Numerical simulation of groundwater flow and temperature distribution in Aegean Coast of Turkey

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Geological studies indicate that one of the most important geothermal systems of Turkey is located in the western Anatolia. There are plenty of studies covering the geological, geophysical and modeling aspects on land. In this study, for the first time, we construct coupled numerical models of fluid flow and temperature offshore Gulf of İzmir and Seferihisar–Doğanbey, using constraints from marine seismic data, which reveal pockmarks, mud volcanoes, and fluid vents. The numerical models were designed by taking into account of main tectonic structures such as İzmir Fault, Doğanbey Fault, Tuzla Fault and Seferihisar Horst. It is found that hydrothermal circulation pattern is influenced by the combination of presence of faults, sediment thickness and seafloor bathymetry. The models here give new insights into the future studies on the possible fluid transport mechanisms.

Keywords. Aegean Sea; western Anatolia; Gulf of İzmir; fluid flow; temperature; numerical model.

1. Introduction

Most research and modeling of hydrothermal systems have focused on deep-sea hydrothermal vents (e.g., German *et al.* 1996; Humphris *et al.* 2002; Singh *et al.* 2006; Fontaine and Wilcock 2007) and onshore hydrothermal/geothermal systems. Potential importance of hydrothermal system in shallow marine environments is investigated by various researchers (e.g., Sedwick and Stüben 1996; Pichler *et al.* 1999; Pichler 2005). Discovered shallow-water hydrothermal systems show a transitional behavior between deep-sea hydrothermal vents and terrestrial hot springs. Due to the effects of marine and terrestrial sources involved, this transitional behaviour makes the shallow-water hydrothermal systems complicated. Mixing of water from different sources effects

the geochemistry of the hydrothermal system, temperature profile as well as the gas content. This interaction also develops favorable environments for shallow-water habitats. This forms an environment which is unique for not only the geosciences but also biochemistry (Pekçetinöz 2010; Ristova *et al.* 2017).

The study area, Gulf of İzmir and Seferihisar–Doğanbey is located on the western coast of Anatolia, Turkey (figure 1). The converging Eurasian and Arabian plates and effects of N–S extension towards the Hellenic arc result in counterclockwise rotation of the Anatolian plate. This southwestward motion is occupied by the dextral North Anatolian Fault and the sinistral East Anatolian Faults since Miocene (McKenzie 1972; Le Pichon and Angelier 1981; Okay *et al.* 2001). Due to this extensional regime, the region is characterized by

Figure 1. Location map of the study area modified from (Ocakoğlu *et al.* 2005). Topography map derived from 1:25,000 scale topographic maps of the Turkish General Command of Mapping with ~ 75 m precision. Active on land faults; ZBF: Zeytindağ–Bergama Fault, BF: Bornova Fault, İF: İzmir Fault, KF: Karaburun Fault, UF: Urla Fault, TF: Tuzla Fault, KMF: Küçük Menderes Fault. Inset figure shows the study area and the major fault zones (NAFZ: North Anatolian Fault Zone; EAFZ: East Anatolian Fault Zone). Bold red line indicates the seismic section part used in modelling.

thin continental crust, high earthquake activities and high heat flow values up to 150 mW/m^2 (Pfister *et al.* 1988; İlkışık 1995). N–S extensional neotectonic regime has formed E–W oriented rift and graben systems such as the Büyük Menderes Graben, the Küçük Menderes Graben and the Gediz Graben. This graben system is highlighted by steep topography associated with active faults (Yılmaz *et al.* 2000). Extensive geothermal

activities in the area and geothermal fields such as Kizildere, Salihli-Kursunlu, Kula-Emir, Aydın-Germencik, are linked to those grabens, active faults and young volcanics (Mutlu and Güleç 1998).

High geothermal potential of the region attracts numerous research groups into the area. A number of studies were performed on land including geology (Bozkurt *et al.* 1993; Collins and Robertson

1997; Bozkurt 2001; Bozkurt and Oberhänsli 2001; Güngör and Erdoğan 2001; Okay 2001; Seyitoğlu *et al.* 2004; Catlos and Çemen 2005; Seyitoğlu and Işık 2009; Candan *et al.* 2011; Koralay *et al.* 2012; Ersoy *et al.* 2012; Gessner *et al.* 2013) and geophysics (Pfister *et al.* 1988; İlkışık 1995; Ozel 2000; Sari and Salk 2003; Drahor and Berge 2006; Özürlan *et al.* 2006; Yagcı 2015) concerning to explore geothermal sites, related to the faults and fractures. The four of the main faults located in the area are Izmir, Cumali, Tuzla and Doğanbey Faults, which host many natural hot springs with venting temperatures ranging from 30 to 78°C (Tarcan and Gemici 2003) (figure 1). Previous studies on land suggested infiltration of the meteoric water down to at least 2 km depth (Genç *et al.* 2001; Serpen 2004; Erdogmus *et al.* 2006; Aksoy *et al.* 2008; Magri *et al.* 2010), heated up by a heat source, and carried up to the surface via those active faults and fractures. Particularly, N–S and E–W oriented faults within the southern coast of Gulf of İzmir play an important role in the circulation of hot water (e.g., Filiz and Tarcan 1993; Serpen 2004; Aksoy *et al.* 2008).

Furthermore, geochemistry and modeling studies were conducted on land (Serpen 2004; Magri *et al.* 2010, 2012) in order to characterize the hydrogeology, fluid chemistry and reservoir properties. Numerical models of Magri *et al.* (2010) explored the possible transport mechanism of the Seferihisar–Balçova geothermal system. They showed that temperature pattern results from the interaction of convective flow and meteoric recharge from horst into the faults.

Even though marine seismic and bathymetric studies show presence of fluid vents (Pekçetinöz 2010; Dondurur *et al.* 2011; Altan and Ocakoğlu 2016), there is no modeling study offshore unlike on land. Pekçetinöz (2010) identified low temperature (maximum 35–40°C) hydrothermal anomalies offshore Gülbahçe Bay. It was also reported existence of the coral habitat and palynomorphs. This cooperation could be suggested presence of hot water outlets in the Gülbahçe Bay during the Late Holocene period. Dondurur *et al.* (2011) and Sarı *et al.* (2016) investigated the Uzun Island and Gediz Delta by the seismic data. Their dataset reveal several biogenic gas accumulations and pockmarks near the active faults and around the pro-delta of Gediz River. Altan and Ocakoğlu (2016) imaged fluid outlets, mud volcanoes and gassy sediments. They also reported that pro-delta sediments of Gediz River is a possible fluid and/or

gas area. Although mapped gas related structures mainly concentrate inside the Gulf, there is a gradual thickening of sediments offshore Balçova through the outer part of the Gulf. This could provide desirable high porosity and permeability conditions to host thermal water rising from deeper geological units (Serpen 2004).

In this study, we performed a set of numerical simulations to address following questions to widen our understanding of geothermal system extending offshore and its correlation with the land: (1) which structural conditions (presence of fault, thickness of sediments, seafloor bathymetry) are favourable for producing low-temperature hydrothermal circulations reported by previous studies within the study area?, (2) which driving mechanism(s) can explain the presence of those hydrothermal vents? and (3) is there any relationship with the on land geothermal system?

2. Materials and methods

2.1 Seismic data

Both single- and multi-channel seismic data were acquired to investigate the area by The General Directorate of Mineral Research and Exploration of Turkey (MTA). Single-channel data were collected in 2000 with 12.5 m receiver interval, 10 m group interval, 1 ms sampling interval, and 1.0 s record length (Ocakoğlu 2004; Altan and Ocakoğlu 2016). Multi-channel data were collected using 48 or 60 channels with 12.5 m receiver interval, 12.5 m group interval and 2 ms sampling interval (Ocakoğlu *et al.* 2005). Single-channel seismic sections were processed by Echos software with a conventional data processing sequence. It includes following steps: transcription, editing, selection of least noisy channel, in-line geometry definition, datum correction, sorting, NMO correction with a constant water velocity of 1500 m/s for the seabed horizon, notch filtering for 15, 16 and 33 Hz frequencies, spherical divergence correction, finite-difference time migration, a trapezoidal band pass of minimum phase hamming filter with the corner frequencies 5–15–50–190 Hz (Altan and Ocakoğlu 2016).

A conventional data processing stream was applied to the multi-channel seismic data as follows: data transcription, in-line geometry definition, source-receiver array datum correction, editing, muting of direct and refracted waves, gain analysis, common depth point sorting, stacking

velocity analysis, normal move-out correction and muting, stacking, spiking and predictive deconvolution, band pass filtering, finite-difference time migration and automatic gain control. Strong multiple reflections were suppressed when it was possible by predictive deconvolution techniques (Ocakoglu *et al.* 2005).

We used 2D single-channel/multi-channel seismic lines (figure 1) to obtain the geometry of general structural units including locations of fault zones and thickness of sediments as well as the sea floor bathymetry. Depth sections were calculated from average RMS velocities obtained from the velocity analyses for multi-channel seismic lines to construct numerical models. For single-channel seismic sections, constant velocities are used. From these depth sections, we determined the thickness of the sediments and the depth of the basement to use them as constraints in the numerical simulations.

Imaged faults are almost vertical in the seismic sections and, are represented with higher permeability zones relative to their surrounding geological units. Thicknesses of faults are kept constant at 50 and 100 m for DOG-1 and Line-4, respectively. Numerical model box includes Plio-Quaternary sedimentary unit and Miocene basement, which are obtained from seismic sections (Ocakoglu 2004; Altan and Ocakoglu 2016). These two main units, separated by an erosion surface, are characterized by their internal reflection coefficient and continuity of high-amplitude reflections (Ocakoglu *et al.* 2004). Yilmaz *et al.* (2000) suggested that this erosional surface marks the boundary between upper Miocene and Plio-Quaternary units. Furthermore, those units were also well correlated with the unconformity identified by the Turkish Petroleum Corporation (TPAO) borehole Foçal1 (figure 1).

Seafloor bathymetry is not flat in seismic sections for both seismic profiles, thus producing different pressure gradients due to varying depth of water column. These pressure gradients were taken into account in the numerical simulations.

2.2 Numerical model

In this paper, we used a coupled transient numerical solution of fluid flow and heat transport to simulate the fluid circulation pattern and temperature along the selected 2D seismic profiles. Finite volume based Computational Fluid Dynamics (CFD) software, ANSYS FLUENT, was

implemented to obtain the numerical solution of steady-state Navier–Stokes equation (e.g., Patankar 1980; Holmes and Connel 1989). Darcy’s law (equation 1) is assumed to hold

$$u = -\frac{K}{\mu}(\nabla P - \rho_w g), \quad (1)$$

where K is the permeability of the medium, P is the pressure, ρ_w is the fluid density, g is the gravitational acceleration and ∇ is the Laplacian operator. The fluid flow is considered laminar and viscous, and inertial effects are neglected. Fluid density (ρ_w) is assumed to vary with temperature according to the Boussinesq approximation (equation 2)

$$\rho_w = \rho_0 [1 - \beta(T - T_0)], \quad (2)$$

where ρ_0 is the density at a temperature of $T = T_0$ and β is the thermal expansion coefficient.

Darcy velocities should satisfy the equation of continuity, written as (equation 3)

$$\nabla \cdot (\rho_w u) = 0. \quad (3)$$

The energy conservation equation is written as follows (equation 4)

$$\rho c_p \frac{\partial T}{\partial t} + \nabla \cdot (u \rho_w c_p T) = \nabla \cdot (\lambda \nabla T), \quad (4)$$

where c_p is the specific heat of the porous medium and λ is the thermal conductivity of the saturated porous medium (McKibbin 1986; Nield and Bejan 1999). Local thermal equilibrium is considered, that is, the temperature will remain the same in the solid as in the corresponding pores.

The thermal and physical rock properties such as permeability, porosity, heat capacity and thermal conductivity, are held constant and uniform for the different rock units (sediments, faults, basement, etc.). They are summarized in tables 1 and 2. Values of these properties are taken from the previous numerical modeling studies (Göktürkler *et al.* 2003; Gök *et al.* 2005; Magri *et al.* 2012), and geological investigations (Tezcan 1966; Yilmazer 1989; Karakullukcu 1991; Öngür 2001; Sari and Salk 2003; Serpen 2004).

In this study, dip angles of faults are about 85 degrees, thus, they are taken as vertical high permeable layers throughout all models. Faults are isotropic and modeled as equivalent porous media (EPM). In other words, they are implemented as high permeable areas of finite extension. The

EPM approach is a well-established technique for representing faults and fractured zones (Weatherill *et al.* 2008; Graf and Therrien 2009), which requires less computational effort than discrete-fracture models. Depending on thermal and hydraulic conditions, faults can behave like a barrier or a conduit to transfer the fluid (Heffner and Fairley 2006). It is well known that faults can have two orders of magnitude permeability (e.g., Bense and Person 2006; Fairley and Hinds 2004; Magri *et al.* 2012). For simulations, constant fault zone permeability value is taken as 10^{-15} m^2 as shown in table 2. This value remains within the permeability range

of previous similar studies. Since porosity values vary from 1 to 20% in permeable fault zones, an average value of 10% was selected for both models in this study. Furthermore, a constant porosity through the entire fault enables faster numerical convergence (Kühn *et al.* 2006).

2.3 Finite-volume mesh structure and boundary conditions

Triangular discretization with variable length is used to produce the numerical models for the 2D seismic lines. Total 233,671 and 79,102 mesh elements are used to construct the models for profiles DOG-1 and Line-4, respectively (figure 2). In the vicinity of the faults and the sediments, the mesh size is selected 15 meters. Away from these regions mesh size is gradually increased up to 50 m. In convergence test, it is found that using different mesh sizes had no substantial effects on the fluid flow and temperature pattern.

The vertical boundaries of numerical models are assumed impermeable and adiabatic, thus,

Table 1. Fluid and heat flow parameters for DOG-1/Line-4.

Parameter	Value	Unit
Density of fluid	1000	kg/m ³
Dynamic viscosity of fluid	5E−5	kg/ms
Specific heat capacity	4200	J/kg K
Thermal expansion coeff.	2.07E−4	1/K
Gravitational acceleration	9.81	m/s ²

Table 2. Permeabilities of geological units.

Geological unit	Permeability (m ²)	Porosity (1)	Thermal conductivity (W/mK)
Plio-Quaternary sediment	2E−16	0.2	1.5
Fault	1E−15	0.1	2.0
Miocene basement	1E−16	0.03	3.5

Figure 2. Model set-up for numerical calculations for DOG-1 (top), Line-4 (middle) and triangular mesh structure (bottom). Boundary conditions are also presented.

mass and heat transfer are not allowed through these walls. Horizontal boundaries of the system are isothermal. Upper wall temperature is kept constant as 10°C. At the bottom wall, fixed temperature boundary conditions are also applied and the constant bottom temperatures of 120 and 50°C are taken for DOG-1 and Line-4, respectively. These values are obtained from previous heat flow studies (Göktürkler *et al.* 2003; Magri *et al.* 2010). Models for both seismic sections consider seafloor bathymetry variations.

Models have open top systems, which allow water to flow in and out. The water column depth determines pressure boundary condition at the top of the model. Gradual pressure changes are applied in transition regions of different depths in seafloor. Numerical simulations indicate that the existence of faults can form the thermal convective flow pattern by constraining the size and location of convective cells (e.g., Lopez and Smith 1995; Yang *et al.* 1998; Simms and Garven 2004; Yang *et al.* 2004; Düşünür Doğan 2014). Even fractures with apertures in the order of a few millimeters can convey significant flow rates of hot water from the depths in the order of a few kilometers (Lowell 1975). Furthermore, faults can trigger convection in neighboring units even though the thermal conditions are not suitable for the convective flow. Previous works show that the strength of the convective flow is proportional to the Rayleigh number. The Rayleigh number of the system, which is an indicator of the mode of the heat transfer and the strength of the convection, is calculated as 4.6 for this study. This value is well below the critical value of 17.65 for open top systems (Simms and Garven 2004). Although the Rayleigh number of the system in this study is below the critical Rayleigh number, faults within the system lead to circulation cells.

3. Results

A set of numerical calculations are performed in order to understand the effect of faulting, sediment thickness and seafloor bathymetry on thermal regime and fluid flow pattern of the area. Numerical models presented here are intended to understand transport processes and their relationship with the active faults offshore. For this purpose: seismic section, temperature distribution and flow paths are correlated to each other.

Figure 3 shows the steady-state results for DOG-1 seismic section located offshore Doganbey, delimited by Tuzla Fault Zone. Study profile of 20 km extends from NW to SE crossing the Seferihisar Rise. Stratigraphy of the model, which includes Plio-Quaternary basin deposits and Miocene basement, has the depth of 2.3 km. According to the seismic section, sediment thickness gradually increases away from the Seferihisar Rise (figure 3a).

It is found that the active faults and the Seferihisar Rise are the main structural units which control the temperature distribution and the fluid flow of the model. Boundary faults of the Seferihisar Rise act as a pathway to the down flow into the sediments and basement. Isotherms in the vicinity of faults and the Seferihisar Rise are bent parallel to the fault flanks, on the other hand, remaining part of the model shows smooth temperature curves as expected. In the rise, temperature gradient slightly increases due to the effects of bathymetry that drives the fluid flow. As an example, 100°C isotherm is located at a depth of ~1.7 km at the flanks, whereas it is at ~0.6 km depth at the center of the rise (figure 3b).

A thin sedimentary layer in DOG-1 seismic section prevents the formation of small-scale circulation cells within. Fluid flow circulates down to the basement along the sides of the Seferihisar Rise and move up to the top of the central high. Average fluid velocities 5×10^{-10} , 3×10^{-10} and 3×10^{-12} m/s are found within faults, sediments and basement, respectively (figure 3c). It is well known that permeability tends to decrease with increasing depth, therefore, we performed various simulations of different basement permeability ranges between 10^{-18} and 10^{-20} m². No particular changes in circulation pattern but modest changes in velocity magnitudes are observed in these simulations. It shows that numerical models are not particularly sensitive to the host rock permeability values within the range of 10^{-18} and 10^{-20} m².

A region on the SE tip of the Seferihisar Rise bounded by normal fault zone is magnified to visualize the small-scale circulation (figure 3d). Streamlines in figure 3(d) suggest that seawater penetrates into the sediments and the faults, and then moves in a clockwise rotation at the southeast side of the rise due to the hydrostatic pressure differences.

Line-4 seismic section also extends 20 km in E–W direction. Study profile highlights normal and strike slip faults on the east and strike-slip

Figure 3. (a) DOG-1 seismic section (Altan and Ocakoğlu 2016), (b) calculated temperature pattern, (c) fluid flow vectors (in order to visualize the fluid flow vectors, all vector length kept constant, independent from their Darcy velocities), and (d) calculated streamlines for a selected area. Streamlines were sparsely plotted for a better view.

fault zone on the west (Ocakoğlu *et al.* 2005; Altan and Ocakoğlu 2016). Both fault zones cut the Miocene basement and Plio-Quaternary sediments and reach to the seafloor (figure 4a). Model extends up to 1.2 km depth, where faults can be marked on the seismic section. As shown in seismic section Line-4, sediment thickness drastically increases from 200 m in the east to 750 m in the center of the profile under the effect of faulting. The existence of the thick sediment and faults are the dominant structural units for this profile (Line-4), which shape the fluid flow and temperature distribution. Far from the normal fault, where the medium is not influenced by fluid circulation, isotherms are smooth and horizontal with the linear vertical temperature gradient. Nonlinear

vertical temperature gradient with peak surface temperature values are seen in the vicinity of normal fault (figure 4b).

Presence of thick sediments on Line-4 promotes the circulation cell penetrating down to the base of the model and moving up to the seafloor (figure 4c). Fluid velocity vectors are oriented in upward direction passing through the normal fault, on the contrary, they point in downward direction inside the strike slip fault zones. Average fluid velocities are 1×10^{-11} , 2×10^{-10} and 5×10^{-11} m/s within faults, sediments and basement, respectively. Fluid circulations are not only found in the fault zones but also in the permeable thick sediment layer (figure 4c). The location of fluid exits are significantly influenced by fluid flow channeling inside

Figure 4. (a) Line-4 seismic section (Altan and Ocakoğlu 2016), (b) calculated temperature pattern, (c) fluid flow vectors (in order to visualize the fluid flow vectors, all vector length kept constant, independent from their Darcy velocities), (d) calculated streamlines for a selected area. Streamlines were sparsely plotted for a better view.

the fault and the sediments. Even though there are diffuse flow, vents predicted by numerical model throughout the Line-4, main fluid exit is located about the normal fault. Maximum temperature for outlet vents are found between 21 and 36°C (figure 4b).

We pay close attention to the normal fault where main fluid discharges are located (figure 4d). In DOG-1 model, normal faults are the dominant effect on the fluid flow pattern, however, in Line-4 model, the thick sedimentary layer and the bathymetric differences are the dominant effects. Calculated streamlines indicate that seawater seeps into thick sedimentary unit resulted in clockwise rotation of fluid flow vectors, similar to the DOG-1 model.

Figure 5(a) shows reflection strength section (modified from Altan and Ocakoğlu 2016) with

upwelling fluid flow zones (indicated by red arrows) in Line-4 and corresponding predicted model streamlines (figure 5b). Altan and Ocakoğlu (2016) marked possible existence of fluid and/or gas saturated zones as well as discharge zones in the Line-4 offshore Gediz River. Similarly, previous seismic attribute study of Gülbahçe Bay reveals the existence of fluid and/or gas saturated zones as well as discharge zones inside the gulf (Pekçetinöz 2010). Dondurur *et al.* (2011) and Sarı *et al.* (2016) mapped gas related features such as gas chimneys and pockmarks near the Uzun Island. They also reported that the rapid burial and oxidization of organic material rich sediments transported by the Gediz River might produce this gassy environment. It is shown that numerical models in this study predict the zones of observed fluid flow and outlet vents well.

Figure 5. (a) Reflection strength for Line-4 (modified from Altan and Ocakoğlu 2016), (b) calculated streamlines. Red arrows indicate expected fluid flow exits via faults and rectangles indicate weak reflection zones on sediments (yellow) and basement (green) units correspond to small scale fluid circulations. Streamlines were sparsely plotted for a better view.

4. Conclusions

Shallow-water hydrothermal systems are excellent candidate to understand the interaction between the processes of deep-water and on land hydrothermal systems. Our approach is based on the simplified models, which are used to figure out hydrothermal regime in one of the shallow-water hydrothermal systems in offshore Izmir. Although simple, such models can be considered as preliminary estimates of fluid flow and temperature patterns in the region. This study is the first one to gain insight of the transport mechanisms of the shallow underwater system of offshore Izmir. Following conclusions are deduced from coupled fluid flow and heat transfer simulations.

- Several parameters such as sediment thickness, presence of faults and seafloor bathymetry, interact but their contributions are not equal on fluid flow and temperature patterns. Tuzla Fault Zone plays a major role in controlling fluid flow distribution, shapes the temperature gradient and influences the locations of outflow vents, which are similar to the previous on land studies. However, fluid flow is not vigorous enough to disturb temperature field away from the Tuzla Fault Zone.
- Pressure gradients due to the bathymetrical differences at both of the seismic sections play a critical and distinctive role in shaping fluid

flow pattern. Therefore, this appears a critical issue for numerical calculations offshore. A special treatment is required for inclined seafloor to define hydrostatic pressure gradient. Otherwise, models demonstrate pseudo-fluid movements at the transition region between flat and inclined surfaces.

- Dominance between hydrostatic and buoyant forces is determined by the permeability of the medium. In numerical models, fluid flow is channeled into the seafloor near to fault zones due to the permeability differences, which produce outlet vents. Small-scale circulations inside the thick sediment column is also triggered by the presence of faults. Those small circulations are in good agreement with the weak reflection zones marked in seismic sections. Localization of the hot fluids via faults can help to produce suitable environment for the shallow-sea habitats.

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