

Structural Evidence For Extensional Domain-Type Geothermal Play In Western Anatolia: A Case Study From Afyon-Akşehir Graben

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Abstract

Afyon-Akşehir Graben (AAG) which consists of the southeastern part of Akşehir-Simav Fault System (ASFS) is one of the active depression areas in Western Anatolia. The western sector of the NW-SE-trending AAG is controlled by many active normal fault segments, namely Erkmen, Gecek, and Gazlıgöl Faults. Two main geothermal fields namely, Ömer-Gecek and Gazlıgöl contain reservoirs of fluid with temperatures up to 130° C, are located on the junction points of Gecek-Erkmen faults and Gazlıgöl-Yarımca faults, respectively. The area contains three unconformity bounded geological units; Mesozoic rocks of the Afyon Metamorphic Zone (reservoir unit), Miocene volcano-sedimentary succession (cover unit), including several sedimentary and volcanic units and Quaternary modern basin-fills of alluvial, fluvial and travertine deposits. This study involves use of geological mapping and structural geology methods to identify play type of geothermal fields mentioned above. Paleostress inversion analysis based on basin-bounding active faults and active extensional cracks along the travertine deposits shows that the AAG has been deformed under the control of multidirectional extension, with E-W and NE-SW to NW-SE orientations since Plio-Quaternary time. These types of extension are directly related with the linkage of cross faults that oriented at high-angle to the strike of NW-SE-trending major breakaway fault of AAG. Field-based studies also reveals that geothermal fields in AAG develops on the interactions of these active faults on the extensional domain type geothermal play without active volcanism coming to the surface.

Keywords

Afyon Akşehir Graben;
Geothermal play type;
Extensional domain;
Western Anatolia

Batı Anadolu'da Genişleme Alanı Tipi Jeotermal Ortamın Varlığına Dair Yapısal Veriler: Afyon-Akşehir Grabeni'nden Örnek Bir Çalışma

Öz

Akşehir-Simav Fay Sistemi'nin güneydoğu bölümünü temsil eden Afyon-Akşehir Grabeni (AAG), Batı Anadolu'daki aktif çöküntü alanlarından birisidir. KB-GD uzanımı AAG'nin batı bölümü Erkmen, Gecek, Gazlıgöl gibi diri normal faylar ile kontrol edilmektedir. 130° C'ye varan rezervuar su sıcaklıkları ile bu bölgedeki en önemli jeotermal sahalar olan Ömer-Gecek ve Gazlıgöl Jeotermal sahaları sırasıyla Gecek ve Erkmen Fayları ile Gazlıgöl ve Yarımca faylarının kesişim alanlarında yer almaktadır. Bölgede yüzlek veren jeolojik birimler, birbirlerinden uyumsuzlukla ayrılan Afyon Metamorfik Zonu'na ait Mesozoik kayaçlar (rezervuar birim), Miyosen yaşlı volkano-sedimanter ve volkanik birimler (örtü birimi) ile Kuvaterner yaşlı alüvyal-flüvyal ve travertenlerden oluşan modern havza dolgularından oluşmaktadır. Bu çalışma, yukarıda bahsedilen jeotermal sahaların ortam tipini, jeolojik haritalama ve yapısal jeoloji gibi saha çalışmalarını içeren metodlar kullanılarak tanımlamayı amaçlamaktadır. Havzayı sınırlayan fay düzlemleri üzerinde yapılan paleostres analizleri ve faylar üzerinde ölçülen güncel açılma çatlakları, AAG'nin Pliyo-Kuvaterner'den beri, D-B ve KD-GB'dan KB-GD yönüne kadar değişiklik gösteren çok yönlü genişlemeli tektonizma etkisinde şekillendiğine işaret etmektedir. Genişleme tipi, AAG'nin KB-GD uzanımlı ana graben fayı ile bu faya yüksek açılı uzanan çapraz fayların bağlantıları ile ilişkilidir. Arazi

Anahtar kelimeler

Afyon Akşehir Grabeni;
Jeotermal ortam;
Genişleme alanı; Batı
Anadolu

bazlı çalışmalar, AAG içerisindeki jeotermal sahaların yüzeye gelmiş aktif volkanizma olmaksızın diri fayların kesişim noktalarında gelişen genişleme alanı tipi jeotermal ortamlara işaret ettiğini göstermektedir.

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1. Introduction

The neotectonic structures of Anatolia have been shaped by deformation model which is affected by the westward tectonic escape of the Anatolian block, core complex formation, subduction related slab edge processes and backarc spreading as a result of collision between African, Arabian and Eurasian plates, in the Aegean region (Figure 1a) (e.g. Dewey and Sengör, 1979; Şengör et al., 1985; Bozkurt, 2001; Biryol et al., 2011). As a result, the Western Anatolian Extensional Province (WAEP), is currently experiencing an approximately N–S continental extension and contains major depression areas with geothermal potentials such as Gediz, Büyük Menderes, Denizli and Afyon-Akşehir grabens (Dewey and Şengör 1979; Şengör and Yılmaz 1981; Şengör et al., 1985; Seyitoğlu and Scott 1991; Yılmaz et al., 2000; Bozkurt 2001; Sözbilir 2005; Özkaymak et al., 2013, Figure 1b). Extensional domain type geothermal plays such as Western Turkey are dominantly controlled by fault or fault-leakage (Moeck, 2014). Because convection or fluid circulations occurs along these faults, geometry and stress modelling of the faults are essential in order to exploration for geothermal potentials. On the other hand, although some geological circumstances such as reservoir temperature, enthalpy, hydrogeology and exergy of these geothermal fields have been well analyzed in WAEP (e.g. Şimşek, 2003; Gemici and Tarcan, 2003; Öztürk et al., 2007; Erkan, 2015; Mertoğlu et al., 2015), the studies on structural controls and geothermal play types of them are quite rare (e.g. Şimşek, 1997; Pfister et al., 1998; Faulds et al., 2009).

Akşehir-Simav Fault System (ASFS) is one of the most active neotectonics structures in the WAEP and contains many geothermal fields between Iğın and Balıkesir cities (Figure 1). Some of them are

located in WNW-ESE-trending and approximately 150-km-long Afyon-Akşehir Graben (AAG) which represent the southeastern part of the ASFS.

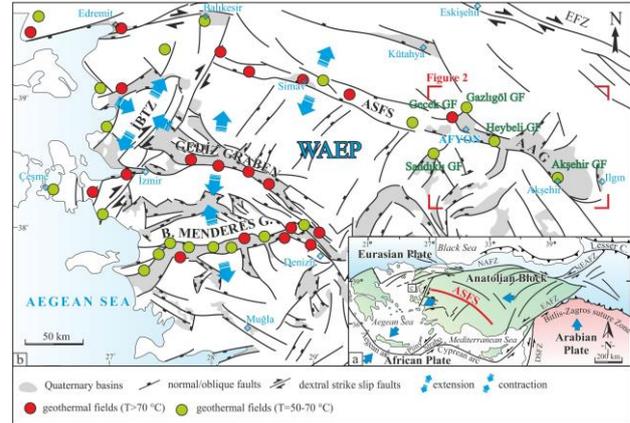


Figure 1. a) Tectonic outline of the eastern Mediterranean area (compiled from Özkaymak, 2015). Abbreviations: ASFS, Akşehir-Simav Fault System; DSFZ, Dead Sea Fault Zone; EAFZ, East Anatolian Fault Zone; NAFZ, North Anatolian Fault Zone; NEAFZ, Northeast Anatolian Fault Zone. b) Simplified map showing the major active basins and geothermal fields in western Anatolia (compiled from Faulds et al., 2009; Özkaymak, 2015; Mertoğlu et al., 2015). Abbreviations: İBTZ: İzmir-Balıkesir Transfer Zone; AAG: Afyon-Akşehir Graben; WAEP: West Anatolian Extensional Province; EFZ: Eskişehir Fault Zone

Gazlıgöl, Ömer-Gecek, Heybeli and Akşehir geothermal fields have the most known geothermal springs. Gazlıgöl and Ömer-Gecek geothermal fields are located in the Afyon Basin (northwestern part of the AAG) and contain reservoirs of water with maximum temperatures of 70°C and 130°C, respectively. Geothermal well location and temperature data are taken from Afyon Geothermal Facilities Tourism Ind. Trade Incorporated Business (AFJET). This study presents new field evidence, including geologic mapping, geomorphologic and

structural analysis of the Gazlıgöl and Ömer-Gecek geothermal fields, to evaluate structural features of their geothermal play types.

2. Geological Setting

2.1. Geology of the Study Area

Afyon-Akşehir Graben is an approximately 150 km long, 4-20 km wide NW-SE-trending active depression which is controlled by a numerous active dip/oblique slip normal fault segments (Koçyiğit, 1984; Koçyiğit et al., 2000; Emre et al., 2011; Özkaymak et al., 2017 and 2019). The length of these faults range from 8 to 29 km, with an average length of about 15 km (Duman et al., 2018; Emre et al., 2018). The historical and instrumental earthquake records indicate the existence of large number of earthquakes that created surface ruptures in this system. The latest one occurred on the Sultandağı Fault with a magnitude of 6.3 (03 February 2002) and caused a 26-km-long surface rupture in the middle part of the graben (Figure 2) (Yürür et al., 2002; Tan et al., 2008).

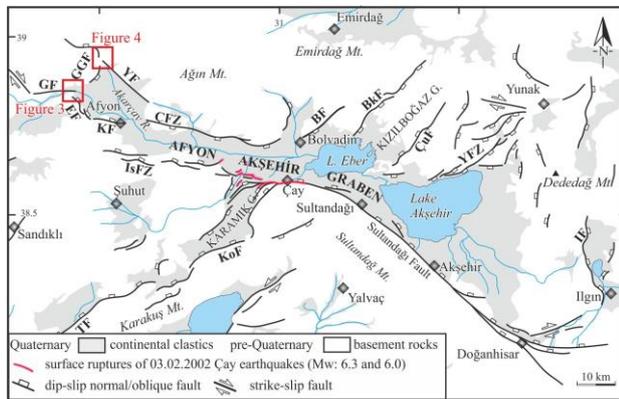


Figure 2. The active fault map of study area (compiled from Emre et al. 2011; Özkaymak et al. 2017) Abbreviations: GF: Gecek Fault; GGF: Gazlıgöl Fault; EF: Erkmen Fault; YF: Yarımca Fault; KF: Karahisar Fault; ÇFZ: Çobanlar Fault Zone; İSFZ: Işıklar Fault Zone; BF: Bolvadin Fault; BkF: Büyük Karabağ Fault; ÇuF: Çukurcak Fault; YFZ: Yunak Fault Zone; IF: Ilgın Fault; KoF: Kocbeyli Fault; TF: Tatarlı Fault.

The western sector of the AAG is controlled by active normal faults, namely Erkmen Fault, Gecek Fault, Gazlıgöl Fault, Karahisar Fault and Yarımca Fault. Gazlıgöl and Ömer-Gecek Geothermal fields

are located in the western part of the graben, where the Holocene deposits and basement rocks are tectonically juxtaposed along the mountain fronts.

2.2. Ömer-Gecek Geothermal Field

Basement rocks in the study area are represented by rocks of Afyon Zone which was metamorphosed under blueschist facies conditions during late Cretaceous and early Cenozoic times (Candan et al., 2005; Pourteau et al., 2010 and 2013). The unit is composed of moderately folded and jointed schist and marbles with quartzite veins. Metamorphic rocks of the Afyon Zone are unconformably overlain by the Miocene-Pliocene sequence which starts with the terrestrial deposits representing the polygenic conglomerate and mudstone alternation. Then, grades upward into volcano-sedimentary deposits comprising of whitish-grey tuffite and agglomerate clasts. On top of this unit is composed of trachy-andesitic lava and volcanoclastic rocks, consisting tuff and agglomerate. The thickness of lava varies between 80 and 100 m (Yıldız et al., 2010). The Afyon Volcanics were previously dated by Ar/Ar method yielding age ranging from 15.5 to 8.6 Ma (Prelevic et al., 2012; Akal et al., 2013). The uppermost part of the succession is represented by cream-beige coloured silicic and clay altered limestone. The sequence is unconformably overlain by the Quaternary modern basin fills consisting of alluvial, colluvial, fluvial and travertine deposits.

Ömer-Gecek geothermal field is located in the northwestern part of the Afyon Basin consisting of four geothermal springs, namely, Ömer, Gecek, Uyuz and Kızık springs. Structures shaping the northwestern side of basin have dominantly dip-slip normal fault character. Several NNW-SSE and NNE-SSW-trending dip-slip normal faults which cut mostly the basement rocks were mapped in the field (Figure 3). These faults also represent the structural contact between Miocene-Pliocene sequence and the pre-Neogene basement rocks to the north. The northern boundary of the Afyon Basin is represented by NE-SW-trending and southeast dipping Gecek fault. Slip lines with an average rake of 78°E indicate the normal behaviour on the E-W-

striking fault planes on site 1 (Figure 3). Along the boundary fault, Miocene-Pliocene terrestrial sediments and recent alluvial are juxtaposed. A few northwest dipping normal fault segments cut Quaternary travertines and forms step-like geometry around Uyuz spring (Figure 3).

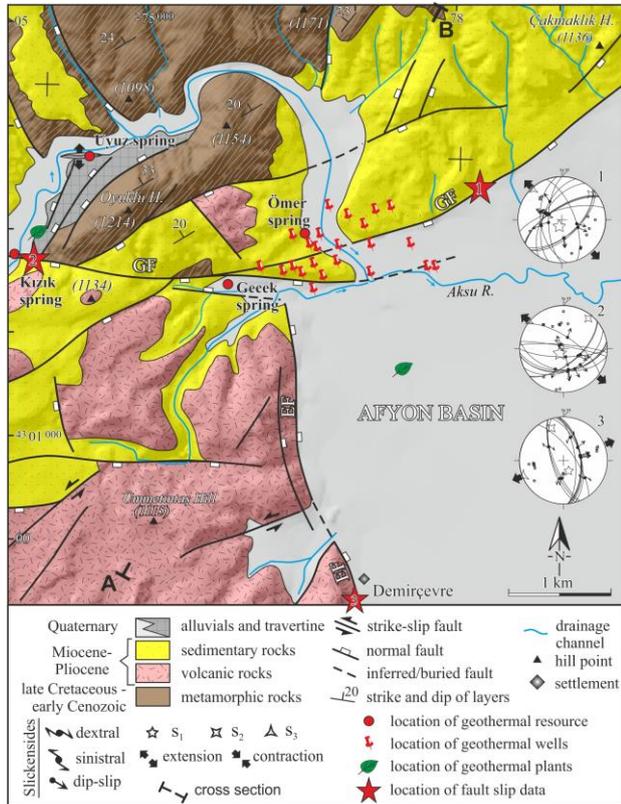


Figure 3. Detailed geologic map of the Ömer-Gecek geothermal field. Note that the results of kinematic analysis of faults are shown on eastern side of the figure. Geothermal well location and temperature data are taken from Afyon Geothermal Facilities Tourism Ind. Trade Incorporated Business (AFJET). Abbreviations: GF: Gecek Fault; EF: Erkmen Fault

Here, E-W-trending fissure-ridge-type travertine formations are exposed on the basinward fault splay. Western border of the Afyon Basin is controlled by a NNE-SSW-trending and east dipping Erkmen Fault which exhibits well preserved slip surfaces indicating N5°W striking normal faulting with a rake of 86° at the site 3. Around Demirçevre town, volcanic rocks cover wide areas on the footwall of the Erkmen Fault while hangingwall is made up of alluvial fluvial sediments. Gecek spring is located on the junction of Erkmen and Gecek

faults at the northwestern corner of the Afyon Basin.

2.3. Gazlıgöl Geothermal Field

Gazlıgöl geothermal field is located in the northeastern part of the Afyon Basin. Many fault splays were mapped both N-S and NW-SE associated with two different fault zones, namely Gazlıgöl and Yarımca faults which merge in the Gazlıgöl urban area (Figure 4).

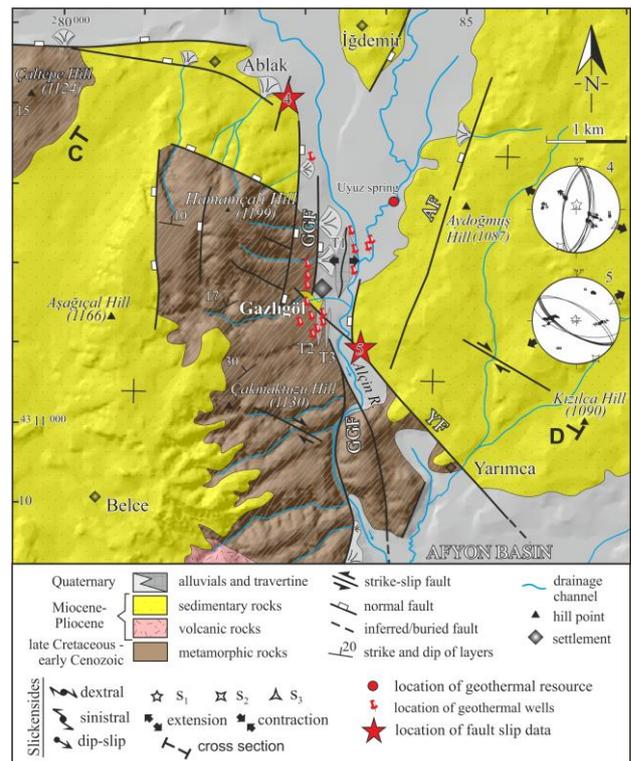


Figure 4. Detailed geologic map with kinematic analysis results of the Gazlıgöl geothermal field. Geothermal well location and temperature data are taken from Afyon Geothermal Facilities Tourism Ind. Trade Incorporated Business (AFJET). Abbreviations: GGF: Gazlıgöl Fault; YF: Yarımca Fault; AF: Aydoğmuş Fault.

These faults also control the northeast border of Afyon Basin. Field studies show that Gazlıgöl Fault bifurcated and cuts the metamorphic basement rocks to the south of the study area. Around the Gazlıgöl city center, N-S directed mountain front exhibits prominent linearity and well-developed alluvial fan deposits. Some well-preserved fault planes are exposed in a road cut, in the north of the

study area and show fault planes dipping in the range of 56°–67° with rakes of 70°–75°. The basin-bounding Yarımca Fault exhibits well preserved slip data indicating N50°W striking oblique faulting with a rake of 50° indicating both normal and dextral slip component at the site 5. The Yarımca Fault also bordered the Miocene-Pliocene sediments. In the study area, Alçın river flows on the N-S-directed structural corridor in a south direction towards to the Afyon Basin. Two geological cross section were measured in the field in order to show geological setting including fault geometry, heat source, heat migration pathway, reservoir and cover units (Figure 5).

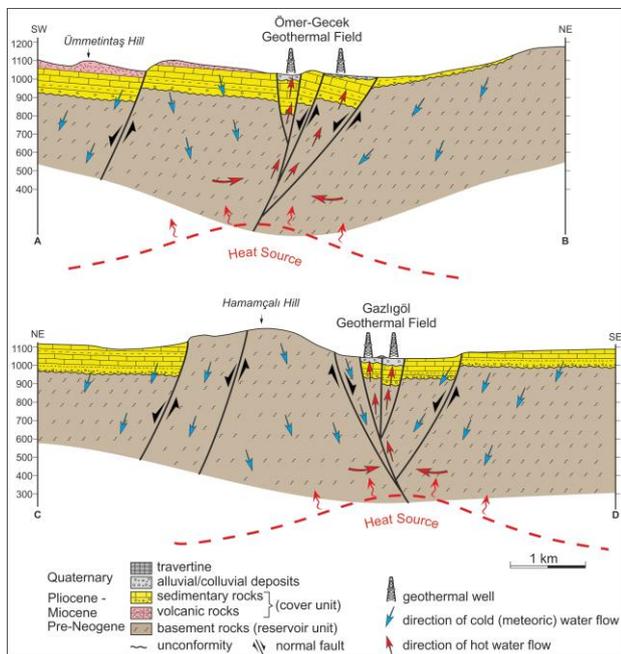


Figure 5. Geologic cross section showing stratigraphic and structural relationships of fault-controlled geothermal fields in Afyon Basin. See Figs. 3 and 4 for the location of cross sections.

Three N-S-trending fissure-ridge-type travertine formations are exposed along these faults. The longest ridge (T1, Figure 4) is about 1 km and mapped in the northeast of the city center while others (T2 and T3) are about 500 m long outcropping in the southern part of the city center. T2 and T3 are cut and displaced by Yarımca Fault. Laterally offset is up to about 20 meters along the fault, providing strong evidence for right lateral displacement. Normal character of Yarımca Fault with a right lateral component of motion is also

evidenced by measuring the fault-slip data (see, the section 2.3). Vertical veins in central part of the ridge can be seen along the T1 in N-S direction. Compound veins of up to 50 cm wide are also measured in the central part (Figure 6).

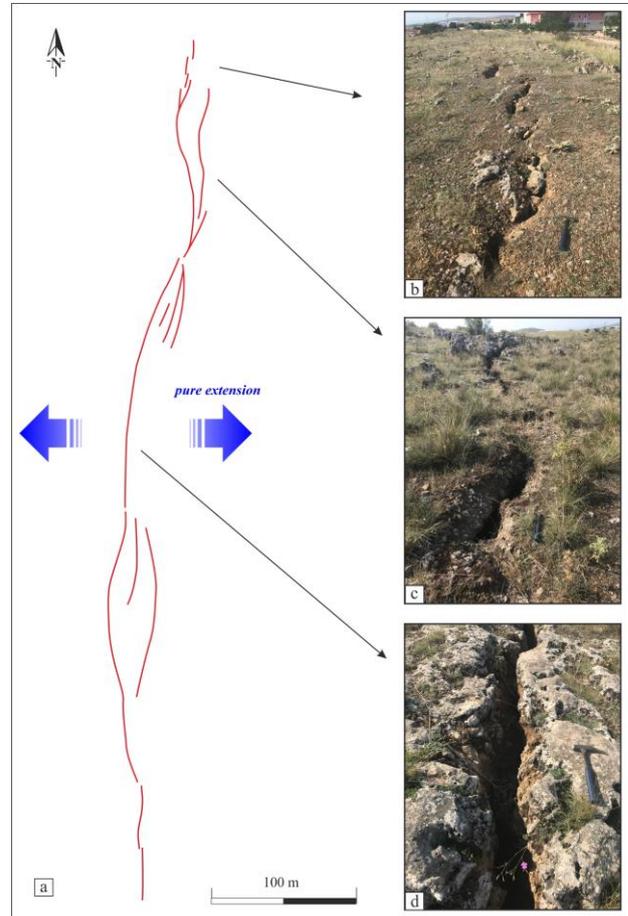


Figure 6. a) Extensional crack geometry of the Gazlıgöl Travertine (T1, see, Figure 3 for the location). b,c,d) Field photographs of the crack.

Extensional fractures on ridge show bifurcating pattern and are mostly left stepping. Measured strikes are in between N15°W and N15°E while the average strike is N-S.

2.4. Kinematic Analysis of Fault-slip Data

During the field studies, we have studied the stress field orientations of mapped faults in order to determine the kinematic framework of faulting in Afyon Basin. Five locations were identified where the sense of Quaternary slip along brittle faults can be determined. The sense of movement along the faults was deduced from kinematic indicators,

including displaced marker horizons, right-stepping, riedel shears and corrugations. Fault-slip data were analyzed using the stress inversion method of Angelier (1984, 1991, 1994), and then computed using software developed by Hardcastle and Hills (1991). Four components of the reduced stress tensor were extracted from the fault-slip data: the directions of the three principal stresses ($\sigma_1 > \sigma_2 > \sigma_3$) and the relative magnitudes for the principal stress axes, expressed by the axial ratio $\varphi = (\sigma_2 - \sigma_1)/(\sigma_3 - \sigma_1)$, with $0 < \varphi < 1$ (Angelier, 1994). The stress regime is determined by the nature of the vertical stresses: extensional when σ_1 is vertical, strike-slip when σ_2 is vertical and compressional when σ_3 is vertical. Delvaux et al. (1997) suggested that the stress regimes also vary by function of the stress ratio, which ranges from 0 to 1: radial extension (σ_1 vertical, $0 < \varphi < .25$), pure extension (σ_1 vertical, $.25 < \varphi < .75$), transtension (σ_1 vertical, $.75 < \varphi < 1$ or σ_2 vertical, $1 > \varphi > .75$), pure strike-slip (σ_2 vertical, $.75 > \varphi > .25$), transpression (σ_2 vertical, $.25 > \varphi > 0$ or σ_3 vertical, $0 < \varphi < .25$), pure compression (σ_3 vertical, $.25 < \varphi < .75$) and radial compression (σ_3 vertical, $.75 < \varphi < 1$).

The computed results of fault slip measurements along the Gecek Fault define steeply plunging σ_1 axes (77° and 79°), but gently plunging σ_2 axes (11° and 12°) and σ_3 axes (06° and 00°) at site 1 and 2. The results suggest that the normal faulting is consistent with a NW–SE pure extensional stress regime ($\varphi = 0,254–0,304$) (Figure 3 and Table 1). Site 3, comprising 10 fault-slip measurements from Erkmen Fault indicate a NE–SW pure extensional tectonic regime. The calculated principles stress axes, σ_1 , σ_2 , and σ_3 have attitudes $153^\circ/68^\circ$, $340^\circ/22^\circ$ and $249^\circ/22^\circ$, respectively. The computed results of fault slip measurements along the Gazlıgöl Fault (site no:4) (Figure 4 and Table 1) define relatively steeply dipping σ_1 , plunging at 81° , whereas the σ_2 and σ_3 axes are almost horizontal plunging at 09° and 02° . The stress field orientations along the Gazlıgöl fault suggest an approximately NW–SE-directed extension. Along the strike of Yarımca Fault, the computed results define an approximately vertical σ_1 plunging at 87° and almost horizontal σ_2 and σ_3 axes, plunging at 03° and 00° . The result suggests a NE–SW pure extension (Figure 4 and Table 1).

Table 1. Results of paleostress analysis from measurements of slickensides in the study area (see Figure 3 and 4 for locations which are showed as red filled stars). Abbreviations: Max ANG: Maximum misfit angle.

no	nature of fault	fault name	σ_1	σ_2	σ_3	φ	Max ANG	Stress regime
1	normal-slip	Gecek	202/77	048/12	317/06	0,304	12	Pure extension
2	normal-slip	Gecek	219/79	039/11	309/00	0,254	22	Pure extension
3	normal-slip	Erkmen	153/68	340/22	249/02	0,655	10	Pure extension
4	normal-slip	Gazlıgöl	007/81	203/09	112/02	0.552	13	Pure extension
5	oblique-slip	Yarımca	326/87	153/03	063/00	0.708	06	Pure extension

3. Discussion and Conclusion

Active extensional tectonic in Afyon Basin is documented by field-based studies including geological mapping, geomorphologic and structural analysis of graben bounding faults to identify structural features of play type of geothermal fields. Mapping studies clearly indicate that structures shaping the northwestern side of the Afyon Basin have dominantly dip-slip normal fault character. These active faults also responsible for the graben formation. Besides this,

the computed results of fault slip measurements along the graben bounding faults suggest NE–SW and NW–SE-directed pure extension. On the other hand, fissure-ridge-type travertine formations on Gecek and Gazlıgöl Faults prove the existence of N–S and E–W directed extensional tectonics, respectively. These results indicate the multidirectional extension stress field in N–S, E–W, NE–SW and NW–SE directions in Afyon Basin have been formed since Plio-Quaternary time. Multidirectional extensional regime in western Anatolia has been subject of many studies (e.g.

Bozkurt and Mittwede, 2005; Bozkurt and Sözbilir, 2006; Rojay et al., 2012; Özkaymak et al., 2017; Özkaptan et al., 2018). Such type of extension is attributed to stress permutations between σ_2 and σ_3 in transfer zones in southwestern Anatolia by Bozkurt and Sözbilir (2006). The computed results of fault slip measurements in Afyon Basin also shows scattered patterns of σ_2 and σ_3 (Table 1). According to this study, these type of extension are directly related with the linkage of cross faults (Figure 5 and 7) that oriented at high-angle to the strike of NW-SE-trending major breakaway fault of AAG. Field-based studies reveal that geothermal fields in AAG develops on the interactions of these active faults on the extensional domain type geothermal play without active volcanism coming to the surface. Similar tectonic models are also proposed for Kızıldere (Turkey), Bradys (Nevada/USA), Souz-sous-Forets (France), Olkaria (Kenya) geothermal fields (Moeck et al., 2014). Fault intersections between several normal faults in AAG cause to highly fractured rocks by connecting the structures and cause the suitable environment to fluids flow (Figure 7).

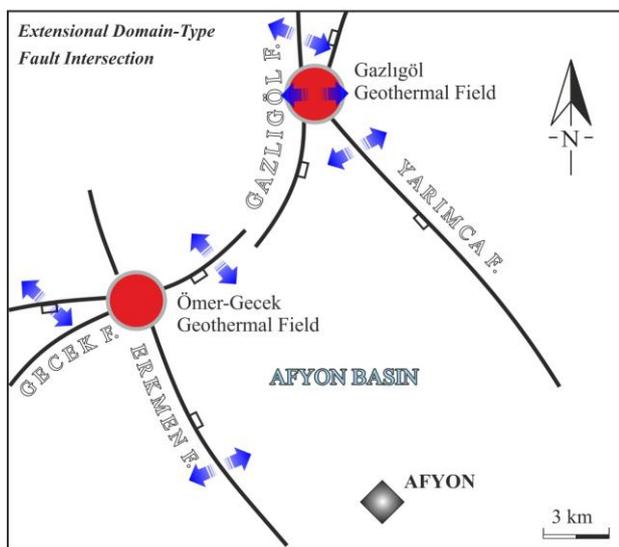


Figure 7. Structural setting of geothermal play for Gazlıgöl and Ömer-Gecek geothermal fields

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