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Hydrogeochemical outline of thermal waters and geothermometry applications in Anatolia (Turkey)

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Abstract

The chemical compositions of a total of 120 thermal water samples from four different tectonically distinct regions (Central, North, East and West Anatolia) of Turkey are presented and assessed in terms of geothermal energy potential of each region through the use of chemical geothermometers. Na–Ca–HCO_3 type waters are the dominant water types in all the regions except that Na–Cl type waters are typical for the coastal areas of West Anatolia and for a few inland areas of West and Central Anatolia where deep water circulation exists. The discharge temperature of the springs ranges up to 100°C, and the bottom-hole temperatures in drilled wells up to 232°C. Geothermometry applications yield reservoir temperatures of about 125°C for Central Anatolia, 110°C for North Anatolia, 136°C for East Anatolia and 251°C for West Anatolia, the latter agreeing with some of the bottom hole temperatures measured in drilled wells. The results reveal that the highest geothermal energy potential in Turkey is associated with the West Anatolian extensional tectonics which provides a regional, deep-seated heat source and a widespread graben system allowing deep circulation of waters. The North Anatolian region, bounded to the south by the dextral North Anatolian Fault along which most of the geothermal sites are located, has the lowest energy potential, probably due to the restriction of the heat source to local magmatic activities confined to pull-apart basins. The East Anatolian region (undergoing contemporary compression) and the Central Anatolian region (where the compressional regime in the east is converted to the extensional regime in the west) have moderate energy potential. Although the recently active volcanoes suggest the presence, at depth, of still cooling magma chambers that are potential heat sources, the lack of well-developed fault systems is probably responsible for the comparatively low energy potential of these regions. Almost all the thermal waters of Turkey are saturated with respect to calcite and, hence, have a significant calcite scaling potential which is particularly high for West Anatolian waters.

Keywords: Turkey; thermal waters; geothermometry; neotectonics

1. Introduction

Turkey, owing to its location in the tectonically active Alpine–Himalayan belt, is characterized by a widespread geothermal activity manifesting itself in the form of numerous hot springs, fumaroles and recent mineralization. The geodynamic history of Turkey has been governed, since the Mesozoic, by the relative movement of the European and the Afro-Arabian plates and the associated episodes of separation, collision, rotation and deformation of the small continental plates in the intervening areas. The

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borders of these small plates constitute seismic belts marked by young volcanics and active faults, the latter allowing circulation of waters as well as heat. The distribution of hot springs in Turkey roughly parallels the distribution of the fault systems and the Tertiary–Quaternary volcanics (Fig. 1). The presence of more than 500 hot springs, with discharge temperatures up to 100°C, points to an important geothermal potential in Turkey that has been confirmed by drilling studies implemented by the General Directorate of the Turkish Mineral Research and Exploration (MTA) since the 1960s. By 1997, MTA had drilled 250 geothermal wells and 45 gradient wells. The main utilization of geothermal energy in Turkey is in domestic heating, greenhouses, and in spas and thermal resorts installed for balneological purposes.

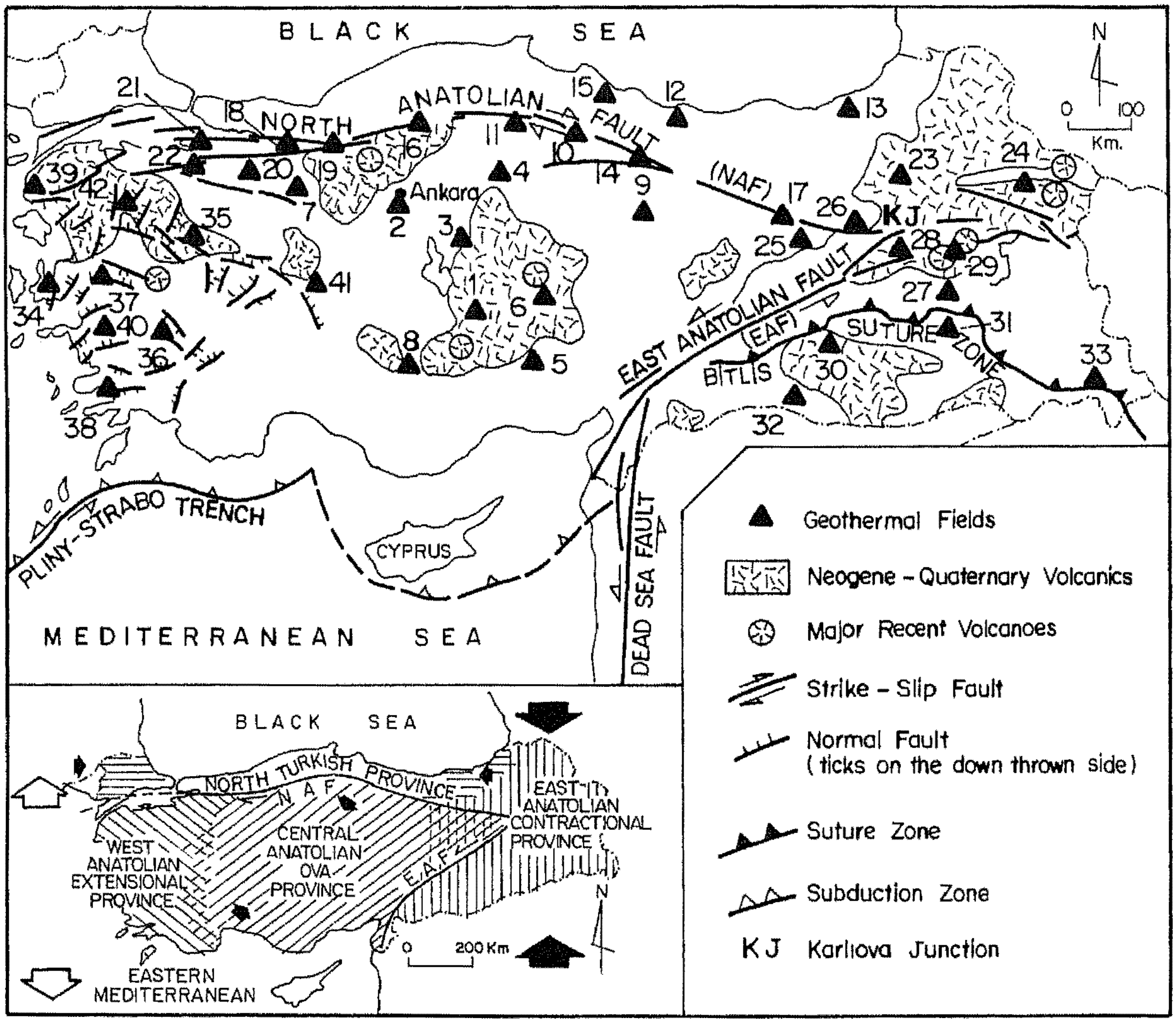

Fig. 1. Distribution of geothermal areas in Turkey in connection with the major tectonic and volcanic features (modified from MTA, 1993). Inset map is from Şengör et al. (1985) and shows the major neotectonic provinces of Turkey. (1) Aksaray, (2) Ankara, (3) Kırşehir, (4) Yozgat, (5) Niğde, (6) Nevşehir, (7) Eskişehir, (8) Konya, (9) Sivas, (10) Amasya, (11) Çorum, (12) Ordu, (13) Rize, (14) Tokat, (15) Samsun, (16) Çankırı, (17) Erzincan, (18) Sakarya, (19) Bolu, (20) Bilecik, (21) Yalova, (22) Bursa, (23) Erzurum, (24) Ağrı, (25) Tunceli, (26) Bingöl, (27) Bitlis, (28) Muş, (29) Van, (30) Diyarbakır, (31) Siirt, (32) Urfa, (33) Hakkari, (34) İzmir, (35) Kütahya, (36) Denizli, (37) Manisa, (38) Muğla, (39) Çanakkale, (40) Aydın, (41) Afyon, (42) Balıkesir.

Additionally, electricity is produced from geothermal energy in the first and only power plant installed in the Kızıldere field (West Anatolia); the plant has been in operation since 1984 with a capacity of 20 Mwe.

This study is concerned with the presentation of the chemical compositions of thermal waters in Turkey, compiled from previous studies, and their overall evaluation: determination of the water types, comparison between waters of tectonically different regions (grouped into four here as Central, North, East and West Anatolian waters), and assessment of more promising areas from the viewpoint of geothermal energy potential. The interest for such a study arises from the increasing demand for the utilization of geothermal energy in various fields in Turkey. The assessment of the geothermal potential is essentially based on estimation of the reservoir temperatures through the use of chemical geothermometers.

2. Geologic and tectonic outline

Geologically Turkey consists of several microcontinents or small continental plates separated from each other by suture zones of various ages. The pre-Mesozoic metamorphic basement (Menderes, Uludağ, Kazdağ and Kozak Massifs in West, Bitlis Massif in East, and Kırşehir Massif in Central Anatolia) is tectonically overlain by Mesozoic ophiolitic rocks representing remnants of Tethyan ocean floor. Cenozoic is marked by both an intense magmatic activity, characterized by numerous granitoid intrusions and widespread volcanic products ranging in age up to historical times, and the formation of extensive sedimentary basins containing marine and terrestrial sediments, reaching, in places, up to thousands of meter in thickness.

The tectonic evolution of Turkey may be divided into two phases, namely the paleotectonic and the neotectonic periods. The paleotectonic period covers the tectonic events governed by the convergence between the Afro–Arabian and the Eurasian plates until about the middle Miocene when the two plates collided along the Bitlis Suture Zone (BSZ) (Fig. 1). The neotectonic period is linked to the post-collisional convergence between the respective plates and has resulted in the formation of several neotectonic provinces characterized by distinctive structures (Fig. 1). Among these structures, the BSZ is the manifestation of the collision between the Afro–Arabian and the Eurasian Plates which occurred in about the middle Miocene (Dewey and Şengör, 1979). The diffuse seismic activity throughout eastern Turkey (Mc Kenzie, 1972; Rotstein and Kafka, 1982) and the folding and thrusting of recent sediments onto the Arabian platform suggest that the convergence is still in progress (Şengör and Canıtez, 1982; Jackson and Mc Kenzie, 1984). The North Anatolian and the East Anatolian faults (NAF and EAF, respectively) are strike–slip faults (with right- and left-lateral sense, respectively) originated in response to the northward movement of the Arabian Plate. The faults are not single ruptures but are narrow zones consisting of small faults of en-echelon geometry. Starting from the Karlıova junction in the east, the EAF extends southwestward where it is connected to the Dead Sea Fault (Arpat and Şaroğlu, 1972, 1975), whereas the NAF extends westwards and, to the west of 31 longitude, is split into several branches characterized by dominant normal faulting component along with strike–slip component (Canıtez and Üçer, 1967; Mc Kenzie, 1972; Dewey and Şengör, 1979). Bounded by these faults, four major neotectonic provinces are recognized in Turkey (Şengör et al., 1985) (inset map of Fig. 1): (1) the East Anatolian contractional province, located east of Karlıova junction where the NAF and EAF meet, and characterized by N–S shortening due to the still continuing convergence along the BSZ; (2) the North Turkish province, situated north of the NAF and characterized by limited E–W shortening; (3) the West Anatolian extensional province, characterized by N–S extension resulted from the west southwestward escape of the Anatolian plate along the NAF and EAF; and (4) the Central Anatolian 'ova' province, characterized by NE–SW shortening and NW–SE extension, and by the presence of large, terrestrial sediment filled basins ('ovas').

3. Sampling and analysis

Water samples used in the present study were collected in different years by a number of workers. Most of the collected samples were analyzed at the

Table 1
Chemical compositions (in ppm) of thermal waters from Central and North Anatolia (TDS = Total dissolved solid content, C.B. = Charge balance error in %. n.a. = not analyzed)

Sample no.[a]	Region/area	T (°C)[b]	pH_{lab}	K	Na	Ca	Mg	HCO_3	CO_3	SO_4	Cl	SiO_2	B_T	C.B.	TDS	Water type	Reference
Central Anatolia																	
Aksaray area																	
1 (s)	Ilısu	31	7.66	19	47	28	12.2	244	0	16	30	129	0.57	2.46	526	HCO_3–Na	Mutlu, unpublished data
2 (s)	Ziga	48	7.17	16	1220	360	58	1305	0	43	1950	49	21	0.70	5029	Cl–Na	Mutlu, unpublished data
3 (w)	Acıgöl-Sofular MTA-2	65	8.61	184	550	20	158	958	18	198	872	170	24	2.75	3159	HCO_3–Na	Akbaşlı (1992)
Ankara area																	
4 (w)	Kızılcahamam MTA-1	73.8	6.90	60	760	48	9.7	1474	0	194	272	79	7.5	2.56	2905	HCO_3–Na	Güleç (1994)
5 (s)	Sey	42.5	6.40	24	240	111	27	830	0	143	20	32	1.5	4.64	1429	HCO_3–Na	Güleç (1994)
6 (s)	Ayaş	30	8.32	28	128	71	58	622	6	134	61	122	0.9	1.04	1231	HCO_3–Na	Özeke and Çetiner (1987)
7 (w)	Haymana H-3	44	6.70	7	36	144	40	634	0	33	5.7	27	0.44	4.21	928	HCO_3–Ca	Özeke (1987)
8 (w)	Melikşah MH1-A	39	8.84	5.85	49	67.5	17.4	345	11	49	10.5	52	0.54	1.75	608	HCO_3–Ca	Keskin (1976)
9 (w)	Mürtet well MT-1	28	8.80	2.2	36.5	40.8	10.9	206	6	32.9	26.9	10	0.12	4.59	372	HCO_3–Ca	Keskin (1974)
Kırşehir area																	
10 (w)	Savcılı-Büyükoba SB-2	34.5	9.63	1	106	4.4	0.2	61	12	45	78	51	n.a.	3.53	359	Cl–Na	Tekin and Tekin (1986)
11 (w)	Tenne T-7	45	6.70	11	160	242	37	864	0	94	235	37	0.8	0.82	1681	HCO_3–Ca	Gündüz et al. (1995)
12 (s)	Çiçekdağı-Mahmutlu	70	6.50	40	1026	308	55.9	393	0	1234	1202	79	n.a.	0.32	4338	SO_4–Na	Canik (1981)
13 (s)	Karakurt	50	6.74	9	69	188	17	451	0	225	54	44	0.13	1.54	1057	HCO_3–Ca	Didik et al. (1994)
Yozgat area																	
14 (w)	Sorgun YS-2	75	7.84	16	480	120	0.48	24	0	327	730	75	6.15	1.95	1808	Cl–Na	Özmutaf (1988)
15 (w)	Boğazlayan-Bahar BB-2	46	6.40	11	410	289	63	848	0	294	576	30	0.3	1.97	2522	HCO_3–Na	Özmutaf and Yüce (1987)
16 (w)	Boğazlayan-Uzunlu UB-2	30	7.37	10.8	99	128	35	586	0	78	101	37	0.14	0.78	1075	HCO_3–Ca	Özgür (1993)
17 (w)	Yerköy-Güvem YK-1	47	7.40	60	2100	821	61	55	0	428	4418	30	6.6	1.63	7982	Cl–Na	Gündüz and Öztan (1994)
Niöde area																	
18 (s)	Kemerhisar min. water	12	6.82	39	1580	192	229	2112	0	395	1950	77	29	0.14	6606	HCO_3–Na	Mutlu, unpublished data
19 (w)	Çiftehan ÇF-1	44.5	8.25	7.8	385	214	24	12	0	839	398	44	3.2	1.20	1927	SO_4–Na	Didik (1991)
Nevşehir area																	
20 (w)	Kozaklı SSK-1	93	6.83	21	440	208	22	427	0	486	632	87	n.a.	4.61	2323	Cl–Na	Hamut et al. (1992)
Eşkisehir area																	
21 (s)	Eşkisehir	40	8.59	2.9	18	73	28	329	6	24	16	26	0.2	1.98	523	HCO_3–Ca	Ölmez et al. (1986)
22 (w)	Sarıcakaya SK-3	55	6.40	16.8	320	40	170	1647	0	87.8	63.8	118	4.4	0.47	2468	HCO_3–Na	Uzel (1988)
23 (s)	Sivrihisar Hamamkrhsr.	35	7.45	2.9	44	55	18	281	0	48	38	20	0.5	3.63	507	HCO_3–Ca	Öktü (1986)
Konya area																	
24 (w)	Ilgın I-1	42	6.80	10	62	118	37	561	0	125	25	30	0.87	2.52	969	HCO_3–Ca	Öktü et al. (1992)
25 (w)	Beyşehir KB-1	35	7.60	1.6	40	216	45	189	0	604	67	32	0.2	3.81	1195	SO_4–Ca	Tekin and Çetiner (1988)
26 (s)	Cihanbeyli-Yapalı	35	6.60	29	355	703	209	1087	0	1704	539	47	n.a.	0.01	4673	SO_4–Ca	Canik (1988)
Sivas area																	
27 (w)	Çermik SÇ-1	45	6.10	38	200	360	97	1903	0	50	193	24.6	2.8	2.77	2868	HCO_3–Ca	Büyük (1982)

North Anatolia																	
Amasya area																	
28 (w)	Arkutbey H-1	42.5	7.05	1	60	32	20	244	0	30	45	26	< 0.1	0.12	458	HCO_3–Na	Erzenoğlu (1989)
29 (s)	Terziköy	37	8.10	4.15	35	73	34	458	0	28.4	12.7	18.4	0.38	2.34	664	HCO_3–Ca	Kartal (1974a)
30 (w)	Gözlek GS-1	40.5	9.07	3.6	86	16	6	224	12	32	14	20	0.4	0.08	414	HCO_3–Na	Demirel and Özgür (1990)
Çorum area																	
31 (w)	Hamamlıçay ÇH-1	30	6.65	3.2	60	55	31	275	0	89	56	13	0.2	0.30	582	HCO_3–Na	Özmutaf and İslamoğlu (1993)
32 (w)	Figani F-2	37	6.30	4.2	46	32.8	18	281	0	21	9.4	26	< 0.1	0.84	438	HCO_3–Na	Özmutaf et al. (1988)
Ordu area																	
33 (w)	Fatsa-Sarmaşık Ilıca-1	50	7.70	1.6	200	9	1	122	0	303	57	44	0.5	3.44	738	SO_4–Na	Erzenoğlu and Tamgaç (1986)
Rize area																	
34 (s)	Çamlıhemşin-Ayder	33	8.62	0.8	57	7	1	12.2	18	92	13.4	49	n.a.	2.73	250	SO_4–Na	Çetiner and Büyük (1987)
35 (s)	Andon İçmesi	14	6.45	26.8	788	311	87.5	2270	0	814	251	46	n.a.	2.99	4594	HCO_3–Na	Ölmez (1979)
Tokat area																	
36 (w)	Reşadiye RHS-1	46.5	6.54	40	840	415	107	2386	0	175	837	54	28	0.54	4884	HCO_3–Na	Erzenoğlu and Cadoğlu (1990)
37 (w)	Artova-Sulusaray AS-3	53.5	8.78	32	880	108	12.1	647	18	747	617	96	9.7	1.44	3168	SO_4–Na	Öktü et al. (1986)
Samsun area																	
38 (w)	Ladik HH-1	38	8.20	2.5	33	20	37	268	0	30	13	17	0.26	1.41	421	HCO_3–Na	Keskin (1987)
39 (w)	Havza SH-3	53	8.60	8.4	146	8.4	4.6	348	6	44	4.9	34	< 0.1	2.79	604	HCO_3–Na	Ergun and Keskin (1990)
Çankırı area																	
40 (s)	Çerkeş-Bedil Köyü	26.5	6.91	71	718	333	55	2989	0	4.3	191	22.5	20.8	0.25	4405	HCO_3–Na	Koçak (1974a)
41 (s)	Kurşunlu-Çavundur	30	7.00	248	2600	25.7	13.7	6521	0	113	769	29.5	63.8	3.62	10384	HCO_3–Na	Koçak (1974b)
42 (s)	Şabanözü-Karakaş	24.5	9.72	1.94	55.2	4.9	93	427	104	35	17.3	14.4	51	6.10	804	HCO_3–Mg	Üngör (1973)
43 (s)	Eskipazar min. water	20	6.90	96	700	212	130	3124	0	35	199	53	16	3.02	4566	HCO_3–Na	Yücel and Hakyemez (1991)
Erzincan area																	
44 (s)	Erzincan	31	6.80	13	630	146	599	3560	0	54	844	176	25	0.61	6047	HCO_3–Na	Özmutaf and Can (1985)
Sakarya area																	
45 (w)	Akyazı-Kuzuluk K-3	82	8.06	45	780	141	17	1891	10	46	411	135	24	0.42	3502	HCO_3–Na	Yücel and Aydoğdu (1994)
46 (s)	Kuzuluk mineral water	20.5	6.50	65	1625	98	36	3746	0	11	702	24	20	0.78	6329	HCO_3–Na	Didik and Dilemre (1992)
47 (s)	Taraklı-Kil	40	6.60	5	35	127	27	555	0	23	11	32	0.2	1.65	815	HCO_3–Ca	Didik and Dilemre (1992)
48 (s)	Taraklı-Acısu	18.5	7.60	12	600	352	396	1178	0	2716	127	17	1.2	1.85	5400	SO_4–Na	Didik and Dilemre (1992)
	Bolu area																
49 (w)	Hamamçayırı HÇ-1	46	7.32	17.5	59	379	65.2	864	0	553	8.25	34	n.a.	2.63	1980	HCO_3–Ca	Canik (1972)
50 (s)	Bolu	45	7.30	16.8	49.3	364	61.5	854	0	619	34.5	20	< 0.1	3.79	2019	HCO_3–Ca	Yücel et al. (1994)
51 (s)	Düzce-Derdin	32	8.65	46.5	2164	49.1	73.7	3583	75	1545	363	70	50.6	0.06	8020	HCO_3–Na	Canik (1972)
52 (s)	Mudurnu	35	6.60	4.7	18.5	157	50	763	0	35	5.9	37	0.15	1.99	1071	HCO_3–Ca	Şentürk and Didik (1985)
Bilecik area																	
53 (s)	Söğüt-Çalu	38	6.43	28	323	54	55	1172	0	114	36	27	4.1	1.39	1831	HCO_3–Na	Özmutaf (1991)
Yalova area																	
54 (s)	Termal	66	7.60	4.6	248	163	1	45	0	831	93.2	44.5	1.03	3.89	14.31	SO_4–Na	Kartal (1974b)
Bursa area																	
55 (s)	Çekirge-Horhor	39	7.22	3.7	23.5	86	24.4	307	0	95.5	7.6	23	n.a.	1.25	571	HCO_3–Ca	İstanbul Üniversitesi Tıp Fakültesi (1975)
56 (s)	İnegöl-Oylat	40	7.26	4.3	17.9	129	7	194	0	215	8	22	n.a.	0.15	597	SO_4–Ca	İstanbul Üniversitesi Tıp Fakültesi (1975)
57 (s)	Armutlu	77	7.30	25	410	258	42	476	0	832	238	48	n.a.	4.45	2329	SO_4–Na	Ölmez (1982)

[a](w) = Well, (s) = Spring.

[b]If not otherwise specified discharge temperatures for springs, well-head temperatures for wells.

Table 2
Chemical compositions (in ppm) of thermal waters from East and West Anatolia (TDS = Total dissolved solid content, C.B. = Charge balance error in %, n.a. = not analyzed)

Sample no.[a]	Region/area	T (°C)[b]	pH_{lab}	K	Na	Ca	Mg	HCO_3	CO_3	SO_4	Cl	SiO_2	B_T	C.B.	TDS	Water type	Reference
East Anatolia																	
Erzurum area																	
58 (s)	Erzurum	38	6.60	40	1715	51	47	1892	0	0	1776	99	20	0.54	5641	HCO_3–Na	Can et al. (1987)
59 (w)	Pasinler PS-2	42	7.56	74	920	69.3	104	1391	0	5	1059	169	6.15	1.05	3799	HCO_3–Na	Uluşahin and Erduran (1992)
Ağrı area																	
60 (s)	Köprü	53	7.00	58	173	208	71	1141	0	144	151	n.a.	n.a.	1.41	1946	HCO_3–Ca	Kurtman and Başkan (1978)
Tunceli area																	
61 (s)	Hozavit	48	6.60	18.8	1491	30	15.8	2233	0	785	542	99.6	n.a.	0.11	5215	HCO_3–Na	Kurtman and Başkan (1978)
Bingöl area																	
62 (s)	Kös	43.5	6.60	35.2	310	200	19.5	1177	0	227	103	36	6.7	1.79	2115	HCO_3–Na	Erzenoğlu and Didik (1989)
63 (s)	Hacıyan	62	7.20	24.2	707	54	23	1251	0	375	257	74	n.a.	0.53	2765	HCO_3–Na	Kurtman and Başkan (1978)
64 (s)	Kolan	45	6.60	91.5	234	242	99	1366	0	85.5	171	33	n.a.	6.09	2322	HCO_3–Ca	Kurtman and Başkan (1978)
Bitlis area																	
65 (s)	Simek	40	7.90	9.8	78.5	7	9.7	146	0	55.8	44.4	15	n.a.	0.10	366	HCO_3–Na	Kurtman and Başkan (1978)
66 (s)	Çukur	40	7.50	14.7	489	80	79	1610	0	29	70	74	n.a.	5.16	2446	HCO_3–Na	Kurtman and Başkan (1978)
Muş area																	
67 (s)	Bazikan	34	7.80	30.3	251	123	84	1391	0	25	51.3	86	n.a.	0.04	2042	HCO_3–Na	Kurtman and Başkan (1978)
Van area																	
68 (s)	Nemrut Dağı	60	6.90	11.6	330	38.4	12.2	909	0	17.6	42.4	36	n.a.	3.22	1397	HCO_3–Na	Kurtman and Başkan (1978)
69 (s)	Muradiye-Dergezin	37	6.60	15.2	134	69	53.5	763	0	70.6	16.8	40	n.a.	1.37	1162	HCO_3–Na	Kurtman and Başkan (1978)
70 (s)	Erciş-Zilan-Hasanaptal	65	6.40	88	850	150	12	1000	0	203	950	80	40	0.29	3377	HCO_3–Na	Ölmez and Güner (1989)
71 (s)	Erciş-Zilan-Ganisipi	78	6.40	68	750	160	8	875	0	540	750	90	34	4.17	3275	HCO_3–Na	Ölmez and Güner (1989)
Diyarbakır area																	
72 (w)	Çermik ÇER-1	51	7.60	22.8	205	36	13	512	0	17	107	62	1.4	2.46	977	HCO_3–Na	Erzenoğlu and Özeke (1990)
Siirt area																	
73 (s)	Billurus	33	6.73	14.8	153	300	72	400	0	624	198	26	0.7	5.28	1792	SO_4–Ca	Can and Ünlü (1982)
74 (s)	Hista Çermiği	63	7.30	22	70	356	54	201	0	1013	93	110	0.3	2.21	1920	SO_4–Ca	Yücel (1989)
75 (s)	Germiab	40	7.40	61.5	873	151	26.4	647	0	1674	115	20	n.a.	0.53	3568	SO_4–Na	Kurtman and Başkan (1978)
Urfa area																	
76 (s)	Yardımcı-Karaali	29.5	6.50	3	40	50	18	195	0	115		12	0.1	0.72	444	HCO_3–Ca	Uzel and Kalkan (1992)
Hakkari area																	
77 (s)	Killogon	41	6.90	26	1057	167	71.7	2196	0	268	691	75	n.a.	0.16	4552	HCO_3–Na	Kurtman and Başkan (1978)
West Anatolia																	
İzmir area																	
78 (w)	Agamemnun AG-1	100	8.70	29	380	11.8	6.9	567	6	174	192	145	2.8	0.31	1516	HCO_3–Na	Şamilgil (1964)
79 (w)	Seferihisar-Cumalı SH-2	150[c]	6.61	577	6300	760	190	256	0	528	11159	24	12.4	1.83	19817	Cl–Na	Eşder et al. (1983)
80 (w)	Doğanbey Tuzlası DT-1	100	n.a.	680	7100	740	240	223	0	623	12500	90	1.9	1.80	22198	Cl–Na	Eşder et al. (1988)
81 (w)	Çeşme Çş-1	56	7.40	388	10075	1551	609	153	0	2981	20431	47	5.4	5.37	36240	Cl–Na	Ölmez (1976b)
82 (s)	Aliağa-Ilıcaburun	56	6.10	220	6350	741	720	830	0	1290	12000	45	14	0.13	22213	Cl–Na	Eşder et al. (1991)
83 (w)	Bergama-Dübek D-1	60	8.70	3.6	360	16	1.2	370	18	446	35	100	n.a.	0.90	1350	SO_4–Na	Yılmazer (1986)

84 (s)	Dikili-Kaynarca	80	7.90	35	540	25	3	540	0	705	71	175	5.5	0.63	2100	SO_4–Na	Yılmazer (1986)
85 (s)	Dikili-Kocaoba	70	8.65	11	310	118	6.1	150	18	790	43	80	0.4	1.39	1527	SO_4–Na	Yılmazer (1986)
86 (w)	Balçova B-1	110[c]	7.90	16.8	16.6	81.4	72	507	0	102	39.7	n.a.	1.5	1.83	837	HCO_3–Ca	Yılmazer and Sünger (1989)
Kütahya area																	
87 (w)	Simav-Eynal EY-3	75	9.61	39	480	2.8	< 1	409	78	493	71	97	4.5	0.96	1675	SO_4–Na	Erişen et al. (1989)
88 (w)	Simav-Çitgöl Ç-3	83	7.00	44	340	34	5.3	573	0	376	57	151	4.2	2.15	1585	HCO_3–Na	Erişen and Yıldırım (1986)
89 (w)	Simav-Naşa N-1	43.5	7.60	7	126	56	13	500	0	82	15	28	2	4.07	829	HCO_3–Na	Güven and Taşkın (1985)
90 (s)	Gediz-Abide Resort	74	7.50	80	640	96	63	790	0	990	97	71	7.6	4.64	2836	SO_4–Na	Uluşahin and Tamgaç (1994)
91 (s)	Hisarcık-Karandere	38	6.72	3.9	11.2	365	53.5	342	0	828	9.5	24	0.65	0.22	1638	SO_4–Ca	Didik (1994)
92 (s)	Emet-Yeşil Resort	42.5	7.44	0.7	11	84	24	275	0	115	12	28	< 0.1	4.11	550	HCO_3–Ca	Uluşahin (1993a)
93 (w)	Yoncalı YON-2	41.5	7.12	2.4	20	120	41	400	0	160	9	32	< 0.1	0.76	785	HCO_3–Ca	Öktü and Tamgaç (1990)
Denizli area																	
94 (w)	Kızıldere KD-6	201[c]	9.42	145	1264	3.1	0.1	2126	258	705	98	430	28.8	1.74	5059	HCO_3–Na	Alpan (1975)
95 (w)	Kızıldere KD-1	200[c]	9.57	135	1280	2.5	0.2	1860	318	770	117	325	26.2	0.99	4838	HCO_3–Na	Ellis and Mahon (1977)
96 (w)	Tekehamamı TK-1	78	6.30	64	530	210	53	1090	0	1070	90	190	n.a.	3.84	3297	HCO_3–Na	Uysallı and Keskin (1971)
97 (s)	Pamukkale	59	7.70	22	130	530	110	1415	0	830	35	43	2.7	0.34	3118	HCO_3–Ca	Şimşek (1984)
98 (s)	Kızıldere-Sarayköy	100	8.00	112	1300	13	1.2	2196	0	812	111	236	22.4	3.51	4804	HCO_3–Na	Şimşek (1984)
99 (s)	Buldan-Kamara	57	6.70	86	580	290	42	1830	0	720	51	120	5.7	1.16	3725	HCO_3–Na	Şimşek (1984)
100 (s)	Çardak-Beylerli	40	6.97	5	95	266	84	366	0	787	86	33	0.1	0.71	1722	SO_4–Ca	Erzenoğlu (1987)
Manisa area																	
101 (w)	Salihli-Kurşunlu SK-2	96	7.90	50	410	18	8.5	1251	5	70	74	138	3.3	7.49	2056	HCO_3–Na	Uluşahin (1993b)
102 (s)	Salihli-Köprübaşı	51	7.20	108	1020	60	24	2471	0	397	127	150	11	0.26	4370	HCO_3–Na	Güner (1993)
Muğla area																	
103 (s)	Köyceğiz	41	6.83	290	8840	962	888	317	0	2748	16400	30	4	1.17	30479	Cl–Na	Şentürk and Tamgaç (1992)
Çanakkale area																	
104 (w)	Kestanbol K-1	76	6.00	630	5100	800	54	317	0	170	9700	86	11	0.03	16868	Cl–Na	Ölmez (1976a)
105 (w)	Tuzla T-1	171[c]	7.40	1280	16640	2920	71	84	0	150	33600	94	22.8	2.38	54884	Cl–Na	Union Oil, unpublished data
Aydın area																	
106 (w)	Germencik-ÖB-1	203[c]	7.23	81	1625	3.6	2.2	1263	0	45	1714	205	63	2.15	5008	Cl–Na	Karamanderesi et al. (1982)
107 (w)	Germencik-ÖB-2	218[c]	9.11	210	1801	< 2	0.5	1598	96	51	1848	450	69	0.67	6132	Cl–Na	Karamanderesi et al. (1982)
108 (w)	Germencik-ÖB-3	232[c]	8.70	172	1770	1.6	< 1	1342	204	72	1819	220	68	0.11	5678	Cl–Na	Karamanderesi et al. (1982)
109 (s)	Ömerbeyli	61	6.98	93	1243	48	4.4	2135	0	35	1059	230	69	5.14	4916	HCO_3–Na	Yüksel (1971)
Afyon area																	
110 (w)	Ömer-Gecek AF-4	92	6.70	158	1750	78.8	10	1294	0	537	1862	198	10.0	0.02	5899	Cl–Na	Mutlu (1996)
111 (w)	Ömer-Gecek R-260	87	7.10	157	1700	106	19	1350	0	514	1842	170	9.6	0.01	5869	Cl–Na	Mutlu (1996)

Table 2 (continued)

Sample no.[a]	Region/area	T (°C)[b]	pH_{lab}	K	Na	Ca	Mg	HCO_3	CO_3	SO_4	Cl	SiO_2	B_T	C.B.	TDS	Water type	Reference
West Anatolia																	
Afyon area																	
112 (w)	Gazlıgöl G-3	64	7.05	88	1088	40	15.6	2934	0	15.8	157	61	14.8	0.02	4416	HCO_3–Na	Mutlu (1996)
113 (w)	Sandıklı SND-1	69	6.85	35	222	168	31.3	555	0	486	123	71	0.6	2.65	1692	HCO_3–Na	Mutlu (1996)
114 (w)	Heybeli HYW-1	56	6.40	58.7	500	347	68.8	1525	0	848	195	43	3	2.03	3589	HCO_3–Na	Mutlu (1996)
115 (w)	Çay-Karaburun KRW	38	6.20	31.3	240	194	41.6	1238	0	166	61	36	0.9	2.25	2009	HCO_3–Na	Mutlu (1996)
Balıkesir area																	
116 (w)	Edremit-Güre Güre-1	40	9.12	6.9	272	31	18	198	12	479	60	31	1.5	0.94	1109	SO_4–Na	Erzenoğlu (1985)
117 (s)	Manyas-Kızıkköy	50	6.85	16.8	160	133	10	476	0	108	213	50	n.a.	3.92	1167	HCO_3–Na	Ölmez and Erzenoğlu (1995)
118 (w)	Gönen G-4	82	7.30	24	460	46	2.2	354	0	473	262	68	7.6	0.09	1697	SO_4–Na	Erzenoğlu and Uluşahin (1990)
119 (w)	Susurluk BK-1	64	9.00	17	580	44	22	390	18	151	709	36	8	0.80	1976	Cl–Na	Özçelik and Özbayrak (1985)
120 (w)	Pamukçu P-2	58	8.15	16	361	26	1	72	1	444	242	102	14	0.54	1279	SO_4–Na	Ölmez and Okut (1989)

[a](w) = Well. (s) = Spring.

[b]If not otherwise specified discharge temperatures for springs, well-head temperatures for wells.

[c]Bottom-hole temperatures.

MTA laboratories. Na and K concentrations were determined by flame photometry and atomic absorption spectrometry. Titration methods were used for Ca, Mg, Cl, HCO_3 and CO_3 analyses. SO_4 was analyzed either by a gravimetric method or by ion chromatography. SiO_2 was analyzed by atomic absorption spectrometry. Finally, B concentrations were obtained by colour spectrophotometry.

From a number of published or unpublished data reporting the chemical composition of a single geothermal site, the one with the lowest charge–balance error was selected as the most reliable composition. Charge–balance error of the waters, except for a few samples, is less than 5% which is within the limits of acceptability. A total of 120 water samples from 42 different geothermal areas were selected. Based on their distribution with respect to the tectonically different regions of Turkey, the waters are grouped into four as Central Anatolian, North Anatolian, East Anatolian and West Anatolian waters.

4. Chemistry

The results of chemical analysis of the water samples are given in Tables 1 and 2 together with laboratory pH measurements and the in situ temperatures (discharge temperatures for springs and well-head or bottom-hole temperatures for well waters). The distribution of the geothermal areas referred to in Tables 1 and 2 is shown in Fig. 1. The chemical compositions are assessed through the use of Cl–SO_4–HCO_3 ternary diagram introduced in Fig. 2.

4.1. Central Anatolian waters

Neogene thick volcanosedimentary series overlying the Mesozoic carbonates and the pre-Mesozoic metamorphics, and the young volcanoes with historical eruptions, are the characteristic geologic features of Central Anatolia where the compressional regime in East Anatolia is transferred into the extensional regime in West Anatolia. The major reservoir rocks of Central Anatolia are comprised by the Neogene volcanosedimentary rocks (e.g., Kızılcahamam-Ankara area), the pre-Mesozoic metamorphics of the Kırşehir Massif (e.g., Terme-Kırşehir area) and the Mesozoic carbonates (e.g., Çermik-Sivas area). The tuffs and the impermeable sedimentary rocks (claystone, marl) of the volcanosedimentary series act as cap rocks of the geothermal system (Şimşek and Demir, 1991; Erişen et al., 1996). The chemical compositions of a total of 27 water samples from Central Anatolia (17 samples from drilled wells and the rest from natural springs) are shown in Table 1. The temperature of waters ranges from 28 to 93°C, the latter being recorded as a well-head temperature in the Kozaklı-Nevşehir area. The waters have pH values ranging from 6.10 to 9.63 and TDS values ranging from 359 to 7982 ppm. They are dominantly Ca–HCO_3, Na–HCO_3 and, to a certain extent, Na–Cl type waters, although a few display Na– and Ca–SO_4 rich characteristics. The bicarbonate-rich waters plot in the peripheral waters field of the Cl–SO_4–HCO_3 ternary diagram (Fig. 2). These waters probably acquire their composition in the presence of high P_{CO2} (with the CO_2 rising from the deep levels and inducing the bicarbonate nature) through the dissolution—at shallower depths—of Na^+–Ca^{2+} ions from the silicic rocks through which they circulate. Chloride-rich waters are generally high-temperature waters, of which the ones from Yerköy-Yozgat and Ziga-Aksaray areas plot in the mature waters field (Fig. 2) suggesting the presence of connate fossil waters in the lithologies through which the deep hot waters circulate. The sulphate-rich waters, on the other hand, plot in the field of steam-heated or volcanic waters. The fact that Central Anatolia is a region where the volcanic eruptions continued even in historical times appears, at a first sight, to support a steam-heated nature for these group of waters which owe their nature probably to H_2S emanations from a still cooling magma chamber, with the oxidation of H_2S resulting in the formation of elemental sulphur and subsequently in the formation of SO_4. However, an examination of the data in Table 1 reveals that these sulphate-rich waters have *B* concentrations considerably below those expected from a volcanic origin. Therefore, some of these waters owe their nature probably to an interaction with sulphate-bearing (gypsum) layers the presence of which is reported from Cihanbeyli area (Canik, 1988). In fact, the Ca and SO_4 concentrations reported for sample no. 26 (Cihanbeyli-Yapalı-Konya) show a stoichiometric proportion supporting the idea of leaching from a gypsum stratum. On the other

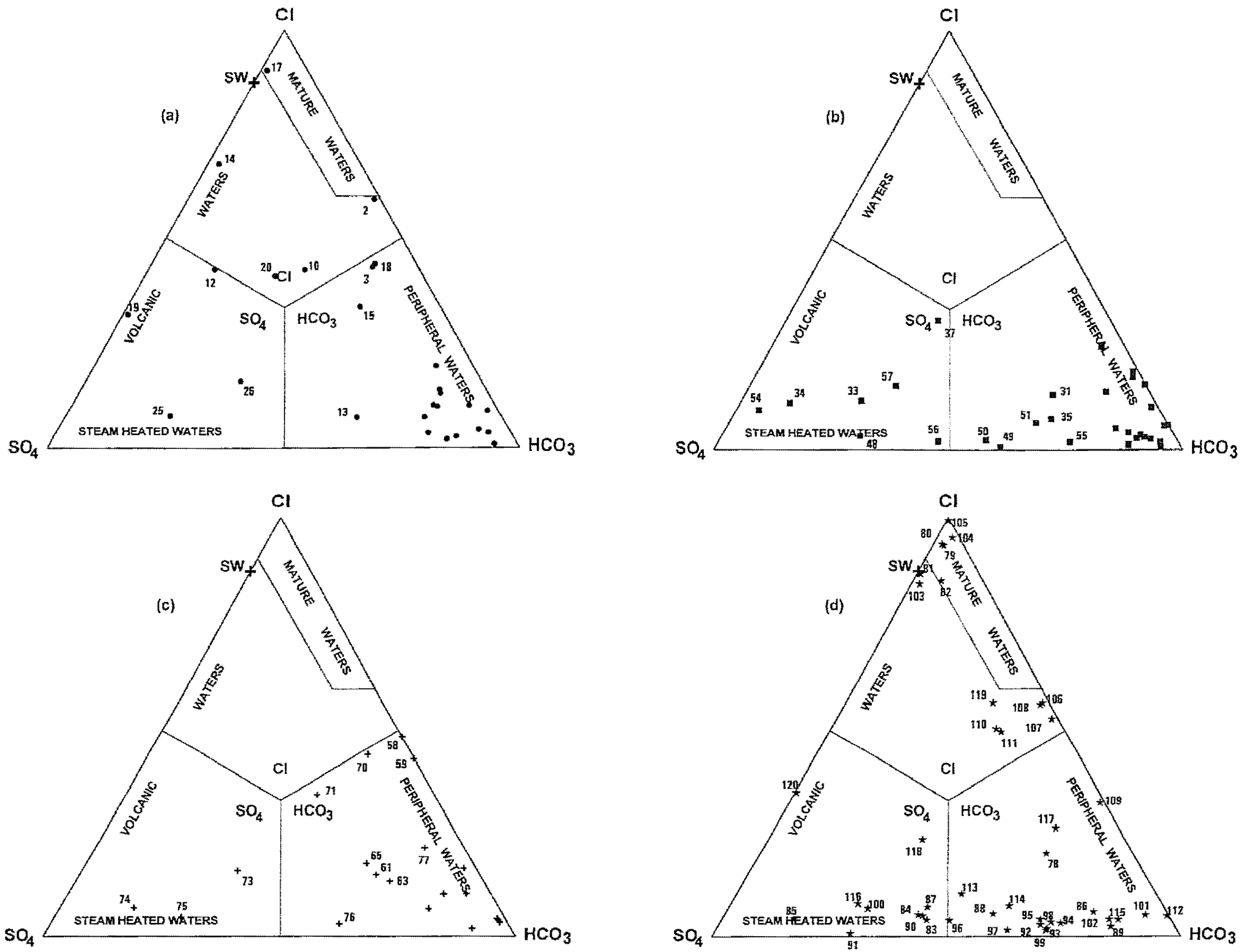

Fig. 2. Cl–SO_4–HCO_3 ternary diagram for the thermal waters (fields from Giggenbach, 1988; units are in mg/kg). (a) Central Anatolian waters, (b) North Anatolian waters, (c) East Anatolian waters, (d) West Anatolian waters.

hand, for Ca–SO_4 water of Beyşehir (sample no. 25) and Na–SO_4 waters of Kırşehir and Niğde areas (sample nos. 12 and 19, respectively), oxidation of H_2S of organic origin can be suspected.

4.2. North Anatolian waters

The important geothermal areas of North Anatolia are located along one of the major neotectonic structures (seismically active zones) of Turkey, namely the NAF. Mesozoic aged recrystallized limestones and pre-Mesozoic metamorphics form the major reservoir rocks of the region, accompanied in places by Mesozoic to Cenozoic granitic rocks (e.g., Rize area) and Neogene volcanics (e.g., Yalova area). The hot springs emerge from the fault and fracture zones developed in relation to the movement along the NAF. The chemical compositions of a total of 30 water samples from North Anatolia (11 samples from drilled wells and the rest from natural springs) are given in Table 1. The highest temperature recorded in a drilled well (in the Sakarya area) is 82°C. The pH values range from 6.30 to 9.72, suggesting a neutral to alkaline character. The TDS content is within the range of 250 to 10384 ppm. The waters are dominantly Na– and Ca–HCO_3 waters, although some display Na– and Ca–SO_4 rich nature, plotting in the peripheral waters and steam-heated fields of the ternary Cl–SO_4–HCO_3 diagram (Fig. 2). The young volcanism confined to the pull-apart basins associated with the NAF is probably responsible for the steam emanations that heat the shallow circulating waters of the region, as well as for the rise of CO_2 and H_2S gases that gave the bicarbonate and sulphate rich character to the waters in which they dissolve. This can in fact be the case for the areas located along the NAF (e.g., Tokat, Çankırı, Erzincan, Düzce-Bolu) where high *B* concentrations (> 10 ppm) accompany the SO_4 or HCO_3 enrichment. Although the *B* data are lacking, the SO_4 enrichment in the waters of Bursa area is also likely to have a volcanic origin as the area is located at the western extension of the NAF. The SO_4-rich nature of Çamlıhemşin-Rize and Fatsa-Ordu areas (which are rather far from the NAF), on the other hand, may be the result of oxidation of massive sulphide deposits widespread along the coast of the eastern half of the North Anatolian region (e.g., Aslaner, 1977; Çağatay, 1977, 1980). Where not associated with high B contents, the bicarbonate-rich nature of the waters is likely to be derived from the dissolution of the carbonate rocks which act as reservoirs for most of the waters.

4.3. East Anatolian waters

East Anatolian contractional province is characterized by E–W-trending folds, manifestation of the N–S shortening, and a widespread volcanism with several young volcanoes emitting gasses and aligned in NE–SW direction. The important geothermal areas of the region are concentrated around these young volcanoes (e.g., Ağrı, Van, Muş, Bitlis areas) or close to the Karlıova junction (e.g., Bingöl area). The pre-Mesozoic metamorphics (gneisses, schists and marbles), Mesozoic–Cenozoic limestones and the basalts of the young volcanics are the main reservoir rocks of the geothermal systems. The chemical compositions of a total of 20 water samples from the region (only two being from drilled wells) are presented in Table 1. The temperature of the waters ranges from 29.5 to 78°C, the pH values from 6.40 to 7.90, and the TDS values from 366 to 5641 ppm. Except the Na–Ca–SO_4 type waters of the Siirt area, all the waters are Na–Ca–HCO_3 type shallow circulating peripheral waters (Fig. 2) acquired their composition from the deep rising CO_2 gas. The CO_2 could have been derived either from the metamorphic processes in the pre-Mesozoic basement, or the dissolution of carbonate rocks, or from the volcanism-related emanations. The Siirt waters, being somewhat remote from the volcanoes, probably gained their SO_4-rich nature through the leaching of this ion from the gypsum layers present in the Cenozoic sedimentary units of the area (Erişen et al., 1996).

4.4. West Anatolian waters

West Anatolian extensional province is characterized by a series of grabens, widespread volcanics of Neogene age (Quaternary volcanism being restricted only to a small area around Kula), crustal thinning (Mc Kenzie, 1978; Makris, 1985) and high heat flow values above the world average (Cermac and Hurtig, 1979; Tezcan, 1979). The hot springs are all aligned

Table 3
Geothermometry results for the thermal waters from Turkey

Region	Sample no.	Disc. T (°C)	Na–K[a]	Na–K–Ca[b]	Na–K–Ca Mg correction[c]	K–Mg[a]	Quartz[d]	Chalcedony[e]	Cristobalite[e]	Amorphous silica[e]
Central Anatolia	1	31	375	106	79	80	152	127	101	30
	2	48	110	78	n.a.	58	101	71	50	–
	3	65	351	288	n.a.	106	170	146	119	46
	4	73.8	214	184	*112*	*114*	*125*	96	74	6
	5	42.5	232	101	92	76	83	51	32	–
	6	30	304	110	n.a.	71	149	123	98	27
	7	44	292	38	n.a.	45	76	44	25	–
	8	39	247	*49*	n.a.	*50*	104	74	*53*	–
	9	28	195	30	n.a.	35	38	7	–	–
	10	34.5	95	*58*	n.a.	*60*	103	73	*52*	–
	11	45	204	*54*	n.a.	*55*	89	*57*	38	–
	12	70	167	113	*94*	*80*	125	*96*	74	6
	13	50	254	46	n.a.	59	96	66	46	–
	14	75	158	*92*	78	*120*	*122*	93	71	–
	15	46	145	60	n.a.	50	80	48	30	–
	16	30	239	*61*	n.a.	*55*	89	*57*	38	–
	17	47	149	112	n.a.	89	80	48	30	–
	18	12	141	130	n.a.	63	123	95	72	4
	19	44.5	131	55	n.a.	109	96	66	46	–
	20	93	179	88	n.a.	76	130	102	79	10
	21	40	273	22	n.a.	32	74	42	24	–
	22	55	186	117	n.a.	48	147	121	96	25
	23	35	201	34	n.a.	36	64	31	14	–
	24	42	274	*56*	n.a.	*53*	80	*48*	30	–
	25	35	168	–	n.a.	17	83	51	32	–
	26	35	217	*70*	n.a.	*57*	99	*69*	49	–
	27	45	289	*87*	n.a.	*72*	*72*	40	22	–
North Anatolia	28	42.5	121	20	n.a.	16	74	42	24	–
	29	37	246	36	n.a.	36	60	28	11	–
	30	40.5	171	69	n.a.	51	64	31	14	–
	31	30	187	39	n.a.	32	47	15	–	–
	32	37	225	*53*	n.a.	*43*	74	*42*	24	–
	33	50	88	64	n.a.	53	96	66	46	–
	34	33	113	38	n.a.	39	101	71	50	–
	35	14	159	94	90	65	98	68	48	–
	36	46.5	179	102	*88*	*72*	106	*76*	55	–
	37	53.5	163	130	*110*	*94*	135	*108*	84	15
	38	38	211	45	n.a.	26	57	25	9	–
	39	53	192	120	*69*	*72*	*85*	54	35	–
	40	26.5	231	129	96	95	68	36	19	–
	41	30	229	230	149	155	79	47	29	–
	42	24.5	161	69	n.a.	14	51	19	3	–
	43	20	259	156	45	91	105	75	54	–
	44	31	131	84	n.a.	31	172	149	121	48
	45	82	192	135	*108*	*98*	155	130	*104*	33
	46	20.5	168	158	70	98	71	39	21	–
	47	40	262	32	n.a.	42	83	51	32	–
	48	18.5	130	62	n.a.	33	57	25	9	–
	49	46	337	*50*	n.a.	*59*	85	*54*	35	–
	50	45	354	*48*	n.a.	*59*	*64*	31	14	–

Table 3 (continued)

Region	Sample no.	Disc. T (°C)	Na–K[a]	Na–K–Ca[b]	Na–K–Ca Mg correction[c]	K–Mg[a]	Quartz[d]	Chalcedony[e]	Cristobalite[e]	Amorphous silica[e]
	51	32	134	139	n.a.	80	118	90	68	–
	52	35	320	22	n.a.	35	89	57	38	–
	53	38	221	130	n.a.	71	76	44	25	–
	54	66	126	42	n.a.	76	97	66	46	–
	55	39	271	27	n.a.	37	69	37	19	–
	56	40	314	22	n.a.	53	67	35	18	–
	57	77	196	88	n.a.	72	100	70	50	–
East Anatolia	58	38	138	139	n.a.	82	137	110	86	16
	59	42	216	186	n.a.	87	169	146	119	46
	60	53	352	114	77	86	*	*	*	*
	61	48	108	115	68	77	137	110	86	17
	62	43.5	243	*103*	n.a.	*90*	*88*	56	37	–
	63	62	159	135	*65*	*78*	121	93	*70*	3
	64	45	371	133	66	94	84	52	33	–
	65	40	251	123	n.a.	67	53	21	4	–
	66	40	152	99	n.a.	53	121	93	70	3
	67	34	248	107	n.a.	68	129	101	78	10
	68	60	161	104	84	69	88	56	37	–
	69	37	243	89	n.a.	58	92	61	42	–
	70	65	235	166	*136*	*123*	*125*	97	74	6
	71	78	225	150	140	121	132	104	81	12
	72	51	241	126	*76*	*84*	112	*83*	62	–
	73	33	230	58	n.a.	54	74	42	24	–
	74	63	344	59	n.a.	66	143	116	92	22
	75	40	206	149	98	101	64	31	14	–
	76	29.5	210	35	n.a.	36	44	13	–	–
	77	41	141	112	70	67	122	93	71	3
West Anatolia	78	100	212	186	74	99	159	135	109	37
	79	150	225	210	99	139	71	39	21	–
	80	100	229	199	84	140	132	104	81	12
	81	56	166	164	59	108	99	69	49	–
	82	56	160	157	n.a.	91	97	67	47	–
	83	60	98	84	n.a.	68	137	110	87	17
	84	80	200	173	*134*	*116*	172	149	*121*	48
	85	70	161	*75*	n.a.	*75*	125	97	*74*	6
	86	110	524	265	n.a.	57	*	*	*	*
	87	75	216	207	171	136	136	109	85	15
	88	83	254	166	*119*	*114*	162	138	*111*	39
	89	43.5	189	67	n.a.	57	77	45	27	–
	90	74	251	172	46	96	119	90	68	1
	91	38	356	2	n.a.	31	71	39	21	–
	92	42.5	199	–	n.a.	9	77	45	27	–
	93	41.5	247	11	n.a.	25	83	51	32	–
	94	201	*244*	*251*	*217*	*238*	*242*	229	193	114
	95	200	*237*	*247*	*239*	*217*	*217*	201	168	91
	96	78	248	133	82	92	177	155	127	53
	97	59	278	57	n.a.	58	95	64	45	–
	98	100	221	*193*	*189*	*171*	*192*	172	142	67
	99	57	266	138	*102*	*104*	148	122	97	26
	100	40	186	28	n.a.	31	84	52	33	–
	101	96	249	200	92	*111*	156	132	*106*	34

Table 3 (continued)

Region	Sample no.	Disc. T (°C)	Na–K[a]	Na–K–Ca[b]	Na–K–Ca Mg correction[c]	K–Mg[a]	Quartz[d]	Chalcedony[e]	Cristobalite[e]	Amorphous silica[e]
	102	51	237	208	90	118	161	137	111	39
	103	41	157	158	n.a.	95	80	48	30	–
	104	76	250	224	178	164	129	101	78	10
	105	171	*212*	*205*	*196*	187	134	107	83	14
	106	203	182	200	162	148	182	161	132	58
	107	218	*245*	266	n.a.	*217*	*246*	234	197	118
	108	232	230	255	251	192	187	166	137	63
	109	61	210	193	161	141	190	170	140	66
	110	92	224	206	*155*	*145*	180	*158*	130	56
	111	87	226	204	129	134	170	146	119	46
	112	64	216	197	94	119	112	82	61	–
	113	69	271	103	*97*	*84*	119	*90*	68	1
	114	56	245	115	*91*	*87*	*95*	64	45	–
	115	38	254	*97*	*96*	*77*	*88*	56	37	–
	116	40	142	*88*	*82*	53	*81*	49	31	–
	117	50	236	*79*	n.a.	*80*	102	*72*	51	–
	118	82	185	133	n.a.	109	117	88	66	–
	119	64	150	123	63	71	88	56	37	–
	120	58	175	128	n.a.	109	138	112	88	18

[a]Giggenbach (1988); [b]Fournier and Truesdell (1973); [c]Fournier and Potter (1979); [d]Fournier and Potter (1982); [e]Fournier (1977); n.a. = not applicable; – = computed geothermometer is less than zero; * = no silica analysis. Italic characters: consistent estimates for the respective sample (see text for further explanation).

along the faults bordering the major grabens. The reservoir rocks of the region are pre-Mesozoic aged metamorphics (marbles, genisses and quartzites) of the Menderes and Kazdağ Massifs, Mesozoic limestones, and the Neogene volcanosedimentary units. The chemical compositions of a total of 43 water samples from West Anatolia are reported in Table 2; 29 of these samples are from drilled wells. The temperature of the spring waters reaches up to 100°C; the highest bottom-hole temperature recorded in drilled wells is 232°C (Ömerbeyli-Germencik-Aydın area). The waters are weakly acidic to alkaline with pH values ranging from 6.10 to 9.61, and have TDS contents between 550 and 54884 ppm. The majority of waters are either Na–HCO_3 or Na–Cl in nature, although SO_4-type waters are also present. The chloride-rich waters are characteristic for the coastal areas (Çeşme, Seferihisar, Doğanbey-İzmir; Kestanbol, Tuzla-Çanakkale; Köyceğiz-Muğla) and their compositions (with Cl/Na ratio similar to that of seawater in Fig. 2) suggest a possible seawater intrusion into the reservoir. It is important to note at this stage that some of the waters from the inland areas, such as Balıkesir and Afyon, also have Na–Cl nature which can not be attributed to seawater intrusion but probably results from the involvement of connate fossil waters. The two most important geothermal areas of West Anatolia, namely the Kızıldere-Denizli and Ömerbeyli-Germencik-Aydın, are characterized by Na–HCO_3 and Na–Cl–HCO_3 enrichment, respectively (Table 2). Considering the distance from the coast, the Cl-enrichment in the Ömerbeyli-Germencik-Aydın area is probably due to the presence of connate fossil waters in the rocks. The HCO_3 nature of the Kızıldere-Denizli area is a consequence of an interaction between waters and carbonate rocks inside the geothermal reservoir. However, the Na– (instead of Ca–) signature of the waters requires a geothermal system characterized by the presence of CO_2 that produces alteration of siliceous material in the system in order to acquire Na. Ca–HCO_3 nature is characteristic of waters from the Pamukkale-Denizli area famous for its spectacular travertine deposits. SO_4-rich waters of Dikili-İzmir, Simav-Kütahya, Gediz-Kütahya and Balıkesir (Table 2) owe their compositions probably to the oxidation of pyrite common in the hydrothermal mineralization observed in these areas (Erler and Larson, 1992; Larson and Erler, 1993).

5. Geothermometry

In order to assess the more promising areas from the viewpoint of geothermal energy potential, reservoir temperatures of the respective areas are assessed through the use of chemical (silica and cation) geothermometers. The silica geothermometers applied to the waters include quartz (Fournier and Potter, 1982), and cristobalite, chalcedony and amorphous silica (Fournier, 1977) geothermometers. The cation geothermometers include Na–K (Giggenbach, 1988), Na–K–Ca (Fournier and Truesdell, 1973), Mg-corrected Na–K–Ca (Fournier and Potter, 1979) and K–Mg (Giggenbach, 1988) geothermometers. The results of geothermometry applications are presented in Table 3.

Regarding the silica geothermometers, amorphous silica and cristobalite (controlling the silica solubility at low temperatures below 150°C; Fournier, 1977) yield temperatures which are below the measured temperatures for most waters suggesting that these geothermometers are not applicable to the geothermal systems in Turkey. The quartz and chalcedony geothermometers (applicable to systems with higher temperatures above 150°C; Fournier, 1977) give results differing from each other in the range of about ±30°C, with the estimates obtained from the latter being always lower than that obtained from the former. Considering the fact that the temperatures of the springs are often much lower than 100°C suggesting dilution, and that the process of dilution can seriously affect the silica geothermometers, the estimates obtained here can not be regarded as reliable. However, since the measured bottom-hole temperatures reach 232°C, and since quartz is the phase controlling silica solubility at temperatures above 180°C (Fournier, 1991), quartz geothermometry seems to be applicable to the West Anatolian region, although it should be used with caution especially for spring waters with temperatures below 100°C.

Of the cation geothermometers applied to thermal waters, Na–K geothermometer gives, for most of the waters, unexpectedly high temperatures ranging up to about 400°C (sample no. 1) to 500°C (sample no. 86). Although the use of ratios, rather than absolute abundances of the ions, makes the Na–K geothermometer less sensitive to the secondary processes (e.g., mixing and boiling) that may change the original reservoir characteristics of waters, this geothermometer may yield erroneous results when applied to low temperature spring waters. This is because at low temperatures Na/K ratio of waters is governed by leaching rather than chemical equilibrium. In fact, most of the anomalously high temperatures in Table 3 belong to the spring waters with low temperatures. The waters from the deep drilled wells (with higher temperatures more representative of reservoir conditions) yield generally more reasonable temperatures usually around 200–250°C (e.g., sample nos. 94, 95, 105, 106 and 107 from West Anatolia), except sample no. 86 (from Balçova-İzmir-West Anatolia) which has a bottom-hole temperature of 110°C and a Na–K temperature of 524°C. The anomalously high Na–K temperature of this sample appears to have resulted from its high Ca content (Table 2) as the Na–K geothermometer is reported to yield unreasonably high temperature estimates for waters having high Ca contents (Fournier and Truesdell, 1973).

Na–K–Ca geothermometer, developed to eliminate the effects of high Ca (Fournier and Truesdell, 1973), yields temperature estimates lower than those obtained by Na–K geothermometer. However, for some samples (e.g., sample nos. 25, 91, 92, 93), Na–K–Ca temperatures are anomalously low (lower than discharge temperatures) suggesting that these estimates reflect the high Ca/Na ratio of the leachate (as the solubility of Ca increases with decreasing temperature), rather than the equilibrium conditions at depth.

Mg-corrected Na–K–Ca geothermometer (proposed by Fournier and Potter (1979) for waters with high Mg contents) is not applicable to most of the waters as the correction factor is beyond the limits of calibration suggesting that the Mg contents of waters are not likely to affect the Na–K–Ca temperatures.

K–Mg geothermometer gives low temperatures which are similar to and in some cases lower than that of the discharge. This is probably due to the increasing solubility of Mg with decreasing temperature and its leaching from rocks during the ascent of waters to the surface; the Mg contents higher than those at reservoir conditions thus result in underestimated temperatures as the geothermometry equation is based on the use of K/√Mg ratios. In other words, since Mg reflects equilibrium at shallower levels, K–Mg geothermometer is not a good indicator of deep temperatures. A combination of Na–K and K–Mg geothermometers, proposed by Giggenbach (1988) as Na/1000–K/100–√Mg ternary diagram, is presented in Fig. 3 and works better for a more reliable estimate of reservoir temperatures. The mature waters plotting in the partially equilibrated field or close to the full equilibrium line in Fig. 3 suggest a maximum of about 250°C for the reservoir temperatures.

Overall, it is not possible to select a single geothermometer as the best representative of the reservoir temperature for a specific region. Therefore, the assessment of possible reservoir temperatures is made here considering only the samples for which consistent results are obtained from at least three geothermometers (italic characters in Table 3). In this respect, taking the maximum values of the ranges yielded by the so-selected geothermometers, the likely reservoir temperatures for the regions are estimated as follows: Central Anatolia, 125°C; North Anatolia, 110°C; East Anatolia, 136°C; and West Anatolia, 251°C. The fact that the highest reservoir temperature is obtained from West Anatolia may suggest that the waters in this region are less affected by the secondary processes (e.g., mixing and boiling) which is in fact reflected in the Na/1000–K/100–√Mg ternary diagram (Fig. 3) of Giggenbach (1988)

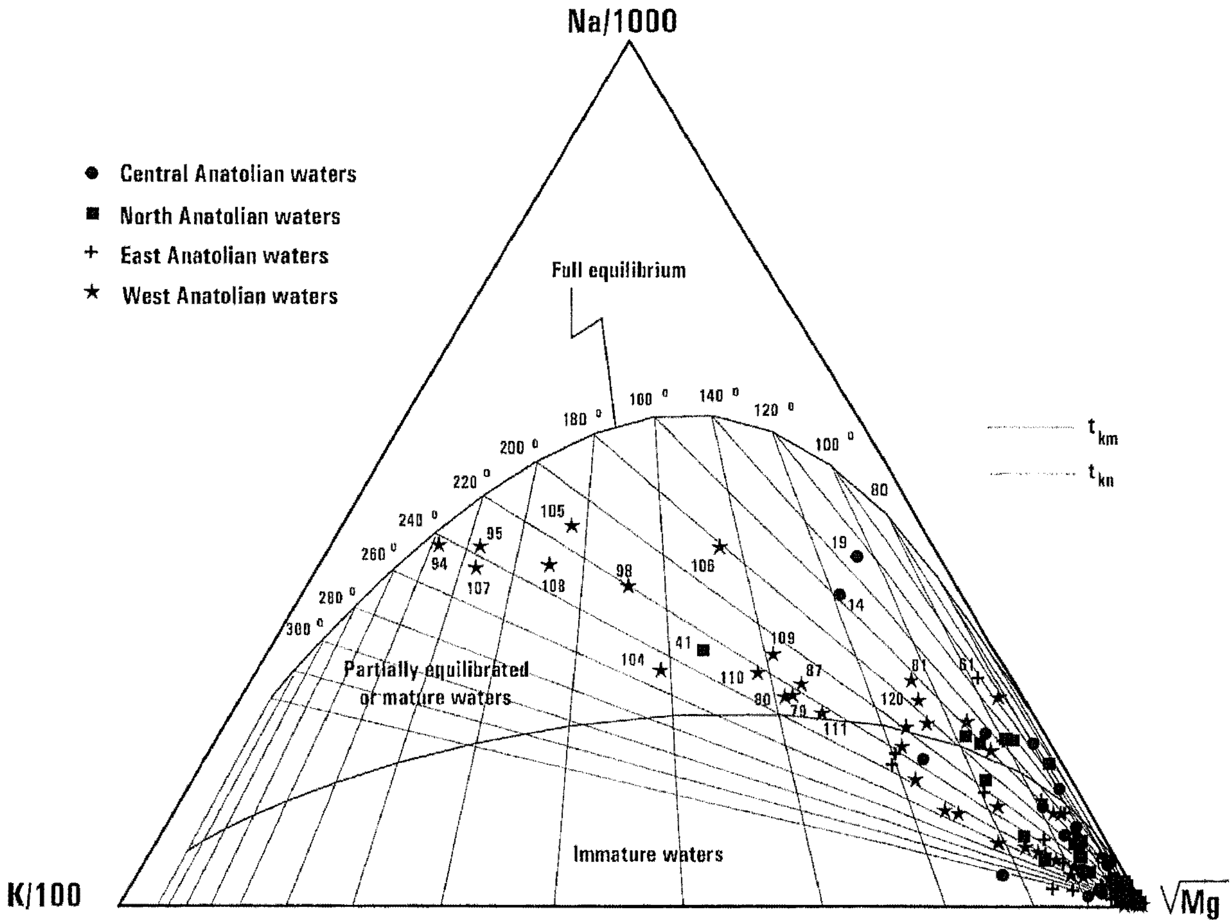

Fig. 3. Na/1000–K/100–√Mg ternary diagram (Giggenbach, 1988) for the thermal waters (in mg/kg).

where most of the West Anatolian waters plot in the partially equilibrated waters field, even some samples plotting close to the full equilibrium line (sample no. 94). Regarding the other regions, on the other hand, except a few plotting in the partially equilibrated waters field, almost all the samples are immature waters. In this respect, cation geothermometers should be used with caution particularly for Central, North and East Anatolian regions. This caution also applies to any spring of moderate or low temperature.

6. Scaling problems for utilization

Calcite scaling is a serious problem in the utilization of thermal waters especially for those with high CO_2 as the loss of CO_2 is the cause of the water becoming supersaturated. In this section, the calcite scaling potential in Turkey is numerically evaluated. Saturation states of thermal waters with respect to calcite at their discharge temperatures are shown in Fig. 4. Saturation calculations were performed through the use of WATSPEC computer programme (Wigley, 1977). As is shown in Fig. 4, most of the thermal waters of Turkey are likely to precipitate calcite and there is a general tendency for the saturation index to increase with salinity which is expressed in terms of ionic strength. In this respect, since they have high temperatures, all the West Anatolian waters are supersaturated with respect to calcite. Especially the waters from Denizli, Aydın and İzmir areas of this region show the highest supersaturation states for calcite, as is also revealed by the widespread occurrences of travertine deposits at the discharge sites. Rather than keeping the CO_2

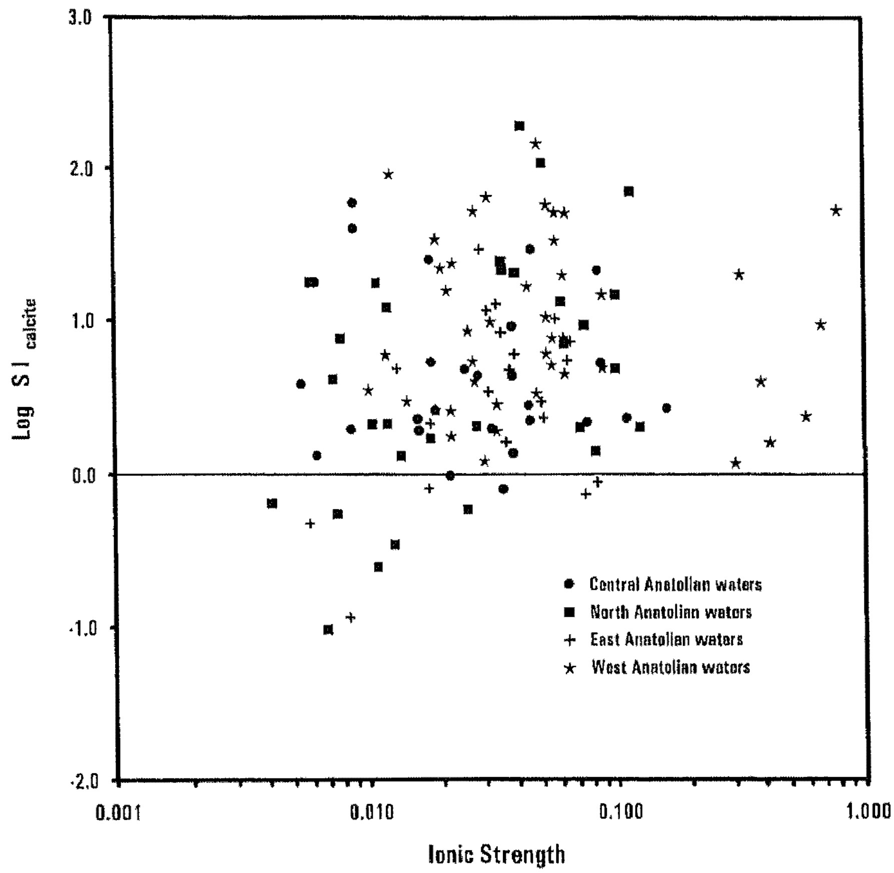

Fig. 4. Saturation index (with respect to calcite) vs. ionic strength for the thermal waters.

in solution by high well head pressures, the use of ferrophos inhibitors and down-hole heat exchangers is the widely used technique in preventing calcite scaling in Turkish geothermal fields.

7. Conclusions

The thermal waters of Turkey are located along the tectonically active structures (North Anatolian Fault and the grabens of West Anatolian extensional province) and/or around the recently active volcanoes (in Central and East Anatolia). The waters are dominantly alkali-bicarbonate and alkali-chloride, and occasionally sulphate type. The bicarbonate type waters probably acquired their nature through the metamorphic processes in the pre-Mesozoic basement, or the dissolution of carbonate lithologies, or the volcanism-related CO_2 emanations. The chloride type waters owe their nature either to sea water intrusion into the aquifers (e.g., coastal areas of West Anatolia), or to fossil connate waters (e.g., inland areas in West and Central Anatolia). The sulphate rich waters are likely to arise from (1) H_2S emanations from probably still cooling magma chambers (e.g., some of the North Anatolian waters); (2) oxidation of sulphide minerals common in the mineralizations spatially associated with the hot springs (e.g., the massive sulphide deposits in the eastern North Anatolian region); (3) leaching of gypsum layers (e.g., some waters in East and Central Anatolia); and (4) H_2S emanations possibly from decomposition of organic matter (e.g., some of the Central Anatolian waters).

The geothermometry applications reveal that West Anatolia is the most promising region in terms of geothermal energy potential, followed in sequence by East, Central and North Anatolia. The distribution of the geothermal potential appears to be controlled by the neotectonic features such that the highest potential is associated with the extensional tectonics (West Anatolia), being driven by the supply of heat from a deep-seated source (upwelling mantle material due to the release of lithostatic pressure) and deep circulation of waters along the faults of the graben systems. The regions with strike–slip tectonics (North Anatolian Fault), however, are not very promising from geothermal energy view point. Although strike–slip faults are supposed to be more deep-seated, allowing deeper water circulation, the lack of a regional heat source underneath (e.g., an upwelling mantle material as in the case of extensional terrains) and its restriction to local magmatic activities (confined to pull-apart basins) are probably responsible for the comparatively low geothermal potential associated with strike–slip tectonics. The East Anatolian region experiencing compressional regime, and the Central Anatolian region transferring the compression in the east to extension in the west, have recently active volcanoes but moderate geothermal energy potential. Despite the availability of a potential heat source (still cooling magma chambers) at depth, the rather moderate geothermal energy potential can be attributed to the lack of well developed fault systems (and hence deep hydrothermal circulation) in these regions.

The thermal waters of Turkey have significant calcite scaling potential which is more pronounced in the West Anatolian waters.

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