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Prediction of weathering development in metarhyolites of the Ilgın (Konya) area, SW Turkey

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Abstract: Fresh to weathered metarhyolites crop out in the Ilgın (Konya) area of the Afyon-Bolkardağ Zone. Determination of the development of weathering was studied by physical (i.e. specific gravity, dry unit weight, saturated unit weight, porosity, void ratio, and degree of saturation by weight) and mechanical (i.e. point load) properties and the "point rock change value" (RCV_p) and "point rock change ratio" (RCR_p) values of the metarhyolite rock samples. The samples were classified in 3 groups (i.e. A, B, and C) representing degree of weathering from weathered to fresh rocks based on their RCV_p and RCRp values. The K2O values are 7.09 wt.%, 8.62 wt.%, and 8.75 wt.% and the matrix ratios are 60%-70%, 50%-60%, and 20%-25% for groups A, B, and C, respectively. The RCV_p and RCR_p values of the studied samples range between 0.952 and 0.99 and 4.973% and 0.989%, respectively. Calculations show that metarhyolites will be completely changed by weathering at a 9.01% RCR_p value according to metarhyolite alkali values varying in the 8.12%-9.40% range, with the average value being 8.89%. At the end of the rock change processes by weathering, the rocks remain chemically as metarhyolite, while their physico-mechanical properties and mineralogical compositions change to become soil. The average K-Ar ages vary between 60.4 ± 0.9 Ma and 64.1 ± 2.00 Ma. The whole-rock alteration can furthermore be predicted by the relationships between the RCR_p and K-Ar ages of the 3 groups, which indicate that the rocks will be fully altered in the next 4.593 and 9.393 Ma. The whole-rock alteration will be completed for group A rocks in 4.6 Ma, for group B rocks in 7.2 Ma, and group C rocks in 9.4 Ma, provided that all the weathering agents take effect under the same conditions across the area.

Key Words: Ilgın, metarhyolite, physico-mechanical properties, weathering, point rock change value, point rock change ratio, K-Ar ages, whole-rock alteration

1. Introduction

The study area is located north of the town of Ilgın (Konya Province) in the Afyon-Bolkardağ Zone (ABZ) (Figure 1). The geology, petrography, geochemistry, and K-Ar ages of the metamorphic rocks of the Ilgın area in the ABZ were described in detail by Özdamar *et al.* (2012). These rocks have various degrees of weathering features.

Weathering is the breakdown of rocks and minerals at and below the earth's surface by physical and chemical processes. The reaction of various agents with rocks and weathering processes are shown by changes in the mineralogical, chemical, physical, and mechanical properties and grain size, or alteration in the weathered material compared to the fresh rock. The changes produced in the fresh rock by weathering can be ascribed to partial or complete decomposition of some minerals, the stability of other minerals, the oxidation of ferrous (Fe^{2+}) to ferric (Fe^{3+}) iron, and the partial or complete mobilisation of both major and minor chemical elements (Carroll 1970). Consequently, the weight changes in rock by weathering and alteration processes are reflected as changes in physical and mechanical properties of rocks. These changes can be measured and the discrete effects of weathering or chemical alteration, or both, may be explained with conventional methods for engineering purposes (i.e. Bell 1994). Two of the useful tools in determining the final rock condition are "point rock change value" (RCV_p) and "point rock change ratio" (RCR_p), proposed by Bozkurtoğlu (2003) and Bozkurtoğlu *et al.* (2006). RCV_p represents the final physical, chemical, mineralogical, petrological, and mechanical conditions of rocks. RCV_p values range from 1 to 0, where the rock condition goes from fresh to fully altered. RCR_p is the rock change ratio related to RCV_p values.

This study focuses on the examination of physical, mechanical, chemical, and mineralogical properties of weathered rocks in the Ilgın (Konya) area. The results allow us to predict the full change in rocks by weathering in metarhyolites in the Ilgın area using RCV_p and RCR_p with K-Ar age values, and this is the first study comparing these values.

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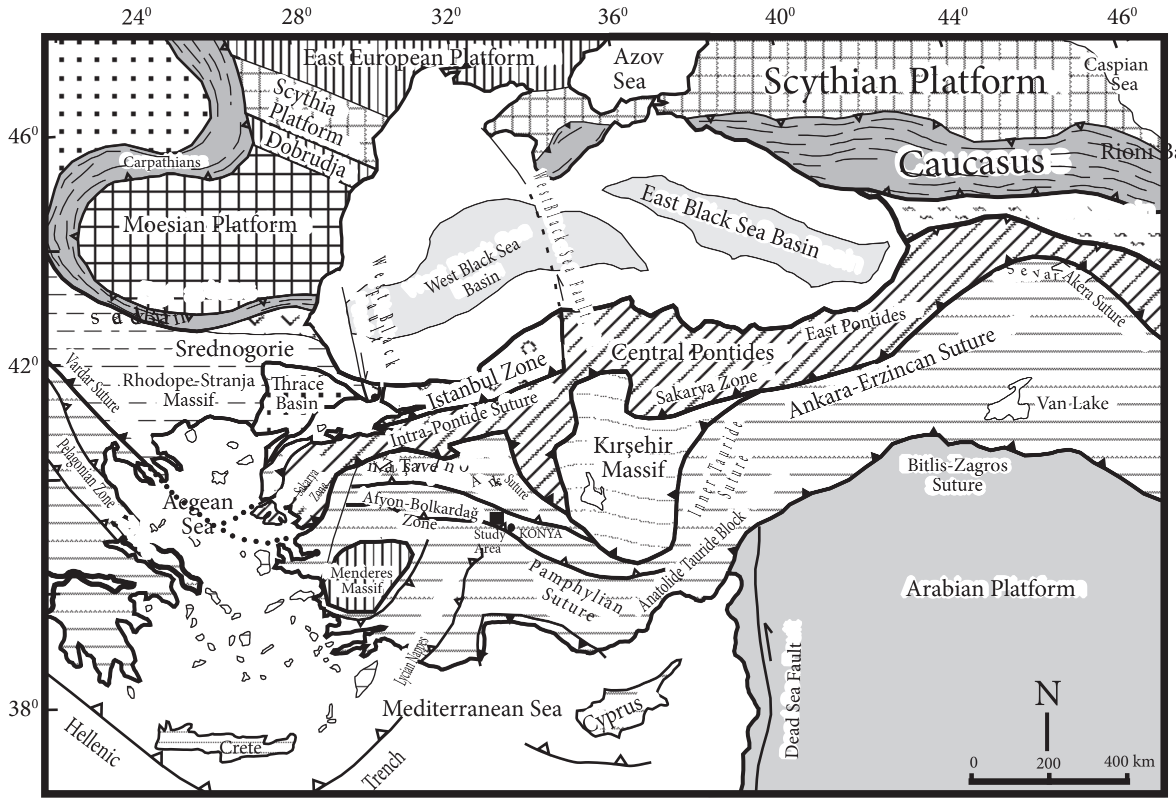

Figure 1. Tectonic units of the eastern Mediterranean Sea-Black Sea region (simplified after Okay & Tüysüz 1999).

2. Geology, petrography, geochemistry, and K-Ar, Ar-Ar, and U-Pb age dating

Two main metamorphic sequences, a Palaeozoic sequence and a Mesozoic sequence, which include metarhyolites, are unconformably overlain by Neogene cover with Quaternary alluvium in the Ilgın (Konya) area, which is a province in the ABZ (Özdamar *et al.* 2012) (Figure 2).

The Palaeozoic metamorphic sequence contains metamorphosed conglomerate, sandstone, siltstone, claystone, limestone, and orthoquartzite. The Mesozoic metamorphic sequence consists of metaconglomerate at the base and fine-grained metasediments, metacarbonate, and intercalated metalavas and metatuffs at the top. Metarhyolites are mostly metalavas and unmapped metatuffs, which occur as thin beds within schists. Neogene sediments consist of yellowish and reddish conglomerate, sandstone, claystone, unconsolidated fragments, and locally carbonate-rich levels. The composition of metarhyolites is made up of 75%-80% groundmass and 20%-25% phenocrysts represented by quartz (Qtz), K-feldspar (Kfs), relict albite (Ab), and possibly sanidine (San). The matrix consists of fine-grained Qtz, Kfs, and Ab and newly formed extensive phengitic white mica. Accessory phases are zircon, rutile, epidote, and apatite (Özdamar *et al.* 2012). The chemical compositions of the metarhyolites are presented in Table 1.

The metarhyolites have 66%-77% SiO_2, 12%-18% Al_2O_3, 5.8%-10.7% K_2O, 0.07%-1.77% Na_2O, 0.1%-1.1% MgO, and <1% CaO, and they plot in the rhyolite, comendite-pantellerite, or rhyodacite-dacite fields in the SiO_2 vs. Zr/TiO_2 diagram of Winchester & Floyd (1977) (Figure 3). Moreover, all samples except one are subalkaline in character (Figure 4) based on the classification of Irvine & Baragar (1971).

The K-Ar ages obtained from the whole-rock samples of metarhyolites are 60.4 ± 0.9 Ma, 62.6 ± 0.9 Ma, and 64.01 ± 2.0 Ma (Özdamar *et al.* 2012). The Ar-Ar phengite ages of the metarhyolites are 63.73 ± 0.06 Ma and 62.64 ± 0.12 Ma, and U-Pb zircon ages of the metarhyolites are 230 ± 2 Ma and 229 ± 2 Ma (Özdamar 2011).

3. Method for generating RCV_p and RCR_p

Specific gravity (γ_s) is a critical measure of rock weathering and alteration (Browne 1998). This is measured by using a pycnometer and can be calculated from the phase diagrams of soil and rock. The ratio of measured values versus values calculated by specific gravity for each sample is the RCV_p (Bozkurtoğlu 2003; Bozkurtoğlu *et al.* 2006). In phase diagrams of soil and rock, the relationship between dry unit weight (γ_d) and specific gravity (γ_s) is given by:

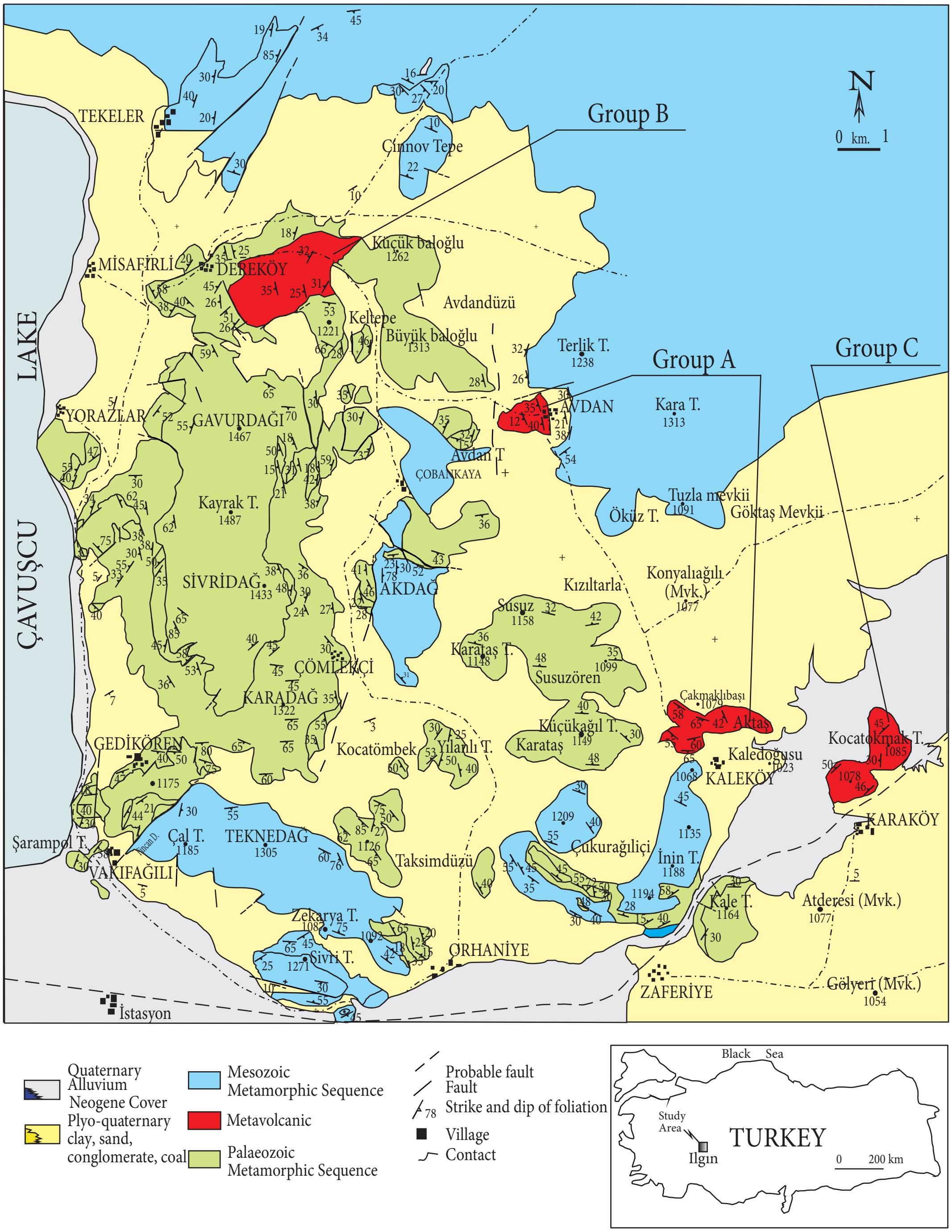

Figure 2. Location and geology map of the study area (from Özdamar *et al.* 2012).

$$\gamma_d = (1 - n)\gamma_s \tag{1}$$

or

$$\gamma_d = \frac{\gamma_s}{1 + e} \tag{2}$$

where n is porosity and e is void ratio.

Specific gravity is calculated by inserting measured values of dry unit weight, porosity, and void ratio. The analysed specific gravity of rock mass ($\gamma_{s(a)}$) is measured with a pycnometer. The estimated specific gravity ($\gamma_{s(c)}$) is calculated by using Eqs. (1) or (2). The RCV_p is generated from the following conditions:

1. If the analysed specific gravity of rock mass ($\gamma_{s(a)}$) is greater than the calculated specific gravity of rock mass ($\gamma_{s(c)}$), then:

Table 1. Geochemical analyses of the metarhyolites (data from Özdamar *et al.* 2012).

Sample no.	SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	CaO (%)	MgO (%)	Na_2O (%)	K_2O (%)	TiO_2 (%)	MnO (%)	P_2O_5 (%)	Ba (ppm)	Zr (ppm)	LOI (%)
A3	70	17.69	1.55	0.1	1.11	0.08	6.64	0.05	0.01	0.05	100	61	2.7
A1	74.87	13.13	1.45	0.45	0.13	1.77	5.8	0.08	0.01	0.06	61	87	1.1
A2	74.58	12.85	0.93	0.94	0.17	0.51	8.09	0.08	0.01	0.04	106	92	1.8
A4	72.24	16.29	1.72	0.06	0.15	0.21	7.82	0.009	0.01	0.03	74	35	1.5
B1	66.91	17.05	1.8	0.9	0.42	0.22	9	0.37	0.02	0.07	134	53	2.8
B2	76.92	12.91	1.2	0.11	0.46	0.07	6.21	0.08	0.009	0.009	79	205	1.5
B3	67.39	17.16	1.66	0.14	0.37	0.14	10.66	0.37	0.01	0.06	299	518	1.8
C1	74.83	13.52	1.05	0.19	0.08	0.76	8.08	0.02	0.009	0.03	177	69	1.4
C2	72.20	14.28	1.46	0.08	0.15	0.26	9.42	0.03	0.02	0.02	139	30.5	1.4

$$RCV_p = \frac{\gamma_{s(c)}}{\gamma_{s(a)}} \tag{3}$$

2. If the analysed specific gravity of rock mass ($\gamma_{s(a)}$) is less than the calculated specific gravity of rock mass ($\gamma_{s(c)}$), then:

$$RCV_p = \left| 1 + \left[1 - \frac{\gamma_{s(c)}}{\gamma_{s(a)}} \right] \right| \tag{4}$$

Eqs. (3) and (4) introduce a new method for quantifying the degree of weathering and alteration in rock material based on specific gravity. Eq. (4) is derived from Eq. (3) empirically. The resultant RCV_p value ranges from 1 to 0, where the RCV_p values of fresh rocks are equal to or very close to 1. In intensively weathered and altered rock processes, RCV_p values approach 0. The RCR_p is also defined with the changes in the entire volume of rocks, as shown in Eq. 5.

$$RCR_p = \left[\frac{1 - RCV_p}{1 - (1 - RCV_p)} \right] x100 \tag{5}$$

In RCR_p, the fresh rock volume is 1, and according to the phase diagram of the soil or rock, the RCV_p shows the present status of rock in the field. The numerator in Eq. (5) represents the changed portion of the rock volume (eroded material) and the denominator is the residual part of the rock volume. As with RCV_p, RCR_p shows the degree of weathering or chemical alteration. RCR_p values near 100% indicate strong weathering and chemical alteration whereas values near 0% indicate minimal weathering and alteration effects. For values of RCV_p equal to or less than 0.5, Eq. (5) provides values exceeding 100%, a condition impossible in nature.

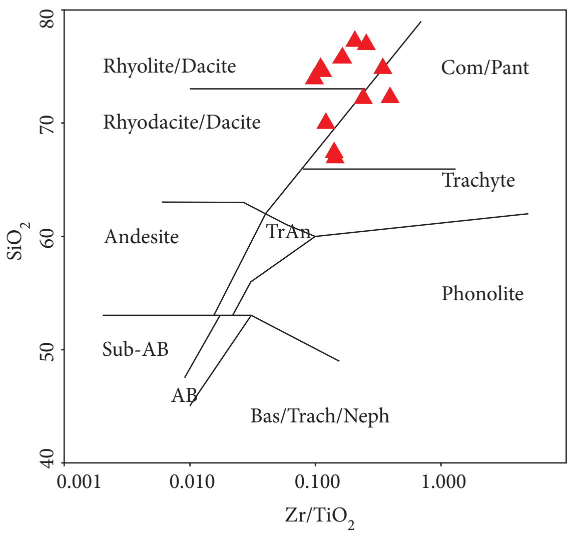

Figure 3. Classification of the metarhyolites of the Ilgın area using the Zr/TiO_2-Nb/Y diagram of Winchester & Floyd (1977) (from Özdamar *et al.* 2012).

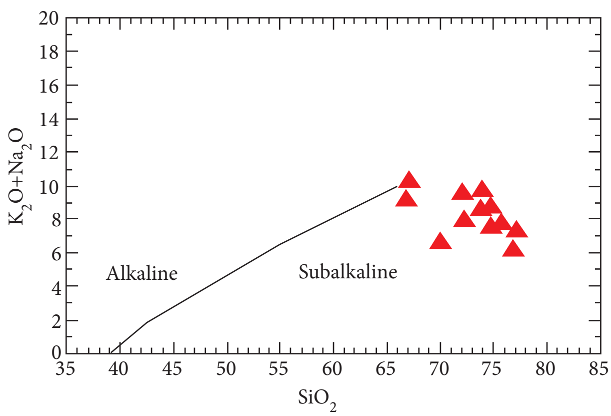

Figure 4. Compositions of the Ilgın metavolcanics using the SiO_2-Na_2O+K_2O diagram of Irvine & Baragar (1971) (from Özdamar 2011).

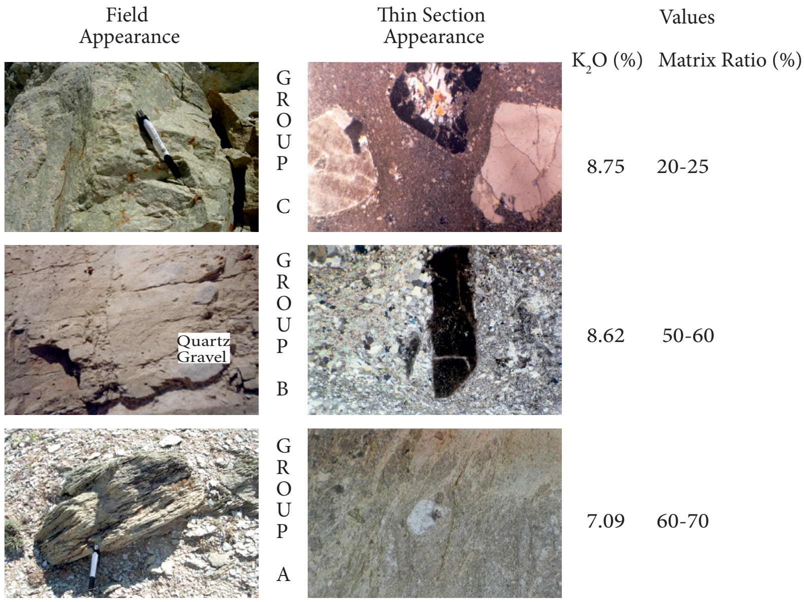

Figure 5. Field and photomicrographs of metarhyolites.

The metarhyolites are classified in 3 groups, namely A, B, and C, which represent their weathering degree from weathered to fresh rocks in terms of their RCV_p values. The appearance of the metarhyolites and their representative thin section images are given in Figure 5, and the RCV_p and RCR_p values of the 3 main groups and their subgroups in the study area are given in Table 2.

In Table 2, the RCV_p and RCR_p values are taken from 5 samples from each subgroup and the 3 main groups' RCV_p and RCR_p. Values are the average values of the subgroups for each main group, and these values are very approximate in Figure 5. The RCV_p and RCR_p values are given in order from fresh to changed (modified) rock in terms of the average RCV_p and RCR_p values of the 3 main groups in Table 1.

The RCV_p values show that the rocks in group C are fresh and the following 2 main groups may be classified as group B, which is moderately altered, and group A, which is altered. The relationship between RCV_p and RCR_p can be described by the following formula, and the correlation coefficient of 0.9999 is given in Figure 6.

$$RCV_p = -(0.0094 x RCR_p) + 0.9993 \quad (6)$$

4. Relationship between RCV_p - RCR_p and physico-mechanical properties

Physical properties not only describe the present conditions of the rocks but are also used as a useful tool for describing engineering properties. The physical properties of the samples studied were analysed based on Turkish Standard TS-699 (Turkish Standards Institution 1982). The average values of physical properties from the study area are given in Table 3.

Table 2. The RCV_p and RCR_p values of the metarhyolites.

Group name		RCV_p	RCR_p	Average RCV_p	Average RCR_p
C	C1	0.990203	0.989379	0.990203	0.989379
B	B1	0.989678	1.042992	0.984221	1.492455
	B2	0.987389	1.277255		
	B3	0.975653	2.495427		
A	A4	0.961439	4.010737	0.951973	4.972632
	A3	0.956346	4.56472		
	A2	0.950466	5.2116		
	A1	0.939777	6.408197		

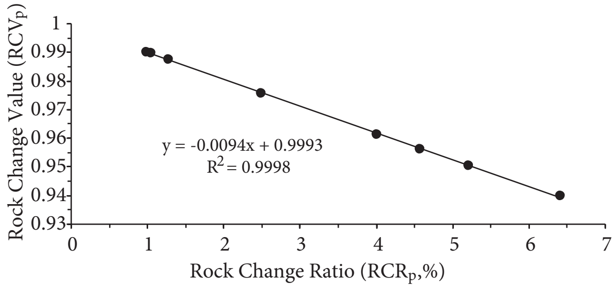

Figure 6. The relationship between RCV_p and RCR_p in the study area.

Density and porosity are 2 fundamental properties of rocks. Density is influenced primarily by both mineral composition and void space, where increasing void space increases porosity and decreases density. The IAEG Commission (1979) grouped the dry density and porosity of rocks into 5 classes, as shown in Table 4.

The rocks studied in the Ilgın area have moderate to high dry density with medium to very low porosity. This description shows that the rock weathering has been affected by atmospheric conditions and that clay products fill the void spaces and cracks in the rocks. The relationships between RCR_p values and physical properties are polynomial (Figure 7, Table 5).

Eqs. (7) through (11), given in Table 5, show that rocks in the study area have a specific gravity (γ_s) of 3244.50 kg/m^3 and a dry unit weight (γ_d) of 3222.30 kg/m^3 when they start to interact with atmospheric conditions (fresh rock) by uplift after metamorphism, in which the RCR_p value is equal to 0% and RCV_p is equal to 1. These equations also explain that rocks in the study area were in the monolith phase and subsequently cracks developed inside rocks, producing porosity (0.0485%) with a 0.75% RCR_p and void ratio (0.00075) with a 0.77% RCR_p, and atmospheric water was held (0.0206%) at a RCR_p value of 0.79%.

Moreover, after the development of porosity with a RCR_p value of 0.75% and a RCV_p value of 0.99225 in the area, the specific gravity (γ_s) value of 2766.28 kg/m^3 and dry unit weight (γ_d) value of 2731.42 kg/m^3 imply that the decrease of these values from the monolith phase is 14.74% for specific gravity and 15.23% for dry unit weight (the RCV_p changed by only 0.00775). The change of physical conditions shows that the weathering rate was fast with very small RCV_p values. These equations (Table 5) explain that the rocks in the study area will change completely at a RCR_p value of 9.01%, at which the RCV_p, specific gravity (γ_s), dry unit weight (γ_d), water content (w), porosity (n), and void ratio (e) values would be equal to 0.914606, 278.33 kg/m^3, 142.76 kg/m^3, 13.25%, 29.75%, and 0.35, respectively. In these conditions, the rocks remain as metarhyolite chemically, but their physico-mechanical properties and mineralogical compositions will continue to change and the metarhyolites will become soil.

Mechanical properties of the rocks in the study area were investigated by point load tests based on those of the International Society for Rock Mechanics (ISRM 1985). The average values of the point load strength index of each sub- and main sample group in the study area are given in Table 6.

One of the useful and commonly used strength classifications for rocks is the point load strength index, shown in Table 7, devised by Franklin & Broch (1972).

The rocks in the study area vary from medium to extremely high strength according to the observed degree of weathering, which increases from group C to group A. However, the average values are in a very high to extremely high strength class, in which the group C rocks represent fresh samples with a 0.990 RCV_p and groups B and A represent the moderate weathering development samples with 0.984 and 0.952 RCV_p values, respectively. The relationship between RCR_p values versus point load strength index values also exhibits a polynomial relationship, with a correlation coefficient of 0.5667 defined in Eq. (12) and shown in Figure 8.

According to Eq. (12), rock strength was 27.08 MPa when the rocks were in the monolith phase, and the

$$I_{s(50)} = -0.3109x(RCR_p)^3 + 4.4355(RCR_p)^2 - 17.726(RCR_p) + 27.08 \qquad (12)$$

Table 3. Physical properties of the metarhyolites.

Group name		Specific gravity (γ_s), kg/m^3	Dry unit weight (γ_d), kg/m^3	Saturated unit weight (γ_{sat}), kg/m^3	Water content (w), %	Porosity (n), %	Void ratio (e)
A	A1	2777.78	2570.34	2586.51	0.63	1.61	0.02
	A2	2777.78	2624.49	2631.23	0.25	0.67	0.01
	A3	2922.51	2721.47	2746.96	0.92	2.51	0.03
	A4	2764.50	2630.70	2640.74	0.37	0.98	0.01
B	B1	2591.70	2549.55	2575.19	1.00	2.55	0.03
	B2	2672.80	2646.22	2668.87	0.85	2.25	0.02
	B3	2416.99	2323.03	2385.97	2.45	5.70	0.06
C		2665.76	2608.78	2620.55	0.45	1.17	0.01

Table 4. Dry density and porosity classification of rocks (IAEG Commission 1979).

Class	Dry density (Mg/m^3)	Description	Porosity (%)	Description
1	Less than 1.8	Very low	Over 30	Very high
2	1.8-2.2	Low	15-30	High
3	2.2-2.55	Moderate	5-15	Medium
4	2.55-2.75	High	1-5	Low
5	Over 2.75	Very high	Less than 1	Very low

changed rock strengths were 16.15 MPa for 0.75% RCR_p (RCV_p = 0.99225), 15.92 MPa for 0.77% RCR_p (RCV_p = 0.992062), 15.69 MPa for 0.79% RCR_p (RCV_p = 0.991874), and 0.041 MPa for 9.01% RCR_p (RCV_p = 0.914606). These changes in the rock strength values also indicate high weathering rates.

The K-Ar ages of the metarhyolites exhibit a meaningful relation between RCV_p and RCR_p values. The K-Ar age is 60.4 ± 0.9 Ma for group C, 62.6 ± 0.9 Ma for group B, and 64.1 ± 2.00 Ma for group A. The relationships between K-Ar ages and RCV_p and RCR_p values are given in Figure 9 and Table 8.

Eqs. (13) through (18), given in Table 8, make a good approach to full-rock changed age. The calculated results for the estimation of the full lifetime of rock change are given in Table 9. The remaining rock lifetime can

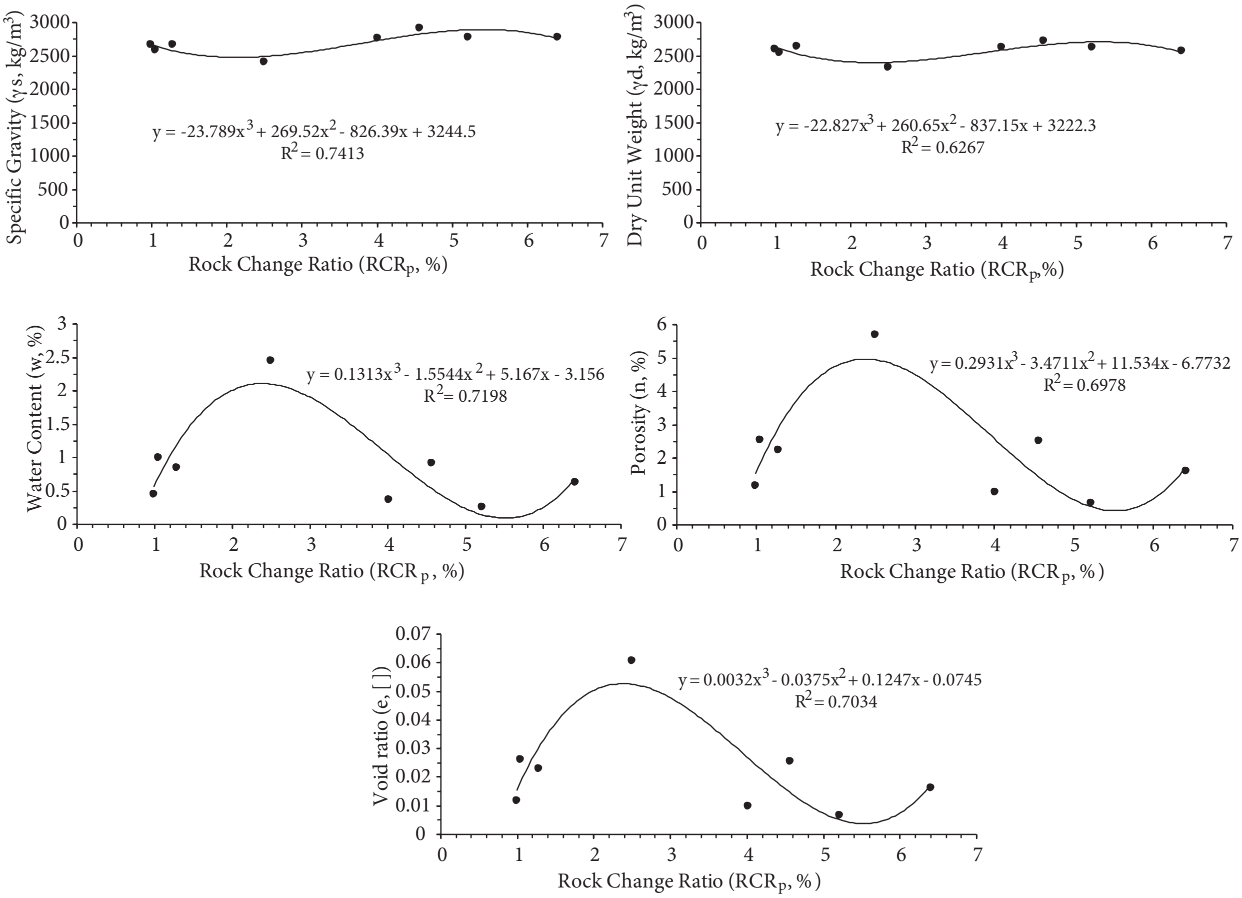

Figure 7. Relationships between RCR_p and physical properties of the metarhyolites.

Table 5. Relationships between RCR_p and physical properties of the metarhyolites.

Relationships between RCR_p and physical properties		Correlation coefficient (r)
$\gamma_s = -23.789 \times (RCR_p)^3 + 269.52 \times (RCR_p)^2 - 826.39 \times (RCR_p) + 3244.5$	(7)	0.861
$w = 0.1313 \times (RCR_p)^3 - 1.5544 \times (RCR_p)^2 + 5.167 \times (RCR_p) - 3.156$	(8)	0.848
$e = 0.0032 \times (RCR_p)^3 - 0.0375 \times (RCR_p)^2 + 0.1247 \times (RCR_p) - 0.0745$	(9)	0.839
$n = 0.2931 \times (RCR_p)^3 - 3.4711 \times (RCR_p)^2 + 11.534 \times (RCR_p) - 6.7732$	(10)	0.835
$\gamma_d = -22.827 \times (RCR_p)^3 + 260.65 \times (RCR_p)^2 - 837.15 \times (RCR_p) + 3222.3$	(11)	0.792

Table 6. Point load strength index values of the metarhyolites.

Group name		Point load strength index values, $I_{s(50)}$ (MPa)	Point load strength index average values, $I_{s(50)}$ (MPa)
A	A1	13.77	7.07
	A2	13.93	
	A3	0.99	
	A4	13.23	
B	B1	11.31	8.06
	B2	8.04	
	B3	5.76	
C		17.55	17.55

Table 7. Point load strength classification (Franklin & Broch 1972).

Description	Point load strength index (MPa)	Equivalent uniaxial compressive strength (MPa)
Extremely high strength	Over 10	Over 160
Very high strength	3-10	50-160
High strength	1-3	15-60
Medium strength	0.3-1	5-16
Low strength	0.1-0.3	1.6-5
Very low strength	0.03-0.1	0.5-1.6
Extremely low strength	Less than 0.03	Less than 0.5

be calculated simply by making a subtraction between current and calculated ages of rocks. These results are given in Table 10.

The highest correlation coefficient values were gathered for the maximum K-Ar age values versus RCV_p and RCR_p values (r = 0.94). The evaluations show that the whole-rock change time by weathering, disintegration, and maybe alteration will be complete after 4.58 Ma for highly weathered rocks (group A), 7.18 Ma for moderately weathered rocks (group B), and 9.38 Ma for fresh or weakly weathered rocks (group C), respectively. These values are geometric means of the calculated minimum, average, and maximum age values of each group.

The group A rocks were formed 230 ± 2 Ma ago and group B rocks 229 ± 2 Ma ago (Özdamar 2011). Metamorphism occurred at 63.73 ± 0.06 Ma in group A rocks and 62.64 ± 0.12 Ma in group C rocks (Özdamar 2011). The relationships between formation ages (FAs) of

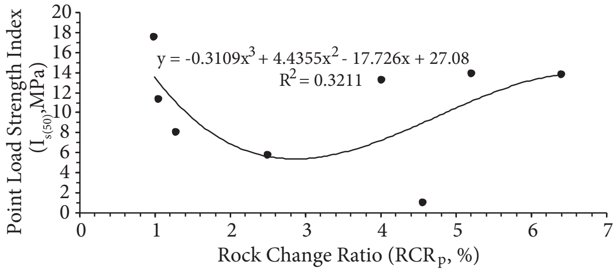

Figure 8. Relationship between RCR_p and point load strength index of the rocks in the study area.

minimum, average, and maximum values and RCV_p and RCR_p values are given in Figure 10 and Table 11. Eqs. (19) through (24), shown in Table 11, give the zone C rocks a formation age of 228 ± 2 Ma. The results also explain why the rocks of this zone remain fresh.

The relationships between metamorphism ages (MtAs) of minimum, average, and maximum values and RCV_p and RCR_p values are given in Figure 11 and Table 12. Eqs. (25) through (30) give the metamorphism age of 62.68 ± 0.11 Ma for group B rocks. This age is close to the metamorphism age of group C and explains the moderate rock-change conditions in group B rocks shown in Figure 5.

5. Results and conclusion

The metamorphic sequences in the Ilgın area have rocks of both Palaeozoic and Mesozoic ages. Metavolcanics are subalkaline and range from rhyodacite to rhyolite. These rocks have moderate to high dry density versus medium to very low porosity values, and their strengths change from medium to extremely high values. With these characteristics, the rock weathering in the field can be determined from fresh to moderately changed conditions.

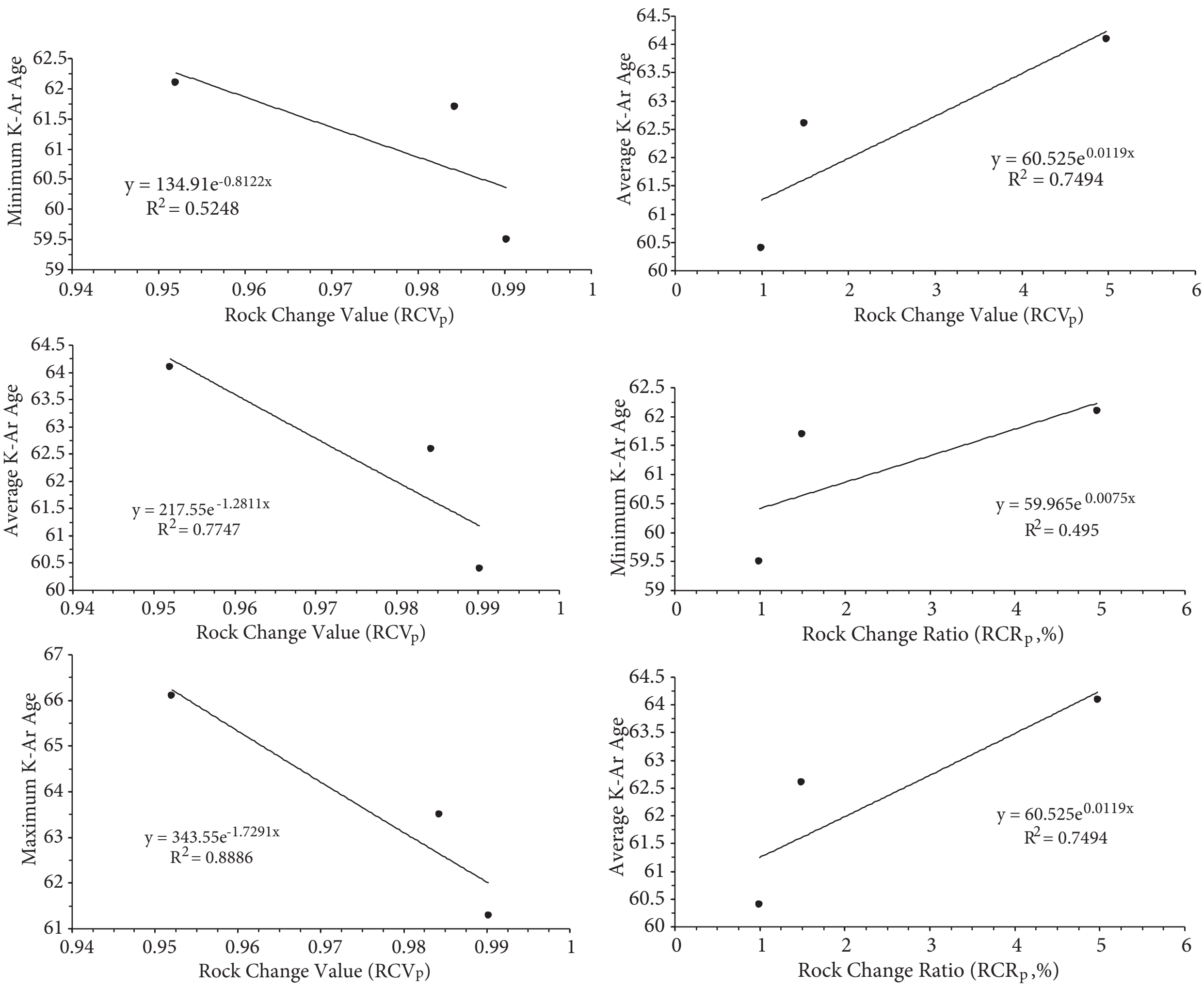

Figure 9. Relationships between K-Ar ages and RCV_p - RCR_p values of the metarhyolites.

Table 8. Relationships between K-Ar ages and RCV_p and RCR_p values of the metarhyolites.

K-Ar ages	Relationships between K-Ar age and RCV_p	Correlation coefficient (r)
Minimum	$(K\text{-}Ar)_{min} = 134.91 \times e^{-0.8122 \times (RCVp)}$ (13)	0.724
Average	$(K\text{-}Ar)_{ave} = 217.55 \times e^{-1.2811 \times (RCVp)}$ (14)	0.880
Maximum	$(K\text{-}Ar)_{max} = 343.55 \times e^{-1.7291 \times (RCVp)}$ (15)	0.943
K-Ar ages	Relationships between K-Ar age and RCR_p	Correlation coefficient (r)
Minimum	$(K\text{-}Ar)_{min} = 59.965 \times e^{0.0075 \times (RCRp)}$ (16)	0.704
Average	$(K\text{-}Ar)_{ave} = 60.525 \times e^{0.0119 \times (RCRp)}$ (17)	0.866
Maximum	$(K\text{-}Ar)_{max} = 61.092 \times e^{0.0162 \times (RCRp)}$ (18)	0.932

Table 9. Lifetime of complete rock changes: calculations between K-Ar ages and RCV_p and RCR_p values.

K-Ar ages according to RCV_p (Ma)			K-Ar ages according to RCR_p (Ma)		
Minimum (Ma)	Average (Ma)	Maximum (Ma)	Minimum (Ma)	Average (Ma)	Maximum (Ma)
64.184	67.405	70.660	64.157	67.375	70.693

Table 10. K-Ar age calculations according to RCV_p and RCR_p values of the metarhyolites.

Group name	Remaining time according to the relationship between K-Ar ages and RCV_p values for fully changed rock			Remaining time according to the relationship between K-Ar ages and RCR_p values for fully changed rock		
	Minimum (Ma)	Average (Ma)	Maximum (Ma)	Minimum (Ma)	Average (Ma)	Maximum (Ma)
C	4.684	7.005	9.360	4.657	6.975	9.393
B	2.484	4.805	7.160	2.457	4.775	7.193
A	2.084	3.305	4.560	2.057	3.275	4.593

In fact, the change of physical conditions of the rocks helps us to understand the high speed of the weathering with very small RCV_p values. Additionally, these rocks were divided into 3 groups defined by their weathering conditions with RCV_p and RCR_p values in order to define the primary physical conditions of the rocks using the relationships between RCR_p and physical properties (Figure 7, Table 5). These equations show that the strength in the monolith-phase rocks was 27.08 MPa, specific gravity (γ_s) was 3244.50 kg/m^3, and dry unit weight (γ_d) was 3222.30 kg/m^3, where the RCR_p value is equal to 0% and RCV_p is equal to 1. After the development of fractures and cracking, the primary porosity, n, became 0.0485%, with a RCR_p value of 0.75%. The voids in bulk composition developed with a 0.77% RCR_p value where the void ratio is e = 0.00075, and atmospheric water would have been held

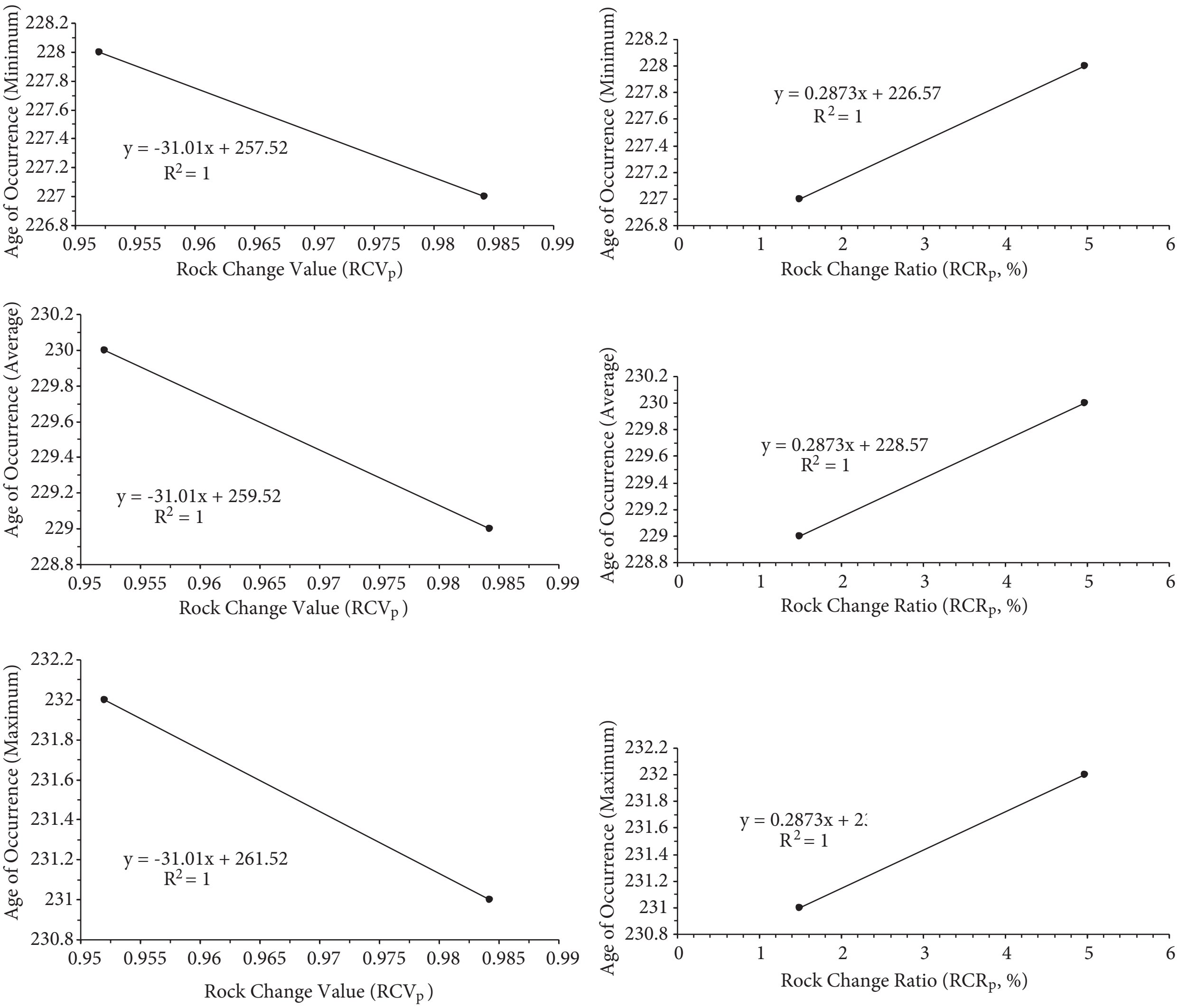

Figure 10. Relationships between formation ages (FAs) and RCV_p - RCR_p values of the rocks in the study area.

Table 11. Relationships between formation ages (FAs) and RCV_p and RCR_p values of the rocks in the study area.

FAs	Relationships between FA and RCV_p	Correlation coefficient (r)
Minimum	$(FA)_{min} = -31.01 \times RCV_p + 257.52$ (19)	1
Average	$(FA)_{ave} = -31.01 \times RCV_p + 259.52$ (20)	1
Maximum	$(FA)_{max} = -31.01 \times RCV_p + 261.52$ (21)	1
FAs	Relationships between FA and RCR_p	Correlation coefficient (r)
Minimum	$(FA)_{min} = 0.2873 \times RCR_p + 226.57$ (22)	1
Average	$(FA)_{ave} = 0.2873 \times RCR_p + 228.57$ (23)	1
Maximum	$(FA)_{max} = 0.2873 \times RCR_p + 230.57$ (24)	1

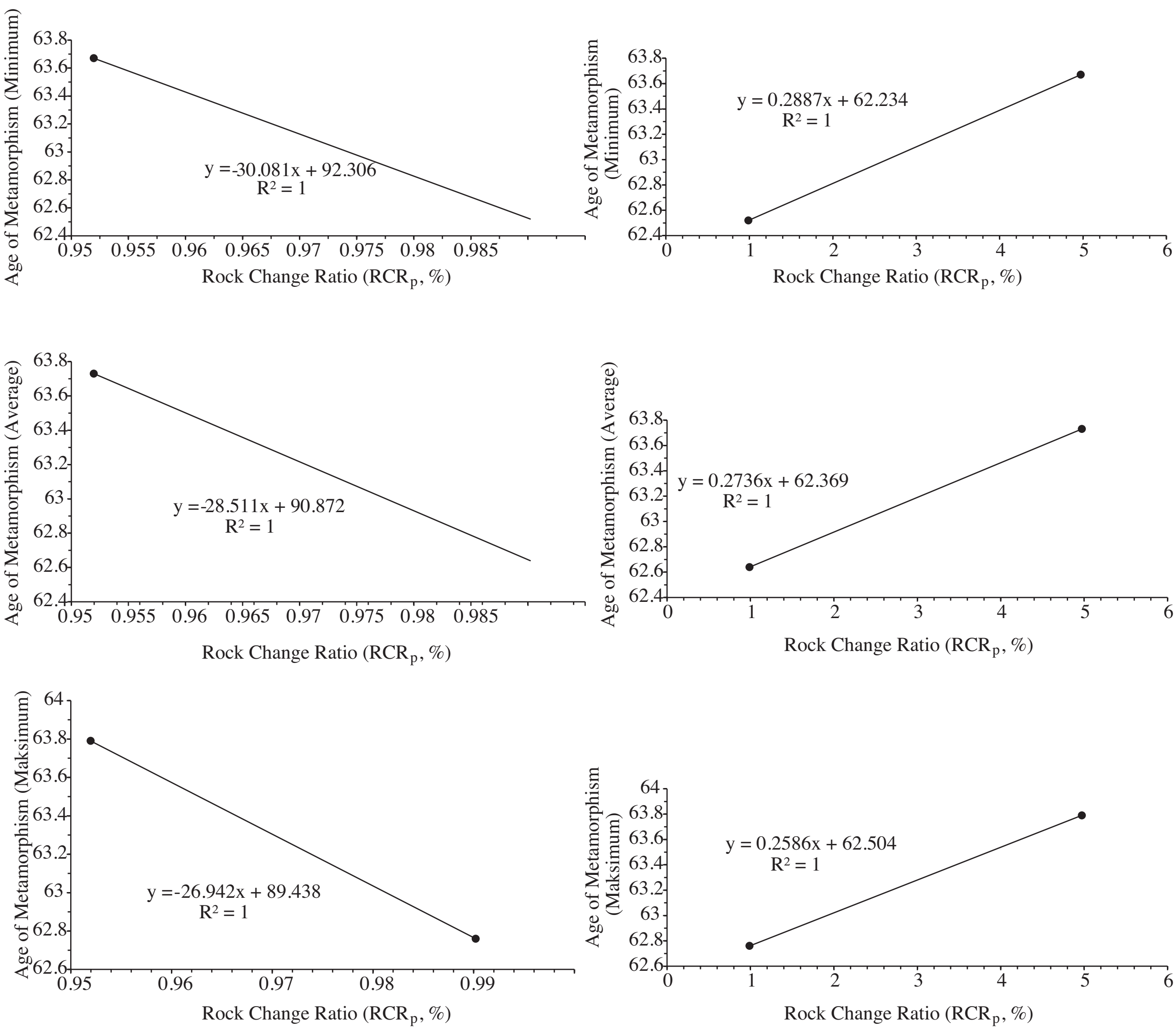

Figure 11. Relationships between metamorphism ages (MA) and RCV_p - RCR_p values of the rocks in the study area.

Table 12. Relationships between timing of metamorphism (MA) and RCV_p and RCR_p values of the rocks in the study area.

MA ages	Relationships between MtA age and RCV_p	Correlation coefficient (r)
Minimum	$(MtA)_{min} = -30.081 \times RCV_p + 92.306$ (25)	1
Average	$(MtA)_{ave} = -28.511 \times RCV_p + 90.872$ (26)	1
Maximum	$(MtA)_{max} = -26.942 \times RCV_p + 89.438$ (27)	1
MA ages	Relationships between MtA age and RCR_p	Correlation coefficient (r)
Minimum	$(MtA)_{min} = 0.2887 \times RCR_p + 62.234$ (28)	1
Average	$(MtA)_{ave} = 0.2736 \times RCR_p + 62.369$ (29)	1
Maximum	$(MtA)_{max} = 0.2586 \times RCR_p + 62.504$ (30)	1

(w = 0.0206%), for the RCR_p is equal to 0.79%. The RCV_p and RCR_p values also show that rocks in the study area change completely with the 9.01% RCR_p value. Dry unit weight will also be smaller than 1.4 Mg/m^3 when the RCR_p is less than 8.11%. In this case, the Ilgın area rocks will also remain as rhyolite whereas the physical, mechanical, and mineralogical properties of the rocks will change for the 9.01% RCR_p value and the soil structure will have formed. The RCV_p value, strength, specific gravity (γ_s), dry unit weight (γ_d), water content (w), porosity (n), and void ratio (e) values will be equal to 0.914606, 0.041 MPa, 278.33 kg/m^3, 142.76 kg/m^3, 13.25%, 29.75%, and 0.35, respectively, for the 9.01% RCR_p.

The rock change was compared with the K-Ar age values rather than the formation ages due to the new formation of the rocks after metamorphism, where the weathering from fresh to weathered rock starts again. The full-rock change is related to the alkali ratio of the rocks. In the Ilgın area the alkali ratio of the rocks changes between 8.12% and 9.40% (the average is 8.89%), where the RCR_p is 9.01% when the total alteration of all rocks will occur. The correspondence between these results explains that the RCV_p and RCR_p values are also very useful index values for determining both the initial and current situation of the rock easily. Furthermore, they also give an opportunity to predict the future condition of the rocks. In this study, the rock conditions in the Ilgın area were forecast with the aim of comparing the K-Ar age values versus RCV_p and RCR_p values. The interpretations show that the timing of full rock alteration in the Ilgın area is between 4.6 and 9.4 Ma.

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