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Geologic and Thermal Evolution of Turkeys Wealthy Geothermal Region, MMM

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ABSTRACT

Recently, Menderes Metamorphic Massive (MMM) had been subjected to a fast structural evolution. This part of Western Anatolia's lithospheric crust has risen more than ten kilometers since post Miocene and this movement is continuing. This uplift has been compensated by a progressive erosion, detachment faults, listric faults, etc. and has been happened in several cycles.

This fast exhaustion of the upper crust in a relatively short period results in a disturbance of the thermal framework of this section. The cooling history of MMM has been remodeled by thermochronological methods and at least two main fast cooling phases have been determined.

A cooling model of the lithospheric crust shows a delayed stabilisation of the thermal gradient caused a high heat flow at this region. This heat flow is irregularly distributed at MMM.

In addition to this region’s high heat flow, a dense framework of faults with different orientations provide a well developed vertical permeable channel system. This allows fluids to infiltrate to sufficient depths to be charged with a considerable amount of heat by interaction with rocks of this warm upper crust.

Thus, more than fifteen medium-entalphy, water-dominated geothermal systems have been found along two E-W oriented long grabens at MMM. These systems occur at the southern side of northern and northern side of southern grabens, at the two borders of the mostly exhausted core complex of MMM.

This geological, structural and thermal framework provides a promising prospect for enhanced geothermal field development studies at the zone extending between these two graben belts where the mostly exhausted part of the MMM spread.

1. INTRODUCTION

MMM, “**Menderes Metamorphic Massive**” comprises most of the western part of Turkey and hosts several geothermal systems. MMM is a geological structure where the geothermal systems are encountered most frequently in Turkey. There are several hot springs (from Pamukkale-Karahayıt systems) at its eastern end to Söke at the western end and extensive engineering investigation and resource development works have been done at these geothermal fields up to now. Some explorations have been done by boring studies at most of these systems, power production are being done at one of these for tens of years. The first two privately invested power plant of Turkey are producing power at here and two others are under construction.

It is obvious that, MMM and two of the large graben systems as Büyük Menderes and Gediz Grabens have several prospects which are suitable for the formation of geothermal resources. It is understandable that there must be some common geological characteristics at these partially or completely known geothermal fields.

For instance, most of these fields have developed at reservoirs with medium enthalpies, with reservoir temperatures between 120-240°C. Their reservoirs have developed generally at different lithological units of metamorphic basement. A typical characteristic of this basement, of MMM, is the complexity of its geological evolution.

There are Miocene to Holocene aged sedimentary deposits overlying this metamorphic basement in the graben depressions. Some shallow reservoir environments have also been developed in them, as had been determined at well investigated fields.

Another common characteristic is the position of these Miocene deposits that filled some old grabens which were formed by NE-SW or NW-SE extending gravity faults which are oblique to actual ones.

Another common and prevailing characteristic is the complicated nature of these old and young graben structures, which exhibit stepwise vertical displacements on several faults. Also the existence of some antithetic faults and some successive horst-graben systems are seen. Furthermore, overlapping of these old and young grabens and existence of some younger sedimentary covers make these structures more complicated.

Another recently understood characteristic of the MMM, is the importance of large regional detachment faults in the neotectonic evolution of MMM and their control on the development of the geothermal systems.

These common characteristics are considered important for at least two reasons. Primarily, geothermal systems have been developed at these structural discontinuities which were formed in several phases. Hot fluids rise from depths to shallow levels over these and these systems and preferentially flow at the intersections of these discrete structural systems. Another reason which makes these common characteristics important is the guidance of the knowledge on these systems, which have been already investigated, to understand the structural framework of other less known systems. Geophysical surveys help gather information about the subsurface that is hidden by young sediments. When the geological model of one of these geothermal systems is proven, it is reasonable to consider this information relevent for other fields too. Thus, several new prospects are being developed at previously noninterested parts of the mid plains at these grabens.

2. RECENT GEOLOGICAL EVOLUTION OF MMM

Menderes Metamorphic Massive (MMM) had been subject to a fast structural evolution recently. This part of Western Anatolia's lithospheric crust has risen more than ten kilometers since the early Miocene and this movement is ongoing. This uplift has been compensated by a progressive erosion, detachment faults, and listric faults, which has happened in several cycles.

2.1 Lithological and Stratigraphycal Characteristics of MMM

Formerly, the metamorphic basement rocks of MMM have been called as Paleozoic in age in past publications. Furthermore, metamorphism has been said to have occurred in a single phase and proceeded mostly at the end of Eocene. Another general acceptance was that the Massive had uplifted at the end of metamorphism and some E-W extending faults and grabens formed as a result of this.

Metamorphic rock units are very similar with Paleozoic-Upper Mesozoic units of Taurides at south and/or Pontides at north of Anatolia. It is obvious that the Massive can't be explained only by Paleozoic units. Some metamorphosed rock units must belonged to Mesozoic.

Nevertheless, research studies on Menderes Massive continued, became more varied and widespread during the last thirty years. Eventually, a rich knowledge base has been developed on the Massive's complex structure.

Menderes Massive Metamorphics are being divided to two main subunits generally: "**Core**" and "**Cover**". "Core" consists of highly metamorphosed schists, leptite gneisses, eyed gneisses, metagranites, migmaties and metagabros. "Cover" consists of micaschists, fillites, metaquartzites, metabasit, metaleucogranite, kloritoide-kyanite schists, metacarbonate and metaolistosthroms.

2.2 Metamorphism of MMM

Stratigraphical sequence and metamorphic history of Menderes Metamorphic Massive (MMM) were compiled in detail and published by Dora and his colleagues. Dora, et al (1995) explain this as "Evaluation of geological information and structural evolution of MMM can be done under the light of multiphase metamorphism model, as below:

I) **Sedimentation of the source rocks of leptitgneiss and core schists, first metamorphism (M1) and basic and emplacements of acidic basic ve acidic plutons**. Oldest rocks of MMM, mudstones, tuffite and shales which were source rocks of leptite gneisses and core schists which were dated to between 585-1870 million years according to zircon detritus had been deposited onto a yet unknown older Precambrian aged acidic kraton. Those units had been metamorphosed (M1) in upper amphybolite-granulitic fascies under the circumstances of Pan African "continent to continent collision" during Precambrian-Cambrian boundary. Synchronous or following metamorphosed granitoides accompanied to this 550 million year before.

II) **Deposition of Paleozoic units of Cover, Variscan Metamorphism (M2) and emplacement of Triassic aged leucogranits**. Paleozoic units consist of quartz arenites, metaconglomerates with granite gravels derived from Pan African Basement and limestone, shale and quartz arenite alternations from bottom to top as deposited over the eroded Pan African Basement during Ordovician-Permo Carboniferous era. This sequence has been metamorphosed during the "*Varisc Orogen*" together with core units (M2) and leucogranites have been emplaced in it during Lower and Middle Triassic. Their ages have been determined as between 240-230 million years.

III) **Deposition of Mesosoic-Tertiary units as Cover series and double "*Tertiary Metamorphism*" (M3, M4)**. Existence of some conglomerates at bottom of platform type carbonates shows that there is a discordance between Paleozoic and Mesozoic sequences. Upper envelope of the Cover sequence consists of an olistostromal unit which covers platform carbonates with boxite deposits and ophyolithic and carbonate blocks deposited during Upper Triassic-Paleocene from bottom to top. Either core or cover units of Menderes Massive have been metamorphosed by a Tertiary two fold process which is related with the closing of Aegean Neotethys Ocean and underthrusting of the Anatolian-Taurid Platform through to north, under the İzmir-Ankara Zone, as similar with Cycladic Complex. "*High Pressure Metamorphism*" (M3) has evolved under circumstances from epidote-blue schists to eclogite and then Barrowian type "*Main Menderes Metamorphism*" (MMM) (M4) developed during the Upper Eocene. Compressive stress environment at the end of this final medium pressure metamorphism brings inner folding and overthrusting of core units over the upper levels of cover sequence.

IV) **Extensional tectonics, synchronous granite emplacements, development of detachment faults, uprising and Depletion of the Menderes Massive**. Extensional tectonics environment which was developed at Western Anatolia during Lower Miocene caused the rising and depletion of MMM and development of huge detachment faults and fragmentation zones have accompanied to this. 19.5 million aged synchronous granites have been emplaced into the Cover series and made contact metamorphism in bedrock. Huge detachment faults and fragmentation zones up to 100 m thick have developed in brittle zones during the uprising and depletion of central massive (Kiraz-Ödemiş Sub Massive). Following these processes graben formed gravity faults were developed under true brittle conditions through E-W directions and cut either these fragmentation zones in Basement or Neogene deposits covering this. Neogene deposits at Gediz Graben have been emplaced tectonically over this fragmentation zone as lean back to south with 15° through these gravity faults. Geothermal systems at the middle of the Massive and several Middle to Upper Miocene medium composition to basic volcanic extrusions are related directly with this graben system."

Not everybody adopts these explanations. For example, some researchers advocate that the metamorphism has developed in only a single phase. According to them, metamorphism of the Basement has developed during Eocene under the medium to high temperature facies (Erdoğan, 1992; Satır and Friedrischen,1986; Hetzel and Reischman,1996).

This type of orogenic belts where some crustal shortening has happened exist at different locations of the world and have been investigated in detail. Recently, some laboratory experiments have been started for investigating the crustal shortening and structures developed then.

2.3 Tectonic Evolution of MMM

First important tectonic movement that occurred at the region is the emplacement of tectonic associations over and over as nappes. Then, NNE-SSW direction overthrustings plunged to west and large scale closed and easterly overthrown isoclinal folds were developed under the NW-

SE directed compression stresses. Gessner, et.al.(2001) models this as at Figure 1.

Ring et al. (2001) has studied P-T conditions of metamorphism at Bozdağ and Çine Nappes. The inverted metamorphic field gradient in the Bozdag Nappe was probably caused during Alpine nappe stacking. The inversion may have been caused by large-scale recumbent folding or, as they prefer, by internal imbrication. Both options can be tested by further tectonic-metamorphic field studies. After this compressional phase tensional stresses have been dominant and gravity faults with WNW-ESE and NE-SW directions were formed. These large displacement faults were developed after Akhitanian. Finally, tension forces emerged from the domal uplift of Menderes Massive started by Pliocene and result gravity faults which are shaping large grabens.

General structural evolution of the region can also be summarized as below according to Yılmaz et.al., (2000) : ‘‘New map data was collected with recent studies conducted at Western Anatolia to finalize the discussions on the timing and general formation mechanism of Western Anatolian graben system, and it was determined that N-S directed grabens had been formed under the E-W stresses at Lower Miocene during the first phase. Some openings developed under the influence of tensional stresses accompanying N-S oblique shear faults make easy the rise of calkalkaline, hybrid composition magmas to surface. A N-S tension stress environment has been prevailing during Upper Miocene. A main breakup fault has formed during this period. A part of lower plate has been arised over the upper plate levels and outcropped at Bozdağ Horst and longitudinal grabens through E-S direction have been formed. Alkali Basalt lavas erupted from these fault systems. N-S elongation has been terminated at the end of Upper Miocene or Lower Pliocene which is already shown by a regional horizontal erosion surface which was developed over Neogene units which covers also Upper Miocene-Pliocene sequence. This erosional surface erased nearly whole topographical irregularities, including Bozdağ Rise.

Then, this erosion surface disrupted by revitalized N-S tensional forces and the structures which controlled the formation of Lower to Upper Miocene sequence, have been cut by roughly E-W oriented gravity faults. This provided that the formation of actual E-W extended grabens at Plio-Quaternary.”

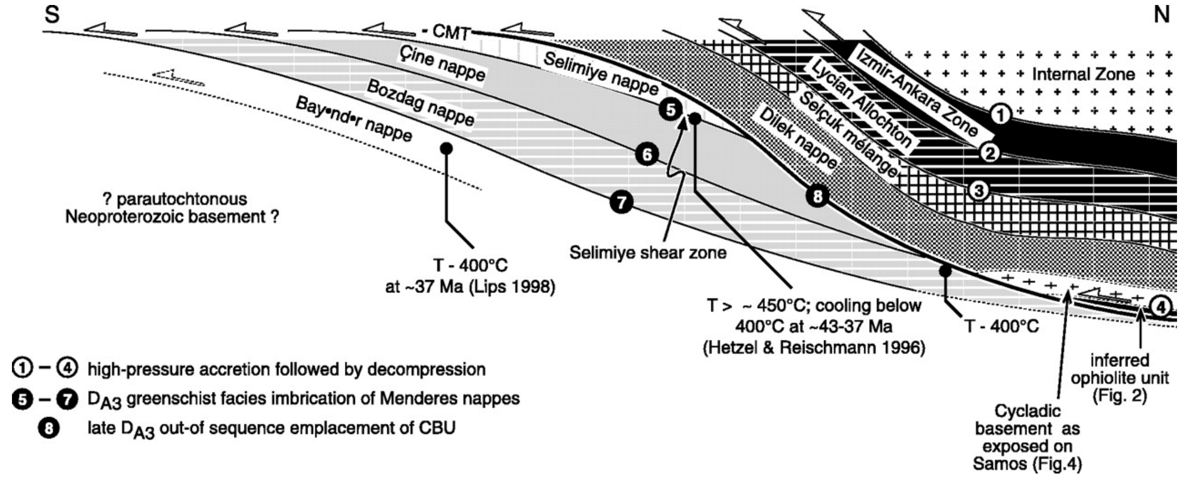

Figure 1: Interpretative thrust sequence during formation of Anatolide belt. Late Cretaceous to early Eocene imbrication of Vardar–Izmir–Ankara suture zone and Cycladic blueschist unit during high-pressure metamorphism (thrusts 1–4), followed by collision of Anatolia causing greenschist-facies imbrication within Menderes nappes (thrusts 5–7)

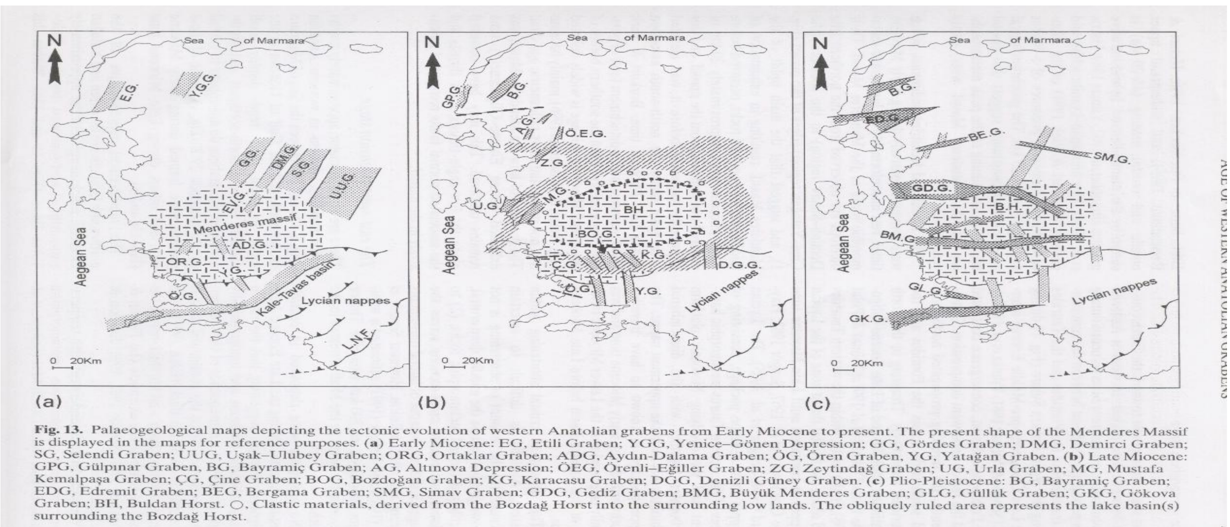

Figure 2: Structural Evolution Phases of Menderes Massive

Tectonic framework of MMM has systematically discussed at Yılmaz (2002), too. There are about ten E-W trending graben structures at Western Anatolia with about 100-150 km lengths and 5-15 km widths. Büyük Menderes and Gediz grabens are main examples of these. Investigations show that thick volcano sedimentary units have been deposited during Lower to Middle Miocene in these continental basins which are limited with N-S gravity faults developed under the E-W tensional forces. Whole Western Anatolia has been covered by interrelated lakes, then. Magmatic and volcanic rocks of this period have high potassic, calkalkaline and hybrid compositions. N-S extension had been started during Upper Miocene. Detachment Faults at Bozdağ at the central region of MMM have started to formation and Bozdağ has emplaced. Reddish colored coarse clastics have been deposited around the Bozdağ while light colored lacustrine limestones at far away. Alkali basaltic lavas extruded during Upper Miocene-Lower Pliocene in a pulsed manner. N-S extension has been slowed for short period at final stages of Lower Pliocene and a regional erosional surface had developed. Actual graben systems has started when N-S extension restarted again.

Graben forming E-W faults interrupted the continuity of old N-S grabens and suspended them.

Okay (2002) has discussed the timing, start and reasons of this process. Okay investigated the Kazdağ Massive at NW Anatolia. Metamorphic core is outcropping at the middle of this massive. Bedrock consists of marble and gneiss which were metamorphosed under 5±1 kbar pressure and 640±50ºC temperatures. Average muscovite and biotite Rb/Sr ages are 19 My and 22 My and points to a metamorphism took place at Oligocene under high temperatures. Cover units consist of a mélange which was deposited in a Cretaceous aged ocean and includes some unmetamorphosed Cenonian eclogitic lenses. Cover and core units separated by a brittle shear zone which consists of two kilometer thick gneiss protoliths. Highly metamorphosed rocks show northerly oriented and northerly plunging mineral lineations. This shear zone was cut by an undeformed granitoid, which was aged as 21 My by Rb/Sr method as similar with ages of accretioanry mélange and highly metamorphosed core rocks. Estimated pressure for metamorphism and granitic emplacement shows that metamorphic rocks had arisen quickly from 14 km depths to about 7 km's along a shear zone about 24 My before. Metamorphic rocks of Kazdağ surrounded by huge amounts of calc-alkaline Upper Oligocene-Lower Miocene aged volcanic and plutonic rocks which were developed on the northerly dipping Helenic subduction zone. All of these show that the Upper Oligocene regional spreading doesn't related with gravitative collapse; but, directly with rolling back on this subduction zone.

A similar process has also been experienced at Menderes Massive. According to the information given by Dora et al(1995) eclogitic outcrops encountered around Birgi and Tire territories had reached up to 13 kbar pressure and 650°C temperatures as evidenced by their maximum burial depth of at least 40 km. This could only have occurred by crustal thickening tectonically, folding onto itself. This part of crust obviously had risen about 40 km since then and depleted by several ways.

Yılmaz et al (2000) conclude that crustal thickening since Upper Cretaceous between Thracia and northern Mediterranean as a result of collision of Taurid and Pontid continental plate fragments through İzmir-Ankara Suture Zone, isn't smaller than 200 km and has been run through to Upper Eocene-Oligocen at north, while through to Upper Miocene at south.

Continental crust represented by MMM now has been shortened about 200 km's during this time period and after this raised about 40 km's since then. Most part of the Massive was depleted during this rise. As a matter of fact, the seismogenic thickness and thermal structure of Western Anatolia was correlated by Pamukçu and Yurdakul (2008) with the effective elastic thickness. The results of this study showed that the strength of the lithosphere of the Western Anatolia resided in average 6 km. The two most reliable indicators of lithospheric strength are the focal depth distribution of earthquakes and relation of gravity anomalies with topography. Beside this, a MT survey conducted by ENEL (1988) has found a low resistivity crustal layer below 7 km depths through to 40 km's.

Some other views contrary or complementary to the above evaluation have been published. The detachment faults concept is an example of this.

Recent detailed structural geological investigations which were done at different metamorphic massive around the world revealed that a thick slab of top layers of the rock column have lost their stability, detached from underlying mass, displaced laterally and these shear systems are being called as "**detachment zones**". Those zones look important for geothermal investigations owing to their intensely fractured, thick fragmentation zones.

Most studied and correlated massive with this kind of structures are "*Menderes Metamorphic Massive*" at Turkey and "*Basins and Range*" at US. There are typical metamorphic core complexes, spreading faults, turtle back faults, shear zones, detachment surfaces and extensional sedimentary basins synchronous with this extension at these two regions according to Çemen (2002). Seyitoğlu (2002) analyze different examples of these structures from Western Anatolia, too.

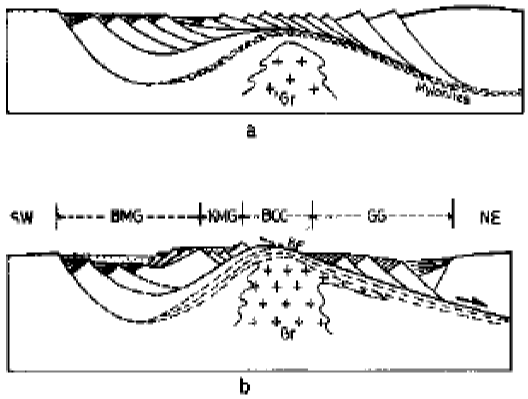

Figure 3: Evolution Model of MMM according to Emre ve Sözbilir(1995)

These vertical rotational tectonic processes can be understood more by magnetostratigraphical data and Alaşehir and Büyük Menderes grabens were investigated by this manner by Şen (2002). Author has dated older ones of four depositional cycles as 14.6-16.7 and 16.73-18.28 My matching to Lower Miocene. Paleomagnetic deviation has found 25º counterclockwise at Alaşehir Graben and 30-40º clockwise at Büyük Menderes Graben and this difference has been attributed to detachment faults. It was concluded that this type of inverse vertical axis deviations at Western

Anatolia is not related with solid crust movements; but must be related with deformation of a thin skin over crust.

Catlos (2002) made Th-Pb ionic microprobe measurements at growing haloos at granats and conclude that detachment zones depleted rock units at depths of crust since Pliocene.

Thus, core of the crystalline massive that is heaving and rising at very large fields is unstabile and slides over the cover units through nearly horizontal, maximum 20° dipping large faults (Figure 3). Some research results were published related with the existence of this kind of structures at Menderes Massive. For example, Emre and Sözbilir (1995) affirm that there are two large detachment faults at metamorphic rock mass at south of Gediz Graben and northern side of Büyük Menderes Graben. The northern side of Büyük Menderes Graben is older (*at the start of Miocene*) and southern side of Gediz Graben fault is younger (*later Miocene*). The Bozdağ core complex is assymetrical; Miocene and Pliocene sediments have deposited in troughs of structures as dominos to the north and as quasi-graben tilted blocks at the south. These faults are active and some seismic activities are being recorded. Bozköy Overthrust as previously described in MMM is a typical detachment fault and Büyük Menderes and Gediz Graben's aren't typical symmetrical grabens and can be explained as latest products of these detachment movements. This coercive modeling looks weaker yet, either than Yılmaz et al's (2000) explanation of the whole Western Anatolian grabens together, or than Candan et.al.(1992)'s translation model of metamorphytes, or young sediment depositions at other sides of Büyük Menderes and Gediz Grabens.

According to the above given quotations and explanations the rising of the Menderes Metamorphic Massive started just after its final metamorphism at the end of Eocene. This rise and depletion process has developed mostly at Bozdağ Rise, at between the north of Aydın and south of Salihli-Alaşehir.

Either the old grabens have been shaped by NW-SE/NE-SW at inner parts of Massive and N-S at outside of it which have controlled the Miocene deposition or the actual grabens shaped by post Pliocene E-W faults are obviously developed under the influence of tensional stresses which were arose at the outer periphery of the Massive as result of its domal rising. Apparently, heaving, formation of old and actual grabens continue to the present.

Currently, continuing earthquake activity along graben faults is direct proof of the continuing stresses over these fault mechanism. Furthermore, Emre and Sözbilir (1995) quoted from Eyidoğan and Jackson (1985) that there are fault surface analysis for some events that these taking place on horizontal or very low angle detachment faults.

But, most obvious proofs of this continuing activity can be detected from geomorphological characteristics of region. As already known that the grabens at two sides of Bozdağ Rise is assymmetrical. The southern side of Gediz Graben is steeper than the northern side of Büyük Menderes Graben. Menderes River is continuously deplaced to southern side of the Graben. The alluvial plain between the river and the northern margin is nto horizontal, but slopes to south. There are alluvial fans at mouths of all valleys at the northern side of the Graben and these are advancing. Northern side faults look young or active with steep slopes and triangular faces.

Strictly speaking, the uprising of Menderes Massive and resulting stresses are occurring on an ogoing basis, but there is not any data about the rate of activity.

2.4 Young Magmatism

There isn't any true young and recent volcanic activity at MMM. Most recent examples are the old volcanism encountered at N-S grabens and their surroundings at the northern edge of MMM. Examples given by Özgür(2003) are 15.0-16.7 My old Middle Miocene volcanic products at Küçük Menderes Valley; and others are Upper Pliocene aged volcanites at Denizli and Söke and 7,5 My to 18 Ky old Kula volcanites which has been noted by Özgür as far as 150 km far. All of these are encountered at outside of MMM and grabens, far from geothermal activities and differing volcanic products which were developed under different petrogenetic conditions and at different phases. It is impossible to explain actual high heat flow with this old volcanism, even their near surroundings. In any event, there are not any old or recent volcanic products at inner parts of MMM, for example around Gediz or Büyük Menderes Grabens. Kula Volcanites are products of deep tension cracks developed at rigid continental crust in low temperatures and situated at far away from Büyük Menderes and Gediz Grabens. Dora et al (1995) referred to Hetzel et al (1995) that the age of youngest magmatic intrusion phase was measured as 19.5 million years.

Magmatism at Western Anatolia outside of MMM shows a similar development. Dilek and Altunkaynak (2009) concludes that "Post-collisional magmatism in western Anatolia began in the Eocene, and has occurred in discrete pulses throughout the Cenozoic as it propagated from north to south, producing volcanoplutonic associations with varying chemical compositions. This apparent SW migration of magmatism and accompanying extension through time was a result of the thermally induced collapse of the western Anatolian orogenic belt, which formed during the collision of the Sakarya and Tauride–Anatolide continental blocks in the late Paleocene. The thermal input and melt sources for this prolonged magmatism were provided first by slab break-off-generated aesthenospheric flow, then by lithospheric delamination-related aesthenospheric flow, followed by tectonic extension-driven upward aesthenospheric flow.

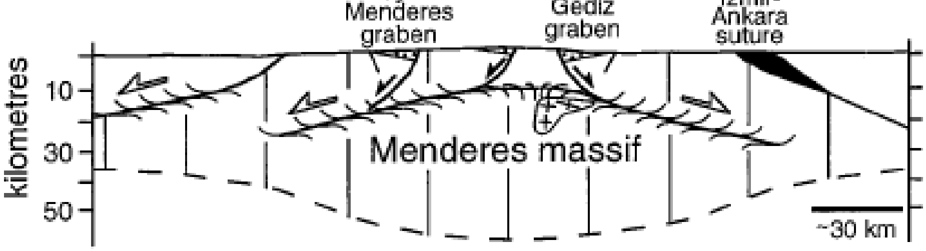

Figure 4: Evolution Model of MMM according to Hetzel et al(1995)

The first magmatic episode is represented by Eocene granitoid plutons and their extrusive carapace that are linearly distributed along the Izmir–Ankara suture zone south of the Marmara Sea. These suites show moderately evolved compositions enriched in incompatible elements similar to subduction zone-influenced subalkaline magmas. Widespread Oligo-Miocene volcanic and plutonic rocks with "medium to high K" calcalkaline compositions represent the next magmatic episode. Partial melting and assimilation fractional crystallization of enriched subcontinental lithospheric mantle-derived magmas were important processes in the genesis and evolution of the parental magmas, which experienced decreasing subduction influence and increasing crustal contamination during the evolution of the Eocene and Oligo-Miocene volcano-plutonic rocks. Collision-induced lithospheric slab break-off provided an influx of aesthenospheric heat and melts that resulted in partial melting of the previously subduction-metasomatized mantle lithosphere beneath the suture zone, producing the Eocene and Oligo-Miocene igneous suites. The following magmatic phase during the middle Miocene (16–14 Ma) developed mildly alkaline bimodal volcanic rocks that show a decreasing amount of crustal contamination and subduction influence in time. Both melting of a subduction-modified lithospheric mantle and aesthenospheric mantle-derived melt contribution played a significant role in the generation of the magmas of these rocks. This magmatic episode was attended by region-wide extension that led to the formation of metamorphic core complexes and graben systems. Aesthenospheric upwelling caused by partial delamination of the lithospheric root beneath the western Anatolian orogenic belt was likely responsible for the melt evolution of these mildly alkaline volcanics.

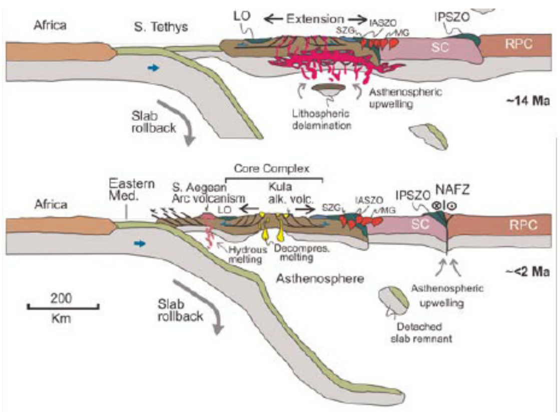

Figure 5: Dilek and Altunkaynak's (2009) Model

Lithospheric delamination may have been caused by 'peeling off' during slab rollback. The last major phase of magmatism in the region, starting c.12 Ma, is represented by late Miocene to Quaternary alkaline to super-alkaline volcanic rocks that show OIB-like geochemical features with progressively more potassic compositions increasing toward south in time. These rocks are spatially associated with major extensional fault systems that acted as natural conduits for the transport of uncontaminated alkaline magmas to the surface.

The melt source for this magmatic phase carried little or no subduction component and was produced by the decompressional melting of aesthenospheric mantle, which flowed in beneath the attenuated continental lithosphere in the Aegean extensional province. This time-progressive evolution of Cenozoic magmatism and extension in western Anatolia has been strongly controlled by the interplay between regional plate-tectonic events and the mantle dynamics, and provides a realistic template for post-collisional magmatism and crustal extension in many orogenic belts."

In conclusion, the unusualy high heat flow expressed by the geothermal systems at Gediz or Büyük Menderes Grabens cannot be explained by volcanic and magmatic activities alone.

2.5 Rifting or Extension

It is not acceptable to say that these graben systems are rifts and the geothermal heat source is volcanic activity. Also, some views on that isotopic chemistry of hot waters shows the water rock interactions, that ^{14}C isotopic composition can be explained by reaction of hot waters and deep carbonate rocks for origin of CO_2. Minor quantities of heavy metals in waters and that F and B's behavior parallel to Na are signs that the water has interacted with metamorphic rocks, which can be used for explaining another models. But some researchers conclude that the recharged waters infiltrated down to 4000 m depths to top of a magma stock and were then heated Özgür (2003). There is a unique proof to this rationalization; mantle origin of the ^{3}He in water. But the author of referred paper close the door to explain Menderes Grabens as rift by only this data, "Most of the ^{3}He loss from mantle are being occurred at oceanic basins as related with the formation of oceanic lithosphere and its cooling. Nonetheless, minor amount of ^{3}He is being lost through continental crust when this is under the influence of actual deformations. Transfer mechanism of Helium from mantle to crust can't be understood appropriately yet …" Güleç(1988) mentioned several probabilities for richness of helium such as richness of mantle origin helium where the actual continental crust is under the influence of extensional tectonics. Or mantle origin helium occurred extensively at Western Anatolia and can be correlated with the existence of mantle fluids at bottom of the crust. Or mantle origin helium could be trapped in continental crust where the thermal stability could be gained again in very long period as could be pointed out by Sclater et al (1981). Obviously, richness of matle origin helium at geothermal waters of this region isn't a simple and reliable indicator for Özgür's (2003) rift hypothesis. In short, geological history of Menderes Massive's itself requires sufficient explanation on the excess amount of mantle origin helium at Western Anatolia.

But, it must be reminded of that Özgür (2003) points out that high temperature gradients can warm up the deeply circulated waters at this region is also probable.

2.6 Graben Fills

Another important study is the estimation of young sediment thickness in Aegean Grabens by 2D and 3D modeling of regional gravity data. Results show that there are more than 1,500 m thick deposits at grabens, up to 2,500 m at Büyük Menderes Graben. Another interesting aspect is that variations of these thicknesses along grabens and increase of these thicknesses where the actual grabens are being wider. It is clear that the equal thickness contours are deviating from E-W and turns to NW-SE at these widening zones. For example, there is an inner basin at the east of Aydın and its sedimentary deposition thickness exceed 1,500 m.

3. COOLING HISTORY OF MMM

There isn't a detailed evaluation study on this subject. But, one important question must be answered: "*Is the rising rate of Menderes Massives greater than the rate of cooling?*"

Can rock masses which were in thermal stability appropriate to related depths of crust and rised fastly to shallower depths be cooled with a rate accordant to the rising of MMM? A rock mass situated for instance at 4 km depth 1 million years before, couldn't find sufficient time to cool from 147°C temperature to 81°C temperature which is appropriate for 2 km depths at normal heat flow conditions with a rising speed of 2 mm/year. It is certain that thermal stability at MMM which is already known with its rising about 40 km in 35 million years, might be deteriorated and recovered time by time owing to increasing and decreasing rising rates. This can be understood more clearly under the light of the prediction as that continental crust can obtain its thermal stability only in 10^8 years which was proposed by Sclater et al (1981). Then, there would not be sufficient time for MMM to reach thermal equilibrium.

This fast exhaustion of the upper crust in a relatively short period resulted in a disturbance to the thermal framework of this section. The cooling history fo MMM has been remodeled by thermochronological methods and two main fast cooling phases have been determined.

The cooling model of the lithospheric crust shows that the delayed stabilization of thermal gradient caused a high heat flow in this region. This heat flow is irregularly distributed at MMM.

The most detailed study on this subject was done by Ring et al (2003). Thermochronological data of the Upper Cretaceous to Tertiary nappe accumulation of the Anatolide Belt at Western Anatolia show a two stage cooling history. Authors have used very reliable fission track thermochronology investigations to do this. $^{40}Ar/^{39}Ar$ ages of mica and fission track measurements at apatite and zircon were used together. Then, thermal history of the mineral samples collected actually from surface from 28 My before today (Figure 7).

As can be seen from the figure, todays minerals which are in balance with average atmospheric temperatures at surface, were warmer than 125°C at 28 My ago. Before 22 My Çine Massive has started to cool first; Gördes Massive had joined to this cooling process after 18 My before. Only the southern belt of Salihli-Alaşehir and north of Aydın have remained with temperatures between 65-120°C. South of Salihli saved its temperatures above 100°C through to 2 My before, or a rock grain which is at surface now might be at appropriate depths for 100°C temperatures. Samples from south of Salihli might remain above 300°C temperatures before 5 My, and cooling had been started after this period at footwall of Northern Detachment Fault at Central Menderes Core Complex. This part of MMM cooled most recently.

Authors interpreted these information to model the evolution of MMM and concluded that the cooling pattern at northern and southern sides of it as symmetrical. They concluded that this cooling process has been developed at two stages which were separated with a boundary at 15 My before.

It is obvious that most depleted belt of MMM is the zone between Küçük Menderes Valley and Gediz Graben. Today outcropping rock horizons had been raised to surface fastly and at very recent times. Heat balance at Upper Crust couldn't adapt itself to this fast rise and depletion, and high heat flow conditions persist.

Thus, there isn't any need for a recent volcanic or magmatic activity to explain the high heat flow at MMM.

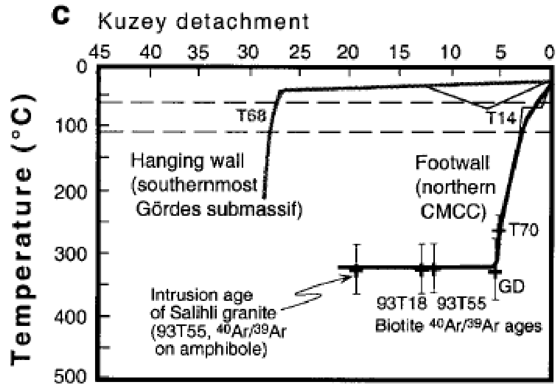

Figure 6: Thermal History At Around North Detachment Fault

4. STRUCTURAL FRAMEWORK AT MMM

In addition to this region's high heat flow, a dense framework of faults with different orientations provide a well developed vertical permeable channel system. This allows fluids to infiltrate to sufficient depths to be charged with a considerable amount of heat by interaction with rocks of this warm upper crust.

Three sets of structural discontinuities existed either at northern or southern part of this core complex region of the MMM. The first set consists of Miocene aged NE-SW and NW-SE trending gravity faults. These graben forming discontinuities generally covered by Upper Miocene to actual sedimentary deposits.

The second and most important structural discontinuity set are detachment faults. Northern and southern detachments outcropped at southern side of Gediz and northern side of Büyük Menderes Graben's. Their average dips are around 20° and fragmentation zones reache up to 120 m.

The E-W trending graben formed gravity faults of actual grabens are most dense and complicated structural discontinuities at the MMM. These grabens are asymmetrical and interpreted as unusual results of extensional tectonics and persistent detachment fault movements. These are listric structures and most of them terminate at related detachment faults. But, main deep ones are located at most inner side of the grabens. These different structural discontinuities provide deep or shallow permeable zones for circulation of geothermal fluids. Especially, intersection zones of above defined structures generally forms best conditions for reservoir formation at MMM.

5. GENERAL CHARACTERISTICS OF GEOTHERMAL SYSTEMS AT MMM

More than fifteen medium-entalphy water-dominated geothermal systems have been found along two E-W oriented long grabens, Gediz and Büyük Menderes Grabens at MMM. These systems occur at the southern side of northern graben and the northern side of the southern graben that are two borders of the mostly exhausted core complex MMM.

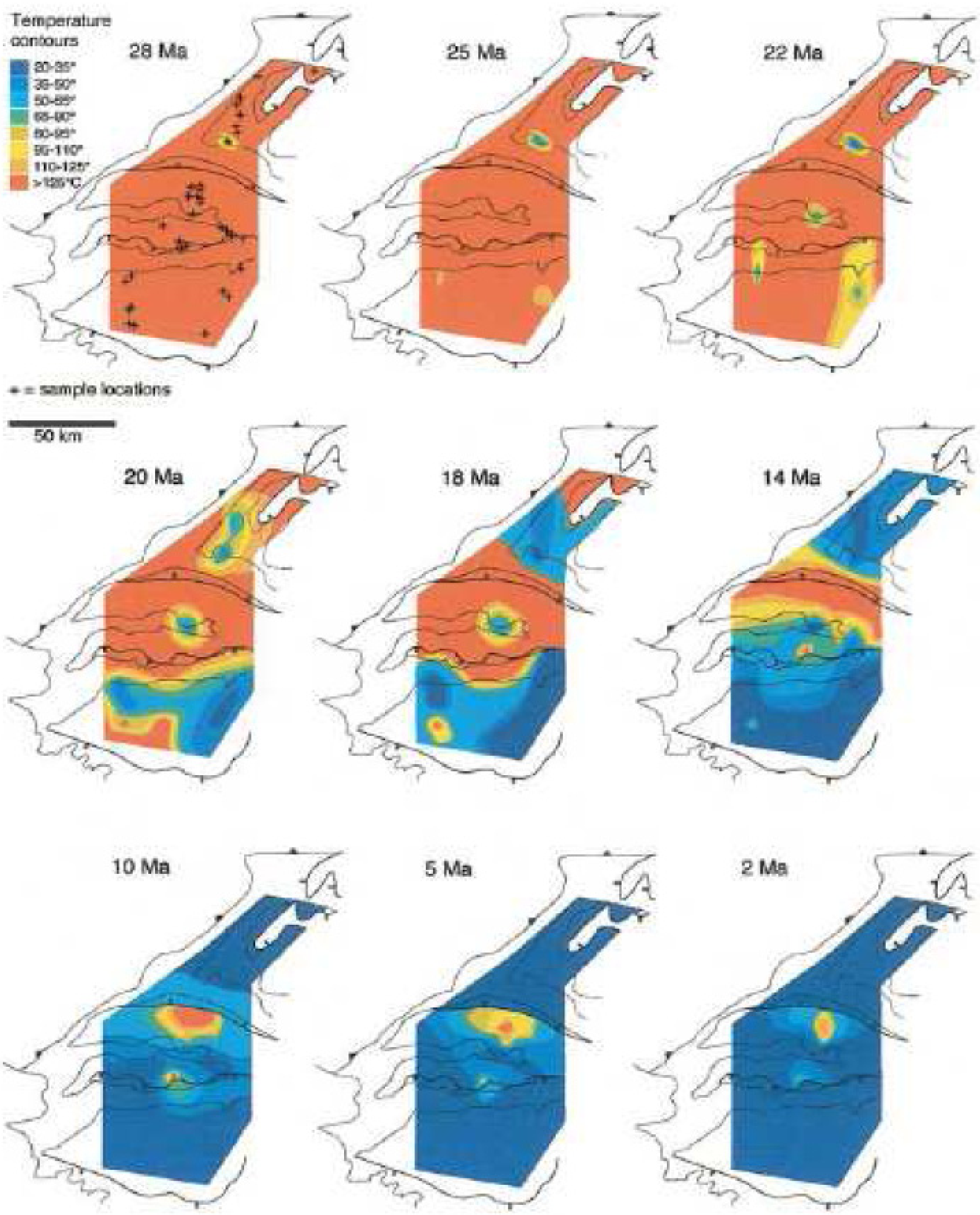

Figure 7: Thermal History of the Menderes Massive Region

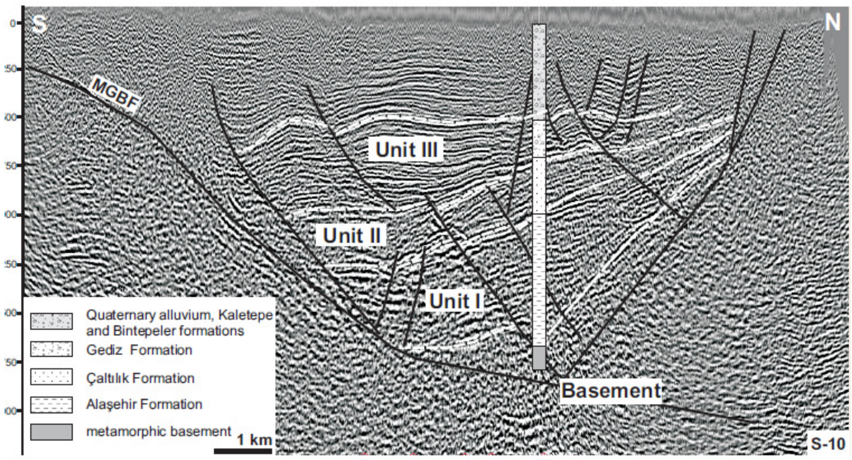

Figure 8: N-S Profile of Gediz Graben (after Çiftçi and Bozkurt, 2009)

Caferbeyli and Kavaklıdere Geothermal Systems at Gediz Graben are partly explored systems and some developing programs currently underway. Upflow zones of these two systems are situated at the middle of the E-W trending graben and located along some deep and steep gravity faults. Upflowing geothermal fluids spread at either in Tertiary sedimentary deposits through to deeper parts of graben or through to shallower southern layers along the detachment fault zone. Some warm water springs, alteration zones and fumerolic relicts are being occurred along a zone where the detachment fault zone intersected with slope surface. Previously, this skew model had been attributed to misinterpretations. But, a proper understanding looks likely to be accepted by most exploration experts. Most of the investigation studies are being conducted at locations where some hidden parts of the systems are expected to be encountered.

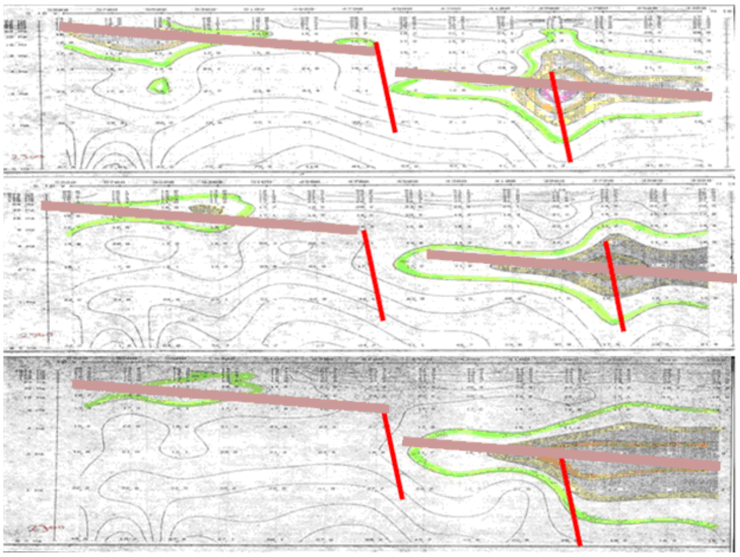

Figure 8: Some CSAMT Anomaly Profiles from Caferbeyli Geothermal Site. An upflowing zone at right (N) and low resistivity zone rising through to left (S) along known Karadut Detachment Fault Zone. Some hot water springs emerge at the southern tip

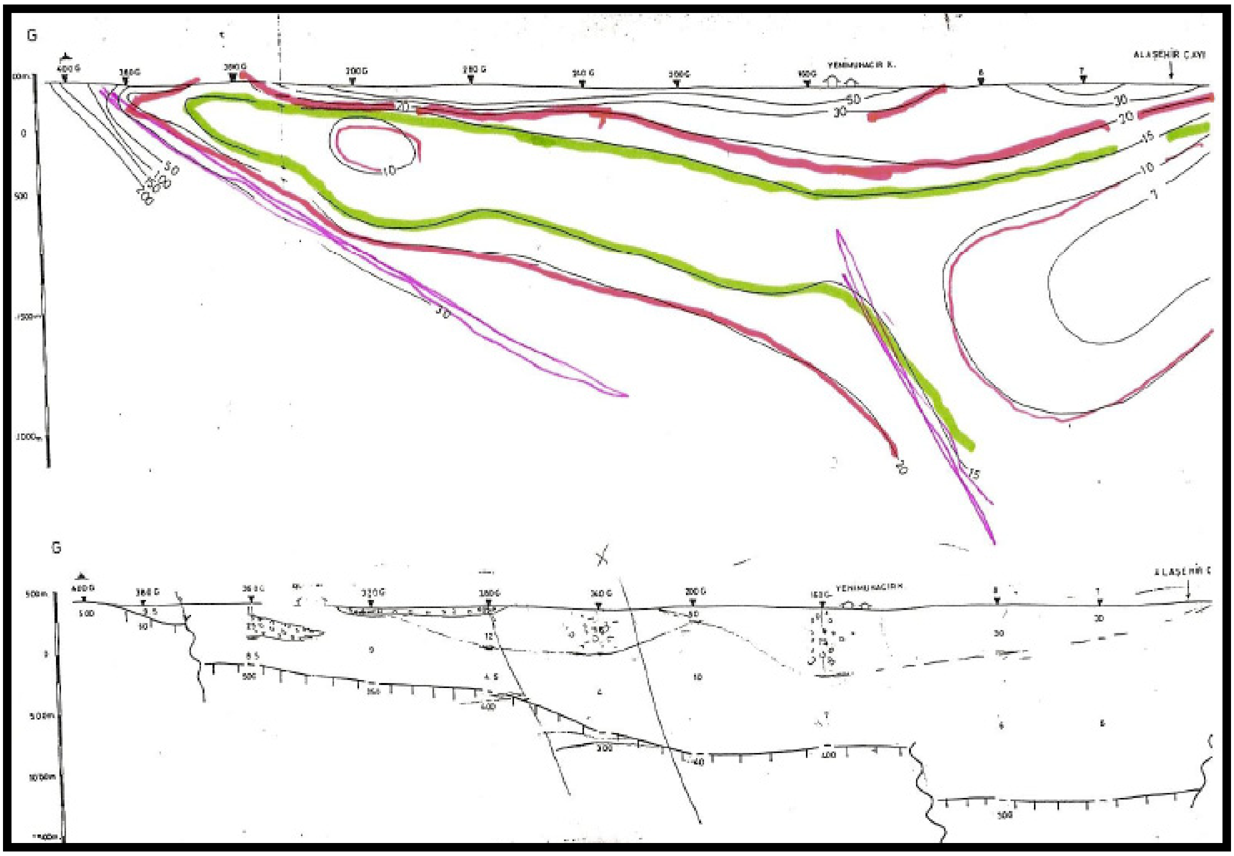

Figure 9: A Resistivity Profile from Kavaklıdere Geothermal Field at Gediz Graben. An upflowing zone at right (N) at the middle of the Graben and low resistivity zone rising through to left (S) along the Detachment Fault Zone

About five prospects are currently being investigated with this concept in mind.

Büyük Menderes Graben has similar characteristics and exploration history. The unique difference is the inversion of directions. Here, asymmetrical semi-graben structures are observed at the northern half of the Graben, in contrast to the Gediz Graben systems. Seven geothermal systems (Germencik, Ömerbeyli, İmamköy, Salavatlı, Sultanhisar, Kızıldere and Sarayköy systems) are in a partially explored state. But even these systems have been developed at their outflowing margins and some development studies are currently being conducted at their hidden upflow zones. Besides these systems, several other similar prospects are being investigated.

Most of these Büyük Menderes Graben sites are located at intersection zones of old NW-SE (Miocene) trending and new (Pliocene to Actual) E-W trending graben faults. Some of these already appear to be related with the Southern Detachment Fault Zone. Conversely, most of the Gediz Graben geothermal systems look likely to belong to the Northern Detachment Fault Zone.

It looks promising to encounter higher reservoir temperatures by following this trend to explore deeper upflow zones of known and predicted systems.

CONCLUSIONS

Menderes Metamorphic Massive, MMM is a very complex structure. Its neotectonic evolution brings a unique thermal history and formation of a high heat flow region. Beside this, overlapping structural discontinuities which were developed by multiphase processes provide a very suitable environment for seepage of ground waters to deeper parts of this high heat flow upper crust along these faults. These faults provide very suitable environments with high secondary permeabilities for rising of overheated fluids to relatively shallow levels.

It is very likely that several new systems will be explored during the following years as well as the fast development of known sites, giving favor of these complicated and well-established concepts related to the evolution of MMM.

This geological, structural and thermal framework also provides a promising prospect for enhanced geothermal field development studies especially at the zone extending between these two graben belts where the mostly exhausted part of the MMM spreads.

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