Arabian Journal of Geosciences (2021) 14:1117
https://doi.org/10.1007/s12517-021-07086-3

ORIGINAL PAPER

Evaluation of physico-mechanical properties with petrographic characteristics of Hisartepe volcanic rocks (Söke-western Anatolia) based on alteration indices

Ahmet Karakaş[1] · Aykut Güçtekin[1]

Received: 20 November 2020 / Accepted: 7 April 2021
© Saudi Society for Geosciences 2021

Abstract
This study reveals the petrographic and geochemical characteristics, physico-mechanical properties, and chemical alteration indices of Hisartepe volcanic rocks with basaltic andesite, trachyandesite, and andesite composition. Although all rocks have common groundmass plagioclase microlites, the porphyritic texture is majorly evident except for aphyric Asartepe samples. Phenocryst rates vary by location, and vesicle rates are around the maximum of 5%. The chemical alteration indices used to determine the degree of alteration of rocks are in a narrow range and indicate a weak and limited alteration. Plagioclase index of alteration (PIA) and sericitization index (SI) imply the alteration degree of plagioclase mineral abundance in most study area rocks. According to these indices, the most altered rocks in the study area are in the NE Davutlar and Hisartepe regions. Petrographic determination and XRD analysis of rocks verify these results. The rocks of the study area yielded uniaxial compressive strength (UCS) varying between 36.80 and 87.40 MPa classified as low and medium strength. Bohme abrasion of the study area rocks changes from 6.90 to 12.65 $cm^3/50\ cm^2$ and increases with the degree of alteration and loss on ignition (LOI). The USC and point load strength values increase with the decrease in phenocryst sizes and ratios. The different results seen in the chemical alteration indices of volcanic rock samples taken from different locations are due to the modal mineralogy in rocks. Petrographic characteristics such as the phenocryst ratio and phenocryst size along with the alteration affect the mechanical properties of the volcanic rocks. As a result, the Sivritepe and Asartepe samples are the best samples in terms of engineering properties.

Keywords Hisartepe volcanic rocks · Physical properties · Mechanical properties · Petrographical characteristics · Chemical-alteration indices

Introduction

Volcanic rocks have been widely used in engineering projects and for commercial purposes. The determination of physical, mechanical, and mineralogical properties of volcanic rock is a crucial step for rock characterization. A series of tests and analyses should be undertaken to determine these properties.

Responsible Editor: Zeynal Abiddin Erguler

✉ Ahmet Karakaş
akarakas@kocaeli.edu.tr

Aykut Güçtekin
guctekin@kocaeli.edu.tr

[1] Engineering Faculty, Geological Engineering Department, Umuttepe Campus, Kocaeli University, İzmit, Kocaeli, Turkey

Hisartepe volcanic rocks, on top of the Neogene units in the Söke Basin, are potential commercial materials and have long been quarried for the crushed rock aggregate production in the region. Thus, a study relating properties of Hisartepe volcanics for rock characterization in terms of alteration degrees was undertaken because no detailed study relating physical, mechanical, and mineralogical properties of Hisartepe volcanic rocks exists in the literature. Thus, this study first defines the mineralogical and petrographic, geochemical, and physico-mechanical properties and then relates these properties to evaluate the Hisartepe volcanic rocks in terms of alteration indices.

Recent studies show how the physical and mechanical properties of these rocks change as a result of a detailed examination of the properties of volcanic rocks such as alteration and petrographic characteristics (Frolova et al. 2010; Nara et al. 2011; Pola et al. 2012; Heap et al. 2014a; Pola et al.

Published online: 07 June 2021

2014; Wyering et al. 2014; Heap et al. 2015). Volcanic rocks exhibit a wide range of mechanical behaviors due to physical and chemical differences caused by both weathering and hydrothermal alteration. With these two basic alterations, the strength of the rocks can decrease by changing the mineralogical, chemical, and physical properties such as fading the color of the volcanic rocks and developing porous structures. The varying amount and types of minerals in the composition of rocks provide important information about the degree of alteration of volcanic rocks. Similarly, the geochemical characteristics, which are the result of changes in the major and trace element concentrations of these rocks, provide information about the degree of alteration, which is associated with the differences in the physical and mechanical properties of the rocks.

The alteration can vary widely from region to region, and there is intense research in the literature on this topic (Slack 1993; Ohmoto 1996; Carvalho et al. 1999). In addition to difficult to measure weathering or hydrothermal alteration effects, it cannot always decrease the mechanical properties of materials (Watters et al. 2000). Many studies in the literature explain weathering or hydrothermal alteration effects and new mineral formation processes depending on these effects (Duzgoren-Aydin et al. 2002; Zimbelman et al. 2004). However, various petrographic and alteration indices related to chemical, petrological, physical, and mechanical properties have been proposed to define the effect of alteration in magmatic rocks (Ceryan et al. 2008; Yıldız et al. 2010; Pola et al. 2012). Besides, although studies related to the differentiation of the strength of the rock changing as a result of alteration are available in the literature (Watters and Delahaut 1995; Zimbelman et al. 2004), it is stated that properties such as mineral content, secondary minerals, and microstructural elements can affect the strength of the rocks (Tuğrul and Zarif 1999; Rigopoulos et al. 2010; Coggan et al. 2013; Heap et al. 2014a). Also, the textural pattern of a rock is a complex factor affecting its mechanical behavior. Changes in the mineralogical composition and texture of basalts affect their physico-mechanical properties (Korkanç and Tuğrul 2004). Arıkan et al. (2007) studied the characterization of weathered acidic volcanic rocks and a weathering classification based on a rating system. They developed the weathering classification system for the acidic volcanic rock materials based on rating porosity, indirect tensile strength, block punch strength, and P wave velocity engineering parameters and suggested another weathering classification system based on visual descriptions and Schmidt hammer rebound values for the rock masses studied. Ündül and Tuğrul (2012) evaluated the influence of weathering on the engineering properties of dunites. They determined the changes in engineering properties mostly related to serpentinization at every stage of weathering and the most suitable parameters for characterizing the degree of weathering of the studied dunites such as loss-on-ignition values, specific gravity, unit weight, water absorption, and effective porosity. Koralay and Çelik (2019) investigated the mineralogical, petrographical, physical, and mechanical properties of moderately welded ignimbrites used as building stones in the Uşak Region (SW Turkey). They stated that the structure of ignimbrites is weak and sensitive to environmental and usage conditions. Monticelli João et al. (2020) studied the relationship between durability index and uniaxial compressive strength of a gneiss rock of the Nova Venécia Complex at different weathering grades in southeastern Brazil. They indicated that the rock studied has one facies with greater susceptibility to weathering, loss of strength, and durability.

This study investigated the mineralogical and petrographic, geochemical, and physico-mechanical properties of Hisartepe volcanic rocks outcropped in the Söke Basin. Petrographic studies included thin section analyses that identified the types of minerals, crystal sizes, and degree of alteration in the rocks. XRF and XRD analyses defined the chemical compositions of the rocks. Physical and mechanical laboratory tests of the rocks provided the essential physico-mechanical properties. Additionally, several alteration indices were used to define the alteration degrees of the Hisartepe volcanic rocks. The relationship between the physico-mechanical properties and alteration degrees of rocks was established for the evaluation of rock quality.

Regional geology and characteristics of volcanic rocks

Hisartepe volcanic rocks are the products of Tertiary volcanism seen in the western Aegean region and are found in different areas as volcanic eruptive centers over the Neogene units along an ENE-WSW direction around Söke and Davutlar in the Söke Basin (Fig. 1). Volcanic rocks, which are the subject of the study, cropped out in the Söke Basin (Gürer et al. 2001; Gürer et al. 2009) between Söke and Kuşadası, north of the Menderes River in the Büyük Menderes Graben basin area. Ercan et al. (1986), Yılmaz et al. (1999), Ünay and Göktaş (1999), Sarıca (2000), Gürer et al. (2001, 2009), and Sümer et al. (2013) explained the tectono-stratigraphical evolution of the Söke Basin. The Neogene units filling the Söke Basin extend from Dilek Peninsula in the south to Kuşadası in the north and there are outcrops in a narrow zone in the N–S direction between Söke and Kuşadası (Gürer et al. 2001). Both strike–slip and steeply dipping normal faults border most of the Söke Neogene basin and most of the basin sediments are terrestrial clastics (Fig. 1).

Volcanic rocks representing the upper levels of the Neogene units are composed of several individual lava flows distributed linearly in an approximately NE–SW direction (Fig. 2a). In volcanism, which has an intermediate and slightly

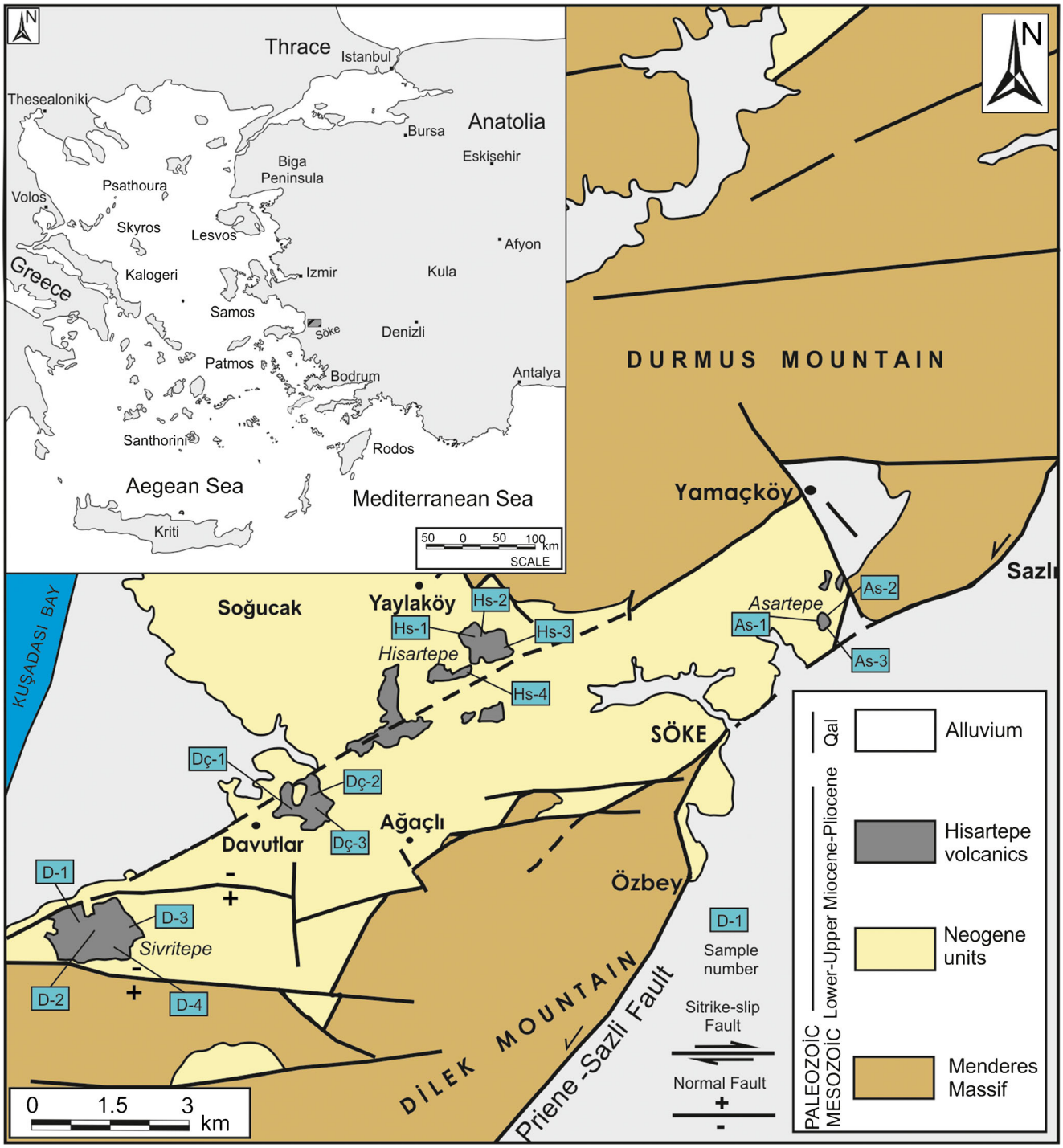


Fig. 1 Simplified geological map of the Söke Basin and its surroundings and distribution of volcanic rocks. The inset map in the upper left corner shows the West Anatolia and locality of the Söke Basin (simplified from Gürer et al. 2001)

basic character, the Sivritepe, Hisartepe, and Asartepe cones are volcanic eruptive centers. Hisartepe volcanism, which did not erupt pyroclastic products, shaped the region with partially low viscosity lavas flowing from volcanic centers. Gray and black volcanic rocks are aphyric and weakly porphyritic and contain common columnar joints with basin pattern structures (Fig. 2b, c). These columnar joint structures develop depending on the topography under the lava. Textural features and degrees of alteration in volcanic rocks present differences in the regions. In the vicinity of Caferli village, the cooking zone observed at the contact between the Hisartepe volcanic lava and carbonate rocks of Kuşadası formation representing the upper levels of the Neogene units indicates that the lavas characterizing volcanism are younger than the Kuşadası

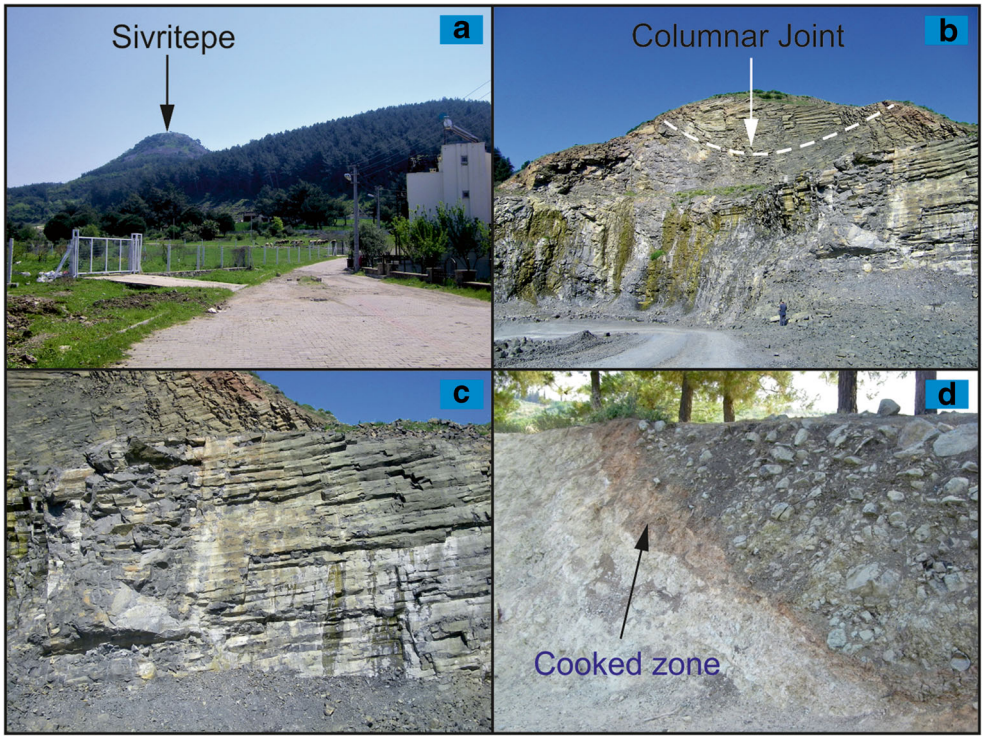


Fig. 2 Field photographs showing the main characteristics of volcanic rocks in the basin (**a**) volcanic eruptive center in Sivritepe (**b**, **c**) columnar joint with basin pattern of the volcanic rocks from Hisartepe (**d**) cooking zone at contact of volcanic rocks

formation (Fig. 2d). In the distribution of these rocks in the region, there are differences in terms of trace element and radiogenic isotope characteristics between those in the western sections (e.g., Sivritepe) and those in the eastern sections (e.g., NE Davutlar, Hisartepe, Asartepe) (Aldanmaz et al. 2019). According to dating studies of samples from different locations of volcanism, various ages were defined between 6.99 ± 0.22 Ma (K–Ar dating; Ercan et al. 1996), 11.56 ± 0.16 Ma (Ar–Ar dating; Uzel et al. 2017), and 12.24 ± 0.09 Ma (Ar–Ar dating; Sümer et al. 2013) for the volcanic rocks. Ercan et al. (1996) defined new ages of 14.1±0.5 Ma (Middle Miocene) with the K/Ar radiometric age determination method for Hisartepe volcanic rocks.

Materials and method

Hisartepe volcanic rocks and samples taken from the volcanic rocks constitute the material of the study. Irregular block samples were collected from rocks at 14 points in four volcanic eruptive centers in the field and these irregular block samples were cut into 5 and 7 cm cube specimens in a marble workshop. These cube specimens were used for petrographic and chemical analyses and for defining the mechanical and physical properties. This study mainly consisted of field and laboratory studies to perform the required tasks for the study. The methods used in the study consisted of analytical studies to be applied to rock samples and evaluation of the results obtained from the laboratory tests, the calculation of the alteration indices, and relating the properties based on the results.

The first effort was to define the mineralogical and petrographic properties of rock samples under a polarizing microscope through thin sections produced from the rock samples. In addition to the thin section analysis, XRD studies have been conducted to assist in the determination of micro-phases. Powdered samples for XRD analysis were analyzed by D8 ADVANCE BRUKER-XRD in the ITU geochemistry laboratory. XRF analyses were performed at ACME Analytical Laboratories Vancouver (Canada) to determine major element compositions. Loss on ignition (LOI) was calculated on the dried samples heated to a temperature of 1000°C. Then, laboratory tests and analyses were performed on the specimens to determine the physical and mechanical properties. The first tests undertaken were to define the physical properties. The physico-mechanical properties of the samples were determined by the tests performed following the standards in the rock mechanics laboratory of the Geological Engineering Department at Kocaeli University. For physical properties, unit weight (γn), specific gravity (Gs), porosity (n), and water absorption by weight (w_a) tests based on TS 699 (2009) were performed in the rock mechanics laboratory. For mechanical properties, uniaxial compression strength (σ_c) (TS EN 1926 2007), point load strength index (Is_{50}) (TS 699 2009), and hardness determination with Schmidt hammer (ISRM 2014) and Bohme abrasion (TS 699 2009) tests were performed. Finally, the alteration indices based on chemical contents were calculated to define the decomposition levels of the volcanic

rocks and establish the relation of physico-mechanical properties with alteration indices.

Results

As a result of field studies and thin section, XRF, XRD analyses, and laboratory tests, the petrographic and mineralogical, alteration, physical, and mechanical properties of Hisartepe volcanic rocks are defined and explained below.

Petrography and mineralogy of volcanic rocks

Ercan et al. (1986), Sümer et al. (2013), and Aldanmaz et al. (2019) previously described the petrography of volcanic rocks around the Söke Basin. The volcanic rocks consist of basaltic andesites, andesites, and trachyandesites. In addition to petrography studies of these volcanic rocks, X-ray diffractometer (XRD) analysis was performed to identify minor mineral phases and some alteration minerals (Fig. 3). Detailed petrographical properties of rocks and XRD analysis results are shown in Table 1. Samples in the Sivritepe region contain andesitic composition and generally in pilotaxitic textures and some places of glomerophyric textures. Plagioclase (Pl), amphibole (Amp), and pyroxene (Px) are the most abundant phenocryst phases and olivine (Ol) phenocrysts are rare in these volcanic rocks. Phenocryst ratios in rocks are between 12 and 22% and the rocks contain vesicles of different sizes. In some samples, the vesicle is not observed, except for one sample, in others it reaches up to 5%. Pl phenocrysts show zoning and sieve texture in these rocks. Amphiboles are widely distributed, forming euhedral and subhedral crystals, and are approximately completely opacified (Fig. 4a). In some samples, reaction rims of small crystals of Px surrounded the partially resorbed quartz (Q).

Amp and Pl phenocrysts are widespread in the samples in the northeast of Davutlar, whereas Px and Ol phenocrysts are less common. Phenocryst ratios are between 8 and 25% and vesicle ratios are approximately 3–5%. In rocks where microlitic and glomerophyric textures are observed, the alteration is much higher than in other locations (Fig. 4b). In plagioclases, sieve textures, cognate Qz crystals, and opacified amphiboles constitute the general magma mixing textures observed in rocks.

In the vicinity of Hisartepe, Px and Ol phenocrysts are more abundant than Amp and Pl phenocrysts, but microlitic and glomerophyric textures are dominant in rocks. Some Ol phenocrysts have widespread serpentinization. Pyroxenes occur as small euhedral/subhedral phenocrysts concerning plagioclases and in some cases (Fig. 4c). Euhedral crystals are 0.5–1 mm in length. In some samples, partially resorbed Q is surrounded by reaction rims of small crystals of Px. Phenocryst ratios in rocks are between 8 and 20% and vesicle ratios are approximately 2–4%. The groundmass in these rocks is microlite-rich and volcanic glass and opaque microphenocrysts.

Unlike other locations, the samples in the vicinity of Asartepe are fresher and phenocryst sizes are smaller (Fig. 4d) than the ones in other locations. In these rocks, Ol and Px phenocrysts are common and Amp phenocrysts are in trace amounts. Phenocryst ratios of the rocks with the microlitic, pilotaxitic, and glomerophyric textures are approximately 5% and vesicle rates are low. Most of the samples do not contain vesicles. Ol phenocrysts are euhedral to subhedral, rounded crystals up to 1 mm in size and some of them exhibit weak alteration to their external margins. Pl, Px, and Ol glomerophyric clusters also occur in all samples.

Whole-rock geochemistry and alteration signs of volcanic rocks

The volcanic rocks found in the region are covered by Le Bas et al. (1986) total alkaline ($Na_2O + K_2O$) versus SiO_2 (TAS) diagram with calc-alkaline character, and basaltic andesite, andesite, and trachyandesite lithologies were determined (Fig. 5). The rocks are saturated with silica but contain 54–61% SiO_2. Besides, MgO values in rocks are low (0.03–0.12%) and have varying Mg (Mg# 52–71) content. The Al_2O_3 (12.16–15.66%) values are high and Cr_2O_3 contents are in the range of 0.02–0.08% in rocks with moderate CaO (4.41–8.90%) values.

Major element concentrations of the samples collected from 4 locations in the region were normalized to the freshest sample in each field, and related diagrams were created (Fig. 6). Since the diagrams are created for the freshest sample taken from the fields, major element changes are relative. According to major element changes, all Sivritepe samples have a slight negative K_2O anomaly. While some samples of the same group have positive MgO and CaO concentrations, some samples have slight positive or negative Fe_2O_3 and MnO concentrations. MnO, MgO, and CaO-positive anomalies are seen in the NE Davutlar samples.

While Hisartepe samples mainly have positive Fe_2O_3, MnO, and negative TiO_2, Al_2O_3, CaO, and Na_2O_3 concentrations, MnO, MgO, and K_2O concentrations vary in Asartepe samples. The decrease in CaO and Na_2O indicates that these elements are highly mobile and preferably removed from rocks during the altering processes.

However, altered samples have high LOI values (LOI: ~3–4% wt%; Table 2) due to the formation of low-temperature minerals such as clay and chlorite, iron oxides, and carbonate fillings, which are seen in thin sections as a result of fluid–rock interaction with post magmatic processes. Major elements such as SiO_2, Na_2O, CaO, and K_2O were recalculated to 100% volatile free and plotted against LOI as a monitor for hydrothermal alteration (Fig. 7). As can be seen in the

Table 1 Petrographic description, whole rock, XRD and major alteration products with the associated rock names.

Sample No	Sample Location	Rock Name	Texture	Rate of Phenocrysts	Phenocrysts	Alteration	Trace Mineralogy
D-1	Sivritepe	Andesite	Slight trachytic, Glomeroporphyritic	~%22	Pl>Amp>Px>Ol>Qz	Sericite, opacite, carbonate	Illite, quartz, calcite, dolomite, albite
D-2	Sivritepe	Andesite	Pilotassitic, Glomeroporphyritic, vesicular (~%20)	~%12	Pl>Amp>Px>Ol	Opacite (rare)	Illite, albite, calcite, dolomite, cristobalite
D-3	Sivritepe	Andesite	Pilotassitic, Glomeroporphyritic	~%13	Amp >Pl>Px>Ol	Sericite, chlorite, opacite,	Illite, quartz, albite, calcite, dolomite
D-4	Sivritepe	Andesite	Pilotassitic, Glomeroporphyritic, vesicular (~%5)	~%20	Amp >Pl>Qz>Px>Ol>Qz	Sericite, chlorite, opacite,	Montmorillonite, calcite, dolomite, quartz
Dç-1	NE Davutlar	T. Andesite	Microlitic, vesicular (~%3,5)	~%12	Amp>Pl>Px~Ol>Qz	Opacite, chlorite (common)	Montmorillonite, illite, quartz, albite, dolomite, carbonate
Dç-2	NE Davutlar	T. Andesite	Microlitic, Glomeroporphyritic	~%25	Pl>Amp>Qz> Px~Ol	Opacite	Montmorillonite, illite, albite, calcite, dolomite, quartz
Dç-3	NE Davutlar	T. Andesite	Slight trachytic, vesicular (~%5)	~%8	Amp>Pl>Qz>Px	Opacite (rare)	Montmorillonite, illite, albite, quartz
Hs-1	Hisartepe	B. Andesite	Hyalopilitic, vesicular (~%4)	~%20	Px>Ol>Amp >Qz, Pl (rare)	Chlorite (common)	Montmorillonite, illite, dolomite, calcite, carbonate, albite
Hs-2	Hisartepe	B. Andesite	Hyalopilitic, vesicular (~%2)	~%10	Ol >Px> Pl>Amp>Qz	Chlorite, carbonate	Illite, quartz, albite, calcite, dolomite
Hs-3	Hisartepe	B. Andesite	Hyalopilitic, vesicular (~%2)	~%15	Px>Amp >Ol>Pl	Carbonate (rare)	Cristobalite, Illite, calcite, montmorillonite, quartz, albite
Hs-4	Hisartepe	B. Andesite	Hyalopilitic, vesicular (~%2)	~%8	Ol >Px>Pl>Amp	Opacite (rare)	Illite, calcite, cristobalite, albite, montmorillonite,
As-1	Asartepe	B. Andesite	Slight trachytic, Glomeroporphyritic	~%6	Ol>Px>Pl	Rare	Calcite, dolomite, quartz, albite
As-2	Asartepe	T. Andesite	Microlitic	~%10	Ol>Px>Amp	Opacite	Montmorillonite, illite, albite, calcite, dolomite, quartz
As-3	Asartepe	T. Andesite	Slight trachytic	~%4	Px>Ol>Pl, Amp rare	Rare	Montmorillonite, illite, quartz, calcite, dolomite, albite

Abbreviations; Pl: Plagioclase, Amp: Amphibole, Px: Pyroxene, Ol: Olivine, QPhotomicrograph exhibiting: Quartz.

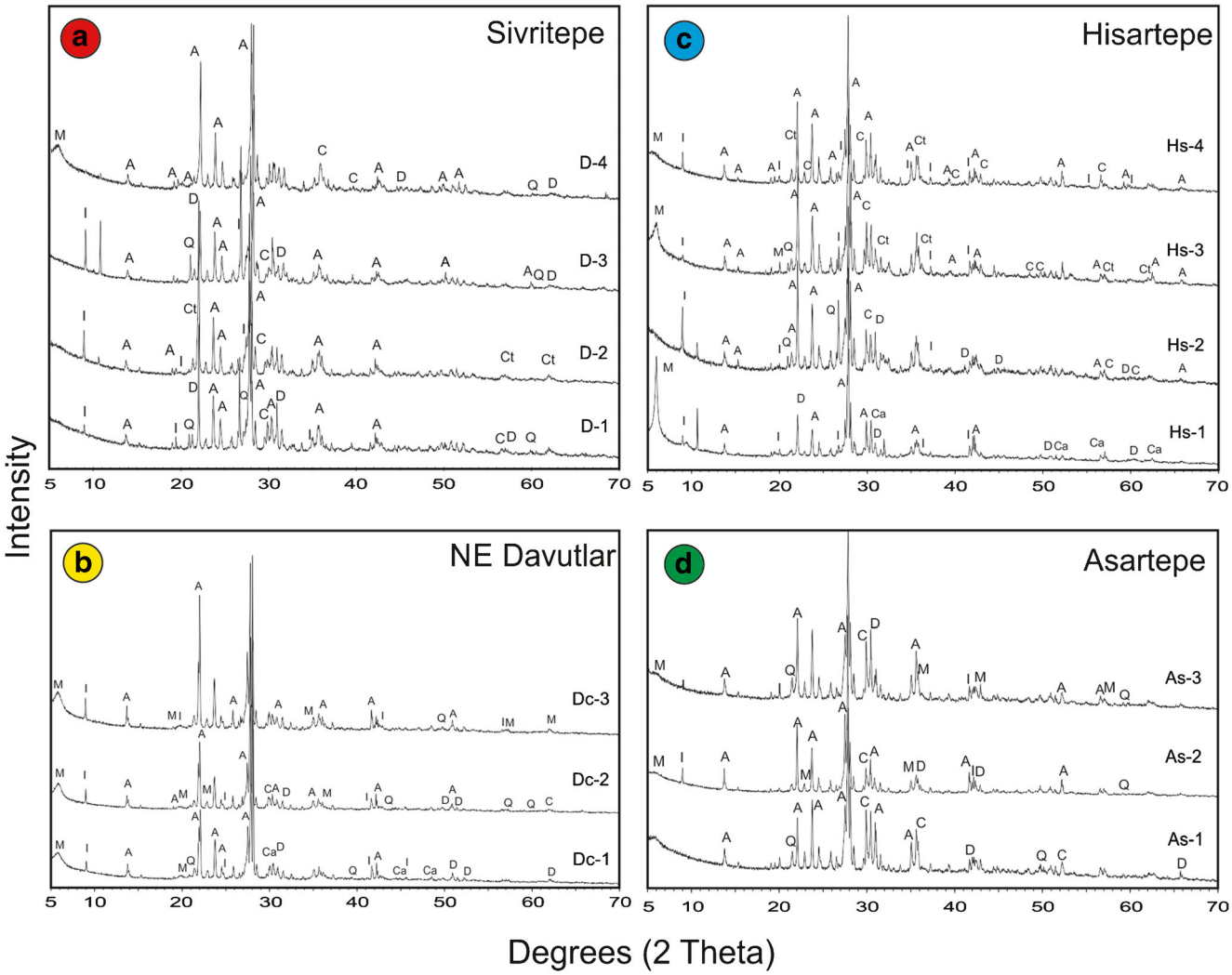


Fig. 3 X-ray diffraction patterns of volcanic rocks (**a**) Sivritepe; (**b**) NE Davutlar; (**c**) Hisartepe; (**d**) Asartepe (A – albite; C – calcite; D – dolomite; Q – quartz; M – montmorillonite; I – illite; Ct – cristobalite; Ca – carbonate)

diagram, there is a weak hydrothermal alteration in the rocks. While SiO_2 contents of the samples did not show significant changes due to LOI (Fig. 7a), CaO and Na_2O contents decreased with the alteration of LOI due to leaching of Na_2O and CaO during alteration (Fig. 7b, c). With a similar effect, Fig. 7d shows an increase in K_2O with increasing LOI values.

To determine the mineralogical and chemical changes that occur in rock as a result of alteration, the chemical alteration indices are used, which can be calculated using the evaluation of major element concentrations and loss of ignition. These changes that occurred during alteration were used to determine the degree of alteration of volcanic rocks and the calculated values are given in Table 2.

AI index (Ishikawa alteration index), one of the indices commonly used for volcanic rocks, explains the formation of sericite and chlorite with the alteration of sodic plagioclase and volcanic glass (Ishikawa et al. 1976). Slight high concentrations in the AI index (AI = 45–51) of the NE Davutlar and Hisartepe samples specify a weak formation of sericite and chlorite in the samples. CIA (chemical index of alteration), which shows the degree of chemical alteration of rocks, is interpreted as a measure of the change of feldspar minerals to clay minerals, and CIA values increase in parallel with the increase in clay minerals in the rock (Nesbitt and Young 1982). These values are significantly higher in NE Davutlar samples than in other groups (Table 2). However, the chemical index of weathering (CIW) values proposed by Harnois (1988) increases as the degree of alteration increases. According to CIW values, weathering can be mentioned in NE Davutlar samples (50–54) and to a lesser extent in Sivritepe (45–48) samples. The increase in CIW and CIA values can be attributed to the loss of mobile cations and the change of crystal structure (Haskins 2006). The high value of CIA is mainly due to an increase in Al_2O_3 content, which can be associated with the accumulation of clay minerals.

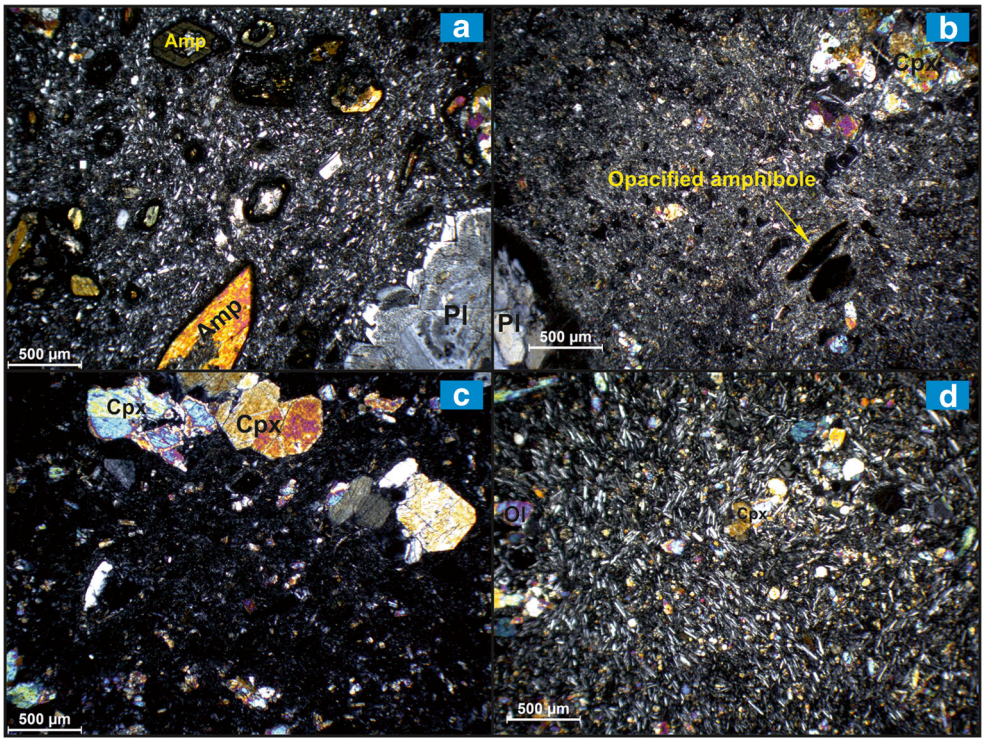


Fig. 4 Photomicrographs showing the main characteristics of volcanic rocks (**a**) completely sieved Pl phenocrysts and opacified Amp phenocrysts in andesite of the Sivritepe region (**b**) Photomicrograph exhibiting glomeroporphric and pilotaxitic textures formed in trachyandesite (**c**) euhedral/subhedral Px crystals in basaltic andesite. (**d**) Photomicrograph displaying microlitic texture formed in basaltic andesite by the occurrences of small prismatic crystals and anhedral grains of CPx in interstices between the crystals of Pl

The plagioclase index of alteration (PIA) verified the degree of decomposition of plagioclase minerals, one of the main components of igneous rocks, into clay minerals by dissolution during alteration processes (Fedo et al. 1995). For this reason, it can be easily used in evaluating the degree of alteration of rocks. According to the PIA index, the values in NE Davutlar (46–60) and to a lesser extent in Sivritepe (41–44) rock groups in the region indicate that the strong mobility of Ca and Na is due to the dissolution of plagioclase (albite). Similarly, the sericitization index (SI) measured the sericite formation as a result of an alteration of plagioclases in volcanic rocks (Maclean and Hoy 1991). According to calculations, sericitization in the NE Davutlar samples is more evident.

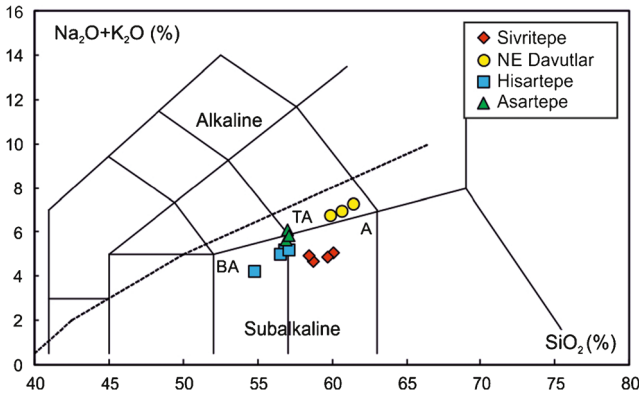


Fig. 5 Classification of the volcanic rocks from the Söke Basin on a TAS diagram of Le Bas et al. (1986). Key to abbreviations: BA – basaltic andesite; A – andesite; TA – trachyandesite

Chlorite–carbonate–pyrite index (CCPI) is a measure of the increase in MgO and FeO and decrease of Na_2O and K_2O concerning the development of Mg–Fe chlorite, which is commonly replaced by albite, K feldspar, or sericite in volcanic rocks (Large et al. 2001). This index is not useful for monitoring the alteration in mafic rocks because they typically have high primarily MgO and FeO abundances (Gifkins et al. 2005). This situation is evident in the unaltered rock-normalized diagrams for Hisartepe samples (Fig. 5). Parker weathering index (WIP) is used to evaluate the weathering intensity of igneous/metamorphic rocks. WIP values are based on the proportions of alkali and alkaline-earth (sodium, potassium, magnesium, and calcium) elements in the rock (Parker 1970). Low WIP values indicate strong chemical alteration, while high WIP values reveal that the rock is not altered. According to the WIP index, NE Davutlar (28–30) and Hisartepe (18–24) samples reflect the most altered rocks in the study area (Table 2).

An acceptable correlation is observed between the alteration degree and chemical indices (AI, CIA, CIW, PIA, SI, and CCPI). While AI, CIA, PIA, and CIW values increase with the alteration, the CCPI decreases. High values obtained from AI, CIA, CIW, PIA indices show increased alteration by petrographic results.

In the K_2O+Na_2O versus sericitization index (SI) diagram, the weak hydrothermal alteration effect is observed in the samples, whereas this effect was more prominent in the samples representing NE Davutlar and Hisartepe (Fig. 8). In the CaO diagram against the sericitization index, it is seen that

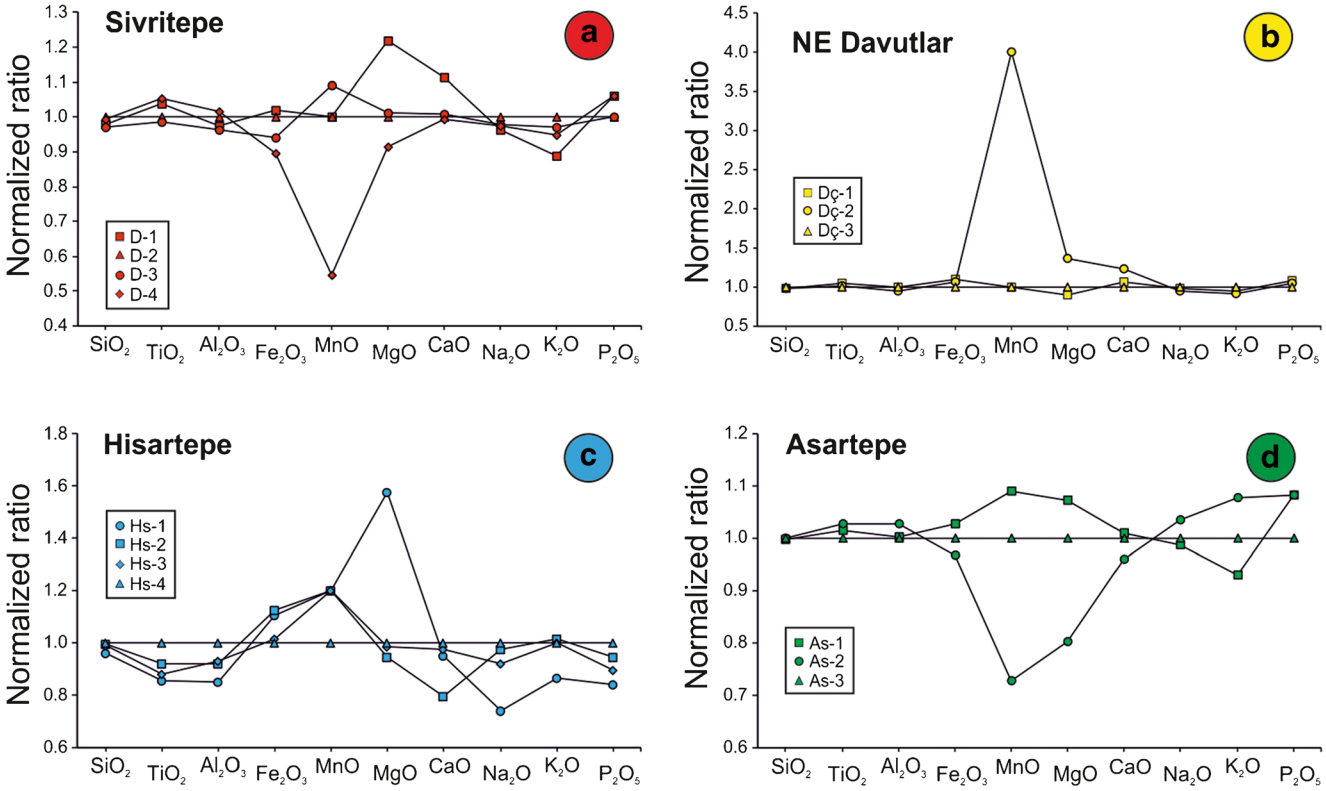


Fig. 6 The unaltered rock-normalized major element pattern for the volcanic rocks

CaO value decreases as the SI value increases in the same group of rocks. Despite the median SI values in the samples, high CaO contents indicate the dominant alteration type of carbonation (Fig. 8, inset diagram). Using the "alteration box plot" that incorporates Ishikawa alteration index (AI) with chlorite–carbonate–pyrite index (CCPI), the alteration trends of the rocks directly show the alteration mineralogy and degree of alteration of each rock unit to their lithogeochemistry. Volcanic rocks with increased sericite–carbonate alteration (Fig. 6d, f) are plotted above the unaltered box with increased CCPI values, whereas samples with increased sericite ± chlorite alteration are plotted to the right of the box due to increased AI values. In the diagram, most volcanic rocks are plotted within the box of the least altered intermediate volcanic host rocks (mainly andesite–basalt region) mainly within the hydrothermal alteration field (Fig. 9). These rocks mainly exhibit trends, which coincide with the carbonate–sericite alteration in the hydrothermal alteration field, which is consistent with the general alteration of calcite and other clay minerals observed in these rocks.

Physical and mechanical properties

Determination of physico-mechanical properties has a crucial role in the evaluation of rocks for various purposes. In this study, physico-mechanical properties of the samples were obtained according to the TS (Turkish Standards) in the rock mechanics laboratory. One of the main parameters of the mechanical properties of the rock is its compression strength. Various tests have been developed in the laboratory to determine this parameter. The most common of these tests are uniaxial compressive strength (UCS) tests performed according to TS EN 1926 (2007) standard on 7 cm cube specimens. With uniaxial compression, the strength of the sample with a certain surface area against the compaction forces in one direction is determined. Point load tests were accomplished based on TS 699 (2009) standard on 5 cm cube specimens, which yielded the point load strength index values (Is_{50}) of the Hisartepe volcanics. One of the mechanical properties is the hardness of the rock, which can be defined as the resistance of a material to scratching, abrasion, surface penetration, and indentation. Schmidt hammer test in laboratory based on the suggested method of ISRM (2014) defined the hardness of the volcanic rock specimens. Another mechanical feature is abrasion, which is the resistance of a material against wearing. Bohme test was used for the determination of abrasion on the 7 cm cube specimens and conducted according to the TS 699 (2009) standard. The results obtained from the physical and mechanical tests on the samples are shown in Table 3. Results obtained from the physical and mechanical tests yielded the numerical range of the properties and allowed the evaluation and comparisons of these properties with mineralogical and petrographic characteristics of the Hisartepe volcanic rocks.

Table 2 The chemical composition and alteration index of the volcanic rocks. All weathering indexes are calculated using oxide values in molar units except for CCPI and SI indices.

Major elements, Oxides (%),	D-1	D-2	D-3	D-4	Dç-1	Dç-2	Dç-3	Hs-1	Hs-2	Hs-3	Hs-4	As-1	As-2	As-3
SiO_2	58.81	60.09	58.46	59.70	60.80	60.02	61.58	54.91	56.96	56.66	57.25	56.96	57.09	57.10
TiO_2	0.79	0.76	0.75	0.80	0.58	0.56	0.55	0.64	0.69	0.66	0.75	0.71	0.72	0.70
Al_2O_3	15.27	15.66	15.11	15.90	15.30	14.63	15.36	12.16	13.22	13.35	14.33	15.17	15.56	15.13
Fe_2O_3	6.76	6.62	6.24	5.93	5.30	5.11	4.83	7.09	7.23	6.50	6.41	6.45	6.07	6.28
MnO	0.11	0.11	0.12	0.06	0.03	0.12	0.03	0.12	0.12	0.12	0.10	0.12	0.08	0.11
MgO	4.57	3.75	3.80	3.43	2.52	3.79	2.79	8.82	5.27	5.52	5.59	5.25	3.92	4.89
CaO	7.79	6.99	7.06	6.95	4.67	5.40	4.41	8.46	7.08	8.66	8.90	8.40	7.97	8.31
Na_2O	2.72	2.82	2.76	2.75	3.06	2.95	3.14	1.90	2.50	2.36	2.57	2.87	3.01	2.91
K_2O	1.97	2.22	2.16	2.11	3.81	3.72	4.04	2.21	2.59	2.55	2.55	2.74	3.18	2.95
P_2O_5	0.17	0.16	0.16	0.17	0.25	0.24	0.23	0.16	0.18	0.17	0.19	0.26	0.26	0.24
Cr_2O_3	0.04	0.02	0.02	0.03	0.04	0.04	0.03	0.08	0.05	0.05	0.06	0.02	0.03	0.03
LOI	1.16	1.25	2.11	2.40	3.48	3.17	3.29	3.70	4.49	3.37	1.48	1.46	1.19	0.93
Sum	100.37	100.66	98.97	100.45	100.28	100.16	100.69	100.56	100.69	100.29	100.53	100.82	100.21	100.47
Mg number	57.25	52.88	54.68	53.40	48.51	59.51	53.37	71.14	59.09	62.72	63.34	61.72	56.13	60.67
Alteration Indices														
AI	38.36	37.83	37.77	36.35	45.02	47.35	47.50	51.57	45.07	42.27	41.51	41.48	39.27	41.13
CIA	42.85	44.71	43.87	45.51	47.29	42.93	47.46	37.21	40.58	37.78	38.68	40.44	41.14	40.19
CIW	45.58	48.00	47.07	48.69	54.20	50.93	54.87	40.15	44.40	40.99	41.80	43.92	45.26	43.92
SI	0.42	0.44	0.44	0.43	0.55	0.56	0.56	0.54	0.51	0.52	0.50	0.49	0.51	0.50
LAI	2.42	2.06	2.04	1.93	1.14	1.33	1.06	3.87	2.46	2.45	2.34	2.09	1.61	1.91
CCPI	70.72	67.29	67.11	65.82	53.23	57.16	51.49	79.47	71.06	71.00	70.09	67.59	61.74	65.59
PIA	41.88	43.86	42.91	44.83	46.37	60.41	46.51	35.02	38.62	35.52	36.70	38.65	39.17	38.19
WIP	25.83	26.68	26.82	26.38	29.81	28.74	30.40	18.82	24.61	23.14	24.62	27.34	28.73	27.66

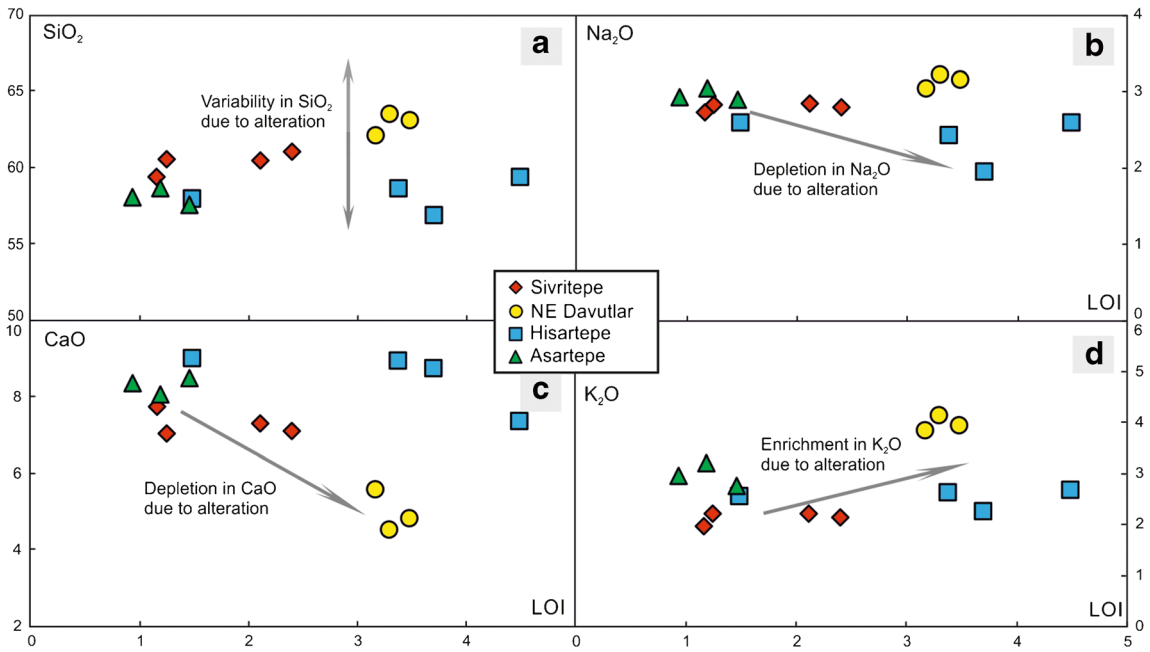


Fig. 7 Major elements vs LOI of the volcanic rocks. LOI is considered an alteration index

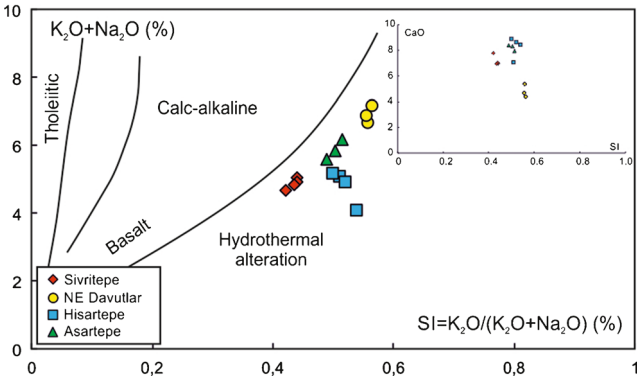


Fig. 8 Binary plot of sericitization index (SI) against (K_2O+Na_2O) (MacLean and Hoy 1991) of the volcanic rocks. The inset diagram shows the variation of SI vs. CaO for the volcanic rocks

The heavy mineral content of the basalts allows the Gs values to take different values. It has shown that Gs is closely related to engineering properties (Shakoor et al. 1982; Cargill 1989). The Gs values of the study area samples vary from 2.554 to 2.791. The Gs mean value of the Hisartepe specimens is greater than the samples of the other groups. The reason why this value is slightly higher in the Hisartepe specimens than the other groups is due to the modal abundance of high-density minerals such as Ol and Px. Porosity in volcanic rocks mainly increases with vesicle formation due to the volatile content of the magma. Also, as a result of fluids dissolving minerals with an alteration in rocks, new voids are formed through mass loss (Ferry 1979; Giggenbach 1984; Henneberger and Browne 1988; Reyes 1990; Simmons and Browne 2000; Esmaeily et al. 2012). Here, there are many factors by which porosity in the rock can vary greatly (Hudyma et al. 2004; Heap et al. 2014b). Porosity has a significant effect on the change of rock strength, and even with a small increase in pore volume, a visible decrease in strength can occur (Sammis and Ashby 1986; Fakhimi and Gharahbagh 2011; Heap et al. 2014a, b). Although the porosity results of the samples examined vary, high porosity values are noteworthy in NE Davutlar samples as the most altered rocks in the study area. Besides, the effect of vesicle rates determined by petrographic studies on porosity is observed in each group. Despite weak alteration in Asartepe samples, the absence of such a relationship can be attributed to the micro-size of the vesicles in these samples.

The hardness of the rocks is determined by the Schmidt hammer test in the field or laboratory in a fast and practical manner. De Beer (1968) developed a classification separating the rocks into hardness classes according to the rebound number obtained from the test. Schmidt hammer values are between 29 and 51 for all samples. These values vary from 31 to 38 in Hisartepe samples, and from 32 to 36 in NE Davutlar samples, and are in hard stone class according to the De Beer (1968) classification of Schmidt hammer rebound value.

The rocks of the study area have UCS values varying between 36.80 and 87.40 MPa. The range and mean values of each group fall into the low and medium strength rock classes according to the Deere and Miller (1966) UCS classification. The NE Davutlar samples, which are the most altered rocks of the region, have UCS values between 38.22 and 60.80 MPa. In addition, the Is_{50} values for the same group varied between 1.96 and 2.38 MPa and are low and medium-strength rock classes. The Is_{50} values varied from 1.96 to 8.77 MPa for all samples. The range of the Is_{50} values for all samples falls into the low-high strength classes, but when the mean value of each group is considered, they are placed in the medium-high strength classes according to the Bieniawski (1975) point load strength classification.

The abrasion loss, which is a physical and mechanical event caused by friction of rock surfaces with abrasive materials, is determined by the Bohme abrasion test. Forces coming into the rock surface in the friction form or impact lead to surface wear. The amount of abrasion depends on the type of material, the shape of the friction surfaces, the friction conditions, and the chemical effects of the environment. Bohme abrasion values of the study area rocks ranged from

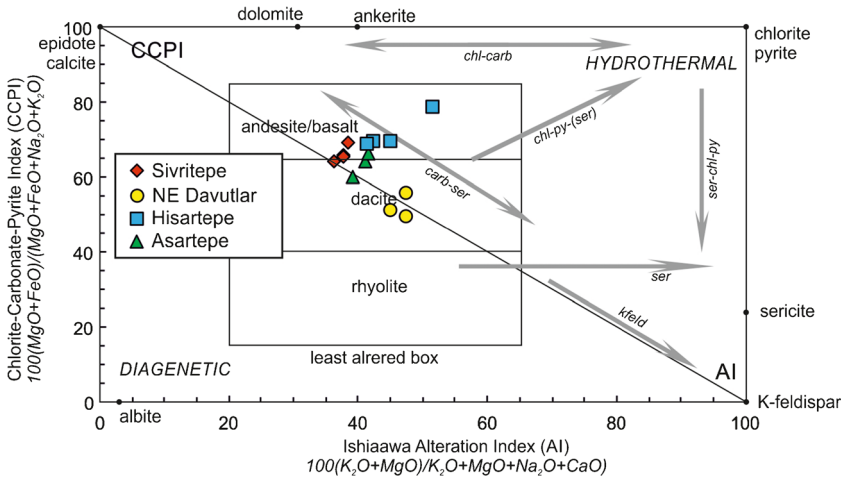


Fig. 9 Plots of Chlorite–Carbonate–Pyrite Index (CCPI; index and diagram was taken from Large et al. 2001) versus Hashimoto Alteration Index (AI; by Ishikawa et al. 1976) of the volcanic rocks. Diagram contains a box for the least altered rhyolites according to Large et al. (2001) as well as nodes for individual alteration minerals (Ab – albite, Kfs – K-feldspar, Cal – calcite, Chl – chlorite, Ep – epidote)

Table 3 Mean values of physical and mechanical properties of the volcanic rocks.

Sample No	Gs	w_a		Bulk Weight	n	Schmidt Hammer	Is_{50}	σ_c	Bohme Abrasion
		By Weight	By Volume						
	(-)	(%)	(%)	(gr/cm^3)	(%)	(N)	(MPa)	(MPa)	(m^3/50cm^2)
D-1	2.750	0.104	0.276	2.442	1.37	40	7.53	60.80	7.48
D-2	2.620	0.608	1.328	2.311	6.63	56	8.7	87.40	6.90
D-3	2.554	0.140	0.360	2.470	3.29	43	6.4	42.62	8.02
D-4	2.621	1.318	3.108	2.306	4.36	51	8.1	79.72	7.43
Dç-1	2.536	1.313	3.166	2.258	5.56	32	2.31	41.46	9.77
Dç-2	2.576	1.459	3.156	2.109	11.98	29	2.23	38.22	12.65
Dç-3	2.569	1.167	2.660	2.208	7.19	36	2.38	60.80	8.82
Hs-1	2.782	0.747	2.183	2.621	5.79	31	6.0	55.48	8.90
Hs-2	2.606	0.283	0.822	2.488	4.53	36	7.47	64.51	8.20
Hs-3	2.791	1.310	3.254	2.484	11.00	30	4.1	36.80	10.86
Hs-4	2.581	0.592	1.499	2.368	4.55	38	7.1	65.30	8.13
As-1	2.725	0.330	0.858	2.515	7.71	45	8.77	85.36	7.12
As-2	2.558	0.954	2.424	2.425	5.20	38	5.46	52.72	8.20
As-3	2.624	0.218	0.547	2.420	7.77	45	9.85	72.55	7.50

6.90 to 12.65 cm^3/50 cm^2. According to these values, the volcanic rocks in the study area are low abradable materials based on the TS standard limit values defined in TS EN 1467 (2014) and TS EN 1469 (2015).

Discussion

Volcanic rocks can exhibit different mechanical behaviors due to chemical and mineralogical changes caused by alteration. The behavior of rocks under loads is closely related to the mineralogical composition and petrographic and discontinuity characteristics (Přikryl 2006; Ündül et al. 2015). Changes in rock strength are observed in non-heterogeneous rocks with relatively homogeneous mineralogical components (Eberhardt et al. 1999; Přikryl 2006). Tapponnier and Brace (1976) revealed that changes in rock failure processes are controlled by various rock constitutes and even the smallest element in the rock can have significant effects on the behavior of the rock.

The hydrothermal alteration of volcanic rocks involves the replacement of primary igneous glass and minerals such as Pl, biotite, Amp, and Px with alteration minerals as a result of the deterioration in the temperature range of 150–400°C in general (Shanks and Thurston 2012). Alteration textures range only from the poor replacement of some minerals or matrixes in bedrock to general rock or partially altered phenocrysts. The glassy rock matrix or fine-grained matrix can be particularly sensitive to alteration and can be completely silicate or replaced with chlorite or sericite as the alteration intensity increases. The high-intensity alteration transformed the majority of all primary minerals in rocks into new hydrothermal minerals (Shanks and Thurston 2012).

The elements are leached from altered minerals and redistributed in the crystal structure of newly formed minerals. In this way, the rocks become more porous and permeable, and have more macro and microfractures, and lose their strength and original appearance due to alteration (Gupta and Rao 2001; Arel and Tugrul 2001; Islam et al. 2002; Taboada et al. 2006; Ceryan et al. 2008; Lee et al. 2008; Momeni et al. 2015). These alterations negatively affect the use of rocks as natural stones and other engineering properties. The degree of alteration in altered rocks can be measured using alteration indices.

The samples selected in the composition of basaltic andesite, andesite, and trachyandesite, which do not contain any fractures, to avoid the negative effects on abrasiveness and other physico-mechanical properties in Hisartepe volcanism near Söke show textural differences in crystal size and shape. In the rocks dominated by microlitic textures in general, phenocryst ratios are higher and phenocryst sizes are higher in NE Davutlar and Hisartepe samples than the other groups. As the phenocryst ratio increases in the same group of rocks, more alteration can be mentioned (Table 1). However, vesicle formations in the rocks are observed in Sivritepe (8%D_2, 5%D_4), Hisartepe (2–4%), and NE Davutlar (3–5%) and Asartepe samples, although they are less at varying rates. Besides, large quartz xenocrysts are remarkably noticed in some Sivritepe (D_1, D_4) and Hisartepe (Hs_1, Hs_2) samples and in all NE Davutlar samples. According to XRD analysis conducted to support petrography studies, illite-type clay minerals are found in Sivritepe and Hisartepe samples, while

montmorillonite and illite-type clays are found together in the NE Davutlar and Hisartepe samples.

The secondary minerals observed in petrographic investigations of rocks and the presence of clay minerals determined in XRD analysis show that these rocks are subjected to different degrees of alteration. In studies on determining the degree of alteration in a rock system, alteration indices are calculated by considering the distribution of chemical elements (major elements). The presence of rocks with a petrographically similar mineralogical and chemical composition such as basaltic andesite, andesite, and trachyandesite in the study area enables the reliable use of major elements in these calculations. Chemical alteration indices differ in rock groups in the study area according to weathering intensity. According to these indices suggested by different researchers (e.g., AI, CIA, CIW), NE Davutlar, and to a lesser extent, Hisartepe samples constitute the most altered rock group in the region. Widespread opacification and carbonation in rocks in the same group support these data.

When the petrographic results of the rock groups and alteration indices were evaluated, mainly altered rock groups and alteration indices coincided, while some indices did not indicate these characteristics. Alteration indices such as CIA and CIW, which show the intensity of clay minerals, and hence the intensity of alteration matches with the high values of NE Davutlar samples. The low values of CIA and CIW alteration indices in the Hisartepe rock group samples, where the alteration is highly observed, can be attributed to the low modal abundance of plagioclase minerals, which strongly contains Al_2O_3 of these samples. A similar situation is observed in the PIA alteration index results. However, the low CCPI values of NE Davutlar samples compared to other rock groups can be because these samples have lower silica content and lower Fe and Mg concentrations than the other groups. In the WIP alteration index results, slightly high values of NE Davutlar samples compared to other groups can be explained by the modal abundance of plagioclase minerals.

In correlation diagrams made to understand the relationships between rock strength and alteration indexes, some correlations are found to be meaningful despite the scattering and differences in the data with generally low-moderate correlation coefficients (r) ($r<0.756$ in Fig. 10). Is_{50} values correlate negatively with alteration indices such as AI, CIW, and SI, and it is uncertain with CCPI index, but shows a weak negative correlation within the same rock groups (Fig. 10). Although there is no significant change in the alteration indexes in Asartepe samples from these groups, variable Is_{50} values can be explained by the phenocryst ratio in these samples. The Is_{50} values increase as the phenocryst ratio and size of the samples decreases. A negative correlation was observed between alteration indices such as AI, SI, and UCS values. In Asartepe samples, a similar phenocryst effect is observed for UCS values. The UCS values of the rocks depend more on grain size than the modal mineralogy. Therefore, the UCS values of volcanic rocks with different phenocryst sizes having approximately similar mineralogical composition are also different. The UCS values of the samples with the most phenocrysts from the rocks of four locations are lower than others (D_1=60.80 MPa; Hs_1=55.48 MPa; $Dç_2$=38.22 MPa; As_2=52.72 MPa).

In the relationship between Schmidt hammer values and alteration indices, there is a clear and negative correlation in alteration indices such as AI and SI. Gs values of the samples correlate negatively with WIP and CIW indices, and positive with the CCPI index. In the correlation diagram created according to the SI alteration index, although the same group of samples has close values, there are differences in Gs values. It is seen that the Bohme values of the rocks increase with LOI (Fig. 10). The lower hardness of hydrous minerals formed with alteration compared to major silicate minerals such as Px and Amp can explain the correlation between LOI values and Bohme results. However, there is a decrease in the Bohme values of aphyric rocks with a low phenocryst ratio among the samples. Bohme abrasion resistance values are slightly positive with AI and CCPI indices, and slightly negative with WIP and CIA indices.

Conclusions

In this study, volcanic rocks of Sivritepe, NE Davutlar, Hisartepe, and Asartepe, which are named Hisartepe volcanic rocks, are investigated petrographically, geochemically, and geomechanically. Rocks are of medium and slightly basic character with basaltic andesite, trachyandesite, andesite composition. Although the microlitic textures are dominant in the rocks, it can be mentioned that there are pilotaxicitic, hyalopilitic, weak trachytic textures with the abundance, size, and alignment of the microlites according to the rock groups. Phenocryst rates are between 4 and 25%, and vesicle rates are generally up to 5%. Pl and Amp minerals are dominant in andesite and trachyandesite samples, and Px and Ol minerals are dominant in basaltic andesite samples. According to XRD analysis, illite, montmorillonite-type clay minerals, carbonate minerals such as calcite, dolomite, and secondary quartz, and albitization are seen in different ratios based on the degree of alteration in rocks. According to the alteration indices calculated to determine the degree of alteration, NE Davutlar and second Hisartepe samples are the most altered rock groups of the region by petrographic results. The alteration indices such as CIA, CIW do not coincide with the altered Hisartepe samples due to the abundance of minerals in the samples. In other words, in this study, the results of alteration indices of petrographically similar rocks are affected by the modal mineral abundance in the rock. However, as the phenocryst ratio

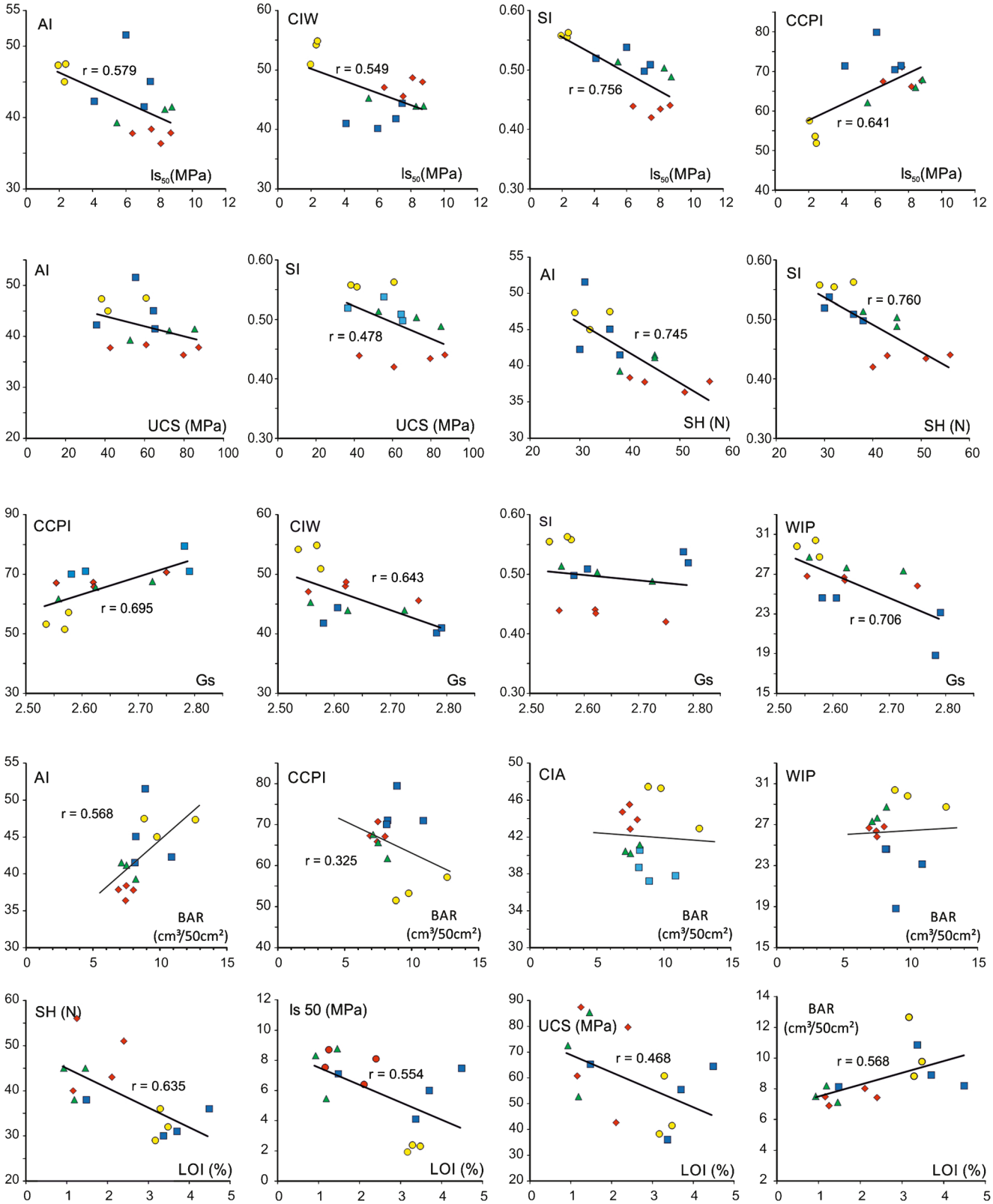


Fig. 10 Relationships between alteration indices and physico-mechanical properties of the volcanic rocks. Key to abbreviations: AI: Ishikawa alteration index; CIW: chemical index of weathering; SI: sericitization index; CCPI: chlorite–carbonate–pyrite index; CIA: chemical index of alteration; WIP: Parker weathering index; Is_{50}: point load strength index; UCS: uniaxial compressive strength; SH: Schmidt hammer; Gs: specific gravity; BAR: Bohme abrasion resistance; LOI: loss on ignition. See Fig. 8 for explanations of the symbols

increases, rocks with similar conditions in the same location show more alteration.

The relationship among the petrography, physico-mechanical properties, and chemical alteration indices was investigated to characterize the material quality of the different volcanic rocks outcropped in the study area. Defining the relationship between the physico-mechanical properties and alteration degrees of the rock material can be beneficial in material characterization. With detailed petrographic investigations, it was observed that the values showing the strength of rocks such as point load strength, and uniaxial compressive strength are related to the phenocryst ratio and sizes, and the rock strength increases with the decrease in the phenocryst ratio and size. Similarly, while the Bohme abrasion values decrease with the reduction in the phenocryst ratio and the phenocryst size, it rises with the increase in the degree of alteration and LOI values. Nearly all of the values of the mechanical properties tested in the investigated volcanic rocks increase as the phenocryst size gets smaller because small-size phenocrysts have stronger interlocking of crystals than large-size phenocrysts. In the light of these results, when petrographic, alteration, and mechanical property results of rock samples taken from four locations in the study area are compared, it can be concluded that increases in the phenocryst ratio, size, and degree of alteration affect the mechanical properties negatively and the most durable and sound samples from these locations belong to Sivritepe and Asartepe regions. Determination of the physico-mechanical properties and alteration degrees of Hisartepe volcanics outcropped in four locations establishes the basis for a better characterization of the rocks.

Acknowledgements This study is a result of the scientific research project supported by the Kocaeli University Scientific Research Projects Coordination Unit, which is greatly acknowledged for financing the project (grant number 2014/085) by the authors.

Funding Code availability is not applicable.

Declarations

Competing interests The authors declare that they have no competing interests.

Availability of data and material All data presented in the text of the article are fully available without restriction from authors upon request.

Code availability Code availability is not applicable.

References

Aldanmaz E, Altunkaynak Ş, Güçtekin A (2019) Some remarks on the nature of mantle metasomatism beneath western Anatolian–Aegean region: contrasting isotopic signatures recorded in the Miocene lavas from the Söke Basin. Geol J 54:3860–3877

Arel E, Tugrul A (2001) Weathering and its relation to geomechanical properties of Cavusbasi granitic rocks in northwestern Turkey. B Eng Geol Environ 60:123–133

Arıkan F, Ulusay R, Aydın N (2007) Characterization of weathered acidic volcanic rocks and a weathering classification based on a rating system. Bull Eng Geol Environ 66:415–430

Bieniawski ZT (1975) The point-load test in geotechnical practice. Eng Geol 9(1):1–11

Cargill JS (1989) Evaluation of empirical methods of measuring the uniaxial compressive strength of rock. Dissertation, Department of Geology, Kent State University 80 p

Carvalho D, Barriga FJAS, Munha J (1999) Bimodal-siliciclastic systems-case of the Iberian Pyrite Belt in Barrie CT, and Hannington MD, eds., Volcanic-associated massive sulfide deposits-Processes and examples in modern and ancient settings. Rev Econ Geol 8: 375–408

Ceryan S, Tudes S, Ceryan N (2008) Influence of weathering on the engineering properties of Harsit granitic rocks (NE Turkey). B Eng Geol Environ 67:97–104

Coggan JS, Stead D, Howe JH, Faulks (2013) Mineralogical controls on the engineering behavior of hydrothermally altered granites under uniaxial compression. Eng Geol 160:89–102

De Beer JH (1968) Subjective classification of the hardness of rocks and the associated shear strength. Proc Reg Confer Africa, Introducer, Cape Town, South Africa 2:396–398

Deere DU, Miller RP (1966) Engineering classification and index properties for intact rocks. Technical Report. Air Force Weapons Lab, New Mexico. AFNL-TR. 65–116

Duzgoren-Aydin NS, Aydin A, Malpas J (2002) Re-assessment of chemical weathering indices: case study on pyroclastic rocks of Hong Kong. Eng Geol 63:99–119

Eberhardt E, Stimpson B, Stead D (1999) Effect of grain size on the initiation and propagation threshold of stress-induced brittle fracture. Rock Mech Rock Eng 32(2):81–99

Ercan T, Akat U, Günay E, Savaşçın Y (1986) Geology of the Söke-Selçuk-Kuşadası region and petrochemical features of the volcanic rocks. Bull Min Res Explor 105-106:15–38

Ercan T, Satır M, Sevin D, Türkecan A (1996) Interpretation of the new radiometric age determinations from the Tertiary and Quaternary volcanic rocks in western Anatolia. Bull Min Res Explor 119: 103–112

Esmaeily D, Afshooni SZ, Mirnejad H, Rashidnejad-e-Omran N (2012) Mass changes during hydrothermal alteration associated with gold mineralization in the Astaneh granitoid rocks, Western Iran. Geochem Explor Environ Anal 12:161–175

Fakhimi A, Gharahbagh EA (2011) Discrete element analysis of the effect of pore size and pore distribution on the mechanical behavior of rock. Int J Rock Mech Min Sci 48:77–85

Fedo CM, Nesbitt HW, Young GM (1995) Unraveling the effects of potassium metasomatism in sedimentary rocks and paleosols, with implications for paleo weathering conditions and provenance. Geology 23:921–924

Ferry J (1979) Reaction mechanisms, physical conditions, and mass transfer during hydrothermal alteration of mica and feldspar in granitic rocks from south-central Maine, USA. Contrib Mineral Petrol 139:125–139

Frolova JV, Ladygin VM, Rychagov SN (2010) Petrophysical alteration of volcanic rocks in hydrothermal systems of the Kuril-Kamchatka Island Arc. Proceedings, World Geothermal Congress. Bali, Indonesia 25–29 April 2010

Gifkins C, Herrmann W, Large R (2005) Altered volcanic rocks–a guide to description and interpretation. Centre Ore Deposit Research, University of Tasmania, Hobart

Giggenbach WF (1984) Mass transfer in hydrothermal alteration systems–a conceptual approach. Geochim Cosmochim Acta 48: 2693–2711

Gupta AS, Rao KS (2001) Weathering indices and their applicability for crystalline rocks. B Eng Geol Environ 60:201–221

Gürer ÖF, Bozcu M, Yılmaz K, Yılmaz Y (2001) Neogene basin development around Söke-Kuşadası (western Anatolia) and its bearing on tectonic development of the Aegean region. Geodin Acta 4:57–69

Gürer ÖF, Sarıca-Filoreau N, Özburan M, Sangu E, Doğan B (2009) Progressive development of the Büyük Menderes Graben based on new data, western Turkey. Geol Mag 146(5):653–673

Harnois L (1988) The CIW index: a new chemical index of weathering. Sediment Geol 55:319–322

Haskins D (2006) Chemical and mineralogical weathering indices as applied to a granite saprolite in South Africa. In: Proc. 10th IAEG Int. Congr. The Geological Society of London, Nottingham, pp 1–14

Heap MJ, Lavallée Y, Petrakova L, Baud P, Reuschlé T, Varley NR, Dingwell DB (2014a) Microstructural controls on the physical and mechanical properties of edifice-forming andesites at Volcan de Colima, Mexico. J Geophys Res Solid Earth 119(4):2925–2963

Heap MJ, Xu T, Chen CF (2014b) The influence of porosity and vesicle size on the brittle strength of volcanic rocks and magma. B Volcanol 76:1–15

Heap MJ, Kennedy BM, Pernin N, Jacquernard L, Baud P, Farquharson JI, Scheu B, Lavallee Y, Gilg HA, Letham-Brake M, Mayer K, Jolly AD, Reuschle T, Dingwell DB (2015) Mechanical behaviour and failure modes in the Whakaari (White Island volcano) hydrothermal system, New Zealand. J Volcanol Geotherm Res 295:26–42

Henneberger RC, Browne PRL (1988) Hydrothermal alteration and evolution of the Ohakuri Hydrothermal system, Taupo Volcanic Zone, New Zealand. J Volcanol Geotherm Res 34:211–231

Hudyma N, Burçin Avar B, Karakouzian M (2004) Compressive strength, and failure modes of lithophysae-rich Topopah Spring Tuff specimens and analog models containing cavities. Eng Geol 73:179–190

Ishikawa Y, Sawaguchi T, Iwaya S, Horiuchi M (1976) Delineation of prospecting targets for Kuroko deposits based on modes of volcanism of underlying dacite and alteration haloes. Min Geol 26:105–117

Islam MR, Stuart R, Risto A, Vesa P (2002) Mineralogical changes during intense chemical weathering of sedimentary rocks in Bangladesh. J Asian Earth Sci 20:889–901

ISRM (2014) Suggested method for determination of the Schmidt hammer rebound hardness: revised version, in Part I - laboratory testing of the orange book: The ISRM suggested methods for rock characterization, testing and monitoring: 2007–2014, Edited by R. Ulusay

Koralay T, Çelik SB (2019) Minero-petrographical, physical, and mechanical properties of moderately welded ignimbrite as a traditional building stone from Uşak Region (SW Turkey). Arab J Geosci 12(23):732. https://doi.org/10.1007/s12517-019-4923-x

Korkanç M, Tuğrul A (2004) Evaluation of selected basalts from Nigde, Turkey, as source of concrete aggregate. Eng Geol 75:291–307

Large RR, Allen RL, Blake MD, Herrmann W (2001) Hydrothermal alteration and volatile element halos for the Rosebery K Lens volcanic-hosted massive sulfide deposit, Western Tasmania. Econ Geol 96:1055–1072

Le Bas MJ, Le Maitre RW, Streckeisen A, Zanettin B (1986) A chemical classification of volcanic rocks based on the total alkali–silica diagram. J Petrol 27:445–450

Lee SY, Kim SJ, Baik MH (2008) Chemical weathering of granite under acid rainfall environment, Korea. Environ Geol 55:853–862

MacLean WH, Hoy LD (1991) Geochemistry of hydrothermal altered rocks at the Horne Mine, Noranda, Quebec. Econ Geol 86(3):506–528

Momeni AA, Khanlari KR, Heidari M, Sepahi AA, Bazvand A (2015) New engineering geological weathering classifications for granitoid rocks. Eng Geol 185:43–51

Monticelli João P, Ribeiro R, Futai M (2020) Relationship between durability index and uniaxial compressive strength of a gneissic rock at different weathering grades. B Eng Geol Environ 79:1381–1397

Nara Y, Meredith PG, Yoneda T, Kaneko K (2011) Influence of macro-fractures and micro-fractures on permeability and elastic wave velocities in basalt at elevated pressure. Tectonophysics 503:52–59

Nesbitt HW, Young GM (1982) Early Proterozoic climates and plate motions inferred from major element chemistry of lutites. Nature 299:715–717

Ohmoto H (1996) Formation of volcanogenic massive sulfide deposits-The Kuroko perspective. Ore Geol Rev 10(3-6):135–177

Parker A (1970) An index of weathering for silicate rocks. Geol Mag 107: 501–504

Pola A, Crosta G, Fusi N, Barberini V, Norini G (2012) Influence of alteration on physical properties of volcanic rocks. Tectonophysics 566–567:67–86

Pola A, Crosta GB, Fusi N, Castellanza R (2014) General characterization of the mechanical behavior of different volcanic rocks with respect to alteration. Eng Geol 169:1–13

Přikryl R (2006) Assessment of rock geomechanical quality by quantitative rock fabric coefficients: limitations and possible source of misinterpretations. Eng Geol 87:149–162

Reyes AG (1990) Petrology of Philippine geothermal systems and the application of alteration mineralogy to their assessment. J Volcanol Geotherm Res 43:279–309

Rigopoulos I, Tsikouras B, Pomonis P, Hatzipanagiotou K (2010) The influence of alteration on the engineering properties of dolerites: the examples from the Pindos and Vourinos ophiolites (northern Greece). Int J Rock Mech Min Sci 47:69–80

Sammis CG, Ashby MF (1986) The failure of brittle porous solids under compressive stress states. Acta Metall 34:511–526

Sarıca N (2000) The Plio-Pleistocene age of Büyük Menderes and Gediz Grabens and their tectonic significance on N-S extensional tectonics in West Anatolia: mammalian evidence from the continental deposits. Geol J 35:1–24

Shakoor A, West TR, Scholer CF (1982) Physical characteristics of some Indiana argillaceous carbonates regarding their freeze–thaw resistance in concrete. Bull Assoc Eng Geol 19(4):371–384

Shanks WCP, Thurston R (2012) Volcanogenic massive sulfide occurrence model: U.S. Geological Survey Scientific Investigations Report 2010–5070-C, 345 p

Simmons SF, Browne PRL (2000) Hydrothermal minerals and precious metals in the Broadlands-Ohaaki Geothermal systems: implications for understanding low sulfidation epithermal environments. Econ Geol 95:971–999

Slack JF (1993) Descriptive and grade-tonnage models for Besshi-type massive sulphide deposits, in Kirkham RV, Sinclair WD, Thorpe RI and Duke JM, eds., Mineral deposit modeling: Geological Association of Canada Special Paper 40:343–371

Sümer Ö, İnci U, Sözbilir H (2013) Tectonic evolution of the Söke Basin: extension-dominated transtensional basin formation in western part of the Büyük Menderes Graben, Western Anatolia, Turkey. J Geodyn 65:148–175

Taboada T, Cortiza AM, Garcí AC, Garcí A, Rodeja E (2006) Uranium and thorium in weathering and pedogenetic profiles developed on granitic rocks from NW Spain. Sci Total Environ 356:192–206

Tapponnier P, Brace WF (1976) Development of stress-induced microcracks in Westerly granite. Int J Rock Mech Min Sci Geomech Abstr 13:103–112

TS 699 (2009) Natural building stones-methods of inspection and laboratory testing. Turkish Standards Institution, Ankara

TS EN 1467 (2014) Natural stone-rough blocks–requirements. Turkish Standards Institution, Ankara

TS EN 1469 (2015) Natural stone products - slabs for cladding–requirements. Turkish Standards Institution, Ankara

TS EN 1926 (2007) Natural stone test methods-determination of uniaxial compressive strength. Turkish Standards Institution, Ankara 19p

Tuğrul A, Zarif IH (1999) Correlation of mineralogical and textural characteristics with engineering properties of selected granitic rocks from Turkey. Eng Geol 51:303–317

Ünay E, Göktaş F (1999) Söke Çevresi (Aydın) Geç Erken Miyosen ve Kuvaterner yaşlı küçük memelileri: Ön sonuçlar. Türk Jeol Bül 42: 99–113 (in Turkish)

Ündül Ö, Tuğrul A (2012) The influence of weathering on the engineering properties of dunites. Rock Mech Rock Eng 45:225–239

Ündül Ö, Amann F, Aysal N, Plötze M (2015) Micro-textural effects on crack initiation and crack propagation of andesitic rocks. Eng Geol 193(2):267–275

Uzel B, Sümer Ö, Özkaptan M, Özkaymak Ç, Kuiper K, Sözbilir H, Langereis CG (2017) Palaeomagnetic and geochronological evidence for a major Middle Miocene unconformity in Söke Basin (Western Anatolia) and its tectonic implications for the Aegean region. J Geol Soc Lond 174:721–740

Watters RJ, Delahaut WD (1995) Effect of argillic alteration on rock mass stability. In: Haneberg WC, Anderson SA (Eds.), Clay and shale slope instability. Geol Soc Am Rev Eng Geol 10:139–150

Watters RJ, Zimbelman D, Bowman S, Crowley J (2000) Rock mass strength assessment and significance to edifice stability, Mt. Rainier, and Mt. Hood. Pure Appl Geophys 157:957–976

Wyering LD, Villeneuve MC, Wallis IC, Siratovich PA, Kennedy BM, Gravley DM, Cant JL (2014) Mechanical and physical properties of hydrothermally altered rocks, Taupo Volcanic Zone, New Zealand. J Volcanol Geotherm Res 188:76–93

Yıldız A, Kuşcu M, Dumlupunar İ, Arıtan EA, Bağcı M (2010) The determination of the mineralogical alteration index and the investigation of the efficiency of the hydrothermal alteration on physico-mechanical properties in volcanic rocks from Köprülü, Afyonkarahisar, West Turkey. B Eng Geol Environ 69:51–61

Yılmaz Y, Genç ŞC, Gürer ÖF, Karacık Z, Altunkaynak Ş, Bozcu M, Yılmaz K, Elmas A (1999) Ege Denizi ve Ege bölgesinin jeolojisi ve evrimi, In: Görür, N. (Eds.), Türkiye Denizleri. Devlet Planlama Teşkilatı, Türkiye Bilimsel ve Teknolojik Araştırma Kurumu yayını, 211–337, Ankara (in Turkish)

Zimbelman DR, Watters RJ, Firth IR, Breit GN, Carrasco-Nunez G (2004) Stratovolcano stability assessment methods and results from Citlaltépetl, Mexico. Bull Volcanol 66:66–79