New Chemical Weathering Indices for Estimating the Mechanical Properties of Rocks: A Case Study from the Kürtün Granodiorite, NE Turkey

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Abstract: The chemical weathering of rock proceeds by water-rock interaction. During weathering geochemically mobile elements, alkali and alkali-earth elements are easily leached from rocks, leaving the residual elements to combine with components from the atmosphere to form new minerals. No single weathering index given in the literature fits the model of the process involved in chemical weathering outlined above. This study deals with the derivation of three new chemical weathering indices by taking both chemical processes such as leaching and new mineral formation into account. The new indices are *chemical leaching index* (CLI), *chemical weathering product index* (CWPI) and *total chemical weathering index* (TCWI). These indices are applied to selected weathering profiles in the Kürtün granodiorite, NE Turkey, in order to estimate the effects of chemical weathering on the physico-mechanical properties of rock materials. The relative variation of the mechanical properties and TCWI display a statistically significant correlation. Besides, it is shown that TCWI and weatherability index, originally defined by Hodder (1984) can be used together to evaluate the effect of chemical weathering on the mechanical behaviour of rocks.

Key Words: weathering, chemical weathering indices, isovolumetric method, engineering properties, granitic rocks, Turkey

Kayaçların Mekanik Özelliklerinin Tahmini İçin Yeni Kimyasal Ayrışma İndeksleri ve Kürtün Granodiyoriti'nde (KD Türkiye) Bir Örnek Çalışma

Özet: Kayaçların kimyasal ayrışması kayaç-su etkleşimi ile oluşmaktadır. Ayrışma boyunca, jeokimyasal olarak hareketli elementler (alkali ve toprak alkali elementler) kolayca kimyasal olarak yıkanırlar. Diğer taraftan, geriye kalan elementler atmosferdeki bileşenlerle birlikte yeni mineralleri meydana getirirler. Önceki çalışmalarda verilen hiçbir kimyasal indeksi tek başına kimyasal ayrışmadaki bu süreçlerin modellemesini ifade etmemektedir. Bu çalışmada, kimyasal yıkanma ve yeni mineral oluşumu gibi kimyasal ayrışma süreçleri dikkate alınarak üç yeni kimyasal ayrışma indeksi oluşturulmuştur. Bunlar *kimyasal yıkanma indeksi* (CLI), *kimyasal ayrışma ürünü indeksi* (CWPI) ve *toplam kimyasal ayrışma imdeksi*'dir (TCWI). Bu indeksler, Kürtün granidiyoriti'nde (KD Türkiye) seçilen ayrışma profillerinde kimyasal ayrışmanın kaya materyalinin fiziko-mekanik özellikleri üzerindeki etkilerini tahmin etmek için uygulanmıştır. Mekanik özelliklerin göreceli değişimi ile TCWI arasında istatiksel olarak anlamlı ilişkiler vardır. Aynı zamanda, kimyasal ayrışmanın kaya materyalinin mekanik davranışı üzerindeki etkisini değerlendirmek için TCWI ve Hodder (1984) tarafından tanımlanan kimyasal ayrışabilirlik indeksinin birlikte kullanılabileceği gösterilmiştir.

Anahtar Sözcükler: ayrışma, kimyasal ayrışma indeksleri, sabit hacim yöntemi, mühendislik özellikler, granitik kayaçlar, Türkiye

Introduction

Weathering is generally defined as the process of alteration and breakdown of rocks at and near the earth's surface by physical, chemical and biotic effects (Selby 1993), and leads to a number of changes in the rocks. Rocks become more porous, individual mineral grains are weakened and bonding between grains are lost.

Weathering products may be deposited within the pores, at grain boundaries and along fractures and/or removed. Permeability may change depending upon the stage of weathering indicating the presence and type of weathering products and the chemical leaching. Due to these changes of the index properties, rock material becomes weaker and more deformable.

The engineering behaviour of rock materials depends not only on stress state and stress history, but also on the sate of weathering. Hence, it is essential for engineering geologists to quantify the changes during weathering. Chemical change during weathering and hydrothermal alteration are quantified in several ways including the normalized value of element (or oxide) using their parent rock concentrations or immobile element concentrations in the samples (Krauskopf 1967; Minarik *et al.* 1983), standard cell calculation (Colman 1982), ratio of elements to immobile elements (Chesworth *et al.* 1981; Colman 1982; Guan *et al.* 2001), measurement and calculation of loss or gain of weight (or volume) based on immobile element (Gresens 1967; Grant 1986; MacLean 1990; Huston 1993) and chemical weathering indices (Jayawardena & Izawa 1994a, b; Tuğrul 1995; Düzgören-Aydın *et al.* 2002; Düzgören-Aydın & Aydın 2003; Price & Velbel 2003).

Weathering indices have been devised to quantify the changes in the index properties of rock materials, some of which are relevant to the engineering properties. Most chemical weathering indices which guess the mechanical properties of weathered rocks regard only chemical leaching such as Parker index, (Parker 1970), lixiviation index (Rocha Fillno *et al.* 1985), mobiles index (İrfan 1996), mobility index (Guan *et al.* 2001), but only a few consider the amount of the weathering products such as Product index (Reiche 1943). Additionally, the chemical weatherability index (e.g., Hodder 1984) is used. To characterize the weathering state and to estimate engineering properties, a single chemical index is used, but this index does not consider all the chemical weathering processes (e.g., Onodera *et al.* 1974; Hodder 1984; İrfan 1996; Tuğrul & Gürpınar 1997; Kim & Park 2003). Hence, new chemical indices are required which take chemical leaching, amount of weathering products and weatherability into account. This paper describes the derivation of new chemical indices which consider all the chemical weathering processes, and which can be used to predict the chemical weathering effect on the mechanical behaviour of the weathered rocks.

A Review of the Present Chemical Weathering Indices

The principal assumption in formulating chemical weathering indices is that the behaviour of chemical elements is controlled solely by the degree of weathering. More specifically, it is expected that, as the intensity of weathering increases: (a) certain major oxides, including Al_2O_3, Fe_2O_3 and TiO_2, considered as 'immobile', remain constant; (b) Si_2O, Na_2O, K_2O, CaO and MgO, considered as 'mobile', decrease; and (c) LOI (loss on ignition) content increases (Düzgören-Aydın *et al.* 2002).

Chemical weathering indices are based on the whole rock major element compositions, with the exception of abrasion pH of feldspar grains (Grant 1969). The two indices not expressed as a ratio of major oxides are loss of water ignition, and combined water in rocks (Sueoka *et al.* 1985; Esaki & Jiang 1999). Most of these indices are expressed as molecular or weight percentage ratios between various groups of major oxides, while the 'Parker index' (Parker 1970) is expressed as atomic proportions of certain mobile elements (Düzgören-Aydın *et al.* 2002). The molecular proportion of each oxide is easily calculated from the percent of the oxide based on weight. Molecular proportions may also be used to calculate weathering indices for materials, which either do not weather isovolumetrically, or have been affected by mechanical processes such as bioturbation in soils (Düzgören-Aydın *et al.* 2002). However, chemical weathering indices calculated from molecular proportions typically are based on the assumption that aluminium is immobile (e.g., Vogt 1927; Ruxton 1968; Nesbitt & Young 1982; Harnois 1988; Fedo *et al.* 1995), an assumption that is not always warranted (Gardner *et al.* 1978; Gardner 1980, 1992; Banfield 1985). On the other hand, using volumetric concentrations as function of dry density of whole rocks allows for the mobility of all elements (Banfield 1985; Eggleton *et al.* 1987; Price & Vebel 2003).

Chemical weathering indices have facilitated research on the geochemistry of the Earth's surface environment over geologic time (Düzgören-Aydın *et al.* 2002). They are widely used in studies of both modern and ancient in situ weathering profiles (e.g., Pera *et al.* 2001; Begonha & Sequeira Braga 2002; Lan *et al.* 2003; Kirschbaum *et al.* 2005). In recent settings, weathering indices are used for demonstrating the impact of climate on bedrock weathering (e.g., Neall 1977), characterizing alteration associated with neotectonic delineations (e.g., Sharma & Rajamani 2000), quantifying the engineering properties of regolith (Malpas *et al.* 2001; Düzgören-Aydın *et al.* 2002), interpreting the weathering history of modern

and ancient sediments (e.g., Crichton & Condie 1993; Ramesh & Anglejan 1995; Fedo *et al.* 1995; Colin *et al.* 1998; Young 1999), evaluating soil fertility and development (e.g., Delvaux *et al.* 1989), categorizing soil and evaluating soil weathering (Souri *et al.* 2006) and simply providing a better understanding of elemental mobility during weathering (e.g., Nesbitt 1979; Colman 1982; Jayawardena & Izawa 1994a, b; Tuğrul 1995; İrfan 1996; Tuğrul & Gürpınar 1997; Kirschbaum *et al.* 2005). Weathering indices also contribute to the prediction models assessing the strength and deformation properties of rocks (e.g., Onodera *et al.* 1974; Hodder 1984; Hodder & Hetherington 1991; Knill 1993; Tuğrul 1995; Tuğrul & Gürpınar 1997; Arel & Tuğrul 2001; Kim & Park 2003), used to predict the durability and weathering condition of the building stone in service (e.g., Esaki & Jiang 1999; Ceryan & Şen 2003; Ceryan & Ceryan 2005) and assessing deterioration mechanisms and weathering depths in monuments (Topal 2002; Topal & Sözmen 2003).

Chemical weathering indices are mainly proposed for felsic and/or intermediate rocks weathered under humid, well-drained conditions (Düzgören-Aydın *et al.* 2002). Only a few, such as 'Bases: R_2O_3' (Colman 1982), are particularly proposed for basic rocks, while several others, such as Parker's index (Parker 1970), are claimed to be applicable for all rocks (Düzgören-Aydın *et al.* 2002).

Hodder (1984) restudied Miura's and Parker's indices using the Aires-Barros (1978) relative indices and showed that a numerical relationship between Gibbs free energy and the indices that defined the weathering reactions may be established. Hodder (1984) also determined a new chemical weathering index (Ks) using the combination of Miura's (1973) and Parker's (1970) indices.

Jayawardena & Izawa (1994a, b) studied the applications of the indices of chemical weathering for Precambrian metamorphic rocks in Sri Lanka. They concluded that measuring the $H_2O^{(+)}$ content of rock materials is a good and reliable method for finding their degree of weathering or weathering condition up to certain level and weathering potential index (WPI; Reiche 1943), product index (PI; Reiche 1943) and Ruxton's ratio (Ruxton 1968) show regular variations with increasing $H_2O^{(+)}$ content of the materials or increasing weathering.

Düzgören-Aydın *et al.* (2002) and Düzgören-Aydın & Aydın (2003) explained that geochemical signatures of weathering should be used to establish a framework for the interpretation of the heterogeneity level and the prediction of the variability in engineering properties of rocks. Before proceeding with the chemical weathering indices, it is useful to recapitulate the main geochemical observations: (a) by and large, weathering is not a subtractive process, (b) the behaviour of major elements and variations in LOI along the weathered profile cannot be solely explained in terms of degree of weathering, (c) sesquioxide content, and type and abundance of clay minerals significantly modify the geochemical signature of weathered materials.

Price & Velbel (2003) evaluated weathering indices with respect to their potential application to saprolite developed on heterogeneous felsic metamorphic parent materials. Their study indicated that the Parker's index is the most appropriate index of alteration to apply to felsic heterogeneous weathered regoliths. The Vogt ratio (Vogt 1927) could also be used for a regolith leached of all alkali and alkaline earth metals, but may not yield as appropriate results as the WIP because it assumes aluminum to be immobile. Application of the CIW (chemical weathering index; Harnois 1988), CIA (chemical alteration index; Nesbitt & Young 1982) or PIA (plagioclase index of alteration; Fedo *et al.* 1995) to heterogeneous profiles should only be done so with extreme caution, because they, too, assume aluminium immobility. The CIA may yield informative results, because it not only includes potassium in its formulation, but also combines potassium with the other alkali and alkaline earth elements. The Ruxton's ratio should not be applied to heterogeneous weathering materials. The success of the WIP may be due in part to its allowance for aluminium mobility (in contrast to other indices), and also because its formulation includes only alkali and alkaline earth metals. Due to their mobility during chemical weathering, alkali and alkaline earth elements may undergo large concentration changes, and, hence, may yield greater compositional variations relative to the unweathered bedrock than other elements.

Modelling Chemical Weathering Processes and Setting New Chemical Weathering Indices

Loughnan (1969) described three simultaneous processes involved in chemical weathering (Figure 1): (a) the

PRIMARY MINERALS

CHEMICAL ALTERATION

RESISTATES	SOLUTIONS		GELS		SECONDARY MINERALS

RESISTATES
unaltered
primary minerals

SOLUTIONS
colloidal
ionic

flocculation

GELS
aluminosilicate
Fe++ oxyhydroxide
ionic

ageing

dehydration

SECONDARY MINERALS
2:1 clays
  illites
  chlorites
  vermiculites
  smectites
   interstratified clays

ion exchange

increased leaching

loss of cations, silica

1:1 clays
  kaolinites
  halloysite

loss of silica

Al oxyhydroxides
Fe oxyhydroxide

lost from system

Figure 1. Processes of chemical weathering (from Fookes *et al.* 1988).

breakdown of the parent material structure with the concomitant release of the constituent elements and molecules, (b) the removal of some of these released constituents in solution, (c) the reconstitution of residue with components from the atmosphere to form new minerals, which are in a stable or metastable equilibrium with the environment.

No single weathering index given in the literature meets the modelling of the process involved in chemical weathering outlined above, and no weathering index would give unequivocal results when applied to the prediction models to assess the mechanical behaviour of rock materials. Thus, a theoretical model is developed in this study.

As decomposition of a mineral results in the formation of new, less dense minerals, the dry density of whole rocks is generally regarded as a measure of the degree of weathering (e.g., Grant 1963, 1964; Millot 1970; Gardner *et al.* 1978, 1981; Gardner 1980, 1992; Colman 1982; Banfield 1985; Eggleton *et al.* 1987; İrfan 1996; Tuğrul & Gürpınar 1997; Kim & Park 2003). However, this may not be so in all cases: Topal & Doyuran (1998) and Topal & Sözmen (2001) clearly demonstrated that the dry density of variably weathered tuffs does not significantly change even after harsh accelerated weathering tests such as wetting-drying, freezing-thawing and salt crystallization tests, probably

because of the absence of newly formed alteration minerals and leaching during such tests. Physical disintegration is the common phenomenon in the accelerated weathering tests. On the other hand, dry density gives a measure of the total loss through leaching, provided that no deposition has occurred from outside the corestone, and neither expansion nor contraction of the rock has taken place (Eggleton *et al.* 1987). Millot & Bonifas (1955) (summarized in English by Millot 1970) were the first to apply the isovolumetric method to the geochemical study of weathering profiles. Gardner *et al.* (1978, 1981) successfully applied the isovolumetric approach to the understanding of saprolite formation on homogeneous granite and diabase. In this approach, total volumetric concentration of any chemical component is defined on dry density of the rock materials (Gardner *et al.* 1978; Banfield 1985; Eggleton *et al.* 1987).

The model developed in this study depends on an isovolumetric approach and takes into consideration the definition of Loughnan (1969; Figure 2). In order to explain the change of the volumetric concentration of major oxides across a weathering profile, the following steps were applied: (i) Modal analysis and whole rock analyses of the sample taken across a weathering profile are performed. (ii) The weight percentage of the major oxide of interest from whole rock analyses of fresh samples is multiplied by dry density of the respective
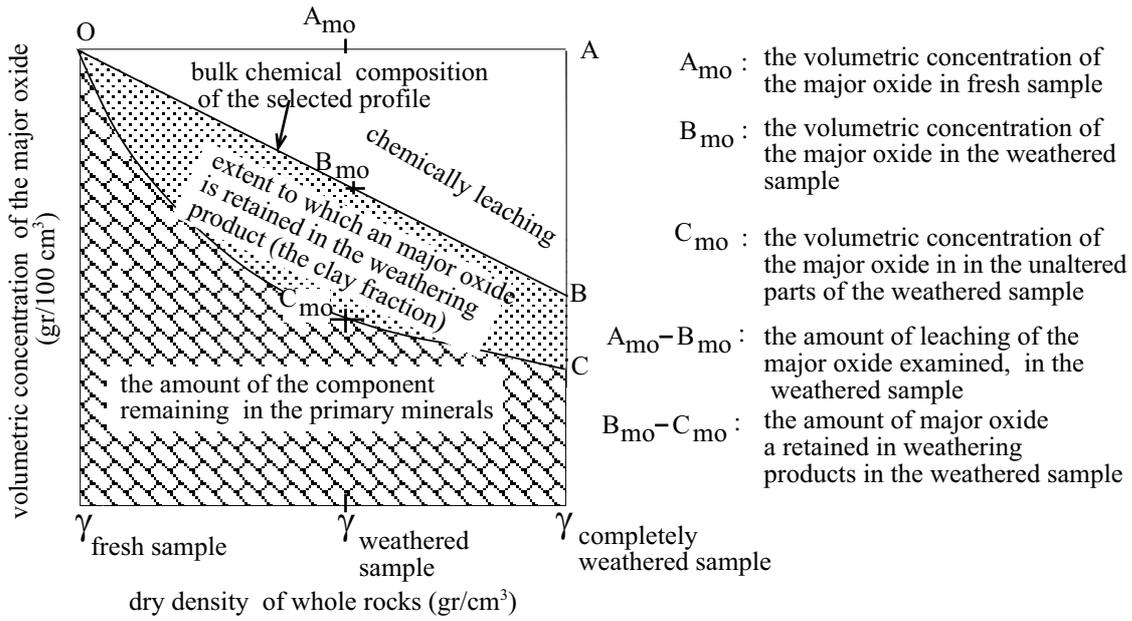
Figure 2. A hypothetical model illustrating the behavior of major oxides during chemical weathering (modified Banfield 1985).

sample. Then the Amos value in Figure 2 is obtained. By means of this Amos value, a parallel line (OA) was drawn. (iii) For each sample weathered to various degrees, the weight percentage of the major oxide is multiplied by dry density. In this way, upon plotting of the dry density as a function of the volumetric concentration of the major oxide, the OB line in Figure 2 is obtained. (iv) By microprobe analysis of the fresh minerals, the major oxide composition of the minerals in the sample is determined. (v) To calculate the total amount of the major oxide in the unaltered portion, the following equation (Banfield 1985) is applied.

$$Wmo = \left[\sum_{i=1}^{n} Mv(i) \times Ow(i) \right] \qquad (1)$$

where Wmo is the weight percentage of the major oxide in weathered sample, i values represent minerals such as plagioclase (i= 1), orthoclase (i= 2), hornblende (i= 3), biotite (i= 3), pyroxene (i= 4), quartz (i= 5), opaque minerals (i= 6), Mv is the volume percentage of minerals found by the modal analysis, Ow is the concentration (in weight percentage) of the major oxide in minerals from the microprobe analysis.

The total amount of any major oxide from Equation 1 is multiplied by its dry density and then the volumetric

concentration of the major oxide in the unaltered portion of the sample is found.

The volumetric concentrations of the major oxides in the unaltered parts of the samples versus the dry density of the samples weathered to various degrees are drawn and then the OC line in Figure 2 is obtained.

The concept of ionic potential is useful in explaining which elements occur together in weathering products and which ones are removed during weathering. The ionic potential, which is proportional to ionic charge (Z) and radius (r), provides a measure of the behaviour of ions towards water. Elements with low ionic potential remain in solution during weathering; elements with intermediate ionic potential are precipitated by hydrolysis; elements with still higher ionic potentials form complex anions with oxygen that are once again soluble (Ollier 1984, Figure 3).

Ca, Na, Mg, and K are geochemically mobile elements. Chemical leaching results in a significant decrease of the oxides of these elements. The ratio of the volumetric concentration of (CaO+MgO+Na$_2$O+K$_2$O) in a weathered sample to that in the fresh sample taken from the same weathering profile gives the amount of leaching for the weathered sample. Therefore, this ratio (equation 2) is defined as the *chemical leaching index* (CLI).
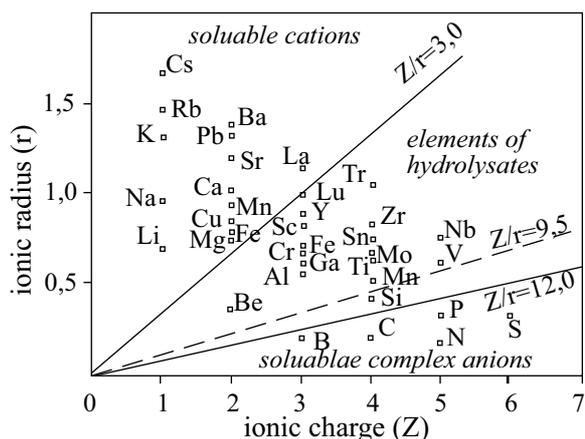
Figure 3. Geochemical affinities of certain elements according to their ionic ratio and charges (after Ollier 1984)

$$CLI = \frac{100(A_{mob} - B_{mob})}{A_{mob}} \qquad (2)$$

where A_{mob} and B_{mob} are the total volumetric concentration of mobile oxides in the fresh and weathered samples, respectively. If the y axis in Figure 2 represents the volumetric concentration of the mobile elements, likewise the CLI can be found for the weathered sample.

Al, Fe, and Ti are less affected by chemical leaching than alkali and alkali-earth elements, and tend to concentrate in weathering products (e.g., Loughnan 1969). If the drainage is well-developed, Si moves away; if not, it also tends to concentrate in the weathering products. The ratio of the total amount of these oxides in the weathering product to those in the fresh sample yields the amount of weathering products. Therefore, the *chemical weathering product index* (CWPI) is defined through the following equation:

$$CWPI = \frac{100(B_{immob} - C_{immob})}{B_{immob}} \qquad (3)$$

where B_{immob} and C_{immob} are the total volumetric concentration of immobile oxides in the whole sample and unaltered portion of the sample, respectively. If the y axis in Figure 2 represents the volumetric concentration of immobile elements, the CWPI can be found for the weathered sample as defined above.

Considering the definition of Loughman (1969), the *total chemical weathering index* can be defined as the sum of CWPI and CLI. Since the rock material can be weathered 100% at most, the TCWI value should be also at most 100. Therefore, the (CWPI+CLI) value has been divided by 2 in order to get TCWI using the following equation (Figure 4).

$$TCWI = \frac{(CWPI + CLI)}{2} \qquad (4)$$
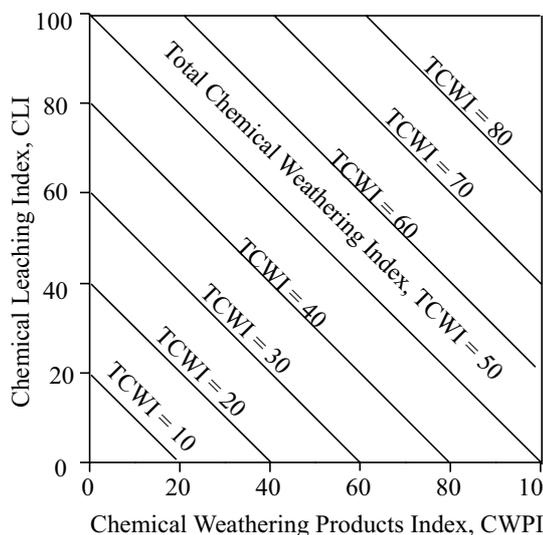
Figure 4. Total chemical weathering index (TCWI) is shown as a function of chemical leaching and the chemical weathering product indices.

A Case Study from the Kürtün Granodiorite (Gümüşhane, NE Turkey)

Geological Setting

The geology of the area between Kürtün (Gümüşhane) and Doğankent (Giresun), Eastern Pontides, NE Turkey, consists mainly of thick volcanic, volcaniclastic and intrusive rocks (Figures 5 & 6). The Kürtün granodiorite is a Late Cretaceous (68.4±3.4 Ma) batholith, intruding Late Cretaceous volcaniclastic rocks (Metal Mining Agency of Japan 1985; Güven 1993). The intrusion comprises hornblende-biotite-granodiorite, crosscut abundantly by dykes of quartz porphyry, dacite and dolerite. The granodiorite is holocrystalline with an equigranular texture and some porphyritic megacrystals of plagioclase. The constituent minerals are plagioclase, quartz, alkali feldspar, biotite, hornblende and, locally, clinopyroxene. Accessory phases are ilmenite, magnetite and titanite. Hydrothermally formed minerals include chlorite, calcite, quartz and epidote.

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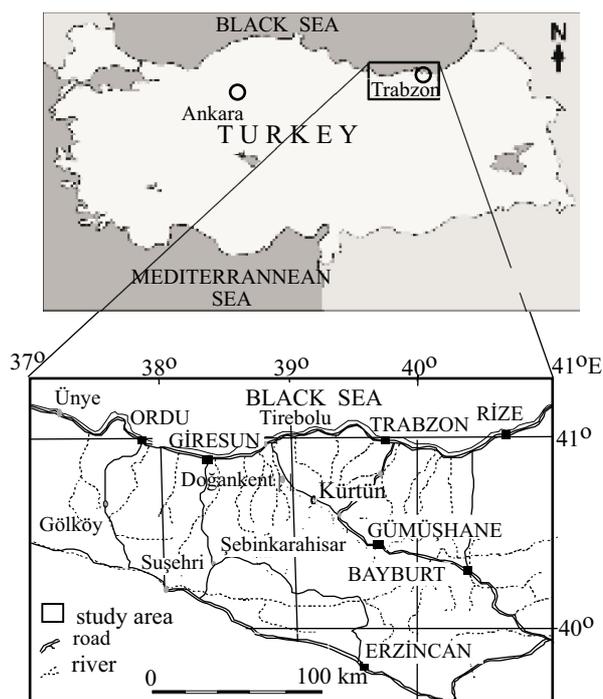
Figure 5. Location of the study area.

Weathering Profiles, Sampling and Test Procedures

The Kürtün granodiorite frequently displays weathering profiles, ranging from fresh rock to completely weathered rock and, locally, residual soils. The weathering zones are easily recognizable and definable. The boundaries between the weathering zones are usually gradual, and run parallel to the topography. However, the boundaries are sharp in shear zones, hydrothermal profiles and colluvium sites. Each zone was sampled along weathering profiles. During sampling, special care was taken to ensure uniformity of weathering and that the weathered zones should be represented. Large blocks, capable of providing a sufficient number of cores were preferred. Completely weathered block samples, that were highly prone to collapse if disturbed, were encased in a box immediately after trimming and the exposed faces coated with wax before attempting to undercut for removal. Then all the surface of the box was coated with muslin and wax. The box was then packed with plastic foam to support the sample during transport.
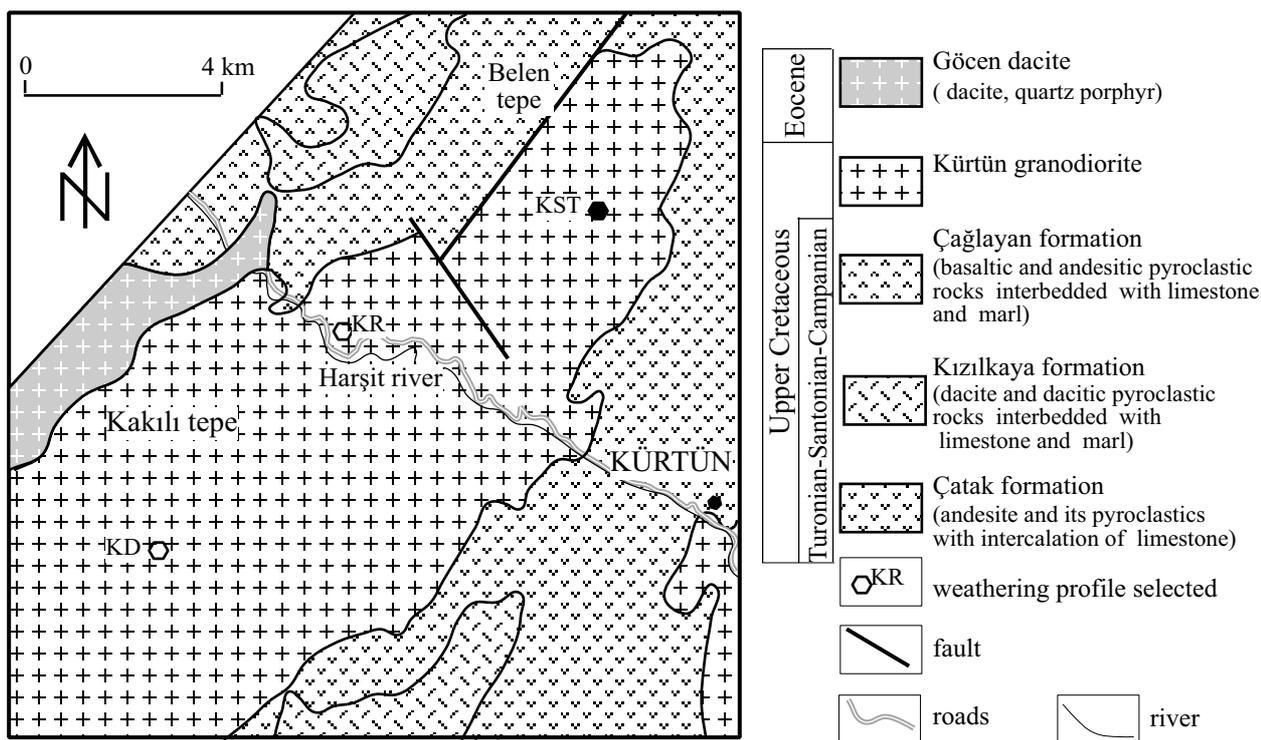
Figure 6. Geological map of the study area.

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Weathering processes occur under constant volume in weathered rocks and saprolite, as indicated by Ollier (1984). With further weathering, the remnant bonds of the saprolite collapse and this leads to the formation of residual soils. Hence, the volume of the weathered material changes during the formation of residual soils (Anon 1995). Because chemical weathering indices proposed in this study do not take volume change into consideration, no samples were taken from residual soils.

Petrographic features were determined by transmitted light microscopy and scanning electron microscopy (SEM), equipped with an energy dispersive X-ray spectrometer at the University of New Brunswick, Canada (Table 1). Mineral analyses were performed using the JEOL Super probe 700 at the University of New Brunswick, Canada (Table 2 & 3). Whole rock samples of each weathered zone were analyzed by X-ray fluorescence (XRF) at Karadeniz Technical University, Turkey (Table 4). The petrographical and chemical indices were calculated using the petrographic and chemical analyses given above (Table 5).

Core samples were tested for physical properties and uniaxial compressive strength according to the methods suggested by ISRM (1981; Table 6). The uniaxial compressive strength test was conducted on cylindrical specimens (L/D= 2.5) under dry conditions. Simultaneously, deformational response to compressive stress was also measured using one pair of electrical strain gauges (for axial strain) fixed to the middle portion of the curved surface of the specimens with epoxy resin adhesive. In this way, the tangent elastic modulus was derived from the slope of a line tangential to the stress-strain curve at a stress level which is specified as 50% of the uniaxial compressive strength. The deformation modulus is determined from the slope of the scan line between zero and the stress level which is specified as the uniaxial compressive strength (Figure 7, Table 6).

Table 1. The modal compositions of the granitic materials at various weathering state from Kürtün granodiorite.

Samples	Qtz	Or	Pl	Hbl	Bt	Pyrx	Cly	Srs	Ep	Chl	Oq
KR1a	24.79	18.42	42.06	5.99	1.1	2.29	0	0	1.07	1.14	2.7
KR1b	23.61	16.01	35.37	4.25	1.58	1.2	2.88	6.22	1.28	3.73	2.67
KR1c1	21.04	12.46	24.65	3	0.79	1.12	9.45	10.87	1.62	5.83	2.04
KR1c2	22.32	10.06	23.79	3.21	0.48	0.84	11.78	12.76	2.1	5.78	1.98
KR1d1	19.1	7.73	15.17	2.17	0.46	0.66	17.15	17.97	1.03	5.2	1.45
KR1d2	19.14	6.02	14.92	1.99	0.2	0.74	17.56	16.48	1.55	4.98	0.97
KR1e1	18.11	4.62	7.62	1.94	0.26	0	16.33	24.91	1.8	4.84	1.35
KD1a	25.98	16.42	39.38	12.33	4.54	0	0	0	0.4	0	0.4
KD2	25.36	14.02	32.92	9.67	3.3	0	3.47	6.41	0.24	2.57	0.4
KD2B	26.12	14.36	31.86	9.13	2.52	0	2.98	4.75	0.78	4.38	1.6
KD 3A	23.33	10.56	29.66	4.97	2.17	0.41	6.76	5.21	2.74	7	2.06
KD3B	21.44	11.96	24.79	5.29	2.61	0	6.82	10.22	2.37	4.01	1.09
KD4A	18.72	8.22	17.77	4.06	1.54	0.35	12.08	9.37	3.19	6.16	1.83
KD5	18.22	5.61	12.59	3.26	0.98	0	16.24	10.78	2.76	5.76	1.49
KST1	25.44	24.95	37.19	5.06	2.7	0	0	0	0.86	1.95	1.45
KST2	24.38	20.84	27.89	4.67	2.47	0	4.65	9.36	1.63	1.53	0.62
KST3	22.88	18.19	18.6	2.55	1.85	0	11.5	13.18	1.33	1.6	1.87
KST4	18.46	9.63	13.75	0.86	2.28	0	21.91	13.71	1.84	2.21	0.85
KST5A	22.09	5.16	2.54	0.67	1.04	0	31.63	13.86	1.03	4.77	0.13
KST5B	21.21	6.47	2.03	0.54	0.7	0	31.54	10.47	1.36	7.17	0.85

(Qtz– quartz, Or– ortochlase, Pl– plagioclase, Hbl– hornblende, Bt– biotite, Pyrx– pyroxene, Cly– clay; Srs– sericite, Ep– epidote; Chl– chlorite, Oq– opaque minerals).

Table 2. Chemical composition of feldspars, their hydrothermal alteration (sericite, epidote and montmorillonite) and weathered products (smectite, illite and kaolinite) from the Kürtün granodiorite.

	plagioclase[1]	K-feldspar	sericite	epidote	beidellite	smectite	illite	kaolinite
N	5	4	5	5	6	8	7	12
SiO_2	55.21(0.58[2])	65.36(0.37)	48.19(1.09)	38.13(0.45)	42.730.94)	51.84(2.79)	55.06(1.85)	45.68(1.81)
TiO_2	n.a	n.a	n.a	0.09(0.01)	n.a	0.04(0.04)	n.a	n.a
Al_2O_3	28.36(0.37)	19.46(0.43)	37.24(83)	25.09(0.59)	31.79(2.07)	30.20(3.99)	24.87(1.26)	37.45(2.23)
FeO*	0.32(0.13)	n.a	0.95(0.10)	11.25(0.47)	2.71(0.76)	4.41(1.37)	2.91(0.95)	0.48(0.25)
MnO	n.a	n.a	0.04(0.02)	0.02(0.01)	n.a	n.a	n..a	n.a
MgO	n.a	n.a	0.48(0.10)	n.a	0.35(0.11)	1.79(0.72)	0.52(0.37)	0.26(0.18)
CaO	5.82(0.52)	n.a	0.45(0.15)	23.24(0.16)	1.90(0.21)	2.18(0.60)	0.86(0.24)	0.66(0.42)
Na_2O	10.08(0.41)	0.74(0.31)	0.06(0.03)	n.a	0.20(0.12)	0.79(*0.39)	1.29(0.77)	0.10(0.08)
K_2O	0.34(0.18)	15.73(0.71)	8.44(0.52)	n.a	0.08(0.05)	0.30(0.25)	3.75(0.86)	0.07(0.05)
Total (%)	100.13	101.29	95.85	97.96	79.76	91.65	89.26	84.70

(N– number of analyses, *– Total Fe-oxide, n.a.– below the detection limits, [1]core composition (rims are enriched more in albite), [2]the number in parentheses represent ±2 Standard deviation

Table 3. Chemical composition of hornblende and biotite and their hydrothermal alteration and weathered products from granitic rocks from the Kürtün granodiorite.

	biotite	vermiculite	hydromica	hornblende	chlorite
N	6	3	4	6	8
SiO_2	40.80(0.67[1])	31.46(1.82)	46.19(0.87)	49.95(0.78)	27.97(1.00)
TiO_2	4.05(0.30)	0.21(0.15)	n.a	0.86(0.12)	0.08(0.03)
Al_2O_3	12.37(0.42)	18.47(0.95)	37.29(0.46)	4.85(0.51)	19.65(0.69)
FeO*	15.33(0.63)	17.49(1.78)	1.14(0.35)	13.14(0.63)	20.99(1.65)
MnO	0.24(0.09)	n.a	n.a	0.67(0.19)	0.52(0.14)
MgO	13.67(0.72)	16.10(1.63)	0.25(0.21)	15.41(0.57)	17.89(1.37)
CaO	3.70(0.18)	n.a	0.39(0.19)	11.26(0.24)	0.14(0.08)
Na_2O	0.08(0.03)	n.a	0.16(0.12)	1.13(0.26)	0.03(0.04)
K_2O	8.04(0.29)	n.a	6.16(0.59)	0.39(0.17)	a.l.a
Total (%)	98.28	83.91	91.58	97.66	87.27

(N– number of analyses, *– Total Fe- oxide, a.l.a.– below the detection limits, [1]the number in parentheses represent ±2 Standard deviation)

Mineralogical and Fabric Properties Across the Weathering Profiles

Feldspar is altered into sericite and epidote at the initiation of weathering following hydrothermal alteration. At the intermediate stage, clay minerals are formed. Vermiculite, chlorite, epidote and Fe-Ti oxides are the weathering products. Biotite is converted into the clay minerals without losing its chemical structure. Hornblende is broken down in the initial stages of the weathering. Quartz grains are scattered and laterally rounded in the only completely weathered granitic materials. In the latest stages of chemical weathering, soil

Table 4. Whole rock analyses of the granitic samples from the weathering profiles on the Kürtün granodiorite.

	SiO_2	TiO_2	AL_2O_3	FeO	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	P_2O_2	LOI
KR1a	67.412	0.144	14.728	1.807	2.759	0.059	1.814	4.912	2.68	3.187	0.003	0.495
KR1b	65.332	0.156	14.765	3.021	3.868	0.052	1.754	4.193	2.296	3.219	0.003	1.34
KR1c1	64.285	0.17	14.871	3.123	3.765	0.055	1.404	3.544	1.827	3.264	0.002	3.689
KR1c2	64.286	0.152	15.377	3.203	3.633	0.054	1.328	3.521	1.948	2.723	0.001	3.774
KR1d1	63.564	0.164	15.235	3.79	4.851	0.059	1.264	2.687	1.789	2.486	0.001	4.11
KR1d2	62.836	0.158	15.582	4.637	4.973	0.057	1.165	2.607	1.793	2.094	0.001	4.097
KR1e1	62.998	0.166	16.237	4.427	4.553	0.056	1.179	2.107	1.605	1.871	0.001	4.8
KD1a	67.655	0.262	15.364	1.706	0.93	0.064	2.805	5.099	2.524	3.124	0.012	0.455
KD2	66.605	0.264	15.646	2.072	0.981	0.067	2.769	4.451	2.405	3.235	0.009	1.345
KD2B	66.154	0.265	15.052	2.341	2.027	0.073	2.557	4.637	2.338	3.075	0.007	1.474
KD3A	64.248	0.263	15.02	2.95	2.895	0.075	2.876	4.307	2.013	3.136	0.005	2.211
KD3B	65.353	0.278	15.595	2.412	2.097	0.063	2.647	4.037	1.869	3.487	0.007	2.154
KD4A	62.18	0.267	14.461	4.375	4.268	0.063	2.342	3.755	1.701	3.276	0.005	3.306
KD5	61.518	0.286	15.86	4.316	4.105	0.07	2.548	3.226	1.549	2.599	0.003	3.919
KST1	67.307	0.185	16.499	1.401	1.653	0.038	1.558	4.123	2.469	4.157	0.007	0.603
KST2	66.462	0.175	18.015	1.214	1.253	0.04	1.539	3.661	1.989	4.375	0.007	1.269
KST3	65.201	0.134	16.326	2.412	2.401	0.033	1.598	3.561	1.852	4.464	0.005	2.002
KST4	62.701	0.175	17.934	1.568	3.967	0.029	1.646	3.033	1.242	3.46	0.003	4.242
KST5A	62.805	0.165	17.353	2.937	4.702	0.029	1.426	2.028	1.118	2.544	0	4.902
KST5B	61.138	0.182	17.597	3.917	5.263	0.036	1.412	1.961	1.018	2.424	0.003	5.058

formation takes place and granitic material is converted into residual and top soil.

Mineralogical and fabric properties of granitic materials from the weathering profiles are summarized in Table 7. The Micropetrographic Index (Ip) is generally used to determine weathering degree, and is defined as the percentage of sound constituents to unsound constituents (İrfan & Dearman 1978a, b). Determination of the percentage of sound to unsound constituents is made using a petrographical microscope. In the weathering profiles, Ip values are >6 in the fresh material, 6–2.8 in slightly weathered materials, 2.8–1.4 in moderately weathered materials, 1.4–0.7 in highly weathered materials and 0.7–0.4 in completely weathered materials.

With increasing grade of weathering, the amount of microcracks and voids increases, and the voids become interconnected. Consequently, porosity (n), effective porosity (ne) and the ratio of effective porosity to porosity increase. The value ne/n is >60% in fresh materials and >85% in completely weathered granitic material. In fresh rocks, grain boundaries are firm but tectonic and regional stresses have caused some openings. The amount of the secondary minerals increases rapidly from the initial stages of the alteration. The amount of alteration products is 6–25% in slightly altered samples, 18–35% in moderately altered samples, 30–45% in highly weathered samples, 42–53% in completely altered samples. The high amount of alteration minerals in slightly weathered samples is caused by the presence of hydrothermal minerals. At the middle stage of the weathering, the amount of weathering products (especially clay minerals) increases significantly.
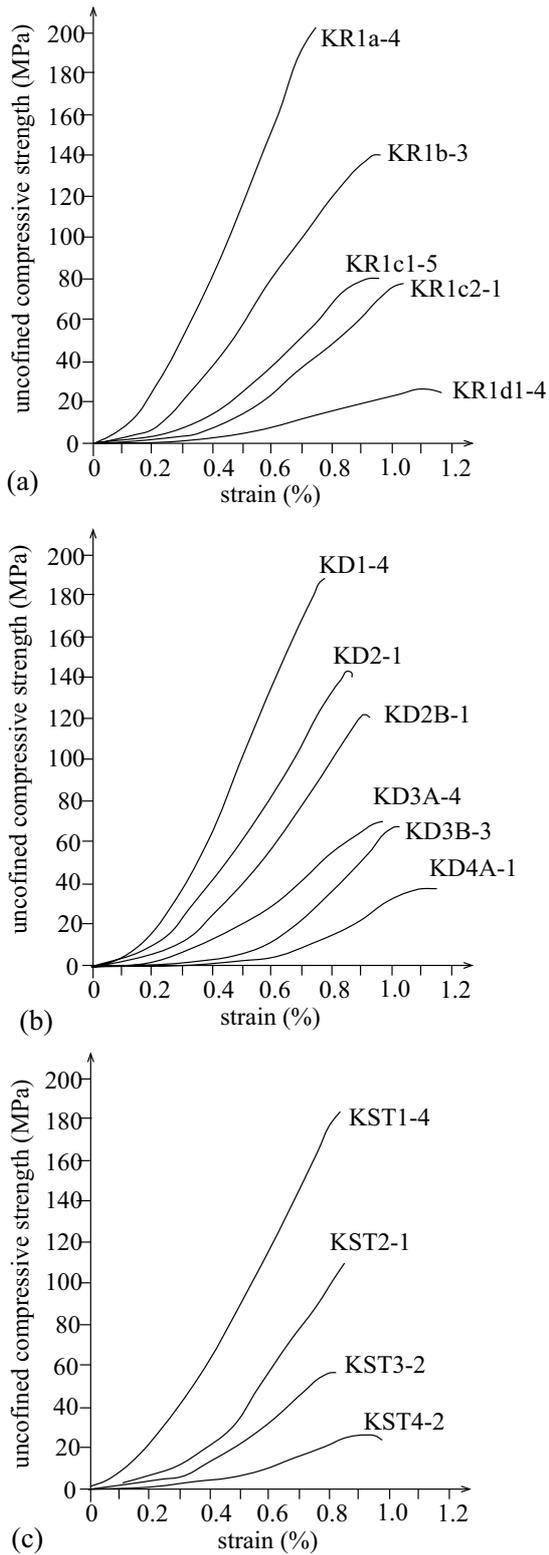
Figure 7. Stress-strain relation for the samples from the various weathering profiles.

Chemical Change due to Weathering

Chemical weathering causes variation in the composition of the rocks by leaching and introduction of new components. Relative variations of the volumetric concentration of major oxides versus the density of whole rocks are shown Figure 9 to determine the behaviour of the major oxides during weathering. SiO_2 concentrations show continuous decrease with increasing degree of weathering, while Al_2O_3 contents are characterized by slight decreases.

Some of the free silicon ions that existed during weathering of the rocks formed clay minerals and the others moved away as colloid in a solution. Because of the low solubility of Al_2O_3, it tends to concentrate in residual weathering products rather than solutions. CaO and Na_2O decrease quickly during the early stages of weathering as a result of the alteration of epidote and hornblende ± plagioclase. Some Ca and Na are probably fixed on the newly formed alteration products, such as clays. MgO is rapidly leached and removed in the early stages of chemical weathering. Some Mg is retained in the mineral structure of clay and chlorite. Titanium is a minor element in the parent granite. Biotite and the more resistant minerals, ilmenite and titanite, are the carriers of Ti. Probably no Ti is removed from the profile. Ti from biotite is transferred to 2:1 clays, and Ti in the accessories is persistent, therefore it may be accumulated in the residual products of weathering (Minarik *et al.* 1983). The FeO content of samples does not show an apparent enrichment or depletion trend. Because ferrous iron oxidizes to ferric iron during the weathering of rocks in oxidizing conditions, the Fe_2O_3 content of samples increases with the increasing degree of weathering. MnO and FeO have similar geochemical behaviour. Loss on ignition (LOI) appears to be a good indicator of chemical weathering as it reflects the amounts of OH^-, H_2O^- and CO_3^- bearing weathering products. However, drainage conditions and the behavior of chemical elements also influence the LOI content (Malpas *et al.* 2001; Düzgören-Aydın *et al.* 2002). Drainage conditions determine the type and abundance of clay minerals and sesquioxides to be formed. In well-drained conditions, clay minerals with 1:1 structure (kaolinite and halloysite) and/or Al and Fe oxyhydroxides are formed. In poorly drained environments, clay minerals with 2:1 structure (illite, chlorite, vermiculite and smectite) are formed (Figure 1). This kind of changes in the major oxides given above leads to an increase in CLI, CWPI and TCWI.

Table 5. Values of mineralogical and chemical indices for the samples at various weathering stage from the Kürtün granodiorite.

	FM	SM	CD	SM/FM	Ip	Ks	CLI	CWPI	TCWI
KR1a	97.35	2.21	0.44	2.3	0.03	1.781	0	0	0
KR1b	84.29	14.51	1.2	17.2	0.19	1.3248	10.34	10.6	10. 47
KR1c1	65.1	27.77	7.13	42.7	0.54	1.0589	24	24.62	24.31
KR1c2	63.09	32.01	4.9	50.7	0.59	1.0288	27.71	28.44	28.08
KR1d1	46.74	41.35	11.91	88.5	1.14	0.8478	40.07	39.61	39.84
KR1d2	43.98	40.57	15.45	92.2	1.27	0.8232	46.06	38.68	42.37
KR1e1	33.9	47.88	18.22	141.2	1.95	0.7626	53.64	48.3	50.97
KD1a	99.05	0.4	0.55	0.4	0.01	2.1171	0	0	0
KD2	85.66	12.7	1.64	14.8	0.17	1.5605	6.34	10.95	8.65
KD2B	85.58	12.9	1.52	15.1	0.17	1.6021	8.67	10.4	9.54
kd 3A	73.15	21.72	5.13	29.7	0.37	1.3925	13.72	18.18	15.95
KD3B	67.17	23.43	9.4	34.9	0.49	1.2292	16.82	22.38	19.60
KD4A	52.49	30.8	16.71	58.7	0.91	1.1705	25.2	30.1	27.65
KD5	42.15	35.54	22.31	84.3	1.37	1.1004	36.58	38.75	37.67
KST1	96.79	2.81	0.4	2.9	0.03	1.5436	0	0	0
KST2	80.87	17.17	1.96	21.2	0.24	1.1627	8.63	15.94	12.29
KST3	65.94	27.61	6.45	41.9	0.52	0.8538	11.98	25.83	18.91
KST4	44.63	40.87	14.5	91.6	1.24	0.6994	30.58	41.67	36.13
KST5A	30.71	52.21	17.08	170	2.26	0.6435	49.37	54.39	51.88
KST5B	31.45	50.89	17.66	161.8	2.18	0.8139	51.16	53.93	52.55

(FM– unaltereted minerals content in the rock materials (%); SM– secondary minerals content (%), SM/FM– the ratio of secondary minerals/ unaltereted minerals (%) CD– micro-fracture plus void ratio (%), Ip– Micropetrographic Index, Ks– Weatherability index (Ks= (Wm/PrI); Hodder 1984), (PrI– Parker Index; Parker 1970), Wm– Miura Index (Miura 1973), CLI– Chemical Leaching Index, CWPI– Chemical Weathering Product Index, TCWI– Total Chemical Weathering Index.

Table 6. The physico-mechanical properties and the relative variation in mechanical properties of the samples from the weathering profiles on the Kürtün granodiorite.

	γ (gr/cm^3)	n (%)	n_e (%)	σ_t MPa	σ_c MPa	E_t MPa	E_s MPa	σ_t^*	σ_c^*	E_t^*	E_s^*
KR1a	2.678	1.32	0.72	20.7	195.6	37500	28986	0	0	0	0
KR1b	2.638	1.94	1.23	12.2	121.5	20000	15600	41.06	37.88	46.67	46.18
KR1c1	2.553	6.24	5.45	6.1	78.3	12821	8453	70.53	59.97	65.81	70.84
KR1c2	2.561	5.59	5.15	4.1	53.7	11236	6598	80.19	72.55	70.04	77.24
KR1d1	2.457	8.47	7.86	1.4	18.9	4000	2155	93.24	90.34	89.33	92.57
KR1d2	2.375	10.5	10.24	1.2	17.4		1750	94.2	91.1		
KR1e1	2.312	16.1	16.03		7.1						
KD1a	2.683	1.37	0.77	22.8	200.3	35443	23821	0	0	0	0
KD2	2.648	2.45	1.77	14.2	135.8	21053	13451	37.72	32.2	40.6	43.53
KD2B	2.634	2.09	1.41	13.2	143.4	17500	15989	42.11	28.41	50.62	32.88
KD3A	2.544	5.81	5.07	5.6	70.6	11905	7268	75.44	64.75	66.41	69.49
KD3B	2.512	7.1	5.42	4.7	62.2	13514	5875	79.39	68.95	61.87	75.34
KD4A	2.456	13.3	12.58	2.6	33.6	6154	3096	88.6	83.23	82.64	87
KD5	2.324	18.53	18.13		2.8				98.6		
KST1	2.644	1.55	0.95	18.2	179.8	27119	21976	0	0	0	0
KST2	2.571	3.6	2.48	8.9	99.3	20896	13119	51.1	44.77	22.95	40.3
KST3	2.496	6.37	5.4	4.7	55.2	11628	7526	74.18	69.3	57.12	65.75
KST4	2.408	11.45	10.98	1.3	10.9	5195	1313	92.86	93.94	80.84	94.03
KST5A	2.315	15.54	15.31		4.6				97.44		
KST5B	2.332	16.33	16.16		6.1				96.61		

(γ– dry density, n– total porosity; n_e– effective porosity; σ_c– uniaxial compressive strength, σ_t– tensile strength; E_s– the module of deformation; E_t– tangent elasticity module; * indicate the relative variation in mechanical properties of fresh samples and weathered samples from the profile selected developed on Kürtün Granodiorite).

Table 7. Fabric and mineralogical features of the variably weathered granitic materials from the Kürtün granodiorite (F– fresh, SW– slightly weathered, MW– moderately weathered, HW– highly weathered, CW– completely weathered).

F	Quartz: 25.5±4.5%, K-feldspar: 20.5±3.5%, Pagioclase: 39.7±2.6 %, Hornblende: 7.8±3.1%, Biotite <4.0% ,Opaque minerals: 2±0.5%. Although no visible signs of weathering are seen, hydrothermal alteration caused some changes on minerals (Figure 8a). Ip (Micropetrographic Index) >6.0, SM (second minerals ratio)< 6%	Holoycrystalline with equigranular texture, fine–medium- (0.5–10 mm) grained, some of plagioclase forms porphyritic mega crystal. Microcrack + void ratio <3.5% Grain boundaries are firm but tectonic and regional stresses have caused some openings. Regular and systematic cracks have developed and crack surfaces are clean, unfilled and some discoloured
SW	Distinguished from fresh granite by the effects of hydrothermal alteration. Sericite and epidote have developed on less than 30 percent of the plagioclases. Less than 15 percent orthoclase shows dissolution effects. Less than 28 percent biotite and 32 percent hornblende have altered to epidote, chlorite and oxide minerals. Ip= 6.0–2.8, SM= 6–25%	Slight colour changes occur due to increasing weathering of biotite. Structurally controlled feldspar dissolution has begun (Figure 8b). Some microcracks developed on biotite due to secondary mineral development related to expansion on the lamely structure. Fe-oxide discoloured appears in some microcracks and discontinuities but grain boundaries are still firm Microcrack + void ratio= 3–4.5%
MW	Less than 35 percent of the plagioclase has decomposed to sericite, epidote and clay minerals. Less than 26 percent of the orthoclase has decomposed to sericite and clay minerals. Chlorite, epidote, Fe-oxides and clay minerals growths make 35 to 51 percent of biotite and hornblende. Ip= 2.8–1.4, SM= 18–35%	Due to dissolution, semi-opaque amorphous aluminosilicates and itches can be seen on plagioclases by microscope. Honey comb structure has started to develop on orthoclase surfaces. Compared to slightly weathered rocks, amounts of micro cracks plus void increase rapidly (Figure 8c). Quartz and plagioclases show fine developed irregular microcracks. Due to increasing dissolution rates, porosity and permeability have also increased. Most of the grain surfaces are discoloured by iron oxides Microcrack + void ratio = 4.5–10%
HW	At this stage the amount of clay minerals has significantly increased. More than 40 percent of plagioclase turns to epidote and clay minerals (Fig 8d). Due to sericite to clay mineral transition, amount of sericite decreases. 32 to 58 percent orthoclase show dissolution effects and on their surfaces clay minerals has started to develop. More than 60 percent biotite and hornblende turns to chlorite, clay and opaque minerals Ip= 1.4–0,7, SM= 30–45%	Microcracks and grain boundaries are well open. Quartz and significant amount of plagioclases were disintegrated. The openings are discoloured by Fe-oxides and some are filled by clay minerals. Microcrack + void ratio= 9–18%
CW	More than 55 percent of the plagioclases have disintegrated and decomposed to clay minerals. Less than 40 percent orthoclase survives and itches, dissolution canals cover their surfaces. Epidote which is a hydrothermal alteration product has decomposed to chlorite, calcite and small amount of opaque minerals. Most of the biotite and hornblende has turned to chlorite, Fe-oxides and clay ninerals. Some orthoclase is relatively unaltered. Quartz is unaltered but disintegrated along the grain boundaries). Ip= 0.7–0.4 SM= 42–53 %	Most of the microcracks and void space are connected, the rock has weakened and it can be broken easily by hand but rock texture is still preserved (Figure 8e). Microcrack + void ratio= 16–23%
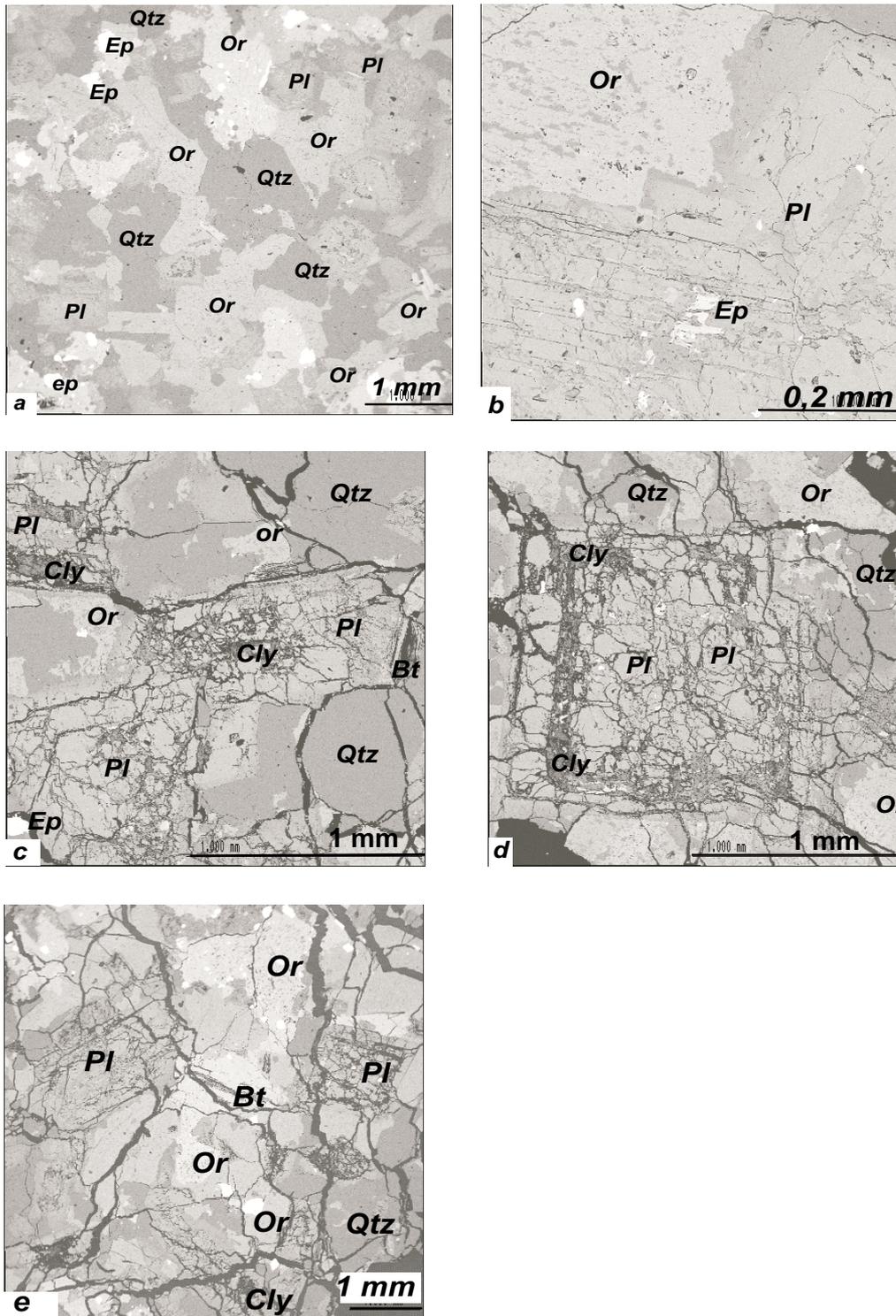
Figure 8. SEM micrographs illustrating petrographic features of the wheathering profiles **(a)** fresh granodiorite, **(b)** structurally controlled feldspar dissolution in slightly weathered granitic materials, **(c)** quartz and plagioclase with fine irregular microcracks in moderately weathered granitic rock, **(d)** weathering state of plagioclase in highly weathered granitic materials, **(e)** the fabric of completely weathered samples (Qtz– quartz; Pl– plagioclase; Or– orthoclase; Ep– epidote; Cly– clay ; Bt– biotite).
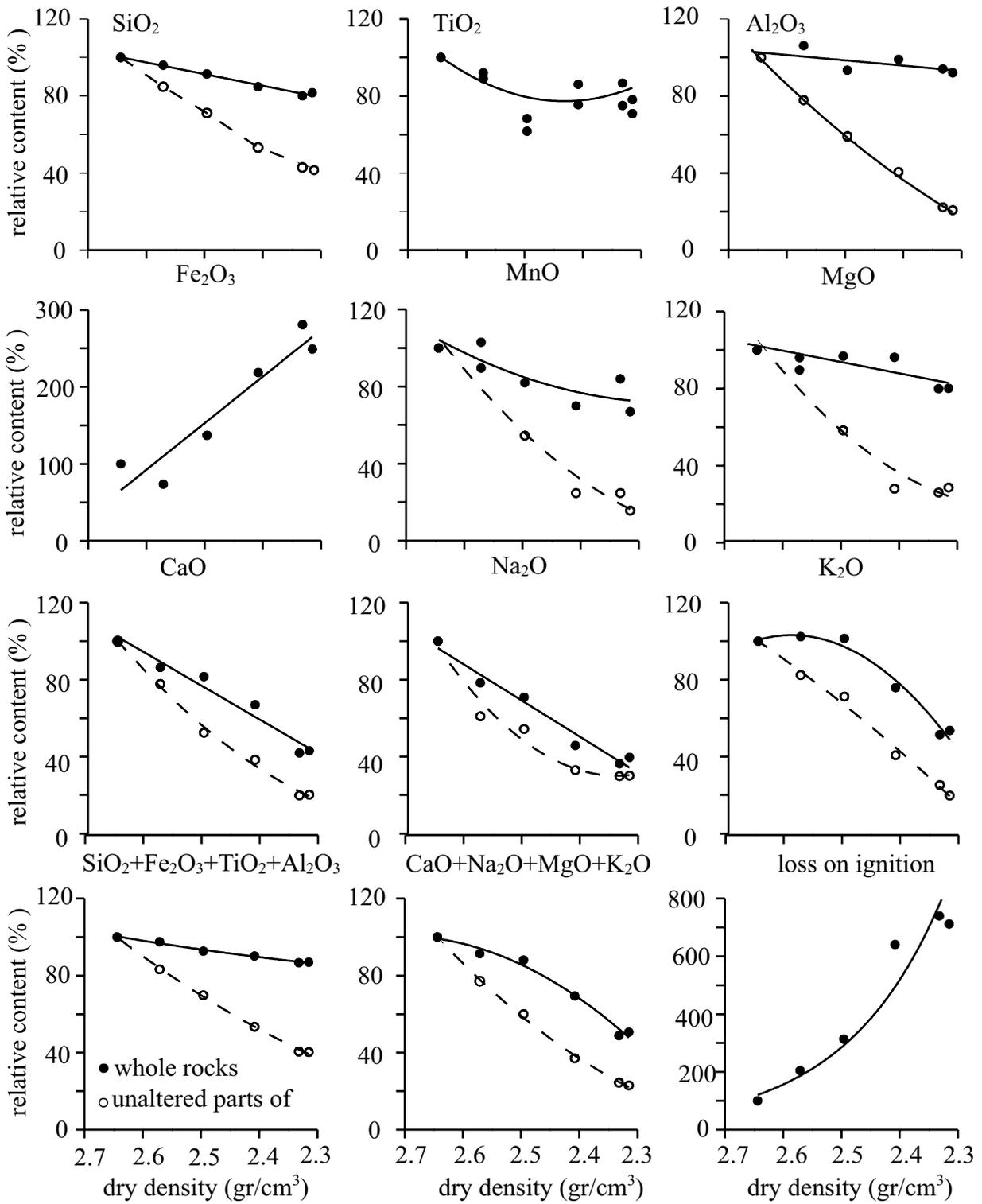
Figure 9. Relative variations of major oxides versus density of whole rocks samples taken from the weathering profile 'KST'.

The Relationship Between New Chemical Indices and Physico-Mechanical Properties

Statistical analysis was applied to explore the possible relationship between the proposed chemical indices and the mechanical properties of the weathered rock materials from selected weathering profiles. Coefficients of determination (R^2) and best-fit curves were calculated by the 'least squares curves fit' method using SSPS for Windows (Norusis, M.J. & SSPS Inc. 1999). Coefficients of determination value higher than 0.64 were considered statistically significant (Johnson 1984). R^2 values between 0.49 and 0.64 were not considered to be significant, but were taken to provide rough estimates of engineering properties involved in the correlation. R^2 at the 95% confidence level was determined for all available data.

The microfracture plus voids ratio depends on the original state of the rock, which is a function of stress history, and the stage of the weathering of the rocks. It increases during weathering due to dissolution of minerals. Therefore, the *chemical leaching index* is related to the amount of microfractures and voids in a unit area (Figure 10a), while the *chemical weathering product index* is dependent on the amount of hydrothermal alteration and weathering products. The amount of secondary minerals increases as weathering increases (Figure 10b). Consequently, the total chemical weathering index increases, as the microfracture plus voids ratio and secondary mineral content increase. The aim of the establishment of the change of TCWI due to weathering is evaluated by the interrelationship between TCWI and the micropetrographic index, because the micropetrographic index was used to quantify the degree of weathering. It is obvious from Figure 10c that there is a reliable relationship between TCWI and Ip.

The chemical, mineralogical and fabric changes due to the weathering is reflected in the index properties and mechanical behaviour. To evaluate the changes in the mechanical properties due to weathering, the following equation (5) is used, which calculates the variation of mechanical properties in relation to fresh samples:

$$X^* = \frac{(X_f - X_w)}{X_f} \times 100 \qquad (5)$$

where X^* is the relative change of mechanical property; X_f is the measured value of the mechanical property on fresh rock; X_w is the measured value of the mechanical property on weathered samples (Table 6).

In the investigated weathering profiles, the variation of uniaxial compressive strength relative to fresh material is <45% in slightly weathered materials, 45–70% in moderately weathered samples, 70–93% in highly weathered material and 90–98% in completely weathered material. The amount of the variation of other mechanical properties is similar to that of the compressive strength (Table 6). The strength and deformation of the rocks show considerable decreases in the first stage of weathering probably due to the drastic increase in the amount of secondary minerals (Table 7). The drastic increase in the amount of secondary minerals can also be seen in the proposed CWPI values (Tables 6 & 7).

The values calculated from Equation 4 are correlated with those of TCWI to evaluate the effect of the chemical weathering on the variation in mechanical properties (Figure 11). The coefficient of determination clearly demonstrates that there is a close correspondence between the TCWI and the relative variation in the mechanical properties. It should be stated here that the TCWI yields only the relative variation and not the absolute variation, since the mechanical properties of the rock materials depend not only on the weathering state, but also on the initial state prior to the weathering.

A good correlation between the chemical weatherability index (Ks), rock durability and mechanical properties have been recorded in the literature (e.g., Hodder 1984; Ceryan & Şen 2003). The weatherability index (Ks) of rocks depends on the amount and type of fresh minerals (FM). In the same rock-types, consequently, Ks decreases in proportion to the amount of the fresh minerals (Figure 10d), so TCWI and Ks are used together to estimate the strength and deformational properties and the following statistical relationships are obtained:

$$\sigma_t = 3.61 + 7.488 Ks - 0.25 TCWI$$
$$(N=14, R^2=0.856) \qquad (6)$$

$$\sigma_c = 35.3 + 71.4 Ks - 1.93 TCWI$$
$$(N=18, R^2=0.876) \qquad (7)$$

$$E_t = 25080 + 1906.3 Ks - 646.8 TCWI$$
$$(N=13, R^2=0.811) \qquad (8)$$

$$CLI = 3.0135\, CD^{0.9171}$$
$$(N = 17 \quad R^2 = 0.779)$$

$$CWPI = 0.555\, SM^{1.1567}$$
$$(N = 17 \quad R^2 = 0.981)$$

$$TCWI = 32.9\, Ip^{-0.617}$$
$$(N = 12 \quad R^2 = 0.926)$$

$$Ks = 0.0474\, FM^{0.772}$$
$$(N = 20 \quad R^2 = 0.751)$$
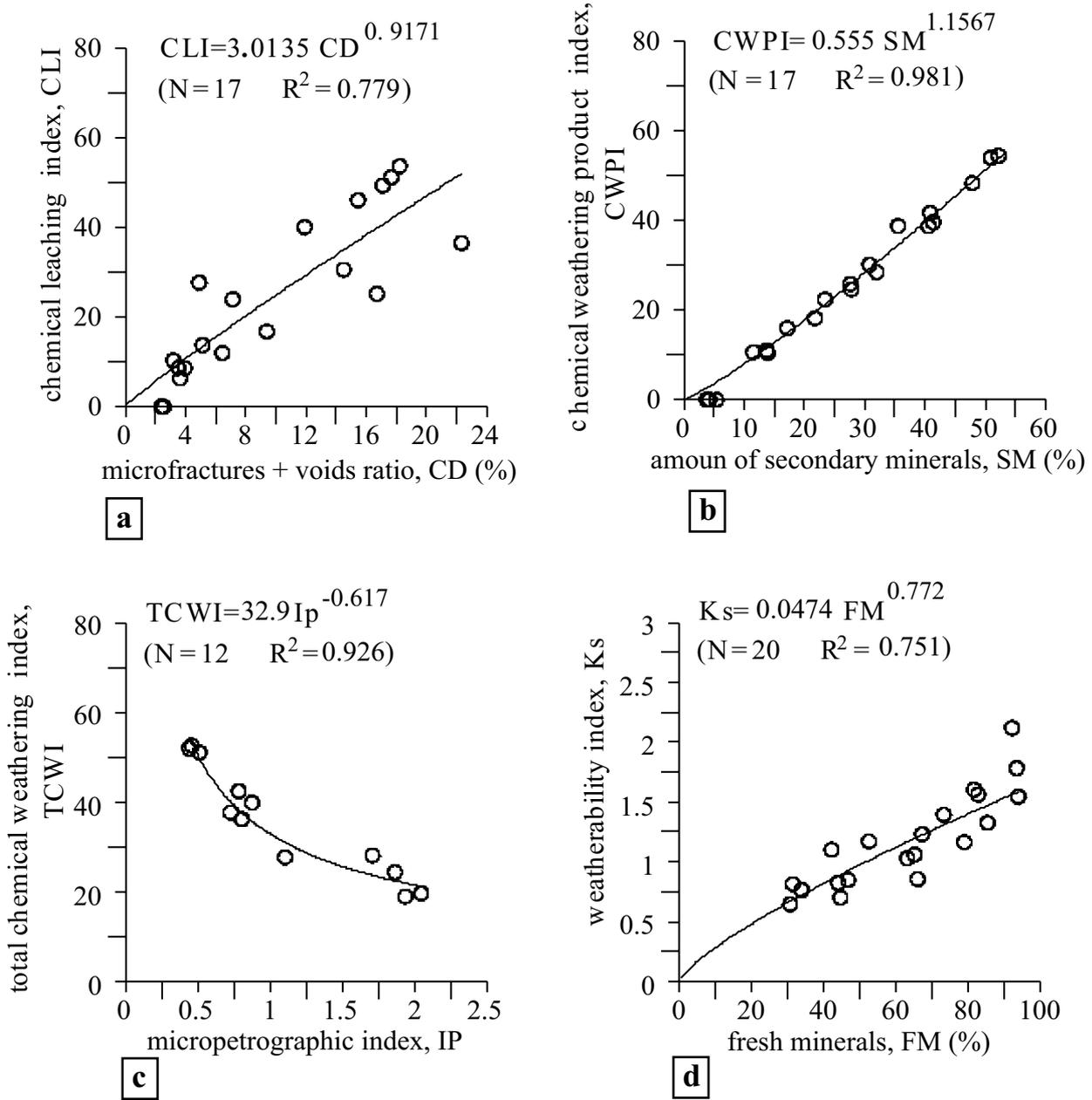
Figure 10. Relationships between (a) chemical leaching index and microcracks+voids ratio, (b) chemical weathering products index and the amount of secondary minerals, (c) total chemical weathering index and micropetrographic index, (d) weatherability index and fresh minerals ratio for the granitic materials at various weathering stage.

$$E_s = 14031 + 4268.95\,Ks - 477.7\,TCWI$$
$$(N = 13,\ R^2 = 0.801) \tag{9}$$

where σ_c is uniaxial compressive strength (MPa), σ_t is tensile strength (MPa); E_s is the modulus of deformation(MPa), E_t is tangent elasticity modulus (MPa). N gives the number of the samples investigated, R^2 is the coefficient of determination.

As can be seen from the coefficient of determination, there are statistically significant correlations between these chemical indices and mechanical properties of the
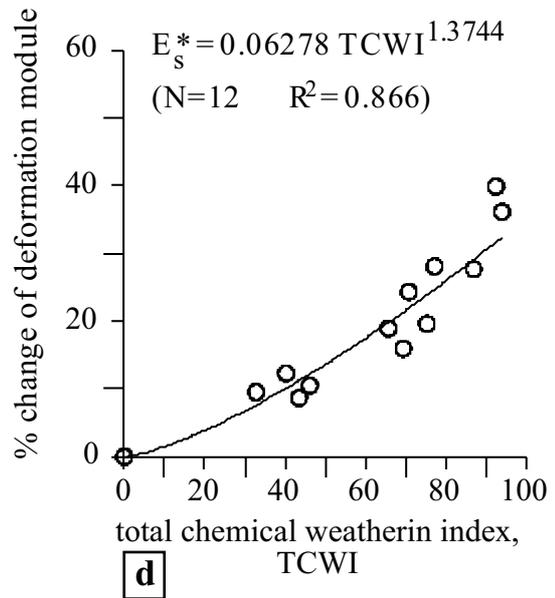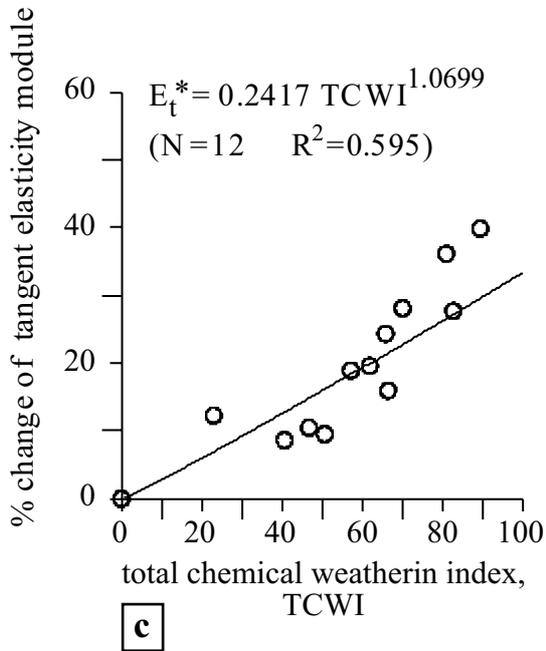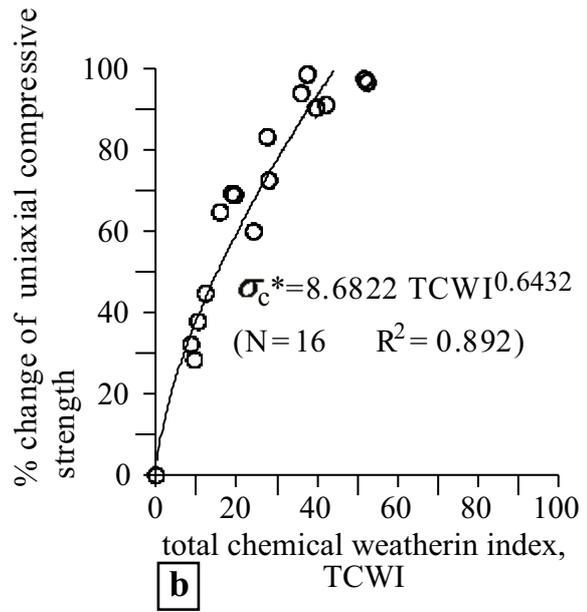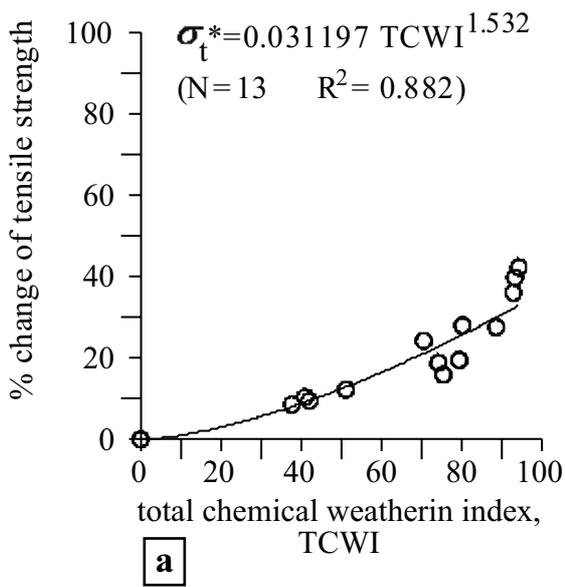
Figure 11. Relationships between total chemical weathering (a) and % change of tensile strength, (b) % change uniaxial compressive strength, (c) % change of tangent elasticity modulus, (d) % change of the modulus of deformation for the granitic materials at various weathering stage from Kürtün Granodiorite.

weathered rock materials studied. The uniaxial compressive strength of rock materials increases with the weatherability, and decreases with weathering. This is also valid for the deformation properties of rock materials.

Conclusion

In this study, new chemical indices were developed, giving suitable and meaningful results when applied to prediction models to assess the mechanical behaviour of

rock materials. In contrast to the former chemical weathering indices, these indices measure all the chemical processes involved in chemical weathering, and quantify its overall effects. The *chemical leaching index* (CLI) is defined by the amount of the geochemically mobile elements leached from rocks. The *chemical weathering product index* (CWPI) represents the ratio of the immobile elements in the weathering product to that in the whole rock. The *Total chemical weathering* index (TCWI) is defined as the sum of CLI and CWPI.

Application of these indices in the assessment of mechanical behaviour yields suitable and meaningful results. These indices are calculated for the samples taken from selected weathering profiles on the Kürtün granodiorite. Statistically significant correlations were found between TCWI and the variation of the mechanical

properties of the granitic materials relative to fresh rock. The strength and deformational properties of the weathered materials were correlated with the values of TCWI and *weatherability index*. Hence, co-usage of these indices can be applied to the prediction models to assess the effects of chemical weathering on mechanical behaviour.

Acknowledgments

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