Environmental Geochemistry and Health

Geochemical characterization of the thermo-mineral waters of Greece --Manuscript Draft--

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| Abstract: | Geothermal areas of Greece are located in regions affected by recent volcanism and in continental basins characterised by elevated heat flow. Many of them are found along the coast and thus, water is often saline due to marine intrusion. In the present study, > 300 thermal and cold mineral water samples were collected along Greece. Samples were analysed for major ions, Li, SiO 2 and isotopes in water. Measured temperatures range from 6.5 to 98°C, pH from 1.96 to 11.98, whilst Total Dissolved Solutes (TDS) from 0.22 to 51 g/L. Waters were subdivided into four main groups: i) thermal; ii) cold; iii) acidic (pH <5) and iv) hyperalkaline (pH >11). On statistical basis, the thermal waters were subdivided into subgroups according to both their temperature [warm (<29 °C), hypothermal (29-48 °C), thermal (48-75 °C) and hyperthermal (>75 °C)] and TDS [low salinity (<4 g/L), brackish (4-30 g/L) and saline (>30 g/L)]. Cold waters were subdivided basing on their pCO 2 [low (<0.05 atm), medium (0.05-0.85 atm) and high (>0.85 atm)]. δ 18 O-H 2 O ranges from -12.7 to +2.7 ‰ vs. SMOW, while δ 2 H-H 2 O from -91 to +12 ‰ vs. SMOW being generally comprised between the Global Meteoric Water Line and the East Mediterranean Meteoric Water Line. Positive δ 18 O shifts with respect to the former are mostly related to mixing with seawater, while only for a few samples they point to high-temperature water-rock interaction processes. Only a few thermal waters gave reliable geothermometric estimates, suggesting reservoir temperatures between 80 and 260 °C. |
| Response to Reviewers: | Reply to the reviewers |
| | Reviewer #1 The article entitled "Geochemical characterisation of the thermo-mineral waters of |

Greece", present comprehensive overview on the geochemical characterisation of thermomineral waters from Greece. The research article takes into consideration more than 300 original data. This is the first article on Greece where the the origin and distribution of the thermo-mineral waters are discussed using both chemical and isotopic data at the same time.

The topic is really interesting for the scientific community and the data are valuable. The article gives also helps in understanding the lack in the current research and give an insight on which Greek areas are studied in more detail.

The paper is well written (for no mother tong English speaker); I could follow the thread of the discussion. In the introduction, the scientific content and state of the art are clearly written.

Some minor suggestion that could help in the better overview of the data:

1. A paragraph should be added discussing the hydrogeological settings. Even a general overview is sufficient.

Reply: We added a few sentences describing the overall hydrogeological setting of Greece.

2. In the case of the Local Meteoric Water Lines (LMWL) please insert all the available LMWL's, Or mention which were selected to be used and why. I believe for a region so big there are more than one LMWL.

Reply: The referee correctly supposes that more than one LMWL was defined for different areas in Greece. These are reported in the cited paper of Argiriou and Lyloudis, 2006. The same authors state that these LMWLs are generally not statistically different from that obtained considering all the published data on meteoric waters collected in Greece from 1960 to 2003 except for a few sites were the collected data were too few. We therefore decided to use the LMWL defined with the whole dataset which is statistically more robust.

Nevetheless, we specified in the text who the LMWL was defined.

3. A ternary plot using would CI-SO4-HCO3 would be useful in describing the geochemical characteristics with the geological settings of the waters.

Reply: We included the CI-SO4-HCO3 ternary plot in the geothermometry section and we added an introductory/explanatory paragraph.

4. Please indicate why in the Giggenbach-diagram that one point falls above the full equilibrium line. Give possible answers for it.

Reply: We added some hypothesis.

5. For the geothermometers please add a supplementary file with the written equations.

Reply: Added

and finally 6. Add a paragraph putting into context the waters and the observed geochemical data on the gases (the published data mentioned in the text).

Reply: We added a paragraph where we talk about the relations between tectonics and fluids.

Taking into consideration the manuscript, data etc. I suggest the paper should be expected after minor revision.

Reviewer #3

Dear Authors,

In this paper (EGAH-D-20-00740) "Geochemical characterization of the thermo-mineral waters of Greece", the authors present a large dataset on the chemical and isotopic composition of the thermo-mineral waters in Greek. The topic is certainly interesting to geochemistry community and Environmental Geochemistry and Health readership

however the text does not seem an original research, as they state, but rather a synthesis of data (hyperalkaline waters dataset coincide with data from Li Vigni et al. 2020 (Ital. J. Geosci., Vol. 140, No. 1 (2021), https://doi.org/10.3301/IJG.2020.20, but the authors fail to mention it through the text and also in the tables). In my opinion the paper show various critical issues. First of all, the scope of the work is limited, and although the authors aim to understand the relationship between water chemistry and geological context, this goal is not pursued and discussed. The results are well presented and the subdivision of the dataset into different groups is certainly acceptable. However, within each water group there are differences in the chemical composition or variations of chemical-physical parameters that are not always justified through a geochemical approach (inter-elemental relationships, R-mode factor analysis etc). Some conclusions are obtained from previous papers and not appropriately proposed and argued on the data available. As a consequence, I think that this paper cannot be accepted for publication in the present form therefore I recommend to rewrite it and organize a new version, probably as review, and subsequently submit it again.

Reply: We acknowledge the constructive criticism of the reviewer and his/her efforts to improve the manuscript. Some very interesting points were raised and we hereby address them. The reviewer claims that "the text does not seem an original research, as they state, but rather a synthesis of data (hyperalkaline waters dataset coincide with data from Li Vigni et al. 2020 (Ital. J. Geosci., Vol. 140, No. 1 (2021), https://doi.org/10.3301/IJG.2020.20, but the authors fail to mention it through the text and also in the tables". All the references are included in the supplementary material Table under the name "References", while we added a phrase in the text to make it more evident. We also specified it in the abstract. Moreover, we have rewritten the scope of this work by including all the topics discussed in the manuscript in the introductory part. We consider that this addition will make the manuscript more clear. Also, we added more plots where we integrated and interpreted the data. Previous explanations were taken into consideration: Finally, we are sceptical of the reviewer's suggestion on re-submitting this article as a review. Indeed, a great number of data is discussed in the manuscript, however only one third of the dataset comprises published data; the rest is unpublished and non-peer reviewed and new concepts are introduced. Hence, we ask for the editor's opinion on the topic.

General Remarks

1) Given that the main objective of the paper is to understand the relationship between water chemistry and geological context It would be appropriate to insert a geologicalstructural map of Greece. The proposed geological map is not suitable as it does not show the type of outcropping rocks. The Moho depth model is not suitable for the submitted paper.

Reply: We included a map with the isopic zones of Greece in Figure 2, and deleted the map of the crustal thickness. The description of the zones, was added in the study area section.

2) in the text some places are recalled several times, can you add them in the Figure 1?

Reply: Added

3) I suggest to integrate Materials and methods section by inserting the methodology used to measure the bicarbonate in water with high pH values; In the table 1 I suggest to add Ionic Balance

Reply: Although expressed as mg of bicarbonate per litre, what we determined was total alkalinity as indicated in the text and in the supplementary table. Ionic Balance was added.

4) Cold gas-rich and Thermal waters show different Kind of hydrofacies, from CaMg-HCO3 to NaCl. Why? Which geochemical processes can explain this?

Reply: We tried to explain the processes bringing to such great variety of hydrofacies in the discussion also adding some binary correlation plot as suggested below by the

reviewer

5) About sixteen Cold gas-rich waters have a NaCl hydrofacies. Why Only few of these waters show important seawater admixing in the dH vs. Cl binary diagram?

Reply: Most of the cold gas-rich waters pertaining to NaCl hydrofacies were originally very diluted waters so that even small admixtures of seawater changed their composition to NaCl waters.

6) When you discuss each water group it would be appropriate to report a graph that justifies the chemical composition and highlights possible differences;

Reply: We inserted binary diagrams in order to better discuss the processes acting in the hydrological circuits of the sampled waters.

7) For Cold gas-rich waters I suggest to use the Bicarbonate vs Ca+Mg and Na vs Cl diagrams in order to verify which geochemical processes take place (i.e. water-rock interaction; seawater mixing, mixing between deep and shallow water etc...)

Reply: We inserted the requested binary diagrams both for the cold gas-rich and for the thermal waters. These were discussed trying to evidence the geochemical processes taking place.

8) For thermal waters, if dissolved sulphate is due to gypsum-rich Triassic evaporates, can you verify this through graphs? Are the redox conditions suitable to the reduction of sulphate into H2S?

Reply: Ca vs SO4 binary diagrams were inserted and discussed. We discussed also the processes leading to the reduction of sulfates to sulfides.

9) I suggest to check the Heat flow map with waters recording the highest values of geothermometric estimations.

Reply: We evidenced the samples with the highest geothermometric estimations on the heat flow map.

10) Have you verified if any tectonic structures carry deep fluids towards the surface?

Reply: We added a paragraph where we talk about the relations between tectonics and fluids as requested also by reviewer #1.

Click here to view linked References

Geochemical characterisation of the thermo-mineral waters of Greece

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Abstract

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Geothermal areas of Greece are located in regions affected by recent volcanism and in continental basins characterised by elevated heat flow. Many of them are found along the coast and thus, water is often saline due to marine intrusion. In the <u>current study</u>, we present study, >about 300 40 unpublished and literature data from thermal and cold mineral water samples werewaters collected along Greece. Samples were analysed for major ions, Li, SiO₂ and isotopes in water. Measured temperatures range from 6.5 to 98°C, pH from 1.96 to 11.98, whilst Total Dissolved Solutes (TDS) from 0.22 to 51 g/L. Waters were subdivided into four main groups: i) thermal; ii) cold; iii) acidic (pH <5) and iv) hyperalkaline (pH >11). On statistical basis, the thermal waters were subdivided 45 into subgroups according to both their temperature [warm (<29 °C), hypothermal (29-48 °C), thermal (48-75 °C) and hyperthermal (>75 °C)] and TDS [low salinity (<4 g/L), brackish (4-30 g/L) and saline (>30 g/L)]. Cold waters were subdivided basing on their pCO₂ [low (<0.05 atm), medium (0.05-0.85 atm) and high (>0.85 atm)]. δ^{18} O-H₂O ranges from -12.7 to +2.7 ‰ vs. SMOW, while δ^2 H-H₂O from -91 to +12 ‰ vs. SMOW being generally comprised between the Global Meteoric 50 Water Line and the East Mediterranean Meteoric Water Line. Positive δ^{18} O shifts with respect to the former are mostly related to mixing with seawater, while only for a few samples they point to high-temperature water-rock interaction processes. Only a few thermal waters gave reliable geothermometric estimates, suggesting reservoir temperatures between 80 and 260 °C.

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Keywords: hydrogeochemistry, stable isotopes, carbon dioxide, geothermometry

1. Introduction

- In the 1960s, the National Tourism Organization (NTO 1966) estimated the number of thermo-60 mineral springs in Greece at more than 750, with nearly 200 of which found on the islands of the Aegean Sea. Even though about a quarter of these springs is nowadays used for balneotherapeutic purposes, archaeological evidence supports the use of some of them since prehistoric times (Fytikas et al. 1999). In classical times until the end of the Roman Empire, thermo-mineral waters were highly appreciated and many of them were mentioned by poets (Homer, Pindar, Aristophanes), 65 historians (Herodotus, Diodorus Siculus, Plutarch) and geographers (Strabo, Pausanias) (Fytikas et al. 1999). At the same time, the first theories regarding their origin were developed (Plato, Aristotle) and their medical use was emphasized (Hippocrates). It is worth mentioning that, during this period, many of the thermo-mineral springs were considered sacred and were dedicated either 70 to the Nymphs or to Asclepius, the God of Medicine. Their religious significance continued until Christian times. Then, this dedication shifted either to Virgin Mary or to Agioi Anargyroi, with the latter being saints known for offering their medical services without reward (Håland 2009). Their balneotherapeutic use declined under the Byzantine Empire and grew again under Ottoman Empire, but it was not before the end of the 20th century that other uses (heat and energy production, industrial use of CO₂, etc.) were applied (Fytikas 1988). In fact, Fytikas et al. (2005) documented 75 that in the early 70's the Institute of Mineral and Geological Exploration (IGME) used for the first time the thermal water for greenhouse heating. However, the great development in geothermal field arrived in 1981 when Greece entered the European Union, and many research projects were funded by the European Commission.
- 80 Greece, located in a geodynamically active area of the Eastern Mediterranean, is characterised by widespread geothermal resources closely linked to the geology of the country (Papachristou et al. 2019). Its puzzling geodynamic regime contributes to the existence of an elevated terrestrial heat flow, which results in several geothermal fields containing both low and intermediate temperature fluids (Fytikas and Kolios 1979). Areas of enhanced heat flow are located in regions affected by Miocene or Quaternary volcanism and in continental basins (Fytikas and Kolios 1979). The 85 geothermal exploration has found high-enthalpy geothermal fields in Milos and Nisyros islands, in the South Active Aegean Volcanic Arc (SAAVA), and low-medium enthalpy georesources in some Aegean islands, i.e. Chios, Lesvos and Samothraki, and in several sedimentary basins of Northern and Central Greece (Mendrinos et al. 2010). Besides, many of these fields are found along the coast 90 as well as in islands and thus, thermal waters are often brackish to saline due to marine intrusion into the costal aquifer (Lambrakis and Kallergis 2005). In fact, according to Minissale et al. (1997), the thermal springs located in the SAAVA are affected by mixing between the local meteoric waters

and the Aegean seawater, while a marine component, sometimes evolved due to processes seated in the deep thermal reservoirs, is found also in hot waters emerging along the coast of the continental basins (Duriez et al. 2008).



Fig. 1 – Geographic distribution of the sampling sites. Insets are enlarged areas with high density of sampling sites. <u>1-</u>
 Samothraki; 2- Strimon Basin; 3- Migdonia Basin; 4- Othrys and Sperchios Basin; 5- Edipsos; 6 – Argolida; 7 - Santorini.

The complex geodynamic and geological setting of the Aegean territory reflects in a great variety of geochemical compositions for many thermal and cold fluid manifestations (Daskalopoulou et al., 2018a, 2019a, Minissale et al. 1989; 1997). The first scientific investigations regarding the chemical composition of the thermo-mineral waters of Greece appeared soon after the birth of the Modern Greek State in 1830. Landerer (1843) gave the first overview of the whole territory and further nationwide studies appeared in more recent times (Pertessis 1937; Lambrakis and Kallergis 2005; Athanasoulis et al. 2009).

110 The scope of this study is to present a large dataset on the chemical and isotopic composition of the thermo-mineral waters of the whole Greek country and discuss their properties in the framework of the geological context of the area. To this aim, we discussed the results of more than 300285 water samples collected from October 2004 to March 2020 (Fig.1) and analysed for their major, minor

and trace constituents and the isotopic composition of water. About one third of the results were

previously published (D'Alessandro et al. 2008; 2011a; 2014; 2017; 2018; Li Vigni et al., 2021; Papachristou et al. 2013) and are here discussed together with the unpublished data to present a more or less complete picture of the whole country. Although spanning over a long time period, the same sampling and analytical methods were applied increasing the internal consistency of the dataset.

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2. Study area

The complex geodynamic setting of the Hellenic territory classifies it in the most tectonically and seismically active areas of the world (e.g., Le Pichon et al. 2001; Taymaz et al. 1991; Tsokas and Hansen 1997). This regime is dominated by three large-scale tectonic structures: (i) the active retreat of the northward subduction of African plate beneath the Eurasian at a rate of 4-6 mm/a (McClusky et al. 2000) forming the back-arc Aegean area; (ii) the mostly N-S oriented crustal extension (Mercier 1981); and (iii) the westward motion of Anatolian plate along the strike-slip North Anatolian Fault (NAF) (Pavlides and Caputo 1994). It is worth noting that the Greek region is the result of the intense collision of several microplates (Aegean, Anatolian and Apulian plate) that took place during the Alpine orogenesis since the Upper Cretaceous involving the subduction of Tethyan Ocean (van Hinsbergen et al. 2005). The volcanism of the area is located in the southern Aegean Sea, while the SAAVA comprises magma of calc-alkaline to shoshonitic suite and signs of crustal contamination (Pe-Piper and Piper 2006).



Fig. 2 – Sketches illustrating the complex geodynamic situation of Greece. (a) Main geologic subdivisions (after Mountrakis, 1985): HH = Hellenic Hinterland; IH = Internal Hellenides; EH = External Hellenides; VA = Volcanic Arc;
(b) Heat flow map (mW/m²) as proposed by Fytikas and Kolios (1979); (c) The Moho depth model (km) as proposed by Grigoriadis et al. (2016); (d) map of the major tectonic structures and the current horizontal stress field main axes (Pavlides et al., 2010).

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Based on the aforementioned complex tectonic setting and the prevailing geological formations, Mountrakis (1985, 2010) divided Greece into three structural <u>isopic</u> zones, which from west to the east are: (i)

(i) External Hellenides that(EH): correspond to a neritic continental sea depositional
 environment; (ii), and consist of the Parnassos, Gavrovo-Tripolis, Ionian and Paxos zones. It
 is worth mentioning that during the Middle-Upper Jurassic, the Ionian zone bearded an
 intracontinental basin with pelagic sediments. According to Doutsos et al. (2006), three major
 rift structures occurred during Mesozoic within the eastern margin of the Apulian continent
 that were reactivated in the Tertiary by forming intracontinental thrusts;

- 150 (ii) Internal Hellenides, which (IH): express various environments and depending, and consist of the Pelagonian, SubPelagonian, Atticocycladic, Circum Rhodope and Vardar zones. Depending on the geographical position they are characterised by obducted ophiolites and deep-sea sediments, neritic sediments, volcanoclastic and sea deposits or flysch; and (iii). Hellenic Hinterland that comprises a Precambrian Silurian continental crust affected by metamorphism (Fig. 2a).. Neritic sediments prevail in the Pelagonian zone, which is 155 considered to be a fragment of the Cimmerian microcontinent, while obducted ophiolites are the most characteristic lithological unit of the Subpelagonian zone. The latter is thought to be the continental slope of the Cimmerian continent towards the ocean, whose sedimentary remnants form the Pindos zone. Both zones consist of sea deposits, and appear a progressively 160 deepening sea towards the west. Similar to the Pelagonian, also the Attico-Cycladic zone is envisaged as a continental fragment with undergone neritic sedimentation. Alpidic lithostratigraphic succession bearing volcanoclastic and sea deposits ending up in deep-sea sediments westwards, and flysch are the lithologies characterizing the Circum-Rhodope zone. The Vardar zone corresponds to the ocean of Tethys characterized by the presence of deep-sea sediments and the obducted ophiolites; 165
 - (iii) Hellenic Hinterland (HH): comprises a Precambrian-Silurian continental crust affected by Alpidic metamorphism, and consists of the Rhodope and Serbomacedonian Massifs. Crystalline rocks are the main lithology for both zones, while neritic deposits and Late Eocene–Early Oligocene granitoid intrusions are present (Fig. 2a).
- 170 From a hydrogeological point of view, the outcropping lithologies in Greece can be subdivided in three major groups. The first is the porous aquifers comprising mainly Quaternary and Neogene sediments (Daskalaki and Voudouris, 2008). These are mostly found within subsident extensional basins and cover about 30% of Greece. The second group comprises all karstic aquifers developed both in the limestone of the sedimentary sequences and in the marble within metamorphic
- 175 complexes (Kallioras and Marinos, 2015). The former crop out mainly in central, western and southern Greece and latter in the northern part of the country, altogether covering about 35% of the whole area. The third group comprises all the remaining lithologies characterised by low permeability or being impermeable (flysch, clays, most metamorphic rocks, volcanites, ophiolites etc.).
- 180 Geology along with volcanism and tectonics favoured the existence of many thermal manifestations and anomalous degassing areas (Daskalopoulou et al. 2019a). The elevated heat flow (Fig. 2b) resulted in numerous geothermal fields from low to high enthalpy (Fytikas and Kolios 1979; Andritsos et al. 2015), while the extensional tectonics (Fig. 2d2b) affected crustal thinning(Fig. 2c)

contributing to fault formation (Grigoriadis et al. 2016) and thus to the ascent of fluids. The elevated heat flow values noticed in the northern part of Greece were associated with the existence of a "first phase" volcanic arc (Fytikas et al. 1984; Vougioukalakis et al. 2004).

3. Materials and methods

- The physico-chemical parameters (temperature, pH, Eh and Electric Conductivity (EC)) were
 measured *in situ* with portable instruments. The total alkalinity was determined by titration with 0.1
 N HCl on unfiltered samples-<u>(expressed as mgHCO₃-/L)</u>. Water samples were filtered (0.45 μm MF-Millipore cellulose acetate filters) and stored in HDPE bottles, whilst the aliquot for determination of cation contents was acidified with ultrapure concentrated HNO₃. Analyses of the water chemistry and the isotopic composition were carried out at the laboratories of Istituto
 Nazionale di Geofisica e Vulcanologia of Palermo (INGV-Pa).
- Water chemistry was analysed using standard methods (APHA, AWWA, WEF, 1995): major cations (Na, K, Mg, Ca) and major anions (F, Cl, NO₃, SO₄) were determined by Ionic Chromatography (ICS-1100, Dionex), Si was determined by Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES; Yobin Ultima). Spectrophotometric methods were used for the determination of NH₄ (Berthelot's reaction). Lithium was determined by Inductively Coupled Plasma Mass Spectrometry (ICP-MS; Agilent) as well as Mg and K, when found below detection limits in ionic chromatography. For all these analytical methodologies, precision was always better than ±3 %. Speciation of waters and Saturation Index (SI) of main mineral phases for each water sample and the calculation of theoretical pCO₂ for cold gas-rich samples were obtained using the
- aqueous speciation PHREEQC software (Parkhurst and Appelo 1999).
 <u>Ionic balance (%) was calculated with the formula:</u>

 {(Σcations+Σanions)/[(Σcations-Σanions)/2]}×100
 where cations are Na⁺, K⁺, Mg²⁺ and Ca²⁺ and anions Cl⁻, NO₃⁻, SO₄²⁻ and total alkalinity all expressed as meq/L.

 210 TDS (Total Dissolved Solutes) expressed in g/L is here intended as the sum of all major anions (F⁻,
- ²¹⁰ TDS (Total Dissolved Solutes) expressed in g/L is here intended as the sum of an major antons (F, Cl⁻, NO₃⁻, SO₄²⁻ and alkalinity as HCO₃⁻) and cations (Na⁺, K⁺, Mg²⁺ and Ca²⁺) plus SiO₂. The oxygen and hydrogen isotopic compositions of waters were determined by using, respectively, Analytical Precision AP 2003 and Finnigan MAT Delta Plus IR Mass-Spectrometry on unfiltered samples. Results are expressed in delta notation (‰) respect to the international standard V-SMOW
 (Vienna Standard Mean Ocean Water). The uncertainties are ±0.1‰ for δ¹⁸O and ±1‰ for δ²H (±1)

σ).

Geothermometric estimations were obtained for some selected samples with the software Solute Geothermometers (SolGeo) that includes 35 geothermometric equations (Verma et al. 2008).

The study area from where the waters were collected is characterised by a great diversity of

4. Results 220

4.1 Water geochemistry

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lithologies and geodynamic environments, which is reflected in a large variety of measured physical-chemical parameters and chemical compositions (Supplementary Material - Table S1). Temperatures measured at spring outlet range from 6.5_°C to 98_°C, while pH varies from 1.96 to 11.98. It is worth noting that the great majority of the samples is delimited in pH values between 5.5 and 9, whilst only few springs show either low to very low pH (< 5) or very high pH values (> 11). TDS concentrations range from 0.22 to 51 g/L. Based on the aforementioned parameters, the sampled waters were divided into cold (< 23 °C) and thermal (> 23 °C) waters, with the former being subdivided according to their pCO₂ values and the latter according to their combined 230 temperature values and TDS concentrations (low salinity, brackish and saline). Waters characterised by either very low or very high pH were considered as extra categories. The ionic balance of the cold and thermal waters is generally within the acceptable range of $\pm 10\%$. Only three samples of each of these groups exceed such limit (3.2% of the cold and 1.8% of the thermal waters). On the 235 contrary both acid (80%) and hyperalkaline (16.7%) water show often strong imbalances. These strong imbalances are not due, as normally considered, to analytical errors. They are mostly due to the presence of less common ionic species not considered in the calculation of the ionic balance. These are OH⁻ in the case of hyperalkaline waters, H⁺, NH₄⁺, ionic species of Fe, Mn, Al, Sr, Ba in the case of acidic waters, and ionic species of S(-II) and of organic molecules in the case of reduced 240 waters. Almost all of the waters with strong imbalances here considered fall within one of these categories.

To better discriminate the different geochemical characteristics of the different groups, the data were plotted in a Langelier-Ludwig (1942) classification diagram (Fig. 3) and are described in detail below.

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4.1.1 Hyperalkaline waters

The hyperalkaline waters are found in the Argolida ophiolites (Peloponnese) and the ophiolitic complex of Othrys (Central Greece). Samples of this group are characterised by very high pH values (11.17 and 11.98) and low salinity (TDS < 0.63 g/L). Temperature ranges from 17.4 to

27.7°C, while alkalinity is expressed mainly asaccounted by OH⁻ ions. According to Barnes et al. (1967), they can be classified as Ca-OH waters (Fig. 3a).



Fig. 3 – Langelier-Ludwig classification diagram for a) hyperalkaline, b) acidic, c) thermal and d) cold gas-rich waters. The yellow star represents the composition of seawater.

4.1.2 Acidic waters

The acidic waters are located in the islands of SAAVA, i.e. Kos (Kokkino Nero and Aspro Nero springs), Nisyros (Stefanos) and Milos (Paleochori). They are characterised by low pH values and a wide range of temperatures, which varies from 1.96 to 4.70 and from 13.9 to 98_°C, respectively. It should be noted that the lowest pH (1.98) and the highest temperature (98_°C) values were documented in one water sample of Stefanos crater (Nisyros). These samples are characterised by CaMg-SO₄ composition (Fig. 3b). Exception is Paleochori (Milos), which falls close to Aegean seawater point and presents the highest TDS content (51.2 g/L).

265 *4.1.3 Thermal waters*

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Samples from this group were collected in hydrothermal fields located along the SAAVA and in continental basins. The diversity of the settings in which they were collected₄ results in a wide range of temperature (from 23.2 to 95.5°C), pH (from 5.73 and 10.01) and salinity (from 0.3 to 43.2 g/L) values. Based on their temperatures and TDS content, they are subdivided into different classes
(Fig. 3c); this subdivision was made following the method of Sinclair (1974) to identify statistically different populations. Three populations were detected based on TDS, while four populations were identified considering the measured temperatures (Fig. 3c). According to their water compositions, they fall into three of the quadrants of the Langelier-Ludwig diagram (Fig. 3c): (i) CaMg-HCO₃ and (ii) Na-HCO₃ water-types, which include mainly low salinity samples (< 4 g/L) and few intermediate salinity samples (4 < g/L < 30), with temperatures almost below 48 °C; (iii) NaCl composition, which includes high temperature and salinity samples with compositions that fall mostly close to the seawater point.

4.1.4 Cold gas-rich waters

280 The cold water samples are characterised by the presence of high levels of geogenic gases found in free and/or dissolved phase. Temperature ranges from 8.8 to 23 °C, pH between 5.20 and 8.72, while salinity shows a wide spectrum of values in terms of TDS (from 0.31 g/L to 30.1 g/L). Based on their CO₂ content calculated as pCO₂ using the speciation software PHREEQC (Parkhurst and Appelo 1999), they were divided into three groups; the groups were identified with the method proposed by Sinclair (1974). After plotting the samples in the Langelier-Ludwig diagram (Fig. 3d), it is noticed that the great majority of the waters with pCO₂ > 0.05 falls in the CaMg-HCO₃ field, whilst samples characterised by low pCO₂ (< 0.05) are scattered in all the sectors of the diagram.</p>

4.2 Isotopic composition

- The isotopic composition of the collected waters ranges from -12.7 to +2.7 ‰ V-SMOW for δ¹⁸O and from -91 to +12 ‰ V-SMOW for δ²H. In the δ²H δ¹⁸O diagram (Fig. 4), the majority of the waters fall between the Global Meteoric Water Line (Craig 1961: <u>GMWL</u> δ²H = 8×δ¹⁸O + 10) and the East Mediterranean Meteoric Water Line (Gat and Carmi 1971: <u>EMMWL</u> δ²H = 8×δ¹⁸O + 22). A Local Meteoric Water Line defined by Argiriou and Lykoudis (2006) (LMWL δ²H = 7.24×δ¹⁸O + 8.2) has been also plotted. Such LMWL has been obtained by the authors including all published isotope data on rainwater collected in Greece in the period from 1960 to 2003 (Argiriou and Lykoudis)
- $\frac{1500 \text{ period from 1960 to 2003 (Arginou and Lykoudis 2006).}{\text{Lykoudis 2006).}}$ Hyperalkaline (Fig. 4a) and most of the thermal and cold waters (Figs. 4c, 4d) follow the Local Meteoric Water Line of Greece defined by Argiriou and Lykoudis (2006) ($\delta^2 \text{H} = 7.24 \times \delta^{18} \text{O} + 8.2$) suggesting. This suggests that the water samples have a meteoric origin, whereas acidic waters show a negative shift for $\delta^{18} \text{O}$ (Fig. 4b).



Fig. 4 – δ^2 H vs. δ^{18} O binary diagrams for the sampled waters.

Some thermal and cold waters are aligned with Aegean seawater point (Figs. 4c, 4d), indicating a mixing between the meteoric water and seawater. As marked in Figs. 4c and 4d, many water samples show a positive δ^{18} O shift. In the case of thermal waters could indicate isotope exchange due to water-rock interaction at higher temperatures (Clayton and O'Neil 1972), while in the case of cold waters may be justified by evaporation processes.

The effect of seawater contamination can be observed in the δ^2 H vs. Cl binary diagram (Fig. 5). Only few cold gas-rich waters show important seawater admixing (Fig. 5b), while this process is very widespread for the thermal waters (Fig. 5a). Some waters collected in Samothraki Island fall outside the rainwater-seawater mixing lines. For these, dissolution of Halite in Miocene evaporites have been invoked (Dotsika 2012).



Fig. 5 - δ^2 H vs. Chloride binary diagrams for the sampled waters. Red arrows show mixing lines between the highest and lowest average isotopic value of rainwater measured in Greece (Argiriou and Lykoudis, 2006).

5. Discussion

5.1 Hyperalkaline waters

The ophiolitic sequences comprise widespread products derived from the hydration of ultramafic rocks, in which olivines and pyroxenes are altered to serpentine-group minerals (Evans et al. 2013). Typical features of waters circulating in serpentinized ultrabasic rocks are elevated pH values (>10), Ca-OH composition with very low concentrations of Mg²⁺ and total dissolved carbon (TDC) mainly present as CO₃²⁻ (Bruni et al. 2002). According to Barnes et al. (1967), two types of waters can be recognised in aquifers hosted in ophiolitic rocks: (i) MgCaHCO₃ waters with pH generally < 10 and (ii) hyperalkaline Ca-OH waters. The former represents the early stage of interaction between the ophiolites and meteoric waters into shallow aquifers (Cipolli et al. 2004), whilst the latter represent its evolution in deep serpentinized ultramafic aquifers under reducing environment (Bruni et al.</p>

2002). Samples of Argolida ophiolites (Peloponnese) are represented by the Agioi Anargyroi
Springs, which are characterised by enhanced pH values (up to 11.98) and Ca-OH composition (D'Alessandro et al. 2018). On the other hand, samples of Othrys (Central Greece) are characterised by many hyperalkaline springs (pH > 11; Ekkara and Archani), which are classified as Ca-OH type waters (D'Alessandro et al. 2014; Li Vigni et al. 20202021).

335 5.2 Acidic waters

Samples of this group present characteristics similar to acidic waters as described in Giggenbach (1988). These waters can be distinguished in three different subgroups each <u>one</u> belonging to a different island of the SAAVA.

- Samples collected at Kos Island are characterised by acid sulfate composition, likely related to the addition of CO₂ and H₂S rich hydrothermal gases to groundwater (Giggenbach 1988), and exhibit high concentrations of Ca²⁺ (up to 508 mg/L) and SO₄²⁻ (up to 2,774 mg/L). These springs are found within an area of strong geogenic soil degassing (Daskalopoulou et al. 2019b). The abundant deep hydrothermal H₂S gas dissolves in the shallow aquifer and is converted into H₂SO₄ by oxidation with atmospheric oxygen dissolved in the meteoric recharge (Nordstrom et al. 2009).
 Such process increases the sulfate content and lowers the pH of the water. The isotopic composition shows a negative shift of δ¹⁸O (up to about 5 ‰ units) respect to the local meteoric water line (Fig. 4b). The effect can be the result of isotope exchange with CO₂ (Karolytè et al. 2017) at low temperature favoured by the high gas/water ratio.
- The sample of Stefanos crater (Nisyros) is characterised by an elevated temperature (98 °C), very
 low pH value (1.98), and an acidic sulfate composition. It was collected in a boiling pool of the hydrothermal explosion crater of Stefanos within the Lakki caldera. The crater is characterised by strong fumarolic activity (Marini and Fiebig 2005), mainly concentrated along the rim. An area of about 1000 m² with many tens of boiling pools is present in the middle of the crater, the water of which probably results from the mixing of condensing fumarolic vapour and meteoric-derived
 shallow groundwater. In the summer dry period the pools' level falls to about 1 m depth, while in winter, after heavy rainfall, the entire bottom of the crater can be covered by rainwater, forming an ephemeral lake. The collected sample has the typical steam heated water composition (Nordstrom et al. 2009) with high concentrations of SO4²⁻, low pH and high temperature. Sulfate is almost the only anion balanced by a lot of cations including Fe, Al and NH4⁺ that have concentrations comparable to the major cations.
 - The Paleochori sample was collected at a small cave on the western end of Paleochori Beach (Milos), and is characterised by high temperature (75°C) and NaCl water type. The water of the

spring comes out with gas bubbles from rocky debris and gets mixed with seawater, when the sea is rough. Its chemical composition is similar to marine water, indicating that, even if the sea is calm, contamination by seawater occurs within the shallowest part of the hydrological circuit. The area is characterised by widespread degassing both onshore as diffuse degassing from the beach and underwater as bubbling hot water (up to 120°C) springs (Daskalopoulou et al. 2018b).

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5.3 Cold gas-rich waters

- As mentioned in Par. 4.3, cold mineral waters have been subdivided into three statistically different populations based on their pCO₂ (<0.05 from 0.05 to 0.85 and >0.85 atm), with the lowest value almost corresponding to the highest limit of organic derived soil CO₂ contribution to groundwater (Chiodini et al. 1995). Therefore, values above this limit indicate a geogenic CO₂ contribution. Recent studies (Daskalopoulou et al. 2018a; 2019a) evidenced that Greece, being a geodynamically active region, is a territory of extensive geogenic degassing. Most of the degassing activity in Greece is associated to thermal anomalies of variable intensity, but especially in Northern Greece the two phenomena are sometimes unrelated. In this area, several cold CO₂-rich mineral waters are known and many of them are appreciated as natural soda waters suitable for human consumption, with some of them being distributed in the whole country (i.e. Doumbia, Souroti and Xino Nero).
- Most of the CO₂-rich groundwater samples were collected in Florina Basin. This is one of the intramontane basins within the Hellenide Orogen, formed by the extensional tectonic regime of the area starting from the Late Miocene (Pavlides and Mountrakis, 1987). The thick and impermeable sedimentary sequence of Florina basin favoured the existence of many CO₂ reservoirs (Karakatsanis et al. 2007). Some of these are industrially exploited by the Air Liquide Greece Company for production of dry ice and filling of pressurised gas bottles. The estimated industrial CO₂ extraction is ~30,000 t/a (Pearce et al. 2004). However, these reservoirs are leaky, thus CO₂ rises up, mainly through faults, reaching directly the atmosphere or being dissolved in great quantities in the shallow unconfined aquifers. The water extracted from many of the shallow wells (<100 m) dug or drilled in these aquifers separates a free gas phase due to the high concentration in CO₂ (D'Alessandro et al. 2011).

The equilibrium of carbonate species is regulated mainly by sources and sinks within the hydrologic circuit. The main sources are the deep-derived geogenic CO_2 dissolution and/or the dissolution of carbonate rock of the aquifers. Losses depend mainly on CO_2 exsolution due to the separation of a free gas phase as water pressure within the aquifer decreases in the shallower levels and/or on precipitation of carbonate minerals due to oversaturation. The majority of samples with high p CO_2

are characterised by $Ca-HCO_3$ composition. The dissolution of CO_2 strongly dominates the chemical evolution of the waters increasing their aggressiveness with respect to the aquifer's rocks.



Fig. $6 - CO_2$ partial pressure vs. alkalinity (a) and vs. Calcite Saturation Index (b) of the cold gas-rich waters. Dashed lines in (a) are concentrations of alkalinity (expressed as mg/L of HCO₃⁻) at the given CO₂ partial pressure at 25 and 50 °C. The grey shaded area in (b) comprises values (±0.5) considered at saturation for the given solid phase.



rocks in their aquifers is ascertained or probable and these rocks control the equilibrium of the dissolved carbonate species. In these waters the dissolved and/or, if present, the free gas phases are dominated by CH_4 or N_2 (Daskalopoulou et al. 2018a; 2019a). Geographically, these waters are mainly distributed in the western part of Greece, where CO_2 degassing is trivial and hydrocarbon-rich areas are present (Daskalopoulou et al. 2018a; 2019a).

- Only few cold water samples have a NaCl composition, indicating a significant seawater contamination of the aquifers. These are located along the coastlines of continental Greece or on islands. Despite their moderately low temperatures $(19.4 20.7^{\circ}C)$ that classify them cold, they have been used in the past as spas and are therefore included in the present inventory. In the Na vs.
- 420 <u>Cl binary diagram (Fig. 7a) they fall along the seawater mixing line. Almost all of the low salinity</u> waters are enriched in Na with respect to the Na/Cl ratio in seawater due to water-rock interaction processes within their aquifers.
- Very few water samples plot along the 1/1 ratio line in the Ca²⁺ vs. SO₄²⁻ binary plot (Fig. 7b) suggesting only a sporadic influence of Ca-sulfate minerals dissolution. Most of the waters are strongly enriched in Ca²⁺ confirming the strong influence of Ca-carbonate dissolution. But as we will see for the thermal waters, Ca²⁺ enrichment may occur also in the case of Ca-sulfate minerals dissolution, when the thermodynamic conditions are favourable to sulfate reduction to sulfide. This is probably the case of most waters collected in the western part of Greece where Triassic evaporitic gypsum is often found in the sedimentary sequences of the area (Rigakis and Karakitsios 1998).
- 430 Thermochemical sulfate reduction can be sustained by the presence of hydrocarbons in the same area (Palacas et al. 1986), which promote the sulfide formation (Machel 2001). Most of the cold water samples are more or less aligned along the 1/1 ratio in a Ca²⁺ + Mg²⁺ vs. alkalinity binary diagram (Fig. 7c) indicating a strong influence of the congruent dissolution of carbonate minerals within their aquifers. Only in few cases the mixing of seawater can be invoked

435 to explain a Ca²⁺ + Mg²⁺ excess with respect to the 1/1 ratio line. On the contrary most of the deviations from this line may be due to oversaturation of some carbonate species. In this case the precipitation of a solid phase will virtually enrich either the cations (Ca²⁺ and Mg²⁺) or the anion (HCO₃⁻) depending on which one is in excess with respect to the 1/1 equivalent ratio. Calcium excess may be favoured by the presence and dissolution of Ca-sulfate minerals while bicarbonate excess may derive from the dissolution of abundant geogenic CO₂. The latter process may justify the formation of the alkaline-bicarbonate waters (Fig. 3d).



<u>Fig. 7 – Binary correlation plots for the cold gas-rich waters. (a) Na⁺ vs. Cl⁻; (b) Ca²⁺ vs. SO₄²⁻; (c) Ca²⁺+Mg²⁺ vs. Alkalinity. Dashed line seawater mixing line, continuous line 1/1 ratio.</u>

5.4 Thermal waters

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Geologically young regions like the Alpine orogen show a high variability in heat flow with respect to older cratonic areas (Pollack et al. 1993). Greece, which belongs to the Alpine orogen, makes no exception and in. In the preliminary map of Fytikas and Kolios (1979), heat flow shows values that

range from < 30 to > 120 mW/m² (Fig. 2b10b). Values above $\frac{65 \text{ mW/m}^2}{100}$, the average continental heat flow (65 mW/m²- Pollack et al., 1993), are considered as positive anomalies. Looking at the map of Fytikas and Kolios (1979), these anomalous values are mainly found in areas with active or recent (< 10 Ma) intrusive or effusive magmatism (Pe-Piper and Piper 2002). These areas are also 455 those with the thinnest crust (Grigoriadis et al. 2016) and subject to active extensional tectonics (Pavlides et al. 2010 (Fig. 2c2b). The highest heat flow anomalies are recorded along the SAAVA. Signs of the increased heat flow are thermal springs and thermal groundwater tapped by drillings. Therefore, it is not a surprise to find the hottest thermal waters in the areas of increased heat flow (Fig. 2b10b). These thermal waters, together with fumaroles and steaming grounds, are the surface expressions of active geothermal systems. Geothermal exploration proved that two of them, located 460 in the active volcanic systems of Milos and Nisyros, are two-phase high enthalpy fields suitable for electricity production. -Explorative drillings tapped geothermal fluids with temperatures up to 320 and 340 °C respectively (Liakopoulos et al. 1991; Chiodini et al. 1993). Geothermal energy was exploited for a period by a power plant at Milos until it was stopped by the protests of the 465 inhabitants complaining for the H₂S released by the extracted geothermal fluids (D'Alessandro et al. 2009). The remaining explored geothermal reservoirs can be defined as hot-water systems (Kaya et al. 2011).

- Many of the geothermal systems are found on islands or are on the coast of continental Greece (Fig. 1). Therefore, seawater plays a major role in determining the composition of the waters released by 470 these systems. This can be evidenced both in their chemical composition with Na/Cl ratios very close to that of seawater (Fig. 38a) and in their isotopic composition (Figs. 4 and 5) nicely evidencing a mixing between meteoric and sea water. From these diagrams it cannot be deduced if seawater acts as a contaminant in the shallowest part of the hydrologic circuit or if it represents a main feeder of the geothermal reservoir. For the high enthalpy systems of Milos and Nisyros, a 475 strong contribution of seawater to the reservoir has been ascertained from the analyses of the fluids sampled from the explorative boreholes (Liakopoulos et al. 1991; Chiodini et al. 1993). However, a clue of a seawater contribution in several other reservoirs is the fact that many of the samples plotting close to the seawater point are those with the highest temperatures (Figs. 3, 4 and 5). As we will see in par. 5.4.1, these are often waters falling in the field of the partially equilibrated waters in 480 the Giggenbach triangular plot (Fig. 79b).
- Many water samples show a very high Na/Cl ratio (Fig. 8a). Almost all come from three graben areas filled by postorogenic sediments mainly deriving from the dismantling of the metamorphic rocks bordering these grabens. These are the Sperchios, Strimon and Migdonia basins. The faults bordering the grabens favoured the formation of hydrothermal systems while the ubiquitous

- 485 presence of Na-rich minerals (e.g. albite) in the metamorphic rocks and in the sediments from them derived allowed the formation of Na-rich waters (Meyback 1987). For the same reasons, similar conclusions may be drawn also for the cold gas-rich waters collected in the Florina basin and some artesian wells along the northern and western coast of Peloponnese (Fig. 7a).
- As seen before for the cold waters, also in the case of thermal waters very few samples fall along 490 the line representative of the dissolution of Ca-sulfate minerals (Fig. 8b). The great majority of the waters are enriched in Ca^{2+} that is mostly explainable by the release of this cation by high temperature water-rock interaction processes. But the sulfate deficit may be, at least partially, explained by the reduction to sulphur and sulfide. While in the high temperature systems such reduction involves only inorganic reactions in the case of lower temperatures microbiological 495 mediated sulphur reduction is also involved, sometimes presupposing the presence of thermophile microorganisms (Chiodini et al. 1998; Brombach et al. 2003; Gilhooly et al. 2014). The rapidly changing physico-chemical conditions in the shallowest part of the hydrothermal circuit induces rapid changes in the oxidation state of sulfur further complicating the picture in a complex interaction between biotic and abiotic influences on the sulfur cycle (Marini et al. 2002; Gilhooly et 500 al. 2014). This may effects also on other dissolved species like for example methane. Strong isotope fractionation of this gas has been, in fact, attributed to anaerobic methane oxidation involving the
- microbial reduction of sulfate as electron donor (Daskalopoulou et al. 2018a). Spas in western Greece are fed by hypothermal or even cold springs. They are generally heated for balneotherapy and considered healthy mainly for their mineral content. Most of them are rich in 505 dissolved sulfide and the exsolved H₂S can be distinctly smelled. This region corresponds to the thick organic-rich sedimentary sequences of the External Hellenides (Fig. 2a), which are considered the most favourable areas in Greece for hydrocarbon generation (Palacas et al., 1986; Rigakis and Karakitsios, 1998). Thus, in the sampled waters methane is generally the dominant gas both in the dissolved and the free gas phase (Daskalopoulou et al., 2018a; 2019a). This is the Greek region with 510 the greatest crustal thickness unfavourable to the uprise of gases and heat from the mantle-(Fig. 2c). Therefore, this area is not prone to the formation of geothermal systems and the slight thermalisation of the waters is mostly the consequence of the deep circulation within regional fault systems. The stratigraphic sequences of the External Hellenides comprise often gypsum-rich Triassic evaporites (Rigakis and Karakitsios, 1998). The presence of sulfates and hydrocarbons favours the formation of H₂S through either Microbial (MSR) or Thermochemical (TSR) Sulfate 515 Reduction (Machel, 2001). The presence of H₂S in the water samples in western Greece is mainly related to these processes rather than being produced in active geothermal systems.

Finally, the $Ca^{2+} + Mg^{2+}$ vs. alkalinity binary diagram (Fig. 8c) shows that the interaction with carbonate minerals is negligible and evidences two main processes affecting these waters: mixing with seawater and dissolution of geogenic CO₂.





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5.4.1. Geothermometry

The ternary diagram Cl-SO₄-HCO₃ (Giggenbach, 1991) is used to examine the maturity of waters. Specifically, mature waters are characterised by high Cl content that originates from a deep-hot geothermal system, while SO₄ type waters usually derive from steam-heated water influenced either 530 by volcanic steam bearing high-temperature HCl or by geothermal steam bearing low-temperature H₂S (Dolgorjav 2009; Rezaei et al., 2018). On the other hand, alkaline waters are typically related to samples of meteoric origin. In the Hellenic territory, hyperalkaline waters, as well as the great majority of cold waters and some thermal waters fall in the HCO₃ field, indicating processes of mixing with the near-surface groundwater during their ascent to the surface (Singh et al., 2015) 535 (Fig. 9a). Enrichment in SO₄ is present in some thermal (Nymfopetra, Nea Apolonia (1,3,4)) waters. These samples (thermal) present low Cl content, high Na concentration and are characterised by calcite precipitation indicated by the presence of travertines in these areas. The fumarolic samples of Stefanos and Paleochori are plot in the SO₄-Cl axis, which is typical of volcanic waters, highlighting the impact of the volcanic activity on the samples. Many thermal gases fall in the field of mature waters. These samples may be considered as samples not affected by secondary processes 540 during the ascent of water to the surface that mainly derive from the deep and hot geothermal systems.

In order to evaluate the applicability of conventional geothermometric estimates, the chemical composition of the thermal waters werewas plotted on a cationic ternary diagram (Giggenbach, 1988) (Fig. 79b). The majority of the samples fall in the immature waters field and therefore, they have to be considered unsuitable for geothermometric estimations. Much fewer samples plot in the partial equilibrium field, while only one sample (Amplas 2) falls above the full equilibrium line. The latter refers to water in which an abundant CH₄-rich gas phase was bubbling (Li Vigni et al., 2021). Waters interacting with CH₄ are often characterised by a strong Mg depletion either because they are mixed with oil field brines (Kharaka and Mariner, 1989) or with hyperalkaline water (Bruni

et al., 2002; Cipolli et al., 2004).
The only samples that plot on or very close to the full equilibrium line are those taken from geothermal exploration wells at Milos (well M2 – Koutroupis, 1992) and Nisyros (well N₂ – Koutroupis, 1992; Chiodini et al., 1993). The estimated temperatures nearly correspond to that measured at Milos (318 °C – Liakopoulos et al., 1991) or is not so far from that measured at Nisyros (290 °C – Chiodini et al., 1993). In the latter case Chiodini et al. (1993) hypothesize a contamination by the seawater used to prepare the drilling mud.



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Fig. 79 - Triangular diagramdiagrams of a) Cl-SO4-HCO3 (Giggenbach, 1991) and b) Na-K-Mg (Giggenbach, 1988).

Many of the partially equilibrated samples are close to the seawater point and thus, the temperature of the reservoir could not be estimated due to the contamination with marine water. Only a few partially equilibrated samples mostly from Samothraki Island and Edipsos area may be considered reliable indicating temperatures up to 240-260 °C (Geotrisi). All these sites were selected and 565 compared to the temperatures obtained from other geothermometric equations using the software Solute Geothermometers (SolGeo – Verma et al., 2008), which estimates the minimum temperature of the aquifer by comparing thirty-five geothermometric equations (Fig. 810a). The geothermometric estimations made with this software are based on the solute concentrations of the sampled waters. Many empirical geothermometric equations have been proposed by different 570 researchers during the years and have been grouped together in this program. Most of them are based on cationic contents of the waters: 13 equations are based on the Na⁺ and K⁺ contents of the waters, 3 on K⁺ and Mg²⁺, 2 on Li⁺ and Mg²⁺, 5 on Na⁺ and Li⁺, 3 on Na⁺, K⁺ and Ca²⁺, 1 on Na⁺, K^+ and Mg^{2+} , 2 on Na⁺, K^+ , Ca^{2+} and Mg^{2+} and finally 7 are silical geothermometers based on the SiO₂ content. For the references of these geothermometers we refer to the paper of Verma et al. 575 (2008) while the formulas are included as supplementary material (Table S2).



Fig. 8—10 – (a) Results of the geothermometric estimations made with the computer program SolGeo (Verma et al., 2008) on selected samples that plotted in the partial equilibration field of the Giggenbach diagram of Fig. 7.–9. (b) Thermal waters plotted on heat flow map (mW/m²) (Fytikas and Kolios, 1979); red triangular indicates the highest estimated temperatures from geothermometric equations.

As generally happens, the equations do not give back a unique temperature, but a wide range. The Na-K geothermometers show mostly the highest temperatures of reservoirs, with up to about 40 °C differences. On the contrary, Li-Mg-K and Na-Li geothermometers present the lowest results; sometimes below the outlet temperature of the spring. It should be mentioned that the Na-K geothermometers are considered the most reliable because less affected by mixing with shallow waters and degassing (Pope et al., 1987).

590 Excluding geothermometers giving estimations at or below the emergence temperature, the narrowest range is shown at thermal waters with estimated temperatures below 120 °C (Fig. <u>810a</u>) and comprise samples from central Greece (Soulanta, Platystomo SPA and Amplas2) and from northeastern Greece (Thermi, Neo Erasmio and Fylachtou).

A few sites gave Na-K estimations up to 160-180 °C (Fig. <u>810a</u>) indicating an important geothermal potential for the area of Edipsos (Northern Evia Island), Traianoupolis (Thrace) and Agioi Anargyroi (Kythnos Island). Only two areas gave estimations above 200 °C and up to 250 °C: the areas of Therma on Samothraki Island and of Agiasmata on Chios Island. For these systems, further studies should ascertain if they might be used <u>also</u> for electricity production.

- To support this hypothesis, Fig.10b evidences a correspondence among thermal springs and heat
 flux. The majority of studied thermal springs are located in areas with heat flux higher of 60 mW/m², whilst the highest values of temperature obtained from geothermometric estimation correspond to areas with elevated heat flow (> 80 mW/m²). The maxima of heat flux (> 120 mW/m²), found along the SAAVA, do not show thermal springs with high measured temperature or high geothermometric estimates. This does not mean that no high temperature geothermal system is present, but only that its impermeable seal is very efficient. As previously mentioned, in fact, two high enthalpy geothermal systems have been ascertained on the islands of Milos and Nisyros by explorative drillings. The geothermometric estimates made with the composition of the captured waters gave results closely resembling the measured temperature in the case of Milos (Fig. 10a). In the case of Nisyros the close correspondence between estimation and measured value is found only for the silica geothermometer (Fig. 10a), which is less influenced by the contamination of the
 - 5.5 Tectonic structures as a fluid carrier

seawater used for the drilling mud (Chiodini et al. 1993).

- After studying the gas emissions of Greece, Daskalopoulou et al. (2018a) noticed a connection
 between lithological facies and dominant gas components. Particularly, the sedimentary regime of EH, where hydrocarbon deposits are present, yield that CH₄ and N₂ are the dominant gas species in the area. On the other hand, CO₂ is the principal gas component in IH and HH, where intrusive and metamorphic formations prevail. On the basis of the geographical distribution of the gases, a similar behaviour between CO₂ concentrations and R_c/R_A ratios is noticed (Daskalopoulou et al., 2018a;
 2019a). This reflects increasing CO₂ and R_c/R_A values in areas characterized by thin crust, elevated heat flow values, Plio-Quaternary volcanic activity and deep routed extensional or transtensional regional faults (Fig. 2b) (Daskalopoulou et al., 2019a); VA displays a higher mantle contribution for both CO₂ and He with respect to EH that present an important crustal input (Daskalopoulou et al., 2019a).
- As faults create a permeable pathway for gases to ascend (Wang and Jaffe, 2004) special attention was given to places with complex tectonics. In northern Greece, the Strymonas Fault System is controlling the tectonics. In this area, gases collected from thermal waters, present an up to 15% mantle contribution for He (considering a MORB end-member). This is likely caused due to the Uand Th-rich minerals (i.e. zircon, apatite etc - Wüthrich, 2009) of the granitoids present in this area;
- 630 the decay of U and Th produces ⁴He thereafter depleting the R/R_A values. Gases collected from the

thermal waters of Euboea and Samothraki are found in the Grecian Shear Zone (propagation of the NAF towards the Hellenic mainland - Şengör, 1979). According to various authors (Güleç and Hilton, 2006; Güleç et al., 2002; Mutlu et al., 2008) almost more than 50 % of the He along some sections NAF derives from the mantle, hence R/R_A values are expected to be enriched in mantle He. Gases collected from the cold waters of Corinth Gulf are generally dominated by CH₄ and N₂ and

Gases collected from the cold waters of Corinth Gulf are generally dominated by CH₄ and N₂ and the associated He shows always R/R_A values typical to pure crustal origin (Pik and Marty, 2009). The same authors explained that the fault system is not connected in depth with zones in which mantle He can be trapped or that reaches the lower crust allowing the uprise of mantle fluids. It is worth mentioning that in the western part of the graben system (Saronikos gulf), where it meets the SAAVA, the Quaternary volcanic activity of Sousaki and Methana allowed CO₂-rich fluids to reach

the surface.

The above described extensional and transtensional deep regional tectonic structures, which are permeable pathways to the earth's surface for mantle or deep crustal fluids, allow also deep circulation of groundwater creating the conditions for the formation of small hydrothermal systems. In the case of the presence of an important heat source, along such tectonic structures some greater or higher temperature hydrothermal systems may form. This is the case of both Samothraki island and Edipsos (Fig. 10b) where the heat source is a Ternary granitic intrusion in the former case

(Dotsika 2012) and a Quaternary volcanic system in the latter (D'Alessandro et al. 2014).

650 Conclusions

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Thermo-mineral waters in Greece are strongly controlled by the geologic and geodynamic setting that characterises the area where they are found. On the basis of pH, hyperalkaline Ca-OH type waters were identified in the ophiolitic sequences of Argolida and Othrys, while acidic waters were documented on islands located along the SAAVA. The former group represents the evolution of waters in deep serpentinized ultramafic aquifers in conditions closed to the atmosphere, while the latter highlights the impact of the volcanic/geothermal degassing on the waters. Based on their temperature, the remaining samples were subdivided into cold and thermal. Cold waters found in the northern part of Greece showed high pCO_2 values and were characterised by Ca-HCO₃ composition. Carbon dioxide dissolution resulted in slightly acidic waters with elevated bicarbonate content. Saturation or oversaturation in the carbonate minerals is not common in this group. Few water samples with intermediate pCO_2 were saturated, while the lack of equilibrium with carbonate minerals underscored the importance of CO_2 dissolution. Cold waters collected in hydrocarbon prone areas of western Greece presented low pCO_2 and were close to equilibrium with the main 665 carbonate minerals suggesting that the petrological regime (sedimentary limestones) governs the equilibrium of the dissolved carbonate species. On the other hand, thermal waters were seemingly controlled by the high heat flow values and the low crustal thickness. Their chemical composition was strongly influenced by mixing processes between meteoric water and seawater. Geothermometry was applicable only in few partially equilibrated waters suggesting reservoir
670 temperatures from 80 °C to 260 °C with the most elevated values (between 200 °C and 260 °C) being found in two islands of the eastern Aegean Sea-<u>(Samothraki and Chios).</u> This extensive dataset represents an almost complete catalogue of hydrogeochemical data on

thermo-mineral waters of whole Greece. It has been gathered over 15 years by the same research group and analysed in the same laboratory ensuring a good analytical uniformity. This database represents therefore a good basis for future studies on the thermo-mineral waters of this country.

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| ID | Sample | Sector (| Coordinates F | N | Altitude | Date | References | Location | Zone | Sigla | T °C | pH | cond Eh | Ca mg/l | Mg | Na mg/l | K mg/l | Alk F | Cl mg/l | NO ₃ | SO ₄ | SiO ₂ | Br mg/l | Li NH | 4 Ionic Balance | TDS mg/l | ∂ ¹⁸ O ∂D d |
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| ID | Sample | Sector | Coordinates | | Altitude | Date | References | Site | Location | Zone | Sigla | Т | pН | cond | Eh | Ca | Mg | Na | K | Alk | F | Cl | NO_3 | SO_4 | SiO ₂ | Br | Li | NH_4 | Ionic Balance | TDS | $\partial^{18}O$ | ∂D d |
|-----|------------------|--------|-------------|---------|----------|----------|---------------------------|---------|------------|---------------|-------|------|------|-------|------|------|-------|------|-------|------|------|------|--------|--------|------------------|------|------|--------|---------------|------|------------------|-----------|
| | | | Е | Ν | m | | | | | | | °C | | µS/cm | mV | mg/l | mg/l | mg/l | mg/l | mg/l | mg/l | mg/l | mg/l | mg/l | mg/l | mg/l | µg/l | mg/l | % | mg/l | ‰ | ‰ ‰ |
| 193 | Archani | 34S | 600606 | 4315575 | 176 | ####### | D'Alessandro et al., 2014 | Achani | Sperchios | Subpelagonian | IH | 27.5 | 11.2 | 570 | -235 | 35.9 | 0.122 | 22.8 | 0.78 | 146 | 0.02 | 14.5 | bdl | 0.48 | 5.8 | 0.1 | 0.32 | n.d. | -0.4 | 228 | -8.6 | -60 8.0 |
| 266 | Archani | 34S | 600613 | 4315572 | 202 | ######## | D'Alessandro et al., 2014 | Achani | Sperchios | Subpelagonian | IH | 27.6 | 11.3 | 538 | -258 | 35.7 | 0.122 | 23.2 | 0.78 | 153 | 0.01 | 17.4 | bdl | 0.96 | 5.3 | 0.1 | 0.29 | n.d. | -6.5 | 237 | -8.9 | -58 13.4 |
| 406 | Archani | 34S | 600613 | 4315572 | 202 | 9/6/2013 | Li Vigni et al., 2021 | Achani | Sperchios | Subpelagonian | IH | 27.5 | 11.3 | 1090 | -209 | 35.0 | 0.010 | 22.1 | 0.79 | 159 | 0.01 | 16.7 | bdl | 0.39 | 5.0 | 0.1 | 0.41 | n.d. | -12.1 | 240 | -8.3 | -59 7.0 |
| 474 | Archani | 34S | 600613 | 4315572 | 202 | ######## | Li Vigni et al., 2021 | Achani | Sperchios | Subpelagonian | IH | 27.7 | 11.4 | 589 | -29 | 34.2 | 0.005 | 22.1 | 0.99 | 139 | 0.02 | 15.5 | 0.1 | 0.06 | 4.9 | 0.1 | 0.31 | < 0.01 | -1.0 | 218 | -9.7 | -60 18.1 |
| 546 | Archani | 34S | 600604 | 4315570 | 194 | ######## | Li Vigni et al., 2021 | Achani | Sperchios | Subpelagonian | IH | 27.3 | 11.3 | 525 | -164 | 34.4 | 0.004 | 22.4 | 0.61 | 141 | bdl | 15.1 | bdl | 0.43 | 5.2 | bdl | 0.19 | n.d. | -1.5 | 220 | -8.8 | -58 12.2 |
| 548 | Archani 159 | 34S | 600571 | 4315552 | 204 | ######## | Li Vigni et al., 2021 | Achani | Sperchios | Subpelagonian | IH | 26.6 | 11.4 | 497 | -202 | 33.5 | 1.13 | 22.5 | 0.66 | 123 | bdl | 15.3 | bdl | 0.43 | 11.8 | bdl | 0.37 | n.d. | 11.6 | 210 | -8.7 | -58 11.4 |
| 549 | Archani 160 | 34S | 600579 | 4315550 | 203 | ######## | Li Vigni et al., 2021 | Achani | Sperchios | Subpelagonian | IH | 26.4 | 11.2 | 526 | -327 | 35.7 | 0.001 | 22.8 | 0.66 | 143 | bdl | 17.4 | bdl | 0.24 | 9.8 | bdl | 0.32 | n.d. | -1.9 | 231 | -8.8 | -60 10.3 |
| 529 | Archani drill | 34S | 601328 | 4315973 | 239 | ######## | Li Vigni et al., 2021 | Achani | Sperchios | Subpelagonian | IH | 22.0 | 11.3 | 450 | -30 | 45.8 | 0.007 | 10.6 | 0.51 | 130 | bdl | 28.9 | bdl | 0.08 | 1.6 | 0.2 | 0.17 | n.d. | -6.7 | 218 | -7.9 | n.d. n.d. |
| 544 | Archani drill | 34S | 601327 | 4315970 | 240 | ######## | Li Vigni et al., 2021 | Achani | Sperchios | Subpelagonian | IH | 22.2 | 11.4 | 525 | n.m. | 48.9 | 0.003 | 11.0 | 0.34 | 132 | bdl | 29.6 | bdl | 0.77 | 1.6 | bdl | 0.14 | n.d. | -2.8 | 224 | -8.1 | -58 6.4 |
| 543 | Kamaroules | 34S | 601018 | 4315720 | 222 | ######## | Li Vigni et al., 2021 | Achani | Sperchios | Subpelagonian | IH | 19.4 | 11.5 | 490 | -124 | 41.9 | 0.027 | 12.8 | 0.34 | 135 | bdl | 19.1 | bdl | 1.44 | 0.9 | bdl | 0.09 | n.d. | -4.3 | 212 | -8.5 | -57 10.6 |
| 243 | Ekkara | 34S | 602784 | 4334991 | 167 | ######## | Li Vigni et al., 2021 | Ekkara | Central GR | Subpelagonian | IH | 22.6 | 11.3 | 764 | -384 | 24.6 | 0.377 | 114 | 1.65 | 189 | 0.28 | 98.9 | bdl | 15.1 | 40.6 | 0.4 | 3.03 | n.d. | 0.7 | 489 | -9.6 | -66 11.0 |
| 475 | Ekkara | 34S | 602820 | 4334018 | 198 | ######## | Li Vigni et al., 2021 | Ekkara | Central GR | Subpelagonian | IH | 25.2 | 11.5 | 463 | -61 | 41.7 | 0.002 | 16.3 | 0.70 | 142 | 0.01 | 17.3 | 0.1 | 0.65 | 1.5 | 0.1 | 0.57 | < 0.01 | -0.9 | 221 | -9.3 | -58 17.0 |
| 540 | Ekkara | 34S | 602820 | 4334018 | 184 | 5/9/2017 | Li Vigni et al., 2021 | Ekkara | Central GR | Subpelagonian | IH | 25.4 | 11.3 | 541 | -270 | 42.1 | 0.003 | 16.6 | 0.46 | 145 | bdl | 17.2 | bdl | 5.52 | 1.6 | bdl | 0.39 | n.d. | -5.1 | 229 | -9.5 | -64 11.7 |
| 537 | Ekkara Ps | 34S | 602786 | 4334990 | 156 | 5/9/2017 | Li Vigni et al., 2021 | Ekkara | Central GR | Subpelagonian | IH | 23.8 | 11.2 | 710 | -317 | 15.4 | 0.132 | 112 | 1.62 | 173 | 0.19 | 91.1 | bdl | 10.5 | 40.3 | 0.3 | 3.23 | n.d. | 1.3 | 449 | -8.9 | -63 8.4 |
| 538 | Kato Pasali | 345 | 602601 | 4334825 | 174 | 5/9/2017 | Li Vieni et al. 2021 | Ekkara | Central GR | Subpelagonian | ш | 18.8 | 113 | 464 | -159 | 37.9 | 0.739 | 33.4 | 1.04 | 117 | bdl | 24.4 | 17 | 16.0 | 25.5 | bdl | 1.75 | n d | 14.5 | 260 | -8.9 | -62 91 |
| 539 | Psoronera | 34S | 602618 | 4334806 | 171 | 5/9/2017 | Li Vigni et al., 2021 | Ekkara | Central GR | Subpelagonian | IH | 23.8 | 11.3 | 632 | -370 | 29.4 | 0.000 | 61.5 | 1.38 | 180 | bdl | 40.9 | bdl | 1.83 | 16.8 | 0.2 | 1.19 | n.d. | 0.9 | 334 | -9.2 | -65 8.8 |
| 483 | Agia Anargyroi | 34S | 695941 | 4138821 | 46 | ######## | D'Alessandro et al., 2018 | Ermioni | Argolis | Subpelagonian | IH | 20.0 | 11.8 | 1200 | 33 | 75.7 | 0.038 | 67.1 | 10.14 | 278 | bdl | 73.6 | 7.9 | 2.98 | 0.8 | 0.2 | 41.4 | 5.4 | 2.1 | 563 | -5.1 | -31 9.4 |
| 484 | Agia Anargyroi 2 | 34S | 695943 | 4138808 | 53 | ######## | D'Alessandro et al., 2018 | Ermioni | Argolis | Subpelagonian | IH | 17.4 | 12.0 | 1440 | 44 | 93.0 | 0.052 | 64.9 | 8.97 | 388 | bdl | 67.9 | 2.4 | 1.30 | 0.1 | 0.2 | 40.5 | 6.1 | -8.0 | 674 | -5.4 | -31 11.9 |

| Geothermometer | Acronym |
|----------------|----------|
| Na–K | TNKFT73 |
| Na-K | TNKT76 |
| Na-K | TNKF79 |
| Na-K | TNKT80 |
| Na-K | TNKA83 |
| Na–K | TNK2A83 |
| Na-K | TNKNN87 |
| Na-K | TNKG88 |
| Na-K | TNKVS97 |
| Na-K | TNKA00 |
| Na-K | TNKC02 |
| Na-K | TNKDSR08 |
| Na-K | TNK2DS08 |
| K–Mg | TKMG88 |
| Li–Mg | TLMKM89 |
| Li–Mg | TLM2KM89 |
| Na–Li | TNLFM81 |
| Na-Li | TNL2FM81 |
| Na-Li | TNLKM89 |
| Na-Li | TNLVS97 |
| Na-Li | TNL2VS97 |
| Na-K-Mg | TNKMNN87 |
| Quartz | TSF77 |
| Quartz | TS2F77 |
| Quartz | TSFP82 |
| Quartz | TSVS97 |
| Quartz | TS2A00 |
| Ouartz | TSV00 |

| Author |
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| Na-K geothermometer of Fournier and Truesdell -1973 |
| Na-K geothermometer of Truesdell -1976 |
| Na-K geothermometer of Fournier -1979 |
| Na-K geothermometer of Tonani -1980 |
| Na-K geothermometer-1 of Arnórsson et al1983 |
| Na-K geothermometer-2 of Arnórsson et al1983 |
| Na–K geothermometer of Nieva and Nieva -1987 |
| Na-K geothermometer of Giggenbach -1988 |
| Na-K geothermometer of Verma and Santoyo -1997 |
| Na-K geothermometer of Arnórsson -2000 |
| Na-K geothermometer of Can -2002 |
| Na-K geothermometer-1 of Díaz-González et al. (in press) |
| Na-K geothermometer-2 of Díaz-González et al. (in press) |
| K–Mg geothermometer of Giggenbach -1988 |
| Li–Mg geothermometer-1 of Kharaka and Mariner -1989 |
| Li–Mg geothermometer-2 of Kharaka and Mariner -1989 |
| Na-Li geothermometer-1 of Fouillac and Michard -1981 |
| Na-Li geothermometer-2 of Fouillac and Michard -1981 |
| Na-Li geothermometer-1 of Kharaka and Mariner -1989 |
| Na-Li geothermometer-1 of Verma and Santoyo -1997 |
| Na-Li geothermometer-2 of Verma and Santoyo -1997 |
| Na-K-Mg geothermometer of Nieva and Nieva -1987 |
| Quartz geothermometer-1 of Fournier -1977 |
| Quartz geothermometer-2 of Fournier -1977 |
| Quartz geothermometer of Fournier and Potter II -1982 |
| Quartz geothermometer-1 of Verma and Santoyo -1997 |
| Quartz geothermometer-2 of Arnórsson -2000 |
| Quartz geothermometer of Verma -2000 |

Equation

| {777/[log(Na/K) + 0.700]}-273.15 |
|---|
| {855.6/[log(Na/K) + 0.8573]}-273.15 |
| $\{1,217(\pm 93.9)/[\log(Na/K) + 1.483)]\}-273.15$ |
| ${833/[log(Na/K) + 0.780]}-273.15$ |
| ${933/[log(Na/K) + 0.993]}-273.15$ |
| $\{1,319/[log(Na/K) + 1.699]\}-273.15$ |
| $\{1,178/[log(Na_m/K_m) + 1.239]\}-273.15$ |
| {1,390/[log(Na/K) + 1.75]} 273.15 |
| $\{1,289(\pm 76/[\log(Na/K) + 0.615)]\}-273.15$ |
| $733.6 - 770.551 [\log(Na_m/K_m)] + 378.189 [\log(Na_m/K_m)]^2 - 95.753 [\log(Na_m/K_m)]^3 + 9.544 [\log(Na_m/K_m)]^3 - 9.544 [\log(Na_m/K_m)]^3 + 9.544 [\log(Na_m/K_m)]^3 - 9.554 [\log(Na_m/K_m)]^3 - 9.544 [\log(Na_m/K_m)]^3 - 9.554 [\log(N$ |
| $\{1,052/[1=\exp(1.714(\log(Na/K) + 0.252))]\} + 76$ |
| $\{883(\pm 15)/[log(Na/K) + 0.894(\pm 0.032)]\}-273.15$ |
| $ \{833/[log(Na/K) + 0.908]\} - 273.15 $ |
| $\{4,410/[14.0-\log(K^2/Mg)]\}-273.15$ |
| $\{2,200/[5.47-log(Li/(Mg^{0.5}))]\}-273.15$ |
| $\{1,910/[4.63-\log(\text{Li}/(\text{Mg}^{0.5}))]\}-273.15$ |
| $\{1,000(\pm 47)/[\log(Na_m/Li_m) + 0.38(\pm 0.11)]\}-273.15$ |
| $\{1,195(\pm75)/[Log(Na_m/Li_m)-0.19(\pm0.25)]\}-273.15$ |
| {1,590/[log(Na/Li) + 0.779]}-273.15 |
| $\{1,049(\pm 44)/[log(Na_m/Li_m) + 0.44(\pm 0.10)]\}-273.15$ |
| $\{1,267(\pm 35)/[log(Na_m/Li_m) + 0.07(\pm 0.10)]\}-273.15$ |
| {11,140/[6 log(Na _m /K _m) + log(Mg _m /(Na _m) ²) + 18.30]}-273.15 |
| [1,309/(5.19-log S)]-273.15 |
| [1,522/(5.75-log S)]-273.15 |
| $\pm 1.345) + 0.28831 (\pm 0.01337) S - 3.6686 \times 10^{-4} (\pm 3.152 \times 10^{-5}) S^2 + 3.1665 \times 10^{-7} (\pm 2.421 \times 10^{-7}) S^3 + 77.034 (\pm 1.3233) S^2 + 1.10333 (\pm 1.3333) S^2 +$ |
| $-\{44.119(\pm0.438)\} + \{0.24469(\pm0.00573)\}S - \{1.7414 \times 10^{-4}(\pm1.365 \times 10^{-5})\}S^{2} + \{79.305(\pm0.427)\}\log S$ |
| $-55.3 + 0.3659 \text{S} - 5.3954 \times 10^{-4} \text{S}^2 + 5.5132 \times 10^{-7} \text{S}^3 + 74.360 \log \text{S}$ |
| $\{[1,175.7(\pm 31.7)]/[4.88(\pm 0.08)-\log S]\}-273.15$ |

216)log S