# Structural, lithological and geodynamic controls on geothermal activity in the Menderes geothermal Province (Western Anatolia, Turkey)

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**Abstract:**

Western Turkey belongs to the regions with the highest geothermal potential in the world, resulting in significant electricity production from geothermal resources located predominantly in the Menderes Massif. Although geothermal exploitation is increasingly ongoing, geological and physical processes leading to the emplacement of geothermal reservoirs are hitherto poorly understood. Several studies on the Menderes Massif led to different interpretations of structural controls on the location of hot springs and of the heat source origin. This paper describes geological evidence showing how heat is transmitted from the abnormally hot mantle to the geothermal reservoirs. On the basis of field studies, we suggest that crustal-scale low-angle normal faults convey hot fluids to the surface and represent the first-order control on geothermal systems. At the basin-scale, connected on low-angle normal faults, kilometric high-angle transfer faults are characterized by dilational jogs, where fluids may be strongly focused. In addition, favourable lithologies in the basement (*e.g.* karstic marble) could play a critical role in the localization of geothermal reservoirs. Finally, a compilation of geochemical data at the scale of the Menderes Massif suggests an important role of the large mantle thermal anomaly, which is related to the Hellenic subduction. Heat from shallow asthenospheric mantle is suggested to be conveyed toward the surface by fluid circulation through the low-angle faults. Hence, geothermal activity in the Menderes Massif is not of magmatic origin but rather associated with active extensional tectonics related to the Aegean slab dynamics (*i.e.* slab retreat and tearing).

**Keywords:** Menderes Massif, structural control, detachment, transfer fault, hot mantle anomaly, slab dynamics

## 1. Introduction:

The high heat flow driving active geothermal systems is often believed to find its source in portions of crust invaded by magmas, but some of significant geothermal provinces are considered amagmatic namely not of magmatic origin in terms of heat source (*i.e.* no magmatic intrusions in the upper crust). In this case, large-scale processes (*e.g.* slab dynamics) inducing large-scale thermal anomalies are favoured, as for the Basin & Range Province in the Western US. In this extensional context, geothermal systems have been described as amagmatic in origin (*e.g.* Benoit 1999; Blackwell *et al*. 2000; Faulds *et al.* 2004; 2011). The exact origin of heat remains debated and, for instance, magmatic underplating under the overriding plate (Wannamaker *et al*. 2006) and/or shear heating in the mantle in actively deforming area (*e.g.* Roche *et al*. 2018) are some hypothesis of heat source possibilities. Despite the well-documented existence of large-scale seismic velocity anomalies in the mantle of the Eastern Mediterranean region (*e.g.* De Boorder *et al*. 1998), very few studies have actually considered such amagmatic geothermal provinces in their large-scale geodynamic contexts (*e.g.* Roche *et al*. 2015; 2016; 2018; Gessner *et al*. 2017). The path of heat transport from mantle to surface, either conductive or through advection of hot fluids, remains to be described in such environments. The Menderes Massif is one of the best examples where such a description can be done, from the mantle to the actively extending crust, up to the geothermal reservoirs.

The Menderes Massif is recognized as an active geothermal area where extensional or transtensional tectonics is accompanied by elevated heat flow values (~ 100 mW $m^{-2}$), which appear to extend to almost the entire Aegean domain (Erkan 2014; 2015). There, high heat flow estimated by Jongsma (1974) may correspond to the low *P*- wave seismic velocity zone described by Piromallo and Morelli (2003). Surprisingly, magmatic activity and related volcanism have been very sparse there in the recent period (*i.e.* Pliocene and Quaternary); the unique volcanic activity occurred in the Kula volcanic field during the Quaternary between 2 and 0.2 Ma (*e.g.* Richardson-Bunbury 1996; Bunbury *et al*. 2001; Maddy *et al*. 2017) where geothermal activity is absent. Existing models suggest probable magmatic reservoirs in the upper crust as heat source of the geothermal system in this area, more or less connected with the Kula basaltic activity (*e.g.* Simsek, 1985; Filiz *et al*. 2000; Karamanderesi and Helvaci 2003; Yilmazer *et al*. 2010; Bülbül *et al*. 2011; Özen *et al*. 2012; Özgür *et al*. 2015; Ozdemir *et al*. 2017; Alçiçek *et al*. 2018). Nonetheless, others authors have also suggested a deeper and larger heat source triggered by slab dynamics (*i.e.* astenospheric mantle flow due to slab rollback and tearing; *e.g.* Kaya 2015; Roche *et al*. 2015; 2016; 2018; Gessner *et al*. 2017). It is then worth studying the consequences of these processes on the distribution of heat at the surface. In this case, recent tectonic activity and related graben structures have a major interest because they could control the fluid flow processes (*e.g.* Tarcan and Gemici 2003; Faulds *et al.* 2010; Haizlip *et al.* 2013; Kocyigit 2015; Kaya 2015; Haklidir *et al.* 2015).

Consequently, this study is dedicated to a multi-scale analysis of the different identified features of several geothermal fields of the Menderes Massif. We present a detailed structural analysis of main geothermal fields (*i.e.* Salihli, Alaşehir, Salavatlı and Seferihisar, Kızıldere, Germencik) to better characterize the fluid flow pattern. It is critical to evaluate which type of faults and which parts of them are most favourable for focusing geothermal activity. Our results are then discussed at different scales including that of the "Menderes geothermal Province". At the scale of lithosphere-mantle interactions, we use a broad compilation of mantle-He and oxygen-hydrogen isotopic data to propose and discuss a new conceptual model explaining the regional thermal anomaly with reference to geodynamic processes.

## 2. Geological setting

### 2.1. The Eastern Mediterranean region

During the Cenozoic, the Eastern Mediterranean region (Fig. 1a) has undergone a two-step tectono-metamorphic evolution. Firstly, in the late Cretaceous-Eocene, the convergence of Africa and Eurasia has led to the closure of the Izmir-Ankara Ocean and to the accretion of subducting continental and oceanic lithospheres (Bonneau and Kienast 1982; Dercourt *et al*. 1986; Jolivet and Brun 2010). Secondly, since the Oligo-Miocene, the kinematics in Mediterranean region has been mainly controlled by the southward retreat of the African slab responsible for back-arc extension (*e.g.* Malinverno and Ryan 1986; Jolivet and Faccenna 2000; Jolivet and Brun 2010; Ring *et al*. 2010). The Oligo-Miocene geological evolution of the Aegean region, including the Menderes Massif and the Cyclades, results from this episode of slab roll-back (*e.g.* Seyitoglu and

Scott 1991; Seyitoğlu *et al*. 1992; Seyitoglu and Scott 1996; Jolivet *et al*. 1996). In addition, recent studies based on geochemical analyses (*e.g.* Dilek and Altunkaynak 2009; Ersoy *et al*. 2010; Prelevic *et al*. 2012), on tomographic models (*e.g.* De Booder *et al.* 1998; Biryol *et al.* 2011; Salaün *et al*. 2012) and on tectonic and magmatic evolution in this area (Dilek and Altunkaynak 2009; Jolivet *et al.* 2015; Menant *et al.* 2016; Govers and Fichtner 2016) invoke the particular slab dynamics beneath western Turkey, which would be characterized by a slab tear since the Miocene (Jolivet *et al*. 2015) (Fig. 1a). The complex geometry of subduction zones and the tight arcs characterizing the Mediterranean region as a whole are direct consequences of slab retreat and slab tearing (Wortel and Spakman 2000; Spakman and Wortel 2004; Faccenna *et al*. 2004; Govers and Wortel 2005; Faccenna *et al*. 2006). Beside the heat wave caused by the advection of hot asthenosphere to shallow depths during retreat, slab tearing tends to efficiently localize deformation, and to facilitate high-temperature metamorphism, crustal melting, granitic intrusions and fluid circulations (Jolivet *et al.* 2015; Menant *et al.* 2016; Roche *et al*. 2018). Therefore, magmatic activity during the Miocene was intense in western Turkey, but it has significantly decreased since 12 Ma (*e.g.* Ersoy *et al*. 2010). In addition, this slab dynamics has a direct consequence on Moho depth, estimated only at ~ 25 – 30 km in the Menderes Massif (based on geophysical data such as receiver functions computed from teleseismic earthquakes from Karabulut *et al.* (2013); deep seismic reflection data from Cifci *et al.* (2011); Bouguer gravity data from Altinoğlu *et al.* 2015 and conductivity data from Bayrak *et al.* (2011)).

The current tectonic evolution in this region is mainly controlled by the westward motion of Anatolia (Reilinger *et al.* 2006) and by N-S extension, both consequences of the same slab roll-back process complicated by several episodes of slab tearing (*e.g.* Faccenna *et al.* 2006; Jolivet *et al*. 2013; 2015). This direction of extension is also well constrained by the orientation of regional-scale anisotropic fabrics, suggesting a large-scale viscous flow in the lower crust and lithospheric mantle since the Miocene (Endrun *et al*. 2011).

## 2.2. The Menderes Massif

The Menderes Massif is located in the back-arc domain of the Hellenic subduction zone in the western part of Turkey (Figs. 1a and 1b), and constitutes a part of the Anatolide-Tauride block. After a first episode of nappe stacking and crustal thickening (*e.g.* Collins and Robertson 1998; Ring *et al.* 1999; Gessner *et al.* 2001a), the thickened crust of the Menderes Massif has undergone a NNE-SSW post-orogenic extension stage since the Oligo-Miocene (*e.g.* Seyitoglu and Scott 1991; Seyitoglu *et al*. 1992; Bozkurt and Oberhänsli 2001; Bozkurt *et al.* 2011). Considered as a single large metamorphic core complex, this massif has recorded a controversial two-stage exhumation process. According to Ring *et al*. (2003), these two stages are symmetrical, first along the south-dipping Lycian and north-dipping Simav detachments on the southern and northern edges of the massif, and then located in the Central Menderes Massif (CMM) along the Alaşehir and the Büyük Menderes detachments (Fig. 1b). But Seyitoglu *et al*. (2004) challenged the first stage of exhumation suggesting that this massif was exhumed initially as an asymmetric core complex in the Early Miocene. In any case, this post-orogenic extension has led to the exhumation of three submassifs, from north to south: the Gördes, Ödemiş (corresponding to the CMM) and Çine submassifs. These submassifs are separated by E-W striking half-grabens that are seismically active. The northern part of the Gördes submassif is limited in the north by the Simav graben, the Ödemiş submassif by the Alaşehir graben (also known as Gediz graben) to the north, and by the Büyük Menderes graben to the south (Fig. 1b, see more details in the Appendix for the studied grabens).

Post-orogenic extension was thus accommodated by three main detachment faults (*i.e.* low-angle normal faults) in the central and northern submassifs, namely:

(i) the Büyük Menderes detachment along the northern margin of the Büyük Menderes graben with top-to-the-S kinematic criteria (Fig. 1b; *e.g.* Emre and Sözbilir, 1997; Gessner *et al.* 2001b; Ring *et al*. 2003);

(ii) the Alaşehir detachment (also named Gediz detachment, Lips *et al*. 2001) along the southern margin of the Alaşehir graben with top-to-the-N sense of shear (Fig. 1b; *e.g.* Emre, 1992; Hetzel *et al.* 1995a; 1995b; Gessner *et al.* 2001b; Sözbilir 2001; Seyitoglu *et al*. 2002; Işık *et al.* 2003; Bozkurt and Sözbilir 2004; Hetzel *et al.* 2013) and

(iii) the Simav detachment, later cut by the high angle Simav normal fault that bounds to the south the Simav graben with top-to-the-NE kinematic indicators (Fig. 1b; *e.g.* Seyitoglu 1997; Isik *et al*. 1997; Isik and Tekeli, 2001; Işık *et al.* 2004).

However, the exhumation history of the Menderes Core complex and the multi-staged activity of the detachments remain matters of debate. Several authors suggest that the Alaşehir graben formation is controlled by (i) low-angle normal faults that have been active since the inception of the basin, and then by (ii) more recent high-angle faults crosscutting the earlier-ones (*e.g.* Hetzel *et al*. 1995a; 1995b; Emre and Sozbilir 1997; Sozbilir 2001; Oner and Dilek 2011). For others, the initiation of the graben involved high-angle normal faults that gradually became low angle with time (*e.g.* Gessner *et al*. 2001b; Bozkurt 2001; Seyitoğlu *et al*. 2002; Purvis and Robertson 2005; Ciftci and Bozkurt 2009; 2010; Demircioğlu *et al*. 2010; Seyitoğlu *et al*. 2014). According to Seyitoğlu and Işik (2015), this last hypothesis may explain the large range values of ages from the Alaşehir detachment, explaining a continuum of deformation since Early Miocene in the framework of a rolling hinge model (Buck 1988) for the formation of the grabens and exhumation of the CMM (*e.g.* Gessner *et al*. 2001b; Seyitoglu *et al*. 2002; 2014). Note that syn-extensional Miocene granitoid intrusions are also recorded in the footwall of the Alaşehir and Simav detachments (*e.g.* Hetzel *et al*. 1995b; Isik *et al*. 2003; 2004).

The early Miocene evolution of the Menderes Massif is dominated by high-angle E-W striking normal faults that root into (Seyitoglu *et al*. 2002) or cut the current low-angle normal faults (*e.g.* Koçyigit *et al*. 1999; Yılmaz *et al*. 2000), and control basin sedimentation (*i.e.* the initiation of the Alaşehir and Büyük Menderes grabens formation; *e.g.* Seyitoglu 1997; Seyitoglu *et al*. 2002). During Pliocene-Quaternary times, another set of high-angle normal faults is recorded, controlling the youngest grabens such as the Küçük Menderes and Simav grabens (Seyitoglu *et al*. 2004) and the current geometry of the basin (Bozkurt and Sozbilir 2004; Kent *et al*. 2016). Furthermore, an additional distributed strike-slip tectonics with a normal component is well observed in the Alaşehir graben with high-angle N-S striking faults crosscutting the Neogene sediments (*e.g.* Çiftçi and Bozkurt 2010; Yilmazer *et al*. 2010; Ozen and Dilek 2011) and affecting the basement of the Menderes Massif (see black dotted line in the Alaşehir graben in Fig. 1b). Similar strike-slip faults are observed in the Büyük Menderes graben, which can be interpreted as transfer faults (*e.g.* Çifçi *et al*. 2011).

## 3. Geothermal setting in the Menderes Massif

### 3.1. Thermal anomalies at different scales

At first glance, there is a strong correlation between the distribution of geothermal fields with its hot springs and the location of detachments (Fig. 1b). According to recent studies (*e.g.* Roche *et al*. 2015; 2016; 2018; Kaya, 2015; Gessner *et al*. 2017), these large-scale structures may represent the first-order control on geothermal fields in this massif. In that instance, Gessner *et al*. (2017) showed that most of hotter thermal springs are located in areas of structural complexity such as Seferihisar, Denizli, Salihli and Alaşehir. Similar correlations between high heat flow values and complex graben structures are emphasized by many studies (Tezcan 1995; Pfister *et al*. 1998; Erkan 2014; 2015). For instance, Erkan (2014) estimated heat flow values of 85 – 90 mW $m^{-2}$, locally higher than 100 mW $m^{-2}$ in the northeastern part of the Alaşehir graben. These data are in accordance with locations of several geothermal reservoirs of interest, but also with shallow Curie-point depth (CPD) published in the Menderes Massif area (Aydin *et al.* 2005; Dolmaz *et al.* 2005; Bilim *et al.* 2016). According to Bilim *et al.* (2016), the average of CPD in the whole Menderes area (assumed to represent the depth of the 580 °C isotherm, Schlinger 1985; Ross *et al.* 2006) is *ca.* 9.5 km with a shallowest point at 6.21 km around the Kula basaltic area. A thermal anomaly thus encompasses the whole Menderes Massif. The same authors also suggest that locations of geothermal fields belonging to the Büyük Menderes graben area coincide with the lowest values of the magnetic intensity, which are aligned along the boundary fault of this graben. Furthermore, using the magnetotelluric method through the northern part of the Menderes Massif, Ulugergerli *et al*. (2007) proposed a large partial melting zone located at ~ 12 km depth and deep intrusions (*i.e.* ~ 15 km depth) located below the Simav graben and the Kula volcano, therefore suggesting abnormal high temperature values.

To sum up, all these studies confirm that thermal anomalies in the Menderes Massif are observed with different wavelengths (*i.e.* crustal-scale to geothermal field-scale), thus different depths. The short wavelength anomalies result from shallow depth processes and those with long wavelength (crustal-scale) from deep processes, and thus large-scale dynamics (*e.g.* Roche *et al*. 2015; 2016; 2018; Gessner *et al*. 2017). However, the plumbing system (*i.e.* circulation pathways) of such hot crustal fluids are not yet properly understood.

## 3.2. Synthesis of fluids and isotopes

### 3.2.1. Studies on oxygen and hydrogen isotopes of the main geothermal fluids

Many studies on the isotopic composition of water samples in the CMM area have been performed (Fig. 2; Filiz *et al.* 2000; Özgür 2002; Tarcan and Gemici 2003; Özen *et al.* 2012; Baba *et al.* 2014). To the first order, they show that most of the data from the Alaşehir and the Büyük Menderes grabens are close to the global meteoric water line (GMWL) thus indicating a meteoric origin for most of the geothermal fluids (Figs. 2b and 2c). Indeed, the distribution of isotopic compositions of the thermal waters in Salihli, Aydin-Germencik, Salavatlı and Denizli-Kızıldere geothermal fields shows a meteoric origin. However, some variations in isotopic distributions can be noted. There is a clear $\delta^{18}O$ shift from the MMWL (Mediterranean Meteoric Water Line) and cold-water values (empty symbols in Fig. 2b) that indicate strong water-rock interaction for all geothermal fields (Figs. 2b and 2c). For example, the isotopic distribution of hot waters in Kurşunlu and in greenhouses well is located below the GMWL, which suggests a probable mixing of deep and shallow thermal waters (Özen *et al.* 2012). Bülbül *et al.* (2011) reported a similar observation from the Alaşehir geothermal field, suggesting that thermal water reservoirs are fed by ground waters of dominant meteoric origin. They estimated cold-water contributions to thermal waters ranging from 75 to 95%. Moreover, the Seferihisar geothermal field, in the Cumaovası basin, shows additional variations in isotopic compositions (Fig. 2d): isotopic values approach the isotopic value of Agean sea water, implying a mixing with seawater related to the proximity of the Mediterranean Sea (Tarcan and Gemici 2003). Similar signatures are observed in the Söke geothermal field (Simsek 2003), with slight deviations from the MMWL line of isotopic distribution, implying an evaporation effect on cold-waters (Fig. 2d). The isotopic composition of thermal waters indicates that they are of meteoric origin and then mixed with seawater in the western part of Söke, particularly near the coast.

### 3.2.2. Helium isotopic signature

In a tectonically active continental setting, the presence or the absence of mantle helium ($^3He$) in hydrothermal fluids can constrain the relationships between tectonics, magmatism and fluid circulation in faulted settings (O'Nions and Oxburgh 1988; Marty *et al.* 1992; Kennedy *et al.* 1997; Kulongoski *et al.* 2005; Pik and Marty 2009). It has been established that the $^3He/^4He$ ratio can be used as tracer of the competing influence of crustal vs. mantle volatiles in various tectonic settings (Mutlu *et al.* 2008). Based on the analyses of water and gas samples, and/or fluid inclusion trapped in calcite, many studies have discussed the isotopic composition of He in the Eastern Mediterranean region (Güleç 1988; Güleç *et al.* 2002; Shimizu *et al.* 2005; Güleç and Hilton 2006; Mutlu *et al.* 2008; Pik and Marty 2009; Karakus 2015). Below, we present a new compilation of recent isotopic studies using the classification of Pik and Marty (2009) (Fig. 3).

In the Aegean domain, the Corinth rift shows a crustal signature while the Hellenic volcanic arc is characterized by high values of $^3He/^4He$ ratio, Ra (> 15% of mantle-He) suggesting a mantle origin (Fig. 3a). In addition, estimated $^3He/^4He$ ratios of samples normalized to the atmospheric $^3He/^4He$ ratio range from 0.10 to 1.44 in the western part of Anatolia (Figs. 3a and 3b). These values are significantly higher than the crustal production value of 0.05 (Mutlu *et al.* 2008). Karakuş (2015) added new data on the $^3He/^4He$ ratios for the Simav geothermal field (values range from 1.36 to 1.57). The highest values of helium ratio correspond to the Quaternary alkaline activity of Kula volcano and to the Pliocene Denizli volcanics (2.52) along the Alaşehir and the eastern segment of the Büyük Menderes grabens (Fig. 3b). These results reveal a mixed origin for helium between mantle and continental crust components.

## 4. Analysis of the tectonic and structural settings of geothermal fields in the Menderes Massif at local and regional scale

In this chapter, we summarize the structural framework of several geothermal fields, in order to identify the main conduits for geothermal fluid flow and related reservoirs. Our field survey consisted of (i) field mapping in order to complement the existing geological and geothermal maps and (ii) structural data acquisition and (iii) general cross-sections. We have first focus on the Alaşehir graben (Fig. 1b), where numerous geothermal wells have been drilled by MTA (General Directorate of Mineral Research and Exploration of Turkey) or by private companies since the 1980s, and where two most important geothermal fields are recognized (Salihli and Alaşehir, Fig.

4a). We will then focus on the Germencik and Salavatlı geothermal fields located along the northern margin of the Büyük Menderes half-graben (Fig. 1b). Finally, the structural framework of the Seferihisar geothermal field is also provided (Fig. 1b). A brief description of all these geothermal systems is presented in the Appendix. They are generally characterized by medium- to high-enthalpy, with reservoir temperature values ranging from 120 to 287 °C (*e.g.* Karamanderesi, 2013; Baba *et al.* 2015).

### 4.1. Structural features of the Salihli geothermal field

At regional-scale, the Alaşehir detachment is one of the best-preserved crustal structure in the study area (Fig. 5a). Both metamorphic rocks and Miocene intrusions in the footwall of the detachment present a pervasive network of kilometric to millimetric structures developed from the ductile-brittle transition to the brittle deformation field during extension and exhumation (Fig. 4b) (*e.g.* Emre 1992; Hetzel *et al*. 1995a; 1995b; Isik *et al*. 2003). Close to the main contact between the Menderes basement rocks and Neogene sediments, the foliation of basement rocks strikes E-W with low to moderate dip values toward the north and carries a N-S trending stretching lineation (Fig. 4). Most ductile kinematic indicators are top-to-the-NNE. All lithologies are deformed by asymmetric structures and folds at various scales consistent with top-to-the-NNE shear sense such as asymmetric boudinaged quartz veins within tight overturned folds indicating a top-to-the-NE sense of shear (Fig. 5b). On the other hand, ductile-brittle fault system corresponds to listric and gently dipping centimetric to decametric faults within schist and marble layers that may reactivate and (or) cross-cut low-angle ductile shear zones (Fig. 5c). This brittle stage is associated with slickenlines and kinematic indicators indicating also top-to-the-NNE motion (Fig. 4a, #2). Finally, the brittle detachment fault plane is well observed in the landscape (Fig. 5a), controlling the present-day topography of the CMM at regional scale and strikes E-W with a moderate dip toward the north (Fig. 4a, #8). It is associated with a thick (approximately 50 cm to 3 m) zone of cataclasites or a thick quartz-breccia vein (Fig. 5d), which locally hosts Sb-Hg(-Au) ore deposits (Larson and Erler 1993). Fault plane and associated striae (*e.g.* Fig. 4a, #3 and #4) are consistent with a NNE-SSW extension. In addition, vein networks mostly filled by calcite or quartz in the footwall of the detachment (Fig. 5e) present an approximately NW-SE (*i.e.* parallel to the detachment) and NE-SW preferred orientations (*i.e.* perpendicular to the detachment) (Fig. 4a, #2). This shows evidence of a significant older fluid circulation in the fault plane during the exhumation of the deeper parts of the Menderes Massif.

In the entire studied area, faults that are particularly abundant play a major role in the formation and development of longitudinal and transverse valleys (*e.g.*, Kurşunlu valley, Alaşehir graben). Three types of plurimetric to kilometric faults, particularly frequent in this area, are observed in the field (Fig. 4a). The first one is characterized by NNE-dipping normal faults (*i.e.* E-W trending) and the second one is defined by sub-vertical N-S striking strike-slip faults (Figs. 4a, #2; 6a and 6b). In the second case, slickenlines are gently plunging consistently 15 to 30°N (Figs. 6a and 6c) and kinematic indicators indicate a main dextral movement with a slight normal component. Locally, these faults are accompanied with a cluster of calcite veins as dilational jog structures (Fig. 6d). The third type of faults consists in a set of conjugate faults strikes NE-SW and dips with an approximately 60° mean dip angle, is well developed in quartzite levels in the Kurşunlu valley (Fig. 4a, #2). The different fault sets, including the detachment and the associated high-angle E-W conjugate normal faults and the N-S strike-slip faults to NE-SW faults, are compatible with N-S extension, where strike-slip faults act as transfer zones between extensional blocks. All these faults affect the basement and the Neogene sediments, but the chronologic relationships are not clear in the field.

4.2. Structural features of the Alaşehir geothermal field

The Alaşehir geothermal field is located between Alaşehir and Salihli in the eastern part of Alaşehir graben. It is one of the most important geothermal areas characterized by the highest reservoir temperature (287 °C) ever reached in Turkey (in a deep well, 2750 m, from Baba *et al.* (2015), Table 1). As for the Salihli geothermal field, the recent tectonic activity is assumed to control the location of the thermal springs and related geothermal reservoirs (Bülbül *et al.* 2011). In this area, the detachment fault plane is attested by the development of a thick zone (~ 1 m) of cataclasites (Fig. 7a). It consists of yellow and red foliated cataclasites directly overlain by unaltered Neogene sediments (Fig. 7b). Close to the kinematics recorded in the area of Salihli, striae are compatible with a NE-SW extension (Fig. 7a and 4, #7). Additional low-angle normal faults in the hanging-wall of the detachment are observed between 1 metre-thick cataclasites and sediments (Figs. 7c, 7d and 7e). Locally pseudotachylytes are observed (Fig. 7f) and medium-angle normal faults in sediments merge with the main fault plane (Fig. 7g). According to Hetzel *et al*. (2013), this brittle deformation stage observed in the Alaşehir detachment system was active from ~ 9 Ma to 4 – 3 Ma. This may be consistent with rapid Pliocene cooling inferred from published thermochronological data (Gessner *et al*. 2001b; Ring *et al*. 2003). While the Alaşehir detachment is well defined in the landscape at Salihli, it is however often crosscut by a set of E-W high-angle north-dipping normal faults in the Alaşehir area (Figs. 4b and 8a). Brittle structures, shallow- and steeply-dipping faults present a marked consistency of the extension direction (Fig. 4a, #6). Locally, fluid circulation occurs along fault planes (Fig. 8b), suggesting that these faults may also control meteoric fluid circulations. The absence of any hot springs close to the E-W striking faults suggest that these faults play as recharge pathway for reservoirs at depth.

Furthermore, another set of faults is observed at some places. At landscape-scale, in the south-east of Alaşehir, we identified triangular facets within synrift sediments due to NW-SE trending high-angle normal fault (Fig. 8c). The latter are horizontally offset from 2 km toward the south in the Narlıdere area, defining a NE-SW transfer fault (Figs. 8c and 1b for the location). Similar features are also observed in the Dereköy traverse valley, close to the Horzum Turtleback structure described by Seyitoglu *et al*. (2014). There, we identified a N-S striking high-angle fault (Fig. 8d). Fault kinematics indicates an early sinistral movement followed by normal movement (Figs. 4a, #5 and 8d). The synrift sediments are offset southward and face the Paleozoic basement of the detachment footwall across the valley, indicating the presence of left-lateral strike-slip fault in the vicinity of the Horzumsazdere geothermal system (black line in Fig. 4a). Close to the detachment and to these N-S strike-slip faults, a weak fumarole activity associated with a probable acidic alteration (with the typical $H_2S$ smell) affects Neogene sediment deposits (Fig. 8e). Down in the valley, several thermal springs (medium temperatures ranging around 25 and 30 °C) reach the surface in Neogene sediments where they form travertines.

### 4.3. Structural features of the Salavatlı and Germencik geothermal fields

South of the CMM, the Salavatlı and Germencik geothermal fields (Table 1 for more information) are respectively located on the northern flank of the Büyük Menderes graben between Sultanhisar and Köşk (Figs. 1b and 9), and at 20 km west of Aydin (Figs. 1b and 10). Similar to the previous geothermal systems, both Salavatlı and Germencik geothermal systems are located close to the Büyük Menderes detachment (Fig. 1b). Even though the age of top-to-the-north ductile deformation is still controversial (*e.g.* Bozkurt 2001; Gessner *et al*. 2001a; Seyitoglu and Işik 2015), all studies indicate a second top-to-the-south ductile-brittle shearing event (*e.g.* Hetzel *et al*. 1995a; 1995b; Gessner *et al*. 2001b; Bozkurt and Sözbilir 2004).

In details, the geological sequence of the Salavatlı geothermal field is composed of Neogene sediments deposited over schist-marble sequences and augen gneiss unit (Fig. 9a). Even though the major structural feature does not clearly outcrop in this area due to strong neo-tectonic overprint, the Büyük Menderes detachment was identified in two different drill holes

(Karamanderesi and Helvaci 2003). According to this study, the marble sequences in the Menderes massif at ~ 800 m depth host the main geothermal reservoirs. Our new field observations suggest that the general structure and the topography are mainly induced by a set of major normal- to strike-slip faults. These faults control the first-order distribution of lithologies of the two main units (augen gneiss and schist-marble sequences, Fig. 9a). The first ones are NW-SE trending faults with opposite dips (Figs. 9b and 9c), showing kinematic indicators of a normal movement. Here, kinematic indicators are compatible with a top-to-SW motion. The second ones are the most important and they strike N-S to NE-SW (Fig. 9c). Locally, slickenlines are well preserved and indicate a sinistral movement. These high-angle faults are characterized by a thick fault gouge and crosscut all earlier structures, such as NW-SE trending faults, and also the detachment (see the profile of Karamanderesi and Helvaci 2003). Close to these main structures, hot springs are often observed (Fig. 9a), suggesting a first-order control on the emergence of thermal fluids. In addition, the presence of N-S to NE-SW trending travertine deposits in higher altitudes (Karamanderesi and Helvaci 2003) confirm the key role of such structures.

The Germencik geothermal field is characterized by numerous fumaroles, hot springs, travertines and widespread hydrothermal alterations (*e.g.* Çamurlu and Bozköy hot springs; Fig. 10a). The Menderes basement rocks are mainly composed of Paleozoic metamorphic rocks such as the augen gneiss and schist-marble sequences, overlain by Neogene sediments. North of Çamurlu hot spring (Fig. 10a), the main foliation of metamorphic units strikes E-W and the Neogene sediments dip slightly toward the north (Fig. 10a). Locally, travertines are located close to this contact (Fig. 10a), showing that it acts as a major drain for fluid circulation. In addition, in the vicinity of Bozköy, the main foliation of metamorphic units strikes NW-SE with a low dip values (~ 5 – 10°) (Fig. 10b), whereas the Neogene sediments dips to the south (Fig. 10c). Such an unexpected change of dip direction may suggest a fault drag area and the possible presence of a N-S high-angle strike-slip transfer fault (Fig. 10a). Here again, the occurrence of geothermal surface expressions suggests that this type of faults favours fluid circulation (Fig. 10d). More recent tectonic features are also well expressed and consist in the development of E-W striking high-angle normal faults (Figs. 10a and 10f). Some of them are characterized by dip values (reaching ~ 60°; Fig. 10e). When such faults root in the Büyük Menderes detachment at depth (Fig. 10e), others dip steeper (~ 80°) and crosscut it. This latter set of faults has allowed for instance the exhumation of the Kızılcagedik Horst. This area is also characterized by numerous deep wells (see location of Ömerbeyli in Fig. 10a), and the highest temperatures were reached in the Büyük Menderes graben (~ 230 °C at a depth of 975 m and 1196 m; Filiz *et al*. 2000). Here, the E-W trending high-angle faults generate a wide fractured zone.

### 4.4. Structural features of the Seferihisar geothermal field

The Seferihisar geothermal field (Table 1 for more information) is located in the northern flank of the Büyük Menderes graben between Sultanhisar and Köşk (Figs. 1b and 11a). The basement of the Menderes Massif in this area is made of metamorphic rocks such as schists, marbles and local phyllite intercalations (*e.g.* Dora *et al*. 1990; Güngör and Erdoğan 2002) topped by the Bornova flysch mélange. This area is similar to the central part of the Menderes Massif, but shows some differences such as lower topography and a hidden tectonic contact localized between the Bornova flysch mélange and the Menderes Massif as suggested by Erdoğan (1990). We briefly present below the relationships between hot spring locations and faults, and we refer the reader to the study of Ring *et al*. (2017) for more information about the Miocene-to-Present tectonic evolution. Field observations show that hot springs are generally located close to NE to SW striking strike-slip faults (Figs. 11a, 11b and 11c). Kinematic indicators suggest a dextral strike-slip movement with lineation pitch ranging from 10°S to 22°S (Fig. 11d). In addition, these faults are characterized by multi-metric damaged zones, locally strongly altered, attesting for recent fluid circulation. Dextral strike-slip movement is associated with dilational jogs and pull-apart structures (Fig. 11a), probably close to the intersection zones between N-S strike-slip fault and the early contact between the Bornova mélange and the Menderes basement rocks (*i.e.* the tectonic contact descibed by Erdoğan (1990)). Furthermore, in places, E-W trending fault corridors cut these first faults (Fig. 11e). These later sub-vertical faults show several sub-vertical and sub-horizontal slickenlines, with plunging values ranging from 85°W to 49°E and 24°E to 4°W, respectively (Fig. 11e). The calculated paleo-stress analysis suggests that kinematic indicators are compatible with a NW-SE extension (Fig. 11a). All along the main road between Cumhuriyet and Orhanlı (Fig. 11a), sandstones of Bornova mélange usually display a strong alteration. Hence, it seems reasonable to assume the existence of others faults, which would be parallel to the previous one in this area.

## 5. Discussion

### 5.1. The Menderes Massif Core complex and associated geothermal fields

The genesis of a geothermal system requires source of high temperatures, reservoirs of large quantity of hot fluids (permeable structures and lithology) and its caprock. All of these features are present in the Menderes Massif, thus explaining the geothermal potential. As seen previously, thermal anomalies show different wavelengths at different depths in the Menderes Massif (*i.e.* crustal-scale to geothermal field-scale). Whereas the short wavelength anomalies result from shallow depth processes and may be associated with N-S transfer faults, the long wavelength (i.e. crustal-scale or mantle-scale) result from deep processes and may be associated with detachments activity. Therefore, as for many geothermal fields in western Turkey and abroad, faults appear to represent a first-order control on fluid flow and heat transport, and thus on the location of reservoirs at depth and hot springs at the surface as leak of reservoir (Fig. 12a). In the following, we first focus on detachments at crustal-scale, then we highlight the role of N-S transfer faults at basin-scale.

### 5.1.1. Crustal-scale: the role of detachments

At the scale of the Menderes Massif, the presence at the surface of numerous hot springs close to E-W striking, northward and/or southward dipping low-angle normal fault (Fig. 1b) suggests that detachments control fluid circulations. These latter are controlled by the current global structure of the Menderes core complex resulting from a multi-staged activity of the detachments since the Miocene. Indeed, ongoing tectonic lets the detachment systems active, and meanwhile, (i) detachment faults became incrementally split into many sections separated by transfer faults and (ii) different sets of faults (*i.e.* E-W striking faults) merge at depth into the detachments (see Seyitoglu *et al*. 2002). This complex tectonic evolution may induce an intense hydrothermal activity (*e.g.* silicified detachment in some areas), for instance within thick damage zone (*e.g.* up to 10 m of cataclasites associated with the Alaşehir detachment are present in the hanging-wall and the footwall of the detachment, Fig. 7) reaching ~ 10 km (containing the ductile-brittle deformation associated with the detachment) according to Bozkurt (2001). One can question whether such detachment fault systems have acted as important conduits for fluid circulations since the Miocene. In any case, these structures generate zones of high fracture density and permeability that channel and host significant fluid flows in the upper crust. They are also connected with most superficial structures (*i.e.* N-S transfer faults) and probably seem highly effective for heat transport and fluid circulation at deeper depth toward specific reservoirs (Figs. 12a and 12b).

Many studies on fluid compositions (Famin *et al.* 2004; Mulch *et al.* 2007; Gottardi *et al.* 2011; Hetzel *et al.* 2013; Quilichini *et al.* 2015) suggest that low-angle detachments permit pervasive meteoric fluid flow downward and/or upward along detachment fault planes, reaching depths of 10 – 15 km. In addition, isotopic studies show the presence of small amounts of deep $CO_2$, $H_2S$, B and He in thermal waters (see our compilation, section 3.2). We thus suggest that large-scale detachment faults may represent the conduits allowing the escape of helium to the surface in the Menderes Massif. In others words, fault-controlled circulation of meteoric fluids is the dominant mechanism to explain the migration of mantle volatiles from the ductile-brittle transition zone to the near-surface (Fig. 12b) (Mutlu *et al.* 2008; Jolie *et al.* 2016). Brittle fault systems are thus probably connected at depth with ductile shear zones (Fig. 12b).

Ductile shear zones may indeed represent efficient pathways for hydrothermal fluids (*e.g.* Oliver, 1996; Taillefer *et al*. 2017). Two main mechanisms explain the fluid migration in the deeper part of the crust: deformation-driven flow (Oliver, 1996) and thermally-driven flow (*i.e.* buoyancy-driven) through the crust, which is favoured by the high (i) permeability of detachments that collect and bring up deep hot fluids and (ii) temperature induced by the shear heating mechanism. This latter term refers to the generation of heat from the mechanical work of tectonic processes (Scholz 1980). It thus increases with slip rate, friction coefficient and stiffness of materials (Leloup *et al.* 1999; Souche *et al.* 2013). Considered as a most rapidly deforming regions (*e.g.* Reilinger *et al*. 2006), western Anatolia domain would favour the development of such mechanism at crustal-scale. Indeed, neo-tectonic activity in the Menderes Massif is characterized by earthquakes occurring in the shallow crust, with the mean depth being shallower in the Simav domain (9.7 km) compared to the western domain (11.9 km) and the central Menderes (11.2 km) domain (Gessner *et al.* 2013). Brittle deformation is still active (*e.g.* the Gediz detachment, Buscher *et al*. (2013)) and may locally occur under high temperatures conditions (*e.g.* 580 °C at ~ 10 km, Bilim *et al*. 2016), probably close to the ductile-brittle transition zone. The numerous ductile shear zones may have had (and perhaps still have; *e.g.* Ring *et al*. 2017) a strong and continuous thermal effect at depth, explaining also the anomalously shallow position of Curie-point depths. Hence, in these areas heat could also be generated by tectonic processes, probably along the brittle-ductile shear zones in the upper levels of the continental crust (Fig. 12b) (Scholz 1980). Although the contribution of shear heating at crustal scale is debated (Lachenbruch and

Sass 1992), more studies would be needed to explore this possibility. In particular, the amount of heat produced and the time constants of such heat production should be addressed.

Furthermore, using a numerical model of coupled fluid flow and heat transport processes, Magri *et al*. (2010) showed that temperature patterns in the Seferihisar-Balçova area result from both interaction of convective flow (*i.e.* buoyancy-driven flow) and meteoric recharge induced by the horst (*i.e.* mixed convection) in the shallower crust. Recently, Roche *et al*. (2018) showed that high temperatures at 6 km depth (300 – 350 °C) are sufficient to allow a high fluid density contrast, permitting upward flow along the low-angle fault, using also 2-D numerical models (see Fig. 8 in their study). This implies that buoyancy-driven flow is superimposed to topography-driven flow in some places. This case is, for instance, well observed in the Seferihisar geothermal systems where the topographic gradient related to the formation of MCC appears to be negligible. This implies that the observed temperature patterns result mainly from the thermally driven flow within permeable faults. In all cases, hot fluids in the detachments will further enhance temperature increase in the upper part of the fault zone, thus generating high thermal gradients in these areas. For instance, Gottardi *et al.* (2011) estimated high temperature gradient of ~140 °C/100 m across the Miocene Raft River shear zone in the United States, as revealed by isotope thermometry. There, the geotherm is quasi-stable over a long time duration. As a consequence, it raises the question whether similar geothermal fields in the Menderes Massif could have been active during millions of years.

Additionally, it is clear that permeability related to fault zones architecture is a first-order control on fluid flow in the upper crust (*e.g.* Caine *et al.* 1996). Our study shows that the thick siliceous microbreccia of the Alaşehir detachment fault plane (Table 2) acts as cap fault of the fluid circulating below this plane. Thus, depending on the area, the detachment can be considered at kilometric-scale as a combined "conduit-barrier" and as a "localized conduit" (Caine *et al.* 1996), where the conduit corresponds to the thick shear zone and the barrier is associated with the fault plane and/or with the hanging wall of the detachment. Depending on the pressure gradients, the flow within the detachment may be characterized by horizontal-flow according to normal kinematic and related dilatancy (Fig. 12a). In both cases, the high permeability in the shear zone favours fluid circulation (*e.g.* in marbles levels through karstification process in the Menderes Massif) and thus generates secondary reservoirs (Fig. 12a).

#### 5.1.2. Basin-scale: the N-S transfer faults

Based on our structural observations, we highlight that strike-slip faults control many geothermal reservoirs in depth, related to hot springs and travertine deposits at the surface. In terms of geometry, for instance, Çiftçi and Bozkurt (2010) suggested, from a seismic profile interpretation, the existence of two kilometric transfer faults with a large normal component in the Alaşehir graben (Fig. 4a). These transfer faults correspond to the location of several travertines oriented NW-SE and NE-SW and hot springs at the surface, which are respectively associated with the Urganlı (Temiz and Eikenberg 2011) and Alaşehir geothermal field (Fig. 4a). Kaya (2015) also suggests that the Tekkehamam geothermal field (located in the southern part of the Büyük Menderes graben, Fig. 1b) is associated with a N-S transfer fault that cuts both the basement and Neogene sediments. Thus, this set of faults is a good candidate to act as conduit for fluid circulation when hot springs and related travertines are located far from the detachment (Fig. 12a; Table 2). Here, horse-tail termination of these strike-slip faults (see more details in Faulds *et al.* 2011), generates many closely spaced faults that locally increase permeability, favouring the growth of reservoirs.

Although no clear chronology between detachments and the N-S strike-slip transfer zones can be observed in the field, we favour a contemporaneous and ongoing development of these faults systems during the development of the sedimentary basin according to Oner and Dilek (2013). They are mainly found at the foothills of the main Menderes mountains, crosscutting the detachments in high topographic zones. Nonetheless, we suggest that these faults may also root to detachments at deeper depth (Fig. 12a). There, pull-apart structures, *en échelon* and relay-ramp faults may be locally developed, generating dilational jogs with vertical pitch that focus fluid circulation and thus geothermal upflow (Fig. 6d and Fig. 11c). In addition, reservoirs are commonly focused at the dilational junction between detachments and nearby N-S strike-slip faults or within the strike-slip faults (*e.g.* Cumalı fault, Figs. 11a and 12a).

To sum-up, these faults define several hundred meters wide relay zones where faults are considered as "distributed conduits" (Caine *et al*. 1996). They are characterized by multiple minor faults, connected with major structures where fluids can flow through highly fractured metamorphic rocks thanks to the seismic pumping mechanism (*e.g.* Sibson *et al*. 1975; McCaig 1988; Famin *et al*. 2005). Consequently, we refer hereafter to these sinistral or dextral strike-slip faults as the "geothermal transverse and transfer faults" related to main reservoirs (Fig. 12a). Hence, these faults should be used as a main guide for geothermal exploration. This hypothesis is opposed to the idea of Gessner *et al*. (2017), suggesting that NNE-SSW-orientated lineaments do not have a significant role in fluid flow pattern.

### 5.2. Possible fluid pathways in the Menderes Massif: from the mantle to the geothermal reservoir

In this study we have emphasized two types of control on hot springs and related geothermal fluid flow in the Alaşehir, Büyük Menderes and Cumaovası basins: a structural control and a lithological control (Table 2), which is also determinant to understand the location of hot springs and to explain the position of reservoirs at depth. In the following, we first propose a fluid pathway at the scale of the Menderes Massif (Fig. 12a) and then we mention a possible long-live duration for this type of systems.

#### 5.2.1. Source to sink

Based on structural analyses of field data and isotopic distribution of waters, we suggest similar pathways of fluids for the Alaşehir and the Büyük Menderes half-grabens, that could also extend to the Simav graben and Cumaovası basin: meteoric cold waters and/or sea waters (*i.e.* for the Seferehisar case) circulate downwards along E-W high-angle to listric normal faults (*e.g.* Salihli and Alaşehir geothermal systems), implying that such faults control the meteoric recharge of deeper reservoirs (Fig. 12a). More generally, meteoric water infiltration along fractured rocks of the basement of the Menderes Massif is controlled by (i) the footwall topography gradient induced by MCC exhumation, and by (ii) the stress regime in the crust, allowing recharge and hydrothermal fluid circulation. Then, temperature of fluids increases progressively. Hot fluids can circulate along the main detachments (*i.e.* Simav, Alaşehir and Büyük Menderes detachments) related to karstified marbles or/in fractured rocks of the basement. During this stage, the geochemical properties of meteoric waters are modified and their composition (*e.g.* $Na\text{-}HCO_3$ type) is mainly controlled by calcite dissolution in the marbles layers of the Menderes Massif under high temperature conditions. Locally, some exchange with mantle-He, $CO_2$, B and $H_2S$ isotopes could occur in deep parts of the crust in the ductile-brittle transition zone (Fig. 12b). Through a seismic pumping mechanism (*e.g.* Sibson *et al*. 1975; McCaig 1988; Famin *et al*. 2005), hydraulic gradients may force fluid downward across the ductile-brittle transition using the high permeability of microcrack networks (*e.g.* after earthquake rupture). After a complex deep fluid pathway, thermal waters may then recharge reservoirs of the metamorphic rocks of the Menderes at depth (Figs. 12a and 12b).

Different lithologies may behave as reservoirs (Table 1). Reservoirs are herein defined by highly fractured but also by karstified carbonate layers of the CMM *(e.g.* Salihli, Alaşehir, Germencik, Salavatlı…; Tarcan *et al.* 2000). For instance, the high-temperature geothermal reservoir observed in Alaşehir, is located in the upper section of the Paleozoic basement, with feeder zones in the upper Paleozoic carbonates at approximately 1150 m and 1600 m of depth (Akin *et al.* 2015). Fractured metamorphic rocks such as quartzite can also act as an aquifer for geothermal fluid (e.g., Kızıldere; Simsek 2003). In both cases, the main reservoirs are located just below the detachments, which is in some places silicified (Fig. 12a). There, blind geothermal reservoirs may also form. Indeed, according to Magri *et al.* (2010), when hydrothermal plumes reach the upper impermeable boundary (*e.g.* the Alaşehir detachment), over-pressured blind geothermal reservoirs are formed. This implies that other geothermal systems in the Menderes Massif are yet to be discovered. In order to fully understand these geothermal systems, stress modelling related to faulting is necessary to bring new constraints on the evolution of fluid pathways (Moeck *et al.* 2009). In addition, other reservoir types may be developed in the hanging-wall of detachments. For example, in the Cumaovası basin, it is made of fractured submarine volcanics of the Bornova mélange (Tarcan and Gemici 2003). Because of the high permeability units in Neogene continental silicoclastic rocks, secondary aquifers may also occur (Fig. 12a). Indeed, Neogene sediments may have highly variable permeability, but they usually rather display mega-cap rocks related to underlying geothermal system (Tarcan *et al.* 2000; *e.g.* the Alaşehir geothermal system).

After a short time of residence (around 20 – 50 years, Simsek 2003) in different kinds of reservoirs, hot thermal fluids can flow along the dilational intersections or junction between the N-S strike-slip faults and the detachment, and then emerge at the surface (*e.g.* Kurşunlu, Sart-Çamur, Germencik hot springs) (Fig. 12a). In this case, the direction of flow is mainly determined by the prevailing permeability and by the regional stress field. Similar features of fluid flow pattern are observed in the Cumaovası basin where the NE-SW trending strike-slip faults affected also the detachment, forming dilational jogs and favouring hot water circulation from karstic and fractured reservoirs to the surface (*e.g.* Figs. 11b and 11c).

### 5.2.2. A long-lived duration geothermal Province?

Hetzel *et al*. (2013) suggested that the Alaşehir and Büyük Menderes detachments recorded a long-lived brittle deformation from around 22 Ma until 4 – 3 Ma. Hence, the low-angle crustal normal faults were (still) active over a long period of time. We thus suggest that detachments controlled magma ascent (*e.g.* Salihli granodiorite, Egrigöz granite) as well as fluid circulation in the Menderes Massif during the Miocene. Nonetheless, the presence of Kursunlu Sb-Hg(-Au) deposit (Larson and Erler 1993) located within the Alaşehir detachment system, implies a drastic change in the fluid pathway evolution compare to the Miocene. Indeed, according to Larson and Erler (1993), Alaşehir detachment conveyed deep circulation of shallow hydrothermal fluids (*i.e.* meteoric origin) with a minor component of crustal and mantellic origin, thus similar to the present-day hot springs. Hence, the mineralizing fluid seems to be not related to the Miocene intrusions. To better characterize this evolution, a detailed study of such deposit would be useful, bringing new constraints on the structural control of the mineralization and the timing of mineralizing processes. This imply that detachments control fluid pathways over millions years (episodic or continuous mineralized pulse(s)?).

## 5.3. Origin of heat source in the Menderes Massif

At geodynamic-scale, the origin of the thermal anomalies propagating all the way to the surface could reflect both slab-rollback and slab tear below western Turkey. Heat can be generated by many processes, including anomalous mantle heat flow mainly due to asthenospheric flow and shear heating (Fig. 12c) (Roche *et al*. 2018). Based on heat conduction, the time scale $t_{diff}$ is defined by the following equation:

$$t_{diff} = L^2 / \kappa \quad (1)$$

where L is Moho depth (meter) and κ is the thermal diffusivity ($m^2\ s^{-1}$). Considering a Moho depth of ~ 25 km under the Menderes Massif (*e.g.* Karabulut *et al.* 2013) and taking a thermal diffusivity (κ) of $10^{-6}$ m² $s^{-1}$, the current thermal anomaly observed at the surface (shown by the presence of numerous sources and gas events) could reflect the thermal expression of a 20 Ma old slab tear at Moho depth. In other words, the heat source at the base of the crust coupled to the exhumation of the MCC is induced by slab dynamics since the Miocene as suggested by previous authors (*e.g.* Jolivet *et al*. 2015; Menant *et al*. 2016; 2018; Roche *et al*. 2018). This increase of temperature recorded in the mantle and in the crust favours the emplacement of a large zone of migmatization and/or magmatic underplating at the base of the crust. This hypothesis is also consistent with:

(i) the presence of high temperatures (~ 580 °C) at shallow depths (~ 10 km under the Menderes; Aydin *et al.* 2005; Bilim *et al.* 2016);

(ii) the current models of Miocene slab tearing in this region (Jolivet *et al*. 2015).

(iii) the enrichment of mantle-He (Mutlu *et al.* 2008), B and sometimes high content of $CO_2$ and $H_2S$ within all thermal waters (Vengosh *et al.* 2002); for instance, mantle-He values suggest that helium is probably transferred to the lower crust by degassed fluids from deep mantle melts (Mutlu *et al.* 2008); these values comparable to that observed in hydrothermal fluids from the western part of the Basin & Range Province (4 – 25% mantle-He) where active volcanism is also absent (Kennedy and Soest 2007).

To sum-up, the lack of significant magmatic activity in this area shows that the upper crust and related magmatic bodies is not a direct heat source for these geothermal systems (Faulds *et al*. 2010). Nevertheless, based on 3-D Vp imaging of the upper crust beneath the Denizli geothermal field, Kaypak and Gökkaya (2012) showed that intrusive magmatic bodies may also explain the heat source of few geothermal systems in this area. According to this study and others (*e.g.* Faulds *et al*. 2010; Kaya 2015; Gessner *et al*. 2017) the spatial distribution of hot springs and fumaroles is associated with the tectonic activity. Using the classification of Moeck (2014), the “geothermal Province” of the Menderes Massif can be considered as a fault controlled system in an extensional domain, where convection occurs along the transfer fault systems. Although most of existing models of geothermal heat source suggest a probable magmatic intrusion in the upper crust, this study argues that the tectonic activity induced by subduction dynamics controls the spatial distribution of heat in the Menderes massif (Fig. 12c) (*e.g.* Kaya 2015; Gessner *et al*. 2017; Roche *et al*. 2018). We thus think that this area may be used as a reference case to better understand the amagmatic geothermal systems/Provinces.

### 5.4. An underestimated geothermal potential?

It is clear that dense fracturing caused by tectonic activity implies a modification of the regional fluid flow, which is controlled by the state of stress in the crust, and influences the localisation and the typology of reservoirs. Reilinger *et al.* (2006) have estimated fault-slip rates in a block model consisting of 19 plates/blocks and using M>4.5 earthquakes above 35 km. Based on GPS-derived velocity field data, they suggested a total extension of approximately 25 mm/yr corresponding to 10.9 ± 0.3 mm/yr for the left lateral strike-slip component and 14.5 ± 0.3 mm/yr of pure extension. This rapid relative motion is twice the rate reported from the Basin & Range Province where Bennett *et al.* (2003) estimate relative motion of 9.3 ± 0.2 mm/yr with high strain rates, using the same method (*i.e.* GPS-derived velocity field data). Faulds *et al*. (2012) showed that the regional pattern of geothermal activity in the same area is directly correlated with strain rates. If we compare, for instance, the total discharge of the Seferihisar geothermal field (*e.g.* 100 – 150 L/s to 300 L/s according to Tarcan and Gemici (2003)), located in a seismically active zone (*e.g.* see compilation from Özkaymak *et al*. 2013) is twice to four times that of the Salihli geothermal field (2 – 80 l/s; Özen *et al*. 2012), which is a less active zone. Paradoxically, the topography is less steep in Seferihisar area than in Salihli area. Therefore, we suggest that active deformation could affect fluid velocity in the upper crust, improving the flow rates of a geothermal system.

Furthermore, the Basin & Range Province is quite similar to the Menderes Province because MCCs are exhumed along low-angle normal faults, and represent a favourable setting for amagmatic high enthalpy geothermal resources (Roche *et al*. 2018). In addition, the origin of the heat of these systems may be also associated with a deeper source induced by subduction dynamics (*i.e*. magmatic underplating under the overriding plate; Wannamaker *et al*. 2006). Because of the similarities between these both geothermal Provinces, we suggest that the geothermal potential in the Menderes is probably underestimated (~ 820 MWe, Geothermal Resource Association estimated in 2018). Indeed, the current geothermal installed capacity of the Basin & Range province is estimated at ~ 2349 MWe (Bertani, 2016).

## 6. Conclusion

Our work is based on a multiscale study and on a compilation of geothermal and structural observations in the whole Menderes Massif. It provides a new vision on the role of a large-scale thermal anomaly below the Menderes Massif and more generally in the Eastern Mediterranean region. We suggest that such regional thermal anomalies at the origin of the Menderes geothermal Province result from the tectono-thermal evolution of the Aegean subduction zone at depth. This Province is characterized by an intense hydrothermal activity, favoured by both a high elevation area and a neo-tectonic activity in absence of magmatic input. Such proxies are related to the Menderes Core Complex evolution, which is structured by three main detachments. We also have identified, at crustal-scale, the essential role of the low-angle normal faults, corresponding to a permeable channelized fluid flow systems for ascending fluid flows. N-S transfer faults then control the position of geothermal systems and should be used as a main guide for geothermal exploration. In addition, we emphasize that the lithological control is determinant for understanding the location of geothermal reservoirs, and may have a strong influence in the fluid circulation pattern of thermal waters. Eventually, we highlight that an episodic model (*e.g.* seismic pumping) and / or a continuous model seem possible over several million years in the Menderes Massif.

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## Tables

**Table1:** Catalogue of hot springs and geothermal fields associated with the metamorphic core complex formation in the Menderes Massif. ADFP: Alaşehir detachment fault plane. Compilation data from Simşek (1984; 2003), Simsek and Demir (1991), Yılmazer and Karamanderesi (1994), Karamanderesi (1997; 2013), Özgür *et al.* (1998a; 1998b), Tarcan *et al.* (2000); Gemeci and Tarcan (2002), Tarcan and Gemici (2003), Yildirim *et al.* (2005), Kose (2007), Faulds *et al.* (2010), Kindap *et al.* (2010), Tekin and Akin (2011), Özen *et al.* (2012), Baba *et al.* (2014 ; 2015), Akin *et al.* (2015) and Tureyen *et al*. (2016).

**Table 2:** Main controls on geothermal fields in the Menderes Massif. BD: Büyük Menderes detachment, BM: Bornova Mélange, FC: Fault controlled, FRC: Fracture controlled, FW: Foot wall, AD: Alaşehir detachment, HW: Hanging wall, KC: Karstic controlled, MU: Menderes Unit, NF: Normal fault.

## Figure Captions:

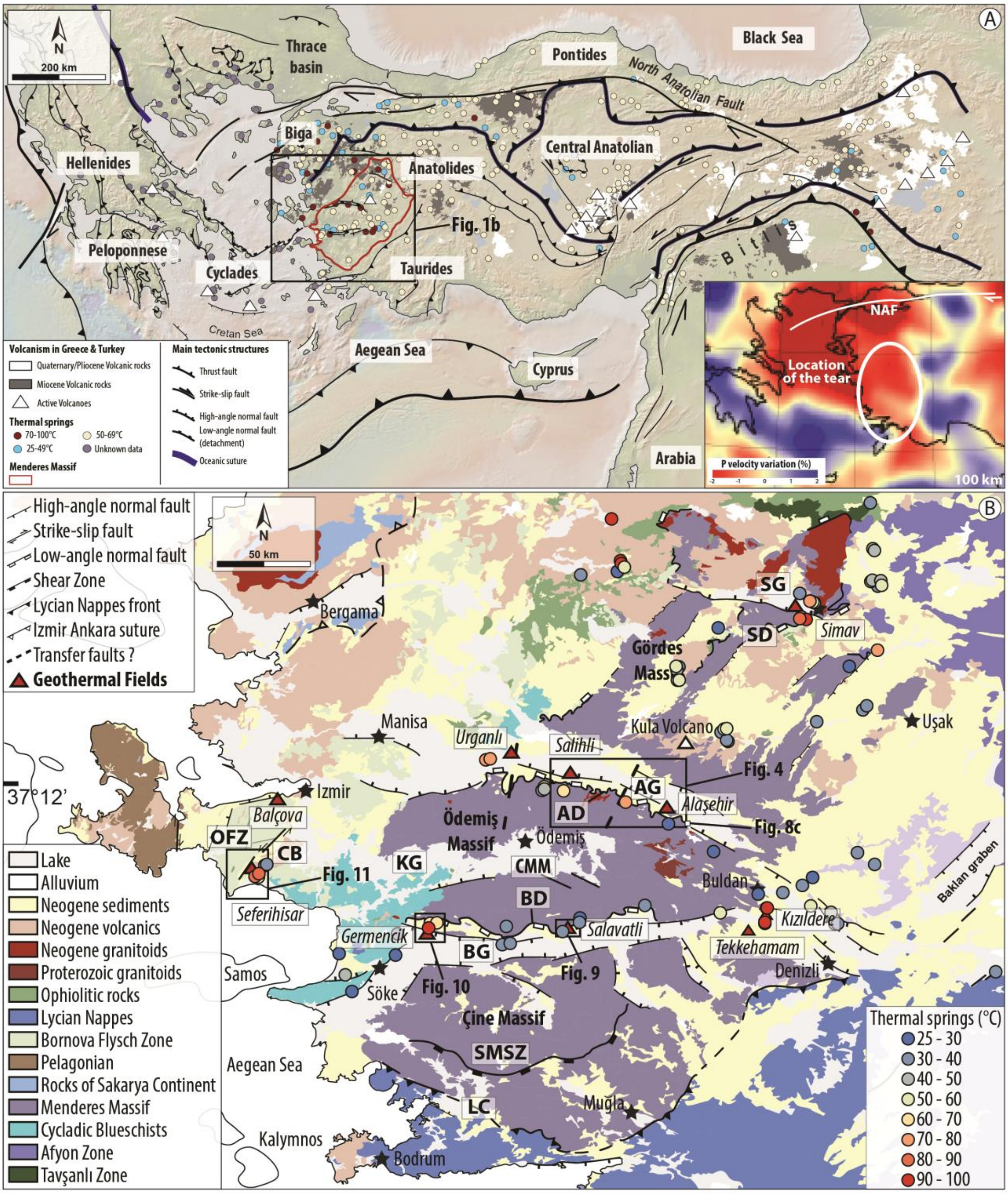


**Fig. 1:** Tectonic map of Eastern Mediterranean region highlighting the main tectono-metamorphic domains and showing location of the study area. Modified from Jolivet *et al.* (2013) and Gessner et *al*. (2013). (a) Simplified tectonic map showing major thermal occurrences based on a compilation of several data sources (Akkuş *et al*. 2005; Bayram and Simsek 2005, Mendrinos *et al*. 2010 and Andritsos *et al*. 2015) and spatial distribution of Upper Terciary-Quaternary

volcanics rocks (from the geological map of the MTA). Note that white triangles indicates active volcanoes. Base maps made with *GeoMapApp* (https://www.geomapapp.org). Tomographic model of Piromallo and Morelli (2003) showing the Vp anomalies at the ~ 100 km depth in the bottom right corner of this Figure. The white circle illustrates the schematized position of the slab tearing. Note that NAF is the abbreviation for North Anatolian Fault. (b) Tectonic and geological map of the Menderes Massif modified from the geological map of the MTA and Bozkurt *et al.* (2011). Red triangles represent main geothermal areas of the Menderes Massif, from Faulds *et al.* (2010) and Kaya (2015). Thermal spring locations correspond to our study, and to the studies from Akkuş *et al*. (2005) and Bayram and Simsek (2005). Also indicated is the position of the Figs. 4, 8c, 9, 10 and 11. Main structures and grabens are indicated in abbreviations: AD (Alaşehir detachment); AG (Alaşehir graben); BD (Büyük Menderes detachment); BG (Büyük Menderes graben); CB (Cumaovası basin); CMM (Central Menderes Massif); KG (Küçük Menderes graben); LC (Lycian contact); OFZ (Orhanlı fault zone); SMSZ (Southern Menderes shear zone); SD (Simav detachment) and SG (Simav graben).

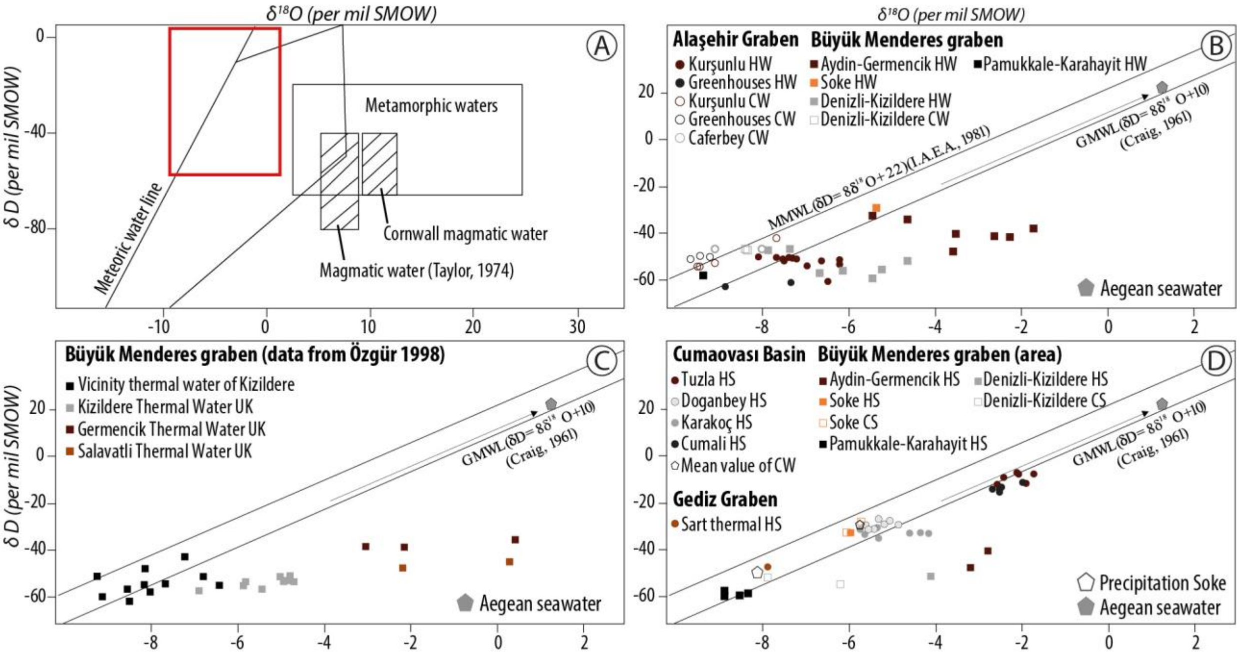

**Fig. 2:** δD vs δ18O diagrams. (a) Plot of δD vs δ18O diagram for different water types. The field of magmatic water and formation waters are taken from Taylor (1974). The field for magmatic waters from the granites of Cornwall is from Sheppard (1977). The meteoric water line is from Epstein *et al.* (1965). The metamorphic water field combines the values of Taylor (1974) and Sheppard (1981). Red rectangle indicates the field of all isotopic data from the Menderes Massif. (b) Stable isotope compositions of the geothermal reservoir fluids in the studied areas showing hot and cold waters wells. Abbreviations: HW (Hot water well), CW (Cold water well). (c) Stable isotopes of different geothermal fields in the Büyük Menderes Graben. Abbreviation: UK (unknow sampling locations). (d) Stable isotopes of springs in three main basins. Abbreviations: HS (Hot spring), CS (Cold spring). Compilation of data from Filiz *et al.* (2000), Özgür (2002), Tarcan and Gemici (2003), Simsek (2003) and Özen *et al.* (2012).

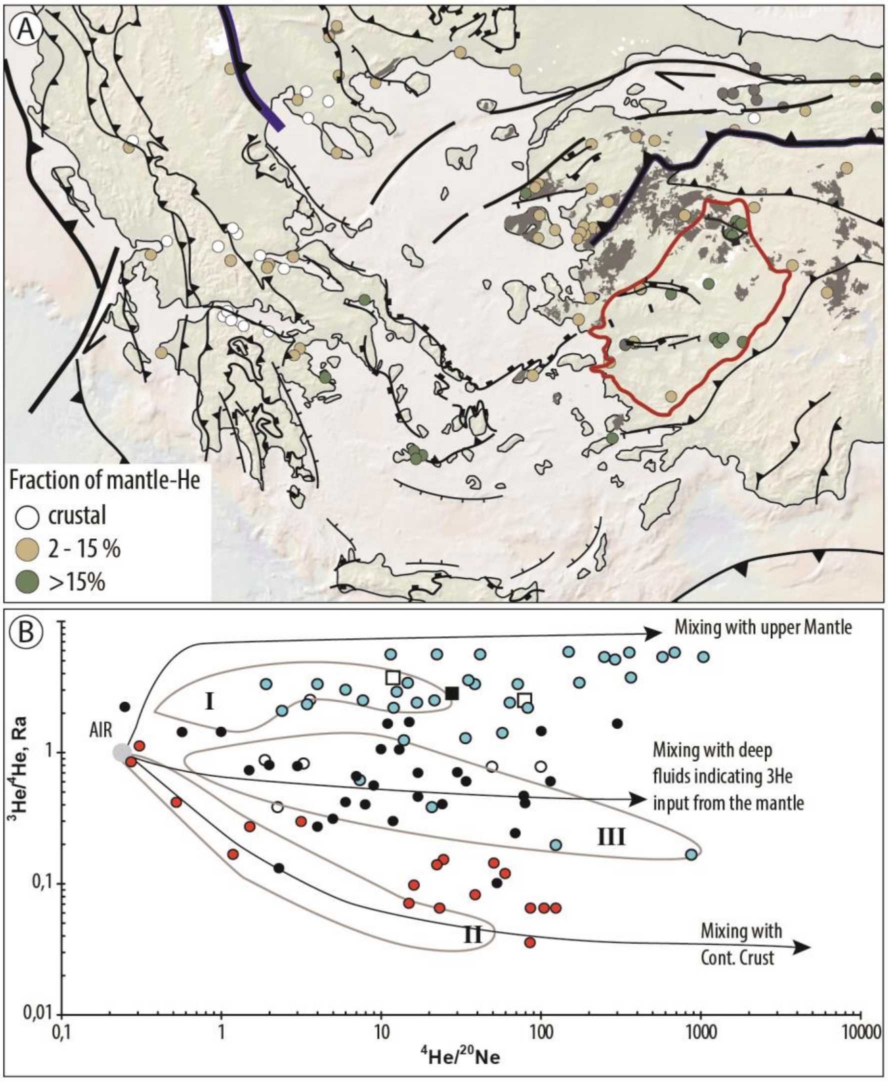


**Fig. 3:** Isotopic composition of Helium. (a) Fraction of mantle-He in hydrothermal fluids from the Aegean Anatolian domains computed from helium isotopic data, assuming mixing between a crustal component (0.04 Ra) and a mantle component (8 Ra), modified from Pik and Marty (2009). Helium isotopic data are from Pik and Marty (2009) and Karakuş (2015). (b) R/Ra diagram for the Eastern Mediterranean region from Güleç (1988), Güleç *et al.* (2002), Güleç and Hilton (2006), Mutlu *et al.* (2008), Pik and Marty (2009) and Karakuş (2015). Black dots showing data of the west Anatolian domain, red dots data of the gulf of Corinth, Blue dots data of the magmatic arc and white dots data of the back arc region in Greece. In addition, white and black squares indicate respectively the Denizli and Kula areas which are located in the Menderes Massif. The fields of the three groups of hydrothermal fluids (Pik and Marty 2009), are also presented: I = arc

magmatic fluids (>15% mantle-He), II = crustal signature (<1% mantle-He), III = other intermediate fluids (2–15% mantle-He).

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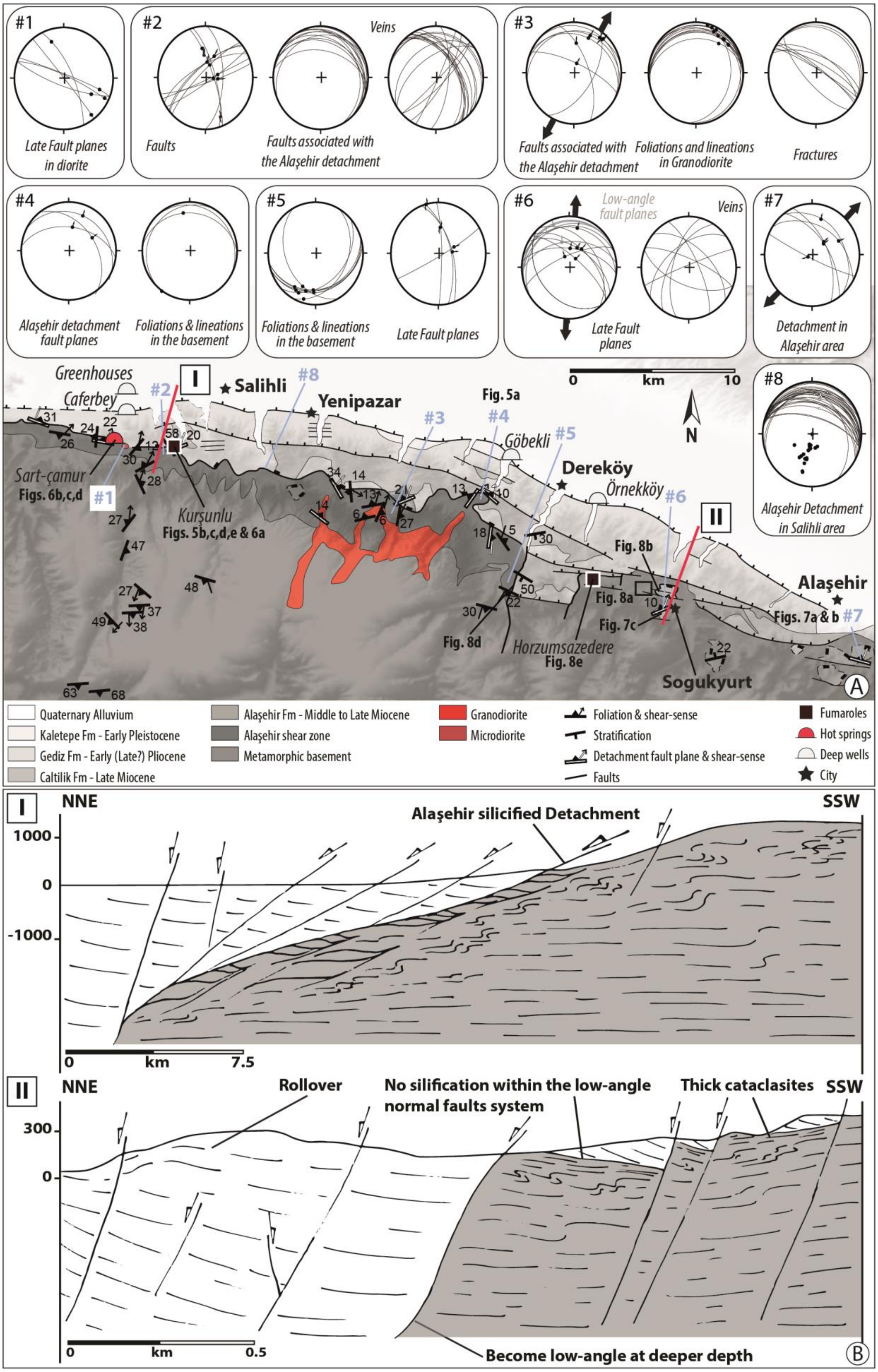

#1
Late Fault planes in diorite
#2
Veins
Faults
Faults associated with the Alaşehir detachment
#3
Faults associated with the Alaşehir detachment
Foliations and lineations in Granodiorite
Fractures
#4
Alaşehir detachment fault planes
Foliations & lineations in the basement
#5
Foliations & lineations in the basement
Late Fault planes
#6
Low-angle fault planes
Veins
Late Fault planes
#7
Detachment in Alaşehir area
#8
Alaşehir Detachment in Salihli area
Greenhouses
Caferbey
Salihli
Yenipazar
Fig. 5a
Göbekli
Dereköy
Örnekköy
Sart-çamur
Figs. 6b,c,d
Kurşunlu
Figs. 5b,c,d,e & 6a
Fig. 8b
Fig. 8a
Fig. 7c
Fig. 8d
Horzumsazedere
Fig. 8e
Sogukyurt
Alaşehir
Figs. 7a & b
km
N
Quaternary Alluvium
Kaletepe Fm - Early Pleistocene
Gediz Fm - Early (Late?) Pliocene
Caltilik Fm - Late Miocene
Alaşehir Fm - Middle to Late Miocene
Alaşehir shear zone
Metamorphic basement
Granodiorite
Microdiorite
Foliation & shear-sense
Stratification
Detachment fault plane & shear-sense
Faults
Fumaroles
Hot springs
Deep wells
City
A
I
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Alaşehir silicified Detachment
1000
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km
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II
Rollover
No silification within the low-angle normal faults system
Thick cataclasites
300
0.5
Become low-angle at deeper depth
B

**Fig. 4:** Geological and tectonic map of the Alaşehir graben modified from Asti (2016). (a) Map showing main structures: the Alaşehir low-angle normal fault, E-W striking high-angle normal faults and N-S striking high strike-slip faults which are described by Çiftçi and Bozkurt (2010). Thermal springs and fumarole activity are also located in the map. Brittle structures, foliation, veins and fractures are presented in Schmidt's lower hemisphere equal-area projection. Detailed results of the fault slip data inversion are also presented using the Win-Tensor software (Delvaux & Sperner, 2003). Also indicated is the position of the Figs. 5, 6, 7 and 8. (b) Cross-sections through the northern part of the Ödemiş Massif. Sections are all roughly parallel to the tectonic transport. To draw the shape of stratification, we used the bedding data of the Neogene sediments from Asti (2016). Colours show different rock types. Cross-sections are indicated by red solid lines in Fig. 4a.

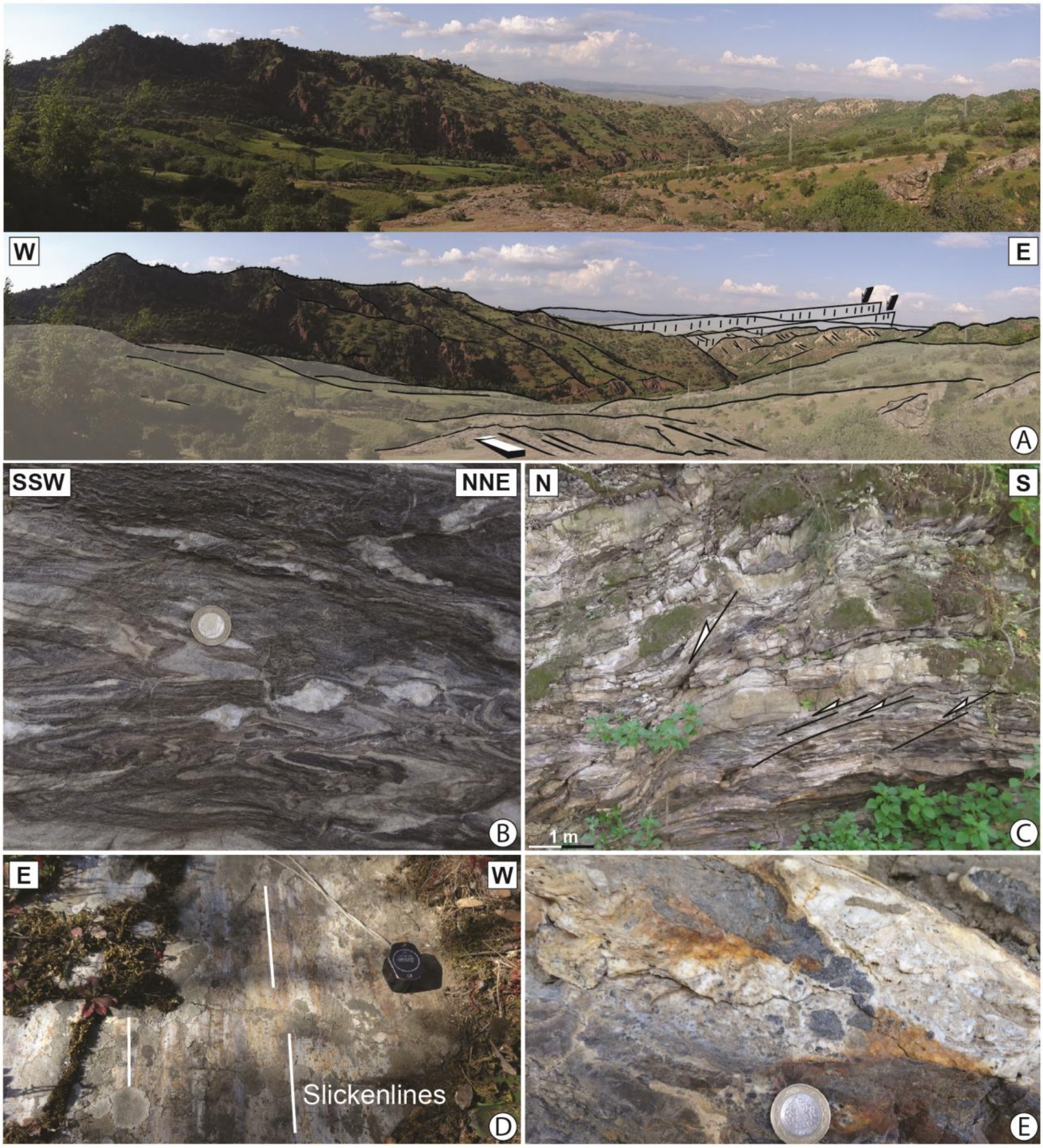


**Fig. 5:** Kinematic of deformation associated with the Alaşehir detachment. (a) Large-scale view of the Alaşehir detachment surface close to Salihli area. (b) Asymmetric boudins compatible with top-to-the-NNE ductile deformation in marbles layers. (c) Representative outcrop recognized as demonstrative of a brittle stage subsequently developed after the ductile one where shear zones are locally reactivated in the brittle field. (d) Fault plane of the Alaşehir detachment with

slickenlines. (e) Calcite and quartz vein parallel to the bedding, located few meters below the main fault plane. The position of the pictures is indicated in Fig. 4a.

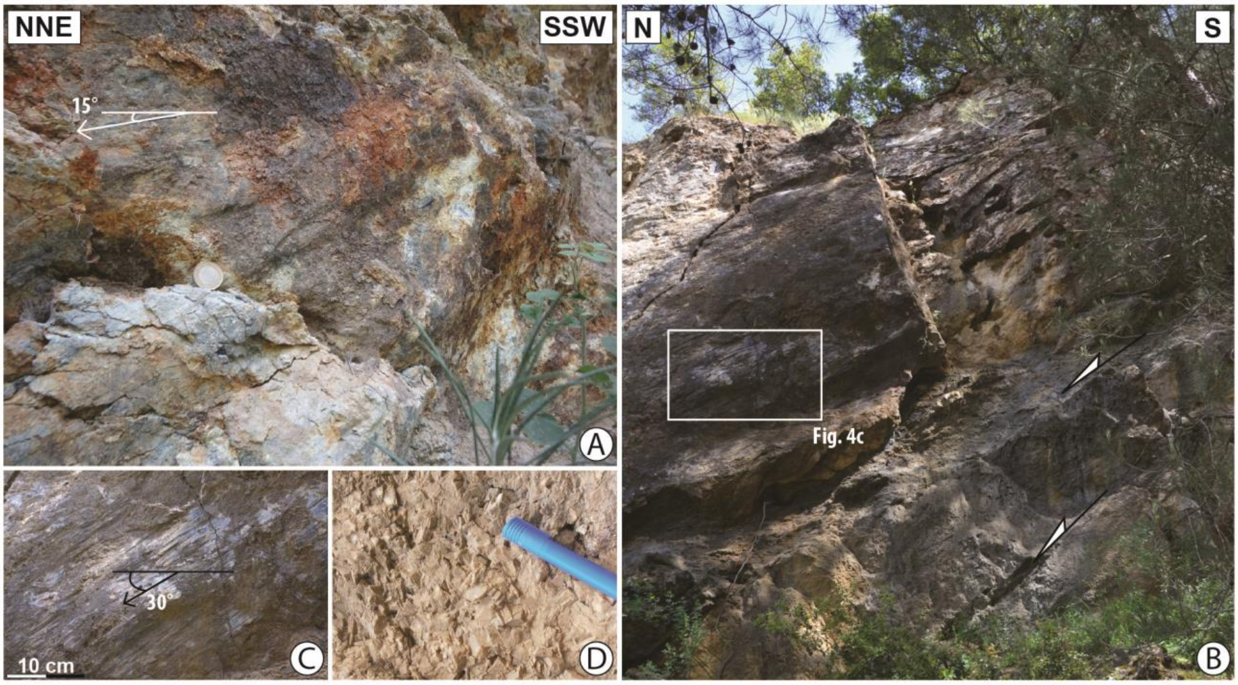


**Fig. 6:** Brittle deformation in the Salihli area. (a) N-S strike-slip fault in the Kurşunlu valley. (b) E-W striking normal faults are cross-cut by N-S strike-slip fault. (c) Close-up view of a slip-plane in the basement of the Menderes indicating nearly horizontal with a normal component slickenlines. (d) Calcite indicating fluid circulation close to the strike-slip fault. The position of the pictures is indicated in Fig. 4a.

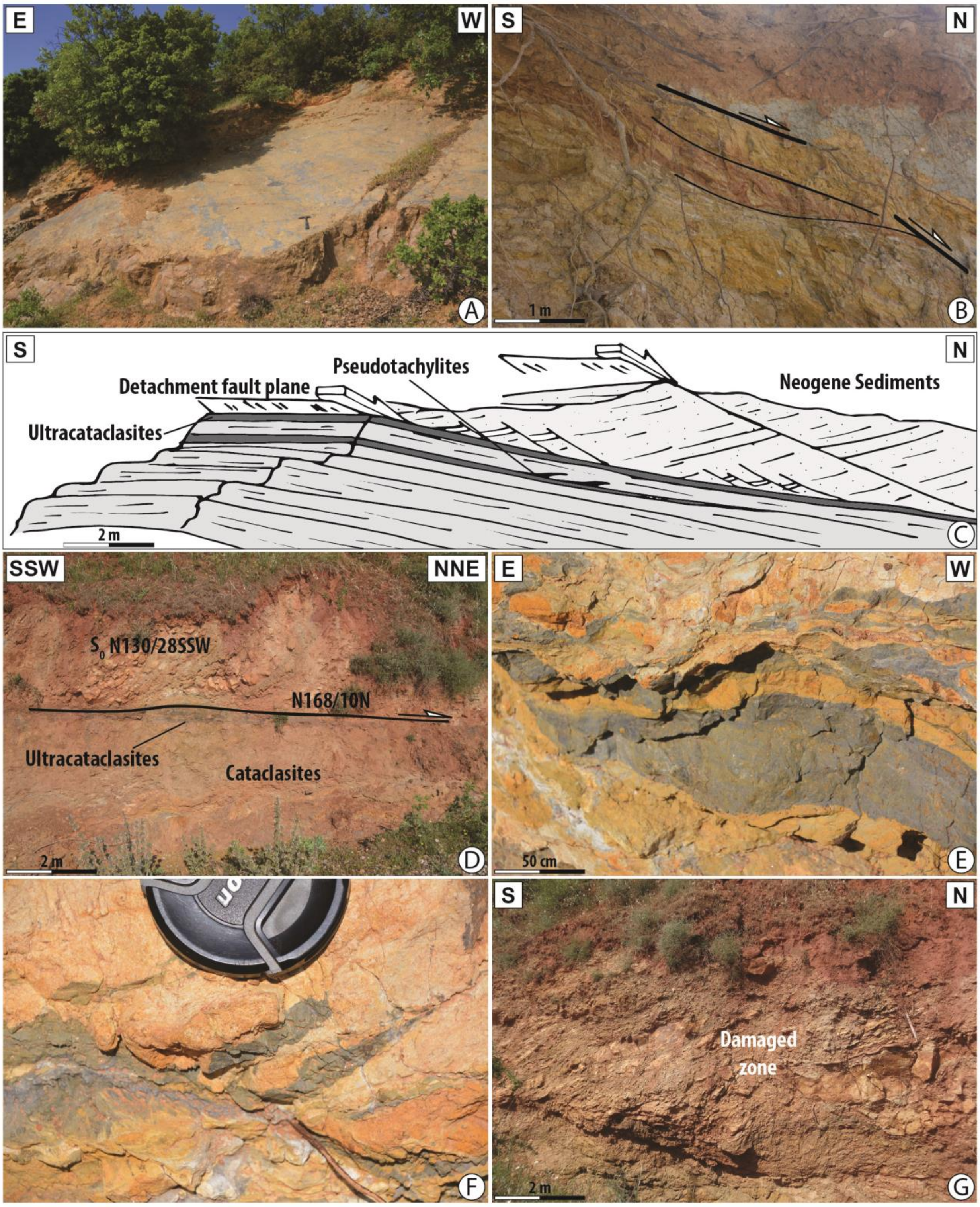


**Fig. 7:** Brittle deformation associated with the Alaşehir detachment in the Alaşehir area. (a) Detachment surface marked by a thick zone of cataclasites. (b) Foliated cataclasites below the main fault plane. Note that the shearing is toward the north. (c) Sketch depicting the relationships between the detachment fault plane and Neogene sediments in the NNW of Kara Kirse. (d) Low-

angle contact between metamorphic rocks (augen gneiss unit) and Neogene sediments. (e) and (f) Close-up view of ultracataclasites and centimetric pseudotachylytes, respectively. (g) Metric damaged zone in sediments. The position of the pictures is indicated in Fig. 4a.

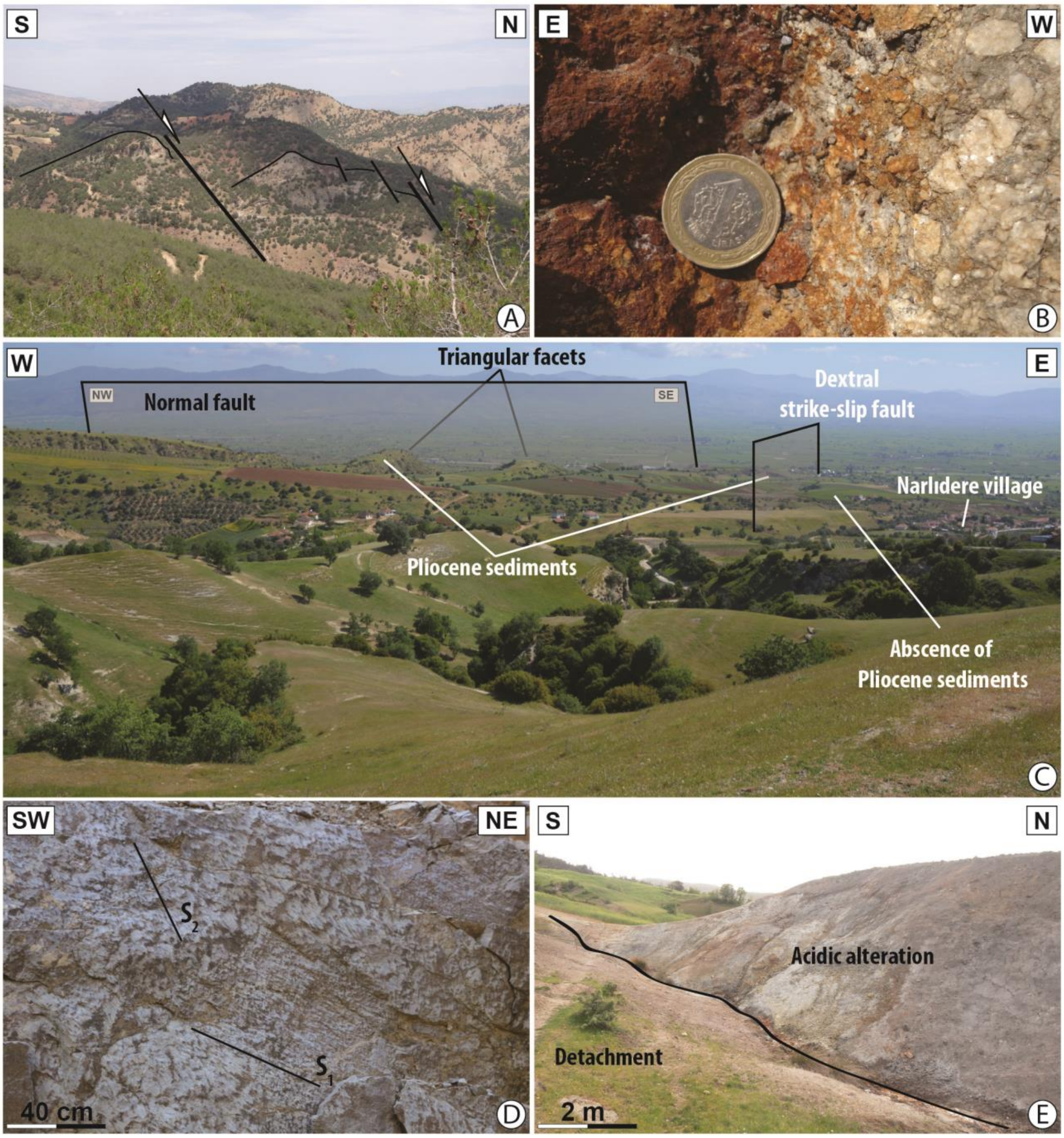


**Fig. 8:** Brittle deformation in the Alaşehir area. (a) Large-scale E-W high-angle normal faults. Outcrop shows hanging wall displacements toward the north. (b) Close-up view of E-W striking fault showing centimetric and angular blocs (*i.e.* cataclase). Note also the alteration of the

basement rocks implying a probable meteoric fluid circulation during fault activity. (c) Land-scape view of triangular facets in the eastern part of Alaşehir. Note the probable position of strike-slip fault. This fault is also mapped by Oner and Dilek (2013). See location in Fig. 4a. (d) Fault plane and associated striae (two generations) of N-S striking strike-slip fault. Note that stereographic projection of striated fault planes corresponds to the number #5 in Fig. 4a. (e) Picture showing an acidic alteration related to fumarole activity. See Fig. 4a for the location of pictures.

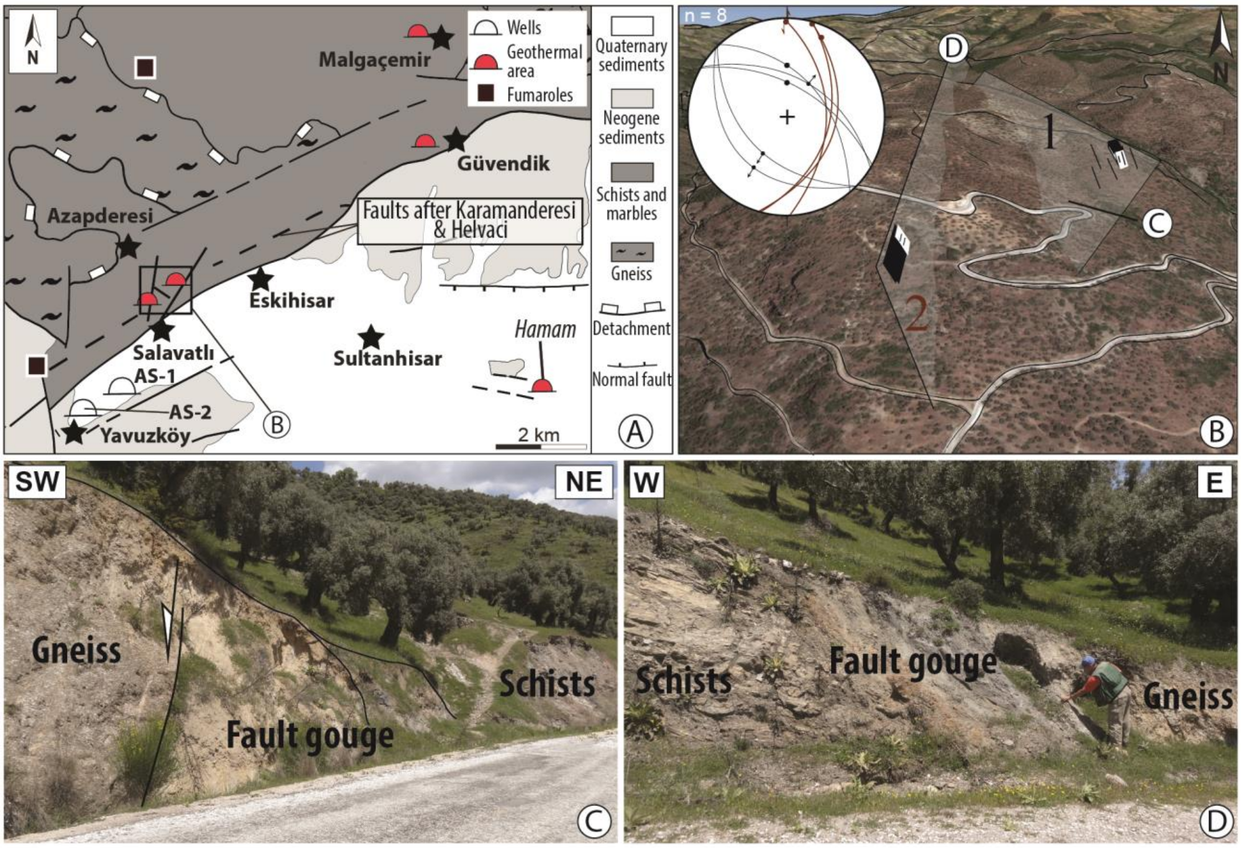


**Fig. 9:** Brittle deformation in the Salavatlı area. (a) Simplified geological map of Salavatlı geothermal field modified from (Karamanderesi and Helvaci, 2003). (b) Google earth view of the area. Main structures and stereographic projections of faults systems are indicated. Location is indicated in Fig. 9a. (c) NW-SE trending normal fault between gneiss and schists. (d) N-S trending faulted contact between schists/marbles sequences and gneiss. Note the metric fault breccia between these both units.

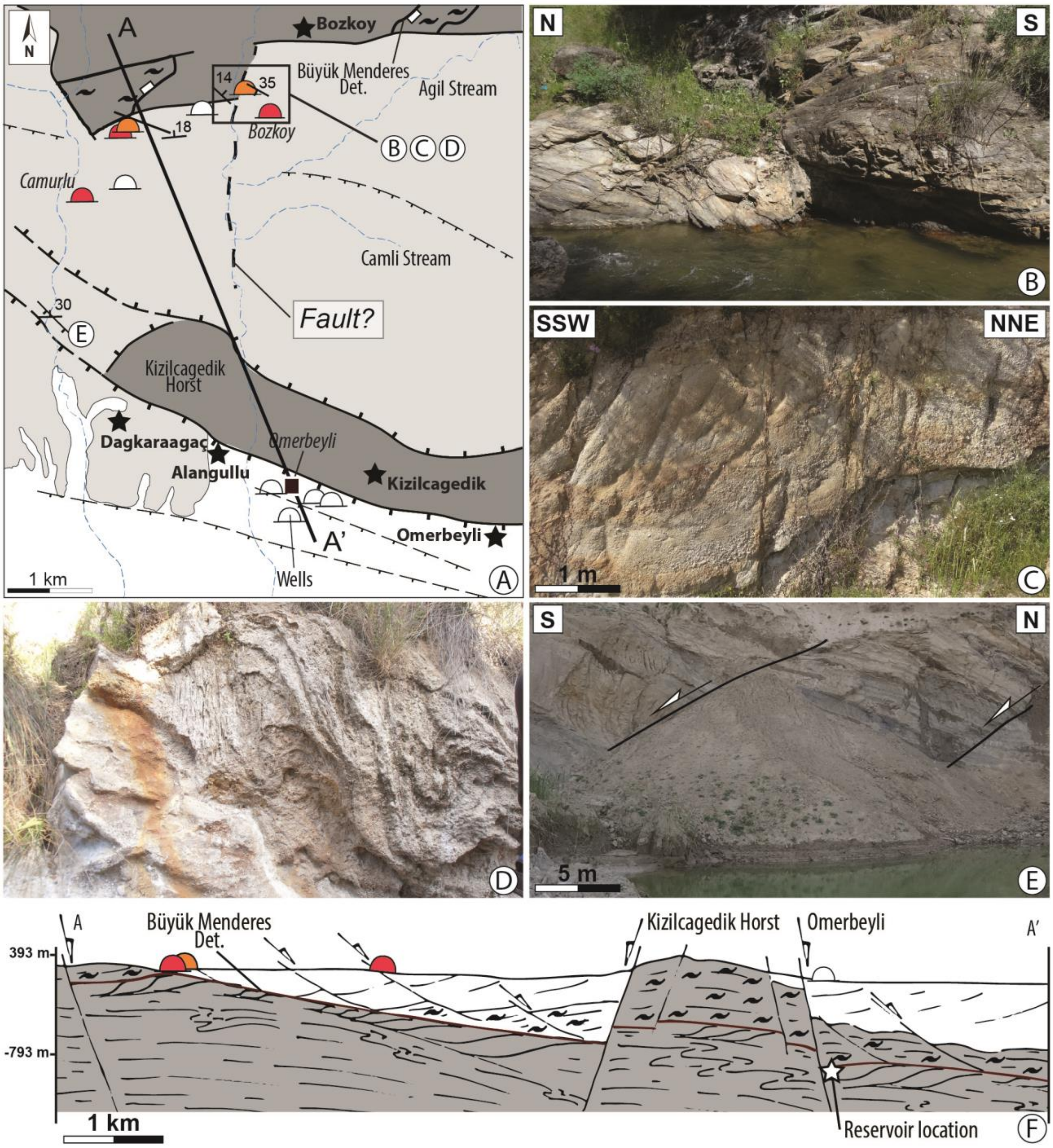


**Fig. 10:** Structures and geothermal activities in the Germencik geothermal field. (a) Simplified geological map of Germencik area modified from Karamanderesi (2013), showing thermal springs and fumaroles locations. (b) Shallow dipping E-W trending foliation in the basement of the Menderes units. (c) Dip inversion of the bedding in Neogene sediments close to the basement. (d) Travertine indicating fluid circulation. (e) Sallow dipping E-W striking fault in Neogene

sediments of the Büyük Menderes graben. (f) Simplified cross-section of the Germencik area (see location on Fig. 10a).

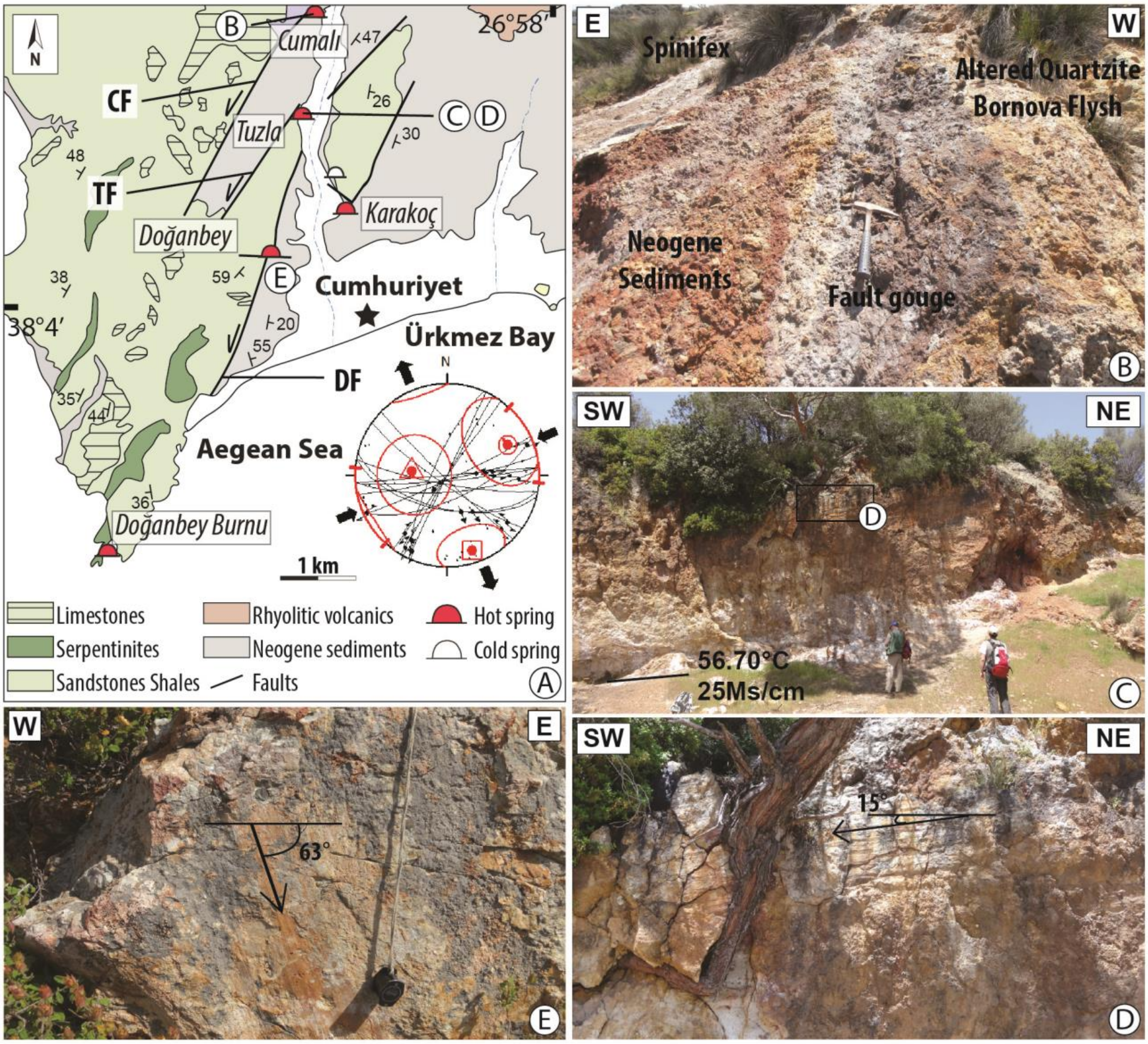


**Fig. 11:** Brittle deformation in the Seferihisar area. (a) Simplified tectonic and geological map of Seferihisar geothermal areas showing main structures: the Cumalı Fault (CF), the Tuzla Fault (TF) and the Doğanbey Fault (DF). Modified from Genç *et al.* (2001) and Drahor and Berge (2006). Also are represented stereographic projections of striations and kinematics of the main fault planes. (b) CF showing the altered contact between the basement and Neogene sediments. (c) Field photograph of TF plane in the Bornova mélange showing a NNE-SSW trending. Note the strong alteration at the foot of the fault implying the presence of hot spring. (d) Close-up view of

the fault plane showing well-preserved slickenlines. (e) Fault plane and associated striae belonging to the E-W trending normal fault. See Fig. 11a for location.

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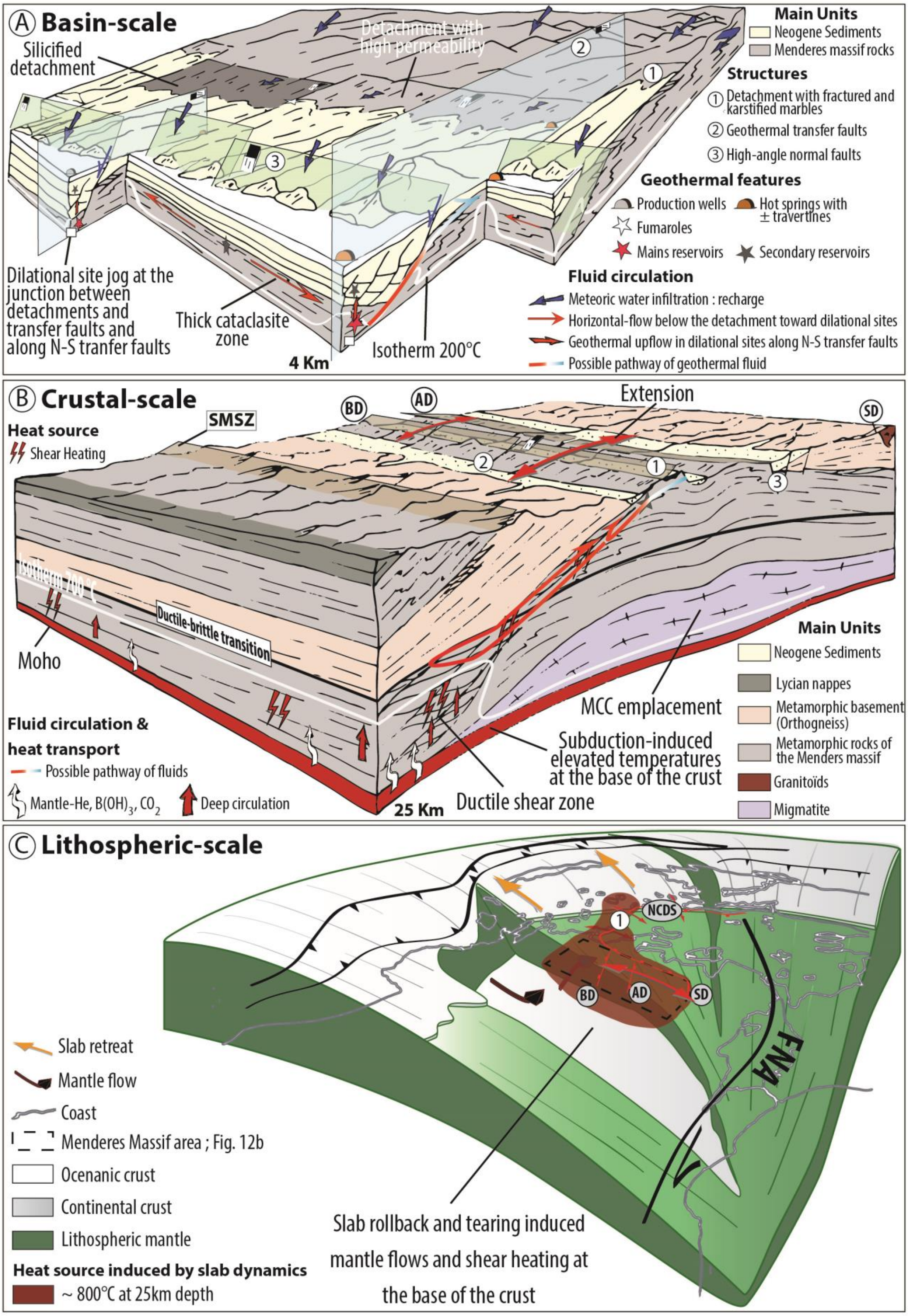

Ⓐ Basin-scale
Silicified detachment
Detachment with high permeability
Dilational site jog at the junction between detachments and transfer faults and along N-S tranfer faults
Thick cataclasite zone
Isotherm 200°C
4 Km
Main Units
Neogene Sediments
Menderes massif rocks
Structures
① Detachment with fractured and karstified marbles
② Geothermal transfer faults
③ High-angle normal faults
Geothermal features
Production wells
Hot springs with ± travertines
Fumaroles
Mains reservoirs
Secondary reservoirs
Fluid circulation
Meteoric water infiltration : recharge
Horizontal-flow below the detachment toward dilational sites
Geothermal upflow in dilational sites along N-S transfer faults
Possible pathway of geothermal fluid
Ⓑ Crustal-scale
SMSZ
BD
AD
Extension
SD
Heat source
Shear Heating
Isotherm 200°C
Ductile-brittle transition
Moho
MCC emplacement
Subduction-induced elevated temperatures at the base of the crust
Ductile shear zone
25 Km
Fluid circulation & heat transport
Possible pathway of fluids
Mantle-He, B(OH)3, CO2
Deep circulation
Main Units
Neogene Sediments
Lycian nappes
Metamorphic basement (Orthogneiss)
Metamorphic rocks of the Menders massif
Granitoïds
Migmatite
Ⓒ Lithospheric-scale
NCDS
BD
AD
SD
FNA
Slab retreat
Mantle flow
Coast
Menderes Massif area ; Fig. 12b
Ocenanic crust
Continental crust
Lithospheric mantle
Heat source induced by slab dynamics
~ 800°C at 25km depth
Slab rollback and tearing induced mantle flows and shear heating at the base of the crust

**Fig. 12:** Conceptual models at different scales showing the heat source origin and main structural controls on fluid flows in the Menderes Massif. (a) Synthetic simplified block diagram at basin-scale showing the relationships between these faults. Numbers show different type of faults. Geothermal features and fluid circulation are also indicated. (b) Role of the detachment on deep circulation in the Menderes Massif. Main structures are indicated in abbreviations: AD (Alaşehir detachment); BD (Büyük Menderes detachment); SD (Simav detachment) and SMSZ (Southern Menderes shear zone). (c) Tentative 3D reconstruction and flow directions in the mantle (red arrows) of the Aegean region before the recent slab tear below the Corinth Rift and after. Red line and red arrows show the main detachments and kinematic of extension in this region, respectively. Yellow arrows indicate the slab retreat in the Aegean domain. Main structures are indicated in abbreviations: AD (Alaşehir detachment), BD (Büyük Menderes detachment), NAF (North Anatolian Fault), NCDS (North Cycladic Detachment System) and SD (Simav detachment).

| | *Geothermal fields* | *Depth & Thickness* | *Flow & Discharge rates* | *Measured temperatures* | *Chemical geothermometers* | *Lithology* | *Capfault and caprock* |
|---|---|---|---|---|---|---|---|
| **Alaşehir graben** | *Salihli* | Reservoir depth varies from 40–400 m | 20 L/s (K-1) and 40 to 80 L/s (other wells in Kurşunlu area) | 83–94°C | | Karstified and fractured marbles of the basement; Çaltılık Formation | Siliceous ADFP and Gediz Formation |
| | | Reservoir depth from 950–1500 m | 30 to 35 L/s | 90–92°C | | | |
| | *Alaşehir* | Reservoir depth from 1150 m and 1600 m | 12 L/s (KG-1) and 6,74 L/s (Ak-2) | 215°C (A5-2) | 80° to 250°C (with vrariability of geothermometers e.g., $SiO_2$; Quartz Steam Loss; Na-K-C) | Karstified and fractured marbles of the basement; Çaltılık Formation | Siliceous ADFP and Gediz Formation |
| | | Reservoir depth from 1750 to 2750 m | 5–90 L/s | 159–287,5°C | | | |
| | *Urganlı-Turgutlu* | Reservoir depth at 460 m | 20 L/s | 62°C | | - | - |
| **Büyük Menderes graben** | *Germencik* | Shallow reservoir depth in sediments (around 285 m) | Average flow rate rate 300 tph | 203–217°C | 150–250°C (Na-K & Na-K-Ca) | Miocene conglomerates and Fractured rocks of the basement | Neogene clastic sediment such as clayey levels |
| | | Deeper reservoir in basement changes depending on the locality from 965 to 2432 m depth | | 191–276°C | | | |
| | *Salavatlı* | Reservoir depth from 750–1923 m | Average flow rate 1480 tph | 148–176°C | 160–175°C (Giggenbach, 1986) | Fissures and fractures zones of the basement | - |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | Reservoir depth at 3224 m | - | 211°C | - | | - |
| | *Kızıldere* | First reservoir depth at 400 m | Average flow rate 1400–1500 tph | 148–198°C | - | Sazak Formation (Pliocene sediments) and quaztites, marbles, gneiss of the basement | Pliocene impermeable clayey |
| | | Second reservoir depth from 1100 m to 1200 m | | 200–212°C | | | |
| | | Just below the second | | 242°C | 250–260°C ($SiO_2$; Na-K-Ca) | | |
| | | Fourth reservoir depth unknow | - | >250°C | - | - | - |
| **Cumaovası basin** | *Seferihisar (Tuzla)* | Reservoir depth from 333–553 m | Total discharge rates of 130 tph | 174–176°C | - | Fractured mafic submarine volcanics and fractured rocks of Bornova mélange; Marbles of Menderes? | Clay-rich zones of the Neogene sediments |
| **Simav graben** | *Simav* | First reservoir shallow depth, 85 m | - | 105°C | 83 to 182°C ($SiO_2$) and 148 to 163°C (Na-K-Ca-Mg) | Neogene sediments: Naşa basalt, Budağan limestone, Arıkaya and Balıkbası formations; Menders units? | Clayey level of Eynal, Akdağ and Sarıcasu Formations |
| | | Second reservoir: around 725 m | | 162°C | | | |

| | Geothermal fields | Structural setting | Structural characteristics | Main controls |
|---|---|---|---|---|
| **Alaşehir graben** | Salihli | HW and FW of the south side of the graben | Intersections between N-dipping detachment, N-S trending strike-slip faults and sometimes E-W trending normal faults | KC, FC, FRC |
| | Alaşehir | HW and FW of the south side of the graben | Intersections between N-dipping detachment, N-S trending strike-slip faults and sometimes E-W trending normal faults | |
| | Urganlı-Turgutlu | HW and FW of the north side of the graben | Intersections between N-dipping detachment, N-S trending strike-slip faults in the basin | FC |
| **Büyük Menderes graben** | Germencik | HW and FW of the north side of the graben | Intersections between S-dipping detachment, N-S trending strike-slip faults and E-W trending normal faults | FC, FRC |
| | Salavatlı | HW and FW of the north side of the graben | Intersections between NNE-SSW trending strike-slip faults and SE-NW striking normal faults | |
| | Kızıldere | HW and FW of the north side of the graben | Eastern termination of major normal fault; Intersections between N-S trending strike-slip faults and E-W striking normal fault | |
| **Cumaovası basin** | Seferihisar | HW and FW of the contact between BM/MU | Intersections between N-S transfer faults and the contact between BM/MU | FC |
| **Simav graben** | Simav | HW and FW of the north side of the graben | N-dipping detachment and intersections between N-S striking transfer fault and S-dipping normal fault | FC |