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Formation characteristics of newly discovered Akçal (Balıkesir) Au-Ag epithermal mineralization in Extensional Tectonics of Biga Peninsula, Western Tethyan Belt

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Research Article

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ABSTRACT

Akçal Au-Ag mineralization is located in one of the most important metallogenic provinces in Tethys Orogenic Belt, Biga Peninsula. In the study area, widespread argillic alteration is observed and mined in previous years. Recent surface exploration and drillhole operation studies indicate that extensional tectonic-related, structurally-controlled Au-Ag mineralization developed parallel along E-W, N55-75E and N30W-trending tectonic zones and NE-SW-trending secondary tectonic zones. Based on field observations and mineralogical-petrographic studies, mineralization was formed in Şapçı volcanics where fluids caused widespread advanced argillic, argillic and propylitic alteration in the study area. Fluid inclusion analyses were performed on transparent-semi-transparent (quartz) crystals in the argillic alteration zone. The primary inclusions consist of two-phase (liquid+gas) inclusions. The homogenization temperature was determined as 190-240°C and the salinity as 0.7-2.7% NaCl in the fluid inclusion measurements. Field observations, mineralogical-petrographic studies, and fluid inclusion data indicate that Au-Ag mineralization occurs in an epithermal system and that the mineralization is not eroded. In west-northwest Anatolia, formation temperature and salinities of the Miocene-aged extensional-related Au-Ag deposits are quite compatible with the formation temperature 190-240°C, 0.7-2.7% NaCl salinity of Akçal Au-Ag deposit. Due to this feature, Akçal mineralization is quite similar to low/medium sulfidation epithermal system deposits.

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1. Introduction

Epithermal gold-silver deposits have been among the important sources of gold and silver production since the first history of mankind. 6 % of the gold and 16 % of the silver produced were obtained from epithermal deposits (Singer, 1995). About 8 % of the world's gold-silver resources are epithermal

deposits (Frimmel, 2008). Epithermal deposits form at shallow depths (~ 2 km) under low-temperature (50-300°C) and low-pressure conditions (<100 atm). For this reason, gold-silver has been produced from epithermal deposits since ancient times until recently (White et al., 1995; Hedenquist et al., 2000; Cooke and Simmons, 2000).

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The Tethyan Orogenic Belt is one of the most mineral-rich metallogenic belts, extending from Europe through Anatolia to Iran and beyond. It formed during Mesozoic and post-Mesozoic times due to the closure of the Tethys Ocean, which once separated the ancient continents of Gondwana and Laurasia (Jankovic, 1997). The belt includes different commodity-bearing various ore deposit types formed in different geodynamic settings (Richards, 2015; 2016).

The Anatolian microcontinent, situated within the Tethyan Orogenic Belt, is among the world's most active tectonic regions. It formed through the collision of Gondwana and Laurasia along their margins (Şengör and Yılmaz, 1981; Şengör, 1984, Figure 1). Anatolia exhibits intense subduction, overthrusting and collision processes, resulting in complex geology and rich mineral diversity.

Located within the Tethys Orogenic Belt (Janković, 1997; Jingwen et al., 2014) or the Tethys Metallogenic

Belt (Yiğit, 2012), Western Anatolia is an important metallogenic province and hosts numerous epithermal, skarn, and porphyry mineral deposits (e.g., Yiğit, 2009, 2012; Bozkaya and Banks, 2015; Kuşcu et al., 2019a, b; Oyman, 2019; Akıska, 2020; Bozkaya et al., 2020; Demirela and Akıska, 2022; Kaya et al., 2023; Gülyüz et al., 2023). Biga Peninsula, one of the most important metallogenic provinces of Asia Minor in Tethyan Orogenic Belt, tectonically forms the western part of the Sakarya Zone at the intersection of Gondwana and Laurasia and contains many epithermal-type deposits. The history of mining in Anatolia dates back to 3200 BC (Strabon, 2000; Abraham et al., 2024).

After the northward closure of the Neotethys Ocean's northern branch, the region experienced collisional and post-collisional crustal thickening along with arc magmatism (Richards, 2009, 2015; Hou et al., 2011; Lu et al., 2015; Chen et al., 2015; Li et al., 2017; Kuşcu et al., 2019a, b). The calc-alkaline magmatism that developed between 52 and 18 Ma in the Cenozoic period in the region has an

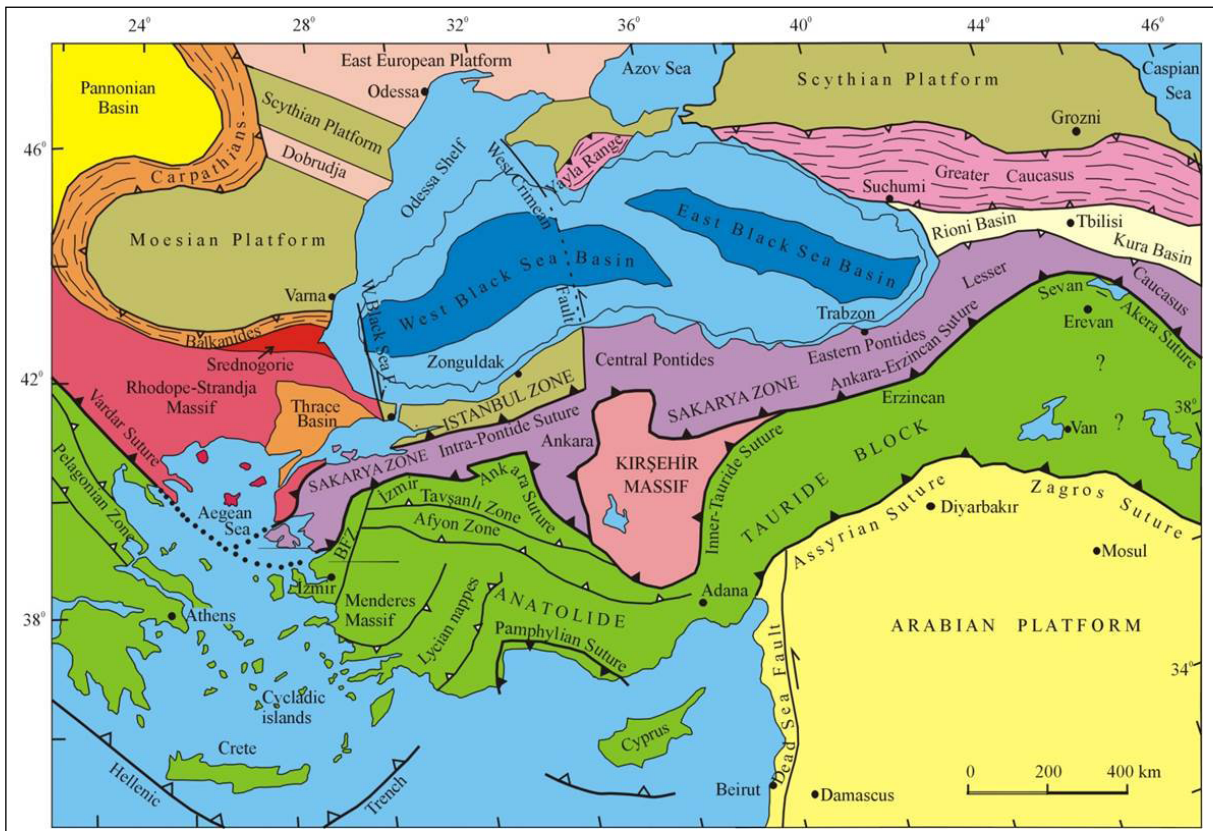


Figure 1- Tectonic map of Türkiye (Okay and Tüysüz, 1999).

ore-bearing (fertile) character similar to other equivalents in the Tethys metallogenic belt (e.g., Richards, 2015; Kuşçu et al., 2019a). West-Northwest Anatolia has been dominated by extensional tectonics since the Middle Miocene (Dewey and Sengör, 1979; Şengör, 1984; Doglioni et al., 2002; Şaroğlu and Güler, 2020 and references therein). Due to the extensional tectonics, many epithermal Au-Ag-Sb-Sb-Hg-Pb-Zn-Cu mineralization systems were formed in the region with E-W, NE-SW and occasionally NW-SE-trending grabens (Figure 2).

The source of the treasures of Troy, which was an important civilisation centre in the Biga Peninsula between 3000-1200 BC, is the Astriya gold mine of a porphyry Cu-Au mineralization (Yıldırım, 2000). Astriya gold mine is known today as Kartaldağ Au mineralization in the Biga Peninsula. In addition, West-Northwest Anatolia has gained importance as a metallogenic region for Au-Ag deposits with the discovery of Ovacık, Kubaşlar and Küçükdere epithermal Au-Ag mineralizations and Karadere Au-Ag and Çatalçam Au-Cu-Pb-Zn-Ag deposits (Çolakoğlu, 2000; Yılmaz et al., 2007; Yiğit, 2012).

Numerous prospects and deposits are known in the region (Figure 2). Considering the rich potential of the region, both the independent mining companies and General Directorate of Mineral Research and Exploration (MTA) have been carrying out intensive exploration and research programmes in recent years.

Akçal mineralization, which is the subject of this study, is located near Akçal Village, northeast of İvrindi District of Balıkesir Province, southeast of the Biga Peninsula in Western Anatolia. The mineralization is associated with parallel NE-SW and E-W trending fault zones located approximately 2 -2.3 km south of the NE-SW trending Balıkesir-Havran Fault zone.

In Western Anatolia, Middle-Upper Miocene aged volcanic and igneous units developed due to extensional tectonics. These units cut Lower Triassic-Upper Miocene aged units formed as a result of crustal thickening (Altunkaynak and Genç, 2008; Genç, et al., 2012; Kayadibi et al., 2023). Hydrothermal Hg-Sb-bearing, brecciated, silicified and argillaceous Au-Ag mineralizations derived from magmatism are widely observed in Western Anatolia.

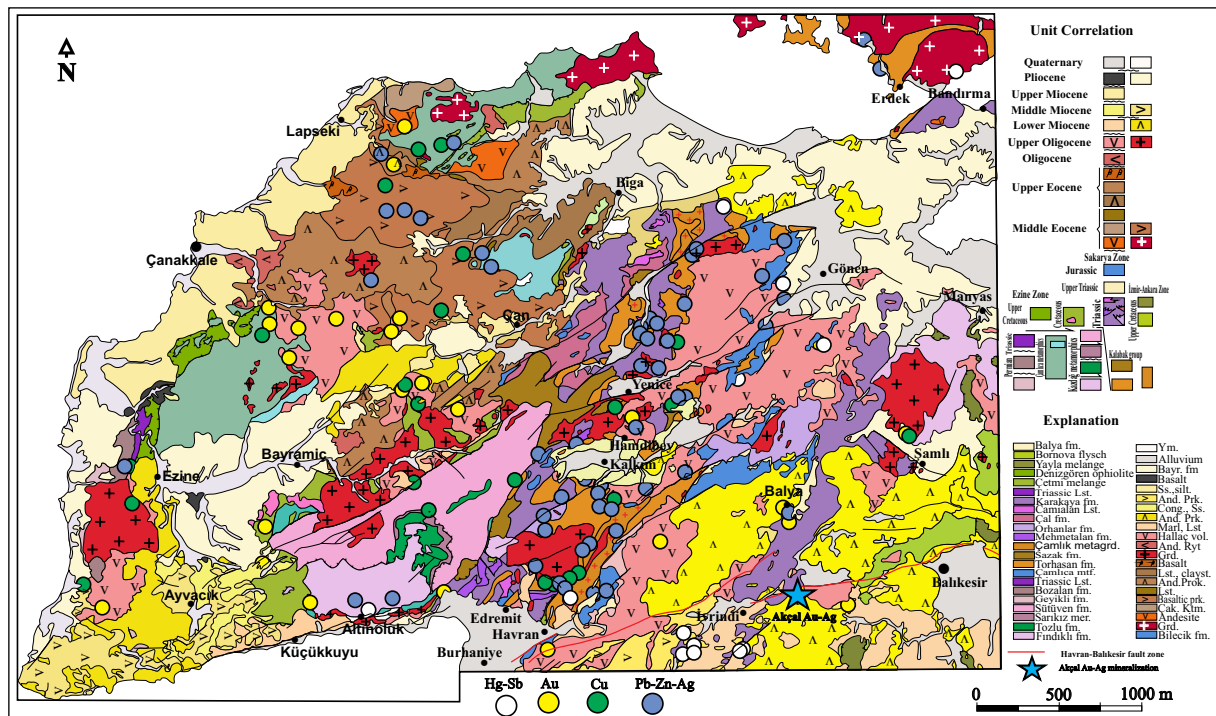


Figure 2- Regional geological map of the study area and its surroundings and the location of Akçal Au-Ag mineralization (modified from Duru et al., 2012).

Drilling operation was also carried out to determine the vertical extension of the mineralization revealed by geological and geochemical exploration studies in Akçal field. Mineralogical and petrographic properties of the host rocks and ore samples, hydrothermal alteration features developed in the host rocks and fluid inclusion studies were carried out to determine the formation conditions. Within the scope of this paper, the properties and formation conditions of the mineralization are discussed by evaluating the findings obtained from mineralogical-petrographic investigation, alteration and fluid inclusion studies.

2. Exploration History

In the Akçal field, intensive argillic (kaoline) zones with an average width of 70-80 m and a length of 1 km are observed parallel to the N55-75E, E-W-trending tectonic zones. In the late 1990s and early 2000s, kaoline production was carried out by an independent mining company by open pit method until 2004. In the following years, it was abandoned due to the depletion of the economic resources. The site was opened for exploration by MAPEG in 2016 and licensed by the MTA. Intensively silicified, brecciated and chalcedonic silica caps and highly argillaceous zones were observed along the tectonic zones determined during the mapping studies of the licence area. The high arsenic and antimony values in the analyses of rock geochemistry samples taken from the identified alteration zones indicate that epithermal mineralization may be present vertically along the tectonic zones and that the system is not eroded. In order to determine the surface extent of the mineralization, a detailed soil geochemistry study was carried out and the surface extension of the mineralization was recognized. Core drilling was planned to determine the vertical extension of the mineralization. As a result of the drilling operation, economically feasible Au-Ag mineralization was determined. Akçal mineralization discovered by MTA was transferred to Türkiye Wealth Fund-Mining Company and named as Güneş project by the company. Lastly, the project is being prepared for operation by Türk Gold Operation Inc.

3. Materials and Methods

As a result of the field studies carried out in the study area since 2016, geology and alteration maps of an area of approximately 2 km² were made and

regular core sampling was carried out by drilling in different directions and inclinations that steeply cut the ore-bearing tectonic zones. Exploration drill studies were conducted in 126 different locations, total 35.000 m drillings. The shallowest drillhole's depth is 113,00 m, the deepest drillhole is 640,00 m. The drill core samples were divided into two equal parts with diamond discs, one of these parts was used for geochemical analysis, mineralogical-petrographic and fluid inclusion analyses and the other half of the core was left in the core boxes as witness samples. The core samples for mineralogical-petrographic and fluid inclusion analyses were firstly macroscopically photographed by examining in detail their relations with the host rocks and ore formations.

Mineralogical and petrographic investigations were carried out at the Mineralogy- Petrography Unit of the MTA using binocular polarised microscopes. The boundary-textural relationships of the host rocks and ore-bearing silica veins were analysed.

The wide distribution of alteration observed in the Akçal field was mapped using a handheld XRF device (spectrometer). In the 1.5 km² area where tectonic zones and alteration are commonly observed in the study area and the mineralization potential is high; a total of 268 samples of 5x10 cm, 10x15 cm etc. were taken from 31 profiles in a N-S direction, with profile intervals of 50 m and sample intervals of 100 m. Typical alteration minerals were quickly identified from both field samples, hand samples and drill cores. Minerals were identified by comparing the spectrum ranges read from the samples with the mineral data in the library loaded into the device memory. Alteration minerals were determined by taking at least three readings from different points on the clean surfaces with Terrespec Holo spectrometer. Based on the table prepared by Corbett and Leach (1998), according to the determined alteration minerals.

Fluid inclusion analyses were carried out at the MTA - Mineralogy - Petrography Laboratory. Two-sided polished fluid inclusion sections were prepared for analysis. Analyses were performed with LINKAM MDS-600 (motorised) cooling and heating systems mounted on a Leica DM 2500 M microscope.

Final melting ($T_{m_{ICE}}$) and homogenisation temperature (TH) values of the samples and salinity and density measurements were carried out according to these values, and the margin of error in all measurements was less than 0.4°C.

4. Geological Setting

The Biga Peninsula, the northwestern end of the Anatolian plate, lies at the westernmost part of the Sakarya Zone. The region is a mosaic of continental fragments with different geological background that came together along the İzmir-Ankara-Erzincan Suture Zone (İAESZ) with the closure of the Neotethys Ocean (Figure 1). The Anatolide-Tauride Belt of Gondwana lies to the south of the margin and the Sakarya Zone to the north (Figure 1). Most of the region consists of volcanic, sub-volcanic and plutonic rocks associated with core complexes (Okay, 1989; Keskin et al., 2008; Parlak et al., 2012; Göçmengil et al., 2018; Aydın et al., 2019; Sarı et al., 2021; Robertson et al., 2023; Yılmaz and Yiğitbaş, 2023; Kayadibi et al., 2023).

Pre-Tertiary units in the region include; Menderes Massif and İzmir-Ankara Zone in the south and east, Sakarya Zone and Rhodope-Istranca Massif in the north and west (Figure 2). The Sakarya Zone, exposed near the study area, is characterized by high-grade metamorphic rocks (amphibolite-granulite facies) that are exposed in massifs such as Kazdağ and Uludağ. These massifs are basement rocks of the Sakarya Zone and are associated with the Kalabak Group, which has undergone greenschist-blueschist facies metamorphism. Additionally, Late Carboniferous-Permian-aged arkosic and carbonate rocks overlie these metamorphic units. The Late Permian-Triassic-aged Karakaya Complex, situated above, is unconformably overlain by Late Triassic to Eocene-aged units (Duru et al., 2012; Koçyiğit, 2023).

The Biga Peninsula and its south, including the study area, were subjected to compressional deformation during the Late Cretaceous-Eocene and Oligo-Miocene, extensional deformation during the Lower-Middle Miocene, and deformation dominated by strike-slip faults during the Neotectonic period (Yılmaz et al., 2001; Duru et al., 2012; Koçyiğit, 2023). Among the volcanic assemblages in the region,

Eocene aged volcanic units exhibit compositions ranging from basalt to trachyte/dacite, while Oligocene aged volcanic rocks are composed of andesite, trachyandesite, basaltic trachy-andesite, basaltic andesite and dacite (Genç et al., 2012). The Lower-Middle Miocene aged volcanics exhibit the same composition as in the Oligocene, while the Upper Miocene aged mafic lavas are represented by basalts.

The first igneous phase in the region developed in the post-collisional Eocene period and is the product of arc magmatism. The igneous rocks, with ages ranging from 45.3 ± 0.9 - 38.1 ± 1.8 Ma, vary in character from basalt to dacite (Altunkaynak and Genç, 2008). Eocene Granitoids are intruded into the basement units of Sakarya Zone and their sub-volcanic and volcanic equivalents are also observed. The region was territorialised in the Oligocene period and igneous activity continued intensively. This phase, which is widespread throughout the region, is characterised by mantle-derived arc magmatism contaminated with crust (Yılmaz et al., 2001). The igneous bodies, which also have sub-volcanic and volcanic equivalents, are generally NW- SE trending. The volcanic rocks in the region are divided into different formations based on their lithological and geochronological characteristics (Genç et al., 2012).

Oligo-Miocene igneous phase is ore-bearing and igneous rocks of this age are the target rocks for mineral exploration. Hallaçlar Volcanics, which is one of the important units especially for mineral exploration, contains advanced argillization and intensive silicification in places, and it contains exhalative Fe and high sulphide gold mineralization.

In the region covering the Biga Peninsula and its south, an intense volcanic activity is observed simultaneously with the lacustrine sediments during the Lower-Middle Miocene period. The volcanics, which are generally composed of andesite, trachyandesite, trachyte, latite, basaltic andesite type lavas and pyroclastics, are named as Ezine Volcanics, Şapçı Volcanics and Yürekli Dacite according to their origin (Genç et al., 2012). Şapçı volcanics (21.2 ± 0.9 Ma; Dönmez et al., 2005) consists of white coloured thick felsic tuffs with ignimbritic units at the base, followed

by acidic lavas and pyroclastics and andesitic, basaltic andesitic lavas and pyroclastics which constitute the last stages of volcanism. Yürekli dacite consists of felsic lava and pyroclastics and is observed in succession with lacustrine sediments. Yuntdağ volcanics consists of andesitic lava and pyroclastics. These units are accompanied by Hüseyinfakı Volcanics and Arıklı İğnimbrite consisting of basaltic and trachyandesitic lava and pyroclastics; Ayvacık Volcanics, Babadere Dacite, Işıkeli Rhyolite and Çamkabalak İğnimbrite, which start with pumice-containing, ignimbritic tuffs in places and dominated by basaltic andesite and andesitic pyroclastics (Genç et al., 2012). The last igneous phase in the region occurred in the Late Miocene (11.0 ± 0.4 - 8.32 ± 0.19 Ma) and it is dominant in terms of alkaline igneous activity where mafic rocks are generally formed (Altunkaynak and Genç, 2008; Figure 2).

The Lower Triassic aged Karakaya Complex, are exposed in large areas in the north-northeast and south-southwestern surroundings of the study area. While the Lower Miocene aged Şapçı volcanics covers large areas, Quaternary aged slope debris and alluvium in

stream beds are observed in a narrow area (Figure 3, 4). The Soma Formation, consisting of Lower Miocene aged terrestrial sedimentary units, which is not exposed on the surface and defined as lateral/vertical transition with Şapçı volcanics, was identified by drilling studies (Sarı et al., 2021) (Figures 3, 4).

4.1. Karakaya Complex

The Karakaya complex (Figure 3), exposed in large areas in the north-northeast and south-southwest of the study area, generally consists of grey-brown colored sandstone, metaquartz, shale, mudstone, metaconglomerate, mafic volcanics and Permo-Carboniferous aged limestone blocks of different sizes (Okay and Göncüoğlu, 2004; Duru et al., 2012). The lithologies within the unit, which does not show a regular lithologic succession, are transitional and/or blocky in lateral and vertical directions. The unit was affected by different intensive tectonic deformation. While primary sedimentary features are well preserved in some areas, blocking and low-grade metamorphism effects are observed in areas heavily affected by tectonic deformation (Tetiker et al., 2015).

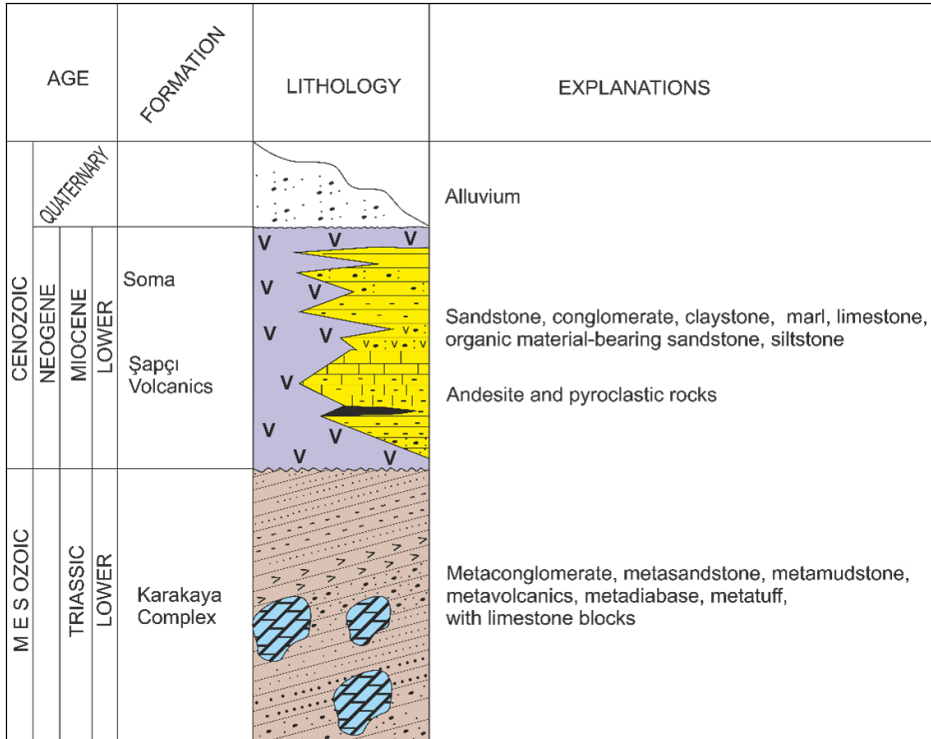


Figure 3- Stratigraphic section of the study area and its surroundings (Sarı et al., 2021).

4.2. Şapçı Volcanics

The unit consisting of white coloured thick felsic tuffs with ignimbritic features at the base, followed by felsic lavas and pyroclastics and andesitic lavas and pyroclastics forming the last stages of volcanism is named as Şapçı volcanics (Dönmez et al., 2005). The volcanism spreads over large areas between Büyükşapçı, Küçükşapçı (Balıkesir) villages and Balya (Balıkesir) district and around İbirlir and Soğucak-Savaştepe district south of Balıkesir (Pehlivan et al., 2007). Şapçı Volcanics outcrop in a large area in the vicinity of the study area (Figure 4).

The fresh andesitic lavas exhibit a porphyritic texture with plagioclase phenocrysts and a colour transition from purple to greenish. Feldspars are partially bleached, amphibole-biotites are opacitized, hematized, chloritized and glassy is observed as

silicified and hematized in places (Figure 5). In areas where tectonic zones are active, it is observed as cream-gray, clayey, pyrite and limonite-hematite, altered andesite with brecciated veins, altered basaltic andesite, altered pyroclastic rocks and altered tuff. Genç et al. (2012) defined the first stage products of Şapçı volcanics as rhyodacite and the last stage products as andesite.

Petrographic examination of the lithic crystalline tuff sample revealed that it is composed of clastic textured, medium-small plagioclase phenocrysts, heterogeneously distributed small quartz, hornblende and biotite crystals, small-medium sized rock fragments consisting of completely carbonated, sericitised minerals, very fine-grained volcanic ash, possible devitrified volcanic glass in places, secondary and opaque minerals such as micro-crystallised sericite, silica and clay. Carbonatization,

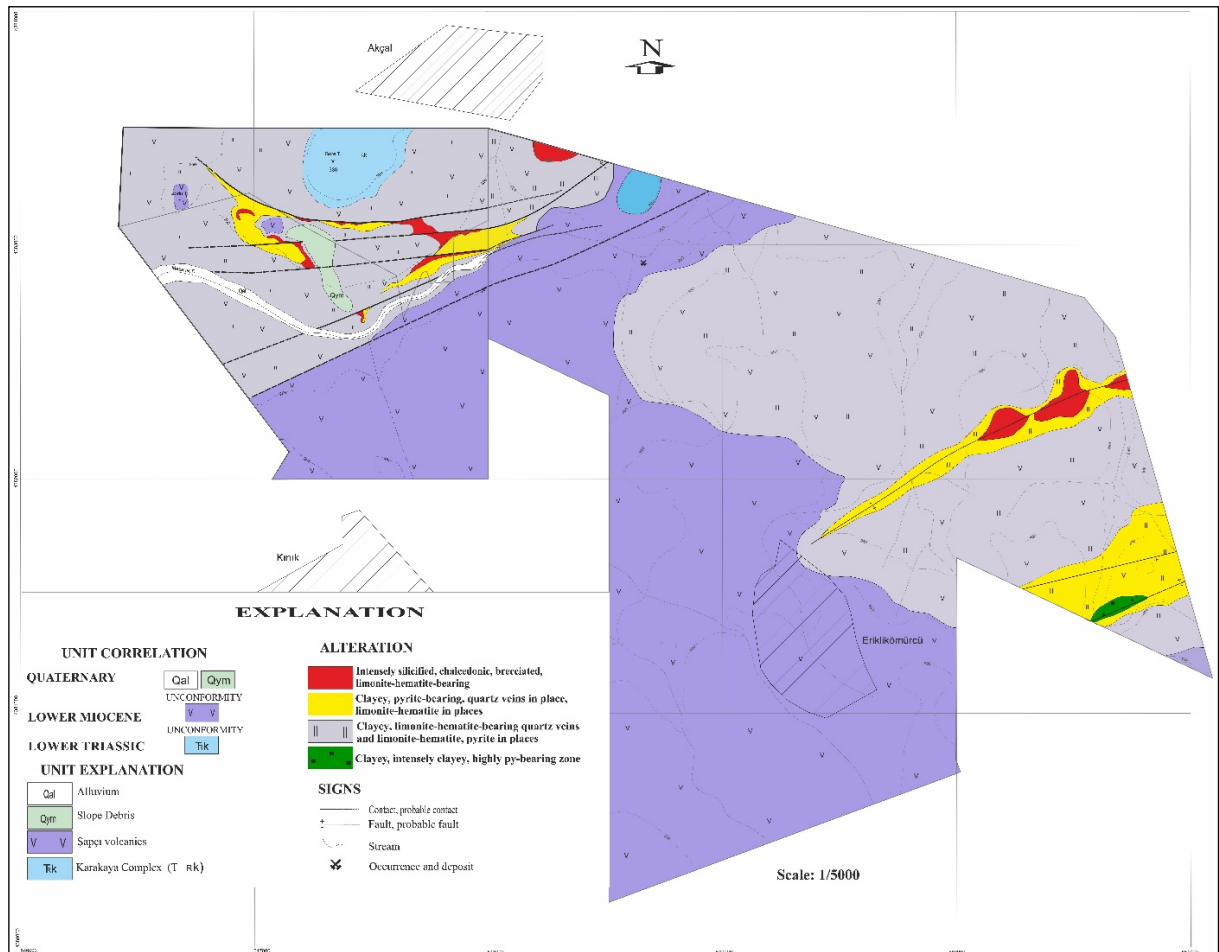


Figure 4- Geological map of the study area (Sarı et al., 2021).



Figure 5- a) General, b) close-up view of andesitic lavas belonging to the Şapçı volcanics in the borehole and highway cut in south of Domuz Hill (X: 4383065, Y: 548359).

silicification, sericitization, chloritisation, argillaceous and opacification are observed throughout the rock (Figure 6).

Petrographic examination of the sample taken from the drill core shows porphyritic texture, small-large crystalline, euhedral to semi-euhedral, polysynthetic twinning, homogeneously distributed

feldspar group (plagioclase) minerals, small-medium crystalline, euhedral-semi-euhedral, homogeneously distributed, free and fused crystals of amphibole-biotite, secondarily apatite mineral, cryptocrystalline textured possible volcanic ash and secondary minerals. Carbonatization, silicification, opalization, chloritization, sericitization and argillization are observed throughout the rock (Figure 7).

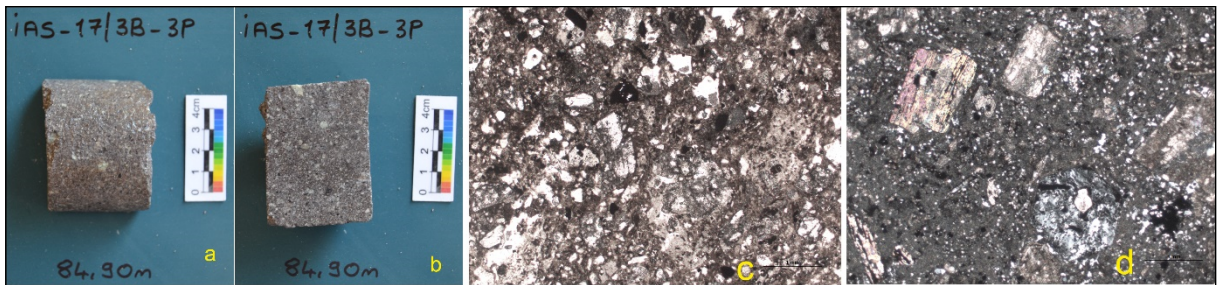


Figure 6- a, b) Macroscopic and c, d) microscopic (c: parallel nichol, d: crossed nichol) view of the petrographic sample of Lithic Crystalline Tuff unit taken from the borehole.

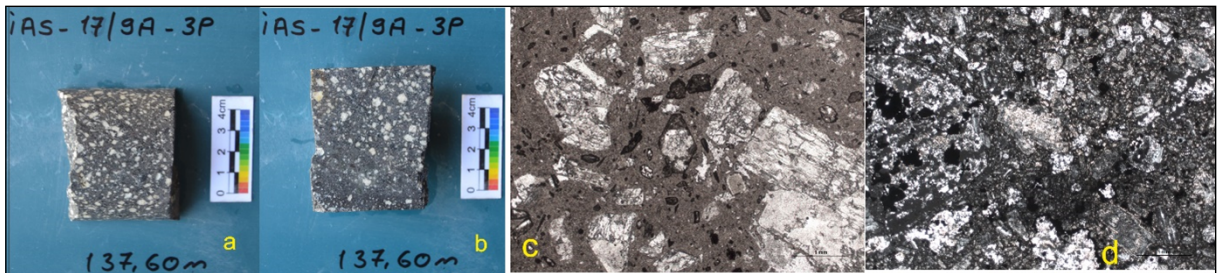


Figure 7- a, b) Macroscopic and c, d) microscopic (c: parallel nichol, d: crossed nichol) view of the petrographic sample of andesite taken from the drill core.

Petrographic examination of the sample taken from the cores belonging to a different drillholes revealed that the rock fragments (volcanic, possible pyroclastic) consist of fine-medium crystals, quartz, feldspar group (plagioclase), biotite and zircon crystals in places. The rock fragments are medium to coarse grained, semi-angular and semi-rounded grained, and pyroclastic rock fragments with flowing texture in the fine grains are also observed. Clayey and many carbonate veins of different thicknesses are observed in places in the rock.

As a result of whole rock and mineral chemistry studies by Aslan et al. (2017), it was determined that Şapçı volcanics are the product of volcanism that developed in the post-collision period. The average crystallisation pressure was calculated as 3.3-4.8 kbar according to the hornblende barometer, and the average temperature was calculated as 903-930°C according to hornblende-plagioclase and Ti-hornblende thermometric data. Temperature, pressure and oxygen fugacity ($\log fO_2$) values for biotite were calculated as 755-788°C, 1.30-1.74 kbar and -14.88-13.98, respectively. Based on these results, the depth of crystallisation was determined as 12-17 km for hornblende and 4.5-6.5 km for biotite.

Dönmez et al. (2005) obtained a whole rock K/Ar age of 21.2 ± 0.9 Ma from a sample taken from the vicinity of Gökçeler village in the north of Balıkesir, while Aslan et al. (2017) determined U-Pb zircon ages

of 22.72 ± 0.19 , 22.97 ± 0.23 and 18.72 ± 0.17 Ma (Early Miocene). According to these data, volcanism was active in the Lower Miocene. The unit is equivalent part of the Hallaçlar formation defined by Krushensky (1976) (Dönmez et al., 2005).

4.3. Soma Formation

The Soma Formation consists of clayey limestone, clay, marl, siltstone, tuffite, sandstone, conglomerate succession or rock types dominated by one or more of these lithologies. It is generally white, yellow, grey, horizontal or nearly horizontal and thin-medium-thickly stratified. It is volcanoclastic in appearance with sandstone, siltstone and pebble with volcanic material in places. It has undergone brittle deformation along tectonic zones. Soma Formation contains lignite formations in various places. (Figure 8).

The unit, which was not observed on the surface in the study area, was detected in drilling works. The claystone, marl levels of the Soma Formation, which consists of grey, dark grey, brown coloured altered andesite, altered tuff and altered pyroclastic rocks and laterally/vertically intercalated with disseminated pyrite±chalcopyrite-bearing claystone, siltstone, sandstone, pebbles, volcanogenic sandstone, siltstone and volcanoclastics, contain bituminous and lignite in places. Petrographic examination of the volcanoclastic units revealed that they are composed of quartz, opaque minerals, small-medium grained



Figure 8- Image of the Soma Formation with claystone, marl and limestone succession in the road cut at the entrance of Ivrendi (X: 4382574, Y: 542104).

rounded volcanic rock fragments, all crystals except quartz are completely carbonated, most of the rock is fine grained and probably consists of volcanic ash (Figure 9).

4.4. Slope Debris

It consists of grey, cream and light brown coloured, clayey in places and abundant sand, gravel and Permian aged, crystallised limestone blocks. It is exposed between Güre Tepe and Mezarlık Dere (X: 4382725, Y: 547313) in the study area (Figures 4, 10).

4.5. Alluvium

It consists of andesite, Permian aged, crystallised limestone pebbles and blocks of brecciated, locally limonite-hematite, and intensely silicified rock pebbles and blocks in sand, silt, clay alluvium in the Mezarlık Stream bed and flood plains within the study area (Figure 4).

5. Tectonism

In the Biga Peninsula, pre-Tertiary rocks are surfaced within tectonic zones that are tectonically

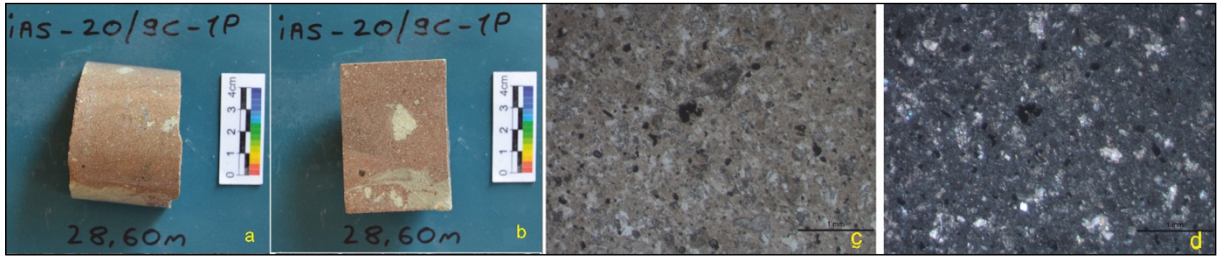


Figure 9- a, b) Macroscopic and c, d) microscopic (c: parallel nichol, d: crossed nichol) views of the Soma Formation volcanoclastic unit petrography sample taken from the drill core.



Figure 10- Slope debris consists of sand, silt, gravel and block-sized Permian aged limestone (X: 4382725, Y: 547313).

related to each other and extend along the NE-SW direction and were distinguished by Okay et al. (1990) and Duru et al. (2012). These tectonic zones consist of İzmir-Ankara Zone, Sakarya Zone, Çetmi Melange and Ezine Zone from east to west. Tectonic structures belonging to Pre-Alpine, Early Alpine, Cretaceous-Paleocene, Neo-Tectonic periods can be observed within these tectonic units that came together in the pre-Eocene period.

The tectonic events and related structures in the Sakarya Zone in which the study area is located are Upper Palaeozoic, Triassic, Upper Cretaceous-Eocene and Upper Tertiary in age. Upper Palaeozoic structures affected the Kazdağ Massif and Kalabak group. The rocks forming the Kazdağ Massif underwent high-grade metamorphism between the Middle Carboniferous and Lower Triassic and were tectonically settled before the Lower Triassic (Duru et al., 2012). The fact that the linear structures (fold axis, mineral lineation, etc.) developed in the Kazdağ metamorphics in the N-S direction is accepted as structures of the Hercinian period (Schuiling, 1959).

The most widespread deformation structures on the Sakarya Zone affected the Karakaya complex during the Triassic period. Although the units constituting the Karakaya complex are primordial transitional with each other, they are often seen as tectonically interconnected and strongly deformed. These tectonic joints show a chaotic structure in the form of a *mélange* in which the units forming the Karakaya complex are located as mega blocks within each other rather than a regular fault system. In the vicinity of the study area, Permian aged crystallised mega limestone blocks are seen along the hills. During the Upper Cretaceous-Eocene period, the Biga Peninsula was under the influence of the compressional regime simultaneously with the settlement of the Çetmi *Mélange* in the north of the Sakarya Zone and the ophiolitic rocks of the İzmir-Ankara Zone in the south on the Sakarya Zone and Ezine Zone (Duru et al., 2012). During the Eocene-Lower Miocene interval when the compressional regime was active, arc magmatism developed due to subduction (Altunkaynak and Dilek, 2006; Koçyiğit, 2023).

In the central and southern part of the Biga Peninsula and around the Kozak Massif, during the Oligo-Miocene period, along with the compressional regime, the extensional regime also started with the effect of tensile forces; granitic intrusions and calc-alkaline volcanism associated with arc magmatism was developed. When the tectonic environment discrimination diagrams of the samples taken from igneous rocks by Engin et al. (2000) were analysed, it was observed that the samples were concentrated in the region represented by arc granitoids but oriented towards the post-collision granitoids. With the extensional regime, the region started to rise in the form of horst-graben. During this period, older units and granitic intrusions were uplifted along the low-angle normal faults (detachment faults), while lacustrine sedimentary environments were formed around Çan, Kalkım, Ayvacık, Havran, Burhaniye, İvrindi, Balya, Gönen, Susurluk, Balıkesir, Savaştepe, Bergama and Soma. During the Oligo-Miocene period, the strike-slip normal faults reactivated as right-lateral strike-slip faults during the Plio-Quaternary period (Duru et al., 2012; Koçyiğit, 2023).

Active right-lateral strike-slip faults developed during the Plio-Quaternary period in the Biga Peninsula, namely: Biga-Çan Fault Zone, Edincik Fault, Evciler Fault, Edremit Fault Zone, Gündoğan Fault, Havran-Balıkesir Fault Zone, Karabiga Fault, Kestanbol Fault, Karacabey Fault, Manyas Fault, Mustafakemal Pasha Fault, Pazarköy Fault, Sarıköy Fault, Sinekci Fault and Yenice-Gönen Fault have been transformed into strike-slip faults by utilising the NE-SW trending faults developed in previous periods (Duru et al., 2012; Koçyiğit, 2023).

Ore-bearing hydrothermal fluids in the study area moved along the E-W, N55-75E and N30W trending faults. These faults are located within the Havran-Balıkesir Fault zone (Figure 2).

6. Alteration

Wide distributed clay alteration is observed in the Akçal field. Along the parallel E-W, N55-75E and N30W and NE-SW trending fault zones in the study area, chalcedonic siliceous zones (silica caps) with brecciated, filled with limonite-hematite in places, with fine quartz crystal growth in places are observed

(Figure 11c). These intensively silicified zones are interbedded with propylitic zones defined as highly kaolinized, limonitized-hematitized (Figure 11a, b), marcasite-pyrite-bearing and chloritized, rarely epidotized-carbonatized silica veins/veinlets.

As result of surface study, advanced argillic zone consisting of illite, smectite, K-illite, Mg-

illite, kaolinite minerals, Argillic zone consisting of illite, smectite group (beidellite, montmorillonite, nontronite, vermiculite, halloysite, kaolinite) minerals and Propylitic zone consisting of chlorite, epidote, calcite/dolomite, albite/adularia minerals. Alteration map of the study area was prepared considering these alteration zones (Figure 12).



Figure 11- a-b) Appearance of silica caps within the highly kaolinized zone containing limonite-hematite, brecciated, pyrite, chalcedonic silica, c) Close-up view of silica caps (a, b; X: 4383014, Y: 547087, c; X: 4382899, Y: 547722).

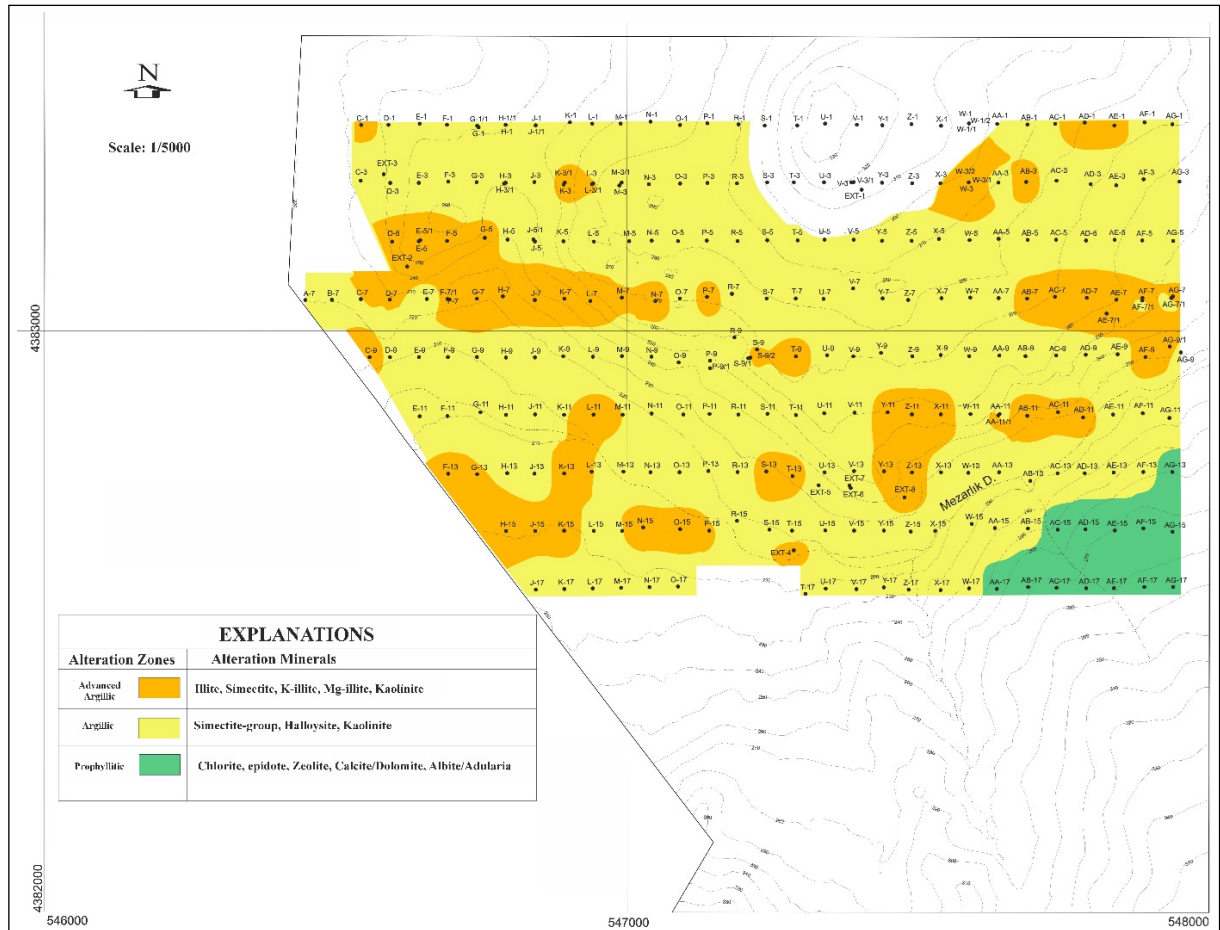


Figure 12- Alteration map of study area (1/2000).

Alteration minerals were also identified during a detailed examination of the drill cores. In order to confirm the identified alteration minerals by spectrometry and to detect the alteration minerals that could not be identified macroscopically; alteration minerals were determined by taking at least one reading from each metre of the drilling cores where alteration changes were best observed, or two and three readings when necessary (for further details Uçar et al., 2024).

The alteration minerals are based on the table prepared by Corbett and Leach (1998) as follows; argillic zone consisting of halloysite, smectite group, kaolinite, dickite±illite-smectite±Mg/K-illite minerals and advanced argillic zone consisting of illite-smectite, illite, kaolinite, alunite, dickite, halloysite, smectite group, jarosite minerals. Vertical alteration zones were determined in the boreholes where alteration minerals were recognised (Figure 13).

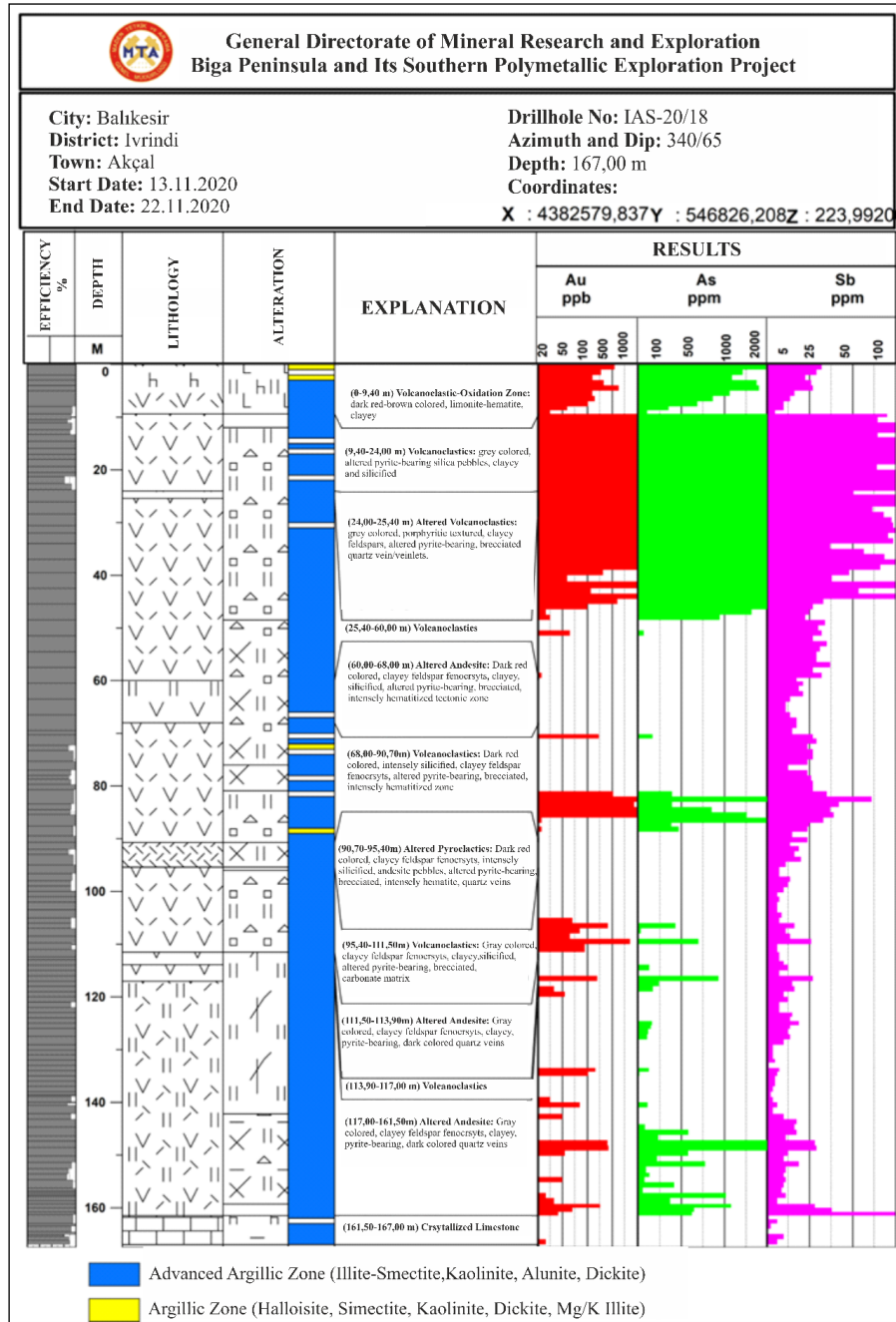


Figure 13- Vertical alteration zonation of borehole IAS-20/18.

7. Mineralization

The Au-Ag mineralization in the Akçal study area was developed parallel along E-W, N55-75E and N30W-trending tectonic zones and NE-SW-trending secondary tectonic zones intersecting the Lower Triassic Karakaya Complex, the Lower Miocene Şapçı Volcanics and the lateral and vertical transitional lacustrine Soma Formation. In the eastern side of study area, mineralization starts from surface (0.00 m) and continues up to 350.00 m along the brittlely deformed, brecciated NE striking fault zone. In the western side of the study area, mineralization starts from surface (0.00 m) up to 100.00 m along the E-W striking fault zone. Ore is formed in brittlely deformed, highly silicified, brecciated zones developed along the parallel fault zones (Figure 14). In Akçal study area, highly silicified sinter, hydrothermal breccia, banded, colloform and cocard textured quartz

vein-veinlets, locally chalcedonic silica and clayey (kaolinitic) N75-85E striking tectonic zones have been identified (Figure 15; Uçar et al., 2024). The intensely silicified zones are found as lenses within the tectonic zones in the E-W, N55-75E and N30W directions between Doruk Tepe and Mezarlık Dere in the mineralization area (Figure 14; Sarı et al., 2019). Disseminated, fine-crystalline pyrite, marcasite and antimony, pyrite, galena and sphalerite are observed in gray-dark gray quartz stockworks in tectonic zones. Gold up to 37.8 ppm was also precipitated in quartz and quartz+carbonate veins/veinlets in disseminated marcasite-pyrite-bearing brecciated zones (Figures 14 and 15). As a result of hydrothermal fluid circulation along the fractures, illite, smectite, K-illite, Mg-illite, kaolinite-containing advanced argillic and beidellite, montmorillonite, nontronite, vermiculite and halloysite, kaolinite-containing argillic alteration zones are formed.

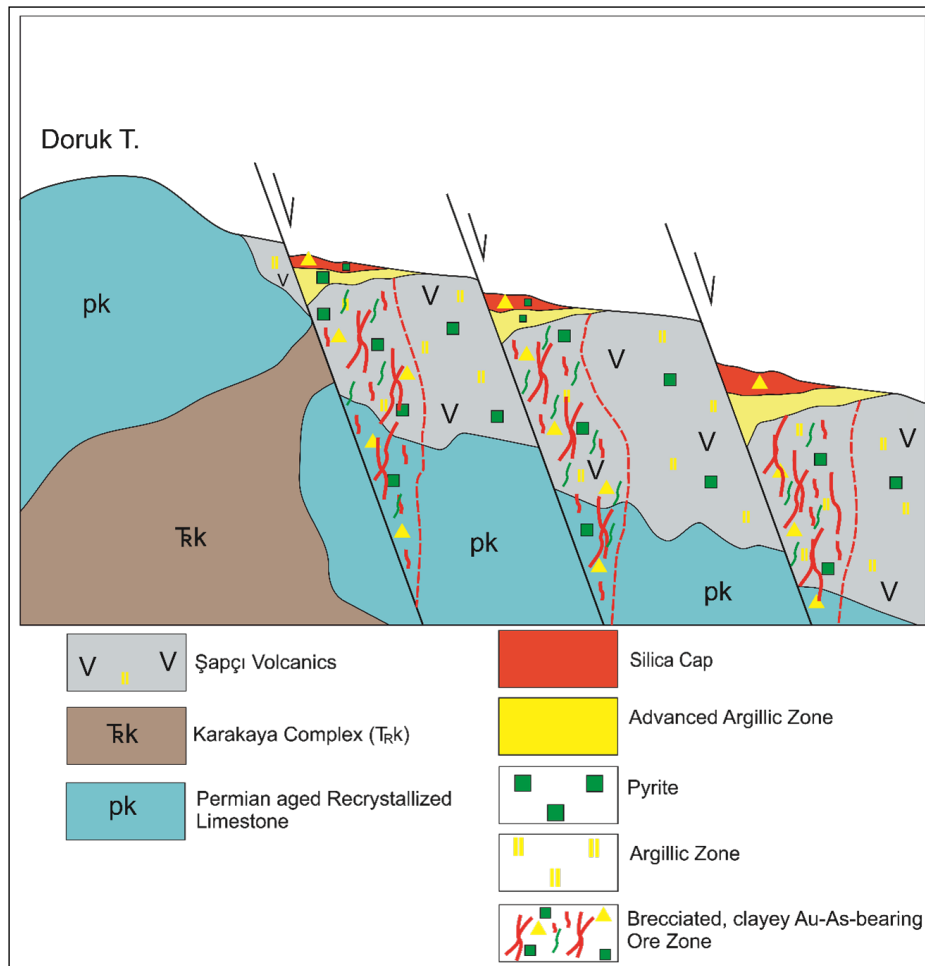


Figure 14- Possible mineralization model of Akçal field.

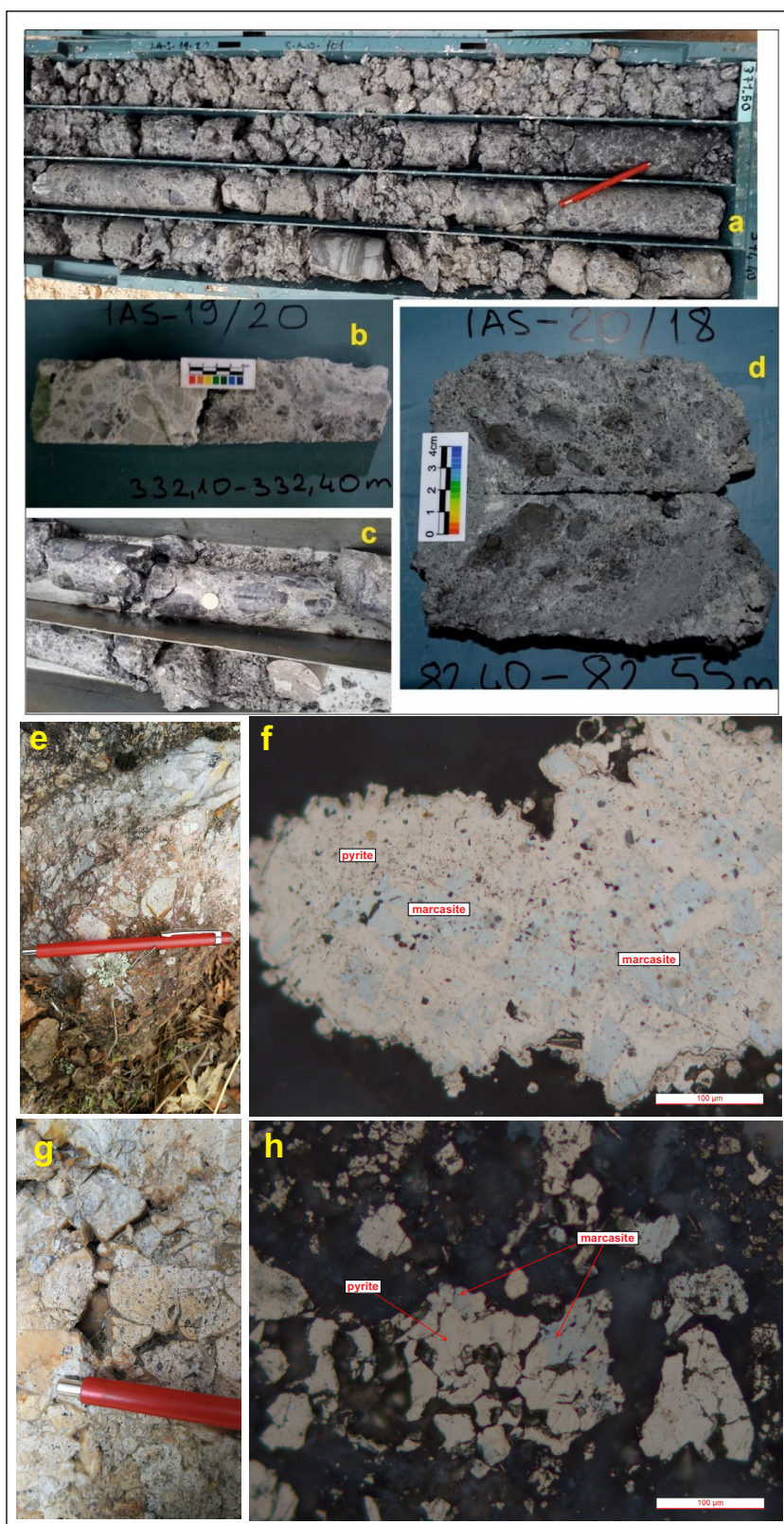


Figure 15- a-d) Brecciated, intensely silicified, clayey ore zones observed in drill cores (X: 4382893, Y: 547699), e) outcrop view of silicified, brecciated volcanic unit, f) microscope view of marcasite and pyrite minerals with colloform texture in polished section, g) outcrop view of silicified, brecciated and colloform textured unit, h) microscope view of hydrothermal pyrite and marcasite minerals in polished section.

8. Fluid Inclusion Data

Fluid inclusion petrography analyses were carried out on the sample belonging to the argillic alteration zone selected from the drill cores (Figure 16a). A total of 48 fluid inclusion analyses, including 38 homogenization temperature and 10 salinity values, were performed on each sample.

The sample generally consists of transparent-semi-transparent and occasionally isotropic sections. In the transparent-semi-transparent (quartz) crystals observed in the sample, inclusions of primary and less abundant secondary origin were found. The

primary inclusions consist of two-phase (liquid+gas) inclusions and single-phase (liquid) and single-phase (gas) inclusions.

Two-phase (liquid+gas) inclusions of primary origin are generally lenticular, triangular, round/ellipsoidal and irregularly shaped with dimensions <2-80.8 micrometres; single-phase (liquid) inclusions are round/ellipsoidal, rectangular and irregularly shaped with dimensions <1-10.5 micrometres; and single-phase (gas) inclusions are round/ellipsoidal with dimensions <1-11.9 micrometres (Figure 16 b, c, d, e).

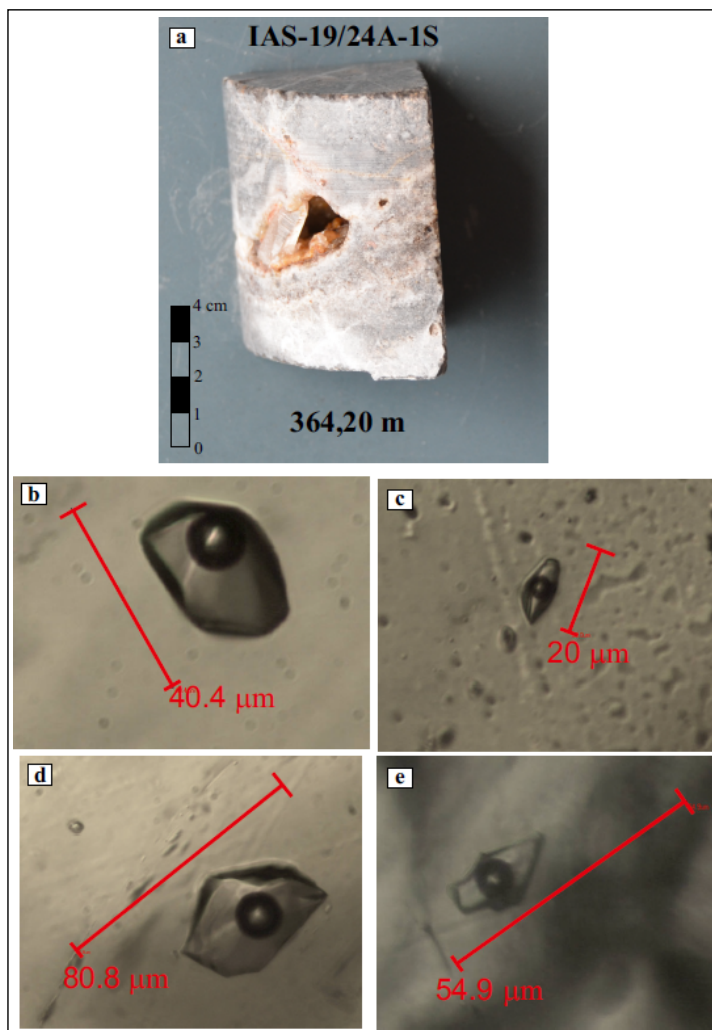


Figure 16- a) macro and b-e) micro view of the sample taken for fluid inclusion measurements from the drill core of Akçal mineralization. Different types of inclusions determined in quartz minerals to which liquid inclusion measurements are applied, a) two-phase inclusion, b) single-phase inclusion, c) liquid-rich two-phase inclusions, d) gas-rich two-phase inclusions.

Inclusions of secondary origin are lenticular, round/ellipsoidal, rectangular and irregular in shape and vary in size between <1-4 micrometres. Due to the very small size of the secondary inclusions, they could not be fully classified compositionally and could not be observed optically during microthermometric measurements.

For example, fluid inclusions were undergone such as necking down and stretching. As a result of the necking down, the inclusions became two-phase and microthermometric measurements were not performed since accurate results could not be obtained in such inclusions.

In two-phase (liquid+gas) inclusions of primary origin, the ratio of liquid phase to gas phase is generally higher and the measured inclusions are homogenized to liquid phase (Figure 16 b, e). For example, 38 homogenisation temperature values were measured in the studies carried out in two-phase (liquid+gas) inclusions of primary origin in transparent and/or semi-transparent (quartz) crystals

and are given in Table 1 below. According to 38 measurements, the homogenisation temperatures of two-phase (liquid+gas) inclusions range from 177-327 °C. As shown in Figure 17, the temperature distribution is concentrated primarily between 190-240 °C, indicating a dominant formation range for the hydrothermal system.

Two-phase (liquid+gas) inclusions of primary origin for which homogenisation temperatures were measured were frozen using liquid nitrogen and their melting temperatures (T_m °C) and corresponding %NaCl equivalents were calculated using the equation of Bodnar (1993) and mass density values were calculated using the programme of Bakker (2003) (Table 2, Figure 17).

In Table 2, it is seen that the salinity ranges between 0.7-2.7% NaCl equivalent and densities between 0.73 and 0.88 g/cm³ in the calculations made in 10 two-phase (liquid+gas) inclusions where homogenisation temperature and final ice melting degree were measured.

Table 1- Homogenisation temperature values measured from fluid inclusions determined in the sample belonging to the argillic alteration zone taken from the drill core.

homogeniSation Temperature Th (°C)	Inclusion Type	homogeniSation Phase	homogeniSation Temperature Th (°C)	Inclusion Type	homogeniSation Phase
177	Two Phases (liquid+gas)	Liquid phase	212	Two Phases (liquid+gas)	Liquid phase
189	Two Phases (liquid+gas)	Liquid phase	215	Two Phases (liquid+gas)	Liquid phase
193	Two Phases (liquid+gas)	Liquid phase	218	Two Phases (liquid+gas)	Liquid phase
195	Two Phases (liquid+gas)	Liquid phase	223	Two Phases (liquid+gas)	Liquid phase
198	Two Phases (liquid+gas)	Liquid phase	223	Two Phases (liquid+gas)	Liquid phase
199	Two Phases (liquid+gas)	Liquid phase	223	Two Phases (liquid+gas)	Liquid phase
200	Two Phases (liquid+gas)	Liquid phase	224	Two Phases (liquid+gas)	Liquid phase
202	Two Phases (liquid+gas)	Liquid phase	226	Two Phases (liquid+gas)	Liquid phase
202	Two Phases (liquid+gas)	Liquid phase	232	Two Phases (liquid+gas)	Liquid phase
203	Two Phases (liquid+gas)	Liquid phase	233	Two Phases (liquid+gas)	Liquid phase
204	Two Phases (liquid+gas)	Liquid phase	252	Two Phases (liquid+gas)	Liquid phase
204	Two Phases (liquid+gas)	Liquid phase	265	Two Phases (liquid+gas)	Liquid phase
206	Two Phases (liquid+gas)	Liquid phase	274	Two Phases (liquid+gas)	Liquid phase
207	Two Phases (liquid+gas)	Liquid phase	286	Two Phases (liquid+gas)	Liquid phase
207	Two Phases (liquid+gas)	Liquid phase	294	Two Phases (liquid+gas)	Liquid phase
209	Two Phases (liquid+gas)	Liquid phase	297	Two Phases (liquid+gas)	Liquid phase
209	Two Phases (liquid+gas)	Liquid phase	305	Two Phases (liquid+gas)	Liquid phase
209	Two Phases (liquid+gas)	Liquid phase	310	Two Phases (liquid+gas)	Liquid phase
211	Two Phases (liquid+gas)	Liquid phase	327	Two Phases (liquid+gas)	Liquid phase

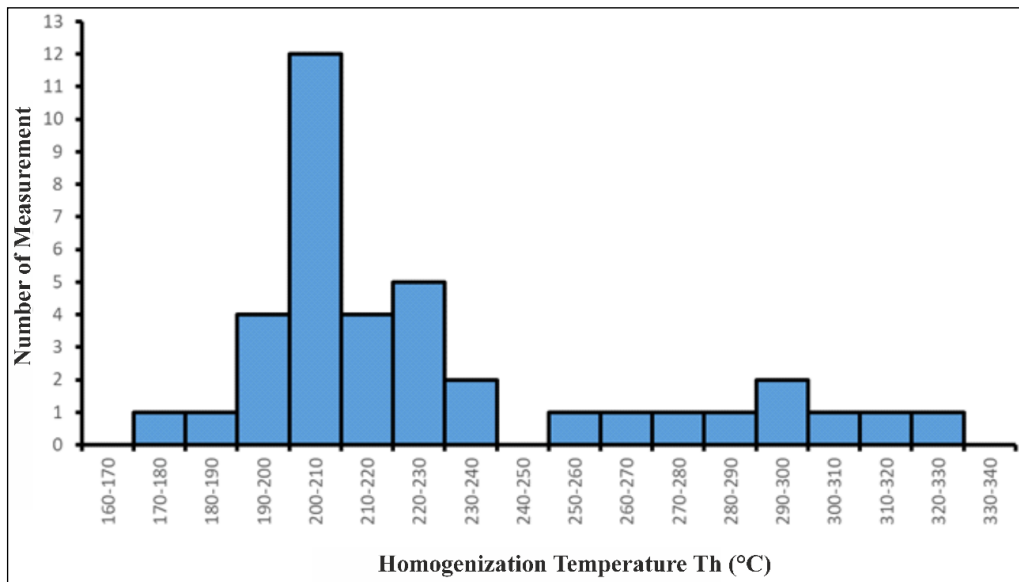


Figure 17- Histogram of homogenization temperatures of two-phase (liquid + gas) inclusions of primary origin determined in the sample belonging to the argillic alteration zone selected from drilling cores.

Table 2- Homogenization, melting temperatures, salinity values and density values of liquid+gas inclusions.

Homogenization Temperature Th (°C)	Tm (°C)	%NaCl equiv.	Density g/cm ³
202	-1.1	1.9	0.88
204	-1.6	2.7	0.88
204	-0.4	0.7	0.87
207	-1	1.7	0.87
212	-1	1.7	0.87
223	-1.6	2.7	0.86
223	-0.6	1.1	0.84
274	-1.5	2.6	0.78
294	-1.2	2.1	0.73
297	1.2	2.1	0.73

9. Discussion

In Biga Peninsula, Western Tethyan Belt, there are many epithermal and porphyry gold deposits which were exploited in ancient times and are still being exploited, containing various commodities. Most of the known mineral systems consist of vein, skarn and porphyry type gold, lead, zinc, copper and molybdenum deposits related to the Eocene-Lower Miocene arc magmatism where the compressional regime was active and mercury, antimony and epithermal Au mineralizations related to the post-collisional magmatism younger than Upper Miocene where the extensional regime was active (Figure 18).

The Akçal Au-Ag mineralization is the latest example discovered in the Middle-Upper Miocene extensional tectonics in Biga Peninsula where uneroded Sb-Hg mineralization-bearing tectonic zones are observed.

Akçal Au-Ag mineralization was formed parallel to E-W, N55-75E and N30W trending tectonic zones and NE-SW trending secondary tectonic zones. Silica caps containing high As and Sb are observed along these tectonic zones (Figure 19).

The determined alteration zones help us to understand the location of the mineralization, whether the mineralization has been eroded or not, at what depths the mineralization may be located and give information about the dimensions and size of the mineralization. Determination of the spatial distribution of alteration minerals plays an important role especially in the burial mineralization.

While the hydrothermal fluids, which played an important role in the formation of mineralization, rose along the fractures, the vapour moved upwards through all kinds of pores. Therefore, the vapour phase spread over a wider area and beidellite, montmorillonite, nontronite, vermiculite and halloysite, kaolinite, pyrite, limonite- hematite-bearing argillic alteration zone is widely observed in the mineralization area.

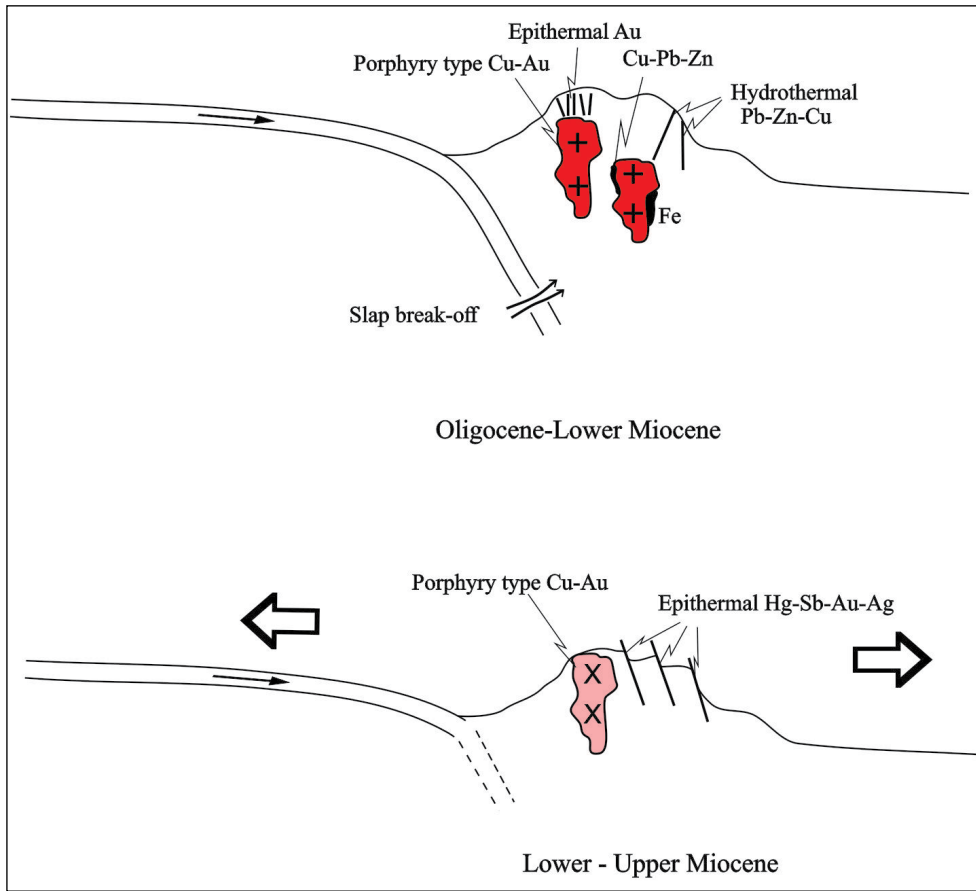


Figure 18- Formation processes of most of the known mineral deposits in the West-Northwest Anatolia region (Sarı et al., 2021).

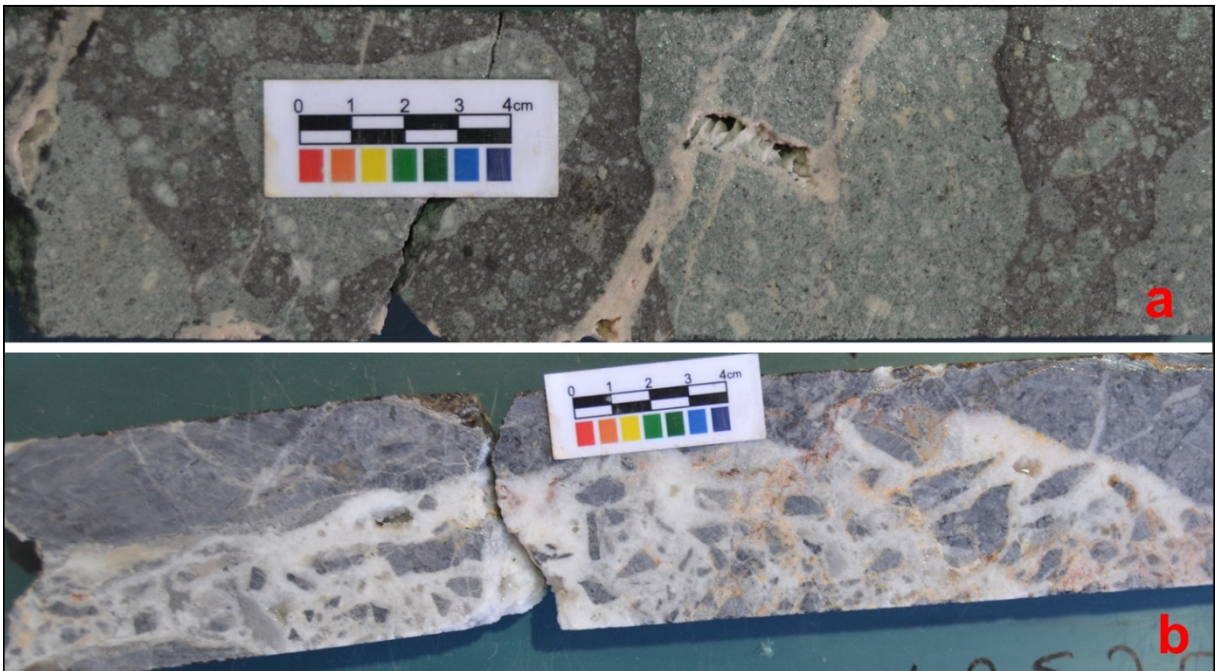


Figure 19- Geological cross section showing Au-Ag mineralization zones developed along parallel tectonic zones obtained from drilling data.

In addition, the homogenization temperature is determined as 190-240 °C and the salinity as 0.7-2.7% NaCl in the fluid inclusion measurements made in quartz minerals in the ore-bearing veins of Akçal mineralization. The alteration and fluid inclusion properties of other mineral deposits formed in Biga Peninsula are similar to Akçal and also shown in

Table 3. The formation temperature and salinities of the known Au-Ag deposits are quite compatible with the formation temperature 190-240 °C, 0.7-2.7 % NaCl salinity of Akçal Au-Ag deposit. Due to this feature, Akçal mineralization is quite similar to low/medium sulfidation epithermal system deposits. Considering the data obtained from the fluid inclusion studies;

Table 3- Characteristics of other low sulphidation gold mineralisations in the Biga Peninsula.

Deposit Name	Deposit type	Host Rock	Alteration Minerals	Fluid Inclusion Results	Explanation	References
Ovacık	Low Sulphidation	Miocene andesite and dacite	smectite, mixed-layer illite/smectite, chalcedonic quartz and adularia, whereas major kaolinite and minor mixed-layer smectite/illite	Main-phase quartz homogenization temperature 150-305°C, average 165-205°C. Freezing temperature -0.4 to -1.2 °C, salinity < 2 wt.%NaCl.	Formed in ENE-striking Bergama Graben	Yılmaz et al., 2007
Küçükdere	Low Sulphidation	Andesitic rocks		Homogenization temperatures of primary inclusions of quartz crystals in breccia veins 174-271°C, 171-250°C, 171-297°C. Homogenization temperatures of calcite crystals in carbonate veins 186-304°C. Homogenization temperatures of quartz crystals in Au-rich quartz veins are 180-230°C. Quartz crystals in brecciated veins are primary inclusions with freezing temperatures of -52.1 to -33.2°C, -43.5 to -34.55°C and -46 to -28.7°C, salinity 1.8% to 5.8 NaCl. Freezing temperatures from calcite crystals in carbonate veins are -51.5 to -44.25°C, salinity is 3.8 to 6.4% NaCl.	Based on the low temperature and salinity data, meteoric water plays important role in the precipitation of metals.	Çolakoğlu and Sezere Kuru, 2001
Sındırgı	Low Sulphidation	Miocene andesite and dacite	mixed-layer illite/smectite, high-crystallinity illite, and kandite	In Sındırgı Kızıltepe Au-Ag mineralization, 3 phases were separated and the homogenization temperatures of quartz crystals are 354 °C (305-395 °C) in phase 1, 231 °C (157-330 °C) in phase 2 and 188 °C (150-241 °C) in phase 3, respectively. The most important phase for mineralization is phase 2. Freezing temperatures are between -0.2 and -2.9 °C. Salinity is 0.5-4.8 wt.% NaCl.	The reason for the high homogenization temperatures especially in phase 1 is explained by the intense hydrothermal flow and high lithostatic pressure.	Yılmaz et al., 2013
Şahinli (Lapseki)	Low/Intermediate Sulphidation	Paleozoic metamorphic rocks and Lutetian quartzfeldspar-hornblende porphyry stock (Ünal-Imer et al. 2013)	illite/muscovite, mixed-layer illite/smectite	The homogenization temperature of the main phase quartz crystals is between 220 and 322°C and the salinity is between 4.3 and 6.9%. In fluid inclusion studies in sphalerites, homogenization temperatures are between 229 and 321°C, salinity between 2.6 and 7.6%. The freezing temperature is -24.5 to -19.0°C.	It indicates that the ore-forming liquids are rich in NaCl-H ₂ O.	Yılmaz et al., 2010
Karadere/Madradağ	Low Sulphidation	Miocene andesitic rocks	quartz-clay-sericite	The fluid inclusions representing the first phase have medium salinity (7% NaCl equivalent) and high temperature (300°C); the fluids representing the last stage show that they have low salinity (0.3% NaCl equivalent) and lower temperature (180°C).	Bladed textures and the widespread observation of liquid and gas-rich liquid inclusions indicate boiling at the Karadere gold deposit. Mineralization developed along the NE-striking tectonic zone.	Oğuz, 2023
Madendağ	Low Sulphidation	Eocene dacites	chlorite/smectite-illite ± kaolinite ve alunite	Primary fluid inclusions in quartz crystals, the homogenization temperature is 235 to 255 °C and the salinity is 0.0-0.7 wt.% NaCl.	These data are suitable for low sulfidation.	İmer et al., 2013

it can be stated that Akçal Au-Ag mineralization developed within the epithermal system where the temperatures and salinities of the fluids are low (epithermal).

When we evaluate at the scale of Akçal; salinity is low for Carlin-type Au mineralization. Barite and fluorite formations are not observed together with quartz, silica and calcite vein/veinlets. Along the

tectonic zones, Au is accompanied by Ag (locally 20,1 ppm). As a host rock Miocene aged volcanism is common in the region. All of these features indicate that the mineralization was formed in a low/medium sulphidation epithermal system. In addition, the observation of textures indicating boiling during the formation of mineralization shows that the mineralization cannot be Carlin-type (Figure 20).

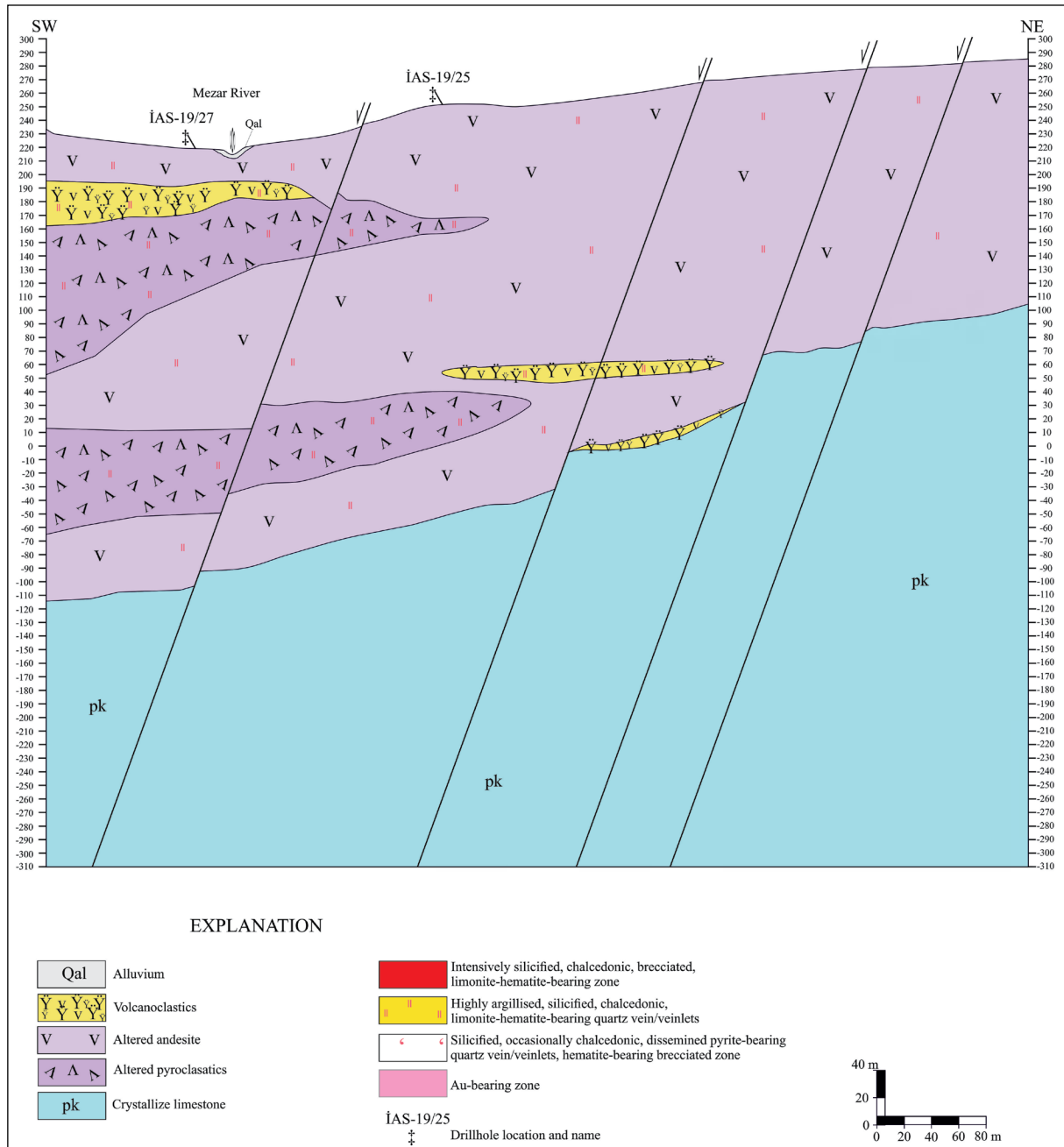


Figure 20- a) Silica vein with ornamentation texture in the cavities of the fault zone in altered andesites, b) Cocarde textures formed in the cavities of silica veins in silicified limestone.

The post-collisional extensional tectonic regime in Biga Peninsula is caused by increase of the structural permeability where fluids circulated and precipitated minerals with economic value to suitable environments. Considering the Akçal Au-Ag mineralization, which is formed in the extensional tectonics, as well as the Ovacık, Sındırgı, Lapseki and Küçükdere Low sulfidation Au deposits, which are thought to have been formed by a similar mechanism on a regional scale, it is possible to identify new exploration target areas in Western Anatolia and the Biga Peninsula.

Acknowledgments

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References

- Abraham, E., Usman, A., Chima, K., Best Azuoko, G., Ikeazota, I. 2024. Magnetic inversion modeling of subsurface geologic structures for mineral deposits mapping in southeastern Nigeria, Bull. Min.Res.Exp. 173, 85–105.
- Altunkaynak, Ş., Dilek, Y. 2006. Timing and nature of postcollisional volcanism in western Anatolia and geodynamic implications. Geological Society of America Special Paper 409, 321-350.
- Altunkaynak, Ş., Genç, Ş. G. 2008. Petrogenesis and time progressive evolution of the Cenozoic continental volcanism in the Biga Peninsula, NW Anatolia (Turkey). Lithos 102, 316-340.
- Akiska, S. 2020. Crystallization conditions and compositional variations of silicate and sulfide minerals in the Pb-Zn skarn deposits, Biga Peninsula, NW Turkey. Ore Geology Reviews, 118.
- Aslan Z., Erdem, D., Temizel, İ., Arslan, M. 2017. SHRIMP U–Pb zircon ages and whole-rock geochemistry for the Şapçı volcanic rocks, Biga Peninsula, Northwest Turkey: implications for preeruption crystallization conditions and source characteristics. International Geology Review 59 (14), 1764-1785.
- Aydın, Ü., Şen, P., Özmen, Ö., Şen, E. 2019. Petrological and geochemical features of Biga Peninsula granitoids, NW Anatolia, Turkey. Bulletin of the Mineral Research and Exploration 160, 81-115.
- Bakker, R. J. 2003. Package FLUIDS; 1, Computer programs for analysis of fluid inclusion data and for modelling bulk fluid properties. Chemical Geology 194, 3-23.
- Bodnar, R. J. 1993. Revised equation and table for determining the freezing point depression of H₂O–NaCl solutions. Geochimica et Cosmochimica Acta 57, 683–684.
- Bozkaya, G., Banks, D. A. 2015. Physico-chemical controls on ore deposition in the Arapucandere Pb-Zn-Cu-precious metal deposit, Biga Peninsula, NW Turkey. Ore Geology Reviews 71, 1-15.
- Bozkaya, Ö., Bozkaya, G., Banks, D. A., Gökçe, A. 2020. P-T-X constraints on the Koru epithermal base-metal (±Au) deposit, Biga Peninsula, NW Turkey. Ore Geology Reviews 119, 103349.
- Chen, J., Xu, J., Wang, B., Yang, Z., Ren, J., Yu, H., Liu, H., Feng, Y. 2015. Geochemical differences between subduction- and collision-related copper-bearing porphyries and implications for metallogenesis. Ore Geology Reviews 70, 424-437.
- Cooke, D. R., Simmons, S. F. 2000. Characteristics and Genesis of Epithermal Gold Deposits, Gold in 2000, Steffen G. Hagemann, Philip E. Brown.
- Corbett, G. J., Leach, T. M. 1998. Southwest Pacific rim gold-copper systems: structure, alteration, and mineralization. Society of Economic Geologists Special Publication 6, 234.
- Çolakoğlu, A. R. 2000. Küçükdere (Havran-Balıkesir) epitermal altın damarlarının özellikleri. Türkiye Jeoloji Bülteni 43(2), 99-110.
- Çolakoğlu, A.R., Sezerer Kuru, G. 2001. Küçükdere (Havran-Balıkesir) epitermal altın damarlarında sıvı kapanım çalışmaları. Yerbilimleri Dergisi 24, 1-11.
- Demirela, G., Akiska, S. 2022. Evaluation of Pb isotope systematics and metal sources of the Biga Peninsula. Journal of African Earth Sciences 187, 104445.
- Dewey, J. F., Şengör, A. M. C. 1979. Aegean and Surrounding Regions, Complex Multiplate and Continuum Tectonics in a Convergent Zone. Geological Society of America Bulletin 90, 84-92.

- Doglioni, C., Agostini, S., Crespi, M., Innocenti, F., Manetti, P., Riguzzi, F., Savascini, Y. 2002. On the extension in western Anatolia and the Aegean sea. *Journal of the Virtual Explorer* 7, 117–131.
- Dönmez, M., Akçay, A.E., Genç, Ş. C., Acar, Ş. 2005. Biga Yarımadası'nda Orta-Üst Eosen Volkanizması ve Denizel İgnimbiritler. *Maden Tetkik ve Arama Dergisi* 131, 49-61.
- Duru, M., Dönmez, M., Ilgar, A., Pehlivan, Ş., Akçay, A. E. 2012. Biga Yarımadası'nın Genel ve Ekonomik Jeolojisi. Editörler: Erdoğan Yüzer ve Gürkan Tunay. *Maden Tetkik ve Arama Genel Müdürlüğü, Özel Yayın Serisi* 28, 326.
- Engin, T., Özkan, Y. Z., Sener, F., Toprak, B. 2000. 1/1000000 ölçekli Türkiye Metalojeni Haritası. MTA yayını.
- Frimmel, H. E. 2008. Earth's Continental Crustal Gold Endowment. *Earth and Planetary Science Letters* 267, 45-55.
- Genç, Ş. C., Dönmez, M., Akçay, A. E., Altunkaynak, Ş., Eyüpoğlu, M., Ilgar, Y. 2012. Biga yarımadası Tersiyer volkanizmasının stratigrafik, petrografik ve kimyasal özellikleri. Biga Yarımadası'nın Genel ve Ekonomik Jeolojisi, MTA Özel Yayın Serisi 28, 122-162.
- Göçmengil, G., Karacık, Z., Genç, Ş. C. 2018. Volcano Stratigraphic Investigation of the Post-Collisional Middle Eocene Magmatism Around İzmir-Ankara-Erzincan Suture Zone (NE, Turkey). *Türkiye Jeoloji Bülteni* 61(2), 131-162.
- Gülyüz, N., Shipton, Z. K., Kuşcu, İ. 2023. Multiphase deformation, fluid flow and mineralization in epithermal systems: Inferences from structures, vein textures and breccias. *Turkish Journal of Earth Sciences* 32(1), 1–20.
- Hedenquist, J. W., Arribas, A. R., Gonzalez-Urien, E. 2000. Exploration for Epithermal Gold Deposits, Gold in 2000, Steffen G. Hagemann, Philip E. Brown.
- Hou, Z., Zhang, H., Pan, X., Yang, Z. 2011. Porphyry (Cu-Mo-Au) deposits related to melting of thickened mafic lower crust: examples from the eastern Tethyan metallogenic domain. *Ore Geology Reviews* 39, 21-45.
- İmer, E. Ü., Güleç, N., Kuşcu, İ., Fallick, A. E. 2013. Genetic investigation and comparison of Kartaldağ and Madendağ epithermal gold deposits in Çanakkale NW Turkey. *Ore Geology Reviews* 53, 204-222.
- Janković, S. 1997. The Carpatho-Balkanides and adjacent area: a sector of the Tethyan Eurasian metallogenic belt. *Mineralium Deposita* 32, 426-433.
- Jingwen, M., Pirajno, F., Lehmann, B., Maocheng, L., Berzina, A. 2014. Distribution of porphyry deposits in the Eurasian continent and their corresponding tectonic settings. *Journal of Asian Earth Sciences* 79, 576-584.
- Kaya, M., Yıldırım, B. A., Kumral, M., Şaşmaz, A. 2023. Sulfur and Carbon–Oxygen Isotopic Geochemistry and Fluid Inclusion Characteristics of the Yolindi Cu-Fe Skarn Mineralization, Biga Peninsula (NW Turkey): Implications for the Source and Evolution of Hydrothermal Fluids. *Minerals* 13(12), 1542.
- Kayadibi, Ö., Gürboğa, Ş., Akıllı, H., Arkan, S., Tan, S., Deveci Aral, Z., Mutlu, H., 2023. Integration of structural, hydrogeological and thermal remote sensing data for the determination of geothermal capacity A case study of the Edremit (Balıkesir) Basin, *Bulletin Mineral Research Exploration* 171, 1–32.
- Keskin, M., Genç, C. Ş., Tüysüz, O. 2008. Petrology and geochemistry of post-collisional Middle Eocene volcanic units in North-Central Turkey: Evidence for magma generation by slab breakoff following the closure of the Northern Neotethys Ocean. *Lithos* 104(1–4), 267-305.
- Krushensky, R. D. 1976. Neogene Calc-alkaline extrusive and intrusive rocks of the Karalar Yeşiller area, Northwest Anatolia, Turkey. *Bulletin Volcanologique* 40, 336-360.
- Koçyiğit, A., 2023. Neotectonics of the Sarıköy-İnova and Çan-Bayramiç-Ezine fault zones: basin formation, age and slip rates, NW Anatolia-Türkiye, *Bulletin Mineral Research Exploration* 172, 119-140.
- Kuşcu, İ., Tosdal, R. M., Gencalioglu Kuşcu, G. 2019a. Episodic porphyry (Cu-Mo-Au) formation and associated magmatic evolution in Turkish Tethyan collage. *Ore Geology Reviews* 107, 119-154.
- Kuşcu, İ., Tosdal, R.M., Gencalioglu Kuşcu, G. 2019b. Porphyry - Cu Deposits of Turkey. Pirajno F., Ünlü, T., Dönmez, C., Şahin, M. (Ed.). *Mineral Resources of Turkey. Modern Approaches in Solid Earth Sciences. Springer* 337-425.
- Li, Y., Selby, D., Condon, D., Tapster, S. 2017. Cyclic magmatic - hydrothermal evolution in porphyry systems: high - precision U-Pb and Re-Os geochronology constraints on the Tibetan Qulong porphyry Cu - Mo deposit. *Economic Geology* 112, 1419-1440.

- Lu, Y. J., Loucks, R. R., Fiorentini, M. L., Yang, Z. M., Hou, Z. Q. 2015. Fluid flux melting generated postcollisional high Sr/Y copper ore-forming water-rich magmas in Tibet. *Geology* 43, 583-586.
- Oğuz, B. 2023. Karadere-İvrindi (Balıkesir) düşük sülfidasyonlu epitermal altın-gümüş yatağında cevher oluşturan çözeltilerin özellikleri. Pamukkale Üniversitesi / Fen Bilimleri Enstitüsü / Jeoloji Mühendisliği Ana Bilim Dalı. Master Thesis.
- Okay, A. I. 1989. Tectonic Units and Sutures in the Pontides, Northern Turkey. In: Şengör, A.M.C. (Eds) *Tectonic Evolution of the Tethyan Region*. NATO ASI Series, vol 259. Springer, Dordrecht.
- Okay, A. I., Tüysüz, O. 1999. Tethyan sutures of northern Turkey. Durant, B., Jolivet, F., Horvath, F., Seranne, M. (Eds). *The Mediterranean basin: Tertiary extension within the Alpine orogen*. Geological Society of London. Special Publication, 156, 475-515.
- Okay, A. İ., Siyako, M., Bürkan, K. A. 1990. Biga Yarımadası'nın jeolojisi ve tektonik evrimi. *TPAG Bulletin* 2(1), 83121.
- Okay, A. İ., Göncüoğlu, M. C., 2004. The Karakaya Complex: A Review of Data and Concepts. *Turkish Journal of Earth Sciences* 13(2), 75-95.
- Oyman, T. 2019. Epithermal Deposits of Turkey. Pirajno F., Ünlü T., Dönmez C., Şahin M. (Eds). *Mineral Resources of Turkey. Modern Approaches in Solid Earth Sciences* 16, 337-425.
- Parlak, O., Çolakoğlu, A., Dönmez, C., Sayak, H., Yıldırım, N., Türkel, A., Odabaşı, İ. 2012. Geochemistry and tectonic significance of ophiolites along the İzmir-Ankara-Erzincan Suture Zone in northeastern Anatolia. In A. H. F. Robertson, O. Parlak, & U. C. Ünlügenç (Eds.), *Geological development of Anatolia and the easternmost Mediterranean* (Vol. 372, pp. 75-106). Geological Society London Special Publications.
- Pehlivan, Ş., Duru, M., Dönmez, M., Ilgar, A., Akçay, A.E., Erdoğan, K., Özer, D. 2007. Türkiye Jeolojisi Haritaları No:96, Balıkesir-İ 19 Paftası. Maden Tetkik ve Arama Genel Müdürlüğü 40 s Ankara.
- Richards, J. P. 2009. Post-subduction porphyry Cu-Au and epithermal Au deposits: products of remelting of subduction -modified lithosphere. *Geology* 37, 247-250.
- Richards, J. P. 2015. Tectonic, magmatic, and metallogenic evolution of the Tethyan orogen from subduction to collision. *Ore Geology Reviews* 70, 323-345.
- Richards, J.P. 2016. Tectonics and metallogeny of the Tethyan orogenic belt: Society of Economic Geologists, Special Publication 19, 387.
- Robertson, A., Parlak, O., Ustaömer, T. 2023. Neotethyan Ankara Melange, central Turkey in its Triassic-Eocene regional tectonic setting including accretionary melanges, magmatic arcs and continental units. *International Geology Review* 65(20), 3192-3247.
- Sarı, R., Küçükefe, Ş., Bademler, F., Bayrakçioğlu, E. D., Deveci Aral, Z., Tokoğlu, M., Üçgül, E., Türüdü, M. Ş., Derin, K. 2021. Akçal (İvrindi-Balıkesir) S:202100265 (Er:3407287) No'lu Ruhsat Sahasının Umrek (Ulusal Madenlerde Rezerv Ve Kaynak Raporlama Komisyonu) Standartlarına Uygun Altın-Gümüş Mineralizasyonuna Ait Maden Jeolojisi Ve Kaynak Tahmin Raporu, MTA.
- Sarı, R., Küçükefe, Ş., Bademler, F., Durgun, M. B., Ersoy, G.G., Deveci-Aral, Z., Dönmez, C., Özkümüş, S., Bozkaya, G. 2019. Preliminary Results of Au-Sb Mineralization Related to Extensional Tectonics in the South of Biga Peninsula: Akçal (Balıkesir-İvrindi) Prospect Area. *International Earth Science Colloquium on the Aegean Region (IESCA, 2019)*, İzmir-Turkey. Abstract.
- Schilling, R. D. 1959. Über eine praherzynische faltungsphase im Kazdağ Kristalin. *MTA Enstitüsü Bülteni* 53, 89-93.
- Singer, D. A. 1995. World Class Base and Precious Metal Deposits - A Quantitative Analysis. *Economic Geology* 90, 88-104.
- Strabon, 2000. *Geographika (Antik Anadolu Coğrafyası)*; Arkeoloji ve Sanat yayınları, 4. Baskı.
- Şaroğlu, F., Güler, B. 2020. Recent Deformation of the Western Anatolia Tectonic Wedge: Block Motions Caused by Escape to the West. *Geological Bulletin of Turkey* 63, 161-194.
- Şengör, A. M. C. 1984. The Cimmeride Orogenic System and the Tectonics of Eurasia. *Geological Society of America Special Paper* 195, 1-82.
- Şengör, A. M. C., Yılmaz, Y. 1981. Tethyan evolution of Turkey, a plate tectonic approach: Tectonophysics 75, 181-241.
- Tetiker, S., Yalçın, H., Bozkaya, Ö., Göncüoğlu M. C. 2015. Metamorphic evolution of the Karakaya complex in northern Turkey based on phyllosilicate mineralogy. *Mineralogy and Petrology* 109, (201-215).

- Ucar, T., McClenaghan, S. H., Lentz, D. R. 2024. Alteration and mineralization features of the Akcal Epithermal Gold Deposit, Biga Peninsula, Western Anatolia, Turkey: Evidence for low-sulfidation Au-Ag-Sb mineralization. *Geochemistry: Exploration, Environment, Analysis* 24(4), geochem2024-031.
- White, N. C., Hedenquist, J. W. 1995. Epithermal gold deposits: styles, characteristics and exploration. *SEG newsletter* (23), 1-13.
- Yıldırım, S. 2000. Batı Anadolu'da Antik Çağ Altın Madenleri. *Mavi Gezegen* 3, 4-10.
- Yılmaz, Y., Yiğitbaş, E., 2023. Tectonic development of the Ankara-Erzincan suture and the Eastern Pontide mountains, Northeast Anatolia, Turkey. *International Geology Review* 66(6), 1216–1239.
- Yılmaz, H., Oyman, T., Arehart, G. B., Colakoglu, A.R., Billor, Z. 2007. Low-sulfidation type Au–Ag mineralization at bergama, İzmir, Turkey. *Ore Geology Review* 32 (1–2), 81–124.
- Yılmaz, H., Sönmez, N. F., Akay, E., Şener, A. K., Tufan, S. T. 2013. Low-Sulfidation Epithermal Au-Ag Mineralization in the Sındırgı District, Balıkesir Province, Turkey, *Turkish Journal of Earth Sciences* 22, 485–522.
- Yılmaz, Y., Genç, Ş. C., Karacık, Z., Altunkaynak, Ş. 2001. Two contrasting magmatic associations of NW Anatolia and their tectonic significance. *Journal of Geodynamics* 31, 243-271.
- Yılmaz, H., Oyman, T., Sonmez, F., Arehart, G. B., Billor, Z. 2010. Intermediate sulfidation epithermal gold-base metal deposits in Tertiary subaerial volcanic rocks, Sahinli/Tespih Dere (Lapseki/Western Turkey). *Ore Geology Reviews* 37, 3-4, p. 236-258.
- Yiğit, Ö. 2009. Mineral deposits of Turkey in relation to Tethyan Metallogeny: implications for future mineral exploration. *Economic Geology* 104, 19-51.
- Yiğit, Ö. 2012. A prospective sector in the Tethyan Metallogenic Belt: geology and geochronology of mineral deposits in the Biga Peninsula, NW Turkey. *Ore Geology Reviews* 46, 118-148.