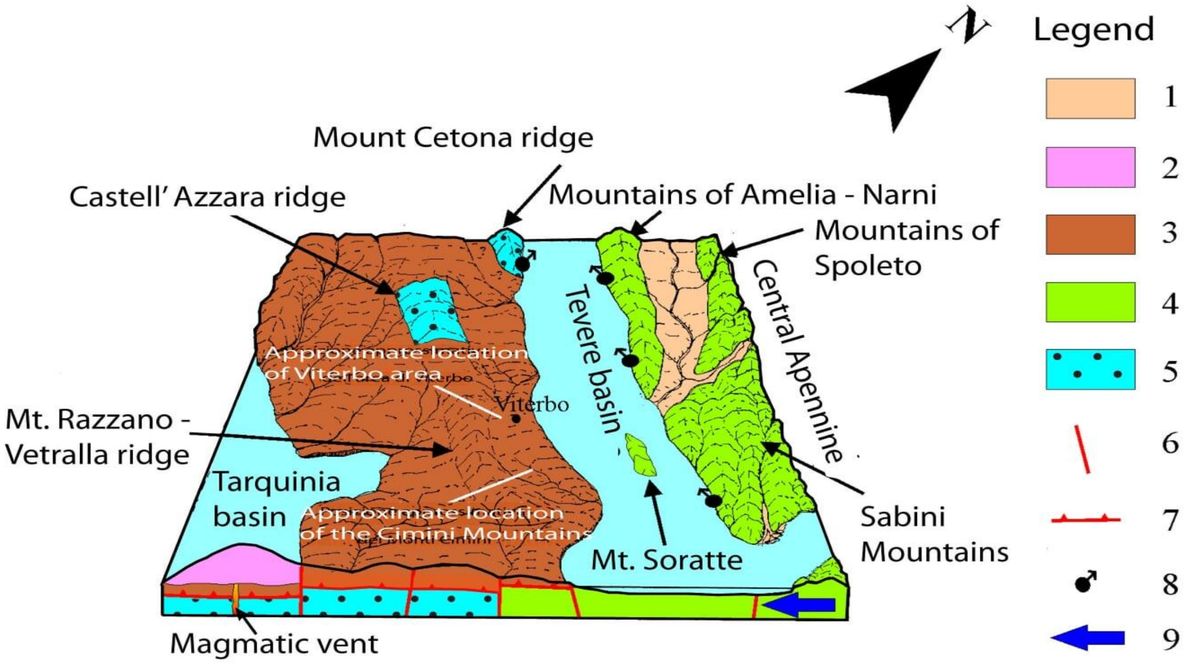

Figure 12 Paleogeographic setting of the area between the Tyrrhenian Sea and central Apennine during lower Pleistocene. **1,** alluvial deposits (Quaternary); **2,** volcanic rocks of the Tolfa Mountains-Ceriti Mountains (volcanic aquifer; lower Pliocene); **3,** Tolfa Flysch (impervious complex; upper Cretaceous-Eocene); **4,** Umbria Marche Succession (carbonate aquifer; Triassic–Paleogene); **5,** Tuscan Nappe (carbonate aquifer; Triassic–Paleogene); **6,** normal fault; **7,** thrust; **8,** spring of cold water; **9,** flow of groundwater from the carbonate aquifer of central Apennine to the carbonate aquifer in the underground of Cimini Mountains and Viterbo area.

Figure 12 shows the Tarquinia and Tevere basins with marine shelf clayey deposits (impervious complex) followed by shallow-water sand and gravel (surface aquifer; symbol 5 in Figure 6) [15, 62, 63], the emerged ridges of Mt. Cetona, constituted by the Tuscan Nappe (carbonate aquifer), and Monterazzano - Vetralla with the Tolfa Flysch (impervious complex) capping the Tuscan Nappe by means of thrust and the area of Viterbo. To the east is the central Apennine with the Umbria Marche Succession (carbonate aquifer), whose physical continuity is ascertained to the west in the subsoil [20] below the Tevere basin as far as to the Cimini Mountains – Viterbo area, where this succession is in tectonic contact with the Tuscan Nappe (carbonate aquifer). The Tevere basin represents the base level for the emergence of the deep groundwater in the carbonate aquifer and for the control of the sites where the cold and thermal waters emerged, as demonstrated by the travertines along the Tevere basin. The impermeable clayey deposits of the Tevere basin were in lateral contact with the edges of the Castell'Azzara and Monterazzano - Vetralla ridges and the emerged reliefs of the carbonate aquifer, in which the deep karst erosion was active, well documented by several forms in many areas [20]. The considerable difference in hydraulic head between the emerged Apennine sector of the carbonate aquifer and the lowered sector of the Tevere basin as far as to the Cimini Mountains - Viterbo area allowed the groundwater to flow from the first to the second sector.

In this hydrogeological context the groundwater emerged forming springs rising along the coasts of Tevere basin and Mt. Cetona ridge consisting of sandy and gravelly shallow-water deposits at actual altitudes of 200-340 m asl due to the uplifting of the central Apennines in the Neogene. During this phase the Viterbo area was characterized by hilly morphology consisting of the Tolfa Flysch separated by E-W oriented river valleys (Figure 12). Furthermore, the difference in hydraulic head between the two sectors of the carbonate aquifer favored the rising upwards of the groundwater along the normal faults forming some springs. Subsequently the magmatic intrusions of the Cimino and Vico volcanism heated the groundwater of the carbonate aquifer in the Cimini Mountains – Viterbo area. Therefore, the thermal fluids rose upwards along the normal faults and emerged, first in the area of the Tevere basin where there are several deposits of travertine (Mancini et al.) [63] and subsequently in the area of Viterbo, whose altitudes, before the deposition of the products from the Vico district (0.5-0.09 Ma) were much lower than the current altitudes (265 up to 65 m asl). The thermal fluids deposited $CaCO_3$ permeating the Vico Varicoloured Bedded Tuffs (0.420 Ma) and the Red Tuff with Black Scoriae (0.150 Ma) (Laurenzi and Villa) [41]. Therefore, the hydrothermal circuit is active since at least 0.420 Ma and most probably more or less simultaneously with the Cimino district, *i.e.* more than 1 Ma. The thermal fluids deposited 114 million m^3 of travertine of the Bullicame Unit and the Case Unit Castiglione (Figure 4) and two swamps were formed (Figure 13). In addition, the uplifting of the central Apennines during the Neogene and the volcanic activity of the districts of Cimino and Vico uplifted the territory of Viterbo with thermal springs up to the current maximum altitude of 320 m asl.

4. Discussion

1. The hydrothermal system is currently experiencing a balance of thermal water consisting of the residual yield of springs (21.7 L/s) and boreholes and wells (39.3 L/s), *i.e.* a total of 61 L/s, which is dec-reasing by at least 162 years and should be considered, in the broadest meaning, as maximum sustainable yield (Kalf and Woolley) [64]. The circuit of the hydrothermal system is driven either by the high hydraulic head (880–960 m) in the recharge area in the central

Apennines, the internal pressure in the confined carbonate aquifer, or the pressure of gases dissolved in thermal water which allow the upward flow and emergence to the surface, despite the hydrostatic pressure exerted by the volcanic aquifer.

2. The Vico Red Tuff with Black Scoriae (0.150 Ma) and the Vico Varicolored Bedded Tuff (0.420 Ma) impregnated with travertine suggest that the thermal circuit has been running over at least 0.420 Ma and most likely since the beginning of activity of the Cimino volcanic district, *i.e.* more than 1 Ma, when the Viterbo area was characterized by a hilly morphology consisting of the Tolfa Flysch (Figure 13).

3. The decrease in yield of springs and boreholes of thermal water is related in part to the following factors (Chiocchini and Manna) [25]:

- The gradual cooling of the Cimino and Vico magmas below the carbonate aquifer resulted in the cessation of the volcanic activity and in the decrease of temperature of thermal fluids.
- The reduction of permeability, due to precipitation of $CaCO_3$ along the cataclastic bands of normal faults and joints of volcanic aquifer, in which thermal fluids flow upwards from the carbonate aquifer;
- The very long period of activity of the hydrothermal system (at least 0.420 Ma, most probably more than 1 Ma).
- The possible consumption of permanent reserves of the carbonate aquifer hosting the hydrothermal system. This consumption is due to the current negative hydrological balance and the lowering of the base level of cold and thermal water in Pliocene-Pleistocene as a consequence of the rapid uplifting of the central Apennines, as well as to repeated climatic variations that occurred in Pleistocene, characterized by four periods of glaciation (Gunz, 1.2-0.7 Ma; Mindell, 0.650-0.300 Ma; Riss, 0.250-0.120 Ma; Wurm, 0.080-0.010) and four inter - glacial periods (1.7-1.2 Ma; 0.7-0.65 Ma; 0. 300-0.250 Ma; 0.120-0.80 Ma), and in Holocene, during which periods of cold - humid climate (Small Archaic Glacial Age: 520 – 350 BC; Small early Middle Ages Glacial Age: 500–750 AD; Small Glacial Age: 1550–1850 AD), alternated with periods of warm - dry climate (Roman Period: 150–350 BC; Middle Ages Period: 1000–1300 AD) and phases of transition between these period (Giraudi, Orombelli, Ortolani and Pagliuca) [65-67].
- Thus, it is likely that the factors mentioned above produced an overall negative impact on the supply of groundwater derived from the carbonate aquifer of the Umbria Marche Succession in the central Apennines, resulting in the consumption of permanent reserves in the carbonate aquifer hosting the hydrothermal system and consequently in the continuing decrease in yield of springs, boreholes and wells.

4. In addition to what is stated in point 3, the continuous abstraction of cold water and thermal water by about 67 years has deeply changed the original balance between the volcanic aquifer and thermal water. In fact, an increase of pumping from thermal water causes a decrease in yield from the springs and flowing boreholes and could result in a decrease in their flow that mixes with the cold water and consequently decreases in its temperature. On the other hand, an increase of pumping from the volcanic aquifer could cause an increase in flow from thermal water toward the volcanic aquifer with an increase of temperature of cold water [21]. Keeping in mind that the exchange of flow by the mixing of thermal water and cold water is ruled by the hydraulic head of the volcanic aquifer and thermal water, abstraction in the central and northern zones, where the mixed waters is greatly extended, has a negative impact on the volcanic aquifer by increasing the mixing between cold water and thermal water and by decreasing their yield and quality.

5. The boreholes and wells which intercepted thermal water interfere with the surrounding springs, boreholes, and wells and possibly with those more distant. The pumping tests have been carried out over periods of a few weeks in boreholes ST1, ST 4, and ST5 (Conforto) [4], 68 hours in well Paliano 1 and 48 hours in borehole ST5 (Baiocchi et al.) [21, 22]. The too short-term pumping tests already recognized by Conforto [4] did not allow the ascertainment of the actual interference with the emergences further away from the tested boreholes.

6. The total volume of travertines in the geothermal area is 114 million m^3. The Bullicame Unit outcrops with five lenticular bodies located in the correspondence of the three normal faults trending NW - SE (Figs. 2, 4a, and 5). The volume of the Bullicame Unit is 110 million m^3, of which 37 million outcrops are in the northern zone, 55 million in the central zone, and 18 million in the southern zone. These values highlight that in the central and northern zones, consisting of 92 million m^3 of travertines (84%), the volume of thermal water flowing to the surface was greater than in the southern zone. Four million m^3 of travertines of the Case Castiglione Unit located in the western side of the flysch complex at Monterazzano (Figure 4a and Figure 5) outcrop in eight small tabular bodies about 10 m thick lacking in springs. These travertines represent the oldest evidence of the activity of the hydrothermal system, which later shifted toward the eastern side of Monterazzano affecting the present geothermal area. The several inactive bodies of travertines with dome shapes of both the Case Castiglione Unit and the Bullicame Unit suggest that, when the flow paths followed by thermal water are progressively occluded by precipitation of $CaCO_3$, the new flow paths shift laterally forming new springs (Figure 14). 114 million m^3 of travertines are the result of the deposition by a huge volume of thermal water, which formed also two swamps (Bagnaccio and Viterbo airport; Figure 15) in the central and northern zones of the geothermal area before the eruption of pyroclastic flows which produced the Vico Red Tuff with Black Scoriae (0.150 Ma).

7. The study of Harvey et al. [68] highlights that availability of water to recharge hydrothermal systems is correlated with thermal fluids and heat flux. Since recharge availability is ruled by stratigraphic and structural setting, permeability, rainfall and topography of recharge areas, it is necessary that, to be credible, the conceptual hydrogeological models should be constructed with a solid suitable geological setting.

8. Concerning the CHM of the Tuscany and Latium regions, according to (Calamai et al., Buonasorte et al., Minissale et al., Senarum Universitatis, Chiocchini et al., Chiocchini and Manna) [6, 16, 17, 19, 20, 25] it is possible to suggest the following fundamental conclusions: (1) the deep confined carbonate aquifer hosting thermal fluids is hydraulically separated from the surface volcanic aquifer with cold water by the very thick impervious complexes of flysch and lower Pliocene clay, which cannot transfer significant volumes of water; (2) the recharge area of the deep carbonate aquifer consists of the Umbria Marche Succession of central Apennines.

9. The Regione Lazio - Direzione Regionale dello Sviluppo Economico e delle Attività Produttive, carrying out the functions attributed to it by law, works to rationalize the use of the geothermal resource, monitoring its sustainable use, in a framework of overall protection of the environmental and hydrogeological structure of its territory and attributes considerable value to the thermal resource, in consideration of the social, economic and environmental value that the use of this resource plays in the Viterbo community. Thus, this Institution, based on the unreliable CHM of Baiocchi et al. [21, 22], established the following provisions for the exploitation of thermal water in the central area of the hydrothermal system.

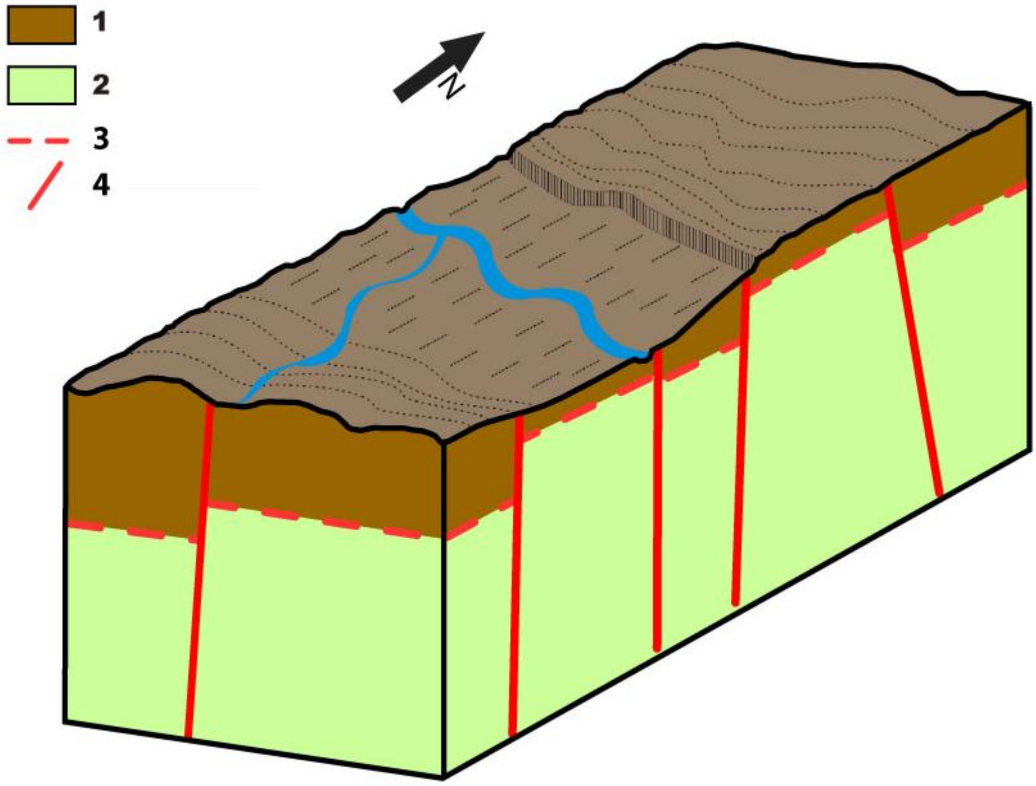

Figure 13 Paleogeographic setting showing the hilly morphology of the Viterbo geothermal area before the activity of the Cimino and Vico volcanic districts. **1,** Tolfa Flysch (upper Cretaceous-Eocene); **2,** Tuscan Nappe (upper Triassic-Paleogene); **3,** thrust; **4,** normal fault.

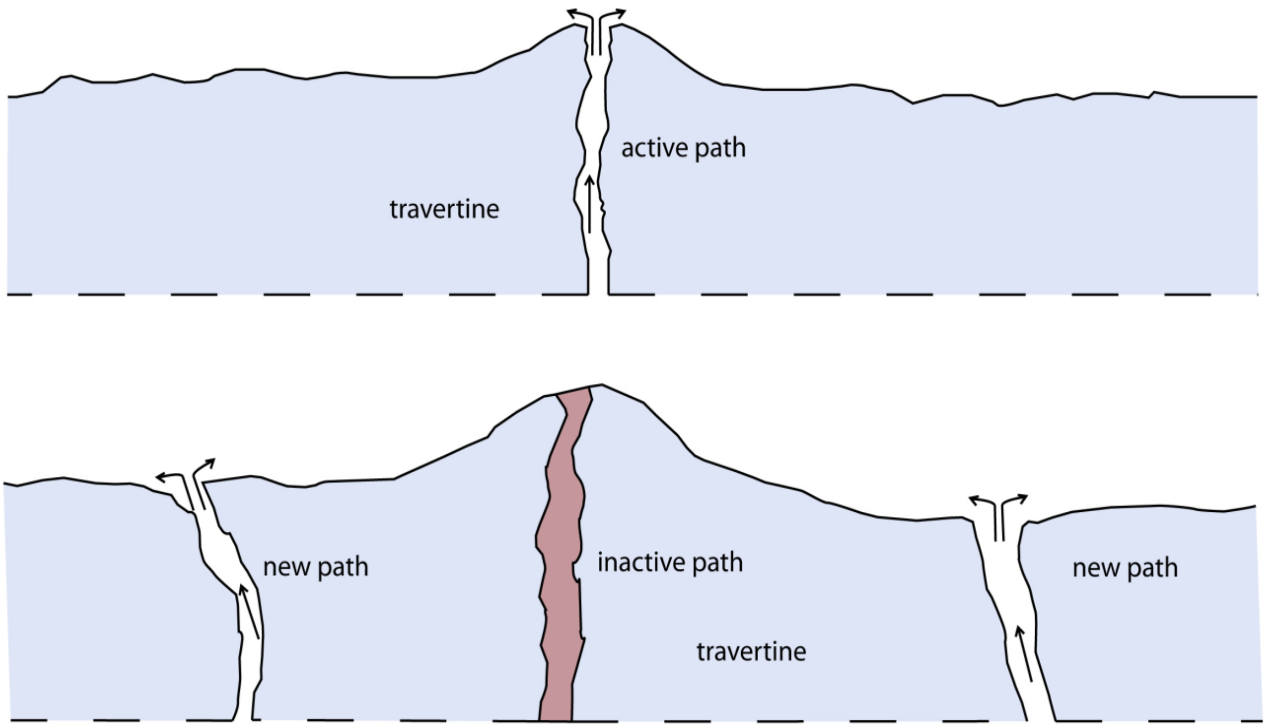

Figure 14 Scheme showing the occlusion of flow paths of thermal water and lateral shifting of the new flow paths.

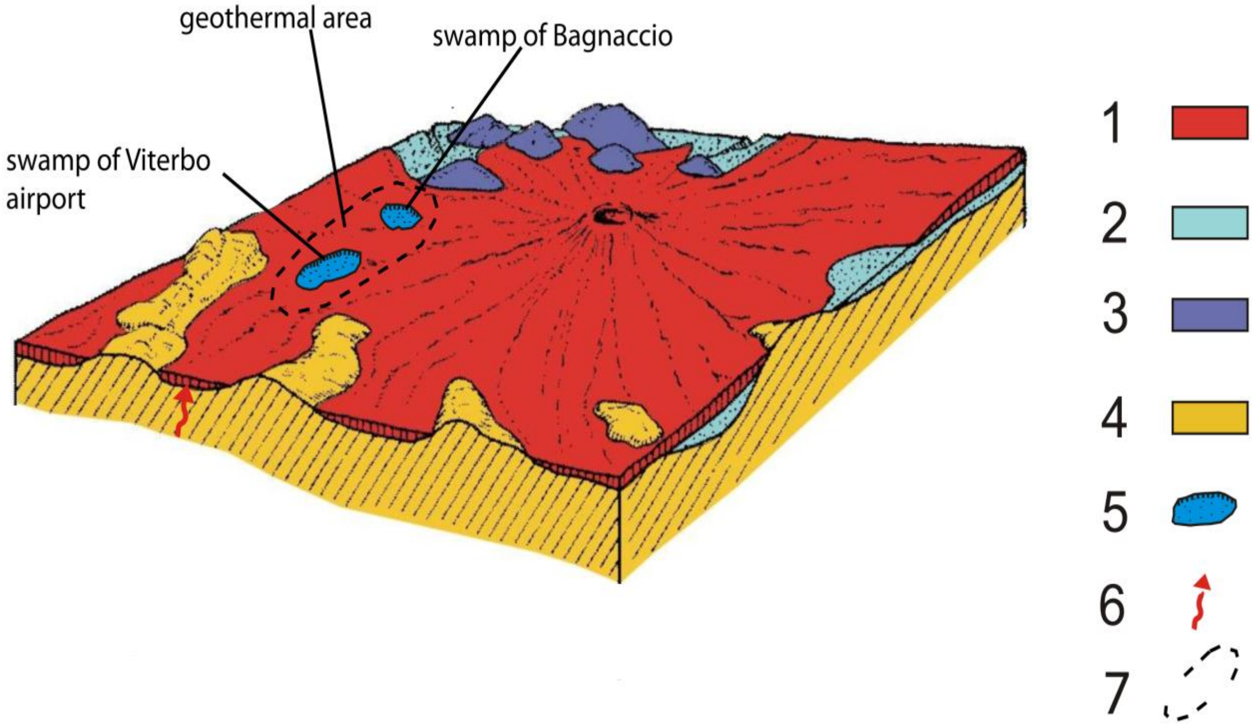

Figure 15 Paleogeographic setting of the Viterbo area before the eruption of pyroclastic flows which produced the Vico Red Tuff with Black Scoriae (0.150 Ma), showing the swamps of Bagnaccio and Viterbo airport. **1,** products of the Vico district older than the Vico Red Tuff with Black Scoriae (middle-upper Pleistocene); **2,** ignimbrites of the Cimino district (lower Pleistocene); **3,** domes of the Cimino district (lower Pleistocene); **4,** Tolfa Flysch (upper Cretaceous-Eocene); **5,** swamp; **6,** flow of thermal water rising upwards; **7,** boundary of geothermal area.

- The mining closure of the S. Valentino well and the re-conditioning of the borehole Zitelle, to be instrumented and closed by a sluicegate.
- The new withdrawal points are identified by the S. Albino and Gigliola wells.
- It is possible to extract the maximum volume of 1,293,000 m^3/year.
- The yields of the extracted thermal water are to be distributed to the emergencies according to the following scheme with the specified flow limits: S. Albino well 6 L/s; Spa of Popes well 23/24 L/s; Gigliola well 10 L/s.

These statements ignore, based on the erroneous and misleading indications of [21, 22], what is reported below.

- The S. Valentino and S. Albino wells intercept the same thermal water that feeds the Bullicame spring and it is also known that the inappropriate manipulations carried out on the S. Valentino well have mortally wounded the Bullicame spring, only 200 m away from this well. In fact, a derivation artificially activates the "caldara" from which the spring emerges.
- The mining closure of the S. Valentino well and the simultaneous withdrawal from the S. Albino well do not eliminate the interference with the Bullicame spring. Furthermore, it should be borne in mind that the mineral sealing of thermal water in boreholes and wells is a delicate operation, to be carried out with great care and in a workmanlike manner, as shown by the imperfect sealing performed by the Terni Company in the boreholes Bagnaccio, Zitelle and S. Sisto

that are still spilling thermal water. It is evident that the imperfect mineral sealing of the S. Valentino well would simply be disastrous.

- The reactivation of the Gigliola well of ex Spa INPS, which is only 180 m away from the Spa of Popes well, is incomprehensible because they interfere either with each other, or with the Bullicame spring. Therefore, the withdrawal from the Gigliola well is useless and harmful.
- The maximum volume that can be extracted from the Bullicame mining concession, equal to 1,293,000 m^3/year, is the result of a wrong calculation and is too high for the hydrogeological equilibrium widely compromised in the central part of the hydrothermal system.

The following investigation could be useful to check the proposed CHM.

- New pumping tests carried out for several days in boreholes ST5 (northern zone) and ST1 (central zone) and well Paliano 1 (southern zone) and contemporary control of springs, boreholes, and wells as far as some km away to check the interference between boreholes and springs.
- High resolution reflection seismic surveying and seismic and geo electric tomography to provide important information on (i) the contact between the hydrogeological complexes, (ii) their physical characters, (iii) the flow paths followed by thermal water flowing upwards through the permeable cataclastic bands of normal faults and within the volcanic aquifer.
- The noble gas radionuclides (^{39}Ar, ^{81}Kr and ^{85}Kr; Yokochi et al. [69] and references therein), providing chronometric information regarding subsurface residence times of the thermal fluids, are another useful tool to improve knowledge of the running of the Viterbo hydrothermal system and to plan its sustainable exploitation.

5. Conclusions

The management and exploitation of groundwater should be based on the detailed construction of a 3D CHM by surface geological and hydrogeological survey, subsurface investigation through boreholes and geophysical prospecting, correct pattern identification of groundwater circulation, real positioning of the recharge area, and the monitoring of the hydrogeological systems. Unfortunately, these essential tools are erroneous and misleading in the research of Baiocchi et al. [21, 22] related to the Viterbo hydrothermal system. Indeed, this area is experiencing a continuous hydric crisis documented by the decreasing residual yield of springs, boreholes, and wells of thermal water over the last 162 years due to both natural factors and the indiscriminate drilling of many wells in the last 67 years. At present the total yield is 61 L/s (21.7 L/s of springs + 39.2 L/s of boreholes and wells), *i.e.* the maximum sustainable yield, and it is very likely that the yield will continue to decrease in the future. Thus, the Regione Lazio - Direzione Regionale dello Sviluppo Economico e delle Attività Produttive, despite having financed the research of Baiocchi et al. [21, 22] that produced the unreliable CHM, should avoid using this model, adopted also by Comune di Viterbo [39], to plan the exploitation of a geothermal resource. In fact, the withdrawal from the Gigliola well, the excessive maximum extractable volume of 1,293,000 m^3/year and more generally the use of the thermal resource on the basis of the CHM of [21, 22] will obtain a result that is exactly the opposite of what is foreseen by the institutional tasks of the Regione Lazio - Direzione Regionale dello Sviluppo Economico e delle Attività Produttive. In other words, subjecting the hydrothermal system to unsustainable exploitation will result in devastating consequences for the environmental and the hydrogeological structure of the hydrothermal system and will cause social, historical, and cultural damage to all thermal emergencies. In particular, the historical Bullicame and Carletti springs appear destined to disappear as 31 springs with a total yield of 40 L/s have been unquestionably extinguished since 1984 throughout the area of the hydrothermal system, and economic damage to the Spa of Popes and Salus Spa & Resort may result. In addition, withdrawals from the volcanic aquifer and thermal water should be drastically limited and severely controlled.

Future investigations have been proposed in order to improve or check the proposed CHM.

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Additional Material

The following additional material is uploaded at the page of this paper: Supplementary material.

Author Contributions

Ugo Chiocchini coordinated and developed the research phases and the manuscript. Giovanni Savarese collaborated in the control of the piezometric levels in the wells and the yield and temperature of the springs, and in the elaboration of the figures.

Competing Interests

The authors have declared that no competing interests exist.

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