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Distribution and significance of hydrothermal alteration minerals in the Tuzla hydrothermal system, Çanakkale, Turkey

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Abstract

Hydrothermal alteration zones have been investigated by X-ray diffraction, mineralogical–petrographical techniques, and geochemical analysis. Examination of cores and cuttings from two drill sites, obtained from a depth of about 814–1020 m, show that the hydrothermal minerals occuring in the rock include: K-feldspar, albite, chlorite, alunite, kaolinite, smectite, illite, and opaque minerals.

In the studied area, silicified, smectite, illite, alunite, and opal zones have been recognized. These alteration mineral assemblages indicate that there are geothermal fluids, which have temperatures of 150–220°C in the reservoir.

The distribution of the hydrothermal minerals shows changes in the chemical composition of the hydrothermal fluid, which are probably due not only to interaction with host rock, but also to dilution of the Na–K–Cl-rich hydrothermal fluid of the deep reservoir by cold sea water at shallow levels. Geochemical analyses of the solid and liquid phases indicate that the hydrothermal fluids of the Tuzla geothermal system are in equilibrium with alteration products.

The tectonic structure of the studied area is caused by NW–SE and NE–SW directional forces. The volcanic rocks where hydrothermal zones are observed in the studied area are of Lower–Middle Miocene age comprise latite, andesite, dacite, rhyolite-type lavas, tuff, and ignimbrites. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Turkey; Çanakkale–Tuzla hydrothermal system; surface and subsurface hydrothermal alteration; clay minerals

1. Introduction

Çanakkale–Tuzla is an active geothermal area in northwest Turkey hosted by rhyolite lavas and pyroclastic deposits (Fig. 1). The general characteristics of the geothermal system have been described by Şamilgil (1966, 1983), Gevrek and Şener (1985), and Gevrek et al. (1986). Two wells (with a depth range of 814–1020 m below ground level) have been drilled; one of which is potentially productive. The study of hydrothermal alteration in geothermal areas can provide useful information on the processes of interaction between geothermal fluids and the host rock (Browne, 1978; Browne et al., 1992; Reyes, 1990).

Hydrothermal mineral assemblages such as smectite, illite, kaolinite, epidote, and adularia can give some indications of reservoir temperatures — the

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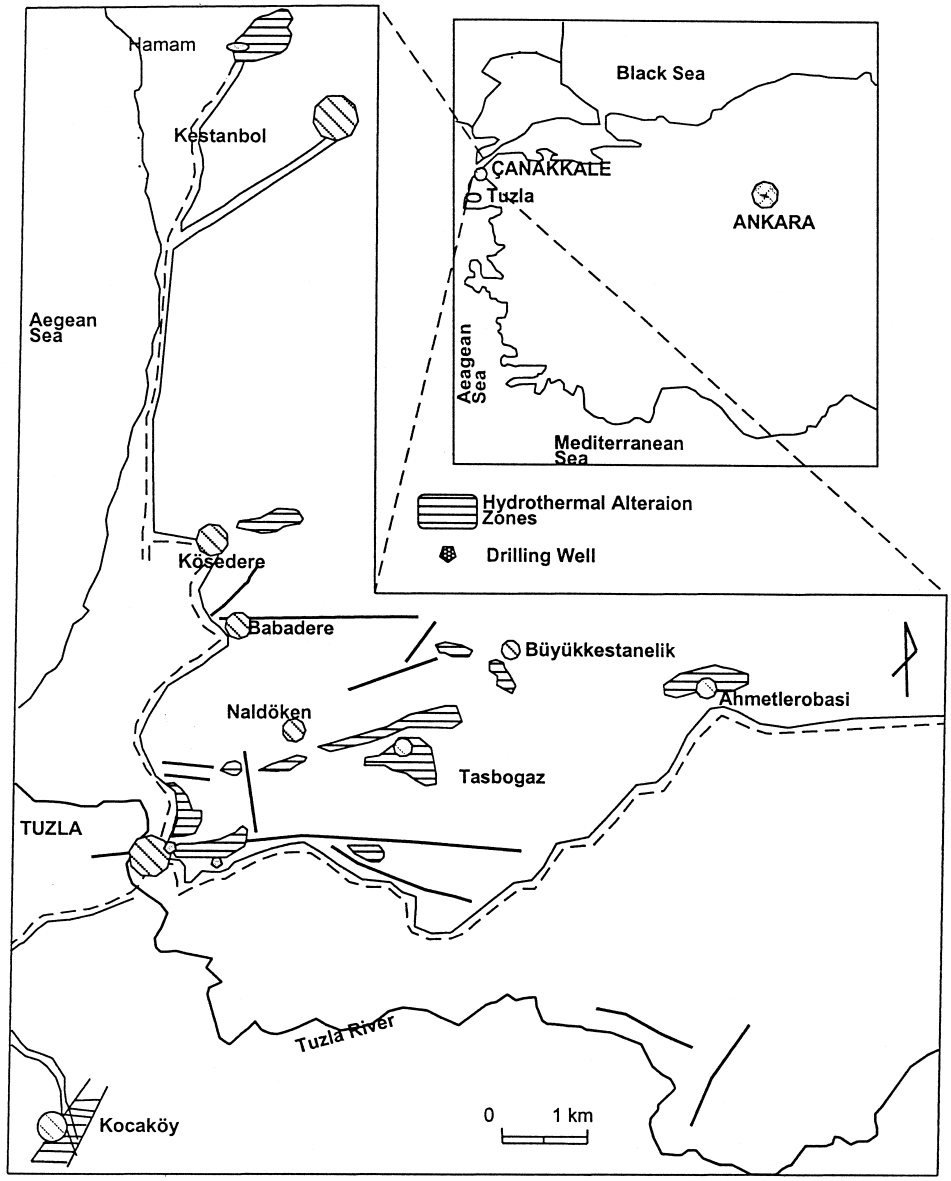


Fig. 1. Location map of the Tuzla hydrothermal system.

potential for scales and for corrosion in geothermal pipelines, fluid chemistry, and permeability — and can guide field hydrology (Browne, 1984).

The aim of this paper is to identify hydrothermal alteration minerals and geochemical changes in the lithostratigraphic units, develop a hydrogeological model, and determine the temperatures of geothermal fluids in reservoir rocks in the Tuzla hydrothermal system (Fig. 1). Geochemical and petrographical analyses have been carried out on 10 core samples of two drillholes and 52 outcrop samples. In an attempt to resolve the nature of the hydrothermal alteration, 62 samples have been analysed using optical microscopy, X-ray diffraction (XRD), and atomic ab-

sorbtion spectrometry (a.a.s) analysis (Table 1, Fig. 7).

2. Geological setting

Studies of surface geology from the system have shown that the basement of the region is formed of Paleozoic metamorphic rocks (Fig. 2). This basement is overlain at an angular unconformity by recrystallised limestone of Paleozoic age. This formation is overlain at an angular unconformity by rhyolithic tuff and agglomerate of Miocene age. The intrusive Kestanbol granite of 28 Ma age intrudes the overlying older rocks (Fytikas et al., 1976).

The upper part of the stratigraphic sequence consists of rhyolitic tuffs, ignimbrite, latitic lavas, and rhyolitic lavas, the products of calcic volcanism of Miocene age.

The tectonic structure of the area under investigation trends in NW–SE, SW–NE directions; zones of hydrothermal alteration occur at diagonal fissures which depend on E–W strike–slipe faults.

3. Analytic methods

The mineralogical composition of about 62 samples, collected from outcrops and drillcores, was determined by XRD analysis at General Directorate of Mineral Research and Exploration of Turkey (MTA). Clay minerals were identified from three

Table 1
Chemical composition of alteration types

Sample	Minerals	CaO	MgO	FeO	Na_2O	K_2O	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	MnO	SO_3	A.K.	Alteration type
TK5	Illite,	1.61	0.39	0.68	3.42	4.9	67.2	14.3	2.7	0.34	0.03	0	3.38	Sericitic
TK12	feldspar,	0.85	0.36	0.04	3.2	5.8	67.7	14.6	2.6	0.3	0.09	0.03	2.5	
A27	quartz,	1.05	0.4	0.01	2.81	5.8	67.3	16.6	1.9	0.3	0.33	0	5.3	
TK14	kaolinite	0.28	0.1	0.14	3.06	5.42	71.6	14.5	1.5	0.4	0.01	0.03	3.5	
TK15		0.35	0.22	0.26	2.9	6.1	71.5	15.2	1.1	0.4	0.02	0.08	2.2	
A1		0.65	0.44	0.34	1.43	4.77	73.2	13.7	1.9	0.3	0.01	0	5	
TK36		0.35	0.43	0.32	2.76	6.75	67.5	16.3	3	0.4	0.04	0.08	2.5	
TK6		2.15	0.8	0.26	3.2	4.2	66	14.7	1.7	0.54	0.13	0	4.8	
T1-2		2.75	0.43	0.44	2.11	9.45	60	16.4	4.72	0.7	0.1	0	3.5	
T1-3		1.31	0.59	0.12	1.38	7.8	65	14	5.57	0.6	0.1	0	4.2	
T1-4		7	2.21	0.7	2.16	4.74	57.9	11.6	4.13	0.5	0.1	0	8.7	
T2-3		10	0.7	1.66	0.32	7.25	56	11.6	3.76	0.6	0.1	0	6.9	
A36		2.05	0.93	0.27	3.19	5.15	66	14.5	4.1	0.77	0.01	0	3.4	
22		1.4	0.01	1.79	2.1	4.3	75.5	13.1	0.02					
TK3		1.1	0.38	0.35	3.35	5.38	72	15	2	0.36	0.04	0	1.3	
25		0.42	0.46	0.32	1.21	6.19	71.5	14.2	2	0.5	0.03	0.5	4	
A22	Smectite,	1.2	0.83	0.24	0.85	3.28	70.5	12.7	2.6	0.7	0.03	0	6	Argillic
A11	feldspar,	0.4	0.64	0.79	0.25	4.4	77.3	8.3	4.6	0.34	0.03	0	2.5	
A19	quartz,	0.63	1.09	0.38	0.68	6.15	69.9	15.5	2.5	0.42	0.01	0	4.2	
T2-4	calcite	9.2	1.42	1.78	1.15	3.5	59	10	2.23	0.6	0.1	0	9.7	
TK35		1.44	0.92	0.31	2.91	4.14	64	15.9	2.7	0.5	0.02	0.08	7.6	
A42		1.95	1.1	0	2.05	5	64.2	15	5	0.62	1.45	0	5.3	
TK21		0.73	0.13	0.05	0.96	0.9	69	13.1	5.9	0.7	0.01	0.02	9	
7		3.32	0.6	1	2.3	3.1	68.5	15.5	2.24					
8		3.2	0.9	2.58	2	3.2	67	14.75	1.14					
19		3.5	0.01	1.07	2.3	4	68.15	15.1	2.4					
20		2.09	0.01	0.3	1.94	4.46	70.63	16.02	1.25					
TK7		1.13	1.41	0.09	1.23	1.05	65.5	14.8	2.1	0.5	0.01	0.08	12.7	
TK8		1.13	1.05	0.09	0.96	0.9	66	16	1.7	0.5	0.02	0.15	12.1	

Table 1 (*continued*)

Sample	Minerals	CaO	MgO	FeO	Na_2O	K_2O	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	MnO	SO_3	A.K.	Alteration type
A51	Kaolinite,	0.19	0.54	0.11	2.32	3.55	69.5	27	4.3	0.53	0.01	0	4.1	Advanced argillic
A28	quartz,	2.15	1.3	0	2.05	1.21	56.6	19.4	3	0.37	0.47	0	8.8	
TK33	feldspar,	0.81	0.87	0.33	2.83	1.45	60.5	18.2	3.4	0.5	0.01	0.03	12.1	
TK11	halite	1.9	2.1	0.07	2.91	1.57	53.1	18.5	3.6	0.6	0.01	0.03	15.8	
A26		0.3	1	0.42	0.18	4.13	57.5	17	7.2	0.88	0.02	0	10.4	
TK38		0.58	1.2	0.15	2.33	2.7	64.1	15.6	2.5	0.5	0.01	0	10.6	
TK42		1	1.16	0.08	2.16	1.45	58.9	15.1	3.6	0.6	0.01	0.03	14.9	
A47		0.63	1.11	0.57	0.39	2.92	48.9	14.4	8.7	0.8	0.11	0	22.6	
A48		0.56	0.28	0.68	0.15	1.55	16.1	6.4	52	0.27	0.01	0	24.9	
A29		1.46	1.06	0	0.32	0.4	49.7	3	36	0.15	0.35	0	10.8	
TK28		1.61	0.3	0.08	0.41	0.67	66	16.2	5.3	0.8	0.02	0.38	9	
A7		24.2	0.88	1.09	2.46	1.2	38.1	8.7	7.6	0.2	0	0	15	
A66		1.5	4.6	0	0.44	2.26	56.7	18.7	6.7	0.88	0.08	0	12.1	
A25		0.4	0.64	0.55	3.68	5.15	63.9	18.1	4.5	1.02	0.02	0	4.7	Unaltered
T1-1		5.25	0.76	0.2	0.55	9.04	56	14.8	7.78	0.7	0.2	0	5.1	
T2-1		2.44	1.1	0.04	2.52	5.84	58.1	15.2	6.15	0.8	0.1	0	6.2	
T2-2		4.44	1.98	0.99	1.45	6.25	56.8	14.2	4.7	0.8	1	0	7	
A38		0.6	1.03	0.31	0.96	6.2	64.1	19.5	3.6	0.65	0.05	0	9.4	
A46		0.12	0.41	0.38	3.9	4.15	63.9	17.4	5.2	0.68	0.02	0	5.5	
A21		0.35	0.9	0.06	0.9	5.5	60	12	8.2	0.7	0.01	0	10.5	
1		1.6	1.1	0.14	2.1	6.95	56	19.5	8.45					
2		4.1	1.5	0.57	2.1	4.2	63.37	15.2	5.02					
3		3.52	0.35	0.22	3.2	5.45	58.5	20.5	5.86					
4		3.4	1.1	0.93	2.8	4.75	63.5	17.5	4.22					
5		2.25	0.72	0.72	2.8	5.05	61.75	17.2	5.2					
6		5	0.01	0.93	3.1	3.57	61.25	19.51	4.67					
9		3.2	2	0.36	2.8	4.87	63	17.3	4.3					
10		3.9	1	0.57	2.7	4.3	59	19.15	5.92					
11		4.3	2.6	0.79	2.8	5.05	60	16.7	5.43					
12		3.55	0.65	0.58	2.8	5.35	62.8	20.5	2.36					
13		5.1	1.95	1.65	2.7	3.1	61.07	18	3.27					
14		7.2	1.5	3.08	2.7	2.65	57.5	18.65	3.28					
15		4.1	3.7	0.72	3.2	5.3	56.5	18.7	5.4					
16		5.2	1.2	1.07	2.7	4.65	58	18.15	5.37					
17		3.22	0.01	0.43	3.1	4.7	62.5	19.6	3.88					
18		1.65	0.7	0.36	2.5	5.57	63.8	18.3	3.55					

X-ray diffractograms (air-dried at 25°C, ethyleneglycolated and heated at 490°C for 4 h) of the clay-size fractions (< 2 μm) extracted by standard sedimentation technique in deionized water.

4. Petrology of volcanic rocks

The majority of volcanic rocks studied were sampled from the lava flows and the pyroclastics from outcrops and cores in the area of the T1 and T2 drillholes shown in Fig. 1.

The lava flows are highly jointed with a pronounced vesicular texture. Microscope studies reveal porphyritic and hyalopilitic texture, with a phenocryst assemblage of feldspar + plagioclase + biotite + hornblende in a matrix of glass and clay minerals. Opaque minerals are pyrite and marcasite, together with calcite, and generally quartz. Kaolinization and sericitization of feldspar are the typical alteration products associated with the samples from the lavas.

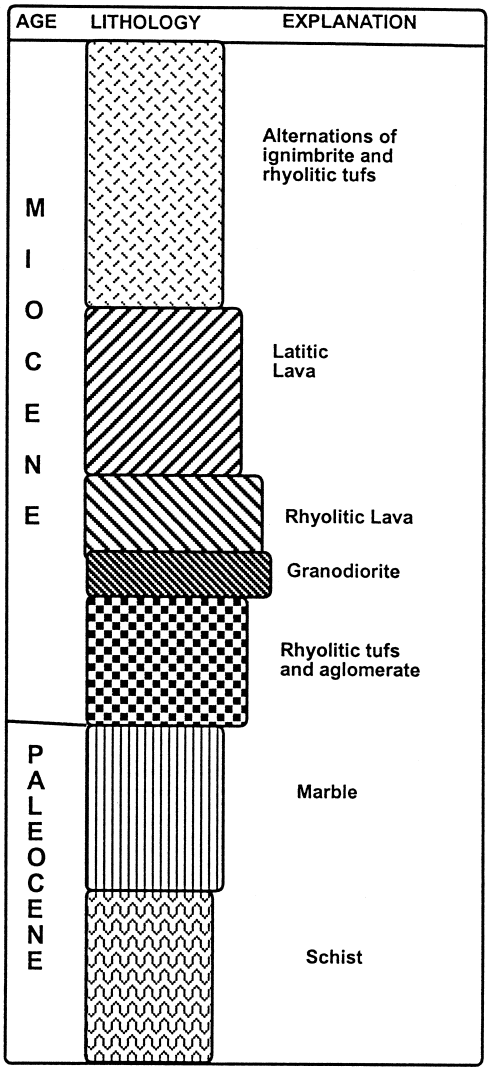


Fig. 2. Stratigraphic section of the Tuzla hydrothermal system.

The pyroclastics consist of tuffs, agglomerates and volcanic breccias. They are grayish white in color and show thick bedding in the studied area. Microscope studies reveal plagioclase (andesin–bytownite) + biotite + hornblende + volcanic rock fragments (vitrophir, spilite, andesite, porphrite, and dioritporphirite) in an acidic glass matrix. Agglomerates and volcanic breccias are intercalated with tuffs. They consist of moderately sorted rock clasts, between 10 and 50 cm in size, in a tuffaceous matrix. Microscopic studies indicated that rock clasts were derived from lavas.

Chemical analyses of various field samples are presented in Table 1. In the volcanic rocks and altered zones, oxide compositions have shown that some elements have the same distinct anomalies. For example, SiO_2 content is 56–64.1% for the unaltered volcanics, 16.1–69.5% for the advanced argillic zone, 59–71.5% for the argillic zone, 56–75.5% for the sericitic zone, and up to 90% for the silicified zone. These values confirm that both the volcanics and pyroclastics units are rich in silica.

K_2O and Na_2O contents in the unaltered rocks range from 3.1% to 9.04% K_2O, and from 0.55% to 3.68% Na_2O. K_2O and Na_2O contents in the advanced argillic and argillic zone are similar, but the advanced argillic zone has a relatively higher amount of K_2O and Na_2O. The sericitic zone has higher K_2O and Na_2O than the other zones and unaltered rocks.

Al_2O_3 and Fe_2O_3 contents in the unaltered rocks range from 12% to 20.5% Al_2O_3, and from 2.4% to 8.45% Fe_2O_3. Al_2O_3 and Fe_2O_3 contents are low in all zones except in the advanced argillic zone.

It has been shown that from the advanced argillic to the sericitic zone in the volcanics, the contents of K_2O, Na_2O, and SiO_2 increase but that of Al_2O_3 and Fe_2O_3 decrease (Fig. 3). Fig. 3 shows that unaltered rocks are geochemically distinct from those of the alteration zones.

5. Distribution of hydrothermal minerals

The formation of hydrothermal minerals is dependent on temperature, permeability, pressure, fluid composition, initial composition of the rock system (important only at less than 200°C for most rocks except, perhaps, limestone), duration of activity, and number of hydrothermal regimes (Reyes, 1990).

Two different hydrothermal regimes are evident in the Tuzla hydrothermal system. The currently active thermal regime is associated with Late Miocene volcanism and/or hydrothermal activity in the Tuzla, Kocaköy, Kestanbol, and Kestanelik fields. The older (fossil) hydrothermal activity in some

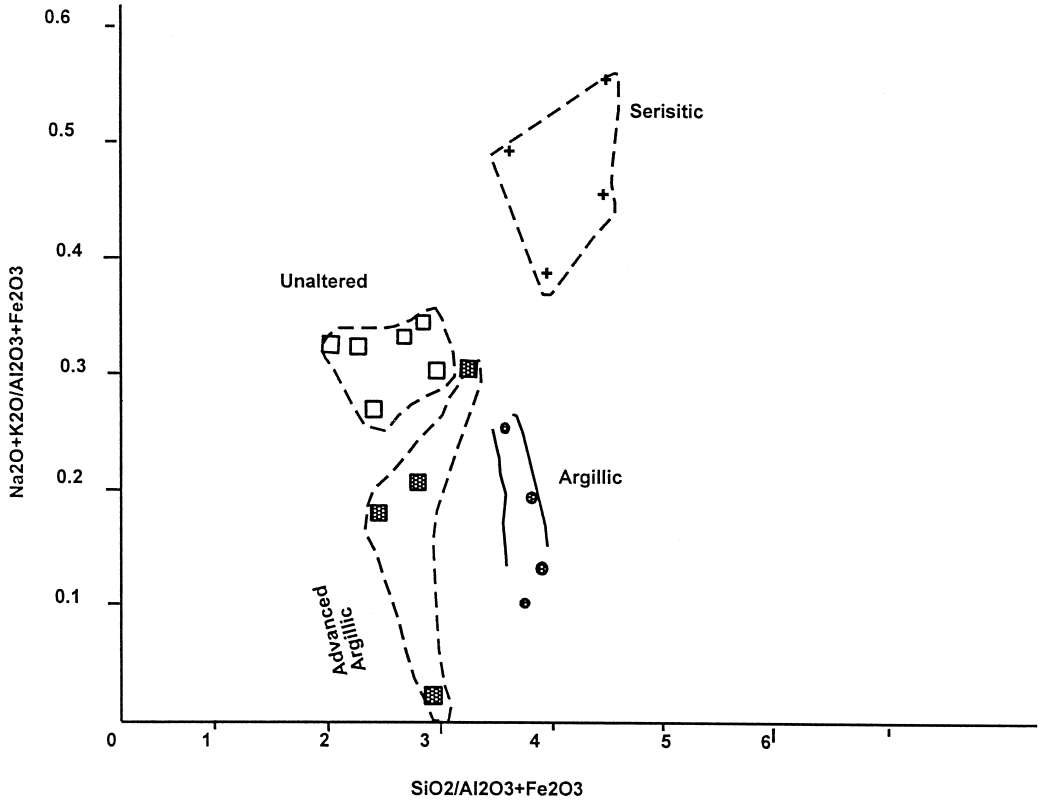


Fig. 3. $(Na_2O + K_2O)/(Al_2O_3 + Fe_2O_3)$ vs. $SiO_2/(Al_2O_3 + Fe_2O_3)$ in the unaltered, advanced argillic, argillic, and sericitic alteration types at the Tuzla geothermal area.

geothermal areas began during the Early Miocene; examples are in the Kösedere, Naldöken, Taşboğaz and Ahmetlerobasi regions (Fig. 1).

Active and fossil alteration assemblages have classified repeatedly observed alteration assemblages into groups. This has been necessary since a very wide range of hydrothermal alteration minerals can be formed (Hedenquist, 1987). Eight areas of hydrothermal alteration drillcore from drillholes (T1–T2) have been evaluated in the Tuzla hydrothermal system. In the following subsections, different hydrothermal alteration zones that have been recognized are discussed.

5.1. Alteration of Tuzla

Fig. 4 and Table 1 summarize the alteration zones and diagnostic minerals in the Tuzla field. Four active hydrothermal alteration zones can be explained further as follows:

(1) Silicified zone: Silica shows a net gain (65–95%), with the most pronounced enrichment in the silicified zone of the Tuzla lava dome at Tuzlatepe (Fig. 4).

(2) Smectite zone: This zone occurs in Ayvacik lava and ignimbritic tuffs at SE of Tuzlatepe. There are smectite and smectite–illite mixed layer clay minerals in this zone.

(3) Illite zone: This zone has illite, kaolinite, halite, and quartz mineral assemblages, and underlies the smectite zone closed to Tuzlatepe (halite occurred as a recent evaporation).

(4) Alunite zone: This zone is produced in Ayvacik lava by the effect of hydrothermal solution, which is sulfate-rich. The mineral assemblages in

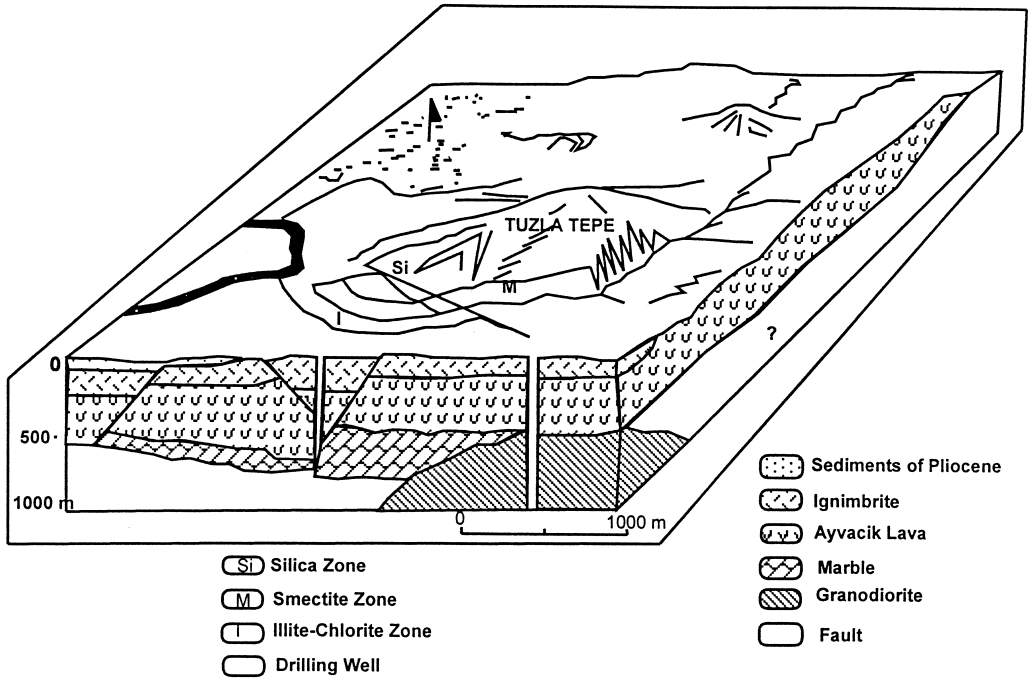


Fig. 4. Block diagram of hydrothermal alteration zones in the Tuzla hydrothermal system.

this zone include alunite, cristbalite, halite, and albite.

5.2. Alteration of Kocaköy

The hydrothermal alteration is controlled by tectonic activity in the Kocaköy field (Fig. 5a). The active hydrothermal alteration zone is an Opal zone that contains only opal, which has been deposited from supersaturated thermal fluids.

From inside to outside, the hydrothermal alteration zones in this field are either a smectite zone or an illite zone (Fig. 5b).

5.3. Alterations of Kestanbol and Kestanelik

The Kestanbol and Kestanelik fields have illite, smectite, and silicified + halite alteration zones similar to other fields (halite is present due to evaporation). All of these fields have active hydrothermal alteration zones (Fig. 5b).

5.4. Alterations of Kösedere, Naldöken, Taşboğaz and Ahmetlerobasi

The Kösedere, Naldöken, Taşboğaz, and Ahmetlerobasi fields have passive hydrothermal alteration zones. These zones are gypsum, montmorillonite, and illite zones (Fig. 5c, Table 1). Figs. 6 and 7 summarize the alteration types in the T1 and T2 wells. Three active hydrothermal alteration types (advanced argillic, argillic, and sericitic) in T2, and only a sericitic zone in T1, are discussed below.

According to Karamanderesi (1986) the mineral distribution of the well Tuzla 2 is as shown in Fig. 7. From this figure, it is evident that calcite, quartz number, and secondary iron oxide minerals are present at all depths. Kaolinite is the common mineral in the ranges 0–100, 400–600, and 700–800 m. Illite is only found between 200 and 600 m. Smectite and mixed layer clay minerals are the most prominent clay minerals that occurs from bottom to top of the well. The mixed layer clays are between smectite and illite in the upper part, and also smectite and

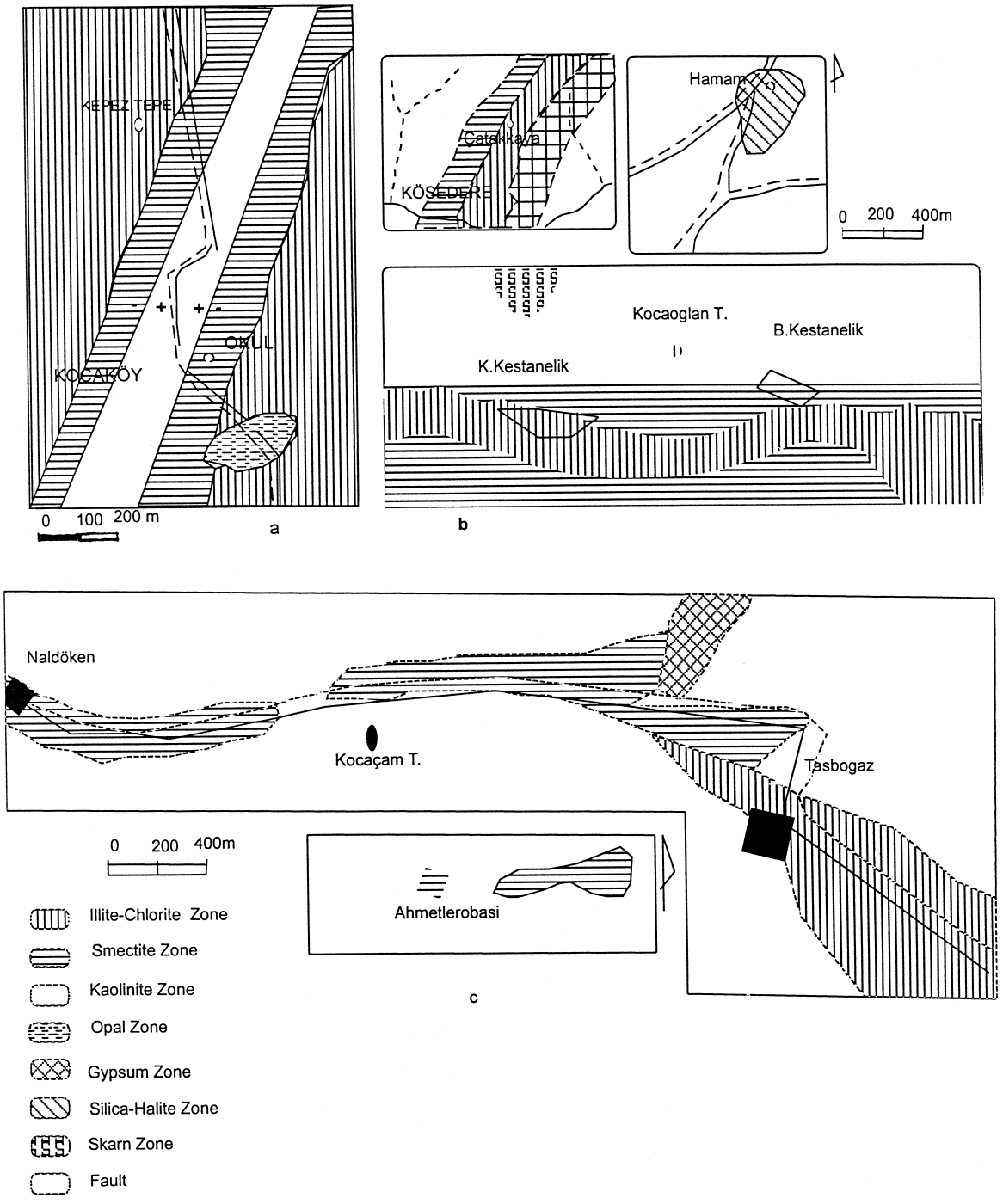


Fig. 5. Hydrothermal alteration maps of: (a) Kocaköy field, (b) Kestane'ik, Kösedere, and Kestanbol fields, and (c) Naldöken, Taşboğaz, and Ahmetlerobasi fields.

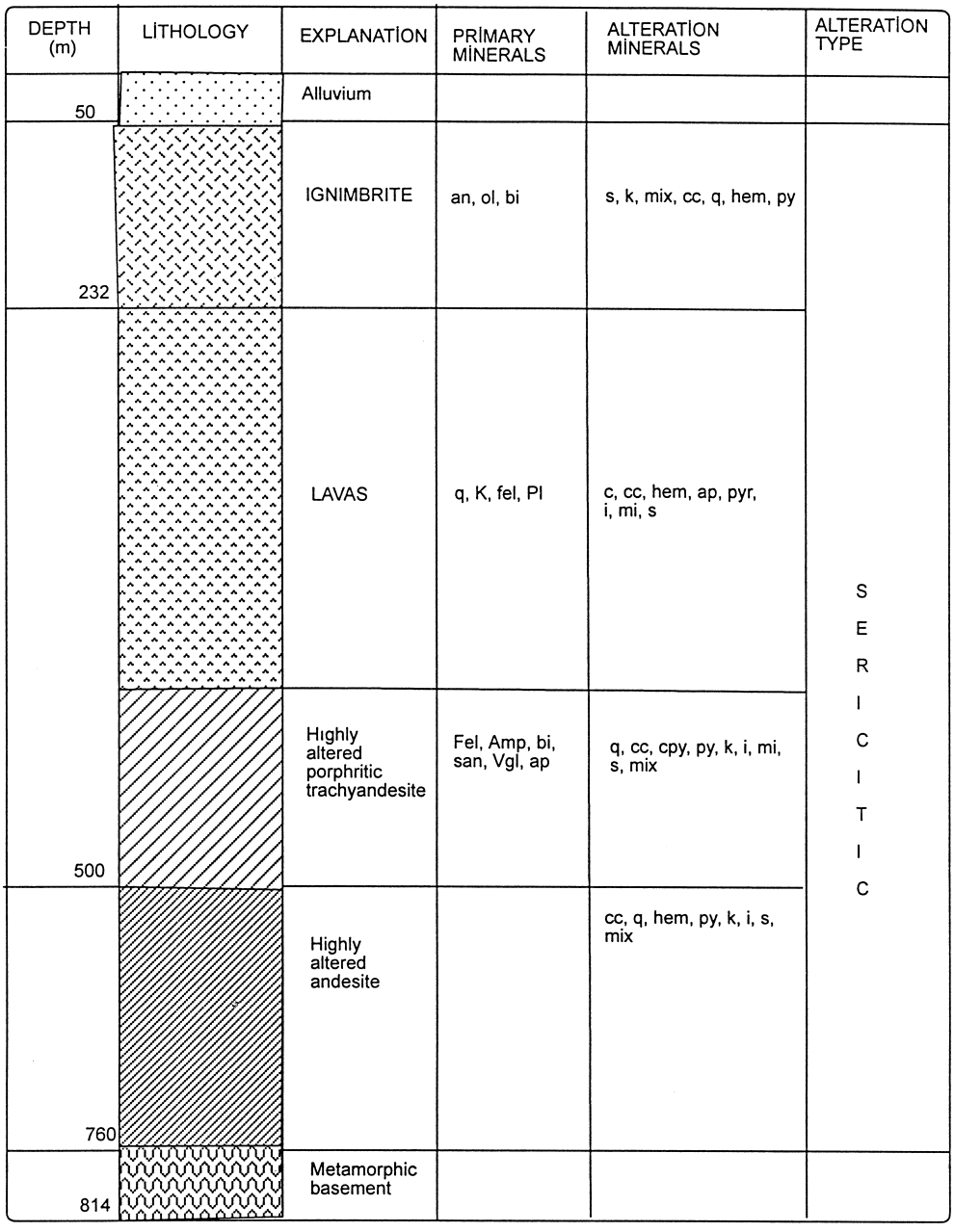


Fig. 6. Vertical distribution of lithology, primary and alteration minerals and alteration types of T1 well. Symbols include: al: albite; an: andesine; ap: apatite; amp: amphibolite; aug: augite; bi: biotite; c: clay; cc: calcite; ch: chlorite; cpy: calcopyrite; ep: epidote; fel: feldspar; hem: hematite; i: illite; k: kaolinite; K-fel: K-feldspar; mag: magnetite; mi: mica; mix: mixed layer clay minerals; ol: oligoclase; or: ortoclase; pl: plagioclase; py: pyrite; q: quartz; s: smectite; san: sanidine; sp: sphene; Vgl: volcanic glass.

chlorite in the lower part. Chlorite is only found within the metamorphic rocks below 600-m depth. Within the metamorphic basement rocks, high-temperature hydrothermal mineralization is found, including epidote, sphene, magnetite, garnet, actinolite, diopsite, and prehnite. These minerals occur at a

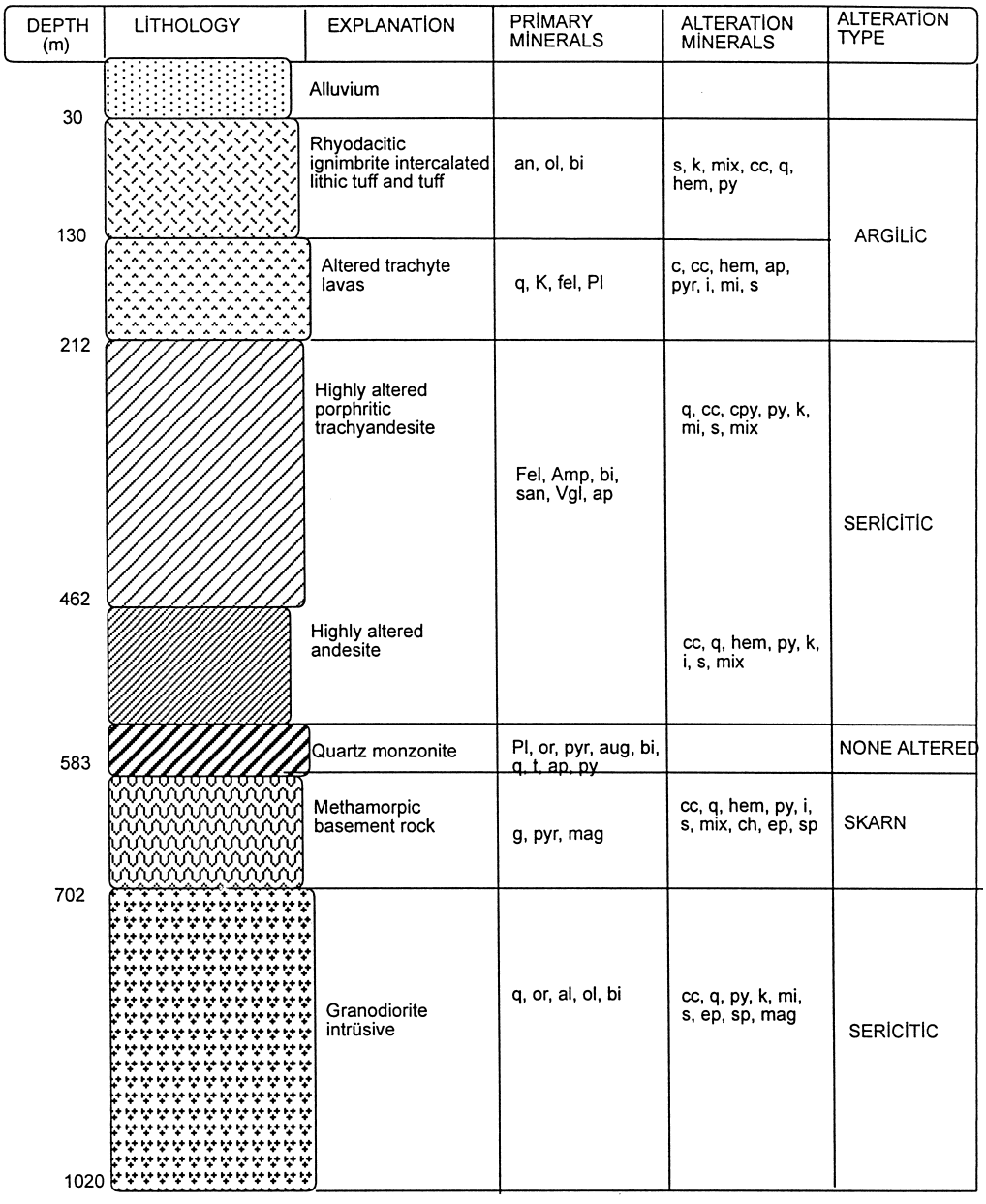


Fig. 7. Vertical distribution of lithology, primary and alteration minerals and alteration types of T2 well. For symbols, see Fig. 6.

depth of 583 m and below 725-m depth. It appears that this assemblage is related to contact metamorphism (e.g., garnet, magnetite, and diopsite) near the margin of the granodiorite and monzonite intrusions.

In the Tuzla 1 well, the metamorphic basement rock showed no evidence of the high temperature assemblages present in the Tuzla 2 well. Apatite was found in some thin sections, and may be a primary

mineral. Barite occurs as a vein mineral with calcite and quartz. Gypsum was observed in only one sample at about 590-m depth.

6. Fluid chemistry and alteration products

The water samples were analysed within a month of sampling. The results of the chemical analyses are presented in Table 2, together with the in situ temperature and pH measurements. It appears from Table 2 that all the waters are neutral in character with pH values ranging from 7 to 8.04. The dominant cation in the samples is sodium and the dominant anion is chlorine. From the piper diagram in Fig. 8, we can say that the $Na^+ + K^+$ content is bigger than $Ca^+ + Mg^+$ and that the $Cl^- + SO_4^-$ content is bigger than $HCO_3^- + CO_3^-$ for water samples from the Tuzla active geothermal area. The dominant waters in Tuzla have NaCl, Na_2SO_4, KCl, and up to 50% alkalinity.

Reyes (1990) pointed out that certain minerals are characteristic of neutral pH, whereas others indicate acid conditions. From these alteration mineral studies and the fluid chemistry of the Tuzla hydrothermal system, we can say that there are two water types present resulting in neutral pH and acid alteration (Table 1).

The action of hydrothermal fluids on the lavas, pyroclastic deposits and the metamorphic rocks causes irreversible changes to the minerals and to the chemical composition of the fluid. To investigate the equilibrium between the secondary minerals and the hydrothermal fluids, we have drawn phase diagrams at 40, 72, 73, 102, and 173°C for the pH that ranges from 7 to 8.04 (Table 2), at vapour saturation pressure and in the presence of quartz. The free energies of the mineral phases and of the dilute anions in the water have been calculated according to thermodynamic data given by Helgeson (1969), Helgeson and Kirkham (1974a,b) and Helgeson et al. (1978,1981). The activity coefficient γ of the dilute anions in the Tuzla geothermal waters and hot springs were calculated from the Debye–Hückel equation.

Table 2
Hydrochemical composition of geothermal waters

	A	B	C	D	Tuzla 1
pH	7.82	8.04	7.72	7.8	7
T (°C)	102	72	73	40	173
Ca^{2+}	3069	3110	931	753	5715
K^+	1912	1904	451	405	2125
SO^{4-}	155	166.2	210	174	176
HCO_3^-	98	122	111	90	100
SiO_2	100	98	96	88	123
Mg^{2+}	90.4	80.8	88	57	101
Cl^-	33855	36159	13116	10989.5	44140
Na^+	17260	18740	7148	6032	22250

The mineral stabilities as a function of log $^aNa^+/^aH^+$, log $^aMg^{2+}/^aH^+$, log $^aCa^{2+}/^aH^+$, and log $^aK^+/^aH^+$ are illustrated in Fig. 9. From Fig. 9, we can say that the hydrothermal fluid is in equilibrium with albite, kaolinite, and K-feldspar in the Tuzla 1 drillhole; chlorite, albite, and K-feldspar in Spring A (102°C); albite, chlorite, and K-feldspar in Spring B (72°C); and kaolinite in Springs C (73°C) and D (40°C).

7. Discussion and conclusion

The Tuzla hydrothermal system is hosted by faults and fractures associated with NW–SE and SW–NE trending zone that was mapped on the surface. The geothermal system is recharged by seawater and has measured temperatures approaching 170°C. Relict mineral geothermometry indicates formerly higher temperature of more than 220°C. Hydrothermal alteration has developed a mineral zonation, which is similar to that of other high temperature geothermal systems. The interaction of the geothermal fluids with the wall rock along fractures has produced quartz (silicified zone) that is a good indicator of permeability in active geothermal fields (Browne, 1978). Besides these alteration minerals, halite has been produced by recent evaporation because of the high content of chloride and sodium in ground water.

Several authors have suggested that the distribution of clay minerals in geothermal areas depends on the thermal structure of the field and on its fluid chemistry (Steiner, 1968; Kristmannsdottir, 1975; Elders et al., 1984; Harvey and Browne, 1991). Fluid temperatures can be inferred from the presence of temperature-dependent hydrothermal clay minerals (Steiner, 1968; Browne, 1978). Smectite is stable at

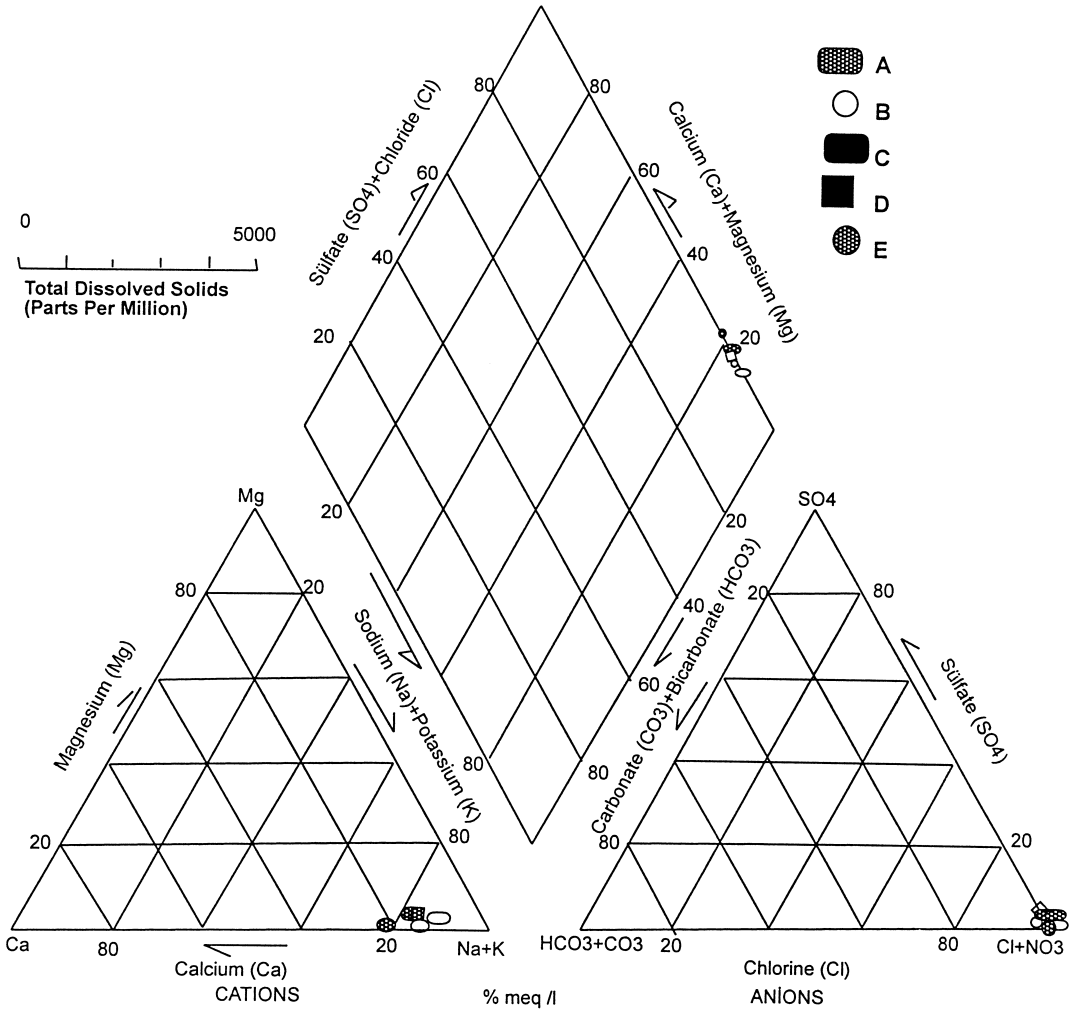


Fig. 8. Piper diagram of geothermal waters taken from the Tuzla geothermal field.

140°C, and illite, above 220°C in active systems (Browne, 1984). Interstratified illite–smectite is stable between these two temperatures with variations in the proportions of illite and smectite being a function of the temperature of deposition. Chlorite at the base of the profile suggests temperatures of 220°C (Kristmannsdottir, 1975). The extensive kaolinite over-printing suggests a later, cooler (120°C) fluid (Browne, 1978).

Fluid/rock interaction at Tuzla has produced a suite of hydrothermal minerals that reflect the hydrology and lithology of the reservoir. These mineralogical changes are also evident in chemical changes that the rocks have undergone. Constituents such as SiO_2, Al_2O_3, Na_2O, K_2O, CaO, and H_2O were redistributed as a result of mineralogical changes, but others (MnO and P_2O_5) are largely immobile.

From the results of petrographical and XRD analyses, and measurements of temperature of well water and spring water, we can say that the hydrothermal alteration minerals of the Tuzla active geothermal field were derived from plagioclase converted to sericite, chlorite, and clay minerals (at 150–165°C), sericite and chlorite (at 165–200°C), and sericite (at 200°C).

The Tuzla hydrothermal system was formerly hotter (more than 220°C) while the temperatures in the pluton were even higher (based on the alteration

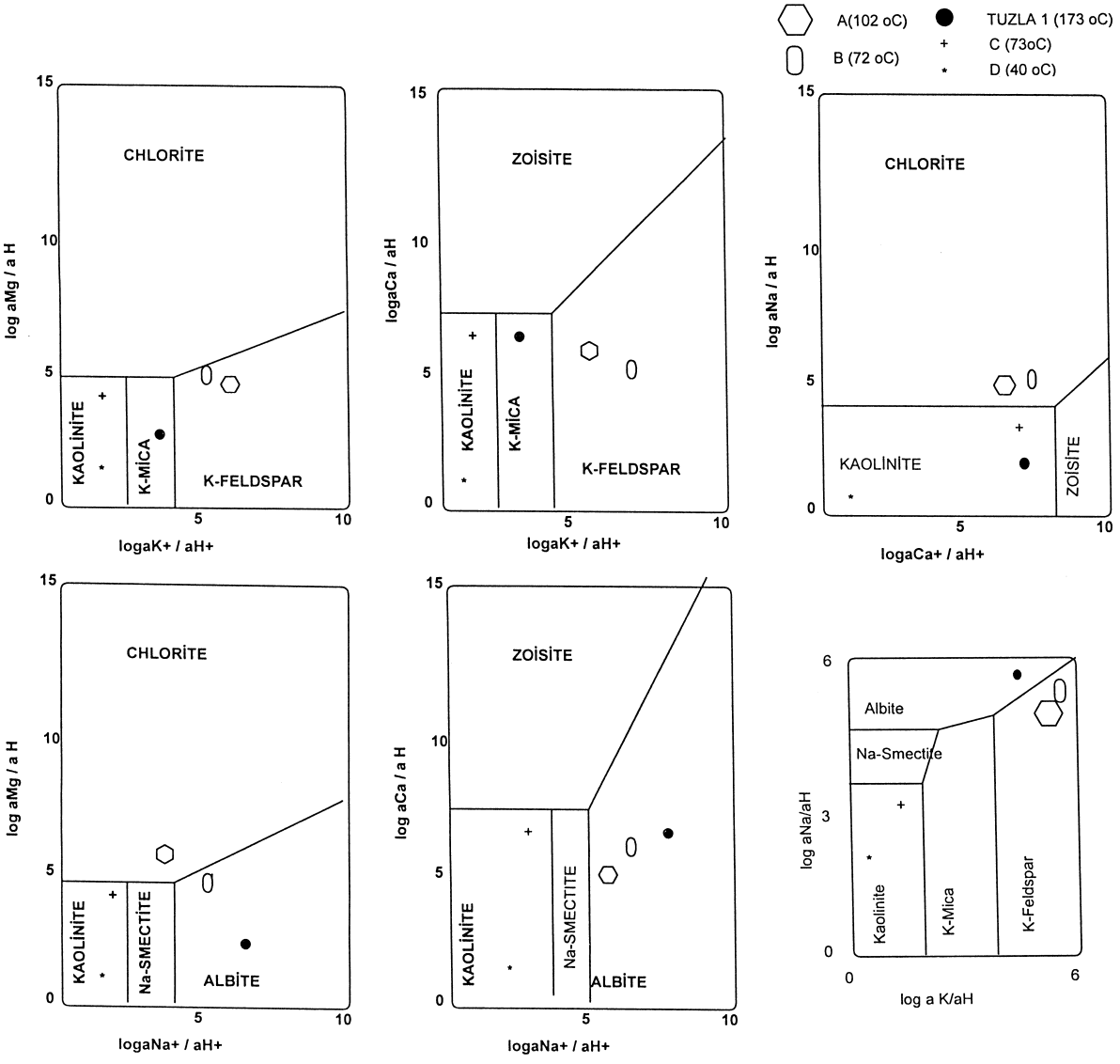


Fig. 9. Activity diagrams of geothermal waters taken from the Tuzla geothermal field.

minerals). Subsequently, the system has cooled to 170°C, but the relict alteration mineralogy still remains.

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