Geoscientific investigations on north of Balçova geothermal system in Turkey

Umran Serpen, Niyazi Aksoy, Tahir Ongur, Mete Yucel, Ilhan Kayan

Abstract—The Balcova geothermal system is located on the 30 km long Izmir fault within the graben that formed Izmir bay in Turkey. In this study, the results of geophysical surveying conducted are discussed with the aim of exploring possible extension of low temperature geothermal system created by a fracture zone on the Izmir fault.

SP, geoelectric, and CSAMT surveys were undertaken by MTA to explore the area from geothermal energy viewpoint. Both the north of the Balcova fracture zone system and the depth of deep Paleozoic basement underlain the dominating formation of area, Izmir Flysch are investigated. SP survey showed some shallow anomalies (30-300 m) along the bed of the Ilica creek starting from the Izmir (Agamemnon) fault, indicating geothermal fluid's flow to the north. The interpretation of Schlumberger resistivity survey, while confirming the deep concealed outflow is confined in the southern Balcova close to the Hot Springs, indicated a shallow concealed outflow far reaching north of the Izmir-Cesme highway. Moreover, two conductive zones detected by resistivity survey around 1000 m depth were interpreted as two low resistivity sedimentary sections in the northern area of interest. CSAMT survey identified two conductive zones, one between 300 m and 500 m and the other below 3000 m depth. The high resistivity zone detected between 500 m and 3000 m in CSAMT survey was interpreted as the Izmir Flysch, and a deep structure was identified between 1500 m and 2000 m. The conductive zones indicated by Schlumberger and CSAMT surveys are discussed from the geological standpoint, and new interpretations for geophysical surveys are recommended.

I. Introduction

THE Balcova geothermal system shown in Fig. 1 is located in the Izmir bay of the Aegean Coast of Turkey. Exploration on the field started in 1962. The resource could not be developed due to scaling problems and moderate temperatures (124^{o}C) encountered in the first 3 shallow wells. The early development of the Balcova geothermal field started in the 1980's for space heating by using shallow wells with downhole heat exchangers to overcome scaling problems. Recent developments on scaling inhibitors encouraged the city authorities to install a district heating system that was started to operate in 1996 and has lately reached a heating capacity of 159 MW_t.

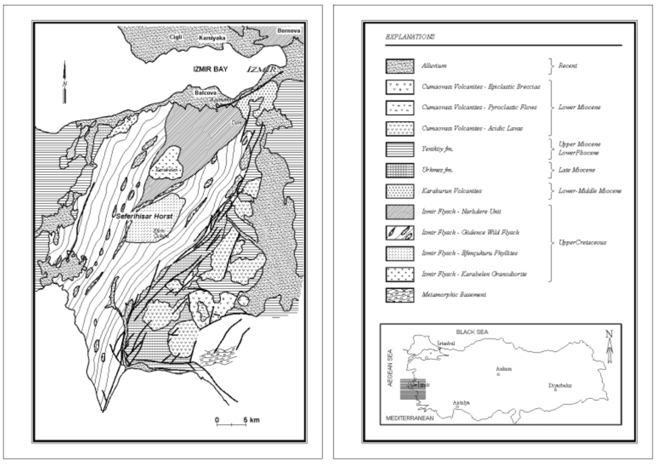

Fig. 1 Location of Balcova geothermal field and simplified regional geological map (after modified [1,3]).

Previous geophysical surveys covered nearby area of Agamemnon Hot Springs and the area up to the Izmir-Cesme highway in its north as shown in Fig. 2 [4,5] The first surveys, measurements of resistivity, SP, and gravity, revealed the thickness of alluvium, pointed out a NE-SW oriented fault under alluvium and indicated the presence of hot waters under Ilica creek bed. The delineation of the outward flow part of the geothermal system was determined by Wenner electrical resistivity surveys. The gravity map did not show a clear anomaly because of the sparse sampling. These investigations provided information on shallow zones close to the Hot Springs. On the other hand, now it is not possible to run other surveys for deeper investigations in surroundings of previously studied area since most of it has lately been inhabited. A recently completed study on Balcova geothermal system indicated that geothermal fluids ascending through the Agamemnon fault flow northwards at shallow and deep fractured zones. Information obtained from the study, shown in Fig. 3, indicates the shallow fluid flow through the alluvium reached beyond the Izmir-Cesme highway [6]. The deep concealed flow to the north seemed to be confined as estimated from the temperature distributions [6]. The area in the north of the Izmir-Cesme highway, which is currently not being inhabited but may become inhabited soon, is very suitable for geophysical surveying.

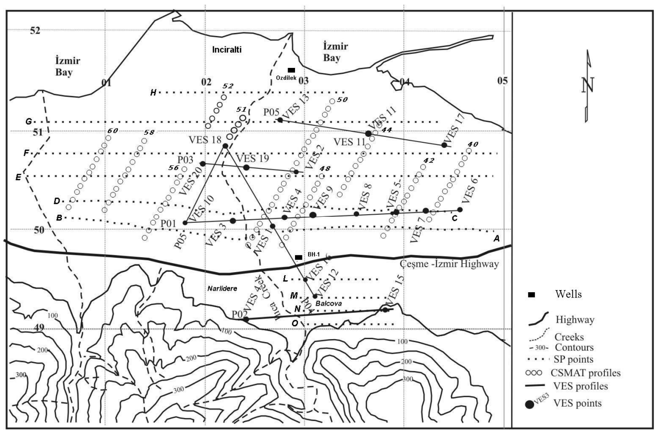

Fig. 2 Locations of SP, resistivity and CSAMT surveying profiles.

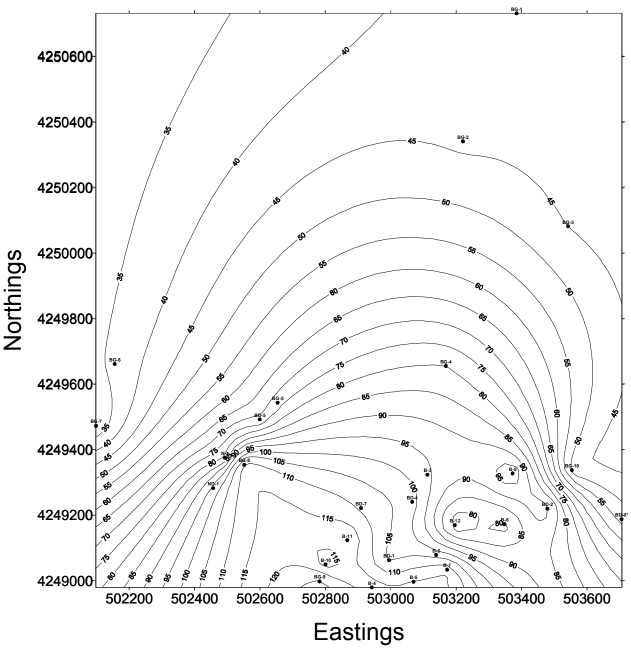

Fig. 3 Temperature distribution at 40 m bsl [7].

The aim of the lately planned geophysical surveys in the vast non-inhabited area of the north of the Izmir-Cesme highway was to put forward the structural features of the field, to investigate horizontal and vertical dimensions of the geothermal system, and to obtain information about the depth of basement formation, or thickness of Izmir Flysch (Serpen, 2000). Permeable intervals were expected to be found at the contact zone between Izmir Flysch and Paleozoic basement. Moreover, the permeable zones could also be found within Paleozoic basement, as encountered in several geothermal systems elsewhere in the Aegean region. Different geophysical surveying methods that would put forward the effect of different physical facts were utilized during these planned studies. Since the main objective of the study was to investigate geothermal features of the area of interest, SP, Controlled Source Audio Magnetotelluric (CSAMT), and partially applied resistivity surveys were proposed [8]. Consequently, this area would be investigated in detail using different geophysical surveying methods, and different physical features of possible geothermal fluid bearing units would be examined both vertically and laterally, and finally 2 or 3 dimensional models of the field would be established.

It was very important to obtain subsurface information about the currently open area in the northern section before being inhabited. The planned studies might not result all favorably, but in that case, the following information could still be obtained: (1) the thickness of Izmir Flysch and (2) the confines of existing geothermal system. Both of them, especially the second one, could shed some light on the development of the Balcova geothermal system that is a low temperature fracture zone system with high temperature at sweep base [6]. Both silica and cation geothermometers point out higher temperatures around 180-200^{o}C, and chloride mixing model also indicates temperatures over, all of which favor a deep investigation [6,9]

II. Geological Setting of the Area

The Balcova geothermal system is situated in the extensively exposed Izmir Flysch unit of Upper Cretaceous age. The field is located at the northern margin of the Seferihisar Horst where the flysch outcrops. While talus breccias cover the northern flank of the Seferihisar Horst in the south of the field, young and recent sediments infill the Izmir bay further north as given in Fig. 1.

The stratigraphic sequence of the area, in general, consists of Upper Cretaceous Izmir Flysch, Miocene sediments, Miocene-Pliocene volcanics, Quaternary talus breccias, and alluvium. The regionally predominant formation, the Izmir Flysch, is composed of different rocks such as sandstone, clayey schist, phyllite, limestone, limestone olistoliths, granodiorite, serpentinite, and diabase. It is difficult to separate categorically the Izmir Flysch into units, because there are lateral and vertical transitions between lithological units. Foldings due to tectonics and displacement of sediments due to gravity slides caused these transitions within the geosynclinal. The Balcova geothermal system wells mainly intersect lightly metamorphosed sandstones, clays, and siltstones of the Izmir Flysch sequence. The thickness of this sequence is estimated over 2000 m, and in places it could be as much as 4000 m [1]. The bottom of the flysch is not observed in the area of interest; however, it is located in the south of Seferihisar horst on the Paleozoic basement with angular discordance [3].

A sequence of tectonic activities had affected the Izmir Flysch unit so intensely that original occurrence of the basin has completely changed. Allochthonous materials such as serpentinites and limestone olistoliths were introduced into the flysch during its sedimentation stage in the Upper Cretaceous era. After sedimentation, the basin started to close because of crustal shortening, and flysch masses were folded. Shear zones were generated at this stage too. Compression continued long after the Miocene, and limiting SW-NE oriented inverse faults were formed [2]. Tectonic activities starting from Messinian have also created a series of east-west oriented faults, and related fractures that first formed the Izmir graben (Izmir Bay) and later helped the formation of Balcova hydrothermal system. The most important fault of the area is the east-west oriented Izmir Fault, locally so-called Agamemnon Fault that extends over 30 km [2]. The Hot Springs of Agamemnon-Balcova geothermal system is located on this fault.

Since the area where geophysical surveying was conducted is filled by the sediments, understanding and interpreting correctly the sedimentation process might help and facilitate the geophysical interpretations. In this context, the paleogeography of the area is carefully examined. Western Anatolian grabens started to a fast development process in the Middle Miocene when the climate of the region was very humid. Also, lake basins were developed among the horst type of mountains in neotectonic depressions. At the end of the Miocene, the climate turned out to be dry during Messinian when the lakes were dried, and flood type of sediments were deposited in deepening lake basins among the rising mountains. There were still lake-marsh grounds with substantial carbonated mud accumulations. New depressions were formed by intense tectonism within basins, and EW oriented grabens were created in this epoch. In other words, underlain lacustrine and then overlain younger continental (flood) sedimentary units are present in depressions of western Anatolia and consequently in the Izmir graben. Continuing sedimentation created very thick deposits in sections where basins were formed within basins. Flood type of continental deposits (Tmoloses such as Bozdag deposit) had been formed from Upper Miocene through Pleistocene. Holocene alluvial deposition is the last epoch of this process and the thin cap of the thick deposition. It is possible to see Middle and Upper Miocene aged sediments in the surrounding elevations of Izmir depression (bay and Bornova) and overlaying continental sediments in the descending skirts to the actual bottom of the bay and Bornova. The continental deposits in the Balcova skirts can be traced from the plain to high elevations. These deposits underlay the Holocene alluvium toward the north. In summary, three different units could be distinguished: (1) fine grained Holocene sea-shore-delta sediments, (2) Pleistocene, and (3) Pliocene fluvial deposits. These are the alternations of coarse and fine grained sediments deposited on shores. In the north of delta and its behind, river flooding sediments and in the south of Inciralti, alluvium deposits were formed.

This complex and dynamic sedimentation process for the era must have been intensely affected by sea level changes related to glacial periods and interglacial periods. Sometimes, these periods dominated by lagoonal, deltaic, and riverine environments could have been alternated. The effects of the last glacial period are more or less known. The sea level in the last glacial period about 15,000 years ago was about 100 m lower than that of current level. During this period, the rivers were wearing out fast, and the valleys were deepening. When the glacial period terminated about 15,000 years ago and when the sea level began to rise, these valleys were quickly inundated by sea and transformed to bays. Until this process reached a relative equilibrium, thick deltaic sediments were accumulated in those environments. Studies conducted between Karsiyaka and Cigli at the northern side of the graben revealed such a ground section [10]. The thickness of fine to medium grained fluvial sediments reaches up to 50 m at the top. And, fine grained Pre-Holocene alluvial deposits below this depth is much more consolidated with respect to upper section. It is certain that this area has been above the sea level at glacial period and was consolidated under high effective stresses created by quickly lowered ground water level. Similar process and similar section of the northern side of the bay can also be brought to the south. The alluvium of Inciralti must be much thicker than that of thought. It is natural that a silty, clayey soil section at the upper parts, which was deposited after the last glacial period, present very low electrical resistivity. This process must have been repeated several times during Quaternary. It is also usual that soil sections similar to the upper one must have been deposited at deeper levels. Besides, coarse grained upper section of this sequence is much thicker at Inciralti side comparing to the northern side's, as can be deduced from some water well logs compiled from this region. It is concluded that the vertical displacement at the Agamemnon Fault System is much greater and faster than that of northern side. The magnitude of the strike of the post Messinian Izmir (Agamemnon) Gravity Fault is proportional to the height of the hills that is situated just behind of the fault scarp as can be deduced from situation of Pliocene sediments, covering the flysch at southwest. The site is closer to the steep slope and its coarse grained footslope deposits. While the presence of big strike at the southern margin of the Izmir Bay is clearly visible with such impressive geomorphology, the smaller magnitude faults confining the bay from the north are also clear. This asymmetrical structure is compatible with most of the asymmetry of the graben formations at the Western Anatolia. Consequently, the thickness of young and recent sediment section (especially of Holocene layers) at northern part of the graben, where the strike is smaller, is interpreted to be minor. In this context, it will be logical to investigate the thickness of the sediments at the north. As known from the water wells drilled in the northern part of the graben, the young sediment thicknesses are greater to the west and southwest. A thickness of over 600 m just across the Balcova region was observed. This sediment thickness toward the midst of the bay might exceed 1000 m. The thickness of the sediments from the seismic studies conducted in the sea was estimated about 850 m in the north-west of the bay within the Izmir Gulf [11]. The thickness at the southern side of the graben that is the area of interest is undoubtedly much more than that of the north. Based on seismic, gravity, and magnetic surveys in the Izmir bay obtained similar sediment thicknesses (600-800 m), which are also increasing to the south of the graben [12]. On the other hand, it is certain that such magnitude of the sediment accumulation did not occur in a quite medium. The sediments in this graben, which is confined by active faults from two sides, had been getting thicker where the strikes of faults increased. And, it can be thought that the rate of sedimentation must have been developed sporadically. In such case, the sediments consist of different types and sizes of material. The sediments become coarse grained when weathering and transport have been accelerated or fine grained in transition periods. On the other hand, fine sands had been deposited at shore environments while sometimes deltaic coastal plain environments have been persisted, such as Karsiyaka and Balcova coastal conditions exhibit today.

III. Geophysical Measurements

The ascending geothermal fluids and deep possible connections of the Balcova geothermal system were explored by the geophysical surveys conducted, and the following methods were carried out to satisfy the objectives of this study:

A. *Self Potential Survey*

SP measurements in geothermal areas generally reveal anomalous regions associated with near-surface thermal zones and faults through which geothermal fluids ascend. Anomalous surface potentials with high amplitudes are commonly measured near upflows of geothermal systems. Repeated measurements show that positive and negative potentials with short and long wave lengths are reproducible over high temperature systems. However, little is known whether such anomalies occur over low temperature prospects [13]. Two important SP surveys were previously run in the area; the first was conducted in the north of Agamemnon fault and the second was carried out in a belt covering both side of Izmir-Cesme highway [5]. Previous studies have been conducted on relatively small areas (7.5 km^2 and less), but the recent study covered an area about 70 km^2 [4]. It is known that SP surveys covering areas greater than 50-100 km^2 can produce representative data [13].

Self-potential measurements in the area of interest were conducted on eleven parallel E-W oriented lines with 50 m of electrode spacing between sea and Hot Springs. The distance between profiles is about 250 m. Derivative map constructed from the measurements is illustrated in Fig. 4. Although many positive and negative polarization effects are seen in the map, most of the polarization are thought to be formed by the effects of artificial sources such as electrical lines, fences, green houses, channels, roads, and walls. As seen in Fig. 4, the polarization effects in sequence are observed along the Ilica creek on N-S direction. These effects are interpreted as hot fluids flowing along the creek. Both reached the same conclusion in their studies [5,4].

The amplitudes observed in southernmost part of the area of interest are on the order of ± 100 mV, which are gradually reduced to ± 10 mV toward the north. This can be interpreted as the fluids are losing their heat while flowing to the north. Temperature distribution shown in Fig. 3 is evidence supporting the above interpretation [6]. To check the deep heat effect on these NE-SW oriented anomalies VES were run in few locations. On the other hand, the fault inferred in two previous SP and resistivity surveying could not be identified in last SP surveying run.

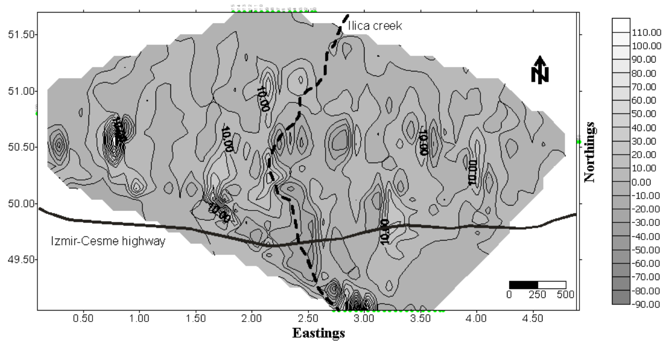

Fig. 4 SP derivative map (modified from [14]).

Significant anomalies among the measurements taken on 11 lines are shown as profiles in Fig. 5. Model solutions on cumulative values of the anomalies indicated that the effect of SP is born from very shallow depths [14]. In fact, hydrogeological model of the Balcova geothermal system identified the occurrence of two concealed lateral hot geothermal outflows. While the deep one (300-600 m) is confined, the shallow one (40-150 m) extends to the north well beyond the Izmir-Cesme highway with gradually decreasing temperatures [6].

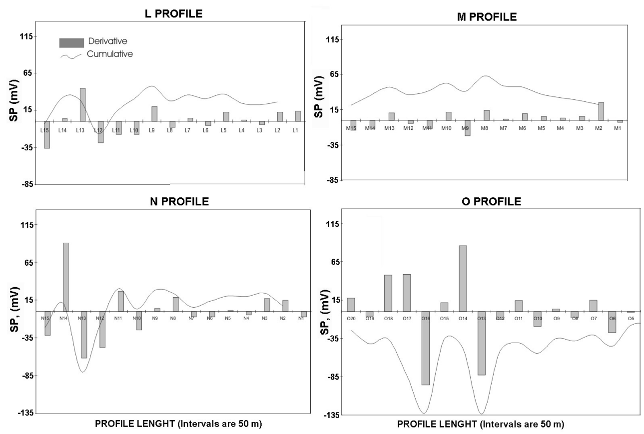

Fig. 5 Graphs of derivative and cumulative values on profiles L, M, N and O [14].

B. *Resistivity Survey*

Vertical Electrical Soundings (VES) using a Schlumberger electrode configuration were used to evaluate vertical and lateral variations in electrical resistivity. Obtained Schlumberger density data is rather sparse; therefore, a combined interpretation of VES and CSAMT measurements can provide more details about subsurface structures [15].

During resistivity surveying, electrodes spacing were adjusted with respect to geological basement depth and the required exploration levels as surface conditions permitted. Maximum theoretical exploration depth was about 3000 m. Different units such as alluvium, possible Neogene units, and Izmir Flysch are distinguished in the area of interest, and the average resistivity values of 100-300 Ωm, 20-40 Ωm and 40-250 Ωm are assigned to these units, respectively [14]. Surveying was conducted on generally E-W oriented lines shown in Fig. 2. The area was also interpreted on the basis of the known geophysical data of the Balcova geothermal field that is situated just in the south of the exploration area. As observed, there are no striking resistivity differences between stratigraphic units; as a result, some units in alluvium and flysch could not be clearly distinguished. Therefore, evaluations and interpretations in some locations were tried to fit to the structures identified by other geoelectrical measurements. On the other hand, some VES measurements were run off the lines to obtain better correlation between lines and to identify correctly the geological structures.

After surveying was completed, apparent resistivity maps were constructed to observe the apparent resistivity distributions laterally at different levels. Apparent resistivity cross-sections vs. depth were also built to follow apparent resistivity distributions along the lines. On the other hand, geoelectrical cross-sections for each line were prepared to identify subsurface geological structures. True formation resistivities and their thicknesses obtained after evaluation of VES measurements along with geological data interpretation [14].

If apparent resistivity distributions from surface to 1000 m are examined as illustrated in Fig. 6, lower apparent resistivities of 10 Ωm, which are considered to represent geothermal anomaly, are spread out from the Agamemnon Hot Springs in the south toward Izmir-Cesme highway. But, a deep conductive zone that could prove the presence of hot geothermal fluids is not seen in the area between Izmir-Çesme highway and the sea, which was the main exploration area of geophysical surveying. Even if a more conductive zone along the Ilica creek with respect to surroundings is seen in the upper sections (20-500 m), this area was not interpreted as hot geothermal fluid bearing active zone due to both its increasing resistivities to the north and its shallow depth [14].

The Balcova geothermal system is a fracture zone system that is related to an important tectonic structure so called the Agamemnon Fault [6]. In this context, sections of low resistivity closures observed in apparent resistivity cross-sections corresponding to the discontinuities ascertained in geoelectric structures seem to be significant. Therefore, the apparent resistivity and geoelectrical cross-sections were evaluated together. Six profiles were formed with the VES measurements taken in suitable places of the area of interest.

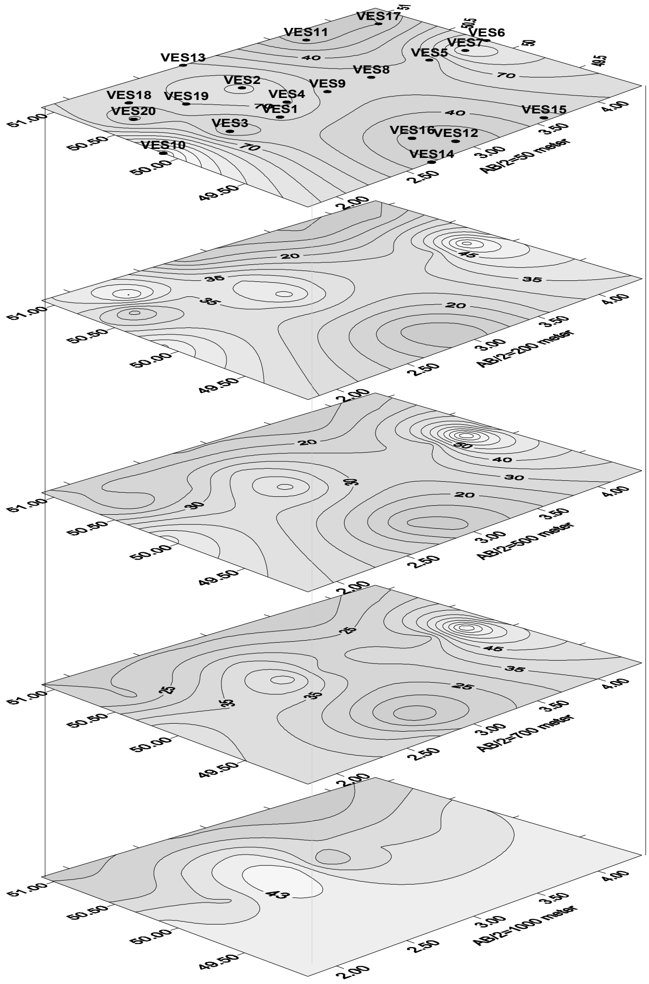

Fig. 6 Block diagram of apparent resistivity distributions [14].

Geoelectrical cross-section on line P01 is shown in Fig. 7. As seen from structural geoelectric cross-section in Fig. 7, the zones with resistivities ranging from 15 to 82 Ωm within the flysch were identified. These zones are not continuously spreading laterally and vertically. The resistivity distribution in Fig. 7 seems to represent the character of very complex nature of flysch with vertical and lateral transitions of clayeyschist-sandstone-claystone units. Resistivities of 15-40 Ωm and 40-85 Ωm matched to clayeyschist-claystone and sandstone, respectively. The deepest VES measurement was run at location VES4 with a half electrode spacing of AB/2=3000 m, and subsurface resistivity structure was theoretically explored up to the depth of 3000 m. The aim of this measurement was to explore and ascertain a possible location of Paleozoic metamorphics and consequently, the thickness of the flysch. But, a third electrical stratum, which could be interpreted as Paleozoic metamorphics could not be identified within the exploration depth. On the other hand, a low resistivity level that could be evaluated as geothermal anomaly is not seen, either.

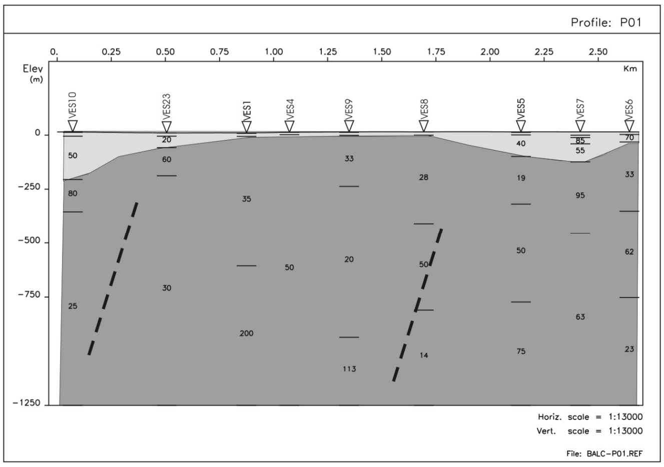

Fig. 7 Geoelectric cross-section of profile P01 [14].

The measurements on P02 profile shown in Fig. 8 were taken in the area where geothermal reservoir is situated, and hot geothermal fluids circulate at temperatures of 100-140^{o}C. Low apparent resistivities were recorded for the flysch in the Balcova geothermal reservoir. The lowest recorded resistivity zone is the interval in which geothermal fluid's flow occurs between surface and 300 m depth. After defining the effect of geothermal fluids on resistivity values in this area, similar effects were investigated in the area of study within the same lithology. Since the Balcova geothermal system is formed along the faults, similar tectonic structures were targeted in the north of the Izmir-Cesme highway.

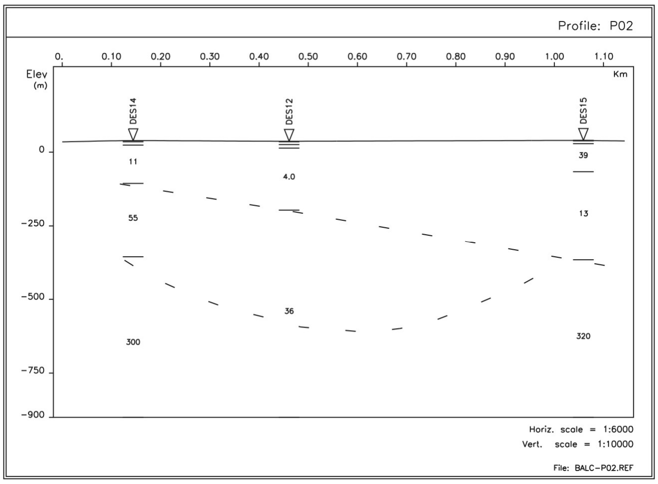

Fig. 8 Geoelectric cross-section of profile P02 [14].

Fig. 9 illustrates 3.5 km long profile PO4 oriented in N-S direction. Maximum VES exploration depth is about 1500 m. True resistivities of 100-150 Ωm calculated after evaluation of VES measurements match to alluvium sequence that is getting thicker to the north assumed Neogene units between the Holocene alluvium and the flysch where the flysch is also getting deeper [14]. These units could not be clearly distinguished due to limited number of data and close resistivity values. Low resistivities (20-35 Ωm) and high resistivities (150-200 Ωm) match to the Neogene units and sandstone units, respectively. A discontinuity, which may be interpreted as a fault due to the drop in resistivities and thicker units, is observed in the profile P04 [14].

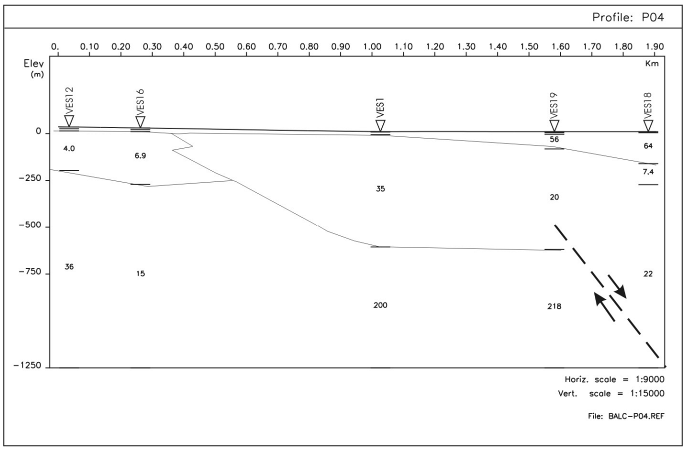

Fig. 9 Geoelectric cross-section of profile P04 [14].

C. CSAMT Survey

Controlled Source Audio Magneto-telluric (CSAMT) surveys have become an important tool for mapping reservoir brines and structures associated with geothermal resources. CSMAT surveys also produce effective results in geothermal exploration provided that it is used together with resistivity survey. Handicaps created by surface aquifers (Balcova case) and alteration zones found in geothermal explorations could be overcome through magneto telluric surveys. CSAMT is one of the best systems to explore depths of 2000 to 4000 m and to investigate the resistivity variations in different depths. Estimates of the thickness of Izmir Flysch and the depth of metamorphic basement were also expected to obtain by using CSMAT method.

The apparent resistivity maps for 6 different frequency (4096, 2048, 512, 128, 32 and 8 Hz) were constructed in the surveying area. Locations of CSAMT profiles are illustrated in Fig. 2. Apparent resistivity maps for 4096 Hz and 8 Hz reflect near surface and deep effects, respectively. Conductive zones are located between profiles of 40-42-44-56 and 58 in the apparent resistivity map of 4096 Hz as shown in Fig. 10. NE-SW oriented conductive zone seems to be displaced to the west toward the profiles of 56 and 58 in the apparent resistivity map of 8Hz. The conductive zones located in the west and northeast of the area of study are illustrated in Fig. 11.

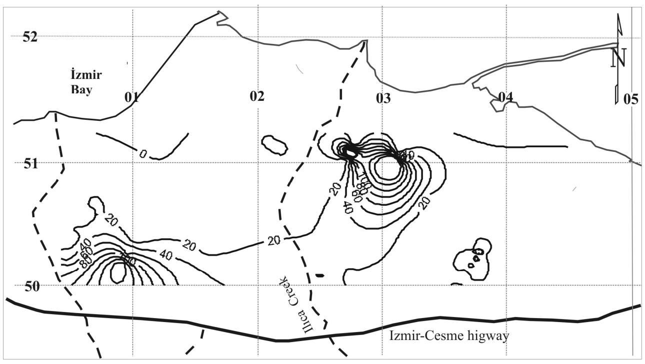

Fig. 10 CSAMT 4096 Hz apparent resistivity map [14].

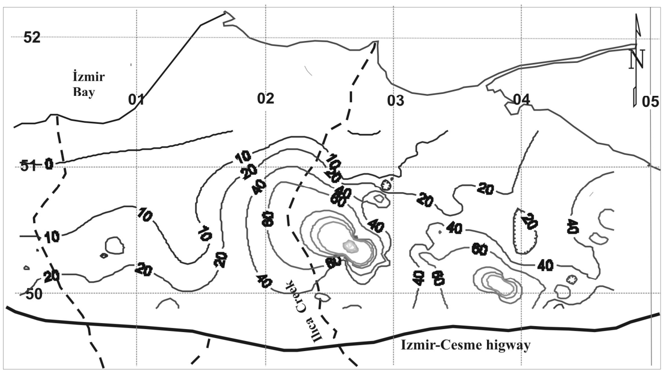

Fig. 11 CSAMT 8 Hz apparent resistivity map (modified from [14]).

To show the deep resistivity distributions, the apparent resistivity cross-sections were prepared from the measurements (8192-0.125 Hz) run along the profiles. Structural geoelectrical cross-sections were constructed after completing modeling studies. Figure 12 illustrates geoelectrical cross-section of profile no. 44 where conductive zones are observed between locations of 4401 and 4413 at 400-750 m and between locations of 4417 and 4423 at 200-400 m and at 1500-4000 m. Figure 13 shows geoelectrical cross-section of profile no. 48 in which conductive zones are observed between locations of 4801- 4811 at about 500 m and between locations of 4803 - 4811 at 1250 - 4000 m. Figure 14 illustrates geoelectrical cross-section of profile no. 58 where conductive zones are observed between locations of 5805-5821 at a depth intervals of 100-400 m and at 2500-4000 m.

IV. Interpretations of Geophysical Data

After the evaluation of SP survey, the focal depths at the anomalies are estimated to be originated from shallow levels between 30 and 300 m. Since polarizations of SP derivative values along Ilica creek are considered as anomalies, VES and CSAMT surveying were conducted in those areas to look for the relationship between tectonic structure and geothermal fluid's dispersion.

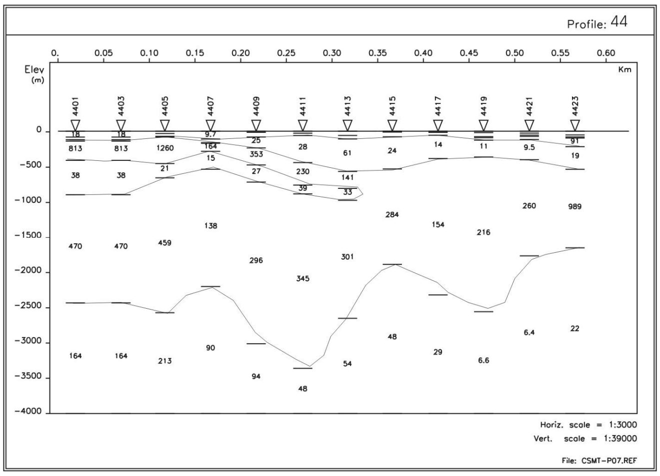

Fig. 12 CSAMT geoelectric cross-section of profile 44 [14].

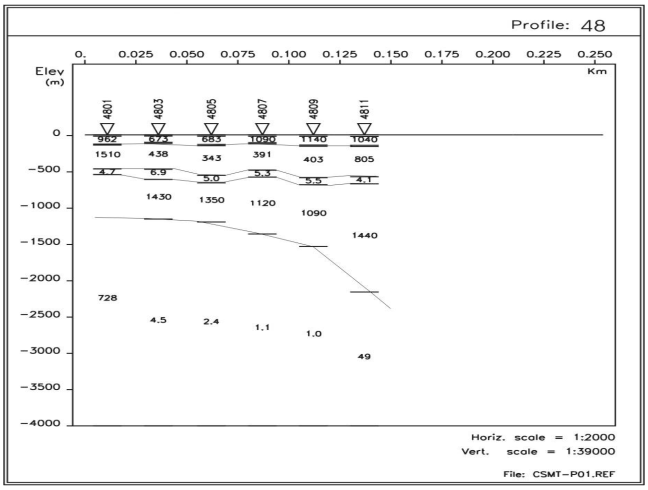

Fig. 13. CSAMT geoelectric cross-section of profile 48 [14].

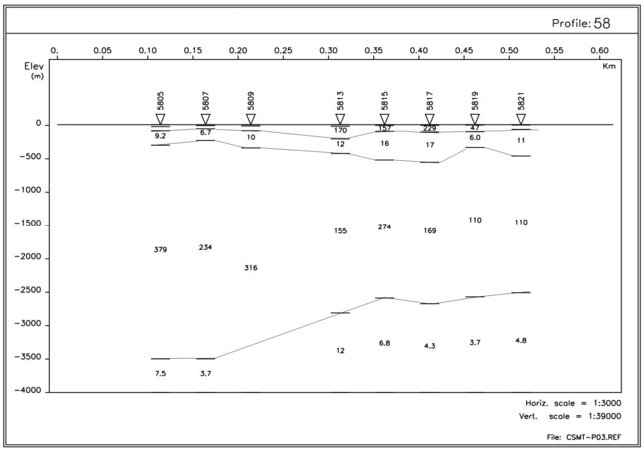

Fig. 14 CSAMT geoelectric cross-section of profile 58 [13].

Overlaid by Neogene and Quaternary units, the Izmir Flysch in the area is the deepest encountered formation and composed of different units. The flysch units are not intersected in Balcova geothermal field wells that are situated in the south. The flysch units were encountered after drilling 30-40 m of alluvium whose thickness increases toward the north. The flysch also deepens toward the north. Some resistivity levels overlying the flysch are assumed as Neogene units [14]. But, the resistivities of Neogene units might also indicate some flysch units.

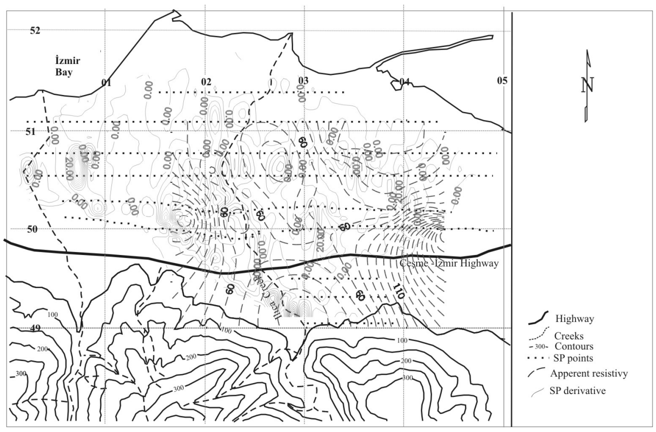

Fig. 15 Map of distributions of SP derivative and apparent resistivity at 50 m (modified from [14]).

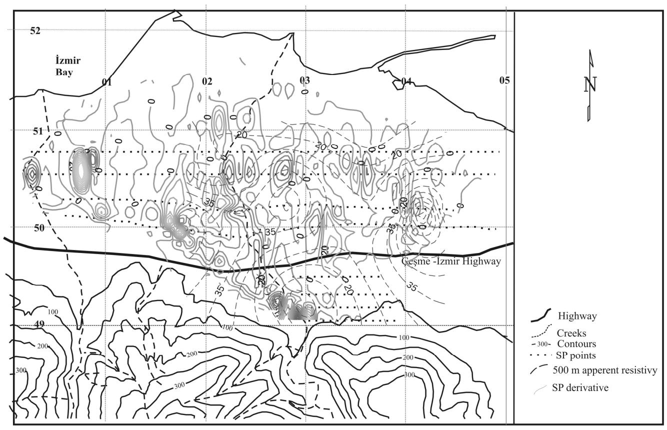

Fig. 16. Map of distributions of SP derivative and apparent resistivity at 500 m [14].

Figures 15 and 16 illustrate apparent resistivity distributions together with SP derivative distribution at 50 and 500 m, respectively. In the upper sections, the low resistivity zone measured along Ilica creek and SP focal depths occur at maximum. Intervals of 150-200 m are interpreted as the flow of geothermal fluid through suitable media that were formed along the creek bed and the alluvium. The direction of geothermal fluid's dispersion observed in upper levels disappears at 500 m level map indicated by the apparent resistivity and the SP interpretations, given in Fig. 16. This fact is confirmed by temperature distributions at 500 m depth level obtained [6]. Moreover, anomaly shows a closing trend between the locations VES 18 and VES 19 at this level. The depth of resistive flysch measured at location of VES 18 is found deeper (1000 m) than those of VES 19 and VES 20. The relatively low resistivity values (about 13 Ωm) were interpreted as the presence of a fault between VES 18 and VES 20 locations [14]. On the other hand, the resistivity values drop to 14 Ωm at VES 8 location. Since the resistivity values of the flysch are around 20-25 Ωm, the low resistivities encountered were also interpreted by [14] as the fluids flowing through an inferred fault proposed by the interpretations of previous geophysical surveys [5,4]. The resistivities rising to the east are not favorably considered for the areas from the geothermal point of view. On the other hand, the resistivities measured at shallow depths (max. 250 m) in the region that lies in the north of the area of interest (VES 11, 13, and 17) are interpreted as the effect of the sea water, which is correct and also confirmed by the salt water produced in a well with 350 m depth drilled close to the sea [16].

The presence of a low resistivity zone at depths between 300 and 500 m is observed along the CSAMT profiles. But, this conductive zone cannot be considered as an extension of geothermal fluid flow that was observed close to the Hot Springs area, since it was not confirmed by temperature distribution data. The high resistivity unit encountered between 500 and 3000 m is interpreted as the Izmir Flysch under which a more conductive structure with respect to overlying units is found up to 4000 m of exploration depth. Figure 17 illustrates this structure, which was attributed to a covered fault at 1500-2000 m [14]. It is interesting that unusually low resistivities observed below 3000 m in Fig.13 and 14 correspond neither to Izmir Flysch, nor to Paleozoic marbles. It is also stated that the low resisitivities at depth may be attributable to the effect of geothermal fluids circulating through Paleozoic age marbles that are thought to be underlain the Izmir Flysch [14].

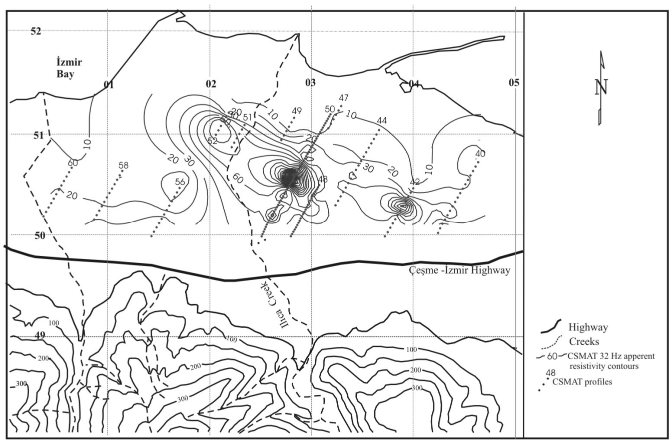

Fig. 17. CSAMT 32 Hz apparent resistivity map [14].

Finally, it is stated that the existing Balcova geothermal system developed between the Agamemnon Fault and the Izmir-Cesme highway does not spread to the north [14] However, some of the geothermal fluid seems to flow through the permeable zones along the Ilica creek. No other zones related to the geothermal effect were defined except for two relatively low resistivity zones encountered around the possible tectonic discontinuities. Unfortunately, there are no CSAMT measurements to clarify the situation in the areas that two relatively conductive zones are detected by VES surveys.

V. Discussion

SP derivative maps and the graphs prepared on measurements taken along E-W oriented lines are the most affected database by the industrial noise. It would also be useful to prepare and interpret the cumulative maps of these SP data that are taken in an environment where horizontal and lateral water movements are expected. Though SP derivative maps could reflect some lateral changes, cumulative maps might provide more information for identifying lithologic systems.

Level maps for several half-electrode spacings and the apparent resistivity cross-sections in different directions from the VES surveys were prepared and interpreted in detail together with one-dimensional modeling done for each location. However, these cross-sections provide valid interpretations in one-dimensional and homogenous media. On the other hand, it is known that the region is affected by vertical faulting systems; therefore, some additional studies are needed in situations where lateral changes take place as observed from the apparent resistivity values in level maps. The maps and cross-sections prepared as a function of half-electrode spacing for a certain value of AB/2 will bring information from different depths at different locations, since resistivity values of the location change laterally. This is caused by the distribution of current intensity in different forms. On the other hand, if the VES values from the half-electrode-apparent-resistivity medium are transferred to a depth-true resistivity medium with necessary transformations, the newly prepared maps and cross-sections will provide more valid information about the lithologic and the tectonic structure of subsurface.

Application of CSAMT method was right in principle since very deep geological information was explored in the area of interest. The database of CSAMT was also formed along the lines with sufficient density, and maps and cross-sections were drawn in frequency-apparent resistivity medium. On the other hand, subsurface structure is tried to be interpreted by using cross-sections prepared from the one-dimensional modeling at each sounding location. Even though some information was obtained with the above methodology, as in the VES evaluation, different information in the same frequency would be obtained from different depths because of different penetration depth problem of electromagnetic waves in media having different resistivities. This could be interpreted as if the information at different depths in level maps appeared to be at the same plane. Two-dimensional cross-sections derived from the one-dimensional inverse solutions would not show details due to reduced formation numbers. The Izmir Flysch containing low resistivity units is widespread and very thick in the area of interest. On the other hand, if there were tectonic structures developed within the flysch, this could provide some clues about geothermal fluids. Consequently, it would be useful to identify the concealed details within the data.

Evaluation methods implemented are correct [14]. However, transferring the data from the frequency-apparent resistivity medium to the depth-true resistivity medium by Bostick Transforms and mapping for certain depth values or preparing Bostick resistivity cross-sections as a function of the depth could bring a new view and different information in details. On the other hand, normalized cross-sections in which vertical conductive belts are better identified could lead new evaluations. In this context, relations between VES data and CSAMT data must be taken into account. By this way, deep and relatively shallow conductive zones observed after the CSAMT surveying could be clarified and matched to a new interpretation of geological model.

The proposition of deep drilling locations around VES 18 and VES 8 locations after the interpretation of resistivity survey is highly arguable [14]. One of these locations is related to the inferred fault with NE-SW direction that cannot be traced on the hills behind the Agamemnon fault [2]. On the other hand, the alluvium of Inciralti could be much thicker than that of thought, if the assumed Neogene units are included into alluvium. It is natural that a silty and clayey ground section in the upper parts that was deposited after the last glacial period present very low resistivities. This process must have been repeated during the Quaternary era. It is also logical that similar ground sections to the upper one must have deposited in deeper levels. Moreover, the temperature distributions do not indicate any anomalous heat flow in the study area neither in Fig. 3 nor in the temperature distributions of the area drawn on the basis of temperatures of numerous water wells [17]. The temperature distributions only indicate a shallow hot fluid flow from the fracture zone in the south to the north. On the other hand, temperature distributions at 500 m indicated in study, do not show any deep concealed outflow further north of the Izmir-Cesme highway, either [6]. Furthermore, Ozdilek well drilled to 350 m depth at a location (Inciralti), further north of the proposed well locations (close to the sea), has a temperature of 33^{o}C at the bottom, and the temperature profile do not support any heat anomaly. Finally, the flysch might have clayey sections that have low resistivities, too. In fact, the well (BH-1) drilled to 332 m just north of the Izmir-Cesme highway intersected 20 m of muddy formation containing gases at the bottom where the well was completed. The electrical resistivities of this sort of soils could be very low. Therefore, it does not seem accurate to match the geophysical data with geothermal fluids without relating to a correct geological model and to propose drilling sites.

VI. Summary and Recommendations

Geophysical surveying conducted in the north of the known geothermal system had two main objectives: (1) discovering a possible extension of known geothermal system to the north and (2) estimating the depth of Paleozoic basement. While the extension of a shallow concealed outflow of Balcova geothermal system to the study area is confirmed by SP and Schlumberger resistivity surveys, no deep extension of the known Balcova geothermal system was found in the northern area. Instead, two possible faults are inferred in the area of interest because of low resistivities encountered around 1000 m depth. The low resistivities in the area of interest are geologically explained as clayey, silty zones formed during Holocene and Plio-Pleistocene. CSAMT surveying revealed a shallow (300-500 m) and the deep (>3000 m) conductive zones. While the shallow conductive zone could be explained geologically with low resistivity formation, the deep conductive zone is found difficult to explain geological wise and may be attributed to the uncertainties of CSAMT surveying after 2000 m of depth. Moreover, a deep structure is identified between 1500 m and 2000 m.

In the light of the information mentioned above and clarifying some discussed issues, the following recommendations are given:

- Prepare the cumulative SP maps to provide more information for identifying lithological systems.

- Prepare new maps and cross-sections after transferring the VES data from half-electrode apparent resistivity medium to the depth true resistivity medium in order to obtain more realistic information about lithogy and subsurface structure.

- Prepare new maps and cross-sections after transferring the frequency-apparent resistivity medium to the depth-true resistivity medium by Bostick transforms in order to obtain a new view and different information in details.

- Evaluate newly found results with geological model supported by geological data obtained from both sides of the Izmir bay.

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U.Serpen, date of birth 1945. He got MSc and PhD degrees from Istanbul Technical University, Petroleum and Natural Gas Department in 1967 and 2001, respectively. He has worked as a drilling, production and reservoir engineer and consultant many geothermal projects all over the world. He joined to Istanbul Technical University in 1988. His areas of interest are drilling, energy economy, geothermal resource assessment, geochemistry and geothermal engineering.
After retiring 2010, he has started to work as a consultant for geothermal energy projects
Assoc., Prof. Dr. Serpen is a member of Geothermal Resource Council and Turkish Petroleum Engineer's Association. He is fluent in English, Spanish and Italian.