GRC *Transactions*, Vol. 33, 2009

Structural Controls on Geothermal Systems in Western Turkey: A Preliminary Report

James E. Faulds[1], Vincent Bouchot[2], Inga Moeck[3], and Kerem Oğuz[4]

[1]Nevada Bureau of Mines and Geology, University of Nevada, Reno, NV
[2]BRGM, Orléans cedex 2, France
[3]Helmholtz Centre Potsdam, Telegrafenberg, Potsdam, Germany
[4]Salihli Belediyesi (Salihli Municipality), Salihli, Manisa, Turkey

Keywords

Structural controls, normal fault, Turkey, Menderes graben, Salihli

ABSTRACT

Similar to the western Great Basin of the USA, western Turkey is a region of abundant geothermal activity currently undergoing significant extension but with relatively little volcanism. Thus, the geothermal activity in western Turkey is generally not driven by magmatic heat sources, at least not within the middle or upper crust. Instead, faults accommodating deep circulation of hydrothermal fluids of meteoric origin are the primary control on geothermal systems in this region. Much of the activity is associated with enhanced dilation on ~E-W-striking normal faults induced by a complex combination of forces, including slab roll-back in the Hellenic subduction zone and collision of the Arabian plate with Eurasia. Although faults control most of the geothermal activity in western Turkey, few detailed investigations have been conducted on the specific structural controls of individual fields. Because knowledge of such structures may facilitate development of exploration models and strategies, we have embarked upon a regional study of the controls on geothermal activity, which includes detailed analysis of fields in the Gediz-Alaşehir graben and reconnaissance studies of several others.

Our findings indicate a variety of structural controls in western Turkey but with several recurrent themes. The two hottest fields in Turkey (Germencik and Kizildere) are focused near the ends of the major normal fault zone that bounds the Menderes graben. We suggest that this fault zone breaks into multiple splays, or horsetails, as it terminates, thus generating a belt of higher fracture density and permeability that accommodates significant fluid flow. Several other fields, including Kurşunlu Canyon and Çamurhamami near Salihli occur at dilational fault intersections between major graben-bounding normal faults and oblique-slip, transversely oriented transfer faults. These systems occupy small dilational jogs, or pull aparts, along transverse faults near the intersection with a major detachment fault, as the transverse faults are refracted across the interface between basement rocks in the detachment footwall and Neogene sediments in the hanging wall. The Eynal geothermal system near Simav is hosted by a complex normal fault system with multiple steps and intersections.

Similar to the Great Basin (USA), most systems in western Turkey occupy discrete steps in fault zones or lie in belts of intersecting, overlapping, and/or terminating faults. The similarities in favorable settings between these two active areas of continental extension suggest that conceptual exploration models can be developed for geothermal activity in particular tectonic settings.

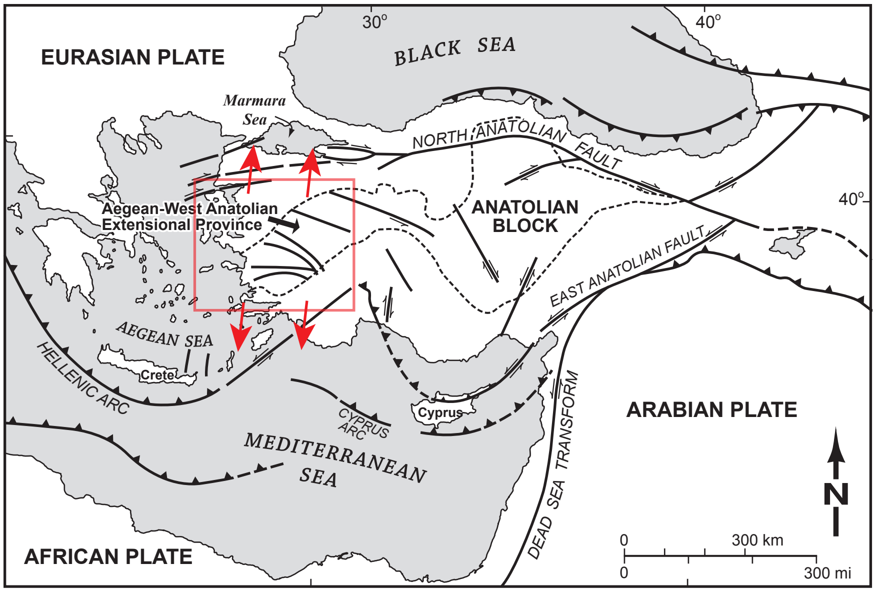

Figure 1. Tectonic setting of Turkey. Slab rollback in the Hellenic arc and westward escape of the Anatolian block, resulting from the collision of the Arabian plate with Eurasia, has induced late Miocene to recent, ~north-south extension (red arrows) in western Turkey. Red box encompasses study area in western Turkey.

Introduction

The collision of the Arabian and African plates dominates the tectonic framework of the eastern Mediterranean (e.g., Jackson and McKenzie, 1984, 1988). In Turkey, this collision has induced the westward escape of the Anatolian block, which is accommodated by the right-lateral North Anatolian fault on the north and the left-lateral East Anatolian fault on the south. Backarc spreading behind the Hellenic and Cyprean arcs combined with the westward escape of the wedge-shaped Anatolian block results in a complex region of extension and transtension in western Turkey, where abundant geothermal activity is focused (Şengör et al., 1984; Westaway, 2003; Aydin et al., 2005) (Figure 1).

Turkey has an estimated 363 MWe of geothermal power potential from ~63 sites (Battocletti, 1999; Satman et al., 2007) and is therefore recognized as the most promising area for geothermal power production in the vicinity of Europe. The majority of the geothermal activity occurs in the tectonically active Aegean and Marmara regions of western Turkey (Figure 2). Transtension dominates the Marmara region, whereas approximately north-south extension has characterized the Neogene in much of the Aegean region. Terrestrial surface heat flow in western Turkey varies from ~50 to 140 mW/m^2, with values exceeding ~100 mW/m^2 in most areas (Tezcan, 1995). Several geothermal fields in this region support district heating systems (e.g., Afyon, Balçova, Salihli, and Simav), but only a few fields currently produce electricity (e.g., Kizildere and Salavatli).

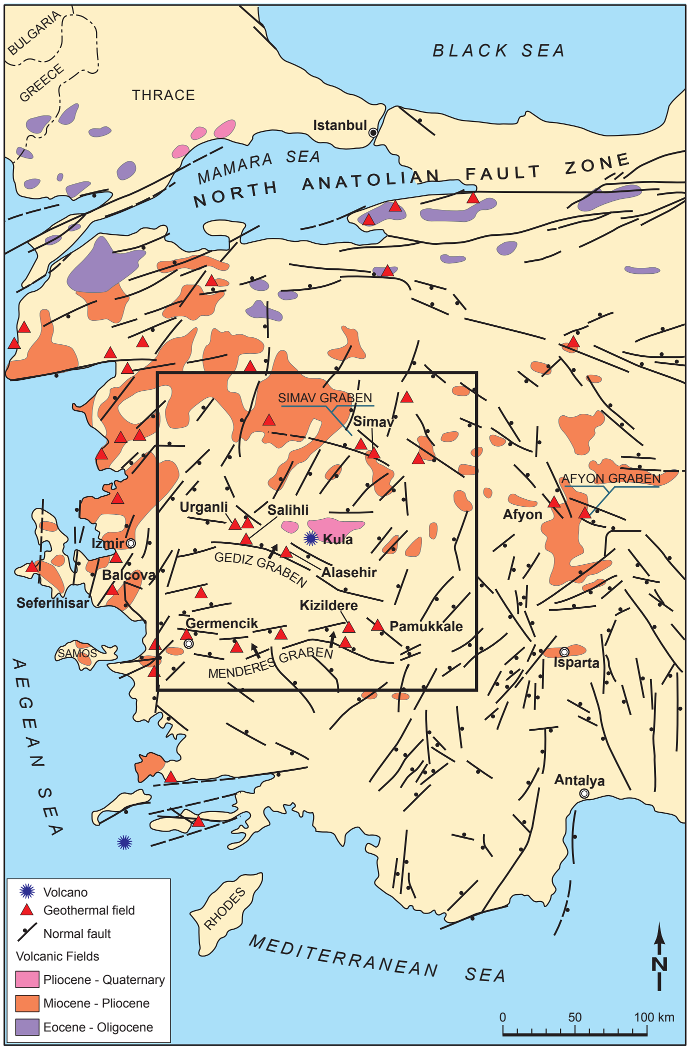

Figure 2. Generalized geologic map of western Turkey showing major fault zones and locations of geothermal systems. Black box surrounds the study area. Note the lack of Quaternary volcanism in the region. The mantle-derived basalts of the Kula volcanic field are the only Quaternary volcanics in the region.

It is noteworthy that recent magmatism has been relatively sparse in western Turkey (e.g., Yilmaz et al., 2001; Innocenti et al., 2005; Agostini et al., 2007) and therefore generally does not provide a direct heat source at upper crustal levels for the geothermal activity. Thus, most of the geothermal activity can be considered amagmatic in origin. In most geothermally active regions, such as the Basin and Range province of the western USA (e.g., Blackwell and Richards, 2004) and western Turkey (e.g., Tezcan, 1995), faults are the primary control on geothermal systems (e.g., Faulds et al., 2006; Şimşek, 1997). In such regions, it is therefore critical to evaluate which type of faults and which parts of faults are most favorable for geothermal activity. Although the structural controls of some geothermal systems have been analyzed in western Turkey (e.g., Şimşek and Demir, 1991; Şimşek and Guleç, 1994; Şimşek, 1997; Pfister et al., 1998; Şimşek et al., 2000a, b; Karamanderesi and Helvaci, 2003; Caglar et al., 2005; Drahor and Berge, 2006), the specific controlling faults of many fields have not been studied. Better characterization of the structural controls is needed to develop and enhance exploration strategies, particularly in the selection of drilling sites in fields with and without surficial expressions.

This paper provides an overview of the structural controls of geothermal systems in western Turkey. Systems were analyzed in the Simav, Gediz-Alaşehir, and Menderes grabens (Figure 2). We conclude that systems of overlapping, terminating and intersecting normal and normal oblique-slip faults host most of the major geothermal systems in western Turkey.

Structural Framework

Much of western Turkey has undergone significant ~north-south extension from early Miocene to Recent time (Sözbilir, 2001; Seyitoğlu et al., 2002; Işik et al., 2003; Purvis and Robertson, 2004). The first phase of extension occurred in the early to middle Miocene and was related to both gravitational collapse of early Tertiary orogenic highlands and roll-back of the south Aegean subduction zone (Purvis and Robertson, 2004). Ductilely deformed early Miocene granites and syntectonic muscovite porphyroclasts in gneisses (Figure 2) indicate an early Miocene onset of extension (Hetzel et al., 1995; Işik et al., 2004). Cooling ages of 20-12 Ma on such rocks further suggest early to middle Miocene tectonic denudation of metamorphic core complexes (Hetzel et al., 1995; Işik et al., 2004). Major north-south extension has continued into late Miocene to recent time and may represent a distinct later phase of extension. Synkinematic ~7 Ma white mica indicates that some detachment faults remained active into latest Miocene time (Lips et al., 2001). In addition, major steeply dipping normal fault zones that cut Pliocene-Quaternary sediments bound the major grabens. Part of the steeply dipping fault zone along the southern margin of the Gediz-Alaşehir graben ruptured in a 6.5 magnitude earthquake in 1969 (Eyidoğan and Jackson, 1985). In addition to the steeply dipping ~E-W-striking normal faults, widely spaced (~2-5 km) transversely oriented (north-northwest- to north-northeast-striking) oblique-slip faults dissect the region. Late Miocene to recent extension may have been triggered by the westward tectonic escape of the Anatolian block in response to the collision between the Arabian and Eurasian plates (Figure 1; Purvis and Robertson, 2004).

Many of the geothermal systems in this region lie within or along the margins of major ~E-W-trending grabens, which are bounded by major low-angle detachment faults and/or steeply dipping normal fault systems. However, recent magmatism in the region has been limited to the Quaternary alkaline basalts of the Kula volcanic field, which lies between the Gediz-Alaşehir and Simav grabens (Figure 2; Ercan, 1993; Richardson-Bunbury, 1996; Tokçaer et al., 2005). Isotopic and trace-element compositions within these basalts indicate derivation primarily from asthenospheric mantle, with a limited lithospheric mantle contribution and essentially no crustal contamination (Alici et al., 2002). Although proximal to several geothermal fields (Figure 2), including those in the Gediz-Alaşehir graben, the deep sources for these basalts indicate that related magmas do not provide a direct source of heat for these geothermal systems.

Structural Controls

We analyzed several geothermal fields in western Turkey to assess the primary structural controls on the geothermal activity. The Salihli geothermal fields were studied in detail, whereas reconnaissance studies were conducted at the other localities (Kizildere, Germencik, Simav-Eynal). This effort represents an initial attempt to characterize favorable structural settings for geothermal activity in this relatively amagmatic region and compare to similar tectonic settings elsewhere (e.g., Basin and Range province, USA). The systems are described from south to north across western Turkey.

Menderes Graben

The Büyük Menderes graben is a 200 km long, approximately west-trending graben stretching eastward from the Aegean Sea to near Denizli (Figures 2 and 3). A major south-dipping normal fault system bounds the northern margin of the graben, juxtaposing Neogene sediments against the Menderes massif (Lips et al., 2001), which consists of Paleozoic metamorphic rocks, including gneiss, schist, marble, and quartzite. Normal displacement on the later high-angle normal faults within this system exceeds 3 km, as evidenced by the depth of basin fill within the graben. Many hot springs are associated with the bounding normal fault zones. Northerly striking transverse faults dissect the northern margin of the graben and commonly extend into the Menderes massif. The two hottest geothermal systems in Turkey, Kizildere and Germencik, are respectively located near the eastern and western ends of the Menderes graben. We conducted reconnaissance studies of these two fields.

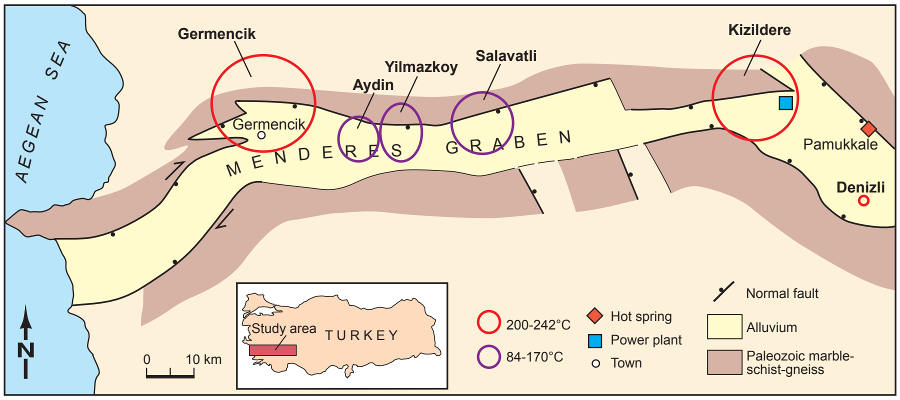

Figure 3. Geothermal fields of the Menderes graben, western Turkey. Reconnaissance studies were conducted on the Kizildere and Germencik fields, which are the two hottest fields known in Turkey. Both the Kizildere and Germencik geothermal systems occur near the ends of the main border fault zone on the north side of the Menderes graben.

Kizildere Geothermal Field

The Kizildere geothermal field lies ~40 km west of Denizli near the eastern end of the Büyük Menderes Graben (Şimşek, 1985; Özgür et al., 1998; Şimşek et al., 2000a; Özgür, 2002). Numerous hot springs and fumaroles are located in the area. The highest reservoir temperature for the field is 242°C, which is the highest temperature reservoir known in Turkey. Kizildere contains the oldest operating geothermal plant in Turkey. TEAS (the Turkish Electricity Authority) installed the plant with 20 MWe capacity in 1984. Geothermal fluids are also used for 6000 m^2 of greenhouse heating and district heating of ~2,000 homes around Denizli.

The main bounding normal fault along the northern margin of the Menderes graben, here referred to as the Menderes border fault, terminates eastward in the vicinity of the Kizildere geothermal field (Figure 3). Here, a complex system of ~E-W striking, south dipping normal faults juxtaposes Neogene sedimentary rocks against the basement rocks of the Menderes massif. All units are also cut by NE-striking subvertical faults (Şimşek, 1985). Geothermal reservoirs are found at ~400 m depth in Miocene limestone and at 1,000-1,242 m in faulted and jointed basement rocks. Impermeable clayey Pliocene sediments form the cap rocks in the region. Significant hydrothermal alteration characterizes the area and includes phyllic, argillic (montmorillonite), silicic, hematitic, and carbonatized zones (Özgür et al., 1998).

The geothermal fluids appear to be controlled by 2 mains types of active faults: 1) The set of parallel E-W-striking, south-dipping faults (main fault) and 2) some NE-striking subvertical faults. For example, a N75°E trending line of fumaroles along a possible normal fault are connected to a NE-striking fault. The high density of faults in this area may be associated with the eastern end of the major normal fault zone on the north side of the Menderes graben. As the fault loses displacement, it breaks into multiple splays (or horsetails). The higher density of faults and greater number of fault intersections generates a broad zone of highly fractured and therefore highly permeable rock, which facilitates the ascent of geothermal fluids.

Germencik-Omerbeyli Geothermal Fields

The geothermal fields of Germencik (Fig. 3) cover a surface area of at least ~6 km^2. They include three discrete areas: 1) Bozkoy on the northeast; 2) Çamurlu-Kavşak on the northwest and 3) Germencik-Omerbeyli on the south (Şimşek, 1984, 2003; Şimşek and Guleç, 1994; Battocletti and Lawrence, 1999). Fumaroles, hot springs, and recent hydrothermal alterations are common in the fields. Active before geothermal exploitation, the Aktaş fumarole (101ºC) was located 3 km northeast of the town of Germencik. The hot springs, with temperatures of 30-92ºC, are concentrated in the Çamur-Bozkoy field, ~6 km north of Germencik (Şimşek and Guleç, 1994). From north to south, this region consists of 1) Paleozoic metamorphic basement composed of augen gneiss, schist and marbles; 2) the small Cenozoic to Quaternary graben of Arzoular, 3) the metamorphic horst of Kizilcagedik, mainly composed of augen gneiss, and 4) the large Tertiary graben of Menderes. Similar to Kizildere, the Menderes border fault bounds the Menderes graben on the north in the Germencik area.

The Germencik-Omerbeyli field is the most significant in the area, as a 45 MWe double-flash power plant was recently constructed at the site. This field lies in the western part of the Menderes graben directly south of the Menderes border fault (Figure 3). The border fault zone is dying out westward in this area, as evidenced by the westward termination of the Kizilcagedik horst and gravity data indicating significant westward shallowing of Menderes graben (Işık and Şenel, 2009). The main geothermal reservoir appears to be focused along the border fault zone at 1-2.4 km depth in marble and quartzite. One well in this area apparently penetrated 25 fault splays. This suggests that the border fault horsetails in this area, thus generating a broad zone of highly fractured rock with multiple fault intersections. The highest reservoir temperature is 232°C, which is the second highest temperature thus far discovered in Turkey. The cap rocks may be clay-rich layers in Neogene basin fill, as well as clay-rich gouge along basin-bounding fault to the east, where the fault has accommodated greater displacement.

Two other structural complexities may favor geothermal activity at the Germencik-Omerbeyli field. First, the Menderes border fault may merge with a major NE-striking right-lateral transfer fault to the southwest (Figure 3). The intersection between these two major faults may generate a region of enhanced dilation in the Germencik vicinity. Second and possibly more important is that a major steeply dipping, ~N-striking cross fault intersects the main E-striking border fault in the Germencik-Omerbeyli area. This cross fault extends across the entire area and cuts both the Kizilcagedik horst and Arzoular graben to the north of the Germencik-Omerbeyli field. The intersection between this cross fault and the multiple splays of the Menderes border fault would further increase fracture density and thus favor deep circulation of fluids. The intersection of the N-S faults with the E-W-striking normal faults probably generated complex zones of highly fractured rock that significantly enhanced deep circulation of fluids (convective cell) and thus controlled the location of the geothermal systems. However, more detailed studies of the area are needed to define the slip sense of the ~N-striking fault zone and overall kinematic evolution of the area.

Salihli Geothermal Fields

Detailed geologic mapping of 30-35 km^2 and structural analysis of faults were employed to assess the structural controls of the Kurşunlu and Çamurhamami geothermal fields in the Salihli area (Figure 4). The structural framework of the Salihli area is characterized by gently to moderately tilted (5-40º) Neogene sedimentary rocks cut by ~E-striking gently to steeply dipping normal faults and northerly (NNW to NNE) striking oblique-slip cross (or transverse) faults. The predominant E-W strike of normal faults and tilting reflects regional north-south extension. The strata are also deformed into multiple, discontinuous WNW- to E-trending folds. Similar to other studies in the region (Seyitoğlu et al., 2000; Sözbilir, 2001, 2002), we conclude that these folds are extensional in origin, resulting primarily from local reversals in the predominant dip direction of normal fault systems.

The two largest faults in the area are the moderately N-dipping Alaşehir frontal fault zone and gently (~10-30º) N-dipping Gediz detachment fault (Figure 4). The Alaşehir frontal fault has accommodated significant uplift and exhumation of the southern shoulder of the Alaşehir graben, bounds the graben on the south, and is marked by Quaternary fault scarps. The Gediz detachment fault accommodated uplift and tectonic denudation of the Menderes metamorphic complex, is typically marked by a thick zone of cataclasis that overprints an earlier mylonitic fabric, but is currently inactive, with no evidence for Quaternary displacement.

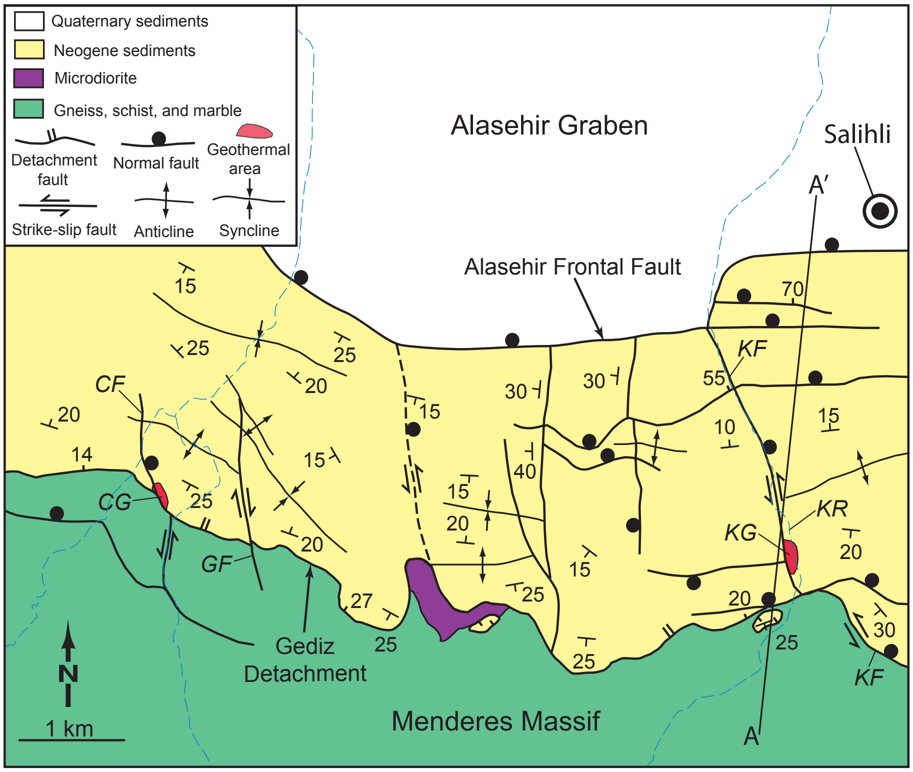

Figure 4. Generalized geologic map of the Salihli area, western Turkey. Both the Kurşunlu (KG) and Çamurhamami (CG) geothermal fields occur near or at the intersections of northerly striking, sinistral-normal transfer faults and the Gediz detachment fault. Left steps in the transfer faults at these intersections are dilational jogs that facilitate fluid flow and geothermal activity.

Numerous minor faults cut the exhumed Neogene sedimentary rocks between the Alaşehir frontal fault zone and Gediz detachment fault. At least some of these minor faults have accommodated Quaternary displacement. Most of these faults strike WNW, dip relatively steeply (~60-65º) to the north or south, and accommodated normal slip. In addition, a subset of northerly striking oblique-slip, steeply dipping transverse faults dissects the area, controlling the location of several large canyons.

The Salihli geothermal fields occur along the active southern margin of the Gediz-Alaşehir graben. Fractured rocks of the Menderes Massif, such as mica-schist, gneiss, and especially marbles, are the reservoir rocks. Cap rocks for the geothermal fluids include clay-rich intervals within the Neogene sedimentary units (Tarcan et al., 2000). Most hot springs and hot wells with good flow rates lie near the gently N-dipping Gediz detachment fault (Figure 4), where it intersects and is cut by ~N-S-striking transverse faults. Karstic marble and breccia along and near the detachment fault provide good channelways for flow, possibly somewhat distal to the main upwelling zone. The reservoir for the Kurşunlu field varies between 10-200 m in depth and resides in highly fractured, commonly karstified zones along the detachment fault. Temperatures at the Kurşunlu field range from 57 to 120ºC. Empirical chemical geothermometers applied to the thermo-mineral waters tentatively suggest that reservoir temperatures at Kurşunlu vary between 150°C and 230°C (Tarcan et al., 2000). Less is known about the Çamurhamami field, where thermal waters issue from a spring at 49ºC and limited drilling indicates hot water to at least 40 m depth.

Thermal-mineral waters from both systems are used for bathing and medicinal purposes, but those from Kurşunlu are also utilized in a district heating system for 5,000 homes in the city of Salihli. The total discharge rate for the main producing wells at Kurşunlu is 145 l/s. The discharge rates are highest where the reservoir is predominantly formed by marbles (versus schist). Average production temperatures are ~90°C for the district heating.

The geothermal fields at Kurşunlu Canyon and Çamurhamami appear to lie at the intersections of minor northerly striking sinistral-normal transfer faults and the Gediz detachment fault. Left steps in the transfer faults at the intersection with the detachment are inferred to represent dilational jogs (i.e., small pull aparts) that provide channelways for geothermal fluids (Figure 4). The left steps may result from refraction across the detachment surface that results from the mechanical contrast between hanging-wall sedimentary rocks and basement gneisses, marbles, and schists in the footwall. Brecciated marble at these intersections provide good reservoirs for the geothermal fluids. We view the reservoirs as plunging gently northward along the intersection of the detachment fault with the transfer faults. Although this model can account for the shallow reservoir and surface springs, it may not predict the location of the main upwelling that feeds these geothermal systems. Major steps in the Alaşehir frontal fault or complex fault intersections between the transverse faults and WNW-striking normal faults may accommodate upwelling in the Salihli area.

Simav-Eynal Geothermal Field

The Simav-Eynal geothermal field is in the northeastern corner of the Simav graben (Figure 2) and is commonly referred to as the Eynal geothermal area (refs). The Eynal geothermal field currently supports 1) a district heating system for the city of Simav, with a capacity of 66 MWt for 3,500 residences fed by a 4 km long pipeline, 2) thermal spring tourism, and 3) greenhouse agriculture (12,0000 m²). District heating of 6,500 residences and electrical energy generation have been proposed. Preliminary feasibility studies indicated the potential to produce an installed capacity of 2.9 MWe energy and a minimum of 17,020 MWh/year electrical energy using the organic Rankine cycle process in a binary power unit (Kose, 2007).

This Simav graben is composed of Neogene and Quaternary sediments floored by Palaeozoic metamorphic (quartzite, mica-schist, and marble) and Cenozoic igneous rocks, such as the middle Miocene Nasa basalt sequence and early Miocene (20 Ma) Egrigoz granite. The main bounding fault to the graben is a N-dipping fault along its southern margin that has accommodated several kilometers of normal slip and is here referred to as the Simav fault. This fault is part of a large semi-continuous WNW to E-W striking fault zone that extends across much of western Turkey and may have accommodated some strike-slip displacement.

Several hot springs, ranging in temperature from 51 to 90ºC, emanate in the alluvium along the northern margin of the basin, where sediments are faulted against basalt. The contact between basalt and alluvium is marked by a complex anastomosing, steeply S-dipping, approximately east-striking normal fault system, which is

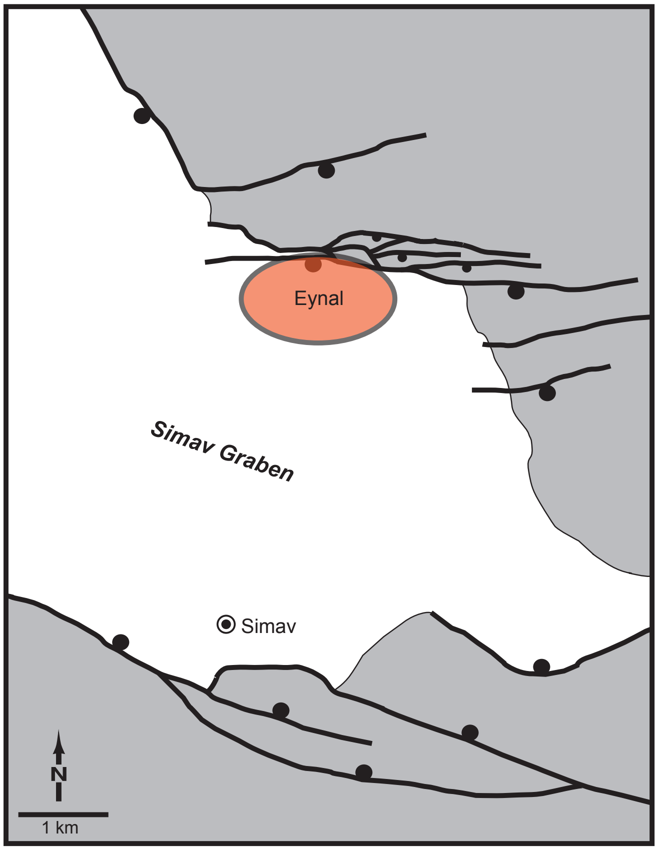

Figure 5. Generalized map of the eastern part of the Simav graben. The Eynal geothermal system occurs in the northeastern part of the graben along an anastomosing system of antithetic south-dipping normal faults. Multiple fault intersections and associated high density of fractures generates a broad zone of higher permeability, which accommodates the ascent of geothermal fluids. Bedrock areas are shaded.

antithetic to the main, N-dipping system on the south side of the graben (Figure 5). Several of these faults are marked by Quaternary fault scarps. The main E-W-trending line of hot springs in the Eynal area is situated in the hanging wall of this anastomosing normal fault system. Opaline sinter was discovered at the surface along some of the hot springs, suggesting a high-temperature system (>180ºC) at depth. Existing wells penetrate to 958 m, but the main reservoir may not be discovered yet. The reservoir may lie in the metamorphic basement and partly in the Miocene igneous rocks. Down-hole temperatures range from ~150 to 165°C (Kose, 2007), and empirical chemical geothermometers suggest temperatures of 175 to 200°C (Gemici and Tarcan, 2002).

The geothermal activity at Eynal may be primarily controlled by multiple fault intersections within the anastomosing S-dipping normal fault system, which have produced highly fractured steeply dipping conduits favorable for fluid circulation. The S-dipping normal fault system along the north side of the graben in this area may partly compensate for decreasing displacement to the east along the main N-dipping fault that bounds the south side of the graben. Additional geologic mapping, structural analysis of faults, and geophysical studies are needed to better define the structural setting and controls of the promising Eynal geothermal field.

Summary

Although many more fields need to be analyzed to fully characterize the structural controls on geothermal systems in western Turkey, some critical patterns are emerging. First, most of the fields occur along ~E-W-striking normal faults, but generally not near the maximum displacement on these fault zones. Instead, most of the systems reside in structural complexities along such fault zones, including a) horse-tailing terminations (Kizildere, Germencik), b) intersections with ~N-striking cross faults (Salihli, Germencik), or c) intersections between multiple normal fault segments (Simav-Eynal). In cases analyzed to date, the structural settings favoring geothermal activity generate conduits of highly fractured rock along ~-E-W-striking fault zones oriented approximately perpendicular to the least principal stress.

These findings are similar to those observed in geothermal fields within the Basin and Range province (USA), where belts of intersecting, overlapping, and/or terminating faults control many geothermal systems (Faulds et al., 2006; Vice et al., 2007). In addition, geothermal systems in both the Basin and Range province (USA) and western Turkey are commonly proximal to Quaternary faults (e.g., Bell et al., 2008). The similarities in favorable settings between these two actively extending areas of continental extension suggest that conceptual exploration models can be developed for geothermal activity in particular tectonic settings.

Acknowledgments

This research was supported primarily by the le STUDIUM program (Orléans, France) and BRGM (French Geological Survey). Partial support was also provided by the U.S. Department of Energy (DE-FG36-02ID14311). We thank E. Bülbül, C. Karahan, and A. Yolal (all with MTA, Turkey) for logistical support and fruitful discussions. Jim Combs provided a helpful review of this manuscript.

References

Agostini, S., Doglioni, C., Innocenti, F., Manetti, P., Tonarini, S., and Savaşçin, M. 2007, The transition from subduction-related to intraplate Neogene magmatism in the Western Anatolia and Aegean area, *in* Beccaluva L., Bianchini, G., and Wilson, M., eds., Cenozoic Volcanism in the Mediterranean Area, Geological Society of America Special Paper 418, p. 1-15.

Alici, P., Temel, A., and Gourgaud, A., 2002, Pb-Nd-Sr isotope and trace element geochemistry of Quaternary extension-related alkaline volcanism: A case study of Kula region (western Anatolia, Turkey): Journal of Volcanology and Geothermal Research, v. 115, p. 487-510.

Aydin, I., Karat, H.I., and Koçak, A., 2005, Curie-point map of Turkey: Geophysical Journal International, v. 162, p. 633-640.

Bartocletti, E., 1999, Geothermal resources in Turkey: Bob Lawrence & Associates, Inc., Report No. INEEL/EXT-99-01282, 68 p.

Blackwell, D.D., and Richards, M., 2004, Geothermal Map of North America: American Association of Petroleum Geologists, 1 sheet, scale 1:6,500,000.

Caglar, I., Tuncer, V., Kaypak, B., and Avsar, U., 2005, A high conductive zone associated with a possible geothermal activity around Afyon, northern part of Tauride zone, southwest Anatolia: Proceedings World Geothermal Congress, Antalya, Turkey, 24-29 April, p. 1-5.

Drahor, M.G., and Berge, M.A., 2006, Geophysical investigations of the Seferihisar geothermal area, western Anatolia, Turkey: Geothermics, v. 35, p. 302-320.

Ercan, T., 1993, Interpretation of geochemical, radiometric, and isotopic data on Kula volcanics (Manisa-W. Anatolia): Turkish Geological Bulletin, v. 36, p. 113-129.

Eyidoğan, H., and Jackson, J., 1985, A seismological study of normal faulting in the Demerci, Alaşehir, and Gediz earthquakes of 1969-70 in western Turkey: Implication for the nature and geometry of deformation in the continental crust: Geophysical Journal of the Royal Astronomical Society, v. 81, p. 569-607.

Faulds, J.E., Coolbaugh, M.F., Vice, G.S., and Edwards, M.L., 2006, Characterizing structural controls of geothermal fields in the northwestern Great Basin: A progress report: Geothermal Resources Council Transactions, v. 30, p. 69-76.

Gemici, U. and Tarcan, G., 2003, Hydrogeochemistry of the Simav geothermal field, western Anatolia, Turkey: Journal of Volcanology and Geothermal Research, v. 116, n. 3-4, p. 215-233.

Hetzel, R., Ring, U., Akal, C., and Troesch, M., 1995, Miocene NNE-directed extensional unroofing in the Menderes massif, southwestern Turkey: Journal of the Geological Society, London, v. 152, p. 639-654.

Innocenti, F., Agostini, S., DiVincenzo, G., Doglioni, C., Manetti, P., Savaşçin, M.Y., and Tonarini, S., 2005, Neogene and Quaternary volcanism in western Anatolia: Magma sources and geodynamic evolution: Marine Geology, v. 221, p. 397-421.

Işik, V., Seyitoğlu, G., and Çemen, I., 2003, Ductile-brittle transition along the Aleşehir detachment fault and its structural relationship with the Simav detachment fault, Menderes massif, western Turkey: Tectonophysics, v. 374, p. 1-18.

Işik, V., Tekeli, O., and Seyitoğlu, G., 2004, The ^{40}Ar/^{39}Ar age of extensional ductile deformation and granitoid intrusion in the northern Menderes core complex: Implications for the initiation of extensional tectonics in western Turkey: Journal of Asian Earth Sciences, v. 23, p. 555-566.

Işık, M., and Şenel, H., 2009, 3D gravity modeling of Büyük Menderes basin in Western Anatolia using parabolic density function: Journal of Asian Earth Sciences, v. 34, no. 3, p. 317-325.

Jackson, J.A., and McKenzie, D.P., 1984, Active tectonics of the Alpine-Himalayan belt between western Turkey and Pakistan: Geophysical Journal of the Royal Astronomical Society, v. 77, p. 185-264.

Jackson, J.A., and McKenzie, D.P., 1988, Rates of active deformation in the Aegean Sea and surrounding regions: Basin Research, v. 1, p. 121-128.

Karamanderesi, I.H., and Helvaci, C., 2003, Geology and hydrothermal alteration of the Aydin-Salavatli geothermal field, western Anatolia, Turkey: Turkish Journal of Earth Sciences, v. 12, p. 175-198.

Kose R., 2007, Geothermal energy potential for power generation in Turkey: A case study in Simav, Kutahya: Renewable and Sustainable Energy Reviews, v.11, no. 3, p. 497-511.

Lips, A.I., Cassard, D., Sozbilir, H., Yilmaz, H., and Wijbrans, J.R., 2000, Multistage exhumation of the Menderes massif, western Anatolia (Turkey): International Journal of Earth Sciences, v. 89, p. 781-792.

Özgür**,** N. 2002, Geochemical Signature of the Kizildere Geothermal Field, Western Anatolia, Turkey: International Geology Review, v. 44, p. 153-163.

Özgür, N., Pekdeger, A., Wolf, M., Stichler, W., Seiler, K.-P., and Satir, M., 1998a, Hydrogeochemical and isotope geochemical features of the thermal waters of Kizildere, Salavatli, and Germencik in the rift zone of the Büyük Menderes, western Anatolia, Turkey: Preliminary studies, in Arehart, G. B., and Hulston, J. R., eds., Proceedings of 9th International Symposium on Water-Rock Interaction, Taupo, New Zealand, 30 March – 3 April 1998, p. 645–648.

Pfister, M., Rybach, L., and Şimşek, S., 1998, Geothermal reconnaissance of the Marmara Sea region (NW Turkey); surface heat flow density in an area of active continental extension: Tectonophysics, v. 291, no. 1-4, p. 77-89.

Purvis, M., and Robertson, A., 2004, A pulsed extension model for the Neogene recent E-W-trending Aleşehir graben and the NE-SW-trending Selendi and Gordes basins, western Turkey: Tectonophysics, v. 391, p. 171-201.

Richardson-Bunbury, J.M., 1996, The Kula volcanic field, western Turkey: The development of a Holocene alkali basalt province and the adjacent normal-faulting graben: Geological Magazine, v. 133, p. 275-283.

Satman, A., Serpen, U., and Korkmaz, B., 2007, An update on geothermal energy potential of Turkey: 32nd Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, SGP-TR-183.

Şengör, A.M.C., Satir, M., and Akkök, R., 1984, Timing of tectonic events in the Menderes Massif, western Turkey: Implications for tectonic evolution and evidence for Pan-African basement in Turkey: Tectonics, v. 3, p. 693-707.

Seyitoğlu, G., Çemen, I., and Tekeli, O., 2000, Extensional folding in the Alaşehir (Gediz) graben, western Turkey: Journal of the Geological Society of London, v. 157, p. 1097-1100.

Seyitoğlu, G., Tekeli, O., Çemen, I., Şevket, Ş., and Işik, V., 2002, The role of the flexural rotation/rolling hinge model in the tectonic evolution of the Aleşehir graben, western Turkey: Geological Magazine, v. 139, no. 1, p. 15-26.

Şimşek, S., 1984. Aydin-Germencik-Omerbeyli geothermal field of Turkey: Seminar on Utilization of Geothermal Energy for Electric Power Production and Space Heating; UN Economic Commission for Europe EP/SEM.9/R.37, Florence, Italy, p.1–30.

Şimşek, S., 1985, Geothermal model of Denizli, Sarayköy-Buldan area: Geothermics, v. 14, p. 393–417.

Şimşek, S., 1997, Geothermal potential in northwestern Turkey, excerpt from Active tectonics of northwestern Anatolia – The Marmara poly-project: A multi-disciplinary approach by space geodesy, geology, hydrogeology, geothermics, and seismology, vdf Hochschulverlag AG an der ETH Zurich, p. 111-124.

Şimşek, S., 2003, Hydrogeological and isotopic survey of geothermal fields in the Buyuk Menderes Graben, Turkey: Geothermics, v. 32, n. 4-6, p. 669-678.

Şimşek, S., and Demir, A., 1991, Reservoir and cap rock characteristics of some geothermal fields in Turkey and encountered problems based on lithology: Journal of the Geothermal Research Society of Japan, v. 13, no. 3, p. 191-204.

Şimşek, S., and Gulec, N., 1994, Geothermal fields of western Anatolia, excursion guide: International Volcanological Congress, Middle Eastern Technical University, IAVECEI-94, Ankara Special Publications No. 8, 35 p.

Şimşek, S., Dogdu, M.S., Akan, B., and Yildirum, N., 2000a, Chemical and isotopic survey of geothermal reservoirs in western Anatolia, Turkey: Proceedings of the World Geothermal Congress, Kyushu-Tohoku, Japan, May 28-June 10, 2000, p. 1765-1770.

Şimşek, S., Gunay, G., Elhatip, H., and Ekmekci, 2000b, Environmental protection of geothermal waters and travertines at Pamukkale, Turkey: Geothermics, v. 29, p. 557-572.

Sözbilir, H., 2001, Extensional tectonics and the geometry of related macroscopic structures: Field evidence from the Gediz detachment, western Turkey: Turkish Journal of Earth Sciences: v. 10, p. 51-67.

Sözbilir, H., 2002, Geometry and origin of folding in the Neogene sediments of the Gediz graben, western Anatolia, Turkey: Geodinamica Acta, v. 15, p. 277-288.

Tarcan, G., Filiz, S., and Gemici, U., 2000, Geology and geochemistry of the Salihli geothermal fields, Turkey: Proceedings of the World Geothermal Congress, Kyushu-Tohoku, Japan, May 28 – June 10, 2000, p. 1829-1834.

Tezcan, A.K., 1995, Geothermal explorations and heat flow in Turkey, in Gupta, M.L., and Yamano, M., eds., Terrestrial heat flow and geothermal energy in Asia: Oxford and IBH publishing Co., Pvt. Ltd., New Delhi, p. 23-42.

Tokçaer, M., Agostini, S., and Savaşçin, M.Y., 2005, Geotectonic setting and origin of the youngest Kula volcanics (western Anatolia), with a new emplacement model: Turkish Journal of Earth Sciences, v. 14, p. 145-166.

Vice, G.S., Faulds, J.E., Ehni, W.J., and Coolbaugh, M.F., 2007, Structural controls of a blind geothermal system in the northern Pyramid Lake area, northwestern Nevada: Geothermal Resources Council Transactions, v. 31, p. 133-137.

Westaway, R., 2003, Kinematics of the Middle East and eastern Mediterranean updated: Turkish Journal of Earth Sciences, v. 12, p. 5-46.

Yilmaz, Y., Genç, Ş.C., Karacik, Z., and Altunkaynak, Ş., 2001, Two contrasting magmatic associations of NW Anatolia and their tectonic significance: Journal of Geodynamics, v. 31, p. 243-271.