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Hydrochemical investigations to locate Homer's hot and cold springs of Troia (Troy)/Turkey

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ABSTRACT

Numerous travellers and scientists since the 1st Century B.C. unsuccessfully searched for the hot and cold springs of Troia (Troy)/Turkey mentioned in Homer's epic poem *Iliad*. It was therefore suggested that over time, the hot spring might have disappeared after an earthquake. This investigation uses geological, hydrogeological and hydrogeochemical methods to identify potential locations of "hot and cold" springs in the vicinity of Troia. Using statistical analyses of temperature, electrical conductivity, pH-values, redox-potential, and oxygen concentrations, 47 suitable wells and springs were chosen for geothermometric calculations using Si-thermometry based on the equation of Verma. None of the identified springs shows elevated discharge temperatures, no scalings give indication for disappeared springs, and only three springs show elevated reservoir temperatures above 95 °C – none of which is close to today's Troia. Springs that locals identified as "hot and cold" show nearly constant temperature throughout the measuring period (±0.1–0.3 K) suggesting they appear warm in the winter and cold in the summer months. These results show that a spring *sensu* Homer never existed in Troia and that Homer possibly meant *one* spring with warmer and colder temperatures relative to the mean air temperature depending on the time of the year.

1. Introduction

This study solely focuses on answering the question of whether there is a location close to the Hissarlık hill in Turkey's Troad (in German texts usually called Troas, locations in Fig. 1) that once might have born a "hot and cold" spring as described in Homer's *Iliad*. Neither shall it be a detailed hydrogeological, hydrochemical, or isotopical depiction of the area nor an identification of potential geothermal resources in the vicinity of the Hissarlık and their connection to deep geological structures or their underground sources. A detailed geological description of the area can be found in earlier literature (e.g. Kraft et al., 1982; Yılmaz, 2003) and preliminary hydrogeological data was provided by Kayan (2000), Wolkersdorfer and Göbel (2004) and Baba et al. (2007). In addition, several studies covered the geological and hydrogeological history of the research area (Bergmann, 2004; Blume, 2003; Bretzler, 2008; Lippmann, 2003; Weber, 2003).

The *Iliad* describes the Trojan War and was written in the 7th century B.C (West, 2011). This epic with 15,963 lines of verse belongs to the most important pieces of poetry in human history (Latacz, 2003) and is considered "the *fons et origio* of Western culture" (Baier, 2017). To the ancient Greeks', Homer (late eighth or early seventh century BC) was their first and most famous poet (Latacz, 2003; Powell, 2007) and in fact, the *Iliad* is the first ever written poem of this kind we know so far. Though the historical basis of the *Iliad* as well as the question of whether Homer ever saw the Troad or if the poet's name was Homer is still a matter of discussion (Latacz, 2003; Ulf, 2003; West, 2011), its influence on literacy, history, natural sciences, and archaeology is beyond all question (Archäologisches Landesmuseum Baden-Württemberg et al., 2001; Hertel, 2001; Latacz, 2003). Since Strabo discussed the geographical details of the Troad 2000 years ago in his *Geographica*

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(Strabo and Groskurd, 1931), numerous authors have been searching for the correct historical geographic setting of the *Iliad* and *Odyssey*. It has often been suggested that the location of the Roman Ilion south of the Dardanelles might be identical to Homer's Troia (this name is used since 1988 to overcome the numerous variations of this locations's name; Jablonka, 2014).

Yet, it was not before the 18th century that systematic investigations of the potential location of the Trojan War were conducted by travellers like LeChevalier (1791), who also published a first topographical map of the western Troad. Spratt and Forchhammer (1888) conducted detailed investigations of the Troad resulting in an excellent topographical map, and Virchow (1879) published the results of his comprehensive geological, hydrological, and hydrogeological investigations of this area. Beside the correct location of Troia itself (Kraft et al., 1982), the search for the hot/warm and cold springs mentioned in the *Iliad* (XXII, 147–156) (Virchow, 1879) was one of the main *foci* of most of the numerous travellers to or investigators of the Troad (Brentano, 1881; Cook, 1973; Eckenbrecher, 1875):

"On they flew along the waggon-road that ran hard by under the wall, past the lookout station, and past the weather-beaten wild fig-tree, till they came to two fair springs which feed the river Scamander. One of these two springs is warm, and steam rises from it as smoke from a burning fire, but the other even in summer is as cold as hail or snow, or the ice that forms on water. Here, hard by the springs, are the goodly washing-troughs of stone, where in the time of peace before the coming of the Achaeans the wives and fair daughters of the Trojans used to wash their clothes." *Iliad* (XXII, 147–156) (Butler, 1999).

Since the extensive excavations of Schliemann (1881, 1884) at a site mentioned to him by Frank Calvert, the hill Hissarlık in the Troad (Biga Peninsula, Turkey; 26°14′18″ E, 39°57′28″ N; geographical coordinates WGS84; elevation 35 m above sea level) is commonly believed to be the location of the historical Troia (Korfmann, 2006; Kraft et al., 1982), though it is heavily disputed by some scholars (Hertel, 2003; Kolb, 2010). Yet, like all the researchers before Schliemann, he did not find the springs mentioned by Homer. This fact of the missing springs was already noted by Demetrius of Skepsis ca. 180. B.C., and based on Demetrius' observations, Strabo describes in his *Geographica* that the hot spring had disappeared at that time (*Geographica* XIII, 1, 43) (Strabo and Groskurd, 1931). LeChevalier, on the other hand, thought he had found a hot and cold spring in the area of the "Kirk Göz" (*40 springs*) near Pınarbaşı, which was called Bounarbachi in the 18th century (LeChevalier, 1791; Siebler, 2009). During the excavations of the Tübingen/Germany and Cincinnati/USA teams, a qanat-system south of the Hissarlık was rediscovered (in the literature called spring cave,

Fig. 1. North western section of the Biga Peninsula (Troas) showing the locations mentioned in the text (pink dots and larger font). Aerial and map sources: GoogleEarth, Wikipedia. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

water mine, water quarry or KASKAL.KUR), excavated and dated (Frank et al., 2002; Kayan, 2000; Korfmann, 1998; Korfmann, 2000). In this connection, the discussion on the location of the hot and cold springs of the *Iliad* revived and was investigated with hydrogeological and hydrochemical techniques in 2001, 2003, 2004 and 2006 (Wolkersdorfer, 2006; Wolkersdorfer and Göbel, 2004; Wolkersdorfer et al., 2004).

Whether or not Homer describes a landscape that existed at the time of his or his source's visit, and if the Hissarlık is the place of Homer's Troia, the *Iliad* is the only written record of a hot spring in the vicinity of "Troia". Since then, no traveller or researcher was able to locate a hot spring as described by Homer (Virchow, 1879). To fulfill the prerequisites of Homer's description, a set of springs must be relatively close to each other and near the place of Homer's Troia. Homer used the Greek word *λιαρός*, which means lukewarm, to describe the hot spring. This implies that the temperature of the spring is at least above the mean daily air temperature and according to his description, mist ("steam" in the words of Homer), technically called "steam fog" (Saunders, 1964), can temporarily be found close to this hot spring. Hippocrates of Kos (c. 460 – c. 370 B.C.) writes about warm and cold springs in general (Crouch, 1993). In his book *De aere, aquis et locis* (Airs, Waters, Places) he describes that the "best [springs] are those that flow from high places and earthy hills. By themselves they are sweet and clear, and the wine they can stand is but little. In winter they are warm, in summer cold. They would naturally be so, coming from very deep springs." (Hippocrates and Jones, 1923). From a hydrogeological point of view, this type of spring reflects the annual mean temperature of the regional flow system *sensu* Tóth (1963), which usually results from longer mean residence times in the subsurface (Fetter, 2001). This description of Hippocrates is like Homer's expression, except that Hippocrates refers to a *single* spring with that characteristic. To avoid future confusion about the meaning of "hot", a spring as described by Homer will be called hot spring *sensu* Homer, and hot springs *sensu stricto* will be called thermal spring in the following text.

Thermal springs cannot be found in the western Troad today, but there are several thermal springs within the Biga Peninsula which were also used as spas in Roman times (distances relative to the Hissarlık): Çanakkale (25 km north east), Kestanbol Kaplıca (25 km south), Akçakeçili (28 km south), Tuzla (44 km south) and several smaller locations (Baba and Ertekın, 2007; Erentöz and Ternek, 1968; Kurtman and Samilgil, 1975; Mützenberg, 1991; Pehlivan, 2003; Şimşek, 1997; Strabo and Groskurd, 1931). Their temperatures at the point of discharge range between 32 °C and 102 °C, and the reservoir temperatures are calculated to be greater than 140 °C. All of these locations are characterized by extensive scaling (Marmara et al., 2020; Mützenberg, 1991), resulting from precipitates of the thermal water, elevated Cl- concentrations, and are located within tectonically active zones or deep thrust systems (Kurtman and Samilgil, 1975; Marmara et al., 2020; Schindler and Pfister, 1997; Şimşek, 1993).

At the time of our first, preliminary visit in the year 2000, no detailed hydrogeological study of the area was known. The only reports available were about two deep wells near Pınarbaşı (Yüzer, 1997) and a more general description of Troia's water supply (Kayan, 2000; Kayan, 2014). To solve the question if there were a hot and a cold spring *sensu* Homer and where they could have been located, a hydrogeological sampling program was conducted within the vicinity of the UNESCO listed

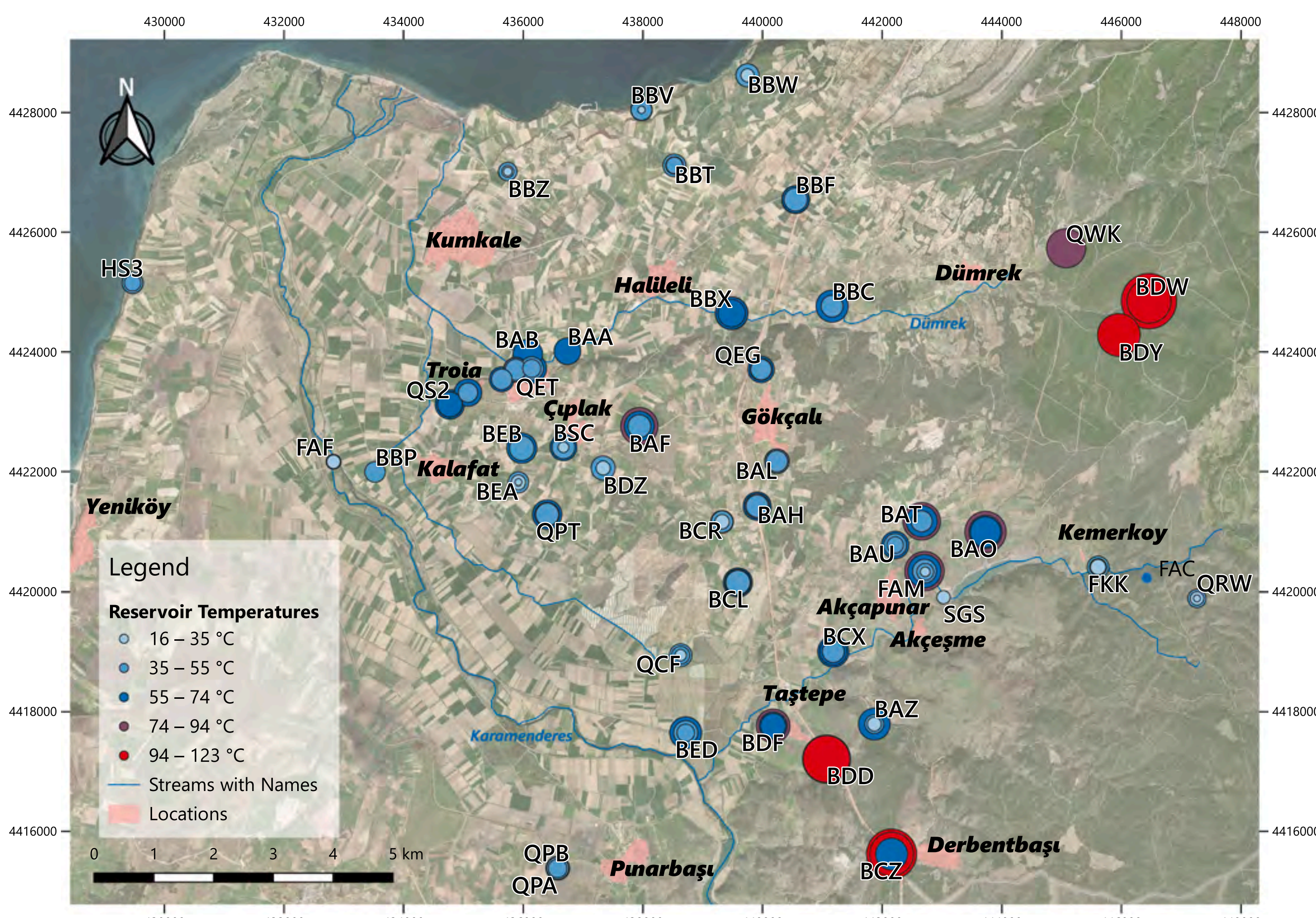

Fig. 2. Map of the western Troad/Turkey showing the location of all sampling points with water analyses and the location of the springs with elevated reservoir temperatures. Size of symbols is proportional to the reservoir temperature. Coordinates are given in UTM WGS84 Zone 35N. Aerial images: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community; background layer: OpenStreetMap community.

"Archaeological Site of Troy" and the "Troia National Park (Troia Milli Park)", also called "Historical National Park Troia" (Schwaderer, 2003) or "Troy (Troia) Historical National Park" (Cengiz, 2020; Everest et al., 2017). This sampling program was based on a detailed geological mapping of the Troia ridge and the plain and consisted of the hydrogeological investigation of 227 sampling locations from four field campaigns between the years 2001 and 2006, 47 of which were analysed in more detail (Fig. 2). Meanwhile, an unpublished report about irrigation water quality in the area (Şener et al., 2002) became available, an ecological risk assessment was conducted, with no additional information about potential springs (Everest et al., 2017), and an evaluation of the potential water use in the Troad was published (Özcan et al., 2007, the ORP values in this paper are the mV readings from a pH probe, not a redox probe). In addition, using a subset of eleven samples from the sampling sites in Wolkersdorfer et al. (2004), Baba et al. (2007) described some hydrogeochemical characteristic of the area.

2. Study area

To study the question where Homer's "hot and cold" spring was located, we chose the area which is commonly considered to be the *Iliad*'s place of action: today's "Archaeological Site of Troy". In its vicinity, rocks can be assigned to two main units of Paleozoic to Quarternary age: (i) Crystalline slates, limestones and serpentinites of the Karadağ unit of the Ezine zone are exposed in the high plateaus south and east of the Troas plain. (ii) Neogene sediments form the flat, elongated ridges in the Troas National Park and its surroundings (Kraft et al., 1982; Okay et al., 1991). In the fluvial plains quaternary sediments are found at the surface (Göbel, 2005).

Neogene sediments of the Troia, Yeniköy and Kumkale ridges belong to the Truva Formation of Upper to Lower Pleistocene age and the Conkbayırı Formation, consisting of clay, siltstone, sandstone and conglomerates. In the eastern part of the Troia Ridge this formation is in tectonic contact with the carbonatic sandstones and gravels of the Alçıtepe formation (Lower Miocene). South and east of the study area, late Oligocene to Miocene basalts crop out. Between these basalts as well as metamorphites and the Alçıtepe Formation, early to mid-Miocene siltstones of the Gazhaneide Formation are exposed (Yaltırak and Alpar, 2002; Yaltırak et al., 2000). For the Troia Ridge itself, an alternating sequence of clayey-silty, sandy and carbonatic sedimentary rocks are described, which were deposited in a shallow marine or a lacustrine depositional area. These rocks were once part of an Eocene carbonate platform in a wide shallow marine gulf region extending to the Black Sea. Tectonic uplift during the Oligocene and Miocene divided this platform into individual blocks subjected to uplift and erosion of varying rates (Kayan, 1996; Okay et al., 1991).

In the Quaternary plains, fluviatile sediments that lie above marine sediments are characteristic. A sandy terrestrial-marine transition zone has partially formed between them. Usually, the marine sediments are composed of fine-grained silt with an admixture of fine sand, which is locally interrupted by coarser, fining upward beach and delta sediments. Typically, the fluviatile sediments are composed of silt, sandy silt and fine to coarse sands, with a predominance of fine grains, partly intercalated with slope debris material (Göbel, 2005; Göbel et al., 2002; Kayan, 1996; Kayan, 1997).

There are two main natural drainage systems in the National Park: the larger Karamenderes river (Karamenderes Çayı, "Scamander") with a south to north flow direction and the substantially smaller Dümrek river (Dümrek Su, Dümrek Çayı, "Simoeis") flowing from east to west. Both drain into the Çanakkale Boğazi (Dardanelles) north west of Kumkale. The Dümrek's source area is in the Salihler plateau East of Troia, and from there the river bears various names until it reaches the National Park. Its catchment area covers 87 km^2 and the electrical conductivity in the Dümrek Dam ranges between 320 and 760 µS/cm with a pH between 7.2 and 7.6 (Demirer et al., 2000) and downstream of Dümrek it has electrical conductivities between 530 and 640 µS/cm with a pH between 7.3 and 7.9 (Wolkersdorfer et al., 2004, sampling location FAL). Based on the observations of Wolkersdorfer et al. (2004) and the reports of Cook (1973), the stream can also fall dry during summer time. According to Yüzer (1997), the Karamenderes has an average discharge of 12.85 m^3 s^{-1} upstream the Bayramiç Dam, and its catchment area covers 1,584 km^2. Kale et al. (2016) report an average discharge of 9.00 m^3 s^{-1} between 1982 and 1997, with a decreasing temporal trend. As a result of agricultural use of the river water, the discharge decreased to 0.3 m^3 s^{-1} east of Troia in 2002. Between 1981 and 2010, the area had an average annual temperature of 15.3 °C, an average minimum temperature of 3.6 °C in February, a maximum temperature of 30.7 °C usually in July, an annual precipitation of 806 mm, and an adjusted potential evapotranspiration of 796 mm (1930–2005; weather station Çanakkale 17112). Due to its intensive agricultural use (Everest et al., 2017), the groundwater table was lowered from 0 to 1.25 m below the surface in 1879 (Virchow, 1879) to 5–15 m below surface 130 years later (Wolkersdorfer and Göbel, 2004).

3. Methods

First, the hypothesis of a destroyed thermal spring needed to be tested. To find a potential destroyed thermal spring, two assumptions had to be made: (a) The surrounding of the destroyed spring should be characterized by scalings of iron-hydroxide, amorphous silica, barite, or travertine similar to those of Tuzla (Fig. 3) or calcite, halite and siderite of Kestanbol Kaplıca (Marmara et al., 2020; Mützenberg, 1991), as all of the principal geothermal areas of Turkey are characterized by scalings (Möller et al., 2004; Mutlu and Güleç, 1998; Tarcan, 2005); (b) Close to the former location of the destroyed thermal spring there should still be recent springs with elevated reservoir temperatures, as it can be assumed that the water's deep source might still be the same as before the destruction.

Therefore, temperature, electrical conductivity, redox-potential, and pH-values of waters in the Troad were measured with a daily calibrated Myron P6 Ultrameter (Myron L Company, Carlsbad, USA), and oxygen with the WTW Oximeter OXI 320 (WTW, Weilheim, Germany). Continuous temperature measurements were conducted with CTD and TD Diver probes (van Essen Instruments, Delft, Netherlands). Si was determined in the laboratory by the silicamolybdate method with a Hach Spectrophotometer DR/2000 (Software Version 3.3) for the 2003 samples and a HACH "Odyssey" DR/2500 spectrophotometer for the 2004 and 2006 samples (detection limit 1 mg L^{-1}). All main ions were analysed at the Department of Hydrogeology of Bergakademie Freiberg (Freiberg University of Mining and Technology)/Germany with ion chromatography using a Merck/Hitachi HPLC. Each sample was filtered in the field through a 0.45 µm cellulose acetate filter (Sartorius

Fig. 3. Salt (light colour) and iron-hydroxide (darker colour) scalings at one of the Tuzla (Ayvacık/Çanakkale) hot springs; the water flows from bottom left to top right. Width of image 1 m.

Göttingen, Germany) without further treatment and stored in a cool and dark place until analyses in the laboratory. ESEM data was determined at BGR, Hannover, with an MLA 650F Quanta FEG ESEM (FEI Company), 45 kV, 30 mA, Mo detector, detector gain 20 eV/chan with a 100 µm step size and 1 s exposure time.

Several methods are available to calculate reservoir temperatures of waters using geothermometers, e.g. the Na/K, K/Ca, K/Mg, and SiO_2-geothermometers (Fournier, 1977; Giggenbach, 1988; Verma, 2000). Na, K, Mg and SiO_2 geothermometers were tested to verify if they are suitable to calculate the reservoir temperatures of the waters in the eastern Troad. To use the Na-K-Mg geothermometry for thermal waters, the maturity index MI (Giggenbach, 1988), which is an indication for the equilibrium between the thermal water and silicate minerals, needs to be above 2. All temperature calculations used are based on the Si mass concentrations of the sampled waters (Table 1). The equations published by Fournier (1977) were used to calculate the reservoir temperatures of the Troian waters (equation (1)). In 2000, Verma (2000) published a revised equation for the Si-temperature dependencies which was used as a basis for the above discussion (equation (2)).

$$T = \frac{a}{b - log\gamma} - 273.15 \quad (1)$$

$$T = \frac{1175.7(\pm 31.7)}{4.88(\pm 0.08) - log\gamma} - 273.15 \quad (2)$$

With *a, b*: coefficients for various mineral species, *T*: temperature in °C, γ: mass concentration of Si in mg L^{-1}.

Beside the literature about the Troad reported in the above paragraphs, all available data about potential hot springs in the Troad and geological mappings as well as reports about the geological situation in the Troad have been used. During the four field seasons, all dug wells, fountains, piped systems, natural dry and wet springs and surface water sources in the investigation area (characteristics were described in Wolkersdorfer et al., 2004) were visited and sampled, and numerous interviews with locals were conducted to find additional information about both “hot and cold” springs as well as dry wells.

A preliminary investigation of 161 sampling sites in the Troia area from the year 2001 included the determination of on-site parameters

Table 1
SiO_2-mass concentrations, the various reservoir temperatures and water types of the Troian waters, sorted by SiO_2-concentrations of the water. Locations are provided in Fig. 2.

location	SiO_2, mg L^{-1}	Verma and Fournier reservoir temperatures, °C							Water Type
		Verma*	SiO_2 Qz†	SiO_2 Qz SL†	SiO_2 Chc†	SiO_2 Crsα†	SiO_2 Crsβ†	SiO_2 Am†	
BDW	66.6 ± 15.1	110.5 ± 32.9	114.7 ± 11.5	113.6 ± 9.8	85.9 ± 12.5	64.2 ± 11.4	16.8 ± 10.8	–2.8 ± 10.0	Mg-HCO_3
BDD	59.5 ± 1.4	105.5 ± 21.2	110.1 ± 1.2	109.7 ± 1.0	80.9 ± 1.3	59.6 ± 1.2	12.4 ± 1.1	–6.9 ± 1.0	Mg-HCO_3
BDY	48.5	95.0 ± 19.2	100.4	101.4	70.4	50.1	3.4	–15.2	Mg-HCO_3
BCZ	40.1 ± 11.0	84.3 ± 31.6	90.5 ± 12.4	92.7 ± 10.8	59.8 ± 13.1	40.4 ± 12	–5.6 ± 11.2	–23.6 ± 10.4	Mg-HCO_3
BAO	29.0 ± 2.1	70.9 ± 20.5	78.0 ± 2.9	81.8 ± 2.6	46.6 ± 3.1	28.3 ± 2.9	–16.9 ± 2.6	–34.1 ± 2.4	Ca-Mg-HCO_3-Cl
BBX	26.4 ± 3.4	66.6 ± 22.5	73.9 ± 5.1	78.2 ± 4.5	42.4 ± 5.4	24.4 ± 4.9	–20.5 ± 4.5	–37.4 ± 4.2	Mg-Ca-HCO_3
BAB	25.8	65.8 ± 17.0	73.2	77.6	41.6	23.7	–21.1	–38	Mn-Mg-HCO_3
BCT	25.0 ± 6.1	63.5 ± 27.3	71.1 ± 9.8	75.7 ± 8.6	39.3 ± 10.3	21.6 ± 9.5	–23.0 ± 8.7	–39.8 ± 8.1	Ca-Mg-HCO_3
BBC	23.2 ± 6.3	60.2 ± 27.9	67.9 ± 10.7	72.9 ± 9.5	36.1 ± 11.2	18.6 ± 10.2	–25.8 ± 9.4	–42.4 ± 8.8	Mg-Ca-HCO_3
BEB	23.1 ± 3.4	60.9 ± 22.8	68.7 ± 5.8	73.6 ± 5.1	36.8 ± 6.0	19.3 ± 5.6	–25.2 ± 5.1	–41.8 ± 4.7	Mg-Ca-Na-HCO_3
BAT	22.2 ± 6.1	58.3 ± 27.9	66.2 ± 10.8	71.4 ± 9.6	34.3 ± 11.3	17.0 ± 10.4	–27.3 ± 9.5	–43.8 ± 8.9	Mg-Ca-HCO_3-Cl
BAF	22.1 ± 4.2	58.9 ± 24.3	66.8 ± 7.3	71.9 ± 6.6	34.8 ± 7.7	17.5 ± 7.1	–26.9 ± 6.5	–43.4 ± 6.1	Mg-Na-Ca-HCO_3-Cl
BAA	22	59.2 ± 16.5	67.1	72.2	35.1	17.8	–26.6	–43.1	Mg-Mn-Ca-HCO_3-Cl
BDF	21.9 ± 1.7	58.9 ± 19.6	66.8 ± 2.9	71.9 ± 2.6	34.8 ± 3.0	17.5 ± 2.8	–26.9 ± 2.6	–43.4 ± 2.4	Ca-Mg-HCO_3
BCL	20.5 ± 1.3	56.4 ± 18.8	64.4 ± 2.4	69.8 ± 2.2	32.3 ± 2.5	15.2 ± 2.3	–29 ± 2.1	–45.4 ± 2.0	Mg-Ca-HCO_3-Cl
BBF	20.5 ± 2.4	56.2 ± 20.9	64.2 ± 4.4	69.6 ± 3.9	32.2 ± 4.6	15.0 ± 4.2	–29.1 ± 3.9	–45.4 ± 3.6	Mg-Ca-Na-HCO_3-Cl
QS2	20.3 ± 0.3	55.9 ± 16.7	63.9 ± 0.5	69.4 ± 0.4	31.9 ± 0.5	14.8 ± 0.5	–29.4 ± 0.5	–45.7 ± 0.5	Ca-Mg-HCO_3-Cl
BCX	19.8 ± 2.9	54.7 ± 22.0	62.8 ± 5.6	68.3 ± 4.9	30.7 ± 5.8	13.7 ± 5.3	–30.4 ± 4.9	–46.6 ± 4.5	Mg-Na-Ca-Cl-HCO_3
GHW	18.7 ± 4.2	52.0 ± 24.9	60.3 ± 8.3	66.1 ± 7.5	28.1 ± 8.7	11.3 ± 8.0	–32.5 ± 7.3	–48.6 ± 6.8	Mg-HCO_3
QPT	18.7 ± 0.7	52.8 ± 17.6	61.0 ± 1.5	66.8 ± 1.3	28.8 ± 1.5	12.0 ± 1.4	–32.0 ± 1.3	–48.1 ± 1.2	Mg-Ca-HCO_3-Cl
BAH	18.6 ± 1.2	52.3 ± 18.6	60.6 ± 2.5	66.4 ± 2.2	28.4 ± 2.5	11.6 ± 2.4	–32.3 ± 2.1	–48.4 ± 2.0	Mg-Ca-Na-Cl-HCO_3
BAL	17.8 ± 1.5	50.7 ± 19.0	59.0 ± 3.0	65.1 ± 2.7	26.8 ± 3.1	10.1 ± 2.9	–33.6 ± 2.6	–49.7 ± 2.5	Mg-Ca-Na-Cl-HCO_3
QET	17.5 ± 1.5	50.1 ± 19.2	58.5 ± 3.2	64.5 ± 2.8	26.2 ± 3.3	9.5 ± 3.0	–34.2 ± 2.8	–50.2 ± 2.6	Mg-Ca-HCO_3-Cl
QEG	16.4 ± 0.5	47.6 ± 16.9	56.1 ± 1.2	62.4 ± 1.0	23.8 ± 1.2	7.3 ± 1.1	–36.2 ± 1.0	–52.1 ± 0.9	Mg-HCO_3-Cl
BED	16.1 ± 3.0	46.4 ± 22.7	54.9 ± 6.8	61.4 ± 6.1	22.6 ± 7.0	6.2 ± 6.5	–37.2 ± 5.9	–53.0 ± 5.5	Ca-Mg-HCO_3
QEE	15.9 ± 2.4	46.2 ± 21.4	54.7 ± 5.5	61.2 ± 4.9	22.4 ± 5.7	6.0 ± 5.2	–37.4 ± 4.8	–53.1 ± 4.4	Mg-Na-Ca-Cl-HCO_3
QNT	15.7 ± 0.1	46.0 ± 15.7	54.6 ± 0.2	61.1 ± 0.2	22.2 ± 0.2	5.9 ± 0.2	–37.5 ± 0.1	–53.3 ± 0.1	Mg-Ca-Cl-NO3-HCO_3
QPA	15.6 ± 1.7	45.6 ± 19.6	54.3 ± 3.9	60.8 ± 3.5	21.9 ± 4.0	5.6 ± 3.7	–37.8 ± 3.4	–53.5 ± 3.1	Ca-Mg-HCO_3
BAU	14.9 ± 2.7	43.5 ± 22.2	52.3 ± 6.5	59.0 ± 5.8	19.8 ± 6.6	3.7 ± 6.1	–39.5 ± 5.6	–55.1 ± 5.2	Mg-Na-HCO_3-Cl
BDZ	14.8 ± 4.3	42.6 ± 26.4	51.3 ± 10.5	58.1 ± 9.4	18.9 ± 10.8	2.8 ± 10.0	–40.3 ± 9.1	–55.9 ± 8.5	Mg-Na-Ca-HCO_3
HS3	14.1 ± 1.9	41.8 ± 20.3	50.6 ± 4.8	57.5 ± 4.3	18.1 ± 4.9	2.1 ± 4.5	–41.0 ± 4.2	–56.5 ± 3.9	Ca-Mg-HCO_3-Cl
BBW	14.0 ± 4.1	40.4 ± 26.3	49.3 ± 10.6	56.3 ± 9.5	16.8 ± 10.8	0.9 ± 10.0	–42.1 ± 9.1	–57.5 ± 8.5	Mg-Na-HCO_3-Cl-SO_4
BCR	13.7 ± 3.0	40.2 ± 23.1	49.1 ± 7.6	56.1 ± 6.8	16.6 ± 7.8	0.7 ± 7.2	–42.3 ± 6.6	–57.7 ± 6.1	Mg-Na-HCO_3
BSC	13.2 ± 4.8	37.5 ± 28.6	46.5 ± 13	53.7 ± 11.7	14.0 ± 13.3	–1.8 ± 12.3	–44.4 ± 11.1	–59.7 ± 10.4	Mg-Na-Ca-Cl-HCO_3
BBT	12.6 ± 0.4	37.8 ± 16.1	46.9 ± 1.1	54.2 ± 0.9	14.3 ± 1.1	–1.5 ± 1.0	–44.2 ± 0.9	–59.5 ± 0.9	Mg-Na-Ca-HCO_3-Cl
BAZ	12.2 ± 1.9	36.5 ± 20.4	45.6 ± 5.3	53.0 ± 4.8	13.0 ± 5.5	–2.7 ± 5.0	–45.3 ± 4.6	–60.5 ± 4.3	Mg-HCO_3
FKK	11.9 ± 0.6	35.9 ± 16.5	45.0 ± 1.6	52.4 ± 1.4	12.4 ± 1.7	–3.2 ± 1.5	–45.8 ± 1.4	–61.0 ± 1.3	Ca-Mg-Na-HCO_3-Cl
BBV	11.2 ± 4.6	31.4 ± 29.4	40.7 ± 14.2	48.6 ± 12.9	8.1 ± 14.5	–7.2 ± 13.4	–49.3 ± 12.1	–64.3 ± 11.3	Mg-Na-Ca-Cl-HCO_3-SO_4
QCF	11.0 ± 2.2	32.6 ± 21.7	41.9 ± 6.8	49.6 ± 6.1	9.2 ± 6.9	–6.2 ± 6.4	–48.5 ± 5.8	–63.5 ± 5.4	Ca-Mg-HCO_3
FAF	10.3 ± 0.3	31.0 ± 15.5	40.3 ± 0.9	48.2 ± 0.8	7.6 ± 0.9	–7.6 ± 0.8	–49.8 ± 0.8	–64.7 ± 0.8	Ca-Na-Mg-Cl
FAM	10.1 ± 2.3	29.4 ± 22.4	38.8 ± 7.7	46.8 ± 6.9	6.1 ± 7.8	–9.1 ± 7.2	–51.0 ± 6.5	–65.9 ± 6.1	Ca-Mg-HCO_3-Cl
SGS	9.8	29.3 ± 14.4	38.7	46.8	6	–9.1	–51.1	–65.9	Ca-Mg-HCO_3-Cl
BEA	8.5 ± 2.1	23.6 ± 22.1	33.3 ± 7.8	41.8 ± 7.0	0.5 ± 7.8	–14.2 ± 7.2	–55.7 ± 6.5	–70.2 ± 6.1	Mg-Ca-SO_4-Cl-HCO_3
QRW	8.2 ± 1.8	22.7 ± 21.1	32.4 ± 6.9	41.1 ± 6.3	–0.4 ± 6.9	–15.0 ± 6.4	–56.4 ± 5.8	–70.9 ± 5.3	Ca-HCO_3
BBZ	8.2 ± 0.9	23.0 ± 17.5	32.7 ± 3.4	41.3 ± 3.1	–0.2 ± 3.4	–14.8 ± 3.2	–56.3 ± 2.9	–70.7 ± 2.7	Mg-Ca-Na-HCO_3-Cl

*Verma (2000) and †Fournier (1977) maximum and minimum temperatures are given for sampling locations with two samples only. Locations with elevated reservoir temperatures are printed in bold and are indicated in Fig. 2. For the Verma (2000) temperatures, max and min values are also based on the uncertainties of the equation coefficients. Fournier (1977) gives no uncertainties for the coefficients of his equations.

such as temperature, pH, electrical conductivity, redox-potential, and O_2-concentration. Based on hierarchical cluster analyses of those parameters, five clusters were extracted and 47 representative sampling locations chosen for the before mentioned hydrochemical analyses and geothermometric calculations. These five clusters had unequal membership and representative locations were chosen such that they represent the area investigated (Fig. 2) based on the geological situation and the importance of the location for answering the research questions, 66 additional sampling locations were added in the subsequent three sampling campaigns, but not used for detailed chemical analysis.

4. Results and discussion

The electrical conductivities of the waters in the study area range between 0.4 and 7.1 mS cm^{-1} ($n = 652$) which agrees with the results of 25 water samples analysed by Özcan (2005). Based on cluster analysis, the waters can be grouped into three distinct water types (type I to III) which also reflect their hydrogeochemical differences (Fig. 4). In general, the waters from the metamorphic and volcanic rocks in the east and the deep wells in the plain as well as most surface waters are characterized by relatively low electrical conductivities (type I: 0.4–2.0 mS cm^{-1}; Fig. 4, top). Medium electrical conductivities are typical for the Troia and Kumkale ridges (type II: 1.8–3.5 mS cm^{-1}) and extreme electrical conductivities (type III: 3.7–7.1 mS cm^{-1}) were found in three isolated wells (BBP, BBK, BAH – 3-letter-codes refer to sampling locations) that are not characteristic for the area (in one year, animal carcasses were found in the water, but the wells showed elevated electrical conductivity in all the years, BBK belonged to Type II water in 3 out of 4 sampling campaigns). In no case, these electrical conductivities are close to typical electrical conductivities for the geothermal areas Tuzla and Kestanbol Kaplıca. There, Mützenberg (1997) measured 19.1 to 67.8 mS cm^{-1}, which is 5 to 36 times higher than the highest electrical conductivity group in the Troad.

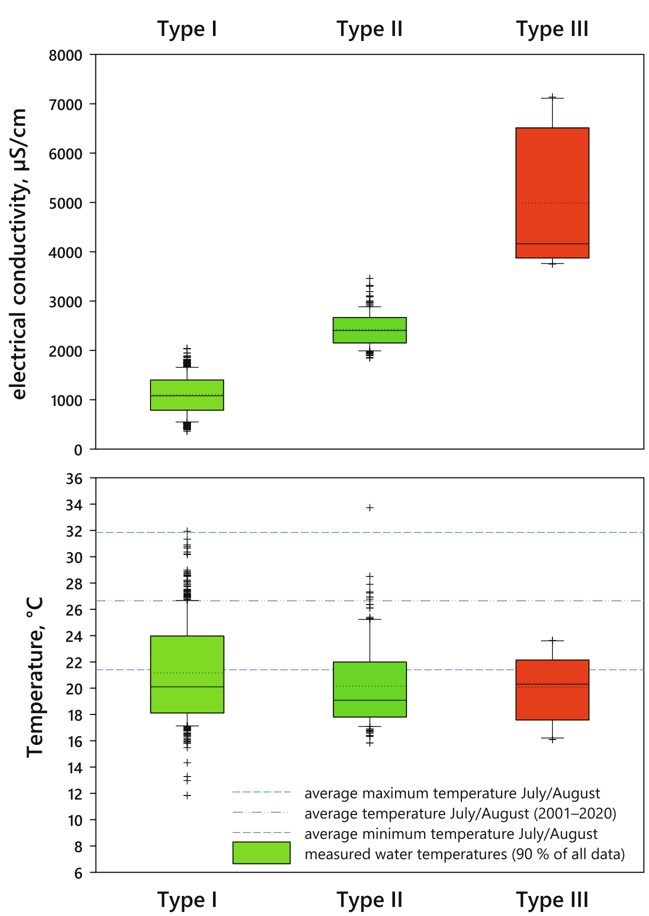

Fig. 4. Histograms of electrical conductivities (top) and temperatures (bottom) of the three water types in the research area. Type 1: $n = 487$, Type 2: $n = 154$, Type 3: $n = 10$.

No statistically significant differences in the water temperatures for the three water types could be found (Fig. 4, bottom). Water temperatures range between 12 °C (mainly groundwater and springs) and 34 °C (surface waters, fountains, and water from pipes) with a mean temperature of 21 °C ($n = 625$), 90% of all values being between 17 °C and 27 °C. None of the 227 sampling locations showed elevated temperatures at the point of discharge, thereby confirming the findings of all previous researches from Strabo and Groskurd (1931) to Virchow (1879) that there is currently no thermal spring close to Troia (Fig. 5). During several occasions, the water temperatures of some of the 40 "Kirk Göz" springs near Pınarbaşı were measured. They ranged between 17.4 and 18.5 °C ($n = 18$), which does not deviate from other temperatures measured in the Troad. It was therefore not possible to verify LeChevalier's observation of a hot and cold spring there.

At some locations, continuous temperature measurements were conducted over periods of several weeks to up to 2.5 years. Their selection was based on oral reports by locals that there are hot and cold springs (spring east of Dümrek: QWK, Fig. 6) or because they are related to the hydrogeological situation of the area (e.g. in the spring caves or the Düden Spring, Fig. 7).

The "Troia National Park" lies in an area of high seismic activity (Okay et al., 1991; Rapp, 1982; Schindler and Pfister, 1997; Yılmaz, 2003), and previous researchers therefore concluded that the hot spring *sensu* Homer has been destroyed by an earthquake (Eckenbrecher, 1875; Schliemann, 1884). Such destructions of springs as a result of an earthquake have reliably been reported for springs in Algeria and the USA (Braun, 1872; Deming, 2002; Wood et al., 1985), though the springs feeding Ingram's Warm Springs Creek (Idaho, USA) reappeared with an even increased flow after the earthquake. In case of the scalings, none of such types of mineral crusts are reported for the area around the National Park by any of the dozens of travellers to the Troad, nor could the geological mapping give any indication for a geothermal field that could have existed prior to a potential earthquake. Yet, there are several up to 10 m thick calcite sinter terraces along the trace of the Roman aqueduct (Aylward et al., 2002) east of Kemerkoy, Civlar (Fig. 8) resulting from Ca-HCO_3-rich water that was preferred as drinking water by the Roman inhabitants (Crouch, 1993; Grewe, 1992) of Ilion. Furthermore, most – but not all – of the Ca-HCO_3-rich waters in the investigated area show calcite sinter (travertine) at the point of discharge (Fig. 9); yet, in no case to an extent similar to Pamukkale for example. However, these scalings in the Troad cannot be taken as a trace of a hot spring, as they are mineralogically and structurally different from the deposits around the thermal springs in the Troad's vicinity, as they have been described by Mützenberg (1991) or Marmara et al. (2020) for Kestanbol Kaplıca and Tuzla.

The second assumption can be verified by using geothermometers. Because the analysed waters had a maturity index between 0.5 and 1.5, as indicated by the water types (Table 1), Na-K-Mg geothermometry could not be used, and presenting a Giggenbach diagram was omitted, because all the analysed waters are in the field of immature waters. Consequently, the SiO_2 geothermometer, which assumes equilibrium of the water with crystalline quartz or amorphous chalcedony, had to be applied. Testing the available SiO_2 geothermometers (Fournier, 1977) for consistency (Table 1) revealed that the most recent data published by Verma (2000) can be used to calculate the reservoir temperatures according to equation (2).

As the SiO_2-geothermometer is sensitive to secondary processes, such as mixing or precipitation, the calculated temperatures must be seen as minimum temperatures. As could be shown (Table 1), only four sampling locations yield reservoir temperatures above 80 °C (Fig. 2): BDW, BDD, BDY and BCZ. All those four are located southeast of the Hissarlık

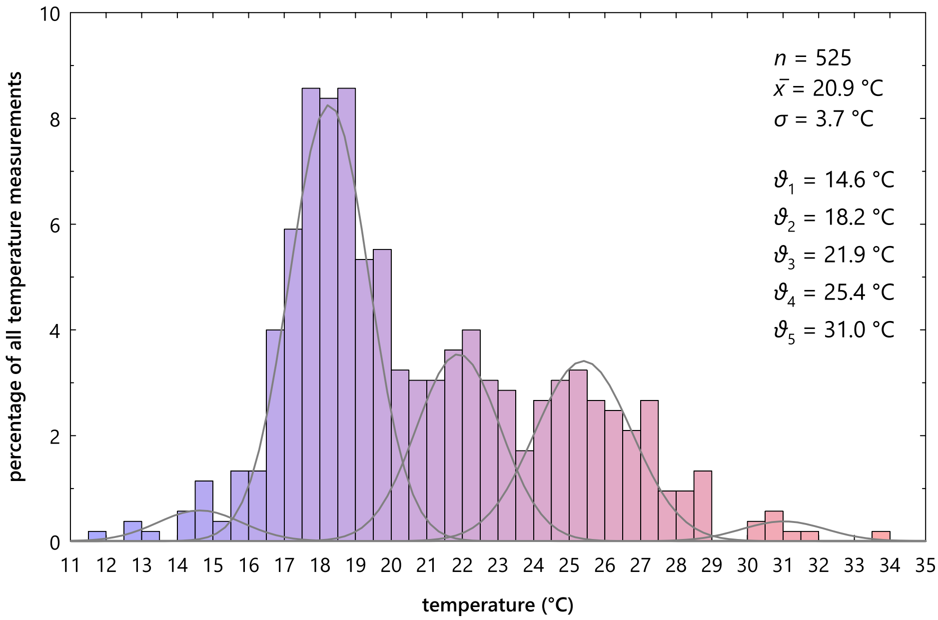

Fig. 5. Histogram of all discharge temperature measurements from surface and subsurface waters in the investigation area between 2001 and 2004. Included are 16 temperature measurements of Virchow (1879). $n = 525$; $\bar{x} = 20.9$ °C; $\sigma = 3.7$ °C. The predominantly trimodal distribution is a result of colder water temperatures for groundwater (≈18.2 °C), near surface wells (≈21.9 °C), and surface waters (≈25.4 °C). The distribution on the lower end belongs to deeper groundwater (≈14.6 °C) and the one on the upper end to fountains that are fed by pipes or reservoirs (≈31.0 °C).

between Taştepe and Dümrek, near the Ovacık thrust, which is at the boundary of the Tertiary sedimentary rocks and the crystalline as well as volcanic rocks. Furthermore, they are all Mg-HCO_3-waters. Two sampling locations (BDD, BCZ) are connected to the same spring system by a pipe, therefore only three locations show elevated reservoir temperatures (Fig. 2): BDW and BDY east-south-east of Dümrek as well as BCZ southeast of Taştepe. At all of these locations, the water temperature at the point of discharge ranges between 17 °C and 22 °C, which is near or below the mean temperature of all the waters investigated (BDD has a mean temperature of 28 °C and was not used for the purpose of this publication, because the water flows in a 2 km long barely-covered pipe which is affected by the daily temperature fluctuations). In no case, scalings such as those near Tuzla or Kestanbol Kaplıca were abundant and also the Cl concentrations of the waters (36 – 72 mg L^{-1}), which can be used as an indication for deep thermal waters, is much lower than at those (9430–38 463 mg L^{-1}) two thermal spring systems (Mützenberg, 1991). The closest of those three locations with high reservoir temperatures is about 10 km away from the Hissarlık.

Based on these results, we therefore conclude that close to today's Troia at the Hissarlık, a thermal spring never existed nor might once have disappeared due to an earthquake. Consequently, if there is nothing like a "hot and cold" spring around Troia, the question of what Homer could have meant when he described a "hot and a cold spring" remains open.

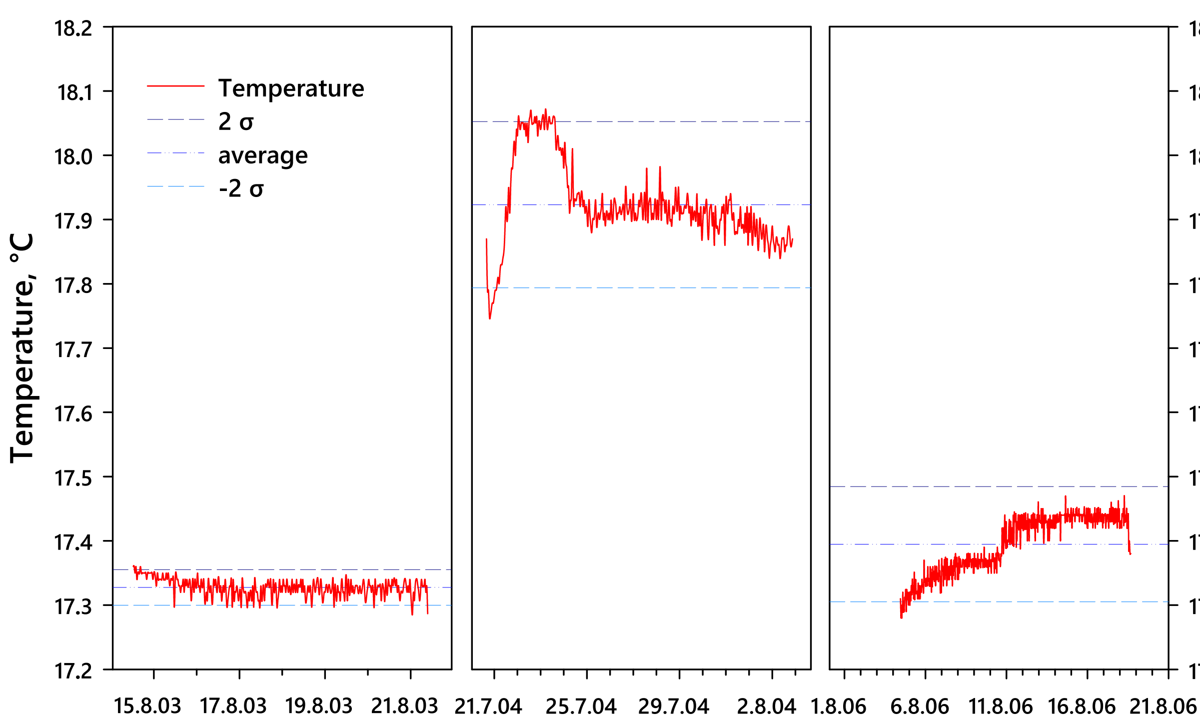

Fig. 6. Continuous temperature measurements at the former drinking water spring QWK east of Dümrek showing a nearly constant water temperature of the spring that locals describe as "warm" and "cold".

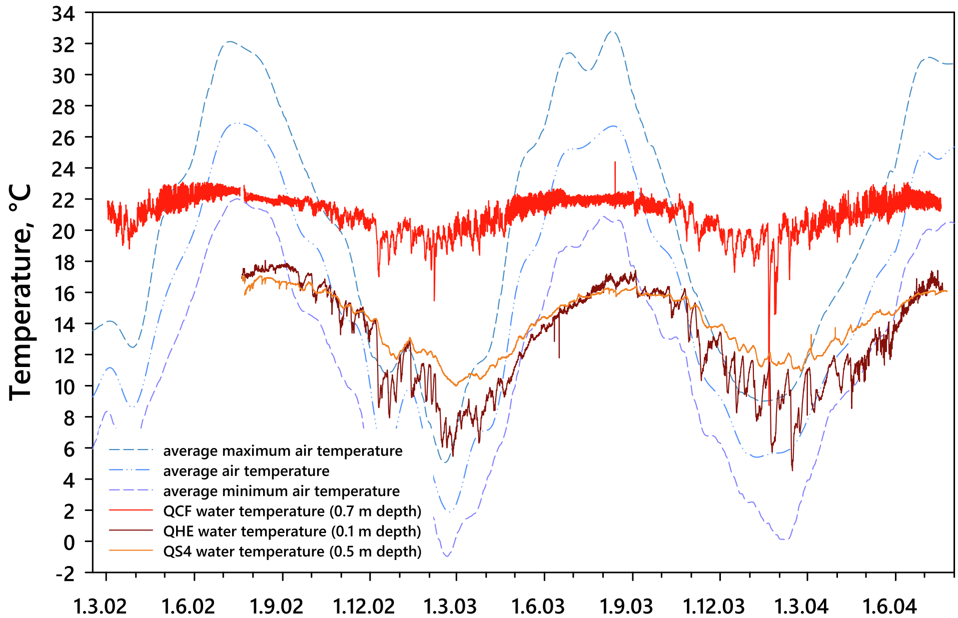

Fig. 7. Over two years continuous temperature measurements in the Düden Spring (QCF) and at two locations within the water mine (QHE: basin 10 m behind the entrance, QS4: 120 m behind the entrance).

5. Implications and conclusions

Numerous local people and previous visitors to the Troad (Eckenbrecher, 1875; LeChevalier, 1791; Virchow, 1879) report about hot and cold springs at different locations in the investigation area by means of organoleptic observation. Continuous temperature measurements in one of those springs (QWK east of Dümrek) showed a statistically significant difference to other springs in the area. While most springs experience a diurnal temperature variation of several Kelvin (Fig. 7) indicative for a local flow system *sensu* Tóth (1963), the groundwater in the investigated area termed "hot and cold spring" by Homer has a quite constant water temperature of 17.3 °C, 17.4 °C or 17.9 °C during the periods of investigations (Fig. 6). This is indicative for the regional flow system *sensu* Tóth (1963) and consequently an indication for a comparably long residence time (Hippocrates uses the expression "coming from very deep springs"), as no diurnial temperature fluctuations were observed, such as for other springs. Furthermore, locals knew of springs which showed steam at different times of the year (Eckenbrecher, 1875; Virchow, 1879), namely those of the before mentioned "Kirk Göz" springs near Pınarbaşı. Two continuous (1 h sampling interval) temperature measurements between 2001 and 2004 at the Düden spring (QCF) and Troia's spring cave (QHE, QS4) demonstrate that the relative water temperature is cold in summer time (21–23 °C), when the water temperature is below the daily mean temperature (23–27 °C) and they are warm during winter time (16–21 °C), when the temperature is above the daily mean temperature (2–8 °C). A very similar description of a set of springs can be found in Plato's *Kritias* where he describes a cold and a warm spring within the range of his castle flowing out of the same location (Platon, 1973; Zangger, 1993). Though he writes about two springs, he explains that in fact he only means *one* spring with hot and cold water. Consequently, it may be assumed that Homer also describes such a system of springs, which is "relatively" cold in summer and "relatively" warm in winter.

Fig. 8. Travertine at sampling location FAC south of the Kemerdere river (east of Kemerkoy, Civlar). Width of image 1.5 m.

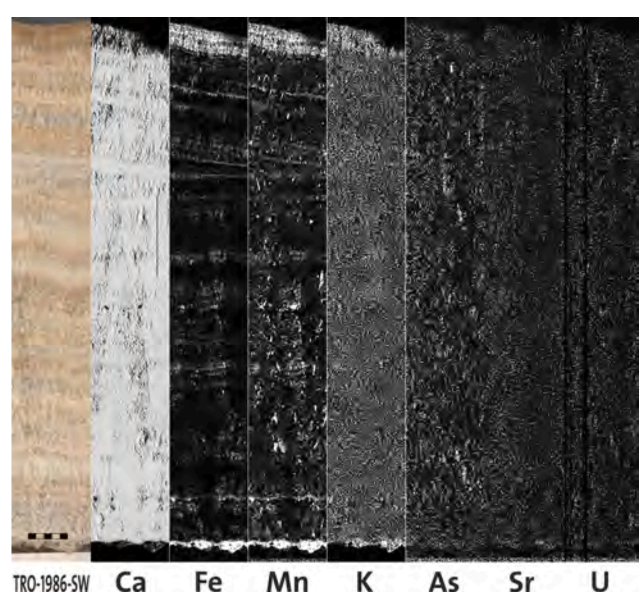

Fig. 9. Qualitative ESEM image of calcite sinter near location QRW. The layering results from difference in the sinter's Fe and Mn as well as K composition. Characteristic metals and As in the Trojan waters (As, Sr, U) are not mirrored in the sinter. Scale 1 cm.

As has been shown in our investigation, there most probably never was a hot, thermal spring in or around the "Troia National Park" because the characteristic scalings and the elevated reservoir temperatures cannot be found. Furthermore, numerous springs fulfill the prerequisite of being "hot/warm and cold" *sensu* Homer. It is therefore apparently not possible to identify Homer's "hot/warm and cold" spring(s) within the Troad and all attempts to locate Homer's Troia by using Iliad XXII, 147–156 might be a fruitless enterprise.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.catena.2020.105070.

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