Characterizing Structural Controls of Geothermal Reservoirs in the Great Basin, USA, and Western Turkey: Developing Successful Exploration Strategies in Extended Terranes

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ABSTRACT

Although conventional geothermal systems have been successfully exploited for electrical production and district heating in many parts of the world, exploration and development of new systems is commonly hampered by the risk of unsuccessful drilling. A major problem in selecting drill sites is that existing geothermal systems are generally poorly characterized in terms of favorable settings and structural-stratigraphic controls. In order to characterize the structural controls on geothermal systems in active extensional settings, we have analyzed numerous fields in the western Great Basin (USA) and western Turkey through integrated geologic and geophysical investigations. Methods include detailed geologic mapping, structural analysis of faults, detailed gravity surveys, studies of surficial geothermal features (e.g., travertine, sinter, springs, and fumaroles), shallow temperature surveys, and geochemical analyses. Our findings suggest that many fields occupy a) discrete steps in normal fault zones (e.g., Desert Peak, Brady's, Nevada, USA; and Simav, Turkey); b) intersections between normal faults and transversely oriented oblique-slip faults (Astor Pass, Nevada, and Salihli, Turkey); c) overlapping oppositely dipping normal fault zones (e.g., Salt Wells, Nevada, USA), d) terminations of major normal faults (e.g., Gerlach, Nevada, USA; Germencik and Kizildere, Turkey), or e) transtensional pull-apart zones (e.g., Lee-Allen, Nevada, and Canby, California, USA; Pamukkale, Turkey). These settings are typically associated with steeply dipping faults, involving conduits of highly fractured rock oriented approximately perpendicular to the least principal stress and commonly along or near Quaternary fault zones. General topographic features indicative of these settings include: 1) major steps in range-fronts, 2) interbasinal highs, 3) mountain ranges consisting of relatively low, discontinuous ridges, and 4) lateral terminations of mountain ranges. Surficial features, such as tufa towers, travertine spring mounds, and sinter deposits, are also associated with many systems. These structural, topographic, and surficial features may indicate hidden or blind geothermal fields, which have no surface thermal waters or steam (e.g., hot springs or fumaroles).

1. INTRODUCTION

Considering a general lack of recent volcanism, the abundant geothermal activity in western Turkey and the Basin and Range province (USA) is somewhat anomalous. Volcanism in both regions generally ceased in late Miocene time. Thus, upper crustal magmatism is not a heat source for most of the geothermal activity in these regions. Instead, high heat flow, regional extension, and deeply penetrating fault systems allow for deep circulation of meteoric water, subsequent heating of those waters, and the return to shallow crustal levels as upwellings of hydrothermal fluids. Faults typically provide the pathways for geothermal fluids within the crust and are therefore the primary control for the efficient transfer of heat from deep to shallow crustal levels in amagmatic regions. Despite the significance of faults in controlling geothermal activity in such regions, relatively little is known about the most favorable structural settings for geothermal systems. Whether certain structures are particularly conducive for geothermal activity is therefore not known. Knowledge of such structures would facilitate exploratory drilling in known, but as yet undeveloped fields, expansion in producing fields, and identification of possible blind (or hidden) geothermal resources. In an effort to enhance exploration models and strategies, we have initiated studies to characterize the most favorable structural settings in extended terranes. Our initial efforts have focused on the western Great Basin in the Basin and Range province (USA) and the Aegean extensional province of western Turkey. Our studies have included detailed analysis of several fields and reconnaissance studies of many other fields. In this paper, we briefly describe the tectonic setting for geothermal activity in the Great Basin (USA) and western Turkey and then report our findings on the structural controls for representative geothermal fields in each area. We conclude that despite differences in overall tectonic setting, the most favorable structural settings for geothermal activity are similar in the Aegean and Basin and Range extensional provinces.

2. TECTONIC AND GEOTHERMAL SETTINGS

2.1 Western Great Basin-USA

Regional transtension essentially facilitates the prolific geothermal activity in the western Great Basin, USA. Here, a system of right-lateral strike-slip faults known as the Walker Lane (Stewart, 1988; Oldow, 1992; Faulds et al., 2005; Faulds and Henry, 2008) accommodates ~20% of the dextral motion between the Pacific and North American plates (Bennett et al., 2003; Hammond and Thatcher, 2004). The San Andreas fault currently accommodates the bulk of this plate motion. The Walker Lane terminates northwestward in northeast California in conjunction with the offshore termination of the San Andreas fault at the Mendocino triple junction (Figure 1). Relatively high rates of recent (<10 Ma) WNW-directed extension (Surpless et al., 2002; Colgan et al., 2004) absorb northwestward declining dextral motion in the Walker Lane, diffusing that motion into the Basin-Range. Abundant geothermal fields cluster in NNE to NE-trending belts in the northern Great Basin orthogonal to the current extension direction (Figure 2). The Walker Lane begins losing displacement to the northwest in west-central Nevada near the southeast margin of the region with abundant geothermal activity. Individual fields appear to be largely controlled by NNE-striking normal faults (Blackwell et al., 2002; Johnson and Hulen, 2002; Waibel et al., 2003; Faulds et al., 2003, 2004). The prolific geothermal activity probably results from a transfer of NW-trending dextral shear in the Walker Lane to WNW extension in the northern Great Basin. Enhanced extension favors dilation and deep circulation of aqueous solutions along NNE-striking faults. The individual belts of geothermal activity may reflect loci of strain transfer (Faulds et al., 2004). Magmatism generally ceased in the region 10 to 3 Ma and thus most of the geothermal activity is amagmatic in origin.

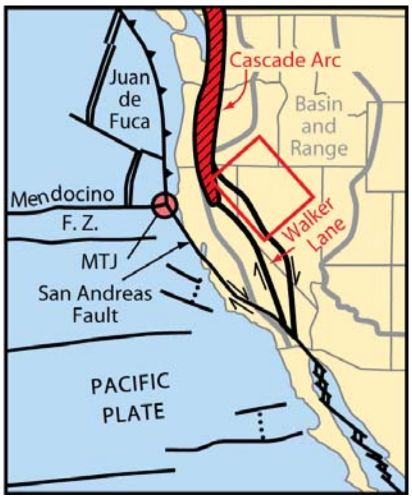

Figure 1: Present tectonic setting of western North America. The red box surrounds the locus of geothermal activity in the northwestern Great Basin. MTJ, Mendocino triple junction.

In the Great Basin, 20 geothermal systems have power plants either installed or under construction with a total capacity of approximately 760 MWe. Fifteen of these sites, with approximately 290 MWe capacity (installed or under construction) are not associated with young volcanism and are thought to owe their existence to active extensional or transtensional tectonics and high heat flow. Terrestrial surface heat flow ranges from 50 to ~120 mW/m^2, averaging roughly 90 mW/m^2 (Blackwell and Richards, 2004). The majority of the geothermal activity occurs in the transtensional, northwestern part of the Great Basin.

2.2 Western Turkey

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 (Figure 3). 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 4). 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 does not provide a direct heat source at upper crustal levels for the geothermal activity. Thus, similar to the Great Basin (USA), most of the geothermal activity can be considered amagmatic in western Turkey.

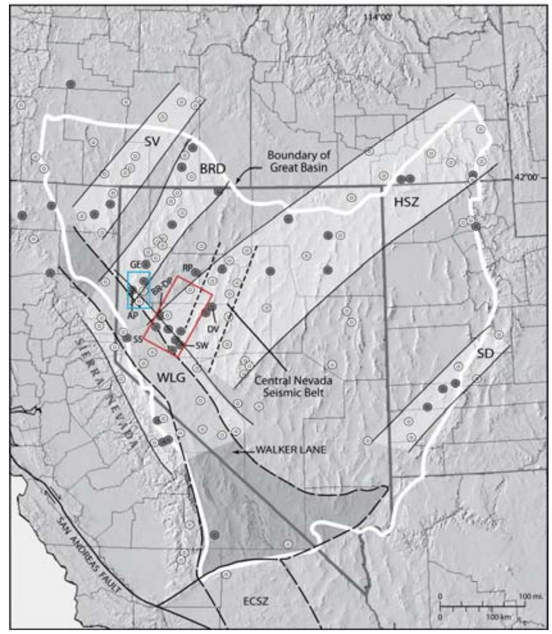

Figure 2: Geothermal belts in the Great Basin (from Faulds et al., 2004). Geothermal fields cluster in the Sevier Desert (SD), Humboldt structural zone (HSZ), Black Rock Desert (BRD), Surprise Valley (SV), and Walker Lane (WLG) belts. White circles are geothermal systems with maximum temperatures of 100-160^{o}C; grey circles have maximum temperatures >160^{o}C. ECSZ, eastern California shear zone. Dashed lines (short dashes) bound the central Nevada seismic belt. Red box surrounds Carson Sink region; blue box encompasses Pyramid Lake area. Abbreviations for individual geothermal fields: AP, Astor Pass; BR-DP, Brady's and Desert Peak; DV, Dixie Valley; GE, Gerlach; RP, Rye Patch; SS, Steamboat; SW, Salt Wells.

The present (2008) installed geothermal power generation capacity in Turkey is about 32.65 MWe, with direct use projects yielding ~795 MWt (Serpen et al., 2009). Eleven major, high-to-medium enthalpy fields in western Turkey have 570 MWe of proven, 905 MWe of probable and 1389 MWe of possible geothermal reserves for power generation. The majority of the geothermal activity occurs in the tectonically active Aegean and Marmara regions of western Turkey (Figure 4), generally along or near major E-W-striking normal faults, including major graben-bounding faults. Transtension dominates the Marmara region, whereas approximately north-south extension has characterized the Neogene in much of the Aegean region. Several geothermal fields in the Aegean region support district heating systems (e.g., Afyon, Balçova, Salihli, and Simav), and a few fields currently produce electricity (e.g., Germencik, Kizildere, and Salavatli). 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). Average heat flux is ~109mW/m^2 (Serpen, 2006).

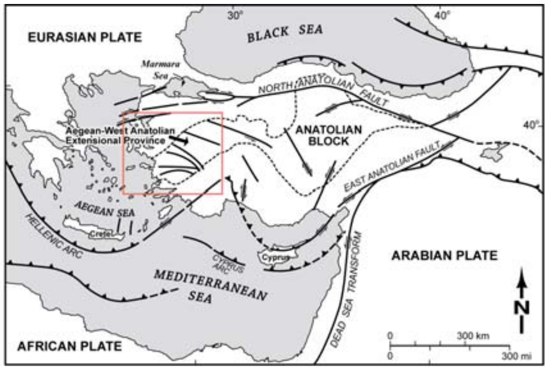

Figure 3: Tectonic setting of Turkey. Slab rollback in the Hellenic arc and westward escape of the Anatolian block, resulting from the collision of the Arabian plate with Eurasia, has induced late Miocene to recent, ~north-south extension in western Turkey. Red box encompasses study area in western Turkey.

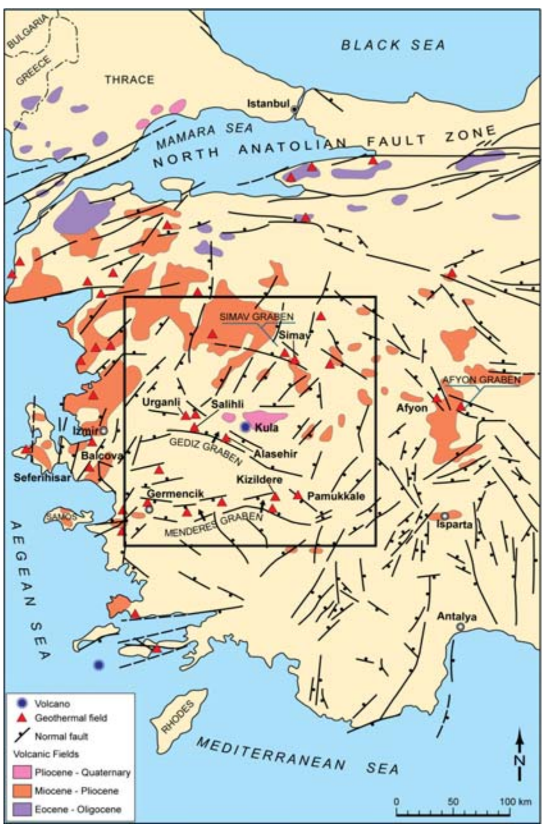

Figure 4: Generalized geologic map of western Turkey showing major fault zones and locations of geothermal systems. Black box surrounds the study area. Note the lack of Quaternary volcanism in the region. The mantle-derived basalts of the Kula volcanic field are the only Quaternary volcanics in the region.

3. GREAT BASIN GEOTHERMAL FIELDS

Although volcanism generally ceased 10 to 3 Ma, the northwestern Great Basin contains abundant geothermal fields, many with subsurface temperatures approaching or exceeding 200°C. The fields are particularly abundant in northern Nevada and neighboring parts of northeast California and southern Oregon (Coolbaugh et al., 2002; Coolbaugh and Shevenell, 2004; Figure 2) and cluster in the aforementioned NNE to NE-trending belts (Faulds et al., 2004). Regional assessments of structural controls show that N- to NE-striking faults (N0°E-N60°E) are the primary controlling structure for ~75% of geothermal fields in Nevada, and this control is strongest for higher temperature systems (Coolbaugh et al., 2002; Faulds et al., 2004). In the northwestern Great Basin, where the extension direction trends WNW, controlling faults generally strike NNE, approximately orthogonal to the extension direction. The controlling NNE-striking structures are typically moderately to steeply dipping normal fault zones, as exemplified at the Dixie Valley (Blackwell et al., 1999; Johnson and Hulen, 2002; Wannamaker, 2003), Rye Patch (Waibel et al., 2003), Brady's, and Desert Peak fields (Benoit et al., 1982; Faulds et al., 2003). However, the region is dissected by many closely spaced NNE-striking normal faults, many of which have little to no geothermal activity along them. Thus, it is important to determine which faults, segments of faults, or structural settings are most conducive for geothermal activity. We describe below the structural settings for four widely spaced geothermal fields in the Carson Sink, Pyramid Lake, and Black Rock Desert regions of the western Great Basin (Figure 2).

3.1 Carson Sink Region

The Carson Sink is a broad region of the western Great Basin that contains a large composite basin, the Carson Sink, and multiple small mountain ranges. It lies directly northeast of the northern Walker Lane. Normal faults dominate the area, but major range-front faults, common in much of the Basin and Range province, are largely confined to the margins of the Carson Sink. The Carson Sink is marked by abundant geothermal activity, including five operating power plants and several promising geothermal fields. We have analyzed the structural controls of several geothermal fields within the Carson Sink region (Faulds et al., 2003, 2006; Hinz et al., 2008) and report the findings on three fields here.

3.1.1 Desert Peak and Brady's

The Desert Peak and Brady's fields lie in the northern Hot Springs Mountains ~80 km east-northeast of Reno, Nevada, along the northern margin of the Carson Sink (Figure 2). The geothermal system at Brady's Hot Springs has an estimated reservoir temperature of 181°C (Shevenell and DeRocher, 2005) and supports a combined flash and binary geothermal power plant with a total electrical generation capacity of 26.1 MWe. The surface expression of the Brady's geothermal system is a 4-km-long, NNE-trending zone of warm ground, fumaroles, and mud pots along the Bradys fault. The geothermal system at Desert Peak, with a reservoir temperature of 218°C (Shevenell and DeRocher, 2005), currently fuels a 12.5 MWe geothermal flash plant.

The Hot Springs Mountains are dominated by a thick (>2 km) section of Miocene volcanic and sedimentary rocks resting on either Oligocene ash-flow tuffs or Mesozoic plutonic-metamorphic basement. The strata are cut by NNE-striking en echelon normal faults and deformed into a series of NNE-trending, moderately tilted fault blocks (Benoit et al., 1982; Faulds et al., 2003; Faulds and Garside, 2003). Kinematic data indicate essentially dip-slip normal displacement on the NNE-striking faults. Fault scarps indicate significant Quaternary extension in the area.

Both geothermal fields occupy left steps or small stepovers in the en echelon, steeply dipping NNE-striking normal fault zones (Faulds et al., 2006; Figure 5). The Brady's field lies along the Brady's fault zone, whereas the Desert Peak field occurs along the Rhyolite Ridge fault zone. Displacement on these fault zones locally exceeds ~2 km. At least one segment of the Brady's fault has accommodated Quaternary normal displacement (Trevor and Wesnousky, 2001). Multiple fault strands in the stepovers provide subvertical conduits of high fracture density that probably enhance fluid flow and facilitate the rise of deep-seated thermal plumes. The NNE-striking faults are orthogonal to the regional WNW extension direction and are thus favorably oriented for fluid flow.

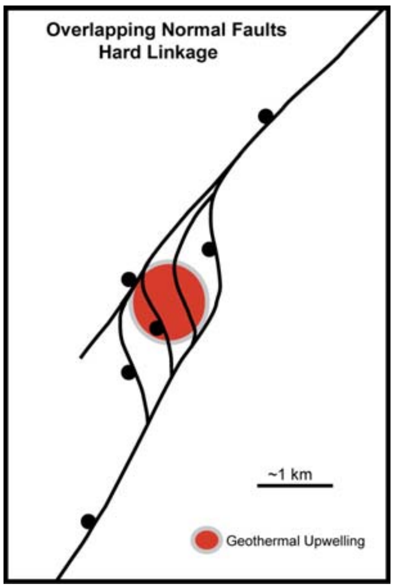

Figure 5: Conceptual model of a stepover in a normal fault zone. Stepovers appear to control the geothermal systems at Desert Peak and Brady's. Multiple minor faults provide hard linkage between two major strands and serve to increase fracture density, thus providing an avenue for the ascent of geothermal fluids.

3.1.2 Salt Wells

The Salt Wells geothermal field occupies the west-southwest margin of the Salt Wells basin ~20 km southeast of Fallon, Nevada, in the southeastern part of the Carson Sink (Figure 2). ENEL recently completed construction of a 10 MWe binary power plant that taps a shallow geothermal reservoir with an estimated temperature of ~140°C. Geothermometry suggests that a deeper reservoir may exist at temperatures of 180-190°C. This area lies near the intersection of the Walker Lane and central Nevada seismic belt, where several historic 6.0 to 7.0 magnitude normal and normal-dextral earthquakes have occurred (Caskey et al., 2004). The stratigraphy consists of middle to late Miocene basalt lavas and lesser interbedded sedimentary rock. Well data suggest that the basalt exceeds 400 m in thickness. The basalt overlies Oligocene ash-flow tuffs and/or Mesozoic granitic and metamorphic basement. The basalts are overlain by Quaternary alluvial fans and lacustrine deposits associated with Pleistocene Lake Lahontan. Gently to moderately E-tilted fault blocks bounded by steep W-dipping northerly striking normal fault zones characterize the structural framework of the area. However, a major east-dipping, northerly striking normal fault zone (here referred to as the Salt Wells fault zone) bounds the west side of the Salt Wells basin and is marked by several Holocene scarps cutting Pleistocene silicified sand deposits. Temperature gradient drilling has defined a large, 12-km-long heat flow anomaly essentially along this fault zone at the Salt Wells geothermal system (Edmiston and Benoit, 1984). This fault zone is dying out southward in the vicinity of the geothermal system.

The Salt Wells geothermal field appears to be localized along the steeply E-dipping Salt Wells fault zone as it loses displacement southward, breaks into several splays (i.e., horsetails), and intermeshes with the W-dipping fault system (Figure 6). The increased fracture density generated by the multiple intersecting faults probably produced greater permeability in the area, which has in turn provided convenient channelways for the geothermal fluids. The steeply dipping geometry of the faults suggests subvertical conduits of highly fractured bedrock.

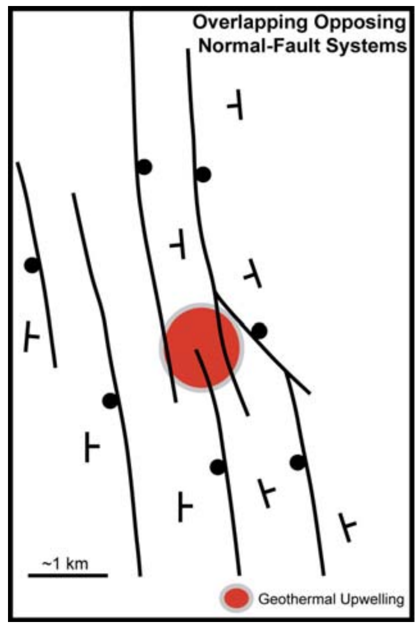

Figure 6: Conceptual model of overlapping, oppositely dipping normal fault systems. Multiple fault intersections in the subsurface increase fracture density and provide pathways for geothermal fluids, as exemplified at Salt Wells. Strike and dip symbols indicate tilt directions of fault blocks.

3.2 Black Rock Desert Belt

The Black Rock Desert Belt is a NNE-trending zone of abundant geothermal activity in the northwestern part of the Great Basin. At least 18 geothermal fields lie in this belt, including seven high temperature systems (>160°C). One small power plant and associated vegetable dehydration facility have been developed in this region, but significant geothermal exploration is now underway with anticipated future development in several areas. The Astor Pass and Gerlach fields are discussed below.

3.2.1 Pyramid Lake Region, Astor Pass

The Pyramid Lake region (Figures. 2 and 7) lies in the southern part of the Black Rock Desert belt near the terminus of a major dextral fault in the Walker Lane (the Pyramid Lake fault zone) and thus occurs in a transitional region between NW-trending dextral shear in the Walker Lane and WNW extension in the northwestern Great Basin. At least six geothermal systems occur within this area. Although none of the systems have been developed, significant exploration has been undertaken. The area contains thick sequences (1-2 km) of mainly mafic middle Miocene volcanic rock intercalated with thin sedimentary lenses, all overlying a Mesozoic granitic to metamorphic basement. Approximately 10 km of dextral offset on the Pyramid Lake fault is transferred in the Pyramid Lake area into WNW extension, which is accommodated on NNW- to NNE-striking normal and normal-dextral faults. Many faults in the area have Quaternary scarps (e.g. Bell, 1984; Briggs and Wesnousky, 2004; Vice, 2008). Abundant geothermal activity characterizes the Pyramid Lake area. Enhanced dilation induced by the transfer of dextral shear into extension may account for the abundant activity. Hot springs upwelling into Pleistocene Lake Lahontan formed many tufa towers in this region. These tufa towers can be used as indicators for locating blind geothermal systems.

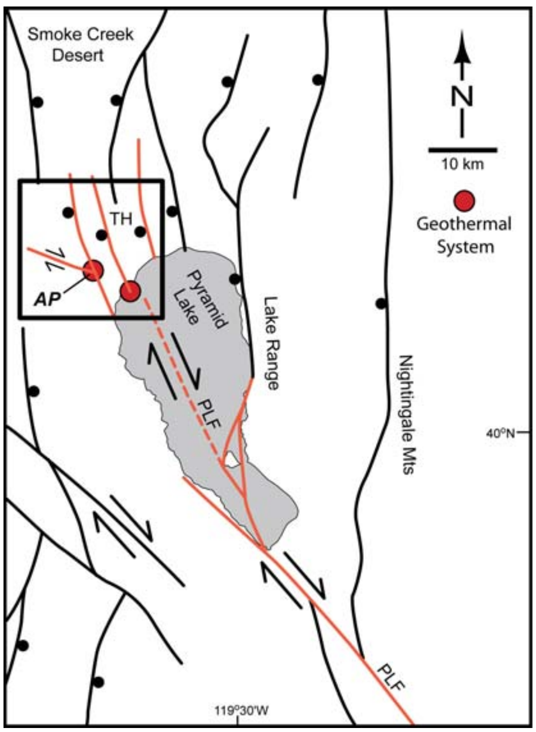

Figure 7: Generalized map of Pyramid Lake area. Two geothermal fields lie in the horse-tailing north end of the right-lateral Pyramid Lake fault (PLF). Dextral slip on PLF diffuses northward into northerly striking range-front faults along the west flanks of the Lake Range and Nightingale Mountains and oblique-slip (mainly normal with minor dextral component on some strands) NNW-striking faults in the Terraced Hills. The Astor Pass geothermal system (AP) occurs at the intersection between a NNW-striking, primarily normal fault and WNW-striking mainly dextral fault. Box surrounds study area. TH, Terraced Hills.

The Astor Pass area lies near the northwest shore of Pyramid Lake (Figure 7). Intersecting linear WNW- and NNW-trending belts of tufa towers at Astor Pass suggest the presence of an underlying or blind geothermal system, but no hot springs or other clear-cut geothermal features are present at Astor Pass. Nearby hot springs along Pyramid Lake have surface temperatures as high as boiling and geothermometer temperatures of 143°-213°C (Mariner et al., 1974; Grose and Keller, 1975) but cannot be developed due to cultural significance to the Pyramid Lake Indian Reservation. We therefore evaluated the geothermal potential of the Astor Pass area, which lies outside the view shed of the culturally significant area.

Detailed geologic mapping and structural analysis elucidated the links between faulting and the inferred blind geothermal system at Astor Pass (Vice et al., 2007). Closely spaced N- to NNE-striking normal and NNW- to WNW-striking dextral-normal faults fragment the area into a series of gently to moderately (~15-40^{o}) E-tilted fault blocks. The intersecting belts of tufa towers probably mark intersecting WNW- and NNW-striking normal-dextral fault zones.

The southwest quadrant of this fault intersection is probably dilational and was therefore recommended for drilling. The drilling to 558 m depth confirmed a geothermal system with temperatures of at least 90°C. Analysis of cuttings shows that the upper part of the reservoir lies in highly fractured, hydrothermally altered basalt and rhyolite units. The closely-spaced dextral-normal faults in the Astor Pass area probably represent the horse-tailing northwest end of the Pyramid Lake fault (Figure 7), whereby dextral slip along the Pyramid Lake fault is progressively transferred to N- to NNE-striking normal faults. Dilational fault intersections or fault geometries appear to be particularly favorable for geothermal activity within this region of enhanced extension.

3.2.2 Gerlach

The Gerlach geothermal field lies in the south-central part of the Black Rock Desert belt on the southeast flank of the Granite Range (Figure 2; Keller and Grose, 1978). Boiling springs, mud pots, and siliceous sinter mark the Gerlach Hot Springs. The quartz and K-Na-Ca-Mg geothermometers indicate a possible reservoir temperature for geothermal fluids of ~160-200°C, which is consistent with the occurrence of siliceous sinter. The stratigraphy of the Gerlach area consists of middle to late Tertiary volcanic and sedimentary rocks that rest directly on Mesozoic granitic and Permian-Triassic metamorphic basement. The Tertiary rocks are overlain by Quaternary alluvial fans, lacustrine deposits associated with Pleistocene Lake Lahontan, and eolian deposits. The Gerlach area is dominated by alluvial fans shed from the Granite Range, which consist primarily of granitic detritus. Lacustrine deposits crop out just to the east and south of Gerlach within the playas of the Black Rock and Smoke Creek Deserts, respectively.

The Gerlach Hot Springs occur at the south end of the Granite Range near the intersection of two major range-front faults, both of which are marked by Quaternary fault scarps. The Granite Range is a large gently NE-tilted horst block bounded by the NW-striking oblique-slip Granite Range fault zone on the southwest and major NNE- to NNW-striking normal fault zones on the east and northeast. The E-dipping fault zone on the east flank of the range dies out southward toward Gerlach. Although the SW-dipping normal-dextral Granite Range fault essentially terminates ~5 km west of Gerlach, several minor strands of this fault zone appear to cut the southern end of Granite Range and extend into the Gerlach area. Although bedrock exposures are not present in the vicinity of the hot springs, we infer that the geothermal activity is controlled by the intersection of steeply dipping NW- and NNE-striking fault zones along the horse-tailing ends of the two major range-front fault zones (Figure 8). The intersections of these steeply dipping faults generate highly fractured subvertical conduits that accommodate the ascent of the hydrothermal fluids.

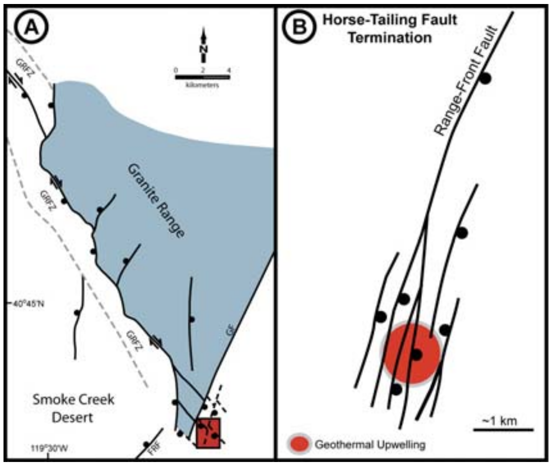

Figure 8: A. Generalized structural map of the Gerlach area. Red box roughly outlines geothermal field. Lightly shaded area denotes the Granite Range. The geothermal field lies near the intersection of two southward terminating range-front faults. FRF, Fox Range fault; GF, Gerlach fault, which is the range-front fault on the east side of the Granite Range; GRFZ, Granite Range fault zone, which forms the range-front fault on the southwest margin of the Granite Range. Balls shown on downthrown sides of normal or oblique-slip faults. B. Schematic termination of a major normal fault, whereby faults break up into multiple splays or horsetail.

4. WESTERN TURKEY GEOTHERMAL FIELDS

Much of western Turkey has undergone significant ~N-S extension from early Miocene to recent time (Seyitoğlu et al., 2002; Işik et al., 2003a; Purvis and Robertson, 2004; Sözbilir, 2001). 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). Major north-south extension has continued into late Miocene to recent time and may represent a distinct later phase of extension (e.g., Lips et al., 2001). 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 3; Purvis and Robertson, 2004). Major steeply dipping ~E-W-striking normal fault zones that cut Pliocene-Quaternary sediments bound the major grabens in western Turkey. Some of these faults have ruptured in recent earthquakes (Eyidoğan and Jackson, 1985). In addition to the ~E-W-striking normal faults, widely spaced (~2-5 km) transversely oriented (north-northwest- to north-northeast-striking) oblique-slip faults dissect the margins of the major grabens.

Many of the geothermal systems in this region lie within or along the margins of the major ~E-W-trending grabens (e.g., Şimşek and Gulec, 1994). Late Miocene to 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 4; 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 4), the deep sources for these basalts indicate that related magmas do not provide a direct source of heat for the geothermal systems. Below, we describe the structural settings for four major geothermal fields in three of the major ~E-W-trending grabens in western Turkey.

4.1 Büyük 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. 4 and 9). A major south-dipping normal fault system bounds the northern margin of the graben, juxtaposing Neogene sediments against the Menderes massif, 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 (e.g., Şimşek, 2003). Northerly striking transverse faults dissect the northern margin of the graben and commonly extend into the Menderes massif. We conducted reconnaissance studies of the Kizildere and Germencik geothermal fields in the Büyük Menderes graben, the two hottest geothermal systems in Turkey, which are respectively located near the eastern and western ends of the graben.

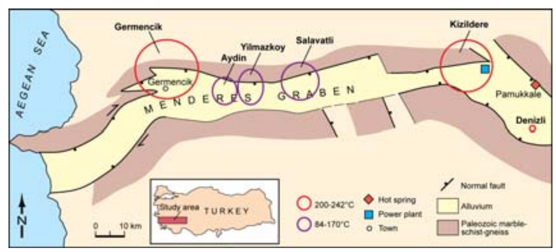

Figure 9: Geothermal fields of the Menderes graben, western Turkey. Reconnaissance studies were conducted on the Kizildere and Germencik fields, which are the two hottest fields known in Turkey. Both the Kizildere and Germencik geothermal systems occur near the ends of the main border fault zone on the north side of the Menderes graben.

4.1.1 Kizildere

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 field known in Turkey. Kizildere contains the oldest operating geothermal plant in Turkey, with an installed capacity of 20 MWe. Geothermal fluids are also used for 6000 m² 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 9). 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 ENE-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. 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 ENE-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 Menderes border fault. As the fault loses displacement, it breaks into multiple splays (or horsetails; e.g., Figure 8B). 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.

4.1.2 Germencik-Omerbeyli

The Germencik-Omerbeyli field (e.g., Şimşek, 1984) is the most significant geothermal system in the western part of the Menderes graben, as a 45 MWe double-flash power plant was recently constructed at the site. This field lies directly south of the Menderes border fault (Figure 9). Fumaroles, hot springs, and recent hydrothermal alterations are common in the area. When active, the Aktaş fumarole (101^{o}C) was 3 km northeast of the town of Germencik along an E-striking high-angle fault. The border fault zone is dying out westward in this area, as evidenced by the westward termination of the footwall horst block and gravity data indicating significant westward shallowing of Menderes graben (Işık and Şenel, 2009). The main geothermal aquifer appears to be focused along the E-W border fault zone at 1-2.4 km depth in marble and quartzite. The highest reservoir temperature is 232°C, which is the second highest temperature field thus far discovered in Turkey. One well 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 (Figure 8B).

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 9). The intersection between these two major faults may generate a region of enhanced dilation in the Germencik vicinity. Second and possibly more important is a major steeply dipping, ~N-striking cross fault that intersects the main E-striking border fault in the Germencik-Omerbeyli area. 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.

4.2 Gediz-Alaşehir Graben, Salihli

Detailed geologic mapping of 30-35 km^2 and analysis of faults were employed to assess the structural controls of the Kurşunlu geothermal field in the Salihli area (Faulds et al., 2008). This field occurs along the active southern margin of the Gediz-Alaşehir graben (Figure 4), where Neogene sedimentary units and basement rocks are cut by a network of E-striking, moderately to steeply dipping normal faults (Figure 10). Fractured rocks of the Menderes Massif, such as mica-schist, gneiss, and karstic marbles, are the reservoir rocks in the Salihli geothermal fields.

Most springs and hot wells in the Salihli area lie near the gently N-dipping Gediz detachment fault, which predates the active Alaşehir frontal fault. Marble and breccia along the detachment provide good channelways for flow, possibly somewhat distal to the main upwelling. The depth to the shallow reservoir in the Kurşunlu field varies between 10-200 m (Yilmazer and Karamanderesi, 1994). Temperatures at the Kurşunlu field range from 63 to 89^{o}C. 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), suggesting a deeper reservoir. Thermal-mineral waters are used for bathing and medicinal purposes, as well as a district heating system for 5,000 homes in Salihli. Discharge temperatures range from 37°C to 155°C, and average production temperatures are ~90°C.

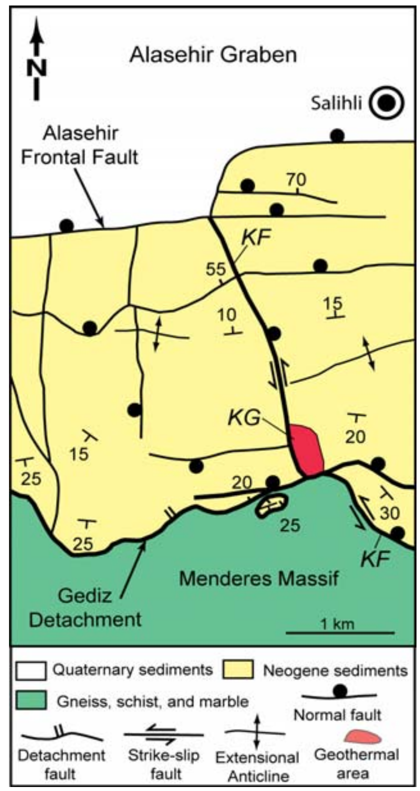

Figure 10: Generalized geologic map of the Salihli area, western Turkey. The Kurşunlu (KG) geothermal field occurs near or at the intersection of a northerly striking, sinistral-normal transfer fault (KF, Kurşunlu fault) and the Gediz detachment fault. The left step in the transfer fault accommodates dilation and therefore facilitates fluid flow and geothermal activity.

The structural framework of the Salihli area is characterized by gently to moderately tilted (5-40^{o}) Neogene sedimentary rocks cut by ~E-striking normal faults and northerly (NNW to NNE) striking oblique-slip cross faults (Figure 10). The predominant E-W strike of normal faults and tilting reflects regional north-south extension. The two largest faults in the area are the moderately N-dipping Alaşehir border fault zone and gently (~10-30^{o}) N-dipping Gediz detachment fault. The former has accommodated significant uplift and exhumation of the southern shoulder of the Alaşehir graben and is marked by Quaternary fault scarps. In contrast, the Gediz detachment fault shows no evidence for Quaternary displacement. It is typically marked by a thick zone of cataclasis that overprints an earlier mylonitic fabric. Numerous minor steeply dipping ~WNW- to E-striking normal 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. In addition, a subset of northerly striking oblique-slip, steeply dipping transverse faults dissects the area.

The Kurşunlu Canyon geothermal field lies at the intersection of a minor northerly striking sinistral-normal transfer fault and the Gediz detachment fault. A left step in the transfer fault at the intersection with the detachment generates a small (~500 m long) dilational zone that provides a channelway for geothermal fluids (Figure 10). The left step may result from refraction of the transfer fault across the detachment, which marks a strong rheological contrast between metamorphic basement and Neogene sediments. We view the reservoir as plunging gently northward along the intersection of the detachment with the transfer fault. Although this model can account for the shallow reservoir and surface springs, it may not predict the location of the main upwelling that feeds the geothermal system. Major steps in the Alaşehir frontal fault and/or complex fault intersections between the transverse faults and WNW-striking normal faults may accommodate upwelling in the Salihli area.

4.3 Simav Graben, Eynal

The Eynal geothermal field lies in the northeastern corner of the Simav graben (Figures. 4 and 11; Gemici and Tarcan, 2002). It 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 (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 ~20 Ma Egrigoz granite (Işik et al., 2003b). The graben is bounded on the south by a major N-dipping normal fault 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. A system of S-dipping antithetic normal faults with much less displacement bounds the northern margin of the basin (Figure 11).

Several hot springs, ranging in temperature from 51 to 90°C, emanate from alluvium along the northern margin of the basin, where sediments are juxtaposed against Nasa basalt along a complex, anastomosing part of the S-dipping antithetic fault system (Figure 11). 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 (>180°C) at depth. Existing wells penetrate to 958 m, but the main reservoir may not be discovered yet. This 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, whereby highly fractured steeply dipping conduits have provided pathways for fluid circulation. The S-dipping normal fault system along the north side of the graben in the Eynal area may partly compensate for decreasing displacement to the east along the Simav fault on the south side of the graben.

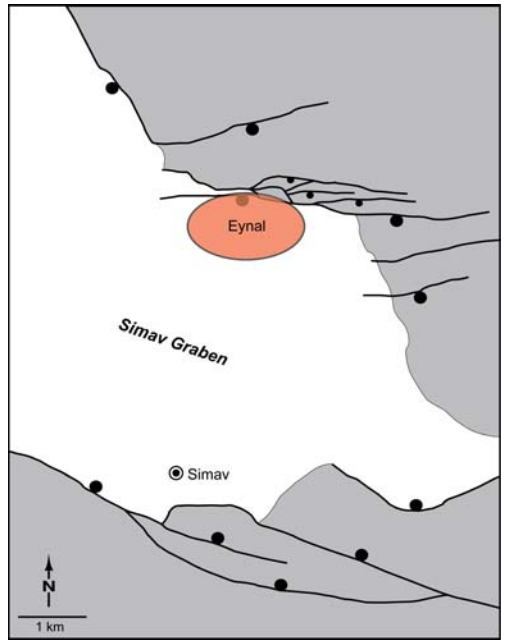

Figure 11: Generalized map of the eastern part of the Simav graben. The Eynal geothermal system occurs in the northeastern part of the graben along an anastomosing system of antithetic south-dipping normal faults. Multiple fault intersections and associated high density of fractures generates a broad zone of higher permeability, which accommodates the ascent of geothermal fluids. Bedrock areas are shaded.

5. CONCLUSIONS

Although many more fields need to be analyzed to fully characterize the structural controls on geothermal systems in extended terranes, several major themes are emerging. First, many of the fields do not reside on major range-front faults but rather on less conspicuous normal fault zones. Despite differences in overall tectonic setting between western Turkey and the western Great Basin (USA), many geothermal fields in both regions appear to occupy discrete steps in fault zones or lie in zones of intersecting, overlapping, and/or terminating faults. It is important to note that major normal fault zones, including many range-front faults, typically horsetail, or splay into multiple strands, near their terminations. In addition, the favorable structural settings typically involve steeply dipping Quaternary fault zones. Structural settings that produce conduits of highly fractured rock along fault zones oriented approximately perpendicular to the least principal stress are critical for geothermal activity in both regions.

Our findings have potentially important implications for geothermal exploration in extended terranes, especially for blind geothermal systems. Exploration strategies may benefit from focusing on features indicative of intersecting, terminating, and overlapping fault systems. Such features may include: 1) discrete steps in range-fronts that typically correspond to stepping or overlapping range-front faults or possibly intersections between major normal faults and oblique-slip transfer faults, 2) interbasinal highs, which characterize overlapping oppositely dipping normal fault systems, 3) mountain ranges consisting of relatively low, discontinuous ridges, which commonly signify en echelon normal fault systems with multiple fault terminations and intersections, and 4) lateral terminations of major mountain ranges, which are typically associated with the horse-tailing ends of major normal faults and/or intersecting normal and strike-slip to oblique-slip fault zones. The similarities in favorable structural settings between western Turkey and the Great Basin (USA) further suggest that broad exploration models can be developed for geothermal activity in particular structural environments.

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