A multidisciplinary approach for the study of the effects of active tectonics along the North Anatolian fault zone: possibilities for the application of the electrical self potential method

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Abstract
The aims of this joint interdisciplinary project «Marmara» of ETH Zürich and the Istanbul Technical University (ITÜ) are to study the effects of active tectonics as evidenced by geology, geodesy and seismology on hydrogeology and geothermics in selected areas along the North Anatolian fault zone. Within the framework of this project thermal water systems in seven different areas have been investigated or are under investigation up to now (Schindler *et al.*, 1993). For three study areas along the North Anatolian fault zone (from east to west) of Kuzuluk/Adapazari, Bursa and of Canakkale the investigations with respect to the geological and hydrogeological features are complete. The now possible hydrogeological characterisation shows encouraging possibilities for the application of new methods like the electrical self potential method for the following reasons: 1) a fully interdisciplinary approach, including seismic survey with especially conceived network, geodetic survey to investigate tectonic movements by the GPS method, geothermic survey combined with geological mapping and hydrogeological investigations of normal mineral and thermal waters; 2) groundwaters of very different chemical and isotopical composition *e.g.*: Ca-HCO_3-type thermal waters of up to 82 °C temperature and total mineralisation of 500 mg/l to 1500 mg/l in the Bursa area, Na-HCO_3-type cold mineral waters of up to 2500 mg/l to thermal waters of same mineralisation of up to 80 °C temperature, containing large amounts of CO_2 of up to 1 l per 1 kg of water (at surface conditions) in the Kuzuluk area and Na-Cl-type waters presenting real thermal brines of up to 65 000 mg/l of total mineralisation and temperatures of up to 100 °C in the Canakkale area; 3) distinct types of hydrodynamic flow regime in areas of different geological and tectonic structure. Based on the results of the investigations within these areas the possibilities of further studies including self potential methods are discussed.

Key words *active tectonics – thermal water and mineral water – isotopic and chemical investigations – multidisciplinary approach of geophysical and hydrogeological methods*

1. Approach and objectives of the hydrogeological part of the presented studies

In order to link the phenomena to be investigated, it was from the beginning one of the main objectives of this project to use an interdisciplinary approach so that the objectives and results of the different groups are combined and discussed continuosly. The aims to be focussed in the hydrogeological part are:

a) *Characterisation of the observed occurrences (springs) of normal, mineral and thermal waters with respect to the given geological structure and tectonic features* – This first stage of the investigation program consists in geological mapping, recognition of tectonic pattern and related surface evidence of natural spring outflow zones, finally resulting in a synthetic geological and tectonic map which contains also the observed hydrogeological features. This step also includes the first on site characterisation of the observed waters at outflow points for physical and chemical parameters such as temperature, pH, electrical conductivity, alcalinity and dissolved oxygen content.

b) *Periodic sampling of outflowing waters of the observed springs and boreholes* – In order to investigate the effect of seasonal variations *e.g.* due to recharge events on the chemical and isotopic composition of the water of the observed springs and boreholes, periodical samplings in summer/autumn – and spring – periods were executed. Additionally for selected springs in the Kuzuluk and also the Bursa area a monthly survey of electrical conductivity and temperature as indicators of main water chemistry and physical parameters were executed.

c) *Characterisation of the hydraulic properties of aquifers and aquitards* – Starting from field observations and mapping a first characterisation of aquifer rock units (*e.g.* in regions of porous sedimentary rocks), or characterisation of type of pathways in fissured crystalline or karstified rock results. As far as available (*e.g.* through the state hydraulic works of Turkey, DSI), existing data on wells, such as core logs, waterlevels and hydraulic conductivity are included in this hydrogeological reconnaissance phase.

d) *Evaluation of the actual hydraulic conditions (recharge, discharge, head distribution, boundary conditions)* – This goal attempted to approach the quantitative aspects of groundwater flow as part of the water cycle, *e.g.* precipitation, evaporation and infiltration rates, as also the amounts of discharge. These aspects are needed especially to evaluate hydrodynamic and geothermic models.

e) *Definition of the natural flow field (with respect to the observed geological and tectonic structure, hydraulic properties, groundwater flow and quality)* – Within this final part of the hydrogeological study the results of field investigations and mapping were combined with the results of hydrogeochemical investigations including isotope methods. These methods used the composition of the groundwater itself as a source of information on the natural processes which influence the groundwater composition along its flow path during transit in underground, from the beginning at its origin in the recharge area to the end point (at spring origin or within a borehole) and time of sampling (Balderer, 1983). For this purpose, isotope methods proved to be the key parameters in hydrogeology *e.g.* furnishing information on:

- conditions of recharge;
- residence time;
- formation specific origin and flow path;
- evolution by water / rock interaction and underground processes.

This information can then be used to define the investigated hydrogeological system in establishing a conceptual model adopting the theoretical concept of groundwater flow of the hydrodynamic flow systems (Toth, 1962, 1963) to the given hydrogeological situation (Balderer, 1984, 1993).

To reveal an ongoing process in the evolution of flow systems a representative distribution of samples in space and time is necessary.

Spacial distribution – Through the representative distribution of sampling points in space (at different locations and at different depths *e.g.* if possible by sampling in boreholes), different sections of flow systems can be reached for one instant (period) of time. That gives for one sampling period (at one instant of time) the possibility to depict the hydrochemical evolution of groundwater within the existing spatial configuration of the flow systems, from the recharge to the discharge zones (depending on residence time and underground processes of water-rock-gas reactions along flow paths; Balderer, 1986, 1993). Such an «instantaneous picture» gives the information of the ongoing processes (especially for slow reaction, slow motion «steady state» process). But to reach this goal a representative distribution of sampling points within the whole flow systems extend is necessary!

Time series – In this case the aim was to investigate the reaction of flow systems (with respect to the chemical and isotopic composition of the water) as a resulting reaction to changes in boundary conditions like as of recharge or other hydraulic conditions. That gives the possibility to analyze the evolution in time at a given place *e.g.* as the displacement of a reaction as a «changing» process. Through repeated sampling or continous monitoring at fixed locations the time variations of chemical or isotopic composition of the groundwater can be analyzed to reveal indications for the velocity of fast reaction processes.

f) *Evaluation of the possible influence of actual processes within active tectonic zones on groundwater flow and quality (including observations on spring deposits such as travertines, observations of short-term fluctuations of hydraulic head regime and seismicity)* – This aspect belongs to a quite new field of interest to investigate the influence of active seismo-tectonic (including volcanic) activity on the hydrodynamic flow field, on groundwater flow and quality (as its chemical and isotopic composition, Dubinchuk, 1991). As such influences are short-term perturbations, the possible reactions consists in instationary, extremly time-dependent variations, or in abrupt but definitive changes in the observed parameters. In order to depict such non systematic and random variations a continuous recording of the parameters to be observed is necessary. For this purpose the following approach is used:

– continuous recording of the hydraulic head of two artesian wells with electrical pressure transducers simultaneously with a seismometer signal. Such a station is already installed and working since spring 1991 at the Kuzuluk site (section 2.3.);

– as further steps the installation of a station for observations of chemical and physical water parameters as electrical conductivity, temperature, eventually also including pH and CO_2 flux is planned;

– in addition the possibility of the application of the electrical self potential method as a new tool for monitoring changes in groundwater flow and composition is under discussion (section 4).

2. Hydrogeological situation and characterisation of the thermal and normal groundwaters

For three study areas along the North Anatolian fault zone (from west to east) of Canakkale, Bursa and of Kuzuluk/Adapazari (fig. 1) the investigations with respect to the geological and hydrogeological features have been completed (Balderer *et al.*, 1991, Greber, 1992, Imbach, 1992, Mützenberg, 1989, Mützenberg *et al.*, 1992, Schindler, 1993). The main aspects of the hydrogeological part of these investigations are summarized in the following section.

2.1. *Saline thermal springs in the Western Biga Peninsula (Canakkale area)*

This first studied area is located in the northwestern part of Anatolia on the Biga Peninsula, known in antiquity as the Troas (fig. 2). Along the western coast, three centers with thermal water discharges occur named Akçekeçili, Kestanbol Kaplica (Kaplica meaning spa) and Tuzla. Since classical times these thermal springs have been used in spas.

The small thermal spring of Akçekeçili appears on the western limit of a complex of about 100 m thick metamorphic series just before they dip beneath Upper Miocene sediments (fig. 2).

Near Kestanbol Kaplica a larger metamorphic complex is exposed along a NE-SW striking normal-dextral fault zone. The two main thermal springs lie on the northern flank of the Ilica valley (fig. 3). The intrusive quartz-monzonite type rocks on both sides of the valley are intensively cleft and show salty exhalations. A 290 m deep hole was made in 1975

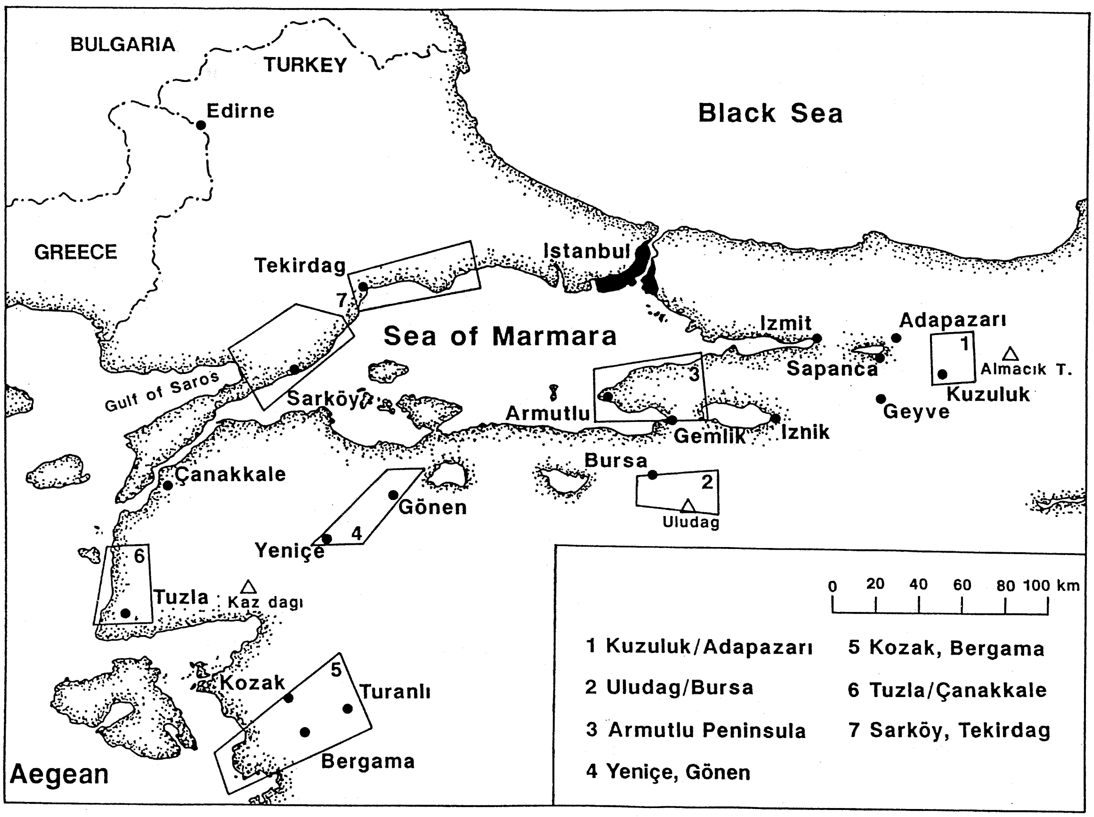

Fig. 1. Schematic representation of the investigated areas (Schindler *et al.*, 1993).

(Yürür, 1985) and met thermal water today used for the spa.

The Tuzla area is dominated by calcaline volcanics and ignimbrites (fig. 4). Below the about 600 m thick volcanic sequence Permian limestones and metamorphic rocks were encountered in two drillings (Karamanderesi, 1987). The thermal activities around Tuzla cover a surface area of about 1 km^2.

Based on the structural pattern of major fault systems (fig. 2) it can be recognized that the origins of the thermal springs within the three investigated areas coincide with the intersection of the following three systems: 1) NNE-trending dip-slip fault zones; 2) major NE-SW striking, right lateral strike-slip faults; 3) sets of NW-SE trending joints/faults cutting through all three thermal areas.

From these observation results that are due to the resulting increase in vertical permeability the intersection of these three major fault systems represents the actual flow path for the rise in the thermal water from the deep reservoir through the nearly impermeable cover of fine grained Miocene sediments to the spring origins at the surface (fig. 4).

The outflow zones of the thermal brines are situated about 20 to 30 m above sea level in the Kestanbol and 20 to 80 m above sea level in the Tuzla area.

In both areas springs of low mineralized fresh water at lower temperatures are observed at the same level or at slightly higher altitudes.

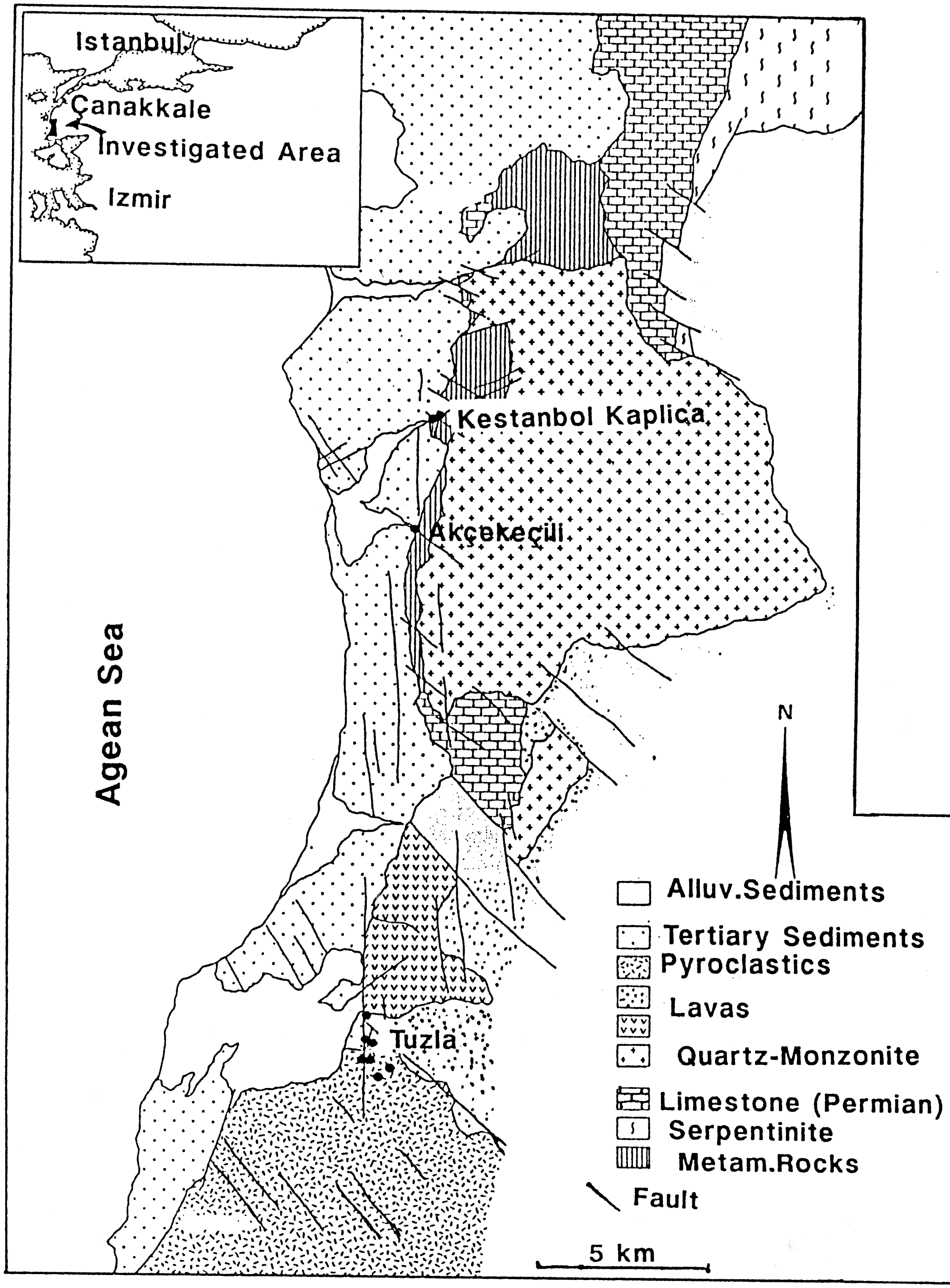

Fig. 2. Geological map of the Western Biga Peninsula (Mützenberg, 1990).

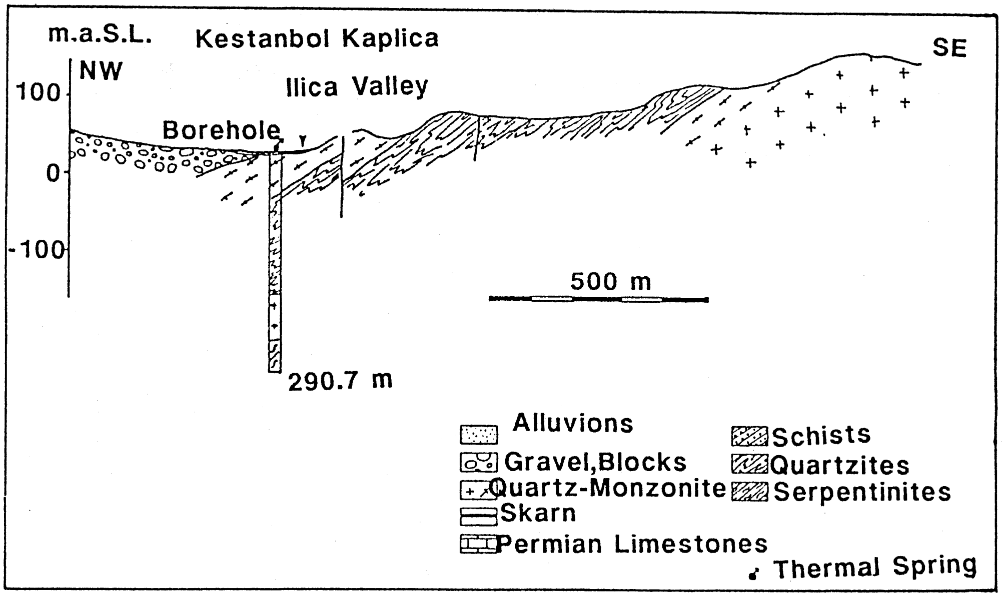

Fig. 3. Geological cross section of the Kestanbol Kaplica thermal area.

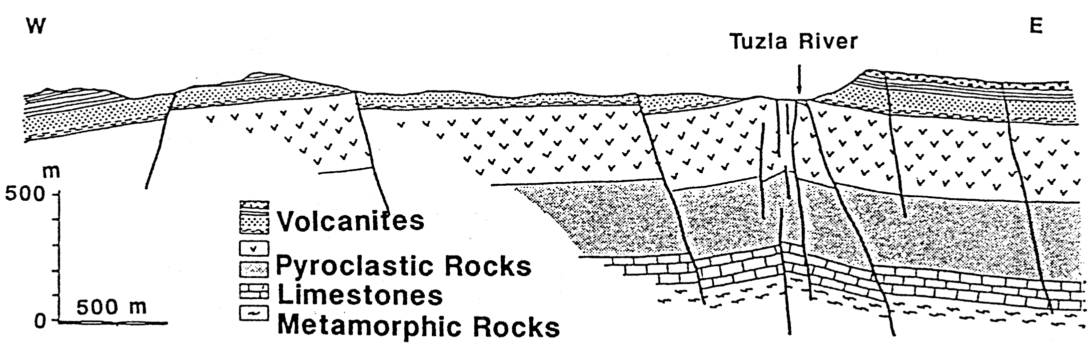

Fig. 4. Geological cross section of the Tuzla area (Mützenberg *et al.*, 1992).

They represent the outflowing local groundwater recharged and circulating in the fissured rocks of the intrusion of the quartz-monzonite in the Kestanbol, or in layers of increased permeability within the volcanic sediments in the Tuzla area respectively.

The temperature and total mineralisation of the outflowing thermal water (of 14 springs and 1 artesian borehole) ranges from 33.5 °C and 16 g/l to boiling point temperature and a maximum value of 65 g/l of total dissolved solids for the highest mineralized spring at Tuzla. Based on the main constituents the brines can be characterized as Na-Cl type with Na about 80 m val% of total cations and Cl greater than 99 m val% of total anions, with a ratio similar to seawater and with Ca greater than K and low concentrations of Mg, SO_4 and HCO_3.

The Ca/Cl, K/Cl, and Li/Cl ratios are markedly increased with respect to seawater. The tritium data reveal that: 1) only some of the low mineralized ground water of freshwater springs (with very low chloride concentration) contain anthropogenic tritium; 2) whereas all heavy mineralized thermal waters of the Tuzla and Kestanbol area do not contain any measurable tritium.

On the δ^2H versus $\delta^{18}O$ diagram in fig. 5 the corresponding values of the low mineralized shallow groundwaters with low chloride concentration are situated along the meteoric water line (with values in the range of -45 to -30‰ for δ^2H and -7 to -5‰ for $\delta^{18}O$). On the same diagram in fig. 5 the values of the thermal brines are situated below the meteoric water line on a line with lower slope (line A) showing a marked oxygen-18 enrichment. Line A could be interpreted as a mixing line between the low mineralized ground waters and the hot thermal brines, where the most concentrated brine of the Tuzla area also represents the most enriched endmember with respect to its stable isotope contents.

Based on the presented results the following conclusions can be made:

As the ratios of non-reactive species of the sampled thermal waters differ very little, it can be concluded that they evolved from a common saline end-member and represent mixing series with low mineralized fresh groundwater. The last mentioned correspond eigther to shallow waters (containing anthropogenic tritium) or heated regional ground waters of meteoric origin. For the saline endmember an evolution from a fossil altered seawater (connate water) is suggested based on the similar Na/Cl and

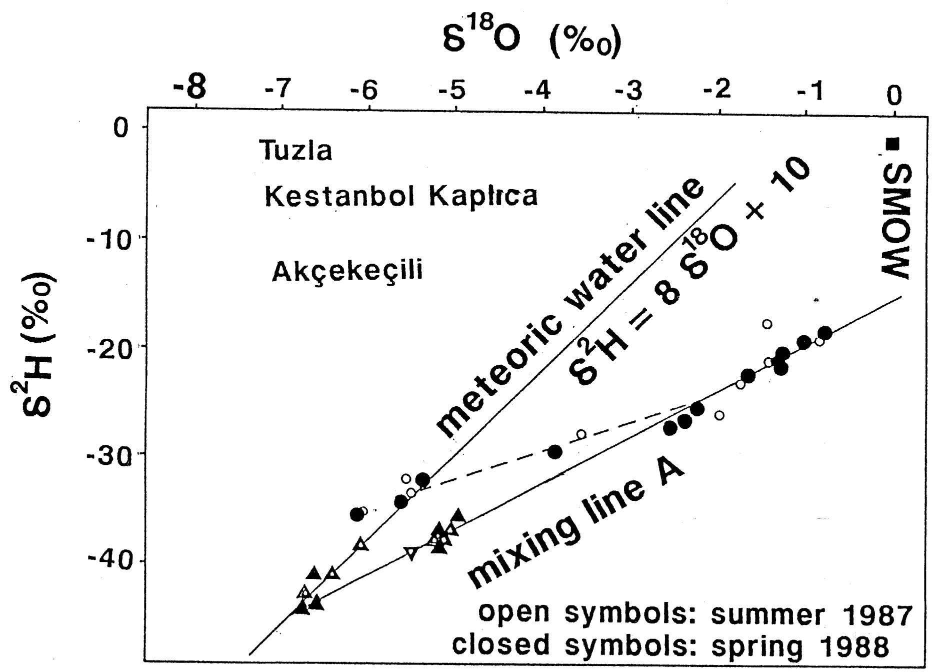

Fig. 5. δ^2H versus $\delta^{18}O$ diagram of groundwaters of the Tuzla-Kestanbol geothermal area. ○ ● Tuzla; △ ▲ Kestanbol Kaplica; ▽ ▼ Akçekeçili.

only slightly differing Br/Cl and B/Cl ratios (Mützenberg *et al.* 1992).

The high salinity and the observed isotopic signatures can be explained by diagenetic reactions in the sediments (Clayton *et al.*, 1966) and water rock interactions at higher temperatures during circulation in volcanic/crystalline and metamorphic rocks (also involving oxygen isotope exchange reactions; Savin, 1980; Kharaka and Carothers, 1986; Balderer *et al.*, 1991).

Therefore the actual composition of the present day outflowing hot waters of the observed springs can be explained by mixing processes with heated fresh water of regional aquifers and locally with near surface groundwater of meteoric origin up to 85%.

The ascent of the saline thermal water results of the combined effect of (1) deep regional circulation along major fault zones, (2) the high heat flow in this region of active tectonic movements and (3) the dilution effect by mixing with low mineralized hot freshwater of low density which leads to the observed upwelling of the hot brines due to the buoyancy effect along zones of high vertical permeability.

2.2. *Investigation of the thermal and cold groundwaters in the Bursa area*

In this area thermal springs, used since the Roman-Byzantine period arise within two locations (Kükürtlü/Bursa and Cekirge) at the northern slope of the Uludag massif (with peak altitude of about 2500 m) just above the valley plain (elevation 150-200 m; Imbach and Balderer, 1990; Balderer *et al.*, 1991; Imbach, 1992; Schindler *et al.*, 1993).

Cold groundwaters with tritium contents between 10 and 23 tritium units, sampled at altitudes between 100 m and 2300 m in the Bursa area and on Mount Uludag, align with respect to their ^{2}H- and ^{18}O- contents along a local meteoric waterline (fig. 6) with a deuterium excess of 17.4‰.

The outflowing hot waters are of Na-Ca-HCO- type (with total mineralisation of 1220 mg/l and temperatures of up to 82 °C) in the Bursa/Kükürtlü area and of Ca-Na-HCO3- type (with total mineralisation of 500 mg/l and of temperatures of up to 46 °C) in the Cekirge area. The analyzed Cekirge thermal waters align with respect to their ^{2}H and ^{18}O- contents also on the defined local meteoric waterline of the cold local groundwaters and reveal tritium concentrations between < 1.3 and 6.3 tritium units. As shown by fig. 6 some mixing processes occur between waters of dry season and wet season due to mixing in different proportions with local groundwaters. The Kükürtlü thermal waters with analyzed tritium values of < 1.3 and 6.7 tritium units differ from the local meteoric water line (fig. 6) showing an enrichment with respect to ^{18}O which seems most likely to be attributed to oxygen isotope exchange reactions with rock minerals due to higher temperatures (calculated reservoir temperatures of > 100 °C, according to Imbach, 1992).

From the observed chemical and isotopic signatures and in consideration of the topographical, geological and also tectonic situation the following interpretation results: the groundwater recharge of the whole area (as well as for cold and hot groundwaters) is concentrated on Mount Uludag and dominated by heavy rainfall, snow and snow melt during the winter period. Based on the deuterium contents of the observed thermal waters combined with the deuterium altitude relation of the local cold groundwaters (Imbach, 1992) two different recharge areas may be distinguished: the Kükürtlü thermal waters would correspond to waters recharged in the altitude range of 1600 to about 2500 m up to the highest peaks of Mount Uludag, whereas an altitude range of 300 to 600 m would be adequate for the Cekirge thermal waters which coincide with the karstified travertine terraces in the western part of Mount Uludag just above the Cekirge village.

For both cases of Bursa/Kükürtle and Cekirge, the outflowing thermal waters represent a actual water circulation system with known recharge and discharge areas. Considering the low mineralisation of these thermal waters a high heat flow or a very rapid accent from depth is to be assumed.

Therefore the present study (Imbach, 1992,

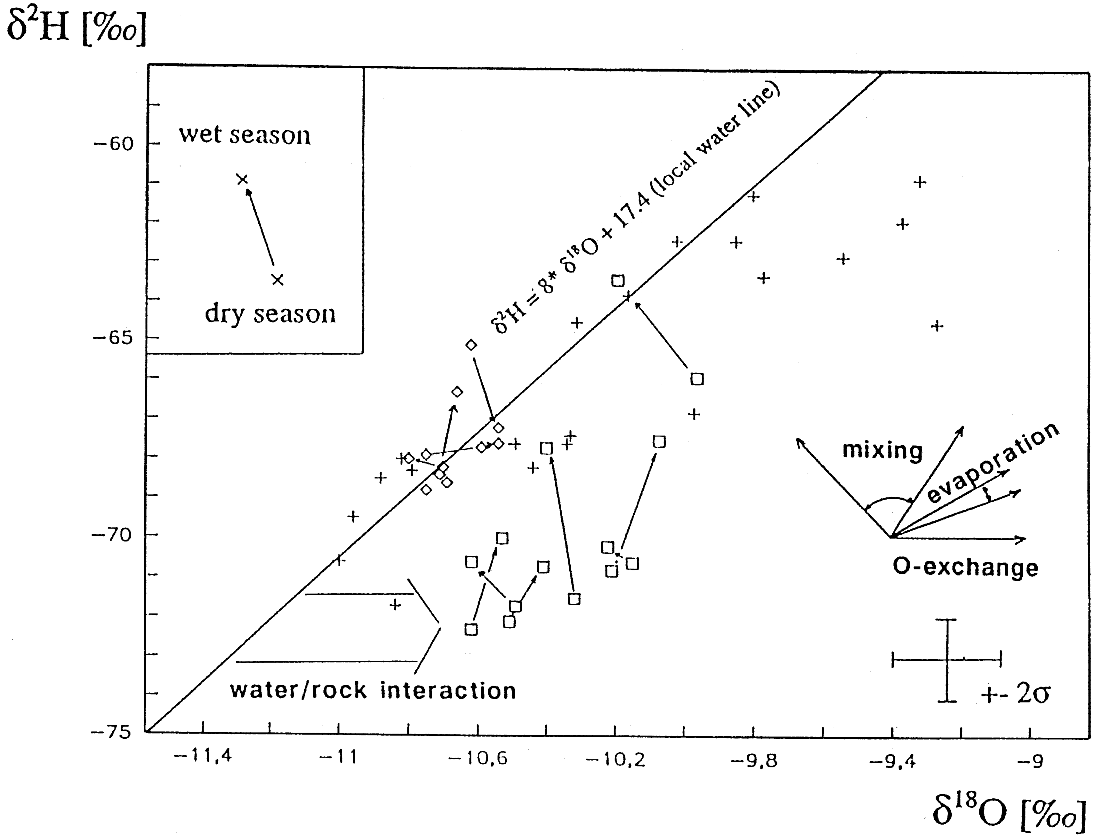

Fig. 6. δ^2H versus $\delta^{18}O$ diagram of thermal and cold groundwaters of the Bursa area. + Cold groundwater; ◊ Çekirge hot water; □ Kükürtlü hot water.

1994) shows that this area of Bursa represents a region of a stable thermal system with recharge in the fissured crystalline and the partly kastified carbonate rocks (marbles) of the Uludag massif, deep vertical circulation due to tectonic structure and high hydraulic gradient leads together with a higher heat flow to the observed hot waters, naturally occurring at intersections of two fault systems. By the cooling process of the outflowing hot water travertine deposits were formed by calcite precipitation beginning from the upmost spring origins. The fact that the springs used today all originate within the altitude range of these travertine deposits indicates a decrease in hydraulic head with time.

Seasonal variations as shown by the tritium values and the stable isotopes are most probably attributed to mixing processes along the flow path inside the aquifer but also in shallow depth at the outflow zones. These mixing processes are induced by changes in hydraulic head, which are increased during the recharge period of autumn to spring and decreased in the summer period as the mainly dry season.

2.3. *Investigation of the thermal and mineral waters of the Kuzuluk area*

Some 40 thermal and mineral waters arise in springs within the subsidence basin of the

Kuzuluk area (Greber, 1992, 1994). All these waters are dominated by CO_2-outgasing due to the tectonic activity in the vicinity of the North Anatolian fault zone.

In this area the mineralized cold and hot waters of outflowing springs are of Na-(Ca)-(Mg)-HCO_3-Cl- type with a total mineralisation up to 3 g/l. At the naturally occurring hot springs (named «central springs») water with temperatures up to about 56 °C, resp. of 82 °C within the two boreholes of about 160 m and 240 m depth were observed. The occurring cold mineral waters of the «marginal springs» are more mineralized, up to 7 g/l. All these mineralized cold and hot waters are characterized by a very high CO_2 content of up to 1 l per 1 kg of water (at surface conditions). But also other evidence of the high CO_2 activity is observed, *e.g.* higher concentrations at outcropping fault zones, which could even be used as a method of dedecting such zones (Greber, 1992). The observed mineralized waters contain generally no anthropogenic tritium in measurable amounts except if some mixing with shallow ground waters occurs. With respect to the δ^2H and $\delta^{18}O$ values as represented in fig. 7, a distinct deviation of the cold mineral and thermal waters from the meteoric water line of the local shallow groundwaters can be observed.

This deviation of the cold mineral and thermal waters from the meteoric water line of the local shallow groundwaters can with respect to the $\delta^{18}O$ values be attributed to water/rock interaction and/or isotopic exchange with the uprising CO_2(fig. 8).

This interaction with uprising CO_2 which also influences the chemical composition of all

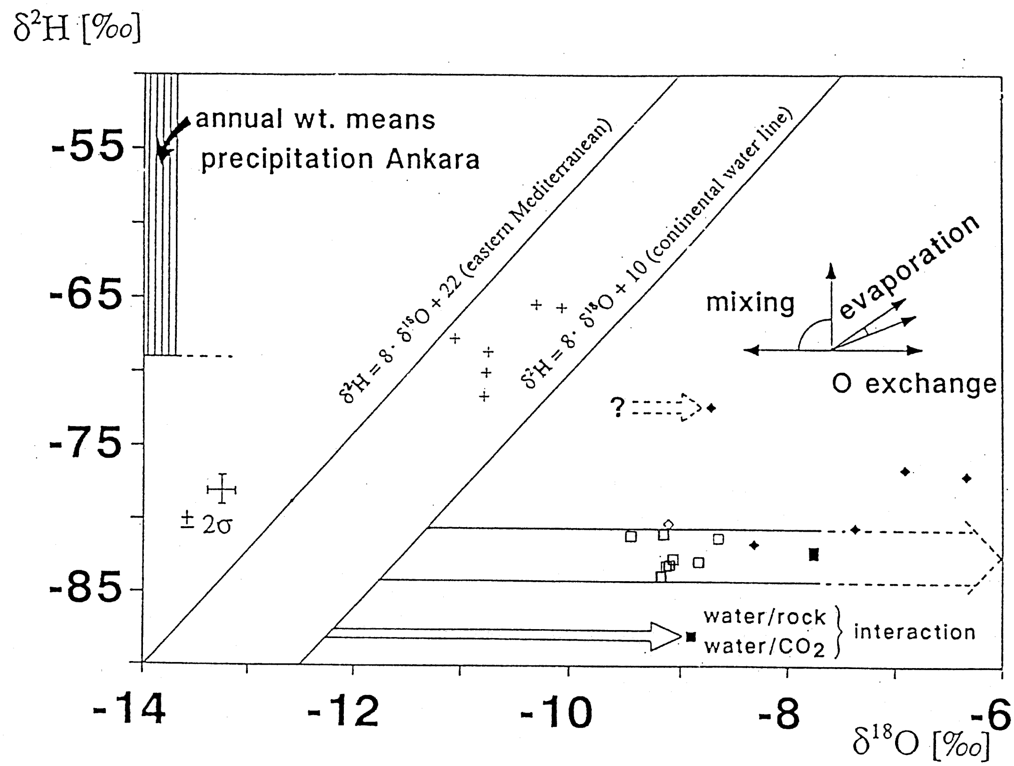

Fig. 7. δ^2H versus $\delta^{18}O$ diagram of shallow groundwaters, thermal and cold mineral waters of the Kuzuluk/ Adapazari area. Marginal group: ■ < 1.3 TU; ♦ 1.3-8 TU. Central group: □ < 1.3 TU; ◊ 1.3-8 TU. Shallow groundwater: + > 8 TU.

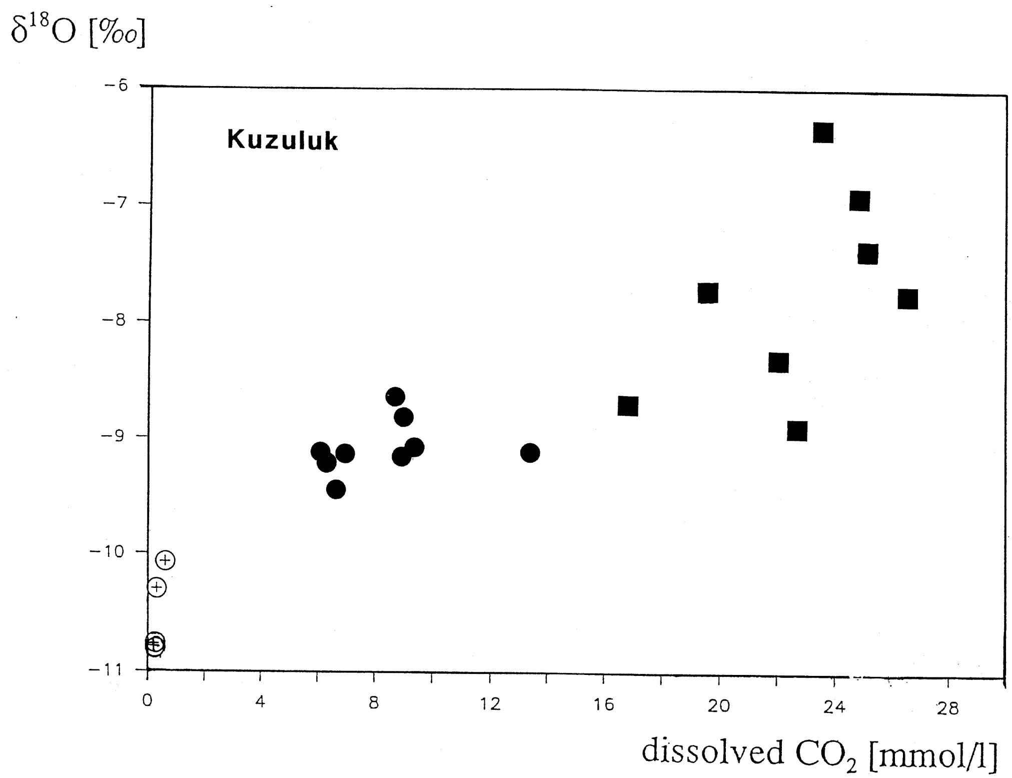

Fig. 8. $\delta^{18}O$ (water) versus dissolved CO_2 diagram (CO_2 values from field titration) of the Kuzuluk/Adapazari area. ■ Marginal group; ● central group; ⊕ shallow groundwater.

the observed thermal and cold mineral waters would infer $\delta^{18}O$ values of $CO_2(g)$ in the range of marine carbonates or silica deposits (Balderer *et al.*, 1991; Greber, 1992, 1994).

Additionally the very low δ^2H values of these waters indicate a distinct origin not connected with the actual recharge groundwaters. One of the possible explanations could be recharge during a period of cooler climate (*e.g.* Pleistocene).

3. Types of hydrodynamic flow regimes in tectonic active areas – information based on hydrochemical investigations

Through its physical properties ground water presents an ideal transport media within the geological underground. As already mentioned, isotopic and chemical composition of a groundwater sample reflects the natural conditions of a given hydrodynamic flow system at a given location and instant of time giving further information with respect to:

- residence time;
- conditions of recharge (infiltration);
- flow path;
- hydrochemical evolution.

But within tectonic active areas the groundwater not only reflects the influence of the processes of recharge/infiltration and flow/migration (with evolution by water rock-interaction) but also influences of internal processes (with the release of fluids and gases) due to the effects of tectonic activity. Indications for such influences of the earth's interior (of the deeper crust or even the mantle) present the concentration and isotopic composition of the groundwater itself and the contents/isotopic ratios of rare elements and of (reactive and noble) gases (but also of dry exhalations as fumaroles). Such influences, but also the often increased heat flow within tectonic active areas will influence the water-rock interaction and also the evolution of the groundwater. The present studies allow the following characterisation with respect to the groundwater flow systems.

In the Bursa area the outflowing hot thermal waters can be derived based on the stable isotopes by recharge of precipitations (rain and snow) within two distinct different altitude ranges on Mount Uludag (and surounding areas) which evolved in the deeper part of the descending pathways by oxygen isotope exchange as a result of the gained higher temperature. This case is well in accordance with the traditional model of regional groundwater flow with the properties needed for geothermal systems: higher heat flow (resp. geothermal gradient) and fast ascendence of the hot fluid by a high conductive regional fault zone (Schindler *et al.*, 1993).

In the Tuzla-Kestanbol area on the Biga Penisula the outflowing high concentrated thermal waters can by their chemical and isotopic composition neither be directly derived from infiltrated meteoric water nor from heated sea water. From the observed chemical and isotopic composition of the water it seems most probable that they are represent mixtures between a deep low mineralized groundwater (containing no anthropogenic produced tritium) and a deep brine situated as connate water of probable marine origin at even greater depth. The mixed and heated water (also in a region of increased geothermal gradient) is driven to the surface by the buoyancy effect along the hydraulically conductive zones along the intersections of three major fault systems.

The mineral and thermal waters of the Kuzuluk area arising within a topographically well defined subsidence basin are, with respect to their stable isotope contents, clearly disconnected from the meteoric waterline not only by a marked oxygen shift (^{18}O-enrichment probably due to isotope exchange with CO_2, Balderer *et al.*, 1991, Greber, 1992) but also by their much lower δ^2H values than the local groundwater of recent recharge.

For the origin of these waters of the Kuzuluk area the following explanations are possible (now of great importance for the understanding of the groundwater circulation in this tectonic active area):

1) the evolution started from infiltration of normal meteoric water. At depth, within the fault system the waters were heated up and have undergone oxygen isotope exchange, most probably in contact with CO_2 coming up from depth (Kipfer, 1991) or produced by a thermocatalytic reaction (Pezdic' *et al.*, 1991) with carbonate rocks in depth (Greber, 1992). If, as usually admitted from experience also in other geothermal areas (Fontes, 1976; Gonfiantini, 1971; IAEA, 1983) no deuterium exchange has to be taken into account, the only explanation for the observed low deuterium contents of these mineral and thermal waters would be that they correspond to waters which infiltrated under different climatic conditions (*e.g.* the cooler and more humid conditions of the pleistocene epoch);

2) the second possibility of evolution is related with a process which also leads to a depletion in the deuterium content *e.g.* as by separation of a steam phase of a deep hot water and condensation in a near surface local meteoric groundwater. This explanation can nearly be excluded because of the very low tritium content of the thermal and mineral waters in the range of near or below detection limit. In any case the oxygen isotope ratio seems to be dominated by the large amount of uprising CO_2). These isotopic signatures of the Kuzuluk waters can best be explained by a conceptual model which is based on the assumption that a deep seated fluid exists within the fractured volcanic rocks which is disconnected from actual recharge. This fluid outflows through fractures in the low permeable top layers of volcanic rocks and ignimbrites (Greber, 1992) not because of the usual admitted mechanism of the hydrologic cycle but because of the local

tectonic configuration of the pressurizing effect of the uprising CO_2 (at the well-head of the 160 m deep borehole at Kuzuluk hot thermal water with 82 °C and a hydrostatic artesian overpressure of 3 bars and additional 2 bars of CO_2 pressure are observed).

In this case not the normal situation of the hydrodynamic flow systems with flow in continuity but the lifting and emptying of a limited reservoir by the effect of upwelling/buoyancy due to the high CO_2-activity to the observed spring origins at surface takes place.

4. Possibilities for the application of the electrical self potential (SP)-method in tectonic active areas

As the electrical conductivity of the water is the most important factor determining the density of current, the SP-method (surface spontaneous potential) is more effective than other electrical methods as it is the only one depending on the groundwater flow itself (Fournier, 1989).

Therefore the application of the SP-method in hydrogeological studies is of special interest especially in yielding the following very important information with respect to the configuration of the hydrodynamic flow systems (Randall-Roberts, 1991):

– areal extent of discharge zones (associated with positive anomalies);
– indications for regions associated with downward flow, recharge or clayey beds (indicated by negative readings);
– identification of locations with gravel paleochannels, fractured volcanic rocks and water-bearing fault zones (signal depth of up to 150 m).

These statements reveal the need for the application of the electrical self potential method in tectonic active areas (with the occurrence of mineralized and thermal waters) as it offers the following possibilities for hydrogeological reconnaissance:

– identification of flow paths (*e.g.* water-bearing fault zones);
– identification of channels and outflow-zones with low flow rates (*e.g.* groundwater- and salt-seeps);
– delineation of boundaries between groundwater bodies of different salinities.

Further magnetotelluric surveys would be interesting in order to elucidate the deep structure as tectonic faults zones, which cannot easily be reconstructed from surface geological mapping because the cover of superficial soils, weathering products and unconsolidated sediments.

Another interesting point consists in the possible link beween the hydraulic and hydrochemical aspects of the groundwater and its physical aspects as moving fluid influencing the electrical surface spontaneous potential. Of special interest is the question of whether this SP-method would give the possiblility of monitoring the water movement itself (as time dependent process) with respect to flow rate and also the chemical composition.

These prospective possibilities of applications further suggest the use of the SP-method (in addition to seismic and hydraulic measurements) as a continuous monitoring method in the search for possible links between tectonic events (*e.g.* earthquakes) and fluctuations of groundwater-flow and composition.

This would then offer the possibility of applying the more expensive methods for monitoring as isotopes and hydrochemical parameters only in selected periods of time of special interest (with high probability of fluctuations of the monitored parameters).

In any case for further research into the direct influences and interdependence of tectonic activity on groundwater flow and composition a fully interdisciplinary approach is necessary with application of geophysical methods, hydrogeological investigations including chemical and isotopic methods also including an analysis of reactive and rare gases.

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