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ORIGINAL PAPER

The alteration degree of the metacrystalline rocks based on UAI, Bolu (Turkey)

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Abstract The geomechanical properties of the metacrystalline rock masses vary due to alteration. The Devonian aged Yedigoller formation crops out in the Asarsuyu valley (Bolu, Turkey). The aim of this study is to investigate the alteration degree of the amphibolite and metagranodiorites based on their geomechanical and petrographical properties. The *P*-wave velocity is 1,613–5,588 m/s and the unconfined compressive strength varies between 12.75 and 99.86 MPa. Several weathering products occurred due to carbonisation, oxidation and sericitation. These rocks, subjected to hydrothermal effects, are classified as "fresh" to "completely altered" according to the unified alteration index (UAI). In addition, the values of the loss on ignition, modified weathering potential index and chemical index of alteration were taken into account for supporting the alteration process. Since the main process is hydrothermal alteration, the rocks which were exposed to alteration are weathered on the slopes after excavation. Weathering classification and the chemical indices indicate this process. Thus, UAI is concluded to be more suitable and credible in order to evaluate the hydrothermal alteration process of such crystalline rocks numerically.

Keywords Bolu · Metacrystalline rocks · Unified alteration index

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Introduction

The behaviour of the rock masses are mainly controlled by the geological structure, mineralogical composition, the degree of alteration and orientation of discontinuities. Instabilities may be encountered for the structures built in the rock mass by the reduction of the cohesion and internal friction angle due to alteration. Weathering and alteration have been used as similar terms, however Caroll (1970), Valeton (1970) and Gary et al. (1972) indicated alteration as the major physical and chemical change of minerals, including hydrothermal processes, weathering and diagenesis. A wide range of studies and classifications were implemented to characterize the weathering and alteration degree of the rock masses using observatory, chemical, petrographical and geomechanical properties (Iliev 1966; Ruxton 1968; Parker 1970; Irfan and Dearmann 1978; Harnois 1988; Komoo and Yaakup 1990; Price 1993; Anon 1995; Kilic 1995a, b; Tugrul and Gurpinar 1997; Gupta and Rao 2000; Gurocak and Kilic 2005; ISRM 2007; Undul 2007). Bozkurtoğlu et al. (2006) have proposed a new method to evaluate the weathering and subsequent alteration processes using physical properties of the rocks around the Tuzla geothermal region. The reduction in shear strength caused by argillic hydrothermal alteration of lavas around the Teide stratovolcano in Tenerife has been discussed (Potro and Hürlimann 2009). Aydin et al. (2002) have reviewed over 30 chemical weathering indices using the pyroclastic rocks of Hong-Kong, and concluded to accompany the chemical data with petrographical analysis. The weathering zones on the metamorphic rocks, and their effect on the geotechnical properties of such rocks have been investigated (Marques et al. 2010). A unified alteration index (UAI) regarding the *P* wave velocity and uniaxial compression strength has been developed in order to represent the alteration degree numerically (Kilic 1999). The UAI

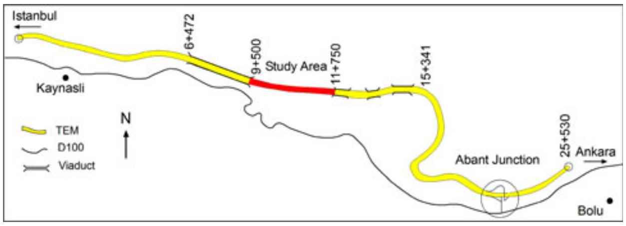

Fig. 1 Location map of the study area (Not to scale)

represents the strength reduction and includes the physical change for various altered rock classes using the wave velocity. The UAI was modified by Kocbay (2003), to the Modified Unified Alteration Index (MUAI). The aim of this study is to investigate the geomechanical properties and alteration degree of the metacrystalline rocks cropping out around the northern slopes of the Asarsuyu valley (Fig. 1). The weathering degree of the metacrsytalline rocks was determined by the ISRM (2007), alteration degree was classified by UAI (Kilic 1999), the chemical indices loss on ignition (LOI; Jayawardena 1993), modified weathering potential index (MWPI; Vogel 1973) and chemical index of alteration (CIA; Nesbitt and Young 1982) were used to support the evaluation of the main alteration process.

Geological setting

Devonian aged metacrystalline rocks of the Yedigoller formation and Quaternary aged Asarsuyu formation are the main units between the Km 9 + 500 to Km 11 + 750 section of the Gumusova–Gerede highway (Fig. 2). The Yedigoller formation includes amphibolite, gneiss, metadiorite, metaquartz and diorite (Aydin et al. 1987). Aplite, andesite, basalt and diabase dikes are encountered with sharp contacts. Amphibolite is metabasic, dark green-brown in color and fine grained. Metagranodiorite is dark grey in color and medium-fine grained (Barka and Lettis 2000). The main tectonic structures around the study area are the paleotectonic thrusts and neotectonic North Anatolian Fault (NAF) (Dalgic 1994), defined as Pontides (Ketin 1966) and Western Pontides (Sengör and Yilmaz 1981). Since the study area is located within the North Anatolian Fault Zone (NAFZ), random joints had developed in the metacrystalline rock mass due to tectonism.

Rock mass properties of the metacrystalline rocks

The joint orientations were determined and samples were collected from the outcrops. Core samples obtained from 19 geotechnical boreholes with depths ranging between 17 and 47 m were examined to define the degree of weathering. Outcrop and borehole samples range between intact rock and residual soil. A preliminary visual inspection was implemented based on ISRM (2007) to classify the samples before laboratory testing. Three main joints exist with dip/dip directions of 40°/106, 71°/194 and 26°/255 (Fig. 3).

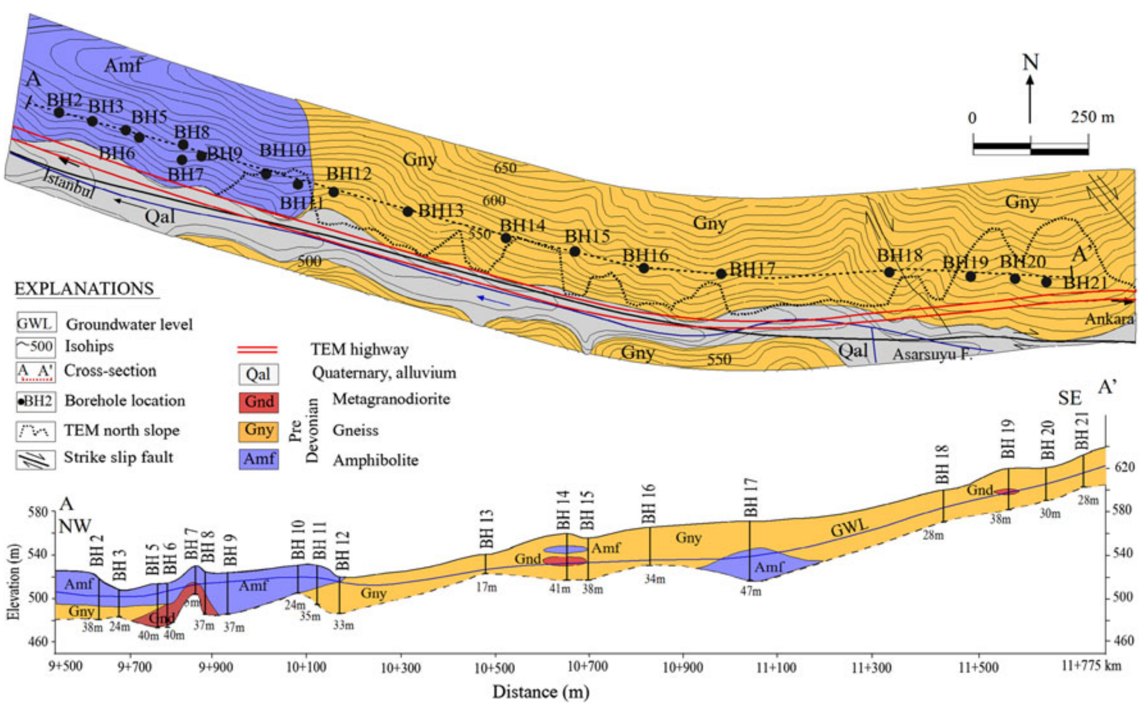

Fig. 2 Geological map of the study area and its vicinity (Modified from Barka and Lettis 2000)

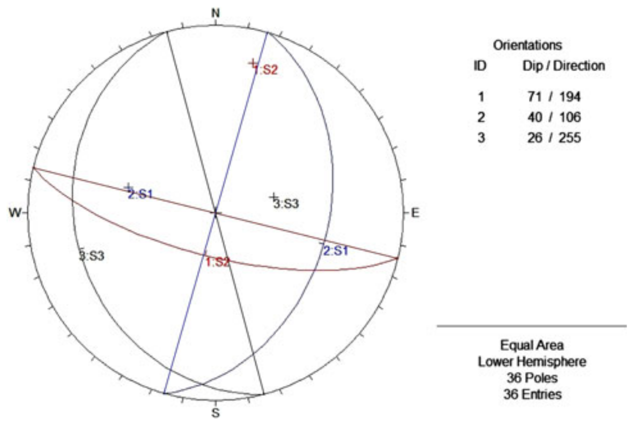

Fig. 3 Stereographic projection of the main discontiniuties

These joints are filled with gypsum, clay, calcite and silica, and they were washed away by rainfall on the surface level of the rock mass (Yurdakul 2006).

Mineralogical and petrographical characteristics

Thin sections of the rock samples representing different degrees of weathering were examined at the Mineralogy and Petrography Laboratory of Ankara University. Dynamic metamorphism is concluded to be the main geological event based on detailed petrographical evaluations. Cataclastic texture with quartz and feldspars is mostly common for the rock mass. Breciation and mylonitic textural features are observed on the thin sections. Amphibole and biotite formed the mafic mineral components of the unit. X-ray diffraction (XRD) studies were performed on the highly weathered samples in order to determine the residual soil types, especially the clay groups. The mineralogical composition of the samples was determined at the Earth Science Application and Research Centre of Ankara University (YEBIM) using the Ni filter, with Cu and Kα radiation. The clay minerals in the whole rock were defined using Brindley (1980), Gundogdu (1982), Gundogdu and Yilmaz (1984) by semi-quantitative procedures. The alteration products are smectite, illite, amphibole, feldspar, quartz, calcite, crystobalite and amorph material (Table 1). The main alteration product ratios and other mineralogical compositions are also given in Table 1.

Geomechanical properties

The northern slopes in the metacrystalline rock mass are formed by metagranodiorite and amphibolite between Km 9 + 500 to 11 + 750 (Zetas 2001). Along the slopes, 19 geotechnical boreholes were drilled by Astaldi S.p.A. In order to classify the rock units within the UAI, the unconfined compressive strength and *P*-wave velocity of core samples were determined (Table 2). Unconfined compressive strength tests and *P*-wave tests were carried out on cylindirical NX (54.7 mm) size core samples following the relevant standards (ASTM 1996b, c). The minimum unconfined compressive strength of the “highly altered” metagranodiorite is 28.6 MPa. It is 33.2 MPa for the “moderately altered” class, while the maximum is 44.6 MPa for the “slightly altered” amphibolite and 80.9 MPa for the “unaltered” metagranodiorite. The mean *P*-wave velocity is 1,656 m/s (extremely altered), 2,625 m/s (highly altered), 3,998 m/s (moderately altered), 4,908 m/s (slightly altered) and 5,079 m/s (unaltered).

Degree of alteration

The alteration degree of the rock units was analyzed according to their mineralogical and petrographical properties, UAI (Kilic 1999) classification and geochemical

Table 1 Mineralogical composition, whole rock XRD and semi-quantitative results of major alteration products with the associated rock names

Sample	Depth (m)	Mineralogical composition (XRD)	(%)	Rock name
N5	Outcrop	Feldspar, chlorite, amphibole, quartz, amorph material, illite	67 Clay 22 Feldspar 11 Quartz	Metagranodiorite
N6	Outcrop	Smectite, illite, feldspar, hornblend–amphibole, amorph material, quartz, chlorite	42 Clay 49 Feldspar 9 Quartz	Mylonitic gneiss
N10	Outcrop	Amphibole, feldspar, quartz, chlorite, amorph material, illite	39 Clay 55 Feldspar 6 Quartz	Mylonitic gneiss
BH8	14.15	Calcite, quartz, amphibole, smectite, chlorite, mica, feldspar, crystobalite	56 Calcite 33 Clay 11 Quartz	Amphibolite
BH8	21.15	Quartz, feldspar, calcite, amphibolite, chlorite, mica, crystobalite, amorph material	45 Feldspar 38 Quartz 17 Calcite	Amphibolite
BH15	8.00	Quartz, feldspar, amphibole, smectite, chlorite, crystobalite, amorph material	66 Feldspar 21 Quartz 13 Clay	Mylonitic gneiss
BH18	7.00	Quartz, feldspar, amphibole, crystobalite, mica	56 Feldspar 31 Quartz 13 Clay	Metagranodiorite

Table 2 Unconfined compressive strength (σ_c), *P*-wave velocity (V_p), Unified Alteration Index (UAI) and alteration degree classes of the metacrystalline rocks

Borehole	Depth (m)	σ_c (MPa)	V_p (m/s)	UAI	Rock type	Alteration degree class
BH9	14.7	29.6	4,750	0.32	Amphibolite	Slightly (0.10–0.30)
BH10	13.0	12.7	1,613	0.78	Amphibolite	Extremely (>0.70)
BH12	26.0	17.7	1,700	0.76	Metagranodiorite	Extremely (>0.70)
BH13	9.60	33.2	4,167	0.41	Metagranodiorite	Moderately (0.30–0.50)
BH14	6.30	99.9	4,569	0.09	Metagranodiorite	Unaltered (<0.10)
BH14	15.5	79.1	4,815	0.17	Amphibolite	Slightly (0.10–0.30)
BH14	20.5	44.6	3,077	0.50	Metagranodiorite	Moderately (0.30–0.50)
BH14	41.0	86.4	5,368	0.07	Metagranodiorite	Unaltered (<0.10)
BH15	27.4	28.6	2,625	0.61	Metagranodiorite	Highly (0.50–0.70)
BH16	27.0	61.9	5,588	0.09	Metagranodiorite	Unaltered (<0.10)
BH17	46.5	84.2	5,000	0.13	Amphibolite	Slightly (0.10–0.30)

data. The UAI represents the alteration degree with five classes based on unconfined compression strength and *P*-wave velocity (Eq. 1, Fig. 4).

$$\mathrm{UAI} = \sqrt{\left[1 - \frac{C_{pa}}{C_{pi}}\right]\left[1 - \frac{\sigma_{ca}}{\sigma_{ci}}\right]}, \quad (1)$$

where, C_{pa}: *P*-wave velocity of altered rock (m/s), C_{pi}: *P*-wave velocity of intact rock (m/s), σ_{ca}: unconfined compression strength of altered rock (Mpa), σ_{ci}: unconfined compression strength of intact rock (Mpa)

The ISRM (2007) weathering procedure was taken into account for comparison only. The suggested method was given in details based on observational inspections (Table 3) mineralogical composition, hydrothermal alteration products and their percentages are given with the related rock names (Table 4). The ratios given within Table 4 were determined from the thin sections, indicating the major hydrothermal alteration products in general terms, while the ratios derived from the XRD analysis were evaluated in Table 1. The XRD is needed when the ratio of the clay exist around the 10 % boundary under thin section inspections.

As a result of hydrothermal alteration; clay mineralisation, chloritisation, carbonisation, sericitation, epidotisation, Fe-oxidation, slight silisification and hydrobiotisation were encountered. Representative samples of various alteration degrees were investigated by geochemical analysis. The alteration degree was defined based on the Loss On Ignition (LOI; Jayawardena 1993), the Modified Weathering Potential Index (MWPI; Vogel 1973) and the Chemical Index of Alteration (CIA; Nesbitt and Young 1982). The MWPI (Eq. 2), CIA (Eq. 3), LOI and UAI (Eq. 1) results were evaluated comparatively (Table 5). The alteration degree is between "extremely altered" and "fresh". Despite this, a general trend could not be observed between the chemical indices and alteration evaluations. It is not convenient to consider a direct relation between geochemical data and geomechanical test results (Fig. 5).

$$\mathrm{MWPI} = \frac{(K_2O + Na_2O + CaO + MgO)}{(SiO_2 + Al_2O_3 + Fe_2O_3 + CaO + MgO + Na_2O + K_2O)} \quad (2)$$

$$\mathrm{CIA} = \frac{Al_2O_3}{(Al_2O_3 + CaO + Na_2O + K_2O)} \quad (3)$$

Table 3 Suggested method for defining the degree of weathering (ISRM 2007)

Term	Description	Grade
Fresh	No visible sign of rock material weathering: perhaps slight discolouration on major discontinuity surfaces	I
Slightly weathered	Discolouration indicates weathering of rock material and discontinuity surfaces. All the rock material may be discoloured by weathering and may be somewhat weaker externally than its fresh condition	II
Moderately weathered	Less than half of the rock material is decomposed and/or disintegrated to a soil. Fresh or discoloured rock is present either as a continuous framework or as corestones	III
Highly weathered	More than half of the rock material is decomposed and/or disintegrated to a soil. Fresh or discoloured rock is present either as a discontinuous framework or as corestones	IV
Completely weathered	All rock material is decomposed and/or disintegrated to soil. The original mass is still largely intact	V
Residual soil	All rock material is converted to soil. The mass structure and material fabric are destroyed. There is a large change in volume, but the soil has not been significantly transported	VI

Table 4 Mineralogical composition, alteration products and ratios of various rock types based on thin-section inspections

Borehole	Depth (m)	Mineralogical composition	Clay (%)	Chloritisation (%)	Carbonisation (%)	Serisite (%)	Epidote (%)	Fe-oxidation (%)	Hydrobiotite (%)	Silisation (%)	Total (%)	Rock name
BH2	25.5	Plagioclase, uralite, tremolite, actinolite	10	15	3						30	Amphibolite
BH3	23.0	Quartz, plagioclase	5	25	10						40	Mylonitic gneiss
BH5	39.0	Titanomagnetite, hematite, tremolite, actinolite	5	15	5						25	Monocrystalline granodiorite
BH9	14.7	Quartz, lemonite, feldspar			15			30			45	Amphibolite
BH10	13.0	Tremolite, actinolite, plagioclase, magnetite, pyrite	20			5			3		28	Amphibolite
BH12	26.0	Plagioclase, Quartz, Al feldspar, amphibole	20	5			2				27	Amphibole gneiss
BH13	9.5	Quartz, plagioclase, Al feldspar	15		10						25	Mylonitic gneiss
BH14	6.3	Quartz, feldspar						5		25	30	Mylonitic gneiss
BH14	15.5	Quartz, plagioclase, epidote	30		20						50	Amphibolite
BH14	20.5	Quartz, plagioclase, serisite	10		60			3			73	Granodiorite porphyr
BH14	41.0	Plagioclase, Al feldspar, quartz	20		5	3					28	Biotite gneiss
BH15	27.5	Quartz, plagioclase, serisite, chlorite	10	20				3			33	Mylonitic gneiss
BH16	27.0	Quartz, plagioclase, feldspar	10	10		5					25	Mylonitic gneiss
BH17	46.5	Quartz, plagioclase, Al feldspar	10		20	3					33	Amphibolite
BH19	20.5	Quartz, plagioclase, Al feldspar, muscovite			10	5	5				20	Meta Granodiorite
BH20	28.5	Quartz, Al feldspar plagioclase, biotite	5	3		5					13	Biotite gneiss
BH21	22.7	Quartz, plagioclase Calcite, Al feldspar, epidote, chlorite	5	10		10					25	Mylonitic gneiss
N6	Outcrop	Quartz, plagioclase, zeolite		10	2			5			22	Mylonitic gneiss
N5	Outcrop	Chlorite, quartz, plagioclase, Al feldspar, amphibole, magnetite	10	10		2					27	Meta granodiorite
N10	Outcrop	Quartz, plagioclase, chlorite, Al feldspar	10		5	15					30	Mylonitic gneiss

Table 5 UAI degree, sample number and depth, mineralogical composition, texture and chemical index values for the metacrsytalline rocks

UAI Alteration degree	Extremely		Highly		Moderately
Sample no. and depth (m)	BH10 (13.0)	BH12 (26.0)	BH15 (27.4)	BH14 (20.5)	BH13 (9.6)
Rock texture	Nemato-blastic	Nemato-granoblastic	Mylonitic	Porphyric	Mylonitic
Loss on ignition (LOI)	1.62	1.23	2.02	1.50	1.62
Chemical alteration index (CIA)	55.2	59.9	63.5	55.4	55.2
Modified weathering pot.ind. (MWPI)	12.56	8.62	13.91	19.35	12.56
Alteration type	Clay mineralis	Clay mineralisat.	Chloritisation	Carbonisation	Clay mineralis
Mineralogical composition	Tremolite, actinolite, Plagioclase, magnetitte	Plagioclase, Quartz, feldspar amphibole	Quartz, Plagioclase, serisite, chlorite	Quartz, Plagioclase Serisite	Quartz, Plagioclase feldspar
Microphotographs					
Rock name	Amphibolite	Amphibole gneiss	Mylonitic gneiss	Granodio. porphyr	Mylonitic gneiss

UAI Alteration degree	Slightly			Unaltered		
Sample no. and depth (m)	BH9 (14.7)	BH14 (15.5)	BH17 (46.5)	BH14 (6.3)	BH14 (41)	BH16 (27.0)
Rock texture	Breccia	Breccia	Mylonitic	Cataclastic	Lepido-granoblastic	Mylonitic
Loss on ignition (LOI)	2.28	1.29	1.66	1.40	2.02	1.55
Chemical alteration index (CIA)	67.1	61.5	57.2	47.8	63.5	61.1
Modified weathering pot.ind. (MWPI)	11.78	10.59	17.42	23.12	13.91	11.79
Alteration type	Fe-oxidation	Clay mineralis	Carbonisation	Silisiication	Clay mineralis	Chloritisat.
Mineralogical composition	Quartz, limonite, feldspar	Quartz, Plagioclaseepidote	Quartz, Plagioclase, feldspar	Quartz, feldspar	Plagioclasefeldspar, Quartz	Quartz, Plagioclase feldspar
Microphotographs						
Rock name	Amphibolite	Amphibolite	Amphibolite	Mylonitic gneiss	Biotite gneiss	Mylonitic gneiss

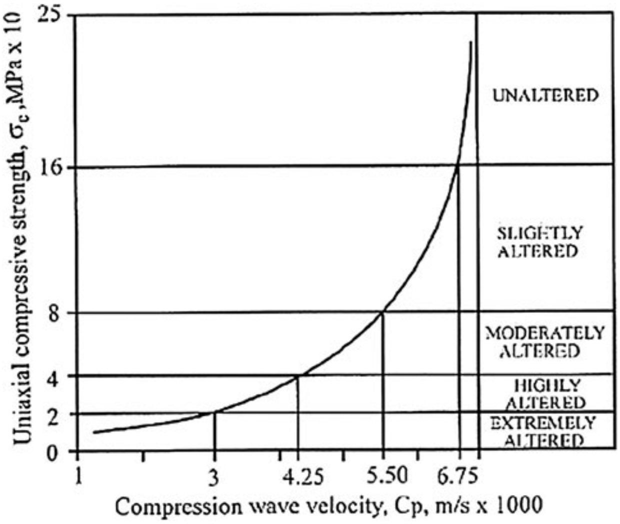

Fig. 4 The relationship between alteration degree, unconfined compressive strength and compression wave velocity (Kilic 1999)

Tectonism, groundwater circulation and joint orientations are the main agents to change the degree of weathering in narrow distances. 'Fresh" to "completely weathered" rocks might exist on the same outcrops. The gathering of the petrographical, chemical and weathering data, microzonation on the northern slopes and a visual zonation of metagranodiorites (Km 11 + 000) were prepared (Fig. 6). The degree of weathering is expected to reduce with depth, however, due to hydrothermal alteration this situation did not occur with the microcrystalline rocks.

The alteration degree and microzonation based on the UAI were evaluated (Fig. 7). The UAI has been offered with five classes of alteration. UAI is <0.10 for fresh rock, while >0.70 is for extremely altered rock. The cross-section based on UAI (Fig. 7) was prepared based on this classification, while the boundaries of the alteration classes are similar to that offered by ISRM (2007). Laboratory tests on core samples have to be conducted to obtain the UAI classes. Unfortunately, only intact samples from the boreholes and blocks removed from the outcrops could be tested. The weathering degree of the remaining levels through the boreholes were determined to evaluate the alteration degree where test results were lacking. Since weathering classification is visual, the products of the microcrystalline rocks and the geochemical data indicate the effect of alteration dominates the rock mass. For the study area, the effect of hydrothermal alteration and tectonism are paramount, thus using the UAI classification could be better in identifying the overall mechanism along the metacrystalline rocks.

Conclusions

This study aims to investigate the alteration degree of the metacrystalline rock mass including amphibolite and metagranodiorites.

Based on the unconfined compressive strength and *P*-wave velocity, alteration of the metagranodiorite and amphibolite samples had a range between "unaltered" and "extremely altered".

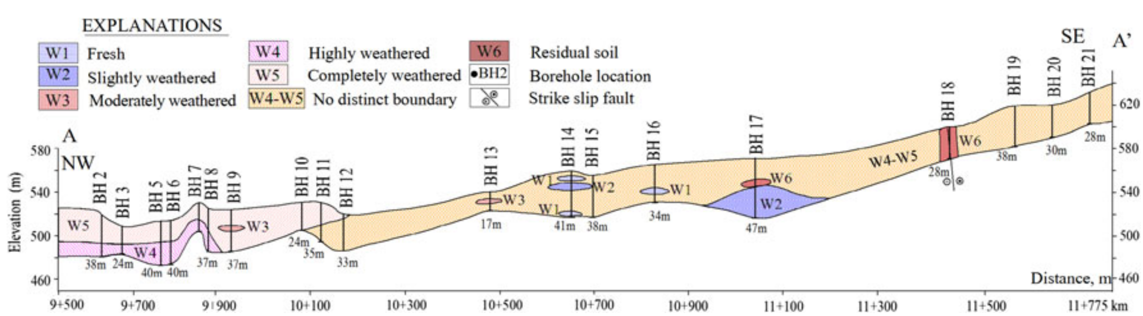

Fig. 5 Microzonation of the weathering degree of the metacrystalline rocks (ISRM 2007)

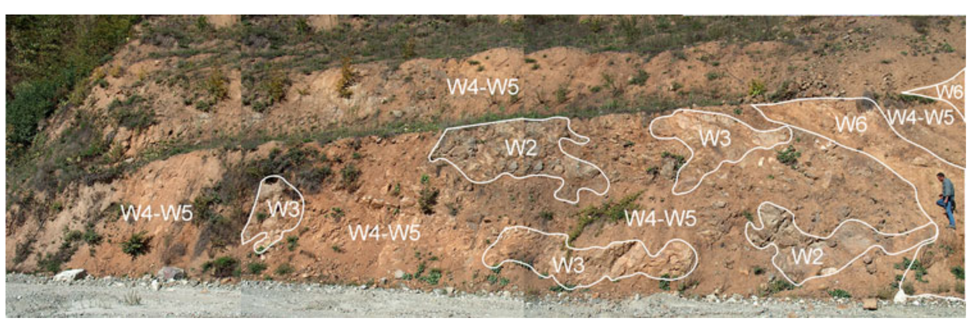

Fig. 6 Degree of weathering on the metagranodiorites (ISRM 2007) at section 11 + 000 km. (*W1* Fresh; *W2* Slightly; *W3* Moderately; *W4* Highly; *W5* Extremely; *W6* Completely weathered)

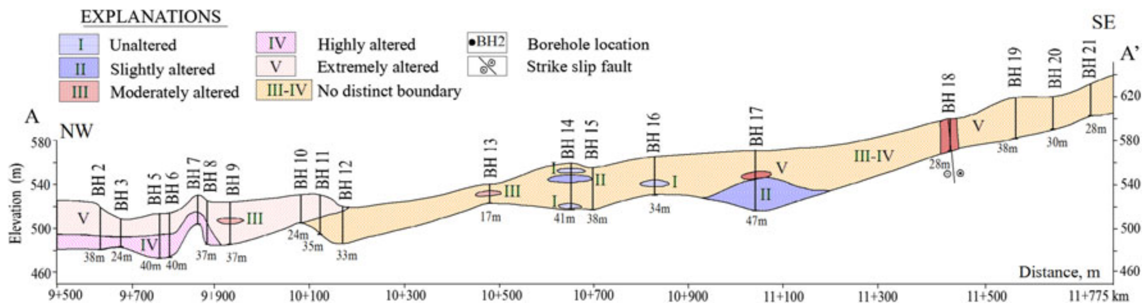

Fig. 7 Classification of the metacrsytalline rocks based on UAI classification

The main process has been defined as hydrothermal alteration based on the geochemical investigations and UAI. The already altered rocks may have been subjected to weathering on the slopes and shallow depths.

The relevant weathering products of the microcrystalline rocks are; clay mineralisation (extremely altered); chloritisation (highly altered), carbonization, clay mineralization and Fe-oxidation (moderately altered), clay mineralization and carbonization (slightly altered) and low amounts of chloritisation, clay mineralization and silisification (unaltered).

Loss on ignition (LOI), modified weathering potential index (MWPI) and chemical alteration index (CIA) values are at the same interval, classifying the microcrystalline rocks from "unaltered" to "completely altered".

The cross-sections based on the weathering degree offered by the ISRM (2007) and alteration degree offered by the UAI (Kilic 1999) are in accordance, but the expected variation of "completely weathered" to "fresh" classification (ISRM 2007) could not be observed as the result of the hydothermal alteration and metamorphism. As a consequence, it is possible that the UAI may give more reliable results for such crystalline rocks exposed to hydrothermal alteration.

Since the unconfined compressive strength and wave velocity are related to the mineralogical composition and are reduced by alteration, UAI results proved to be applied to such crystalline rocks. Moreover, the variation of the chemical indices are within the same limits with the UAI alteration classification.

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