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Borehole Geology and Subsurface Hydrothermal Alteration of the Sandıklı Geothermal Field, Afyon-Türkiye

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ABSTRACT

The Sandıklı geothermal field is located on the eastern part of western Anatolia (Türkiye). The field is hosted by volcanic rocks. Samples from two wells were kindly made available for this study, namely from AFS-12 and AFS-13 drilled to depths ranging from 450 to 500m.

The wells were located in a major fault controlled porphyry hydrothermal system (hydrothermal upflow zone). A widespread and intense porphyry-type hydrothermal alteration zone has developed in the Neogene Sandıklı volcanics at 4.5 km NE of the Karacaören village (Sandıklı), as a result of the intrusion of syenite-monzonite porphyries. From distal zone to the intrusion center, propylitic (epidote, chlorite, carbonate minerals, albite, K-feldspar), argillic (alunitization, illitization), phyllic (sericitic; quartz, sericite, pyrite) and potassic (alkali metasomatic; K-feldspar and biotite) developed, respectively, under wide range of pH and Eh conditions.

The reservoir is hosted by interbedded pyroclastic and lavas of trachyandesite composition with some basaltic andesites and trachytic tuffs. The primary minerals present in the Sandıklı subsurface rock samples are mainly sanidine, pyroxene, biotite, plagioclase, nosean and apatite. In general, carbonatization and chloritization are common in the matrix and pyroxene phenocrysts of the trachytic rocks.

On mineralogic (XRF, SEM-EDS) and petrographic investigations on the wells at 50-60 m, silicification, and chalcedony and hematite formation are common. In the SEM-EDS studies, 0.75 – 1.25 % Ag was measured from the hydrothermal quartz. At deeper levels, abundance of hematite and pyrite with marcasite and sericite increase due to the hydrothermal alteration. At 110-180 m levels, euhedral Fe-Ti oxide minerals (hematite-Fe_2O_3 or titanomagnetite-$Fe_{2.5}Ti_{0.5}O_4$, including Ti) are observed. However, primary apatites and titanomagnetite minerals associated with sanidine and euhedral pyroxene (augite) occur within the trachyandesite. In the SEM study, it is observed that the surfaces of the apatites were rounded and decomposed, due to the intense hydrothermal alteration. At 350-400 m levels, depends on hydrothermal alteration, euhedral pyrite crystals were formed within the dolomitic limestones (the Çaltepe formation is not observed on surface). Within this pyrite which replaced the dolomite and at the boundary of dolomite-pyrite, euhedral gypsum minerals were formed. At deeper levels, in sandstone alternating with dolomitic limestone, epidotization is common.

1. INTRODUCTION

The Afyon-Sandıklı region lies along the western part of the Taurus mountain range of Turkey. The Afyon zone is low-grade metamorphic terrain lying from the Menderes Massif on the west towards the Uşak-Sandıklı (Afyon) on the east (Özgül 1976). In the Sandıklı region, Paleozoic, Mesozoic and Tertiary units are observed (Figure 1).

The study area is located in the Sandıklı region at 40 km SW of the Afyon (Figure 1). As related to the neo-tectonism and active volcanism of western Anatolia, a widespread and intense hydrothermal alteration and geothermal system has developed in the study area. Mutlu and Güleç (1998) were studied on the chemical compositions of thermal waters in Turkey. According to the authors, the hot springs are all aligned along the faults bordering the major grabens in western Anatolia. The reservoir rocks of the region are pre-Mesozoic metamorphics (marbles, gneisses and quartzites) of the Menderes Massifs, Mesozoic limestones, and the Neogene volcanosedimentary units (Tolluoğlu et al., 1997). The distribution of hot springs in the Sandıklı (Afyon) region roughly parallels to the fault system that caused intense porphyry-type hydrothermal alteration at 4.5 km NE of the Karacaören village (Sandıklı) (Figure 1) (Gündoğan et al., 2009). Miocene volcanism, around the Sandıklı region, formed different products at wide ranges, and alkaline, calc-alkaline lavas such as trachyte, andesite, trachyandesite (latite), latite basalt, phonolite and tephrite, tuffs and ignimbrites have formed during Middle-Upper Miocene at different stages. Hydrothermal alteration is very common in these volcanic products.

In the Sandıklı region, hydrothermal alteration of the volcanic rocks is commonly observed from the Hüdai thermal springs towards east and northeast of present geothermal system.

2. METHOD OF STUDY

Representative 150 samples from two wells were kindly made available for mineralogic-petrographic investigation, namely AFS-12 and AFS-13 drilled to depths ranging from 450 to 500 m, at the region between Hüdaihamamı and Sandıklı. Two methods were used for studying of the drill cutting from the wells AFS-12 and 13 in the Sandıklı area.

Initially, the drill cuttings collected at every 2 m depth were analyzed in thin section with petrographic microscope. Finally, the mineral paragenesis in the clastic samples was identified by using XRD and SEM-EDS techniques.

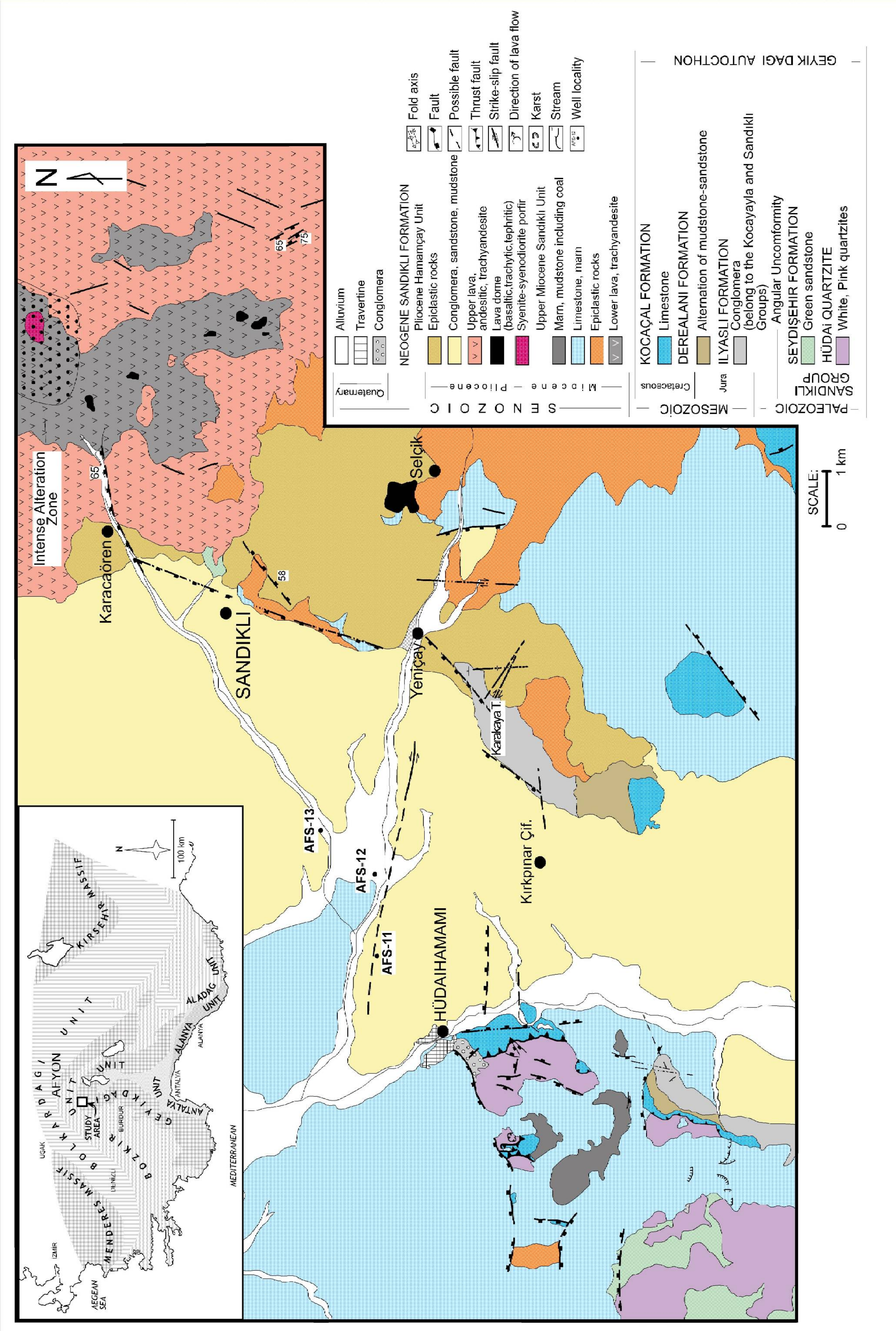


Figure 1. Simplified geological map of the Sandıklı area (compiled after Öngür 1973).

3. SUBSURFACE GEOLOGY

Hüdai geothermal system is an area of out-flow zone in the Sandıklı (Afyon) region. In ancient times, Hüdai hot springs were a geothermal area that its flowrate was totally 100 L/s. In previous studies indicated that there were several natural springs in the Sandıklı geothermal area (e.g. Çağlar, 1950; Ronner, 1962). Çağlar (1950), Ronner (1962) have also reported that the thermal water temperatures as 65-69 °C and 85 °C, respectively. In study of MTA by Akkuş et al. (2005) from old wells measured thermal water temperatures and flow rates are 45-70 °C and 112 L/s, respectively. In this study, thermal water temperatures and flow rate from the wells AFS-12 and AFS-13 measured 80.6-78°C and 75-80 L/s, respectively. Although scaling is common in the wells near the Hüdaihamami (Sandıklı) in the wells AFS-12 and AFS-13, corrosion occurs (Figure 2).

Figure 2. Thermal water pipe line scaling in Afyon Sandıklı Hüdai hot springs from hot water production well.

Mutlu and Güleç (1998) reported that the temperature of the spring waters reaches up to 100 °C in western Anatolia. The waters are weakly acidic to alkaline with pH values ranging from 6.10 to 9.61, and have TDS contents between 550 and 54884 ppm. The majority of waters are either Na-HCO_3 or Na-Cl in nature, although SO_4-type waters are also present. The chloride-rich waters are characteristic for the coastal areas (Çeşme, Seferihisar, Doğanbey-İzmir; Kestanbol, Tuzla-Çanakkale; Köyceğiz-Muğla) and their compositions suggest a possible seawater intrusion into the reservoir (Vengosh et al., 2002; Tarcan and Gemici, 2003). It is important to note at this stage that some of waters from the inland areas, such as Balıkesir and Afyon, also have Na-Cl nature which cannot be attributed to seawater intrusion but probably results from the involvement of connate fossil waters (Mutlu and Güleç, 1998).

The major lithologies in the studied wells (AFS-12 and 13) are alluvium, Quaternary sediments, epiclastic-volcanoclastics and lava flows and basement rocks, and the subsurface sequences are similar in the wells.

Well AFS-12 was drilled down to 550 m (UTM coordinates x=4258911, y=257191, z=1020 m). The lithologies in the well from surface to depth are alluvium (10 m), Quaternary sediments (40 m), epiclastic-volcanoclastics and lava flows belong to the Neogene Sandıklı Formation-Pliocene Hamamçay unit (220 m) and basement rocks Geyikdağı Otoctone) (280 m), respectively.

Well AFS-13 was drilled down to 422 m (UTM coordinates x=4259211, y=257591, z=1020 m). Similarly, the lithologies in the well from surface to depth are alluvium (10 m), Quaternary sediments (33 m), epiclastic-volcanoclastics and lava flows belong to the Neogene Sandıklı formation-Pliocene Hamamçay unit (200 m) and Paleozoic Sandıklı group basement rocks (142 m), respectively.

4. HYDROTHERMAL ALTERATION

On mineralogic-petrographic investigations on the well AFS-12, volcanic and volcanoclastic rocks observed at 50-270 m, are commonly trachyandesite in composition (Figure 3). Rarely, the clasts, derived from lamproitic rocks, were obtained in the volcanoclastics. Xenolith inclusions rich in mafic minerals, are common in trachyandesites . In some of volcanic clasts, nosean and apatite as an accessory mineral are observed. At 120-135 meters, because of alteration of euhedral leucites, cavities had developed in rock clasts belong to leucitites. At 200-270 meters, a series that consists of interbedded pyroclastic, epiclactic rocks and trachyandesitic lava flow, were determined. Carbonatization and chloritization are common in matrix and pyroxene pheoncrysts of trachytic rocks (Figure 4). At 270-550 meters, the units belong to the Sandıklı basement rocks (Derealanı Formation, Seydişehir Formation, Çaltepe Formation and Hüdai quartzite) are observed. The Derealanı Formation consists of interbedded siltstone-mudstone. Euhedral pyrite minerals are common in this formation. In the Seydişehir Formation that consists of interbedded mudstone-siltstone alternating with dolomite-dolomitic limestone, fossil shells are observed. Hematite- and pyrite-bearing ore formation is common in dolomitic limestone unit. In cements of the Hüdai quartzite, consisting of interbedded siltstone and sandstone including quartz, sericitization is commonly observed. In the well AFS-12, hematite- and pyrite-bearing ore formations increase from surface to depth.

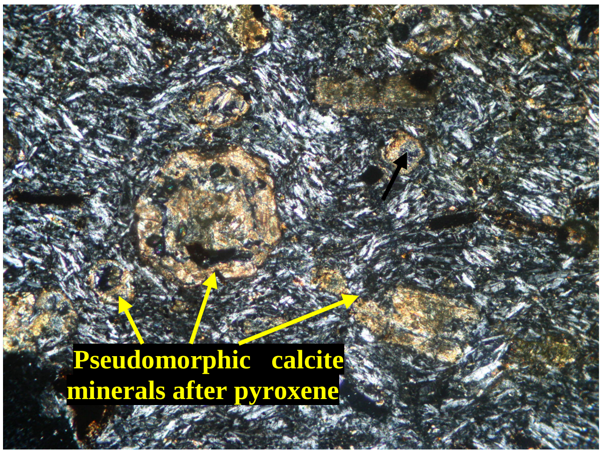


Figure 4. Photomicrograph showing pyroxene minerals in trachyandesite replaced by calcite related to the hydrothermal alteration (Pseudomorphic calcite minerals).

Mineralogic-petrographic investigations on the well AFS-13, silicification and formation of chalcedony, hematite and pyrite minerals are observed between 50 and 60 meters (Figure 5). Chalcedony replaces the sanidine minerals.

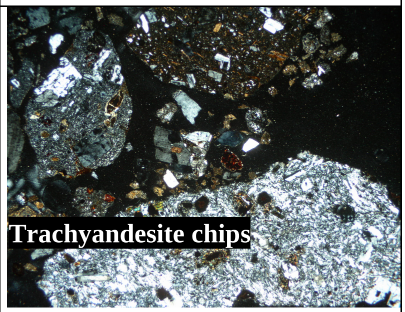
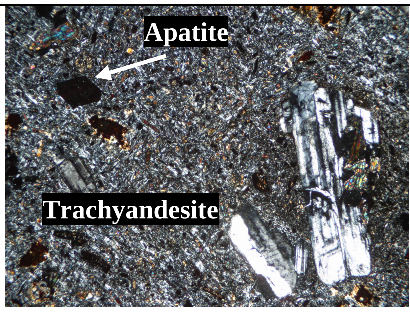
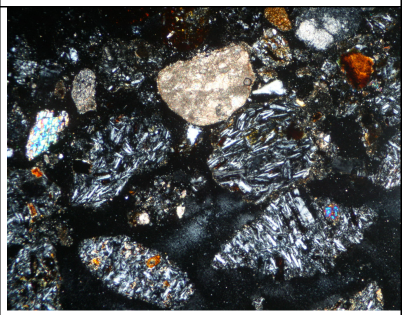
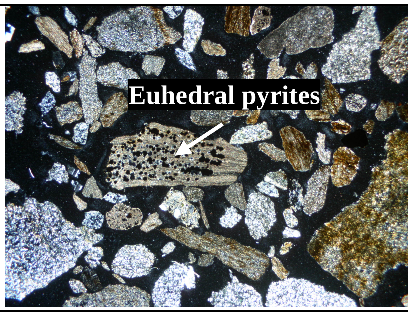
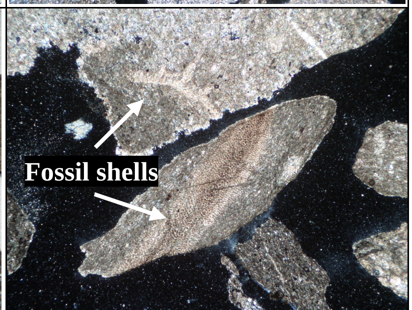
Deepth (m)		Explanations	Microscope Images	
0-50		Alluvium and Quaternary: Coarse grained volcanogenic pebblestone-sandstone.	-	-
50-80	Neogene-Sandıklı member (Pliocene Hamamçay member)	Lava and pyroclastic grained-volcanogenic pebblestone-sandstone. Mostly is composed of trachyandesite and rare lamproitic lithics.		
80-270		Sandstone which is composed of trachyandesitic lithics. Euhedral apatites are common in lithic fragments. Carbonatization and chloritization are common in matrix of trachitic flow textures and pyroxene phenocrysts. Unconformity		
270-350	Mesozoic rocks	***BASE ROCKS*** ***Derealanı Formation:*** Composed of siltstone-mudstone intercalation. Euhedral pyrite formations are common in siltstone.		
350-480	Paleozoic Rocks (Sandıklı Group)	***Seydişehir Formation:*** Composed of siltstone-mudstone intercalation which consists of dolomite and dolomitic limestone. Fossil records are observed within siltstones.		
480-550		***Çaltepe Formation:*** Hematite and pyrite mineralization are common within the dolomitic limestone. ***Hüdai quartzite:*** Composed of sandstone and siltstone intercalation consists of dominantly quartz crystals.		

Figure 3. Photomicrographs showing the lithological facies of the well AFS-12 from surface to depth.

In deeper levels, abundance of hematite and pyrite increase due to the hydrothermal alteration. At 110-180 m levels, euhedral, however, primary apatites and titanomagnetite minerals associated with sanidine and euhedral pyroxene (augite) occur within the trachyandesite. Because of hydrothermal alteration, the surfaces of the apatites were rounded and decomposed (Figure 6). Fe-Ti oxide minerals (hematite-Fe_2O_3 or titanomagnetite-$Fe_{2.5}Ti_{0.5}O_4$, including Ti) are observed (Figure 7).

At 405 m level, due to the hydrothermal alteration, euhedral pyrite crystals were formed within the dolomitic limestones (called the Çaltepe formation, not observed on surface). Euhedral gypsum minerals were obtained within the pyrite which replaced the dolomite, and at the boundary of dolomite and pyrite minerals (Figure 8, 9 and 10).

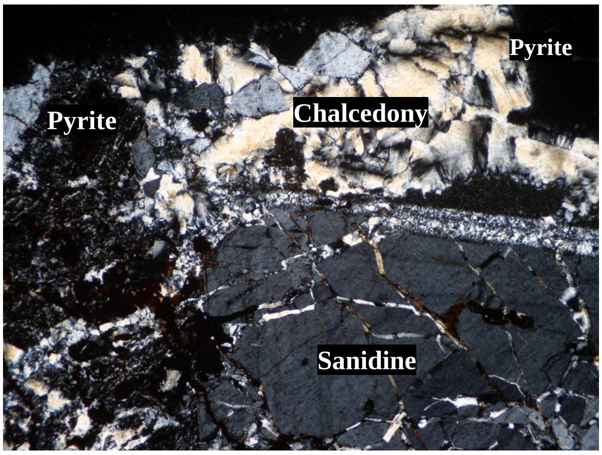


Figure 5. Photomicrograph showing sanidine mineral in trachyandesite replaced by chalcedony and pyrite related to hydrothermal alteration.

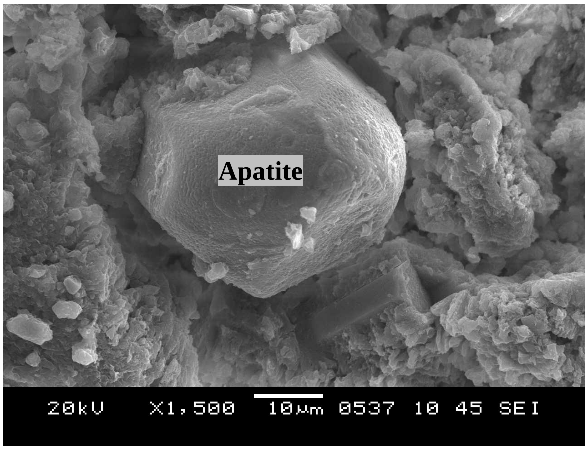


Figure 6. Backscattered-SEM image showing euhedral apatite crystal [$Ca_5(PO_4)_3(OH,F,Cl)$] within the trachyandesitic rock fragment from the well AFS-13 at 185 m level. Because of the hydrothermal alteration, the surfaces of the apatite were rounded.

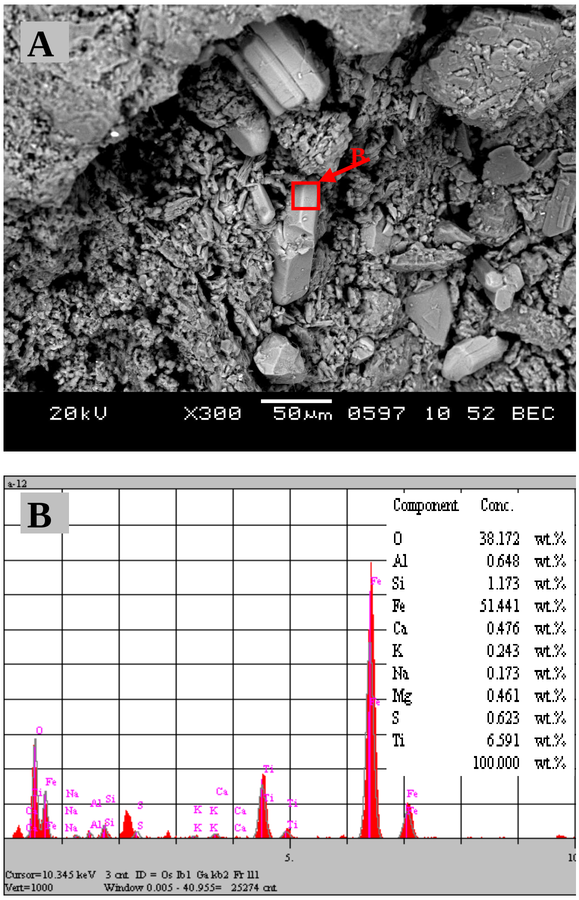


Figure 7. Backscattered-SEM image showing euhedral Fe-Ti oxide titanomagnetite ($Fe_{2,5}Ti_{0,5}O_4$) or Ti-bearing hematite (Fe_2O_3) minerals within the trachyandesitic rock fragment (chips) from the well AFS-13 at 110 m level (A), and EDS analyses (B).

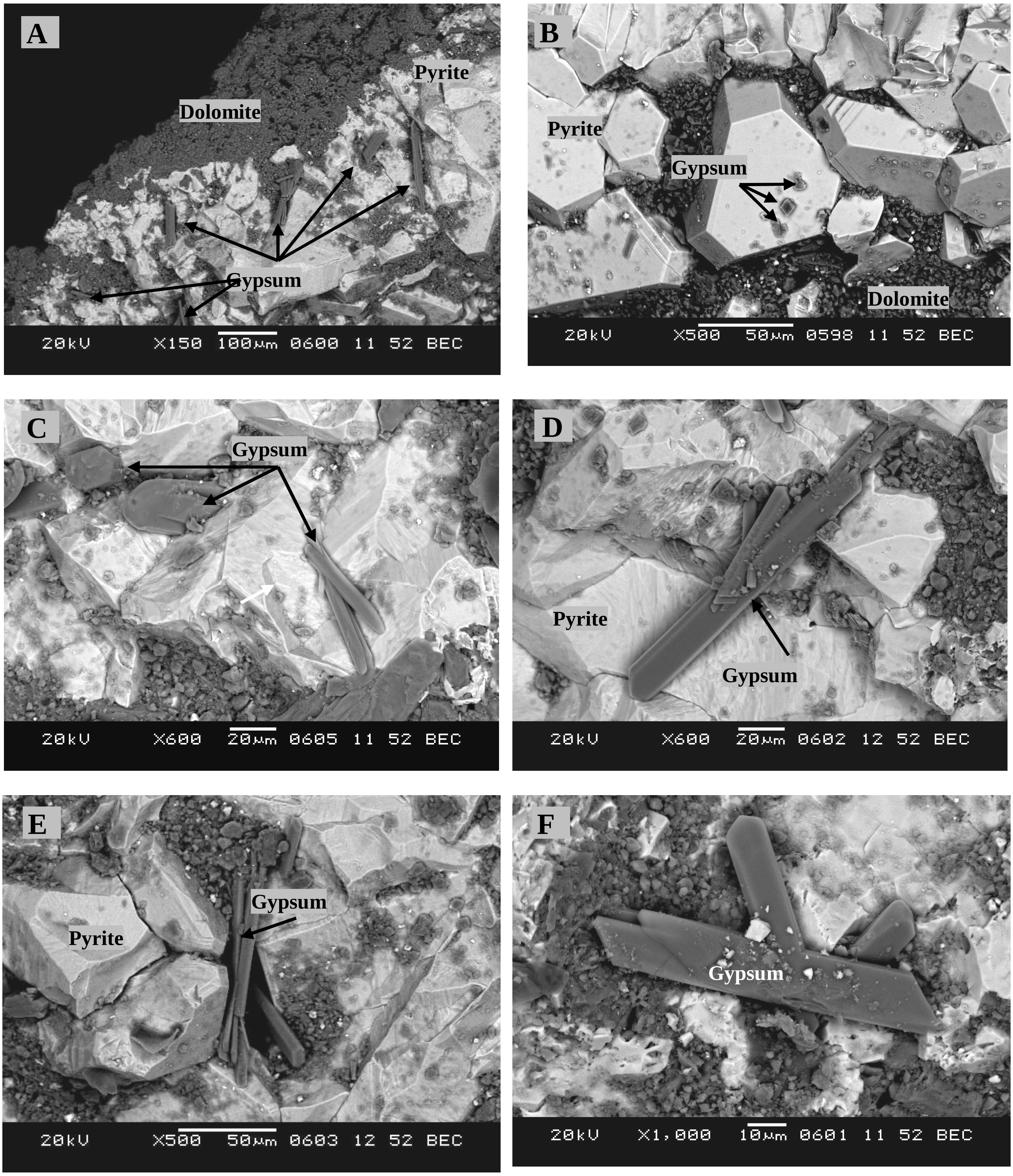


Figure 8. Backscattered-SEM images showing euhedral gypsum minerals formed at the boundary of dolomite and pyrite minerals from the well AFS-13 at 405 m level.

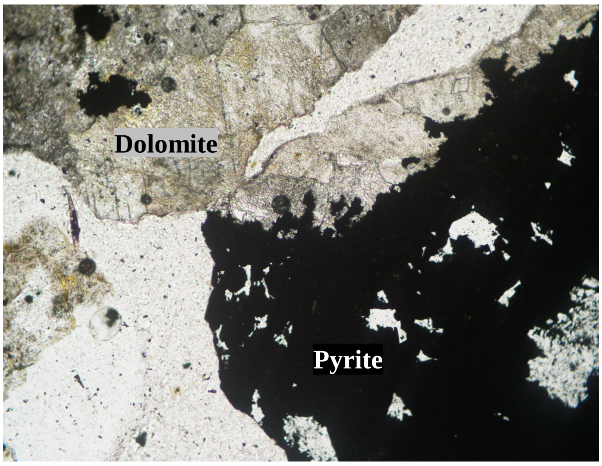


Figure 9. Photomicrograph showing dolomite minerals, replaced by pyrite related to the hydrothermal alteration.

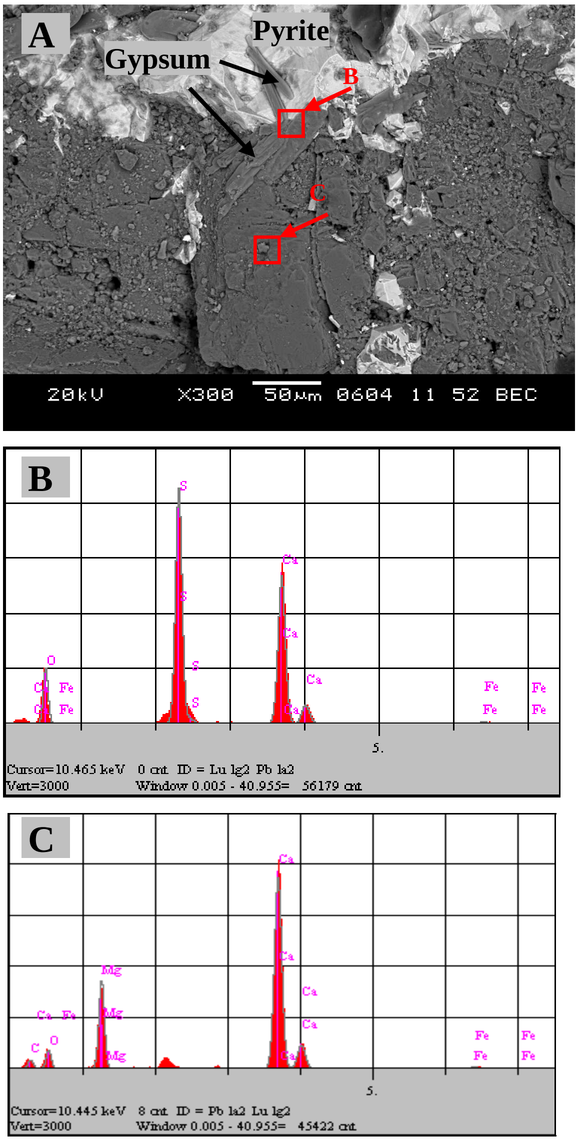


Figure 10. (A) Backscattered-SEM image showing euhedral gypsum minerals formed by replacement of pyrite at the boundary of dolomite and pyrite minerals within the dolomitic limestone (Çaltepe Formation) from the well AFS-13 at 405 m level due to the hydrothermal alteration, (B) EDS analyses of gypsum which replaced dolomite, (C) EDS analyses of euhedral dolomite.

The anhedral pyrites which replaced dolomite in dolomitic limestone, have Ag, Te, and As (< 1%), and Nb (3-4%) anomalies (Figure 11). Measured Ag values for euhedral secondary (epigenetic) quartz minerals, formed due to the hydrothermal alteration, range from 0.75% to 1.25% (Figure 12). Zeolite (amisite?) and Mg-calcite minerals were also obtained in this dolomitic limestone. EDS analyses of these two minerals give Nb (>5%), Te (1.5-6%) and Ag (0.4-1%) anomalies.

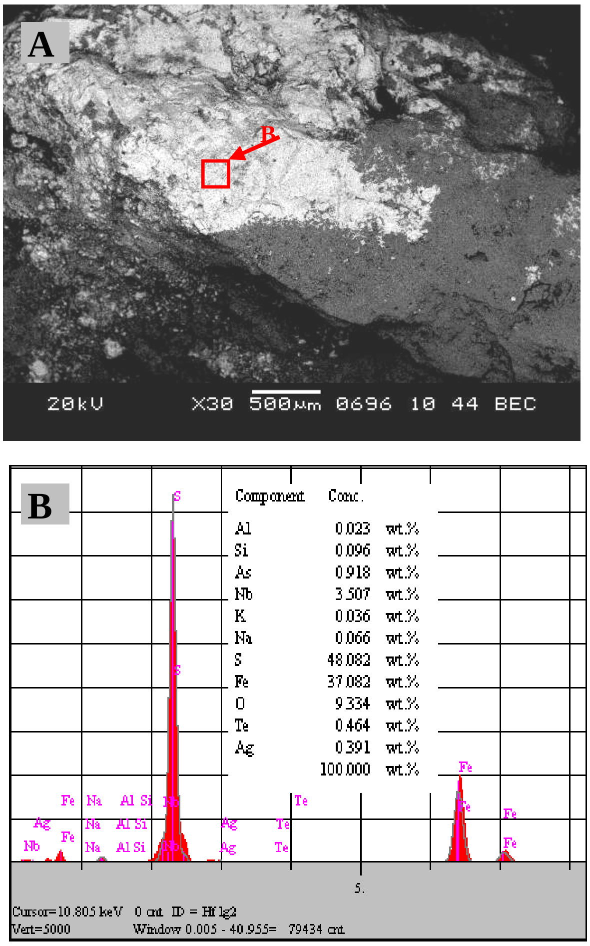


Figure 11. Backscattered electron image showing anhedral pyrite which replaced dolomitic limestone formed within the dolomitic limestone (Çaltepe Formation), related to the hydrothermal alteration from the well AFS-13 at 410 m level (A), and EDS analyses (B). Measured Ag, Te and As values and Nb values for anhedral pyrite are <1% and 3-4%, respectively.

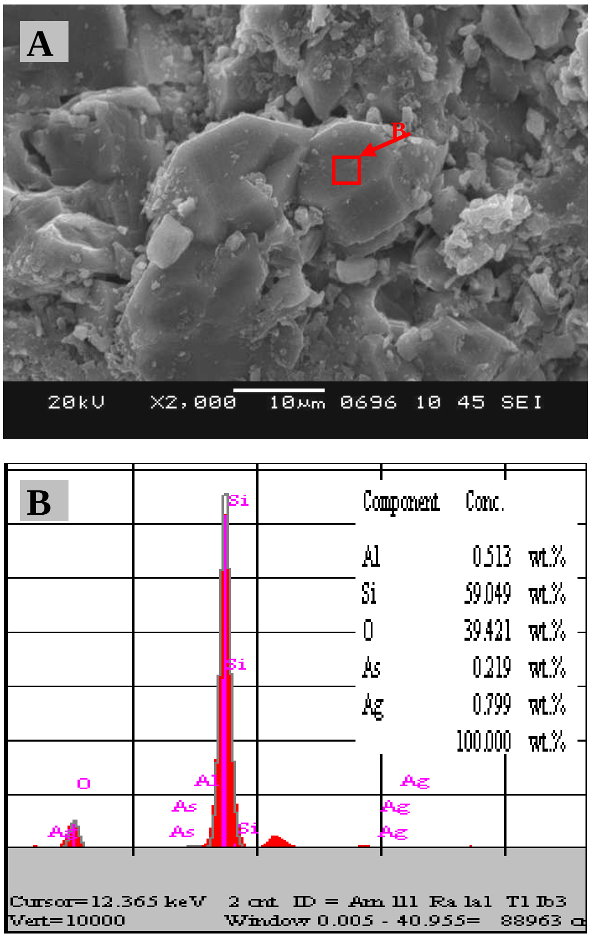


Figure 12. Backscattered-SEM image showing euhedral secondary (epigenetic) quartz formed within the dolomitic limestone (Çaltepe formation), related to the hydrothermal alteration from the well AFS-13 at 410 m level (A) and EDS analyses (B). Measured Ag values for quartz range from 0.75% to 1.25%.

5. CONCLUSIONS

A widespread and intense hydrothermal alteration zones and geothermal systems have developed in the Sandıklı (Afyon) region. In the study area which geothermal system is observed, Miocene volcanism formed different products at wide ranges, and alkaline, calc-alkaline lavas such as trachyte, andesite, trachyandesite (latite), latite basalt, phonolite and tephrite, tuffs and ignimbrites have formed during Middle-Upper Miocene at different stages. The hot springs of the Sandıklı region are located along the fault system that caused intense porphyry-type hydrothermal alteration and mineralization at 4.5 km NE of the Karacaören village (Sandıklı).

The major lithologies of the wells AFS-12 and 13 are alluvium, Quaternary sediments, epiclastic-volcanoclastics and lava flows and basement rocks. The primary minerals present in the Sandıklı subsurface rock samples are mainly sanidine, pyroxene, biotite, plagioclase, nosean and apatite. In general, carbonatization and chloritization are common in the matrix and pyroxene phenocrysts of the trachytic rocks. Mineralogic-petrographic investigations on the wells, silicification, and chalcedony and hematite formation are common near surface. Abundance of hematite and pyrite with marcasite and sericite increase due to the hydrothermal alteration from surface to depths. Primary apatites and titanomagnetite minerals associated with sanidine and euhedral pyroxene (augite) occur within the trachyandesite at deeper levels.

The hydrothermal mineral paragenesis suggests that there were several mineralizing episodes, and this geothermal system must be considered with the porphyry-type hydrothermal alteration and mineralization at 4.5 km NE of the Karacaören village (Sandıklı).

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