

Characterisation of weathering propagation from joint surfaces in different rock types



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Abstract

The propagation of weathering into adjacent rock material from joint surfaces represents a significant gap in the Engineering Geology field, requiring further investigation and detailed analysis. The impact of weathering on the engineering properties of rocks stands as an indispensable consideration in geotechnical designs, as it intricately alters the quality of the rock mass across temporal scales. This also influences the engineering lifetime of structures (slopes or tunnels) and the appropriate design parameters for these structures. This study encompassed a thorough analysis of various properties, including the physical, mineralogical, and textural attributes of the rock. This investigation sought to reveal how these properties undergo transformation as the process of weathering from a joint surface extends into the adjacent parent material. Physical properties were assessed using the Schmidt hammer test to derive rebound numbers (R-values), while mineralogical and textural analyses were conducted through Polarized Light Microscopy, Scanning Electron Microscopy (SEM), X-Ray Fluorescence (XRF), and X-Ray Diffraction (XRD) techniques. Weathering indices, including the Chemical Index of Alteration (CIA), Mineralogical Index of Alteration (MIA), Chemical Index of Weathering (CIW), and Plagioclase Index of Alteration (PIA), were used to assess the degree of weathering across each sample. Indications of weathering were evident at the periphery and adjoining rock material of the samples. Fracturing was deemed as being one of the main drivers during the process of propagating weathering. The thin sections indicated that the process of weathering propagated further into the unexposed portion of the rock, unnoticeable to the naked eye. Weathering indices revealed granite as the least weathered rock sample, followed by quartz-diorite and shale. Samples with lower quartz content experienced a greater reduction in hardness (strength), indicating the role that mineralogy plays in the ability of a rock to resist the weakening effects of weathering. The chemical composition of a rock, as determined by X-ray Fluorescence (XRF) analysis, provides valuable insights into both the degree of weathering the rock has experienced and its potential for future weathering. This relationship is primarily influenced by the mineralogical composition of the rock, as different minerals weather at varying rates. Igneous rock samples exhibited a linear correlation between weathering degree and visible weathering propagation depth. The relationship between the decrease in hardness (strength) and the depth of weathering propagation revealed that as the depth of weathering propagation increased, the greater the decrease in hardness of the rock material adjacent to the joint. The joint weathering classification scheme adaptation, in which the methods of Amin et al. (2000) and Barton et al. (1977) were combined and used as a basis for the adaptation proposed, indicated that the igneous rock samples classifies as intermediately weathered, whereas the sedimentary rock sample (shale) classifies as slightly to intermediate based on the percentage decrease in hardness (strength) from the unexposed regions of the samples to the exposed regions of the samples as well as the zoning and depth of discolouration observed within the material adjacent to the joint opening. Each rock type showed distinct joint zoning patterns resulting from weathering propagation. This indicated that each rock responded differently to the process of propagating weathering. This highlights the importance of recognising that not all rocks react to weathering in the same way and emphasises the inadequacy of a single classification system for diverse rock types.

Keywords: weathering; propagation; mineralogy; engineering properties, fracturing, hardness

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LIST OF ABBREVIATIONS

Term	Definition
XRD	X-Ray Diffraction
XRF	X-Ray Fluorescence
SEM	Scanning Electron Microscopy
CIA	Chemical Index of Alteration
PIA	Plagioclase Index of Alteration
CIW	Chemical Index of Weathering
MIA	Mineralogical Index of Alteration
JCS	Joint Compressive Strength
JRC	Joint Roughness Coefficient
R-value	Rebound number
XPL	Cross Polarized Light
PPL	Plain Polarized Light

1. Introduction

The classification of weathered rock is complex at both the material and mass scales, often oversimplified in current approaches, highlighting the need for further research. Accurate modelling, representative of reality, is essential for ensuring long-term structural stability (Hencher, 2004). Weathering is a key yet poorly understood process in rock degradation, which involves disintegration and decomposition influenced by mineralogy and texture (Fakunle, 2016; Bhutia, 2016; Mulenga, 2015; Blean, 2012; Riaz et al., 2001; Hencher, 2004; Bell, 1992). It alters physical, chemical, and discontinuity properties, impacting geotechnical designs for tunnels, dams, and slopes. Understanding weathering is thus crucial in the field of Engineering Geology for improved stability assessments.

Discontinuities play a major role in the engineering behaviour of rock masses (Bell, 1992). Investigating the effects of weathering along these features is essential (Ismail et al., 2019). The limited documentation on the progression of weathering from joint surfaces into the surrounding rock material has created a gap in the Engineering Geology field. This study aims to address this gap and explore the impact of weathering on the engineering properties of the rock material adjacent to joints and other exposed surfaces. Specifically, it explores how weathering alters the hydro-mechanical behaviour of the rock material and its influence on the overall engineering response of a rock mass. To enhance the understanding of this process, a comprehensive weathering classification scheme will be developed, focusing on the characteristics of both the joint and the adjacent rock material. This scheme, informed by the findings of this study, will offer a more precise and reliable method for classifying joints, specifically tailored to the three rock types analysed.

Weathering influences the usability of rock for construction and varies throughout the engineering lifetime of the rock material (Yıldız et al., 2009; Fakunle, 2016). Accurate prediction of the future geotechnical properties of the rock mass is essential for ensuring the safety and robust design of engineering structures (Hack et al., 2020).

To achieve these objectives, the study employed a detailed analysis of the rock's physical, mineralogical, and textural properties. Physical properties were determined using a Schmidt hammer test to generate a rebound number (R-value). Mineralogical and textural characteristics were examined through Polarized Light Microscopy, Scanning Electron Microscopy (SEM), and analyses via X-Ray Fluorescence (XRF) and X-Ray Diffraction (XRD). Additionally, various rock weathering classification schemes were employed to assess the weathering degree of the rock. These schemes include Barton et al. (1977), Martin et al. (1986), Price (1993), Amin et al. (2000), Bell (2014), and Fakunle (2016). These classifications provide valuable insights into the overall quality and condition of the rock mass, including the effects of weathering. By combining these methods, the study aims to gain a comprehensive understanding of the impact of propagating weathering on both the rock material and the rock mass.

The safety, and sound design of any engineering structure for its entire lifetime, can only be guaranteed if the present and future geotechnical properties of the rock mass can be predicted (Hack, et al., 2020). While all materials are susceptible to weathering, the rate at which this process occurs varies significantly, as highlighted by Fakunle (2016). The inter-particle bonding between rock grains greatly influences a rock's vulnerability to weathering. The rate of weathering in rocks or rock masses plays a pivotal role in shaping landscape development, soil formation, and the preservation of structures such as buildings and monuments. There is a clear emphasis on the importance of accurately determining and estimating the rate of weathering as well as the susceptibility of rocks and rock masses to weathering (Israeli et al., 2018). This understanding is crucial for ensuring the workability and safe design of structures throughout its engineering lifespans, including in applications such as slopes and tunnels

(Fakunle, 2016). The rate of weathering, particularly chemical weathering, is determined by various factors including the intrinsic properties of the rock or rock mass, its geological history, and the prevailing environmental conditions such as temperature and the availability of water (Fakunle, 2016). The rate of weathering is predominantly governed by the durability of the material, a factor heavily influenced by the mineralogy, texture, and porosity of the rock or rock mass, as noted by Bell (1992). Additionally, the excavation methods utilised during the development of open pit and underground mines can significantly impact the rate of weathering (Hack, 2012). Poor execution of excavation methods can lead to an accelerated rate of weathering; for instance, inadequate blasting techniques may result in rapid unravelling and structural loss, leading to increased permeability of the rock and ultimately a higher-than-anticipated rate of weathering (Hack, 2012).

The rate of weathering in a rock mass is reduced over time as residual and weathering products remain on the rock mass surface, which prevents contact between the fresh rock mass surface and weathering agents (Fakunle, 2016; Tating et al., 2013; Bell, 1992; Fookes et al., 1988). Thus, creating a protective layer over the underlying rock mass (Bell, 1992). When erosion removes this protective layer of weathered products, and the fresh surface is once again exposed, will weathering continue to take place and propagate into the rock (Fakunle, 2016; Tating et al., 2013; Bell, 1992). According to Allison et al. (2010), when a rock surface that has been previously unexposed is suddenly exposed to atmospheric conditions through excavation or other human activities, it undergoes a notably accelerated rate of weathering. Peck et al. (2011), further highlights the considerable challenge in accurately estimating the potential deterioration of a rock mass over time. In scenarios such as the construction of a raise bore or ventilation shaft, the detachment of rocks within the shaft walls is predominantly influenced by increased exposure to air and water, affecting both the rock material and the infillings within the joints.

In open pit mine environments, repeated wetting and drying cycles caused by environmental factors like rainfall and evaporation result in significant physical and mechanical deterioration. These cycles lead to the expansion and contraction of pore structures and discontinuities within the rock mass. Over time, this process increases porosity and reduces cohesion between grains and discontinuities, thus weakening the material's structural integrity and decreasing the shear strength of the discontinuities present within the rock mass (Bang et al., 2024). Additionally, wetting–drying cycles cause the development of microcracks and fractures within the material, further exacerbating degradation and reducing strength and structural performance (Chen et al., 2024). Consequently, the cumulative effect of these cycles diminishes the load-bearing capacity of exposed materials and heightens the risk of slope instability and failure in open-pit mines. Thus, understanding and mitigating the impacts of wetting and drying cycles are crucial for maintaining the safety and longevity of mining operations. Mitigation of the effects of these cycles include implementing an effective dewatering strategy, such as the installation of horizontal drains, depressurisation wells, and comprehensive groundwater monitoring systems (Peksezer-Sayit et al., 2022).

Weathering results in disintegration and growth of fractures at both large and small scales, thus weathering takes place at two different scales. The first scale is the weathering of intact rock samples, known as the material scale, during which laboratory testing and core logging are performed to determine the effects that weathering has on the properties of an intact rock sample. At this scale, little to no heterogeneity exists, and the classification of the weathering grade is simple with very few complications. A rock mechanics approach, involving the analysis of the physical behaviour of the rock through applications within the engineering and structural geology field, is suitable for investigation and analysis. The second scale, known as the mass scale, studies the effects of weathering on the properties of a rock mass. This scale is utilised during the preparation of engineering geological models for construction projects. These rock masses can be heterogeneous and contain many discontinuities,

different characteristics, textures, and fabrics. At intermediate stages of weathering, there may be a mixture of softer and harder materials in these rock masses, causing difficulties during excavation, piling, and drilling. The heterogeneous characteristics of these rock mass units make it difficult to characterise, derive parameters (physical and mechanical properties), test for, and analyse in a realistic manner (Hutchinson, 2018; Hencher, 2004; Amin et al., 2000).

2. Literature Review

This literature review discusses the multifaceted effects of weathering on rocks and rock masses, surrounding both material and mass scales. It evaluates different rock mass classification schemes, highlighting the importance of each scheme in assessing weathering impacts. The review looks at how propagating weathering influences the physical, chemical, and mechanical properties of rocks, as well as the rate at which weathering occurs and the susceptibility of rock materials to weathering from joints and other exposed surfaces. By amalgamating existing research, this review gives a comprehensive understanding of weathering processes and its implications. Furthermore, it emphasises the importance of considering future weathering when designing engineering structures to ensure long-term stability and performance.

2.1. Physical and Chemical Weathering

A change in the state of a rock or rock mass from an initial condition to a new condition is caused by the process of weathering (Goel et al., 2015). Weathering is a process that occurs at or near the Earth's surface, involving one or more physical, chemical, or biological mechanisms (Bhutia, 2016). The mechanisms behind the weathering process involve any process that results in the weakening of the hydro-mechanical properties of rocks and other geomaterials (Alonso et al., 2006). Weathering can be described as the physical and chemical changes in a rock or rock mass over time due to temperature, water, and/or vegetation (Hack et al., 2020). Weathering is the continuous process of decay that occurs through disintegration, decomposition, or a combination of both (Bhutia, 2016; Fakunle, 2016; Hencher, 2004). According to Price (1993), the process of weathering results in the irregular deterioration of a rock mass, thus adding complexity to the rock mass which is inherently complex due to its heterogeneous structure, composition, and external forces; weathering further increases this variability and unpredictability.

Weathering affects the physical and chemical properties of both intact rock and rock mass. This process breaks down materials into fragments of varying shape, size and chemical compositions which may further weaken the rock mass. Physical and chemical weathering processes can thus control the rate at which rocks and rock masses weather, by taking place, either simultaneously, or at different times during the breakdown process of a rock or rock mass (Bland et al., 2016). Both chemical and physical weathering influence the rock mass surface; however, chemical weathering is the dominant weathering process that takes place in the subsurface of a rock mass (Fakunle, 2016).

Furthermore, environmental conditions, including climate, play a pivotal role in determining the pace and character of weathering phenomena (Fakunle, 2016; Tating et al., 2013; Bell, 1992). In regions characterised by high humidity, chemical weathering processes prevail, while in cold and arid

environments, physical weathering mechanisms become predominant (Fakunle, 2016; Bell, 1992). The process of weathering is most intense during hot, wet climatic conditions, thus during these conditions, weathering is expected to occur at greater depths (Goel et al., 2015). The influence of weathering under hot, wet conditions will consequently be greater and must be considered to a greater extent compared to other types of climatic environments. The depth and rate of propagating weathering, which originates at an exposed surface of a joint or another discontinuity, will also be greater under these environmental conditions.

Physical or mechanical weathering leads to the fragmentation or cracking of rock formations and masses. This process causes rocks to break down into smaller particles without altering their chemical composition or mineralogical structure (Macheyeki et al., 2020; Bland et al., 2016; Alonso et al., 2006). Fakunle (2016) concurs, emphasising that physical weathering facilitates the creation of discontinuities within rock masses. The main causes of physical weathering include fluctuations in both temperature and pressure (Macheyeki et al., 2020). Alonso et al. (2006) identifies three key factors that govern the process of physical weathering: the presence of discontinuities such as joints, bedding planes, and fracturing; the phenomenon of slaking; and finally, the expansion of clay minerals.

Chemical weathering alters the chemical and mineralogical composition of rock material or rock mass (Bland et al., 2016). As a result, primary minerals in the rock may transform into secondary minerals (clay minerals and oxides). Figure 2-1 shows the major and minor pathways for the creation of secondary minerals and the presence of clay minerals in a rock, or rock mass is indicative of chemical weathering that took place. Subsequently, as the process of weathering progresses, the amount of clay minerals is likely to increase (Fakunle, 2016). The most important chemical reactions include sulphide mineral oxidation, dissolution of the bonding, or cement, and the process of hydration (Alonso et al., 2006). Moreover, chemical weathering diminishes the material's strength to the extent that physical weathering processes can exacerbate permanent damage to rocks or rock masses. This results in a higher degree of breakdown compared to rock material or rock mass that has not experienced chemical alteration through chemical weathering processes (Bland et al., 2016). Israeli (2018) discusses this phenomenon, highlighting how chemical weathering augments the process of physical weathering by diminishing the strength of the rock material. The chemical weathering process is encouraged by the physical weathering process, as physical weathering results in an increased surface area, thus providing a greater area for chemical reactions to occur (Macheyeki et al., 2020; Panchuk, 2015; Alonso et al., 2006). The results of the interplay between physical and chemical weathering are provided by Israeli (2018), indicating that enhanced diffusion (chemical weathering), which takes place at the boundaries of micrometre-sized grains in a rock, results in the mechanical detachment (physical weathering) of rock particles. This further underscore the intrinsic relationship between physical and chemical weathering processes.

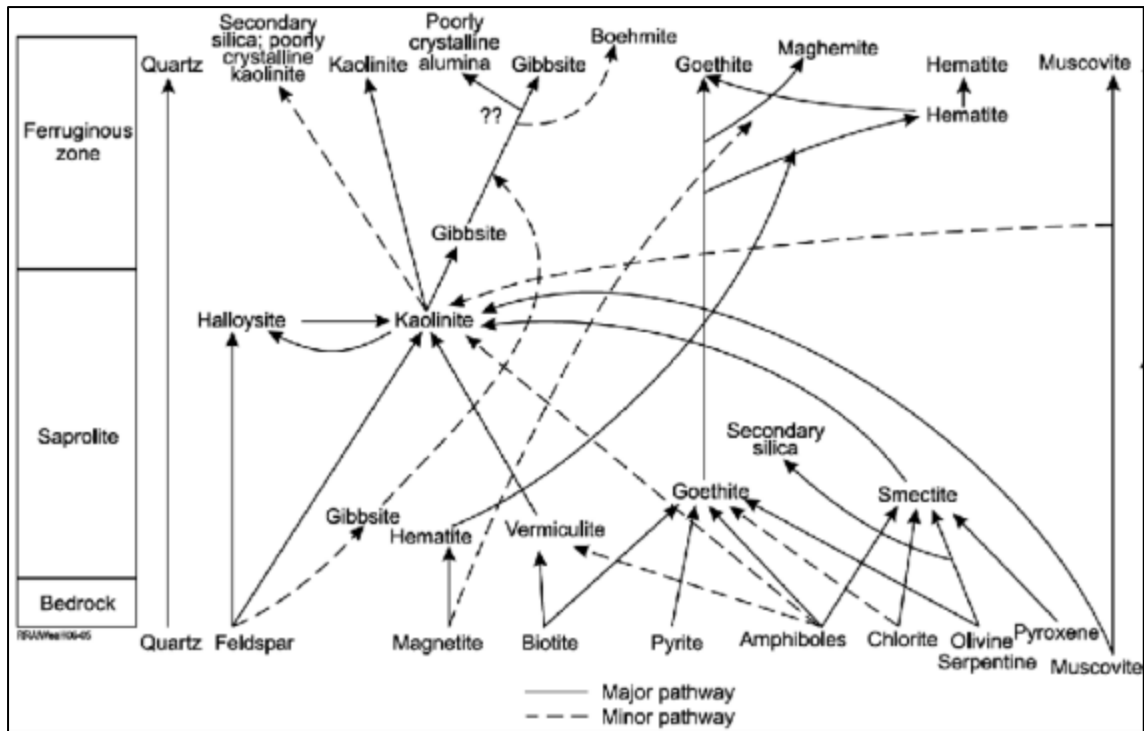


Figure 2-1: Weathering pathways from primary minerals to secondary minerals (Laukamp et al., 2013).

2.2. Weathering of Rock Material

The properties of a rock material are primarily controlled by the texture, mineralogical composition, fabric, as well as the weathering state. Therefore, different rock types, as well as its weathering products, will inherently possess varying strengths and weaknesses due to the subsequent histories and conditions it was subjected to during rock formation (Fakunle, 2016). Momeni et al. (2017) highlights that the physical and chemical properties of a rock, prior to weathering, influence the extent to which weathering changes the properties of a rock. This observation highlights the 'snowball effect' wherein the initial physical and chemical properties of a rock significantly influence the rate, type, and intensity of subsequent weathering processes. The mineralogical, physical, and chemical alterations induced by weathering lead to changes in the rock's engineering properties, ultimately affecting its quality and suitability for use in the construction industry (Momeni et al., 2017; Yıldız et al., 2009).

Physical and chemical changes take place due to the formation of new minerals, as well as the leaching out of a significant number of chemical components, as elucidated by Velde et al. (2008). The presence of water in or on the rock or rock mass, causes chemical reactions, such as hydrolysis, or hydration to take place, thus resulting in the creation of secondary minerals (Macheyeki et al., 2020; Alonso et al., 2006). Furthermore, the chemical properties that influence the rate of weathering include the proportions of low- and high-reactivity minerals within the rock material. Grotzinger et al. (2014) states that the stability (i.e., reactivity) of rock minerals increase opposite to the sequence of the Bowen's Reaction series (Figure 2-2). Bell (1992) explains that the conditions under which minerals form (temperatures and pressures) has a significant impact on the stability of the minerals under atmospheric conditions. Thus, the minerals that have crystallised during the early stages at relatively high temperatures and pressure will be less stable than the minerals that crystallised during later stages at lower temperatures and pressures (Grotzinger et al., 2014). Mafic-to Ultra-mafic minerals are the most unstable minerals at or close to the earth's surface, consequently making rocks that contain these minerals (dunites, peridotites, basalts, and gabbro), more prone to weathering compared to the rock

types containing Felsic minerals (Acidic igneous rocks) (Bell, 1992). Felsic minerals, such as quartz, orthoclase feldspar, Na-rich feldspar (plagioclase), and mica, in a rock will classify as low-reactivity minerals, whereas the Mafic minerals, such as amphibole, pyroxene, and olivine, will classify as high-reactivity minerals (Grotzinger et al., 2014).

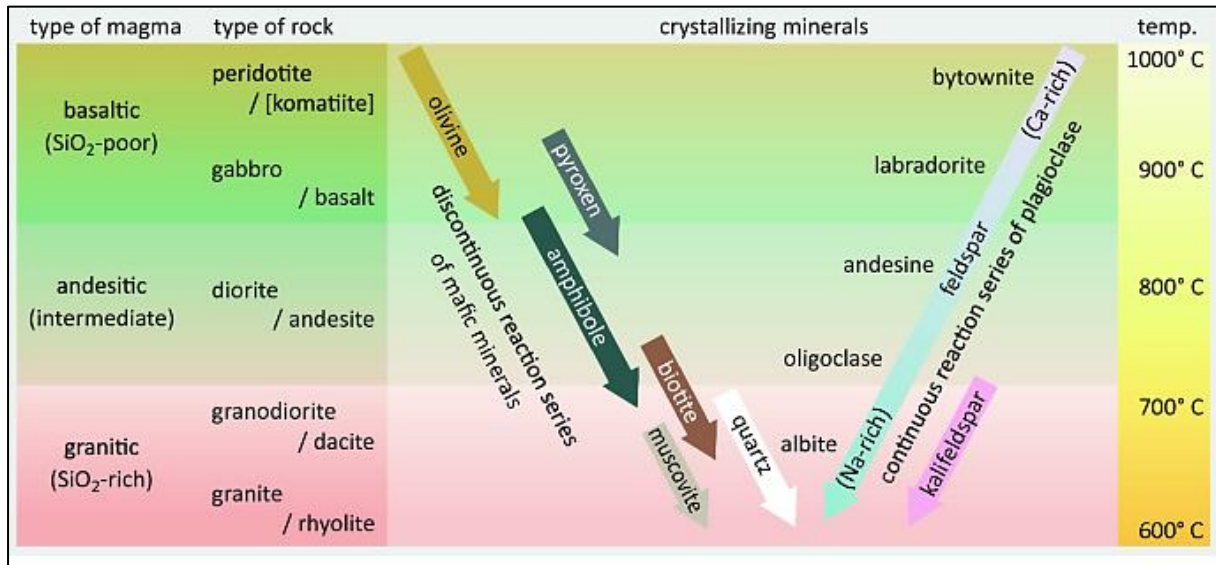


Figure 2-2: Bowen's Reaction Series (Meschede et al., 2019).

Hack (2012) states that the rock mass becomes more stable over time in terms of weathering susceptibility due to mineralogical and chemical changes (increased proportion of low-reactivity minerals). The rate of weathering consequently decreases with time. This statement agrees with the observations made by Israeli et al. (2018), showing that as the low-reactivity mineral proportion increases, the weathering rate decreases in a non-linear fashion. When the low-and high-reactivity minerals have equal quantities, the process of grain detachment contributes a minimum of approximately 50% to the total weathering rate. This takes place due to particular dissolution of the high-reactivity minerals present within the material. This selective dissolution causes large congregations of the low-reactivity minerals that are present in the rock. These clusters then become detached, thus resulting in grain, or particle detachment. This mechanical detachment process leads to changes in the porosity, as well as the permeability of the rock. Bell (2005) briefly mentions a similar process during which a highly porous framework of individual grains is left behind, once the weathered material has been removed. Israeli et al. (2018), further mentions that the progression of fractures can be enhanced through the process of preferential dissolution of the minerals with a higher reactivity. In addition, Gu et al. (2020) highlights that microfractures are an important factor that dictates the rate of weathering in shales. On the other hand, Bell (1992) asserts that clay minerals exhibit significant stability and low reactivity under atmospheric conditions. This view is supported by Bleam (2012), who emphasises that minerals found within the clay fraction (<0.002mm), predominantly comprised of clay minerals, are the least prone to chemical weathering. Alonso et al. (2006) notes that rocks such as shale exhibit minimal reactivity when their water content remains at natural levels. However, exposure to drying under atmospheric conditions accelerate disintegration more rapidly than when subjected to higher water content levels.

The type of weathering and the rate at which it occurs depend on the texture and mineralogical composition of the rock (Bleam, 2012; Bell, 1992). Fine-grained igneous rock varieties, such as basalt, have been observed to exhibit lower susceptibility to physical weathering compared to coarse-grained counterparts like gabbro. Consequently, coarse-grained rocks may undergo more extensive physical

disintegration, whereas fine-grained rocks often exhibit a higher propensity for chemical alteration due to their larger specific surface area (Bhutia, 2016; Mulenga, 2015; Riaza et al., 2001). However, this generalization oversimplifies the interplay between grain size, porosity, and fracturing, all of which significantly influence weathering processes.

For example, while fine-grained rocks inherently have higher grain boundary density and reactivity at the nanoscale (Israeli et al., 2018), coarse-grained rocks are frequently more porous due to a poorer degree of grain packing, resulting in larger pore sizes and lower specific surface area (Benavente et al., 2021). This porosity, coupled with microfracturing or larger-scale fractures, can significantly enhance the weathering susceptibility of coarse-grained rocks. Thus, a highly fractured and porous coarse-grained rock could weather more rapidly than a pristine fine-grained rock, contrary to the general assumption (Israeli et al., 2018).

The influence of porosity and specific surface area (SSA) is crucial in understanding these dynamics. Greater porosity facilitates chemical weathering and frost action, while SSA determines the extent of exposure of reactive surfaces to weathering agents (Macheyeki et al., 2020; Panchuk, 2015; Cheremisinoff, 1998). As Mulenga (2015) elaborates, vesicular volcanic rocks with greater surface areas weather faster than non-vesicular varieties. Therefore, the weathering susceptibility of a rock material is predominantly controlled by a combination of its grain size, porosity, pore size, and the presence of fractures. Acknowledging these interplaying factors provides a more accurate understanding of how different rock types respond to weathering.

2.3. Weathering of Rock Mass

Weathering typically occurs along major joints initially, where concentrated water flow serves as the main driver of both weathering and erosion (Amin et al., 2000). As a result, joint surfaces are the primary sites for the formation of secondary minerals and erosion (Hencher, 2004). The notable changes in the physical characteristics of a joint are caused by fracturing along the grain boundaries, microcracking within grains, and thermal expansion of mineral grains into the opening (Ehlen 2002).

The initial signs of weathering are often noticeable due to variations in colour on the joint surface compared to the parent rock (Bell, 2005; Price 1993; Bell, 1992). As chemical weathering progresses, discolouration in the form of staining may be visible from the joint surface into the surrounding rock material due to the transformation of primary minerals into secondary minerals (Amin et al., 2000). For example, in granitic rock masses, the breakdown of feldspar and mica often leads to the formation of secondary minerals. However, joint surfaces are more susceptible to weathering than the parent rock. Subsequently, discolouration tends to be most noticeable at the joint surfaces which can extend into the parent rock. The colour change is primarily due to the iron-bearing minerals in the granite, which react when exposed to oxygen and moisture. As a result, the iron interacts with oxygen and undergoes a chemical transformation during the weathering process. Consequently, this oxidation can impart a reddish or yellowish colour to the joint surface (Fell et al., 2014). Physical weathering can also result in fractures and cracks, which let more air and moisture into the rock and speed up the oxidation process within these granitic rocks. Gu et al. (2020) argue that microfractures are the main microstructural characteristic that promotes chemical weathering processes. Therefore, the formation of microfractures play a significant role in the propagation of chemical weathering, as it extends into joint surfaces and the surrounding parent rock.

Furthermore, Hirata et al. (2019) examined spheroidal weathering in columnar basalt which creates regions with varying degrees of weathered material that commence from the joint surfaces and extend toward the centre of the column. The results showed that colour changes from a dark top layer to a white zone and finally to a light grey zone indicate a concentric trend in this type of weathering (Figure 2-3).

The authors showed that the migration of oxygen and other ions from water that entered the rock matrix through the surrounding joints caused chemical weathering of the basalt. Plagioclase grains started to dissolve and change into halloysite during this phase, while olivine was altered to iddingsite around the phenocrysts. Gibbsite was also formed due to the dissolution of halloysite at the joint surfaces. The authors also observed that the smaller pore-size layers beneath the surfaces of both columnar and certain cross joints exhibited less intense plagioclase weathering, which resulted in the exfoliation of the outer portions of these layers and the creation of internal cracks. Consequently, there was a comparable outcome between the parent rock and the joint surface in the weathered zones of these columnar basalts. As weathering progressed from the joint surface into the rock material, the weathered zone expanded, ultimately resulting in the formation of rounded core stones.

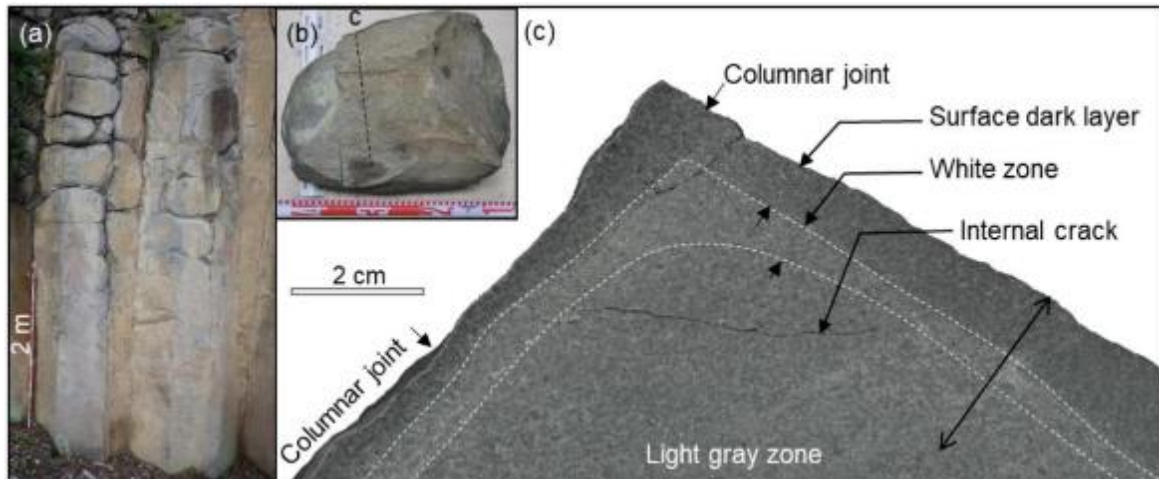


Figure 2-3: Sampling of columnar-jointed basalt. (a) Outcrop of the lower colonnade of the Ogura lava. The upper part of the outcrop indicates that curved cross joints are separating the rock columns vertically. (b) Sample. (c) Cross-section of the sample at its corner, viewed from the columnar axis. The double-headed arrow in the lower right corner indicates the crosscut along which XRD and XRF measurements were made (Hirata, et al., 2019).

2.4. Effects of weathering on discontinuity properties of a rock mass

The study of rock mass behaviour should include the properties of both the intact rock and discontinuities. When evaluating the hydromechanical behaviour of a jointed rock mass, the physical characteristics of the joints play a major role. The strength, deformational behaviour, and hydraulic behaviour of rock masses are all conditioned by discontinuities. Weathering affects the properties of joints, which impacts the hydromechanical behaviour of a jointed rock mass, thus influencing the strength and deformational behaviour of the rock. Therefore, it is necessary to understand how discontinuity parameters such as spacing, persistence, roughness, aperture, filling, seepage and the wall strength of the jointed surface are affected by weathering and how the influence of weathering on these parameters impact the behaviour of the rock mass (Figure 2-4) (Perkins et al., 2022; Shu et al., 2019; Morelli 2014; Hoek, 2000).

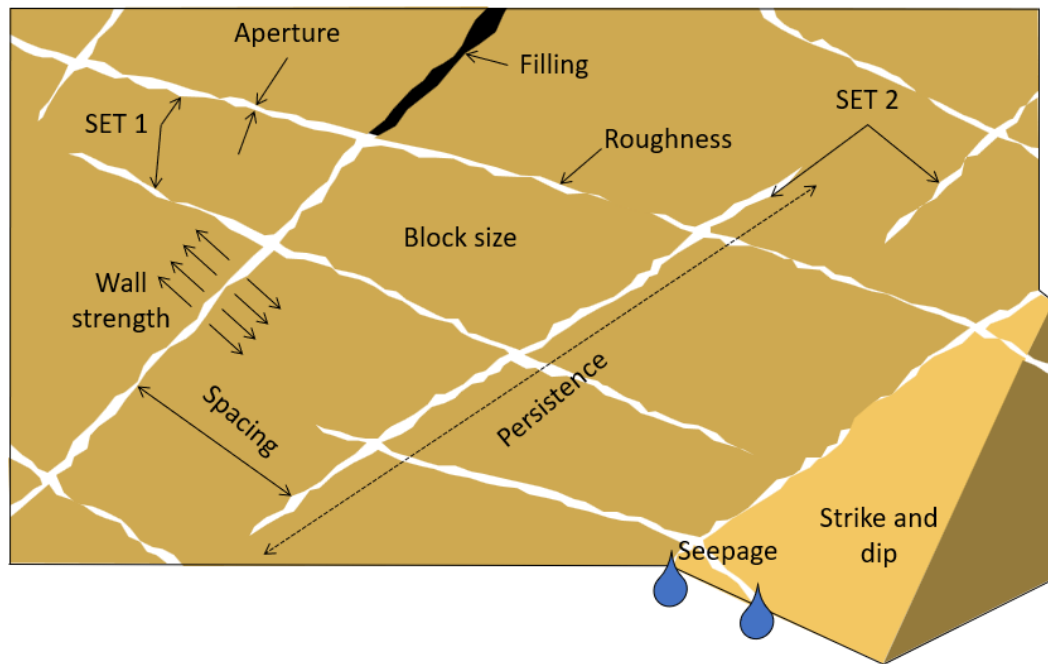


Figure 2-4: Diagram representing geometric properties of discontinuities (Hudson, 1989 cited in Dippenaar et al. 2020)

Weathering influences the geometry of a joint, including the spacing of the joint sets, persistence, and aperture (Barton et al., 1997; Price, 1993). Spacing refers to the perpendicular distance between joints of similar orientation and properties. The intersections of these joint sets within rock masses create discrete blocks which is influenced by the frequency of spacing between the joint sets (Devkota et al., 2009). Physical weathering processes can decrease the joint spacing within rock masses by forming new joints that propagate into the rock material, which causes a reduction in the size of rock blocks (Hack et al., 2020; Macheyeki et al., 2020; Kalenchuk et al., 2006). Several researchers (Elmoultie et al., 2012; Rogers et al., 2007) suggest that joint persistence, defined as the areal extent of a joint, is an important parameter in determining the block size and volume of the rock mass.

Additionally, Barton (1978) asserts that smaller block sizes in a rock mass correlates with a decrease in the strength of the rock mass, which reduces the overall structural integrity of the rock mass. However, as weathering progresses from moderate to highly weathered states, this effect may diminish or reverse due to cementation processes or the presence of infill material, thus reducing the joint apertures and the visible appearance of discontinuities within the rock mass (Ehlen, 2002). The physical aperture is defined as the actual opening between two joint surfaces whereas the hydraulic aperture is described as the aperture that governs fluid flow (Bisdom, 2016; Liu, 2005). The hydraulic aperture is either equal to (in the case of smooth joint wall surfaces), or smaller than the physical aperture of the joint opening (Zhao, 2017; Bisdom, 2016, Lavrov, 2016, and Liu, 2005). The hydraulic aperture is reduced due to the roughness of joint surfaces (Zhao, 2017). As weathering decreases the roughness, the hydraulic aperture increases. Weathering can also increase the aperture due to stress relief or plant root wedging. This increase allows for the joint opening to be filled with weathered material (Fakunle, 2016). Consequently, the accumulation of gauge (infill material) diminishes the porosity of the joint and reduces its hydraulic aperture (Barton et al., 1997).

The impact of weathering on the strength of materials has been extensively discussed by several authors (Benavente et al. 2021; Hack et al. 2020; Momeni et al. 2017). These researchers concur that weathering processes lead to a reduction in the strength of intact rock. This diminished strength is attributed to the

effects of weathering on the physical, mineralogical, and chemical properties of the rock. Ismail et al. (2019) emphasise that one of the most significant impacts of weathering on rock material is a notable decrease in strength. The uniaxial compressive strength of rock materials varies due to differences in the mineralogical and chemical composition, as well as the degree of alteration of the rock material, crystal shape and the mineral sizes. As such, there is an inverse relationship between the uniaxial compressive strength of the rock and the mineralogical alteration of the rock material (Yıldız et al., 2009). A non-linear relationship exists between the apparent porosity of the material and the uniaxial compressive strength. As weathering progresses, the strength of the rock decreases and the porosity of the material is increased, this decrease in strength leads to the advancement of physical weathering (Gu et al., 2020).

The intact rock strength is severely decreased as the degree of weathering increases. The shear strength parameters, which include the internal friction angle and cohesion, are reduced as the degree of weathering increases. However, the opposite may occur depending on the rock type, this phenomenon primarily arises from the varied response of minerals within the rock to weathering, leading to distinct weathering patterns among them. Consequently, the shapes of mineral grains become diverse, resulting in differing levels of surface roughness. This variance increases the internal friction angle, thereby enhancing the shear strength of the material as weathering advances. However, as weathering persists further and weakens the bonds between minerals, the shear strength gradually diminishes (Marques et al., 2017; Mulenga, 2015; Hack, 2012; Hencher, 2006).

Moreover, weathering significantly impacts the shear strength of joints within rock masses (Hack et al., 2020). The higher the degree of weathering at the joint's surface, the lower the shear strength. Changes in the microstructural behaviour of the rock material adjacent to the joint opening cause this reduction. This can occur when the primary minerals that compose the parent rock are altered into clay minerals along the surfaces of the joints (Ismail et al., 2019; Woo et al., 2010). In addition, Woo et al. (2010) explain that the reduced shear strength is caused by reduced joint wall strength and a reduction in both the peak and residual friction angles. Therefore, understanding how the weathering rate affects the behaviour of rock masses both before and after excavation, as well as the impact of discontinuities on the stability of these rock masses, is crucial for various engineering geological applications, including mining and construction (Buocz, et al., 2014; Department of Minerals and Energy, 1999).

The shear strength of a joint is significantly influenced by its surface roughness, which subsequently affects the overall shear strength of the rock mass. As noted by Dippenaar and Van Rooy (2016), roughness refers to the surface distribution of large-scale waviness and small-scale asperities along the fracture walls. To determine the mechanical properties of rock joints, Barton (1973) first introduced joint roughness coefficient (JRC) values. A joint with a higher JRC indicates greater roughness, suggesting a stronger joint. Conversely, smooth or planar joints exhibit reduced shear strength compared to their rough counterparts. Additionally, a decrease in roughness of the joint surface, caused by weathering along the joint, results in a reduced shear strength of the joints; the reduced shear strength is caused by a decrease in dilation (Hencher 2004; Martin et al., 1986). Papaliangas et al. (1990) identified a relationship indicating that as the thickness of the infill material increases, the shear strength of the joint decreases. Furthermore, the authors proposed that in certain situations, the interface between the infill material and the joint wall is the weakest point against shear stresses. This led to the conclusion that the minimum shear strength of a joint with infill material lies somewhere between the strength of the boundary between the joint wall and the infill, and the strength of the infill material itself. However, Woo et al. (2010) contends that the joint wall conditions, as well as the qualities of the thin layers of rock material next to the joint walls, influence both the strength and deformational properties of the overall rock mass. To govern the shear strength of the discontinuities, the thickness of these thin layers

only needs to be a fraction of a millimetre for planar joints and a few millimetres for weathered rough joints.

The type of weathering process, whether physical or chemical, influences the physical and mechanical properties of the infill material. In clean, unaltered discontinuities the joint strength would be assumed to be equal to that of intact rock. This type of joint is considered to be homogenous in terms of mineralogical composition of the parent rock. In contrast, a coated surface exhibits various minerals on the joint surface as a result of chemical weathering. These coatings usually form during intermittent fluid flow through fractured unsaturated rock masses (Weisbrod et al., 2000). Open joints create effective fluid migration paths, thus resulting in the formation of secondary minerals on the joint wall (Liu et al., 2014). Conversely, physical weathering produces infill material comprising of residual soil or rock fragments. Overall, intense and continuous weathering along joints alters the joint walls, where the joint conditions can be described as stained with some discolouration or filled with some altered material (Ehlen, 2002; Amin et al., 2000). The altered material within the joint walls increases as weathering increases and depending on whether the thickness of the infill is greater or less than the amplitude of the irregularities (roughness) on the joint wall, this will have an overall effect on the shear strength of the discontinuity (Barton et al. 1997).

The joint wall compressive strength is affected by several factors including the mineralogy of the parent rock, the degree of weathering, and the presence or absence of the filling material between the joint walls. Barton et al. (1977) related the joint wall compressive strength to the weathering stage of a rock mass ranging from stage 1 to stage 5 and summarised the findings as follows:

- Stage 1: The joint wall compressive strength (JCS) is equal to the uniaxial compressive strength of the unweathered intact rock material. – *weathering effects very minimal*
- Stage 2: Limited reduction in the joint wall compressive strength. The joint compressive strength thus becomes less than the uniaxial compressive strength of the unweathered intact rock by approximately 25%. – *slight weathering effects*
- Stage 3: Joints are considered weathered, and water-conducting. The rock blocks are defined as impermeable. The joint wall compressive strength at this stage is a small fraction (less than 50%) of the uniaxial compressive strength of the unweathered intact rock material. – *intermediate weathering phase*
- Stage 4: Weathering has propagated inward towards the adjacent rock blocks. The joint compressive strength consequently reduces at the walls of the rock blocks to below 25% of the uniaxial compressive strength of the intact rock. The uniaxial compressive strength of the intact rock becomes compromised at this stage and continues to decrease slowly. – *high weathering phase*
- Stage 5: The uniaxial compressive strength of the intact rock is reduced to a value equal to the JCS. The rock mass is considered permeable throughout. – *an advance stage of weathering.*

Several authors (Cabria, 2015; Woo et al. 2015; Bandis et al. 1993) noted a decrease in the compressive strength of joints as weathering transitions from unweathered to completely weathered material on the joint wall. This observation aligns with similar conclusions drawn by Barton et al. (1977). For instance, Bandis et al. (1983) observed that as the weathering degree of joint walls in dolerite and sandstone samples increased, the compressive strength of those joint walls decreased. Woo et al. (2010) conducted a Schmidt hammer rebound test to determine the strength of the material adjacent to the joint surface. Weathering along joint openings can decrease the Joint Compressive Strength (equal to the uniaxial

compressive strength when the joint is unweathered) by up to 25% of the UCS. The results also indicated that the rebound index values were lower at the joint opening and higher at the intact rock material. Thus, the intact rock is stronger than the joint wall, as the rebound index measured by the Schmidt hammer test correlates with rock compressive strength. Cabria (2015) corroborates this finding, noting that weathering leads to a weakening of the joint walls. Spalling of joint wall surfaces may occur, specifically in a granitic rock mass, due to kaolinization of feldspars, and hydrolysis of micas. The weathering stage of a rock mass can thus be determined by obtaining the Joint Compressive Strength of joints present within the rock mass (Barton, et al., 1977).

2.5. Effects of weathering on the geological engineering properties of rocks

The engineering properties of a rock mass such as permeability and durability are modified as a result of physical and chemical weathering (Yıldız et al., 2009). Chemical weathering in conjunction with microfracturing (physical weathering) result in increased porosity and permeability of the rock (Gu et al., 2020). Changes in the texture, mineralogy, degree of fracturing, colour, and porosity take place during the weathering of rocks (Yıldız et al., 2009). These changes result in the alteration of the microstructural behaviour of the rock material (Ismail, 2019).

Permeability is described by several authors (Summerscales, et al., 2019; Yuksel et al., 2018; Fidjestøl et al., 1998) as a measure of how easily a fluid, gas, or specific chemicals under pressure can move through a porous medium. Yuksel et al. (2018) state that pore size and the degree of connectivity between pore spaces (i.e. effective porosity) play a crucial role in governing the permeability of a rock's microstructure. The permeability of a rock is influenced by the shape and distribution of pore spaces, as well as the amount of clay minerals present (Šperl et al., 2008). Rocks prone to creating large amounts of clay minerals during the weathering process (basic igneous rocks), may exhibit different permeability changes compared to rocks that weather into lesser amounts of secondary clay minerals (felsic igneous rocks). While clay minerals may have high porosity, the permeability is significantly low, resulting in a porous medium with low overall permeability. Bell (2005) further mentions that the permeability of the rock mass may reduce, due to the formation of clay material during the process of mineral decomposition. These clay minerals can fill fractures and pore spaces, thus resulting in a decrease aperture size, and less fracture connectivity. Consequently, changes in permeability due to weathering depend on the rock's intrinsic properties—such as type, texture, and mineralogy—as well as its weathering stage (Cabria, 2015).

The permeability of a rock mass is increased when the weathering grade increases (Martin et al., 1986). As weathering grades increase, Hencher (2004) observed that rock materials—including Jurassic and Cretaceous volcanic rocks, sedimentary layers, and granitic intrusions—become more permeable. This increase in permeability can be attributed to an increase in void size, thus increasing both effective and total porosity of the material. Bell (2005) adds that the permeability of a rock mass is often initially increased during the process of weathering, due to the creation of fractures, thus increased secondary porosity, within, and in between the grains of a rock. Worthington et al. (2016) states that fractures formed through physical weathering eventually become enlarged through chemical weathering processes, such as rock skeleton and fabric decomposition, which contributes to the increased permeability of the rock (Momeni et al., 2017). The development of existing discontinuities, and creation of new discontinuities results in an increase in the seepage of fluid into and through the rock mass. Joints experience extension during weathering, which further increases connectivity, and consequently increases the permeability of the rock mass (Hencher, 2004). The connectivity between joints plays a significant role in the pattern of fluid flow, and solute movement (Zhao, 2017). Thus, indicating that if the connectivity were to change, so will the pattern of fluid flow, and solute movement.

Weisbrod et al. (2000) further elaborate that coated joint surfaces possess greater surface area, increased relief, and significantly rougher, more heterogeneous topography. These features induce changes in flow paths within joint openings and impact the sorption properties of the joint walls.

Porosity can control the process of weathering as well as be affected by it (Molina Ballesteros, et al., 2010). Chemical weathering causes an increase in the number and size of pores in a rock (Fakunle, 2016). These changes lead to further modification of the density and compressibility of the rock material (Hencher, 2004). As weathering progresses, the density, and volumetric stability decreases, whereas the porosity of the rock material increases significantly (Gu et al., 2020; Fakunle, 2016; Bell, 2014). The growth of voids is the main process responsible for the decrease in density, and increased porosity of the rock material (Hencher, 2004). Yıldız et al. (2009) suggests that changes in material porosity induced by weathering significantly impact water absorption. Navarre-Sitchler et al. (2015) highlights that weathering not only increases porosity but also augments mineral surface area. Concurrently, the process of weathering, significantly influences particle size distribution by decreasing the size of the grains within the rock, thus resulting in a greater proportion of smaller sized grains. These effects enhance the material's water-holding capacity (Navarre-Sitchler et al., 2015).

Moreover, Fakunle (2016) observes an escalating water content ratio with increasing degrees of weathering within a rock mass. A correlation of a positive nature exists between the mineralogical alteration index (MI), and the water absorption properties of a rock (Yıldız et al., 2009). Both Benavente et al. (2021), and Weisbrod et al. (2000), agree that these observations made by Fakunle (2016), and Yıldız et al. (2009), may be due to an increase in the specific surface area (SSA) as weathering continues to progress. The higher the SSA, and condensate pore volume, the greater the capacity, as well as the susceptibility of water retention into the rock material will be (Benavente et al., 2021).

Physical weathering in shale results in the alteration of rock strength, permeability, swelling, and stiffness of the material (Alonso et al., 2006). When assessing the durability of various rock types, Momeni et al. (2017) highlights that a rock's durability is largely influenced by its mineralogical composition. For instance, higher quartz content correlates with lower degradability and greater overall durability of the rock's constituent minerals. Additionally, the texture of the rock exerts significant control over its resistance to weathering effects. Larger mineral sizes correspond to a higher Durability Index, as elucidated by Momeni et al. (2017). In the case of shale, its durability is intricately linked to factors such as lithification degree, cement type, and origin rather than solely dependent on silt and clay content, as suggested by Alonso et al., (2006).

The durability of a rock signifies the degradability of that rock material. Thus, the lower the durability of a rock material, the greater the degradability of the rock will be (Momeni et al., 2017). The results from a Slake Durability Test, performed by Momeni et al. (2017), indicated a decrease in the durability Index of granitoid rock types, as the weathering grade increases, thus showing that weathering causes a decrease in the durability of the rock material. This occurrence has been observed and documented by other authors including Bell (2014,1992), and Mulenga (2015). Šperl et al. (2008), mentions that the durability of a rock is influenced by the physical property of porosity. Thus, if the porosity of a material is changed during the process of weathering, so will the durability of that material. Bell (2014), and Mulenga (2015) explain that increased porosity, results in greater weatherability (i.e., lower durability).

2.6. Classification of Weathered Rock Masses

The classification of weathered rock masses is essential for ensuring the long-term stability of structures, both above and below ground. Discontinuities, such as joints in rock masses, significantly influence the geomechanical behaviour of these materials, controlling both the rate and sequence of weathering (Packulak et al., 2019; Amin et al., 2000). These joints create zones of differential weathering, affecting the structural integrity of the rock mass. Over time, weathering can degrade the physical and mechanical properties around discontinuities, further reducing the strength of the rock mass and leading to potential damage during or after construction (Zhu et al., 2020).

Understanding the degree of weathering is critical to assessing the stability of rock masses over their engineering lifetime. Weathering reduces shear strength, which is a key determinant of a rock mass's ability to resist forces such as those encountered during excavation or the support of structures (Fakunle, 2016). Factors like joint surface roughness, infill material, thickness, scale effect, and applied stress all influence critical stability properties, including shear strength, angle of friction, and cohesion (Buocz et al., 2014).

Rock mass classification schemes are an indispensable tool in understanding these weathering processes. They provide a quick, yet detailed, description of the weathering stages a rock mass undergoes, helping predict the behaviour of rocks in unexplored areas (Fell et al., 2014). Although the complexity of weathering cannot be fully captured by a single classification system, these schemes offer valuable qualitative insights into rock mass behaviour (Norbury et al., 1995). The characterization of weathered rock masses is crucial for assessing whether a rock is suitable for construction purposes, as weathering significantly alters its usability (Yıldız et al., 2009).

For a classification scheme to be effective, it must clearly distinguish different zones within the rock profile, account for all material variations, and adapt to various climatic conditions (Bell, 1992; Martin et al., 1986). This ensures the rock mass's engineering behaviour is well understood, allowing for the design of structures that remain stable over long periods of time. Price (1993) argued that the BS 5930:1981 classification scheme did not account for all rock types and had no direct link to engineering implications of weathered rock material. As a result, the author suggested an alternative classification system that considers weathering in terms of engineering significance (Table 2-1). In this classification scheme proposed by Price (1993), the rock is classified into three weathering classes (A, B, C) alongside the description of the engineering significance, ranging from no significant issues to problems with excavation stability and foundation bearing capacity.

Later on, Amin et al. (2000) proposed a classification scheme for weathering at both material and mass scales. The weathering grades of infill material and joint blocks are analysed individually, then the entire joint-block system is evaluated as a whole. The rock mass weathering grade is determined by the volume of the dominant material. If the infill material exceeds 50% of the volume, its weathering grade dictates the zone grade; otherwise, the joint block's grade prevails. Therefore, higher weathering grades result in weaker infilling, affecting the strength and behaviour of the material. Furthermore, Amin et al. (2000), states that the process of weathering originates at the joint walls, after which the weathering laterally propagates into the adjacent rock blocks. The conceptual classification scheme to determine the stages of weathering for a joint assumes that the rate of weathering is equal on both joint walls of the joint opening, thus creating identical zoning on both sides of the joint. The weathering stages range from stage 1, which represents a joint that has undergone little to no weathering, to stage 5, which represents highly to completely weathered joints. The least weathered material will be located within the rock blocks, whereas the highly weathered material will be located closer to the centre of the joint (Figure 2-5). A typical example of a stage 5 weathering is illustrated Figure 2-6 which represents

a filled joint in a Granitic rock mass. The weathering grade decreases as the distance from the central part of the filled joint increases and the effective aperture, as well as the depth of discolouration, increases with each stage of weathering.

The banding illustrated in Figure 2-6, represents a filled joint in a Granitic rock mass classified as stage 5 weathering. As indicated in Figure 2-6, the weathering grade decreases as the distance from the central part of the filled joint increases. The effective aperture, as well as the depth of discolouration, increases with each stage of weathering. Amin et al. (2000) also suggest that before residual soil fills a previously closed joint, the walls of the joint typically undergo a minimum of four weathering stages (2 to 5). Joint failure is most likely to occur through the central zone of the weathered joint, which represents the most weathered portion of the discontinuity. Consequently, the section of the joint that has experienced the highest degree of weathering exerts the greatest influence on its behaviour (Amin et al., 2000; Papaliangas et al., 1990).

Bell (2014) suggested a classification scheme that considers the discolouration characteristic, and other visible signs of alteration on a granitic rock mass (Table 2-2). This classification scheme is rock type specific and can thus not be used for other rock types, which restricts the usability of this classification system.

Fakunle (2016) proposed integrating the BS 5930:1999 standard with the Slope Stability Probability Classification (SSPC) system to assess the degree of weathering in rock masses (Table 2-3). This integration aims to enhance classification accuracy by combining the detailed geotechnical descriptions of weathering stages provided by BS 5930:1999 with the probabilistic approach of SSPC, which evaluates slope stability based on statistical analyses. The benefit of this combined approach lies in its ability to offer a more comprehensive understanding of weathering effects on rock mass behaviour, thereby improving the reliability of engineering assessments and informing better decision-making in geotechnical projects.

In summary, various classification schemes have been developed to understand the weathering processes and their impact on rock mass stability. These schemes share several similarities, such as emphasizing the importance of weathering, linking weathering stages to engineering implications, and considering both material and mass scales. They also recognise the creation of differential weathering zones due to discontinuities like joints. However, the schemes differ in their classification criteria, weathering stages, and evaluation approaches. Price (1993) uses three weathering classes (A, B, C) with descriptions of engineering significance, while Amin et al. (2000) evaluates weathering grades of infill material and joint blocks individually before assessing the entire joint-block system. Bell (2014) focuses on discolouration characteristics and visible signs of alteration, and Fakunle (2016) integrates the BS 5930:1999 standard with the Slope Stability Probability Classification (SSPC) system for a probabilistic approach. Each scheme provides valuable insights into the weathering processes and their impact on rock mass stability, helping engineers make informed decisions in geotechnical projects. By understanding these similarities and differences, engineers can select the most appropriate classification scheme for their specific needs, ensuring the stability and safety of their structures over time.

587 Table 2-1: Weathering grade scale indicating the three main classes that can be related to engineering significance
588 (Price, 1993):

Class	Description	Engineering Significance	Interpretation (based on Martin et al. (1986))
A	Effectively unweathered	Not significant	Weathering does not need to be considered
B	Significantly weathered	Problems of excavation stability	The impact of weathering on the engineering properties of the rock mass should be considered in the design process, as weathering can reduce the shear strength of discontinuities.
C	Severely weathered	Problems of excavation stability and foundation bearing capacity	Weathering has significantly influenced the engineering properties, necessitating its consideration to ensure the stability and functionality of engineering applications.

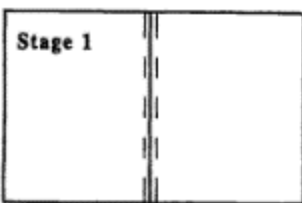
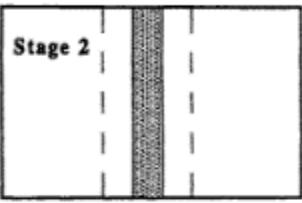
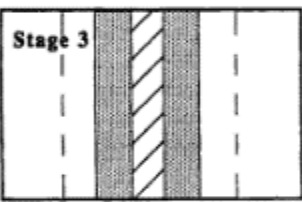
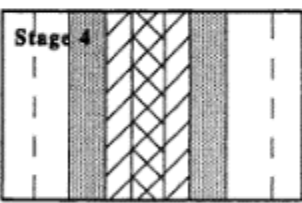
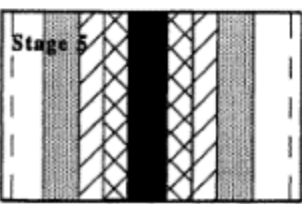
Weathering stages	Material — description and grade	Rock mass — zone and weathering class
	Block: stain margin in joint blocks indicates weathering starts to penetrate into the joint wall, but rock material is still intact and sound. Grade I Joint: discoloration on joint surfaces. Grade II	Zone I: SW with discoloration on joint surfaces
	Block: material closer to the joint is highly discoloured. Grain boundaries start to open but material is not friable. Stain margin penetrates deeper. Grade I (if volume % of fresh blocks > discoloured volume). Joint: surfaces completely discoloured, joint beginning to open-up with slight scaling of joint wall material. Grade III	Zone I: SW with highly discoloured joint surfaces and in material closer to the joint.
	Block: Grade II and III layers occurs deeper in the block but less than 50% of the block volume. Grade I (approaching Grade II). Joint: Previously Grade III layer and joint walls begin to disintegrate to friable material, transition from completely discoloured rock to soil. Increase in 'effective' joint width due to presence of infill material scaling of joint wall. Grade III or IV (depend on vol. %).	Between Zone I and approaching Zone II, with moderately & highly decomposed/disintegrated friable material in the joint aperture (specify volume of infill as % of intact joint block).
	Block: Layer of Grade II and III cover more than 50% of block volume. Compare vol.% of Grade II and III. Grade II (slightly weathered material is dominant). Joint: Filled with highly and completely decomposed/disintegrated material Grade IV & V (previously Grade III and V, respectively). Original texture still intact. Grade V (if completely weathered material is dominant)	Zone II (if vol. % of dominant infill material < than the slightly weathered block), joint is filled with highly and completely decomposed/disintegrated material (specify volume of infill as % of slightly weathered block).
	Block: Volume of Grade II and III cover more than 50% of block. Probably at this stage Grade III material is more dominant than Grade II. Blocks almost completely affected by weathering Grade II I. Joint: joint aperture is filled with three different grades of material; highly and completely decomposed/disintegrated materials and residual soil (with original texture destroyed). Grade V or VI (whichever is dominant)	Zone II but approaching Zone III. Joint is filled with completely decomposed/disintegrated materials and residual soil (specify total volume of infill as % of blocks). Note: if volume of infill is greater than block then, the most dominant infill grade material dictates the zone grade.

Figure 2-5: Proposed description and classification of weathering stages of filled joints in granite (Amin et al., 2000).

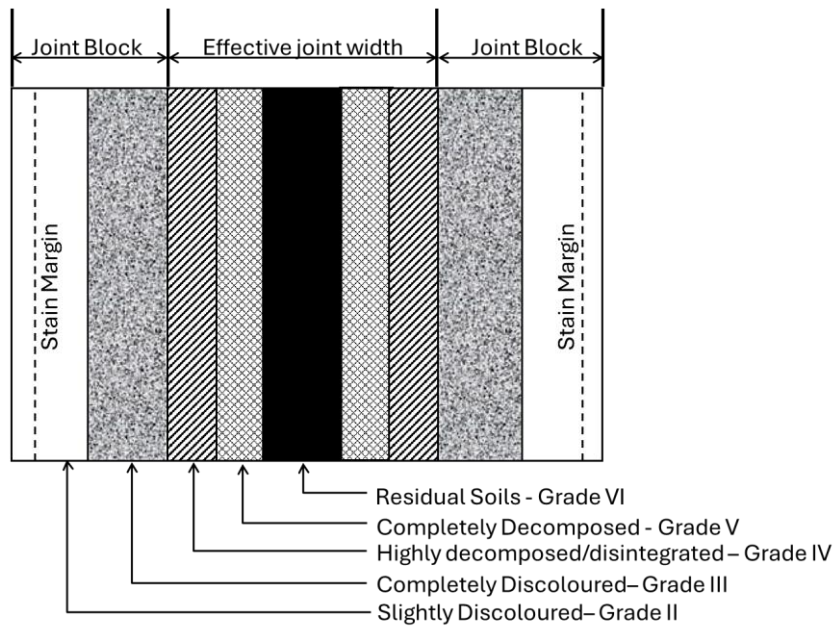


Figure 2-6: Banding pattern for the infill and joint blocks at weathering stage 5 (Amin et al., 2000).

Table 2-2: Classification of weathered granitic rock masses based mainly on the visible signs of alteration (Bell, 2014).

Term	Description
Unweathered	No visible signs of alteration in the rock material. Fracture planes may exhibit staining or discolouration.
Slightly weathered	Fractures show signs of staining or discolouration and may contain a thin layer of altered material. Discolouration may extend from the fracture planes into the rock up to 20% of the fracture spacing (i.e., less than 40% of the core is discoloured).
Medium weathered	Slight discolouration extends from fracture planes for a distance greater than 20% of the fracture spacing (i.e., generally the greater part of the rock). Fractures may contain altered material. The core surface is not friable (except in poorly cemented sedimentary rocks), and the original texture of the rock is preserved. Partial opening of grain boundaries may be observed.
Highly weathered	Discolouration permeates throughout the rock. The core surface is friable and often pitted due to the washing out of highly altered minerals by drilling water. The original texture of the rock is largely preserved, though grain separation has occurred.
Completely weathered	The rock is entirely discoloured, resembling soil in external appearance. Internally, the rock texture is partially preserved, but grains have completely separated.

Table 2-3: Description and classification of weathered rock masses for rock masses ranging from moderately strong to very strong in the fresh state (Fakunle, 2016).

Grade	Classifier	Typical Characteristics	Weathering Index (WE)
1	Fresh	Unchanged from original state	1
2	Slightly Weathered	Slight discolouration, slight weakening	0.95
3	Moderately Weathered	Considerably weakened, penetrative discolouration. Large pieces cannot be broken by hand.	0.90
4	Highly Weathered	Large pieces can be broken by hand. Does not readily disintegrate (slake) when dry sample immersed in water.	0.62
5	Completely Weathered	Considerably weakened. Slakes in water. Original texture apparent.	0.35
6	Residual Soil	Soil derived by in-situ weathering but having lost retaining original texture and fabric.	-

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600 3. Methodology

601 Three rock samples—quartz-diorite, granite, and shale—were analysed during this study. The inclusion
 602 of two igneous rocks and one sedimentary rock provides insight into how propagating weathering
 603 affects different rock types. This approach allows for a comparative assessment of their varying
 604 responses to weathering processes. Properties that were looked at included both the physical and
 605 mineralogical properties of the rocks, and how these properties changed as the distance from the joint
 606 surface was increased into the adjacent rock material. Testing methods included X-Ray Diffraction
 607 (XRD), X-Ray Fluorescence (XRF), weathering indices, Schmidt hammer test, Polarized Light
 608 Microscopy, and Scanning Electron Microscopy (SEM). Figure 3-1 illustrates the methodology
 609 followed during the course of this study. Detailed descriptions of each of these methods follow below.

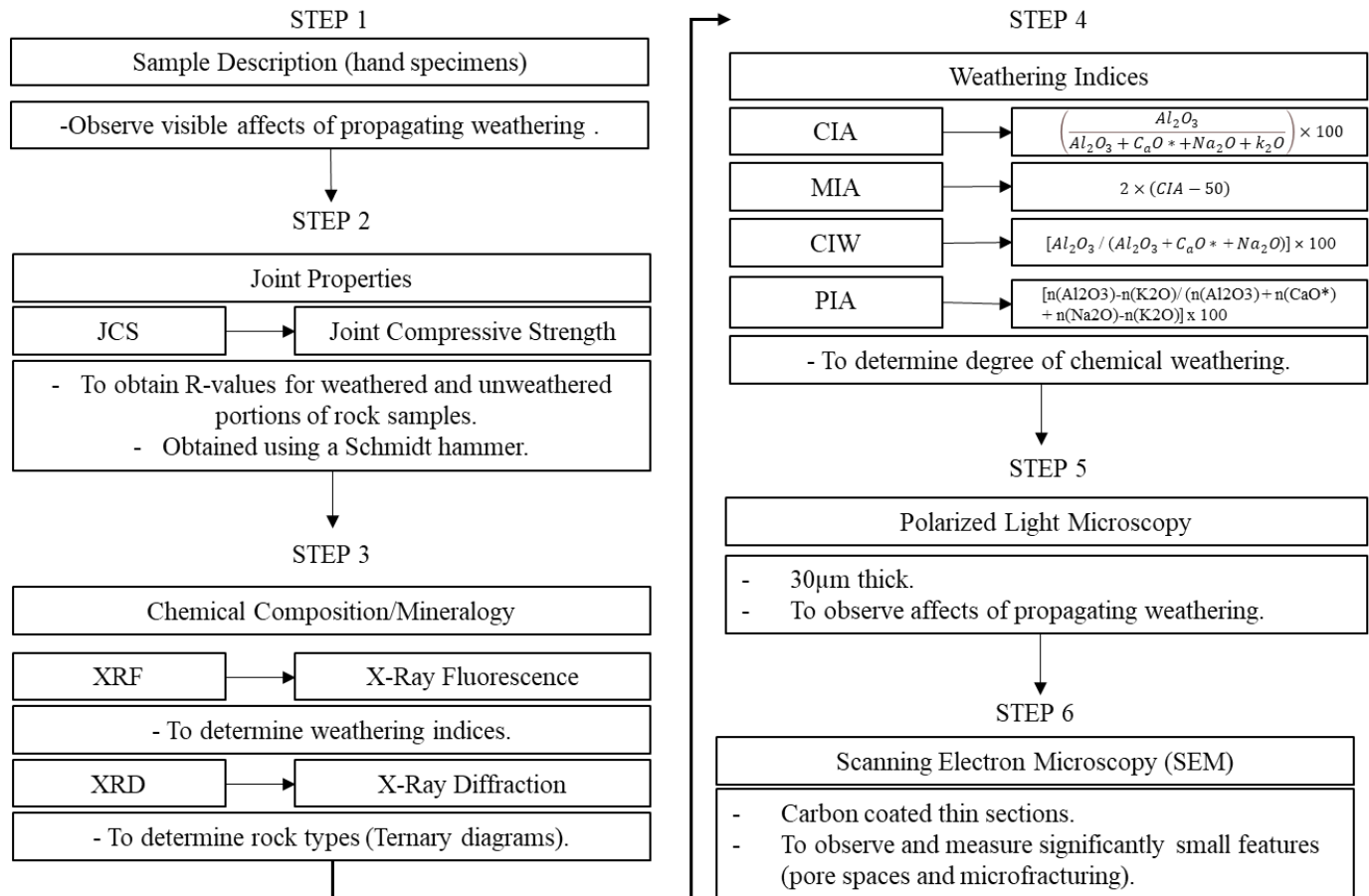


Figure 3-1: Methodology flowchart.

3.1. Samples

The rock samples included quartz-diorite (located in Nelspruit within the Nelspruit Suite), granite (unknown location – was found as an ideal sample at the University of Pretoria, possible Nero Africa Granite from Rustenburg, North-West province), and shale (located within the Silverton Formation in the Pretoria Group).

In this study, the precise origins of the rock samples were deemed non-essential, as the primary objective was to examine the propagation of weathering within various rock types. The focus was on assessing the current state of the rocks and understanding how weathering affected the material adjacent to discontinuities. By utilising the unweathered portions of the rock samples as controls (i.e. unchanged reference used for comparison), the research isolated the impact of propagating weathering processes. Consequently, detailed information regarding the samples' exact locations and ages is not pertinent to the investigation. The selection process for the rock samples entailed that joints or other exposed surface be present, and visible propagation of weathering be evident within the material adjacent to the exposed surface. Figure 3-2 shows the three rock samples selected and analysed during this study. The quartz-diorite sample was a cored specimen collected from a drilled borehole, whereas the granite and shale samples were hand specimens collected in the field.

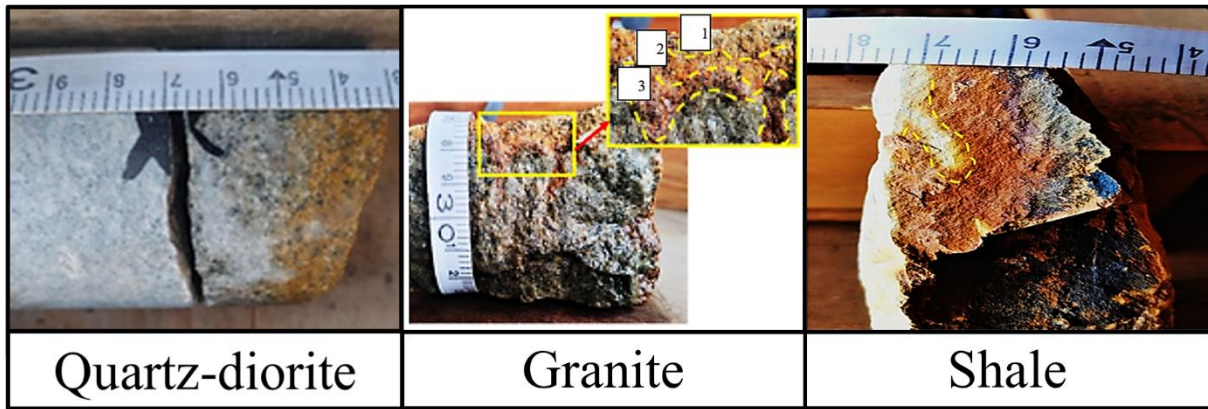


Figure 3-2: Rock samples analysed.

3.2. Joint Compressive Strength

A Schmidt hammer rebound test aided in the determination of the hardness of the different zones, starting from the joint surface and then moving further into the adjacent, fresher parent material. The instrument was placed perpendicular to the surface and gradually pushed towards the surface until impact. The number displayed on the screen of the hammer represented the rebound number or R-value. The rebound number and the compressive strength of a material are directly proportional to one another (Katuwal, 2019). The varying rebound numbers for each zone (10 per region) were then used to determine an average hardness for each region, thus establishing the influence that the propagating weathering had on the hardness parameter of the material adjacent to the joint opening.

The Schmidt hammer rebound test, while widely employed for assessing the surface hardness of materials, presents several notable limitations. The accuracy of the test is influenced by surface irregularities; rough or uneven surfaces can yield inconsistent rebound values, necessitating surfaces be smoothed prior to testing. Additionally, the size and rigidity of the sample are critical; smaller specimens or those lacking adequate support may move upon impact, resulting in reduced rebound numbers. The orientation of the hammer during testing also affects rebound readings; maintaining a consistent hammer orientation is crucial for reliable results. Furthermore, the spacing between successive test impacts can influence outcomes; maintaining a consistent spacing of a few centimetres between each impact helps prevent interference between test points and ensures that each measurement reflects an independent assessment of the material's surface hardness. When testing areas exposed to weathering, the affected zones may be limited in size, necessitating closer spacing of impacts compared to fresh regions. (Buyuksagis et al., 2007). To mitigate these limitations, all samples were placed on concrete slabs and properly supported (inside wooden core boxes) to hinder any movement, a smooth surface was tested where possible, and a spacing of a few centimetres between each blow within the fresh portions of the samples was kept. The portions of the samples that were exposed to propagating weathering were small areas, thus the impacts from the Schmidt hammer were spaced closer together compared to that of the fresh regions. The impact of this was considered when analysing the Schmidt hammer test results. Schematic representations of how the samples were supported, the locations and orientation of the Schmidt hammer are illustrated in Figure 3-3.

Schmidt hammer orientation

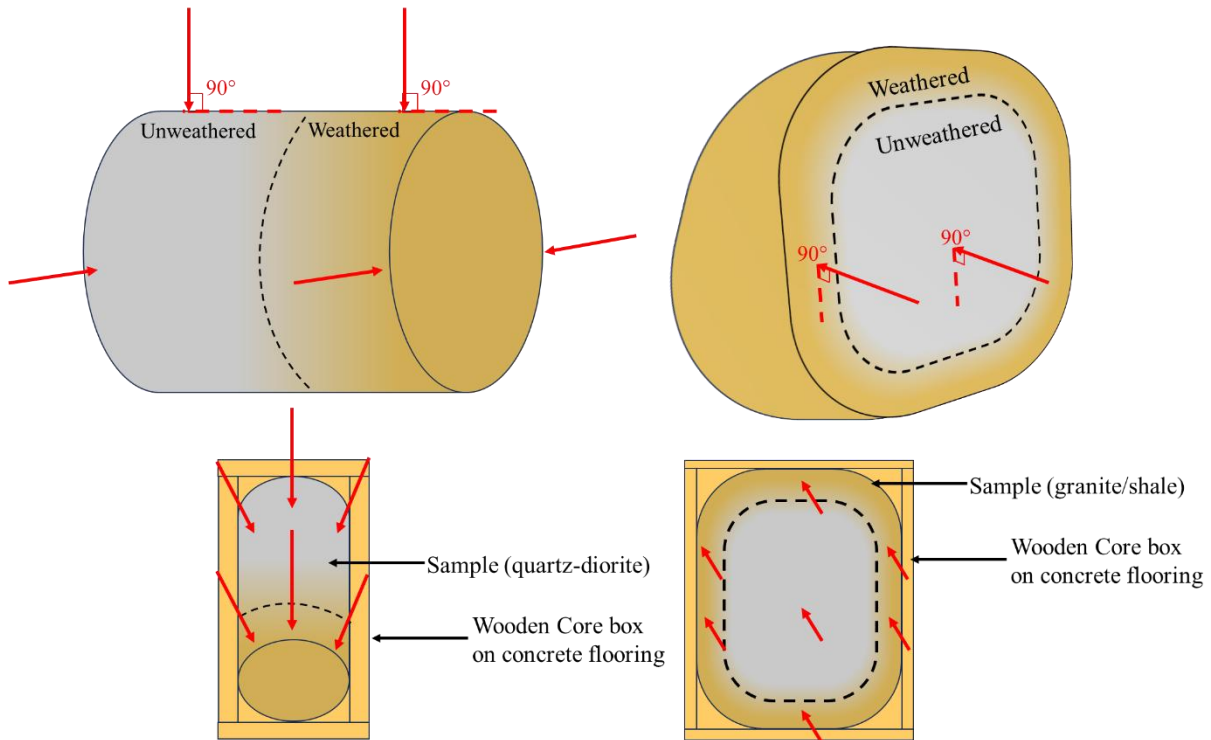


Figure 3-3: Schmidt hammer orientation and sample stabilisation.

3.3. X-Ray Fluorescence (XRF)

X-Ray Fluorescence refers to the emission of distinct secondary X-rays from a substance that has been activated by exposing it to several high-energy X-rays, or gamma rays. The emitted X-rays are indicative of the types of atoms present within the samples. This type of analysis is suited for qualitative elemental analysis. It aids in determining the elemental composition of a substance (Ardebili et al., 2019).

The procedure to prepare the samples for X-ray Fluorescence was as follows (Ardebili et al., 2019):

- The sample was grinded to a fine powder. Sample must be greater than 1 gram.
- Once this was done, a chemical flux was mixed with the powdered sample.
- The sample was then placed into a furnace or gas burner to melt. The process of melting resulted in the creation of a homogenous glass that could be analysed in the XRF-spectrometer.
- The abundance of the elements present within the sample could then be calculated.

This procedure was carried out by the Council for Geoscience.

Major elements (wt%) were determined by X-Ray Fluorescence Spectrometry (XRF) on fusion disks. H₂O- and L.O.I. were determined gravimetrically at 100 and 1000°C respectively.

The purpose of the XRF analysis during this study was to determine the weathering indices for each rock sample. The oxides focussed on were SiO₂, Al₂O₃, Fe₂O₃, CaO, Na₂O, P₂O₅, K₂O and TiO₂. The L.O.I. percentage was also analysed for each sample and correlated with the relative water content of

each sample, since the L.O.I. includes both free and chemically bound water, as well as organic material and carbonates (Ündül and Tuğrul, 2011).

3.4. X-Ray Diffraction (XRD)

X-Ray Diffraction provided insight into the crystallographic structure, chemical properties, as well as some physical properties of a material. This analysis was conducted at room temperature and pressure. XRD is well known for providing both qualitative and quantitative analyses of the crystalline phases present within a substance, thus the X-Ray Diffraction analysis aided in the characterisation of compounds based on a diffraction pattern created by a diffractogram. This pattern was produced by x-rays returning from the surface of the sample (Hamilton, 2008).

The procedure for X-Ray Diffraction analysis was as follows (Hamilton, 2008):

- The sample went through a grinding process in order to produce a fine powder.
- The mounting procedure for a small volume sample used the Tape method. The Tape Method involved either pouring the sample onto double stick tape, which was mounted on a glass slide, or if a sample slurry is being used, the slurry must be smeared to a uniform thickness on a glass slide at an appropriate height. An aluminium holder was used to check the tape height. The slurry sample was allowed to dry before analysis of the sample took place. Slide was clearly labelled, and this label was then entered into the X-Ray Diffraction machine so that the electronic output may be identified. Once the output was available the results could be analysed.
- The X-ray pattern produced was compared with reference data to distinguish the different crystallographic phases present within the sample.

The samples were analysed using a PANalytical X'Pert Pro powder diffractometer in θ – θ configuration with an X'Celerator detector and variable divergence- and fixed receiving slits with Fe filtered Co-K α radiation ($\lambda=1.789\text{\AA}$). The mineralogy was determined by selecting the best-fitting pattern from the ICSD database to the measured diffraction pattern, using X'Pert Highscore plus software. The relative phase amounts (weight% of crystalline portion) were estimated using the Rietveld method. The facilities used during this analysis were provided by the University of Pretoria. Sample preparation was performed by both the experts available and the author. The XRD results were then be used to plot the rock samples on a QAP-diagram and ternary diagram for classification of mudstones to identify the specific rock types.

Limitations associated with the XRD analysis include that minerals present in low concentrations (1%-5%) within the sample are difficult to identify, and XRD also requires the sample to be crystalline, thus amorphous iron-oxide may not be detectable (Fewster, 2023; Holder et al., 2019).

3.5. Weathering Indices

The XRF results were used to establish the weathering indices for each sample. These weathering indices included the Chemical Index of Alteration (CIA), Mineralogical Index of alteration (MIA), Chemical Index of Weathering (CIW), and the Plagioclase Index of Alteration (PIA).

These indices evaluate the extent to which mobile cations (e.g., calcium, sodium, potassium) have been depleted relative to aluminium. This depletion reflects the progression of mineral breakdown, as primary minerals (such as feldspars) are progressively altered into secondary minerals (for instance, clays). In general, higher index values indicate more advanced stages of weathering. However, while these indices provide valuable insights into weathering intensity, they do not directly measure the

absolute percentage of primary minerals consumed. Instead, they serve as proxies for weathering intensity—a relationship that is also influenced by the original rock composition and local environmental conditions (Nesbitt & Young, 1982).

3.5.1. Chemical Index of Alteration (CIA)

The Chemical Index of Alteration, (CIA), represents the degree of chemical weathering a rock has experienced. The Chemical Index of Alteration (CIA) value increases as the degree of chemical weathering increases (Goldberg, 2010). CIA values that range between 50 and 60 are indicative of a rock that has been exposed to a low degree of chemical weathering, whereas CIA values ranging from 60 to 80, indicate a rock with a moderate degree of chemical weathering. If the CIA values reach 80 and above, an extreme degree of chemical weathering can be assumed (Yıldız et al., 2009). It is important to note that the CIA value is significantly influenced by the grain size of the sample and the provenance of the sediment. Thus, this can lead to sedimentary rocks, like shale, showing a high CIA (Krissek & Kyle, 2001). Equation 1 is used to determine the CIA of a rock sample.

$$CIA = \left(\frac{Al_2O_3}{Al_2O_3 + CaO^* + Na_2O + K_2O} \right) \times 100 \quad \text{Equation 1}$$

CaO* is the amount of CaO incorporated in the silicate fraction of the rock.

McLennan (1993) corrected the carbonate, apatite, and Na₂O content using the formula shown in Equation 2 where the degradation of feldspar and the formation of clay minerals is the main process that takes place during chemical weathering. Major element analyses need to be performed to establish the amounts of Al₂O₃, K₂O, Na₂O, and CaO (Goldberg, 2010).

$$n(CaO') = n(CaO) - 10 \times n(P_2O_5)/3 \quad \text{Equation 2}$$

3.5.2. Mineralogical Index of Alteration (MIA)

The Mineralogical index of alteration (MIA) was utilised to evaluate the degree of mineralogical weathering and is used as a tool in partitioning chemical elements between the primary minerals and their equivalent secondary minerals. An MIA value of 0 to 100 can be achieved. The lower the value, the less the degree of mineralogical weathering experienced by the material and the less Na₂O. The MIA was calculated as follows (Voicu et al., 1997):

$$MIA = 2 \times (CIA - 50) \quad \text{Equation 3}$$

3.5.3. Chemical Index of Weathering (CIW)

The Chemical Index of Weathering, also known as the CIW, produces high values (> 85) for rocks that are rich in K-feldspars (orthoclase), regardless of the degree of weathering, which can be misleading (Fedo et al., 1995). (Equation 4).

$$CIW = [Al_2O_3 / (Al_2O_3 + CaO^* + Na_2O)] \times 100 \quad \text{Equation 4}$$

3.5.4. Plagioclase Index of Alteration (PIA)

The Plagioclase Index of Alteration (PIA) aids in removing the effects of K-enrichment, which takes place during the burial and diagenesis process (Mangold et al., 2019) as is shown in Equation 5.

$$PIA = [n(Al_2O_3) - n(K_2O) / (n(Al_2O_3) + n(CaO^*) + n(Na_2O) - n(K_2O))] \times 100 \quad \text{Equation 5}$$

3.6. Polarized Light Microscopy

A thin section is a thin slice of rock (usually 30µm). This slice was prepared in a laboratory and used with a polarizing petrographic microscope. The thin slice of rock was mounted with epoxy on a glass slide. The purpose of thin sections was to investigate the optical properties of the minerals present within the rock sample. Thin sections aided in identifying the origin and evolution of the parent material (Dabek et al., 2023).

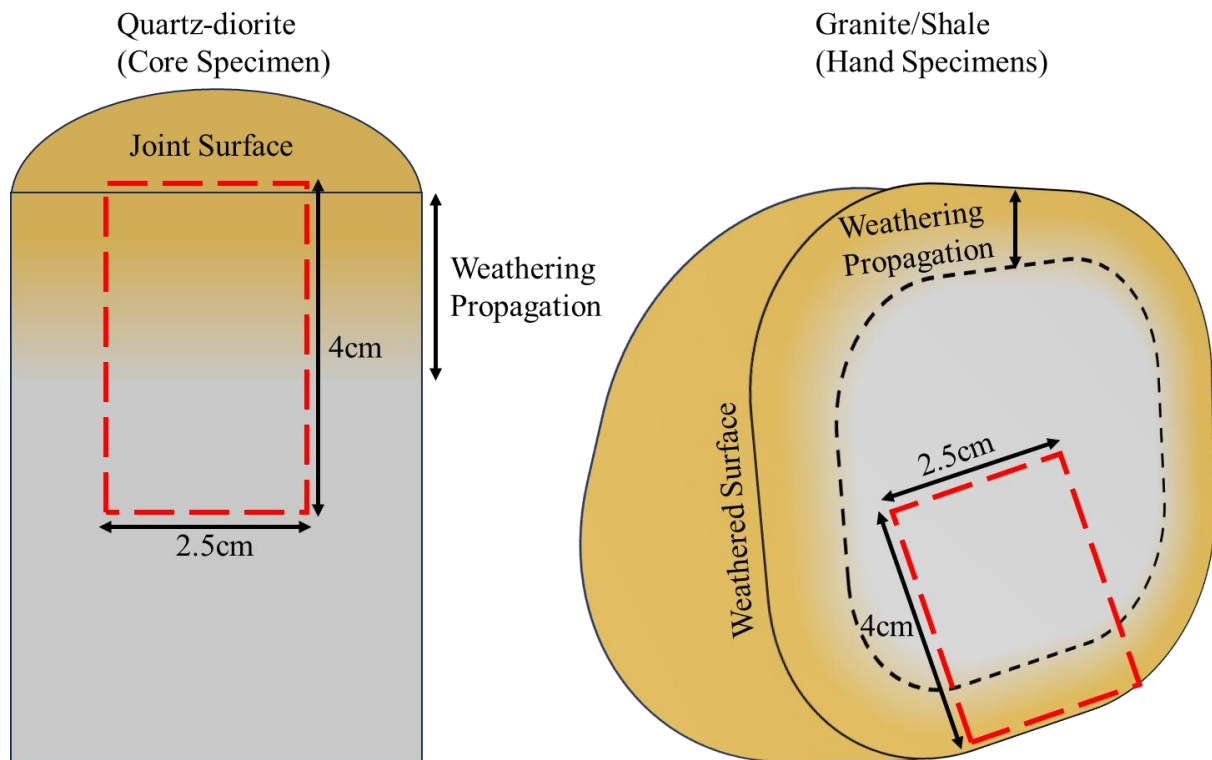
The procedure for preparing thin sections was as follows (Dabek et al., 2023):

- Thin slice of rock was cut with a diamond saw.
- This sample was then ground optically flat.
- Sample was mounted on a glass slide and grounded smooth by using a progressively finer abrasive grit until a thickness of 30µm was reached.
- The thin section was then placed between two polarizing filters that were set perpendicular to each other.
- The optical properties of the minerals in the thin section influence the colour and intensity of the light passing through the thin section and towards the viewer.
- The optical properties of rock forming minerals differ from each other, thus resulting in these minerals being easily identifiable.
- The minerals present within the rock could thus be identified.

Samples preparation was performed by experts at the Council for Geoscience.

In the case of this study the thin sections were cut perpendicular to the joint surface (Figure 3-4). This enabled the viewer to be able to see the change in texture, and mineralogy from the joint surface and further into the adjacent rock material. The thin sections were 2.5cm in width and 4cm in length.

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Figure 3-4: Location of thin sections.

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The equipment utilised in order to obtain the photomicrographs (thin section images) was the LEICA DM 2700 Light Microscope provided by the University of Pretoria. This microscope has the ability to view the thin sections in both Cross-Polarized Light (XPL) and Plane-Polarized Light (PPL). The Cross-Polarized Light (XPL) images were used to observe birefringence, interference colours, extinction angles, and twinning in minerals. These features help identify minerals that are difficult to distinguish under Plane-Polarized Light (PPL), as Cross-Polarized Light (XPL) reveals internal structures and crystalline orientations. Plane-Polarized Light (PPL) provides information about the colour, pleochroism, relief, and transparency of the minerals. This aids in identifying minerals based on their natural appearance (Perkins et al., 2022). XPL and PPL were thus used in conjunction with each other to offer complementary views that allowed for a comprehensive mineralogical analysis of the thin sections. The magnification used during this analysis varied based on the sample and which features were being focussed on. The magnification used is stated in the results section.

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The individual thin sections were divided into exposed, transitional, and unexposed areas, depending on the sample (Figure 3-5). The exposed sections refer to the joint surface and the adjacent material, while the unexposed sections consist of areas that remain unaffected by the propagating weathering process. The transitional section lies between the exposed and unexposed areas, where the effects of weathering diminish but do not completely cease. This classification aids in understanding the varying impacts of weathering on the rock samples. A total of three thin sections were made (one for each rock sample analysed):

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- Thin section 1: Quartz-diorite
- Thin section 2: Granite
- Thin section 3: Shale

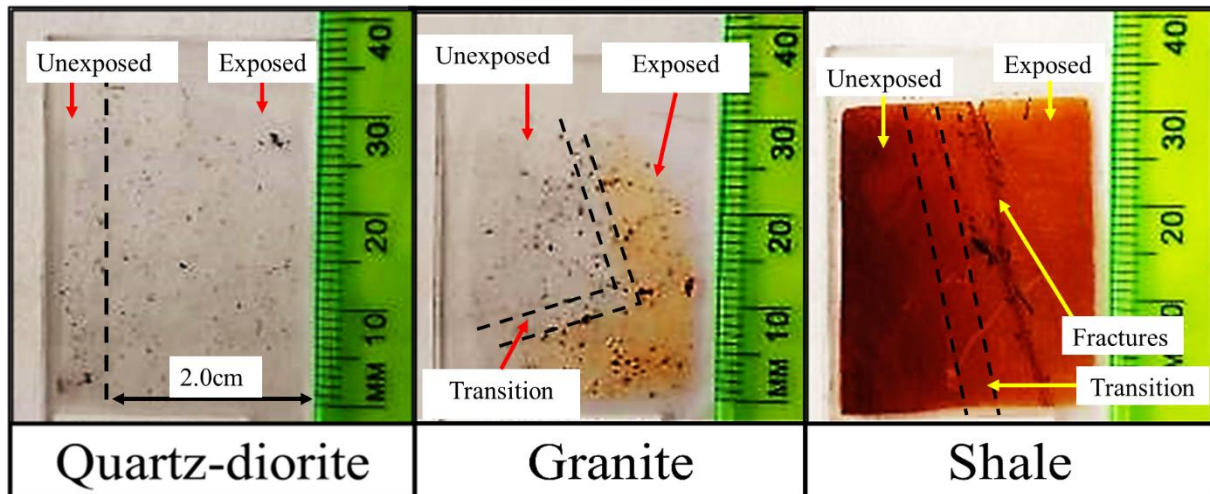


Figure 3-5: Thin sections analysed.

3.7. Scanning Electron Microscopy (SEM)

Scanning Electron Microscopy (SEM) is an investigative tool used to produce high magnification images of the surface topography of a sample. A focussed beam of electrons, from an electron gun, is used to produce these complex images. This beam is focused on a small spot on the surface of the sample. The SEM then detects, and records secondary high energy electrons emitted from the surface of the sample. Significantly small features and objects can be measured by using Scanning Electron Microscopy (Temiz, 2022).

The procedure for Scanning Electron Microscopy (SEM) began with cutting a thin section of the sample perpendicular to the joint surface. The back side was then polished to remove surface topography and carbon-coated to prepare the section for analysis (Temiz, 2022). The thin sections were divided into exposed and unexposed sections and analysed accordingly.

The Scanning Electron Microscope and additional equipment were provided by the University of Pretoria. The microscope used to obtain the images during the analysis was the FEGSEM: Zeiss 540 Ultra. The Zeiss 540 Ultra is a high-resolution field emission scanning electron microscope (FE-SEM) integrated with a focused ion beam (FIB) system, designed for advanced material analysis. The magnification used during this study varied throughout the analysis depending on the sample and which features needed to be emphasised. The magnification is specified in the results section. In comparison to optical microscopy, scanning electron microscopy (SEM) offers several advantages such as higher resolution and magnifications, greater depth of focus, which allows for more of the sample to be in focus simultaneously, and SEM can detect variations in composition, thus enabling detailed analysis of material properties (Davies et al., 2022; Goldstein et al., 2018; Reimer et al., 2008).

4. Results

This section presents all results obtained through the study's methodology. It includes descriptions of each sample, analysing physical features such as depth of weathering propagation, textural changes, and fracturing. Petrological observations from thin sections for each sample are discussed. SEM analysis results identify micro fractures, pore spaces, and signs of weathering. The XRF and XRD results highlight relationships between specific oxides and minerals, indicating weathering resistance and the extent of weathering propagation. XRF was primarily used to calculate weathering indices,

while XRD identified rock types. A summary section compares and illustrates the relationships between physical and chemical observations.

4.1. Description of Visible Characteristics of quartz-diorite

4.1.1. Quartz-diorite

The following observations can be seen in Figure 4-1 (a)-(e). Joint surface A showed discolouration in the form of a yellowish-brown hue in Figure 4-1(a) and was observed up to 2.00 cm from the joint surface. A slight change in texture is visible in (a), changing from less defined grain boundaries at and near the joint surface to more defined boundaries further from the joint. The size of the minerals became larger as the distance from the joint surface increased. Fracturing parallel to joint surface A was observed approximately 4 mm from the surface in Figure 4-1(b). On closer analysis the fracturing increased closer to the weathered surface of the joint. The joint surface had a yellowish-brown to orange hue. A portion of the material adjacent to joint surface A was exposed through breakage as shown in Figure 4-1(c). The exposed surface had a reddish-brown hue and possessed a greater percentage of mica. Quartz was visible in both layers as medium to fine-grained particles.

Large feldspar grains are present on the other surface of the joint (Surface B) shown in Figure 4-1(d), and the joint surface has an orange to brown colour. A fracture that was parallel to joint surface B (similar to the fracturing observed in Figure 4-1(b)), can be seen in Figure 4-1(e). This parallel fracture is 1.5 cm from joint surface B. A powder-type substance was present on the joint surface. The texture of the rock material adjacent to the joint opening was soil-like, and the grain boundaries became less defined closer to the joint surface.

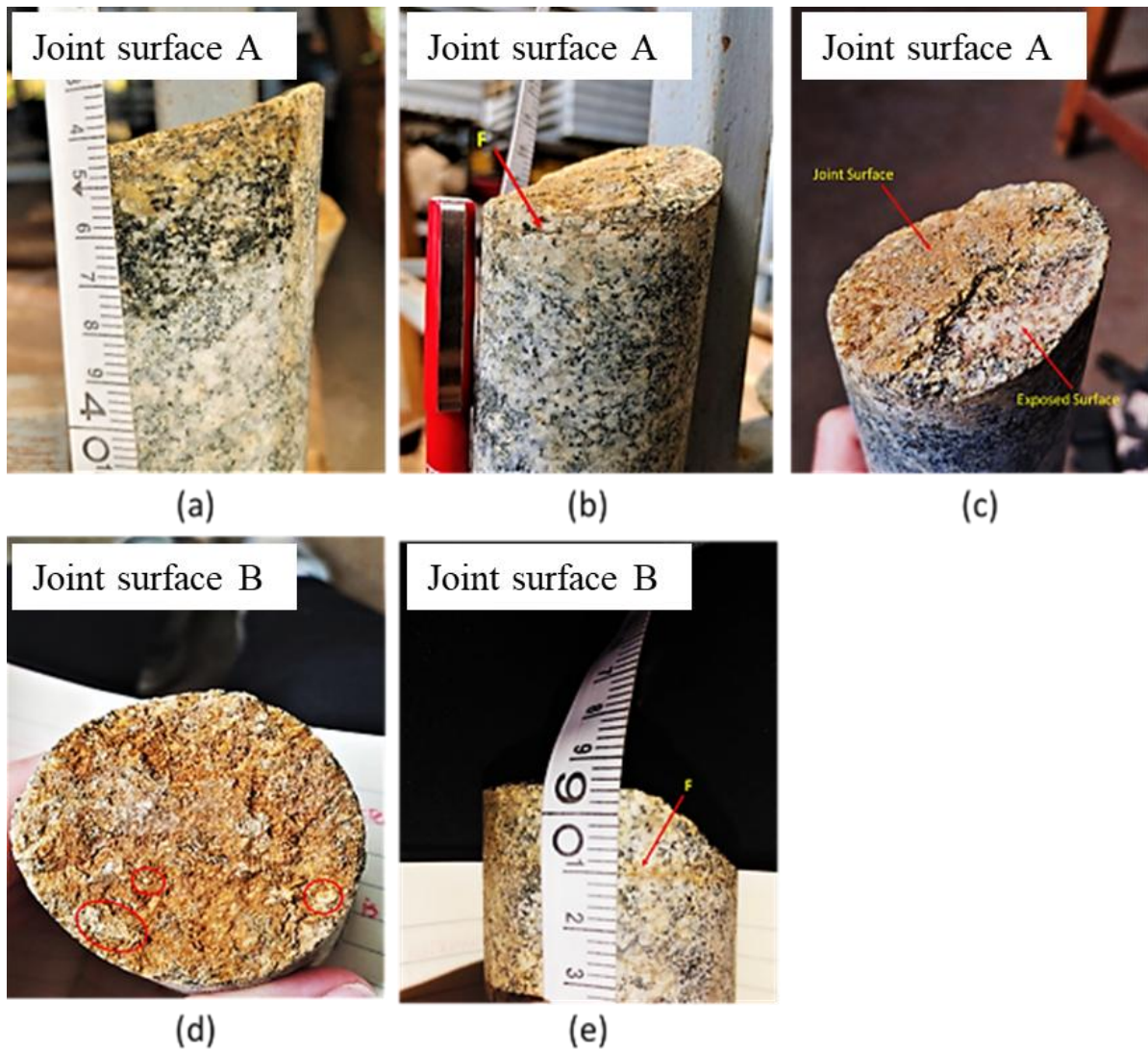


Figure 4-1: (a) Discolouration propagating into rock material adjacent joint surface A. (b) Fracturing parallel to joint surface A. (c) Discolouration on joint surface A with portion of adjacent rock material exposed. (d) Discolouration of joint surface B showing large feldspar grains. (e) Fracturing parallel to joint surface B.

4.1.2. Granite

The following observations can be seen in Figure 4-2(a) to (d)

The granite sample showed a weathering rim of approximately 1.1 cm in depth. The weathering rim can be divided into three weathering zones (a). Zone 1 is represented by the outer edge of the sample. This zone was yellowish-light brown in colour, almost white and ranges in thickness from 3 mm to 5 mm. Zone 1 featured a porous to soil-like texture. Zone 2 was approximately 2-3 mm in width and the grains were slightly more cemented compared to that of Zone 1. Zone 2 had a yellowish-orange hue, thus appearing darker than zone one. Zone 3 had a reddish-dark brown colour and had a similar texture to the unweathered, central portion of the hand specimen. Zone 3 had a width of approximately 3 mm. Upon further examination, fracturing was observed starting at the surface of the specimen and propagating deeper into the central, unweathered zone of the specimen Figure 4-2 (b-c). The fractures were created as a result of progressive weathering and are responsible for the overlapping of the three weathering zones in some areas of the weathering rim. Propagation of weathering into the adjacent

material of the fractures was clearly visible in the form of discolouration (d). This discolouration is similar to that of zone two and three of the weathering rim.

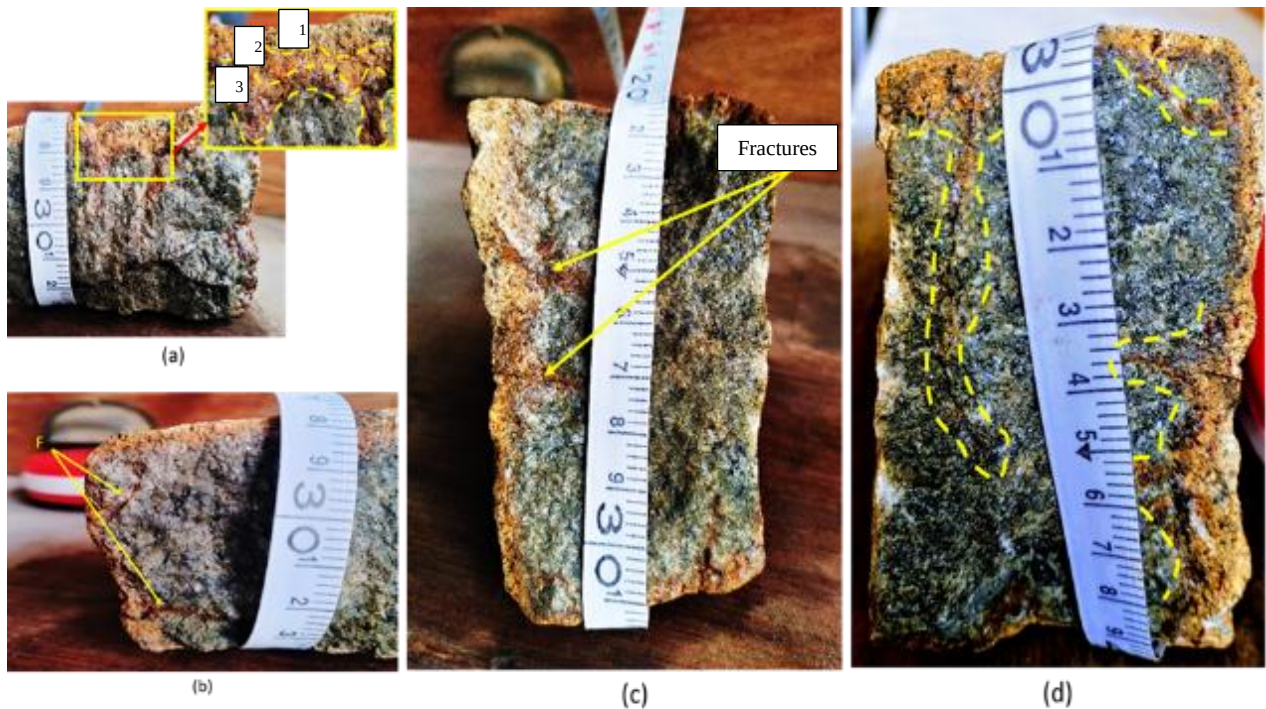


Figure 4-2 (a) Hand specimen 1 showing propagating weathering rim zones. (b and c) Visible fracturing starts at the edge of the specimen. (d) Propagation of weathering into rock material adjacent to fractures.

In Figure 4-3 (a) there are four zones are visible, however, there was some overlap between these zones. The outer layer, which is labelled as zone 1, is similar in colour and texture as described previously in Figure 4-3. Zone 2 also possesses similar characteristics to that of zone 2 shown in Figure 4-3 (a). The third zone in Figure 4-3 (a) has a rust-like appearance. This zone (3rd) overlapped with both the 2nd and 4th zones. Zone 4 is dominated by a black-coloured mineral. Upon closer examination, the black mineral was present in zone 3 as well, but to a lesser extent. Fracturing was present in the top-right corner of the sample Figure 4-3 (b)). The fracturing originated at the weathered surface and propagated deeper into the adjacent rock material.

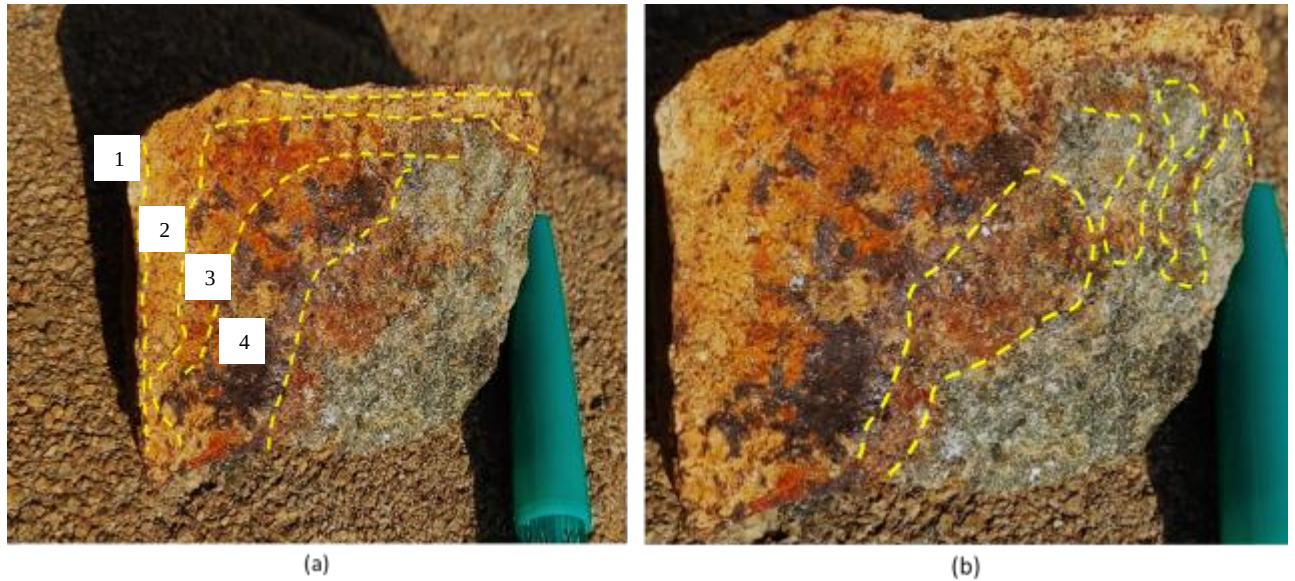


Figure 4-3: (a) Newly exposed surface with 4 zones separated based on colour. (b) Fracturing in the top-right corner of the newly exposed surface and a zone similar in colour to the material adjacent to the fracturing.

4.1.3. Shale

The following observations can be seen in Figure 4-4 (a)-(d).

The weathering rim on this sample can be divided into three zones. Zone 1 represents the outer edge of the rock and had a thickness of approximately 1mm. This zone (1) was yellowish white in colour and had a crumbly and chalky texture. This zone left a white-coloured powder behind when scratched. Zone 2 was yellowish-brown in colour and was less powdery compared to zone 1. Zone 2 was approximately 2mm in width. Zone 3 was reddish-brown in colour and had a width of approximately 3mm.

Overall, the outer surface (zone 1), of the specimen was significantly dull and powdery. The specimen caused staining, which was indicative of the presence of clay minerals. When making use of a hand lens, zone 3, consists of individual reddish-brown lines, that were clustered together.

Propagation of weathering into the material adjacent to the fracturing can be seen in Figure 4-4 (b). The propagation of weathering is apparent because of the lightness in the colour of the material adjacent to the fracture.

The samples also contained some black minerals. The black minerals were most commonly present along the fractures within the sample. The location of this black mineral indicated that it formed due to the process of propagating weathering.

In Figure 4-4 (d), the zones of the weathered rim were visible. This image also showed various other features including the presence of a mineral with a rust-like appearance (1), the black mineral (2) and small portions of a mineral that had a dark red colour (3).

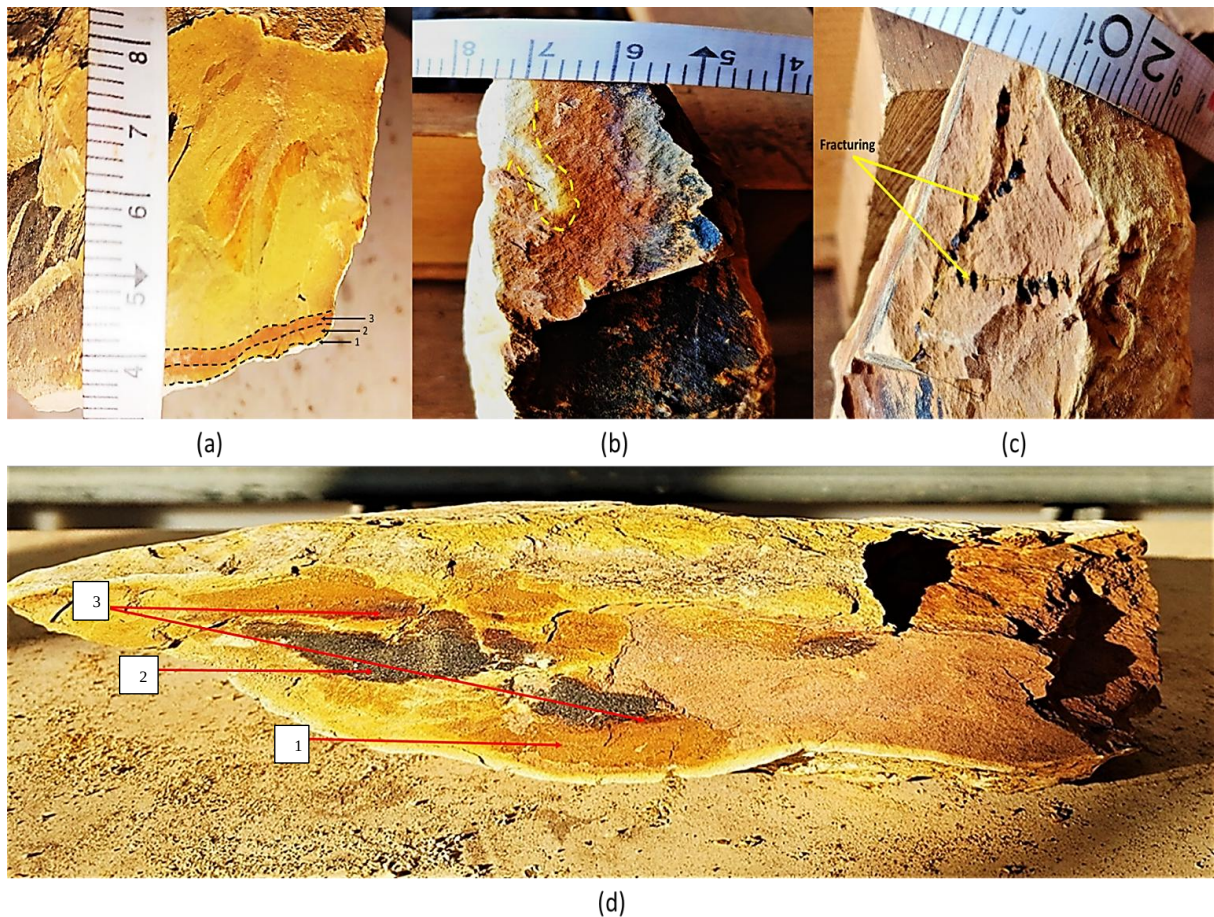


Figure 4-4: (a) Zones of propagating weathering. (b) Propagation of weathering from fracture. (c) Black mineral present along fracturing in shale sample. (d) Exposed surface of shale showing precipitation of different minerals on surface and zones of propagating weathering.

4.2. Petrology

The thin sections were oriented perpendicular to the joint or weathered surfaces of the samples to visualise the propagation of weathering into the adjacent rock material. Each sample's thin sections were analysed for grain sizes, signs of alteration, and fracturing.

4.2.1. Quartz-diorite

Figure 4-5 shows the physical thin section of quartz-diorite. The visible propagation depth in the quartz-diorite sample was measured at approximately 2.0cm. The exposed and unexposed regions are indicated in Figure 4-5.

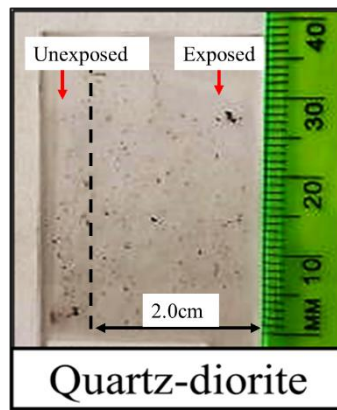


Figure 4-5: Thin section quartz-diorite.

Exposed surface

This section shows images captured of the exposed surface of quartz-diorite. Figure 4-6 contains thin section images as follows:

- a) This image shows signs of alteration along grain boundaries and intergranular fracturing on the right side of the thin section.
- b) The size of the biotite grains on the right side of the thin section. The sizes of the grains are as follows: 706 μ m (bottom) and 646 μ m (top). Signs of discolouration along fractures and grain boundaries can also be seen in this image.
- c) Discolouration along grain boundaries and a lack of large dark-coloured grains (biotite and actinolite) in this region.
- d) Signs of alteration visible. Darker minerals have little to no structure and are significantly altered. A large degree of fracturing is present and discolouration along some fractures can be seen.
- e) Discolouration (yellow and brown) and fracturing are present on the right side of the thin section. Some biotite minerals are present however, these minerals show signs of alteration in the form of brown discolouration on the minerals.
- f) Discolouration and fracturing are present on the right side of the thin section. The size of the quartz grains are as follows: 244 μ m, 465 μ m, 488 μ m, and 498 μ m. A highly altered region is visible in the top right corner of the section. This opaque mineral contains fracturing, which is filled with a dark brown mineral and has inclusions of quartz and feldspar grains, thus indicating a high degree of alteration taking place. This opaque mineral is an Fe-oxide.
- g) Signs of alteration and discolouration can be seen in this image. Brown and yellowish-brown discolouration along fractures and on the surface of minerals is also visible in this region of the thin section.
- h) Fracturing withing grains and alteration along fractures are visible in this region.

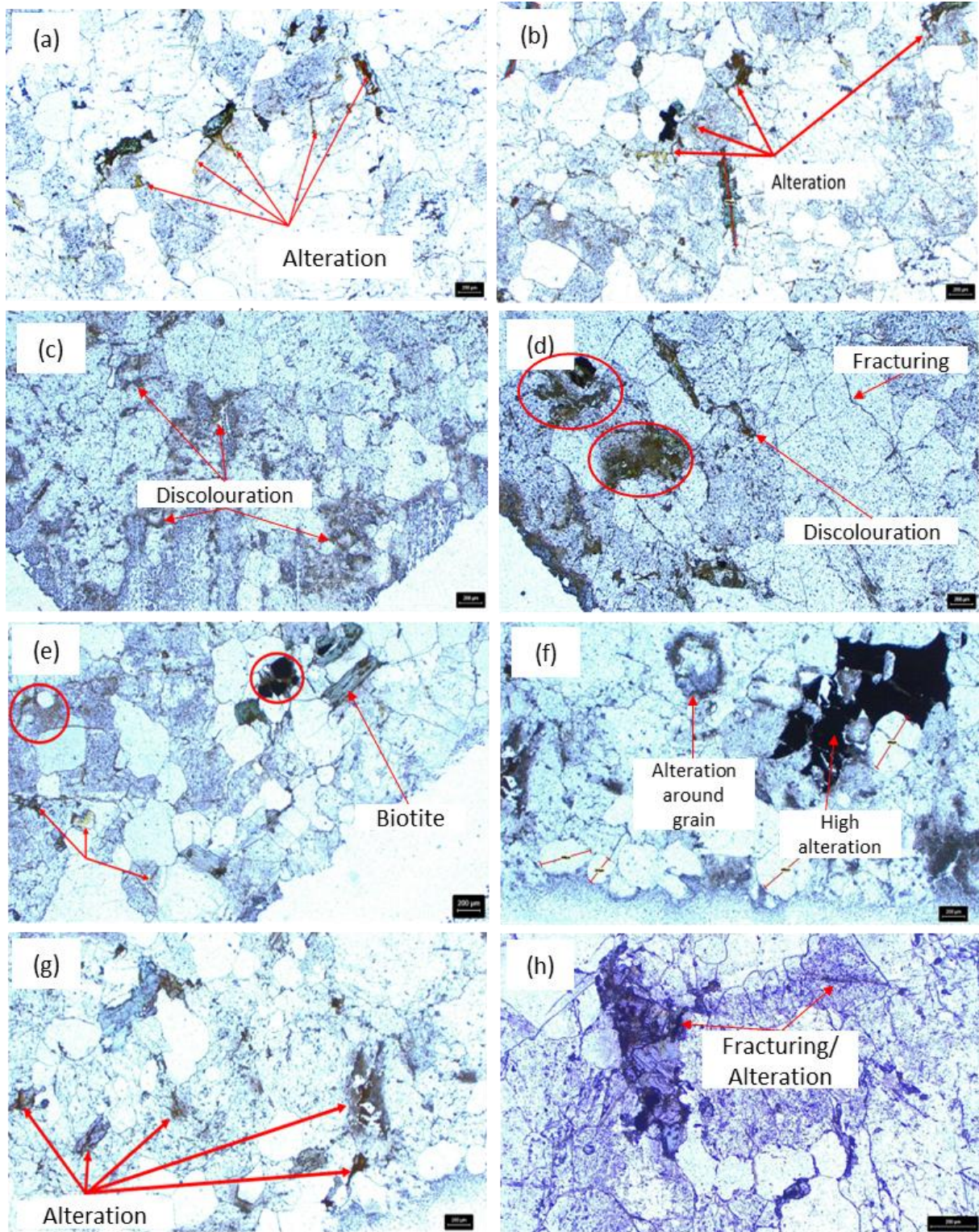


Figure 4-6: Thin section images and descriptions of the exposed surface and adjacent material of the sample in PPL at x2.5 magnification.

Figure 4-7(a) to (f) shows the exposed surface of quartz-diorite in both PPL and XPL at 2.5x magnification. Images (a) and (b) reveal a high degree of fracturing both between and within grains, while (c) and (d) display discolouration along these fractures. In images (e) and (f), some discolouration is also visible along grain boundaries and fractures.

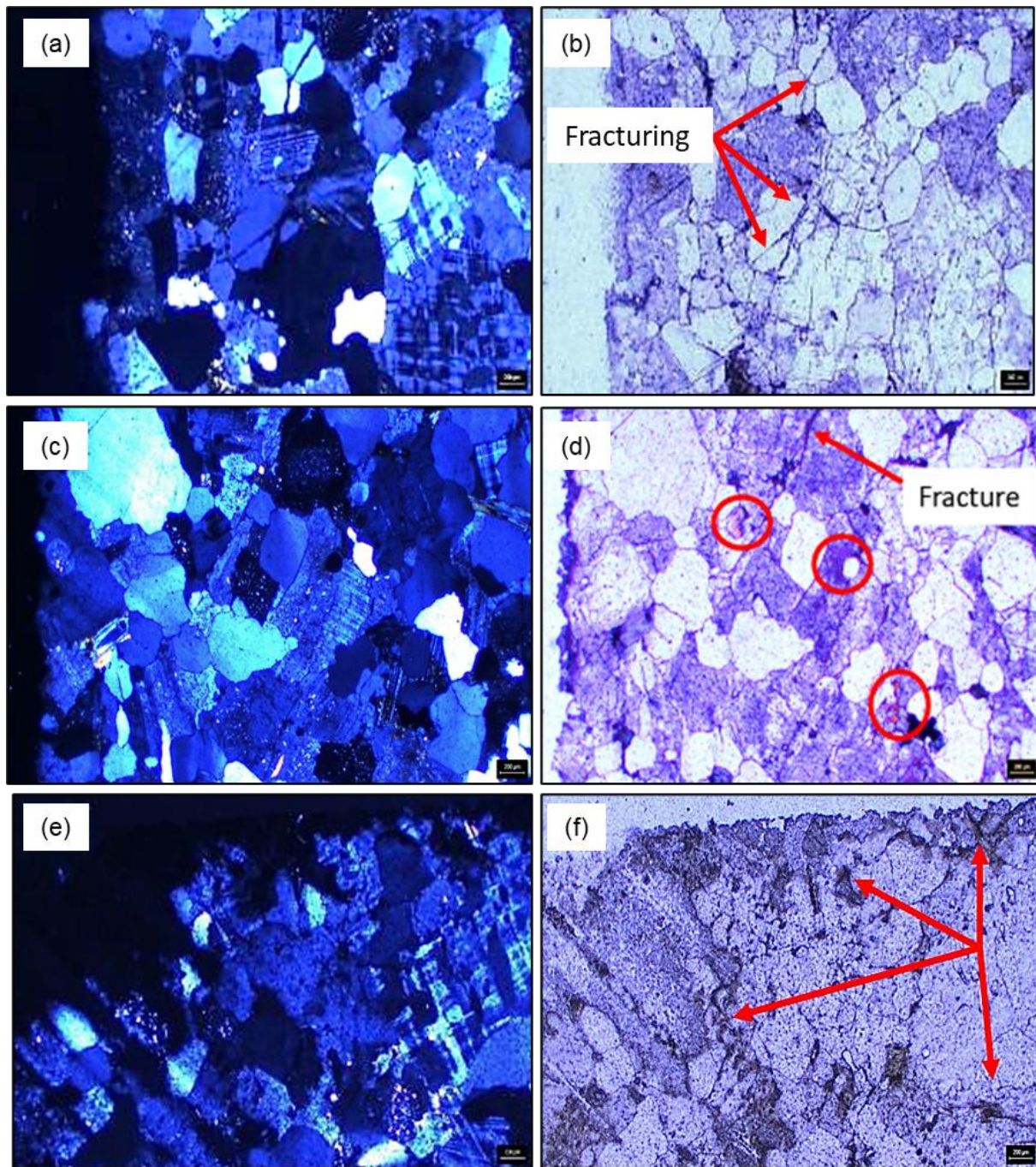


Figure 4-7: Exposed surface of the sample 1 in XPL (left) and PPL (right) at x2.5 magnification.

971 *Unexposed Surface*

972

973 The unexposed surface was preliminary identified based on the lack of visible discolouration. The
974 unexposed portion of quartz-diorite is shown in Figure 4-8.

- 975 a) The size of a quartz grain in this region of the thin section is 770 μm .
976
977 b) Greenish minerals are present in this image along with limited signs of alteration
978 concentrated within the vicinity of the darker minerals.
- 979 c) This image shows limited signs of alteration and some biotite and actinolite grains.
980 Fracturing and discolouration can be seen along grain boundaries on the left side of the
981 image.
- 982 d) Actinolite grains at and near the unexposed surface with minimal signs of alteration
983 visible.
- 984 e) The size of the actinolite and biotite cluster is 2012 μm . The cluster is showing signs of
985 alteration. Some alteration along the grain boundaries is also visible.
- 986 f) Biotite and actinolite crystals are present in this this region. Alteration of the biotite and
987 actinolite minerals are visible in the form of brown discolouration within the minerals
988 (right set of arrows). Signs of alteration along some grain boundaries are visible in this
989 image (left set of arrows).
- 990 g) The sizes of quartz grains in this image are as follows: 405 μm 205 μm 789 μm 365 μm .
991 Some yellowish-brown discolouration on the surface of grains and along grain boundaries
992 can be seen. The dark brown colour on the actinolite minerals points to alteration. Signs
993 of alteration within quartz grain at bottom of image.
- 994 h) The Size of an actinolite mineral in this region is shown in this image (931 μm).
- 995 i) The size of a quartz grain in this region is 752 μm .

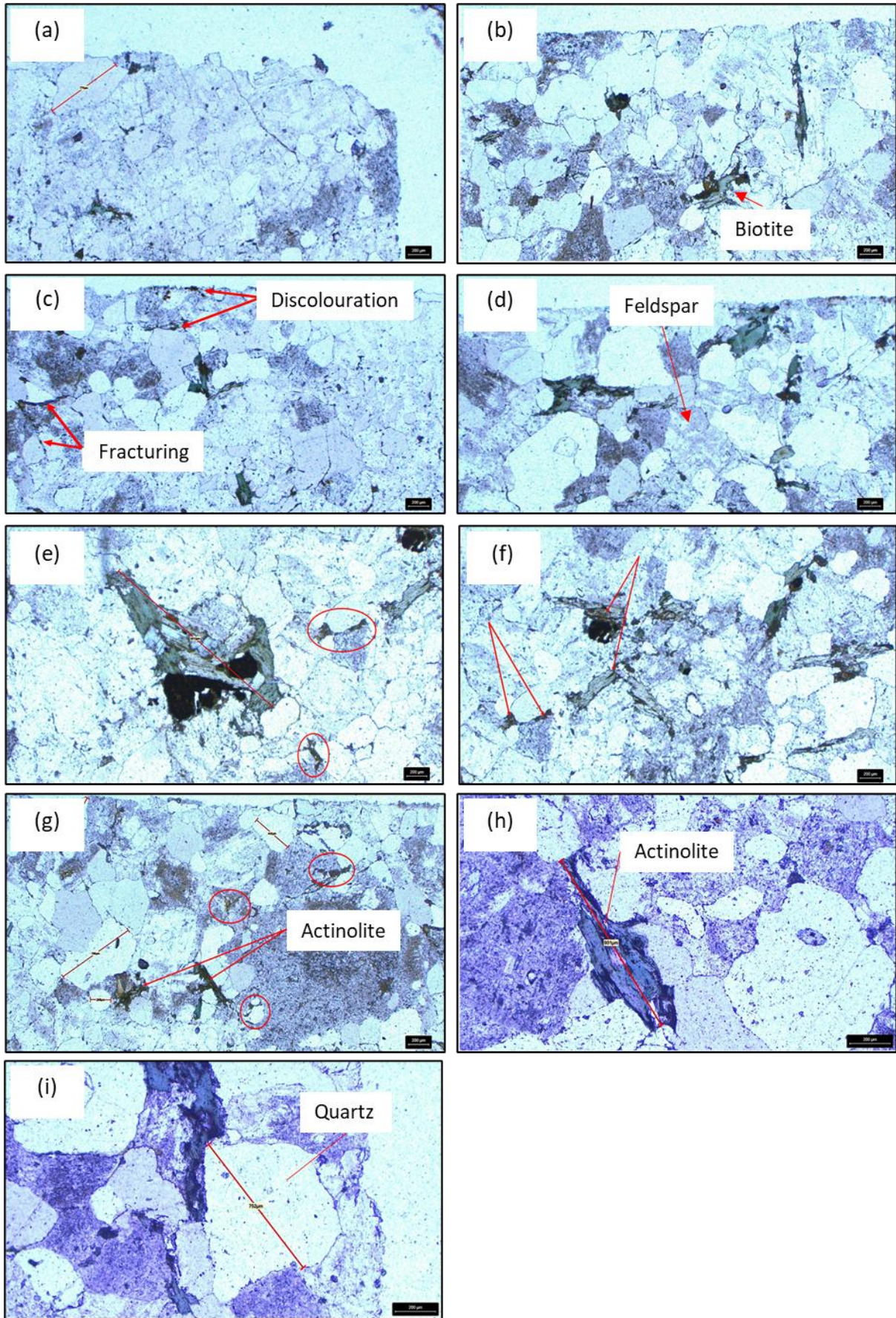


Figure 4-8: (a) to (i) Thin section images of fresh region of quartz-diorite with (a) – (g) at 2.5x magnification and (i) at 5x magnification. All images are in PPL.

4.2.1. Granite

The thin section in Figure 4-9 exhibits discolouration along the right and lower edges, corresponding to the exposed areas of the sample. In contrast, the top-left regions, representing unexposed surfaces, display minimal to no discolouration. The exposed, transitioning, unexposed surfaces are indicated in the image below.

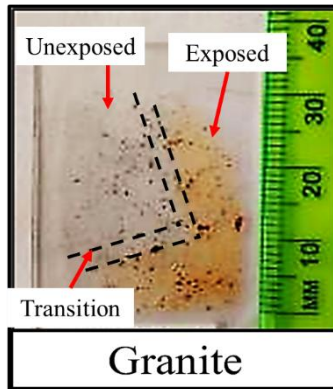


Figure 4-9: Thin section of granite.

Exposed Surface

Figure 4-10 (a)-(d) shows images captured at and near the exposed surface of granite.:

- a) Discolouration along the fracture on the right and propagation of alteration originating at the fracture surfaces. Discolouration is predominantly affecting orthoclase and plagioclase. The darkening of mineral grains is visible on the left side of the thin section. This process originates at the exposed surface of the sample. An open pore space is also visible and has a size of approximately 1001 μm .
- b) The sizes of the rust-coloured minerals at and near the exposed surface are as follows: 285 μm , 384 μm , and 1482 μm . A large pore space is also visible in this image. Discolouration and staining can be seen around the large reddish-brown mineral. Signs of alteration can also be seen on the left side of the image. quartz grains show the least amount of change compared to the other minerals present.
- c) A large amount of darker coloured minerals (possible amphibole grains) is present in the weathered zone of the sample. Discolouration is present along fractures and on the surface of most minerals, with quartz grains showing the least amount of discolouration and fracturing.
- d) This image shows yellow staining along grain boundaries and fractures within the feldspar grains, predominantly. This is a clear sign of alteration at the exposed surface of the sample. Significant fracturing is also visible in this region of the thin section.

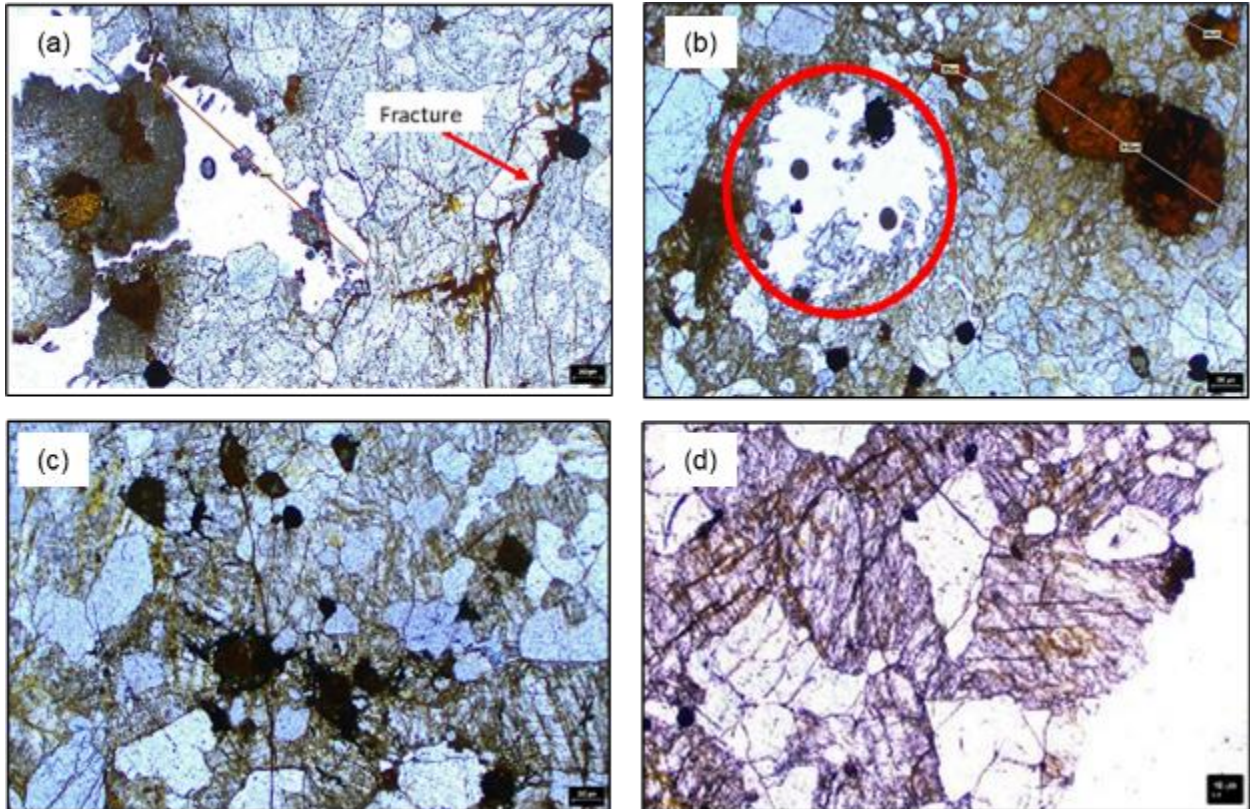


Figure 4-10: (a)-(d) Exposed surface at 2.5 magnification in PPL for granite.

Transitioning Zone

This section contains the images captured of the transitioning zone between the weathered and fresh portions of granite (Figure 4-11):

- The transition from the weathered to less weathered portion is visible in this image with yellow staining present at the bottom of the image and the portion with less yellow staining at the top of the image. Fracturing and discolouration of the darker minerals (possible amphibole grains) are still present in the upper portion of the image, which indicates that the lack of a change in colour does not mean that weathering has not affected the visibly unchanged portion of a rock.
- This image shows the transition between weathered and less weathered zones of the thin section. Discolouration (brown) can be seen along fractures and yellow staining is present, predominantly in the lower portion (weathered zone) of the image.
- This image is taken at the edge of the weathered zone (bottom right). Pore spaces are present in this image; however, these spaces are smaller compared to the pore spaces closer to the exposed surface. Alteration in the upper region of the image can be seen through the discolouration of the darker minerals (possible amphibole grains) and along the fracturing. The degree of fracturing is significantly less in the upper (less weathered) portion of the image.

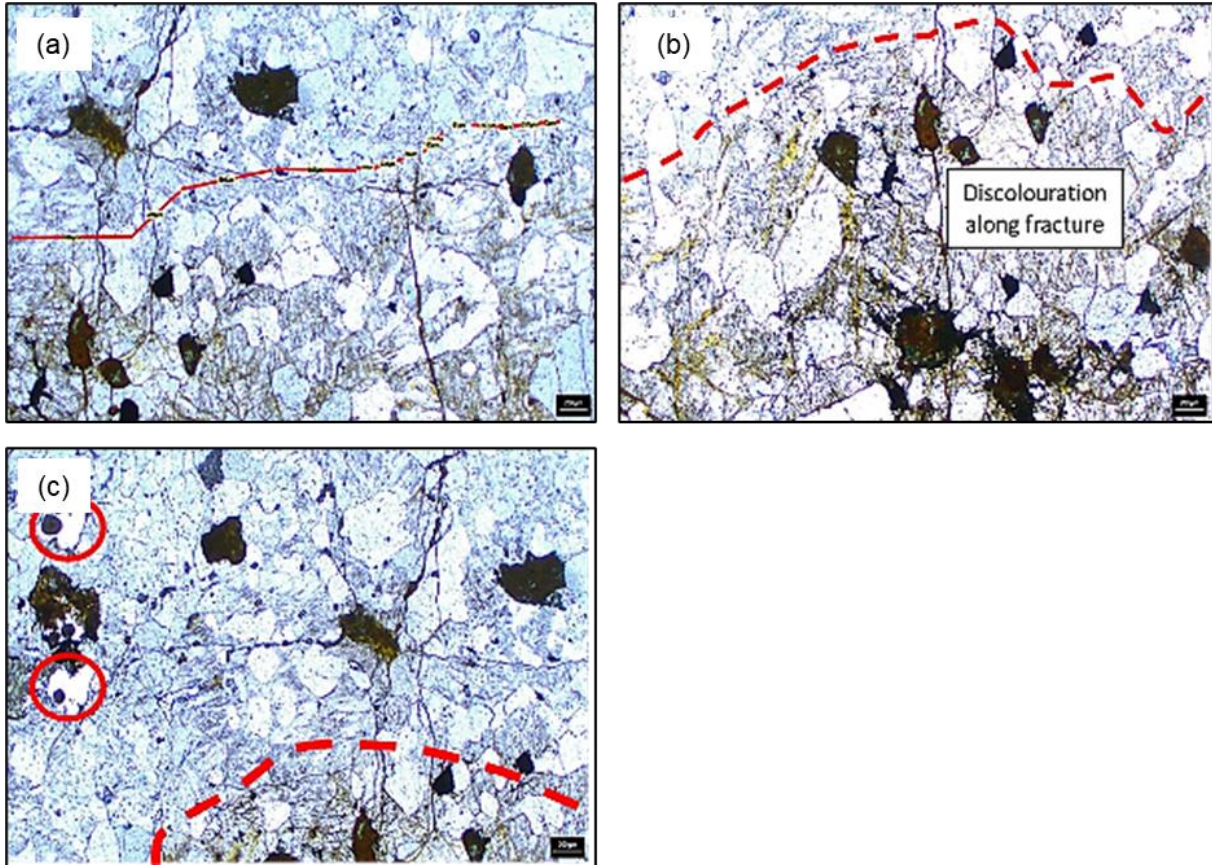


Figure 4-11: (a) – (c) Transitioning zone between weathered and less weathered portion of granite at 2.5x magnification, in PPL.

Unexposed Surface

This section contains images captured of the unexposed portion of granite. These images can be found in Figure 4-12(a-b).

- a) The unexposed surface is shown in this image. Notice the lack of discolouration.
- b) The size of the darker minerals closer to fresh surface range from 315 μ m to 589 μ m.

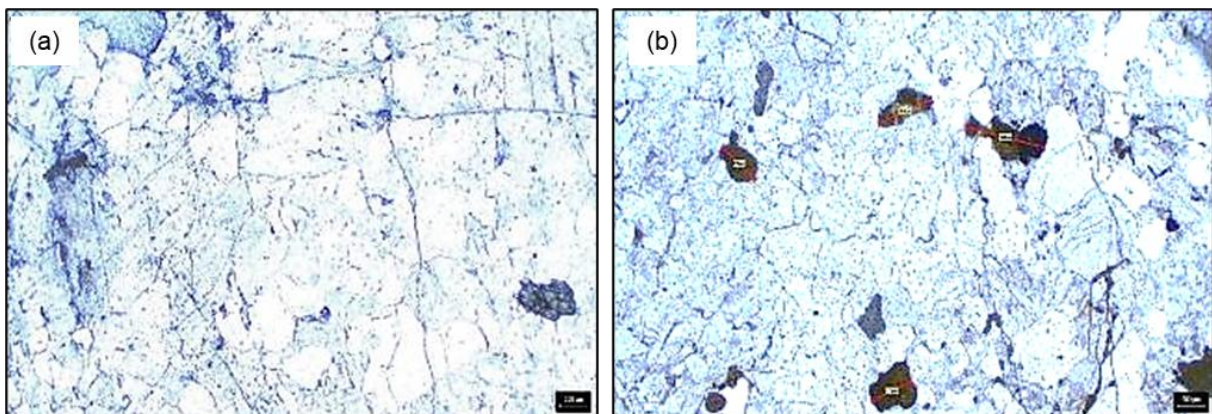


Figure 4-12: (a) and (b) Unexposed surface of granite at 2.5x magnification in PPL.

4.2.3. Shale

A prominent fracture extends through the entire length of the thin section, with discolouration visible along its path. The right side of the thin section appears lighter in colour compared to the left, indicating that the right side represents the exposed surface, while the left corresponds to the unexposed portion. An image of the thin section is shown in Figure 4-13.

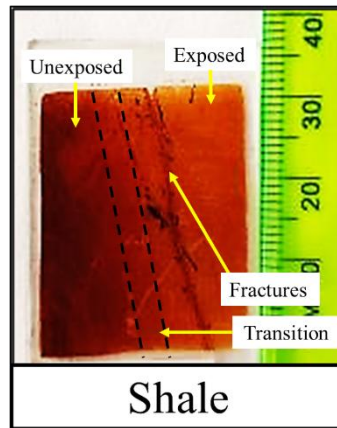


Figure 4-13: Thin section of shale.

Exposed and Transitioning surface

The images shown in Figure 4-14 (a-f) indicates the right portion of the thin section which includes the exposed surface, as well as the rock material adjacent to the exposed surface.

- This image shows fracturing on the right side of the thin section. Note the discolouration in close proximity to the fracture and how the intensity of the discolouration decreases as the distance from the fracture is increased. Discolouration is taking place along micro fractures on both sides of the major fracture.
- This image is showing fracturing that originates at the surface of the bottom right corner of the thin section. Discolouration (small veins of a yellowish-brown colour) can be seen and is greatest closer to the surface and along the fractures. These smaller fractures originate at the major fractures. Propagation of weathering is thus visible in the form of both fracturing and discolouration.
- This image of the right side of the thin section is showing fracturing and a significant amount of open pore spaces. A black-coloured mineral is present within the fracture. Lesser pores are present closer to fracture, which could indicate that a high degree of weathering leads to infilling of pores created prior to increased weathering.
- This image shows the bottom left corner of the thin section. The image shows little to no open pore spaces and/or fracturing.
- This image shows the right side of the thin section. Some open pore spaces can be seen in this image and compared to the left side of the thin section, the right side of it shows a greater amount of pore spaces.

- f) The transition between the weathered and unweathered zone can be seen in this image. The left side of the image corresponds to the more weathered zone of the thin section. A clear difference in texture is visible. The left side (weathered) is showing a greater amount of pore spaces compared to the right side (fresher).

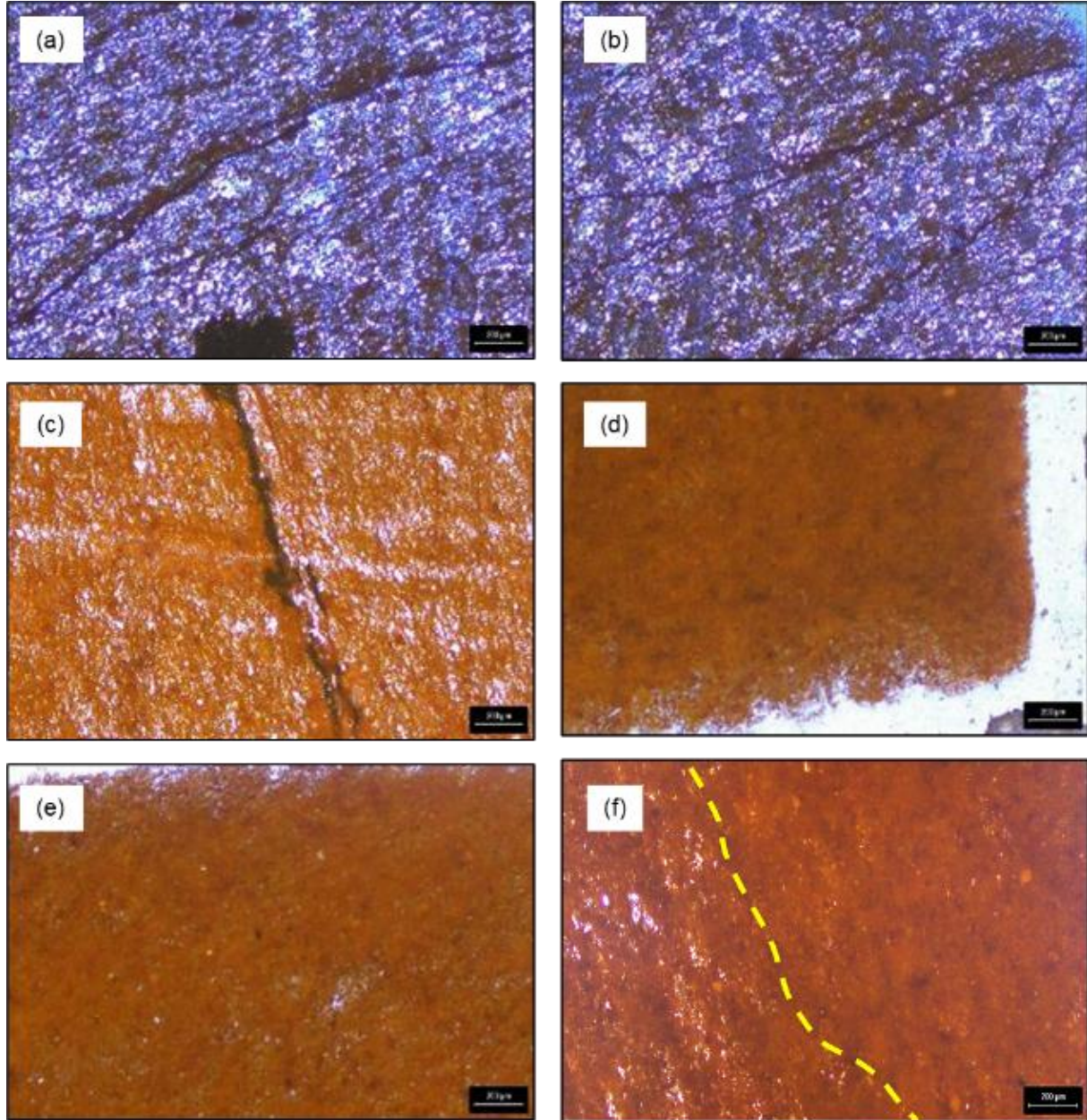


Figure 4-14: Shale thin section images of exposed and transitioning zone at x5 magnification with (a) –(b) in XPL and (c) – (f) in PPL.

Unexposed Surface

This section contains the images captured of the left side of the thin section, which is the unexposed portion of the rock. Figure 4-15 (a-b) shows the unexposed surface. Both images indicate a significant lack in pore spaces and a dark colour compared to that of the exposed region of the sample.

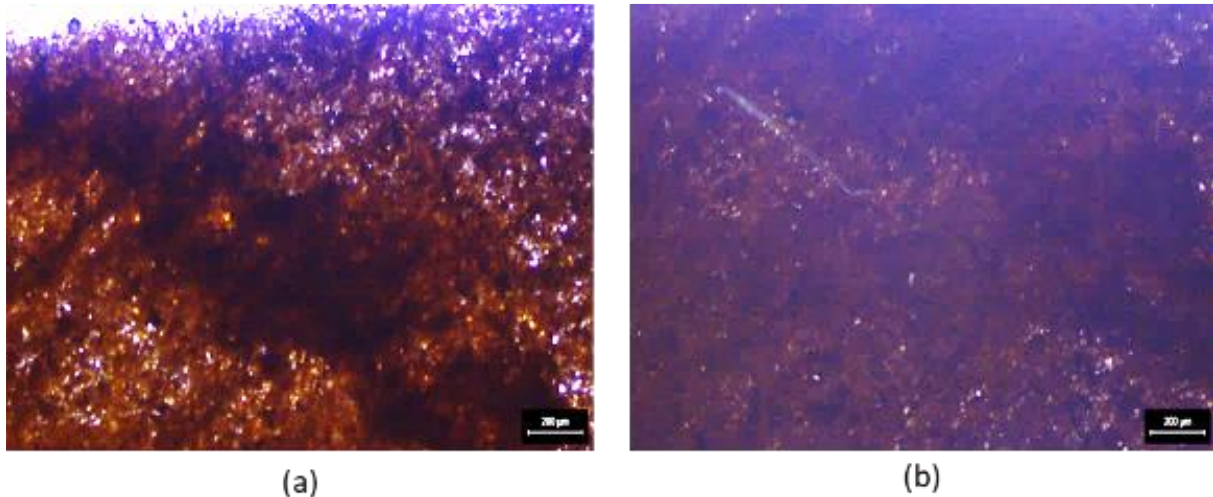


Figure 4-15: (a) and (b) Shows images captured of the unexposed region of the shale thin section at x5 magnification in PPL.

Fractures in shale

This section contains images captured of the fracturing present within shale (Figure 4-16).

- a) This image shows a fracture originating at the central top portion of the thin section. Note the brown discolouration taking place around the fracturing.
- b) This image shows fracturing and open pore spaces closer to the right side of the thin section.
- c) This image shows a central point connecting several fractures. This point is open, whereas the fractures leading to it are mostly filled with a black mineral. This is an indication of the black mineral being an infilling that propagates from the exposed surface initially. Upon closer examination, the central pore space has a thin black lining as well.
- d) In this image, the top section corresponds to the right side of the thin section, and the bottom section corresponds to the left side of the thin section. Note that the depth of propagating weathering differs on the left and right sides of the fracture. The top (right side of thin section) shows greater depth of propagation compared to the bottom (left side of thin section).
- e) In this image, the left section corresponds to the right side of the thin section. Fracturing and pore spaces are present to a larger degree on the left side of the image (right side of the thin section), thus indicating a higher degree of weathering on the right side of the thin section. It seems like the material adjacent to black fracture contains the least number of open spaces and this could be an indication that filled fractures hinder the propagation of weathering.
- f) Propagation of weathering shown through discolouration (yellowish-brown) along micro-fracturing. Some parts of the fractures are filled with the black mineral whereas other parts of

the fractures still remain open with a black lining, which indicates that the black mineral acts as an infilling within the fractures. Some pore spaces can also be seen in this image. The circled area shows the propagation of weathering in the form of discolouration along grain boundaries.

- g) Signs of propagating weathering are indicated through discolouration along micro-fracturing, originating at the fracture surface.
- h) The right part of the image corresponds to the left side of the thin section. A clear difference in colour can be seen and signs of propagation of weathering on the left side of the image are present as discolouration along the grain boundaries.
- i) In this image the material adjacent to the fracture changes as the distance from the fracture is increased. The material adjacent to the fracture has fewer open spaces compared to the material further away. This is an indication of a higher degree of weathering.

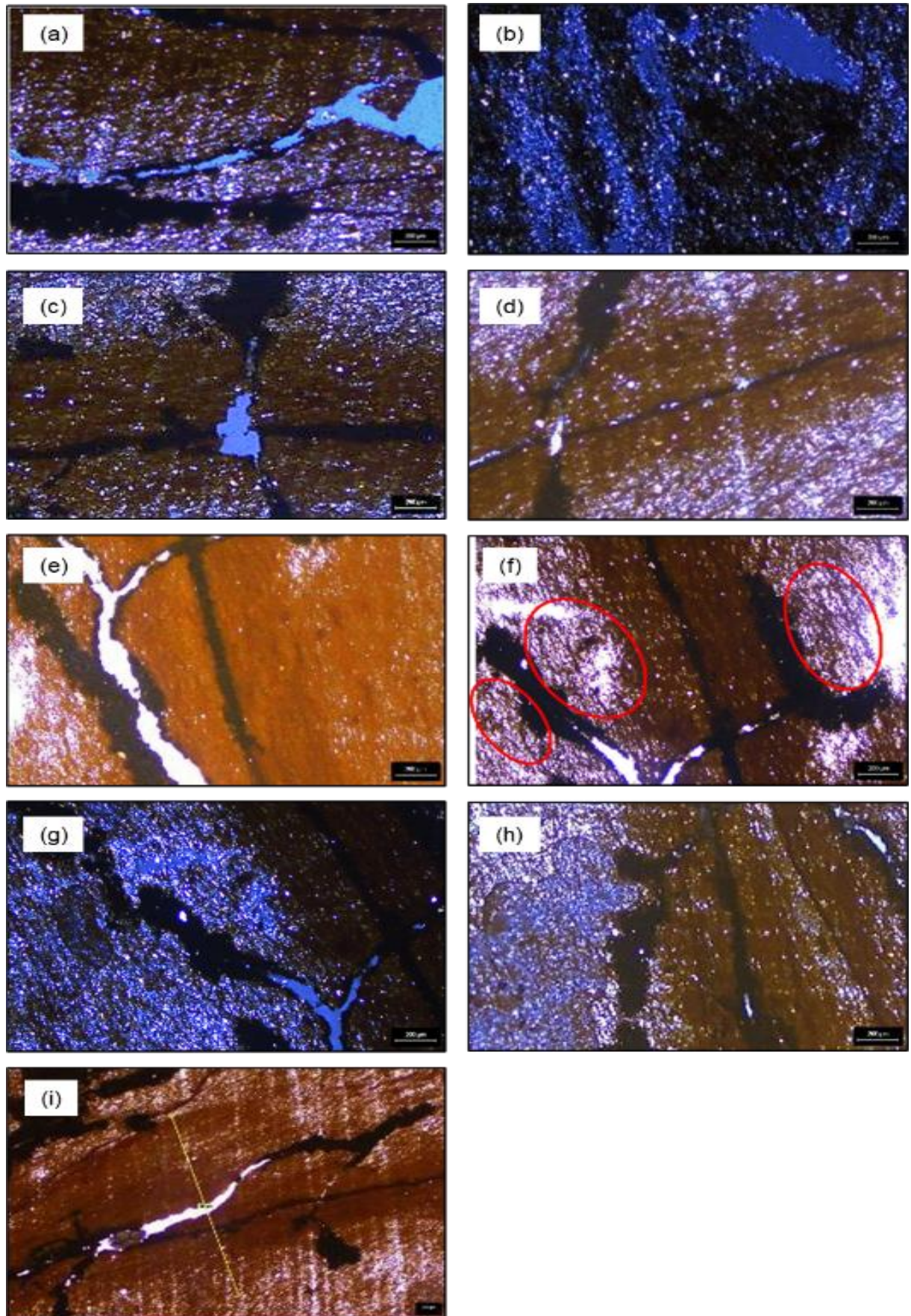


Figure 4-16: (a) to (i) Fracturing in shale at 5x magnification and (i) at 2.5x magnification (a - d, g - h) is taken in XPL, and (e-f, and i) is taken in PPL.

4.3. Scanning Electron Microscopy

The thin sections were carbon coated and placed in the scanning electron microscope to observe microfracturing, pore spaces, and other signs of weathering. This was done for each sample.

4.3.1. Quartz-diorite

The exposed and unexposed surfaces are shown in Figure 4-17 (a) – (h):

- (a) A biotite grain can be seen within a pore space and alteration is visible in the vicinity of this pore.
- (b) Signs of alteration are prominent in this region. Alteration and open pore spaces can be seen in the right portion of the image, which corresponds to the rim of the sample.
- (c) A rectangular shaped open pore space at the weathered surface can be seen. Alteration along grain boundaries is significant.
- (d) Alteration along grain boundaries is evident in this portion of the sample.
- (e) The needle-like minerals are the actinolite minerals present within the sample. These minerals have only been observed on the unexposed surface. A pore space can also be seen in this image with signs of alteration surrounding it
- (f) No fracturing and minimal signs of alteration can be seen in this image.
- (g) Fracturing remains along grain boundaries but is insignificant.
- (h) Slight alteration along grain boundaries can be seen in the image.

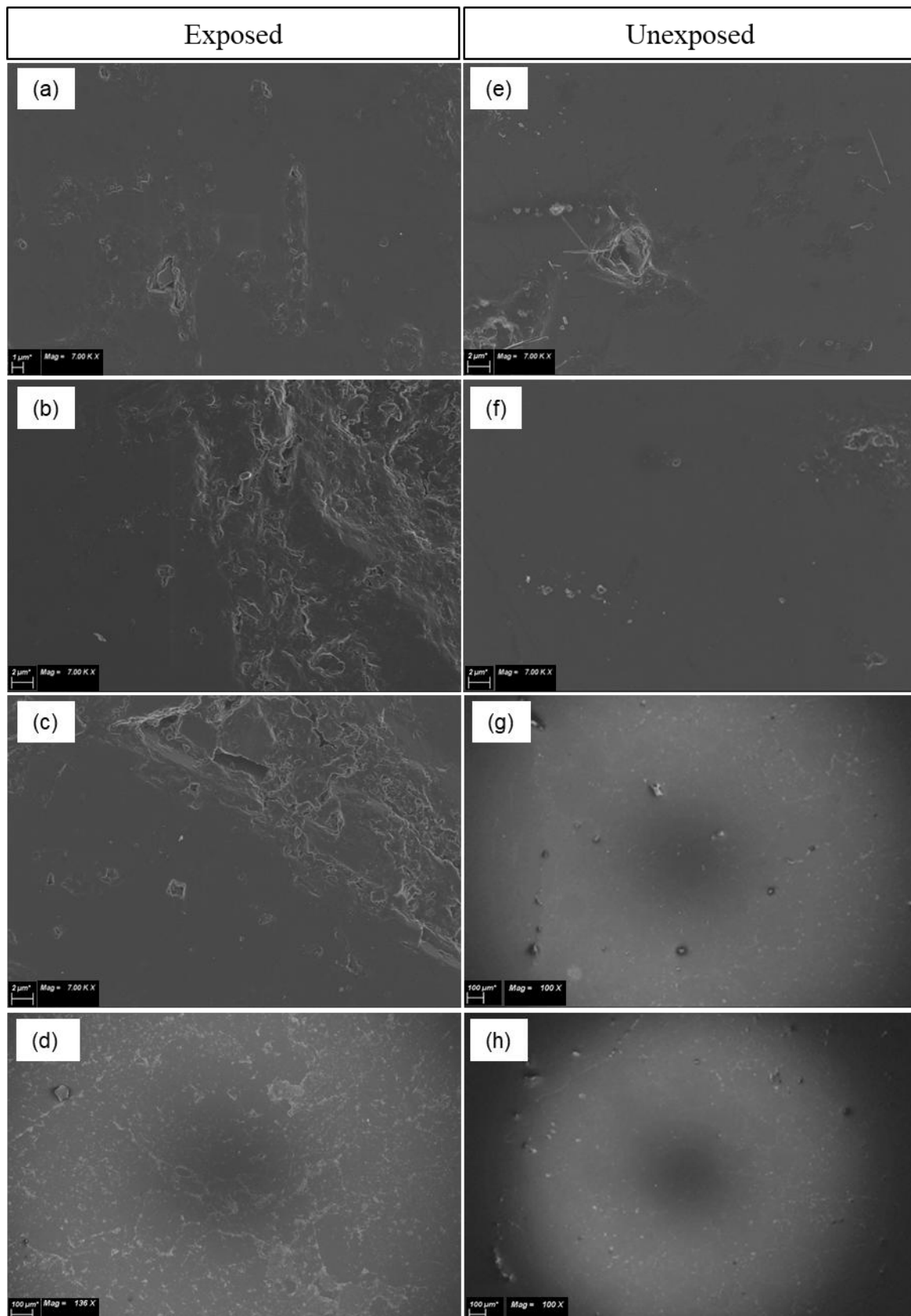


Figure 4-17: SEM images of exposed (left) and unexposed (right) surface for quartz-diorite with (a -c) and (e – f) taken at 7.00K magnification , (d) at 136K magnification and (g – h) at 100K magnification.

4.3.2. Granite

The exposed and unexposed surfaces are shown in Figure 4-18 (a) – (d):

- (a) Textural evidence of alteration can be seen. A high degree of fracturing is noted as well as pore spaces within the grains. Iron-Oxide minerals are present on the surface of most of the grains in this image and are concentrated along the boundaries of these mineral grains. Minerals structures have been distorted and changed due to the process of propagating weathering.
- (b) Fracturing and alteration along these fractures prevail in the exposed region of the sample. Fracturing takes place within and in between grains.
- (c) A pore is visible in the upper right corner of the image. Alteration can be seen surrounding this pore. A lack of micro-fractures can be seen as the distance from the pore is increased. Slight alteration along grain boundaries can be observed.
- (d) Alteration is present in the form of discolouration and limited fracturing along grain boundaries.

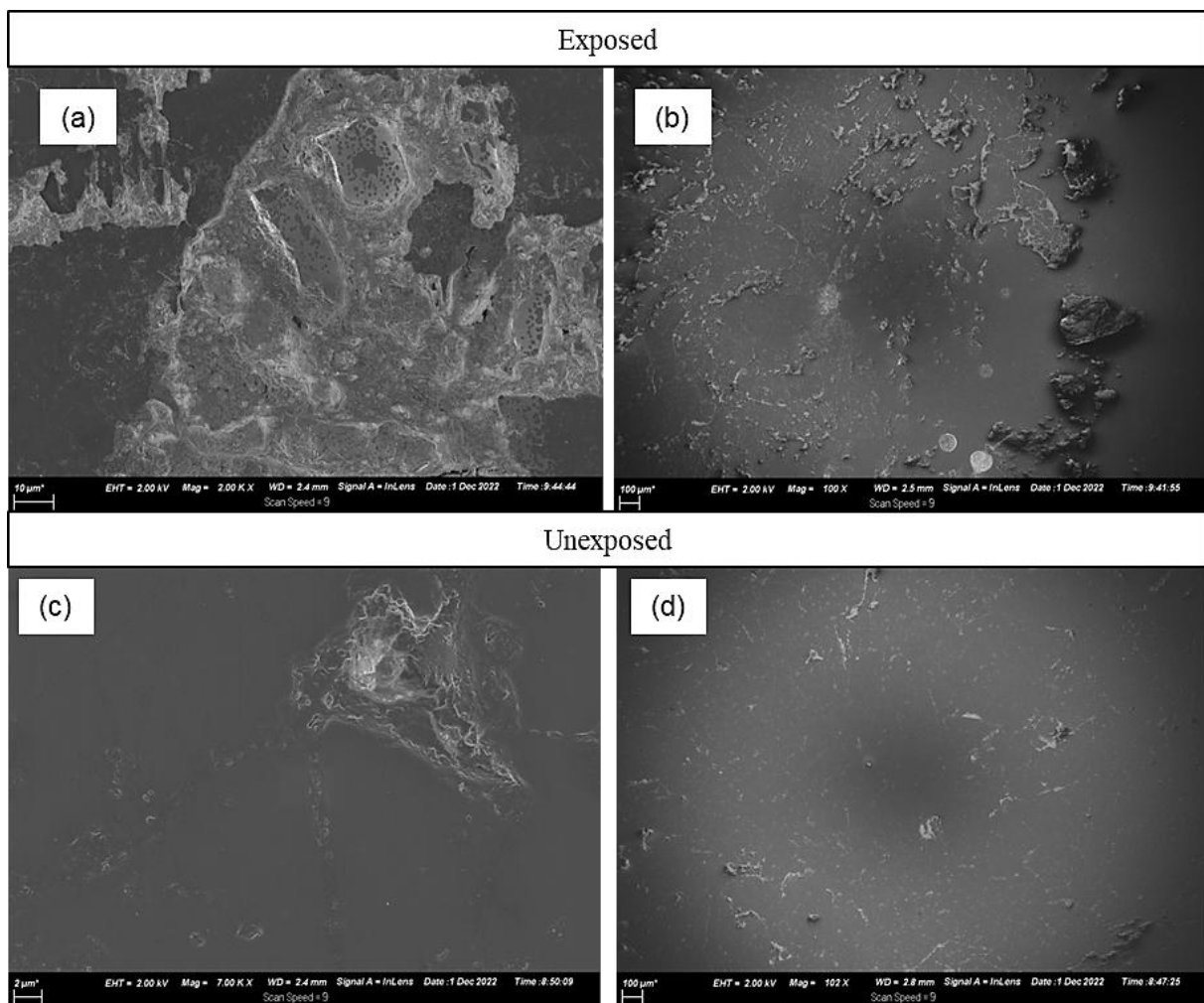


Figure 4-18: SEM images of exposed (a – b) and unexposed (c – d) surfaces for the granite sample.

4.3.3. Shale

The exposed, transitional, unexposed portions and fracturing of the sample is shown in Figure 4-19:

- (a) This image shows a portion of the exposed region of the sample. Fracturing was observed in this section as well as an increase in the size and number of rough textured minerals.
- (b) Little to no fracturing was visible in this section of the sample. Slight alteration around individual grains can be seen. Mineral grains appear rounder.
- (c) No fracturing was observed in this section of the sample. Increased angularity for individual mineral grains.
- (d) A fracture is shown with significant signs of alteration adjacent to the fracture. Micro-fracturing can be seen originating at the fracture and propagating further into the adjacent material.
- (e) A fracture is present with significant signs of alteration propagating from the fracture surface. The light-coloured mineral on either side of the fracture resembles that of Fe-oxides. Micro-fracture can be observed in the material adjacent to the major fracture.

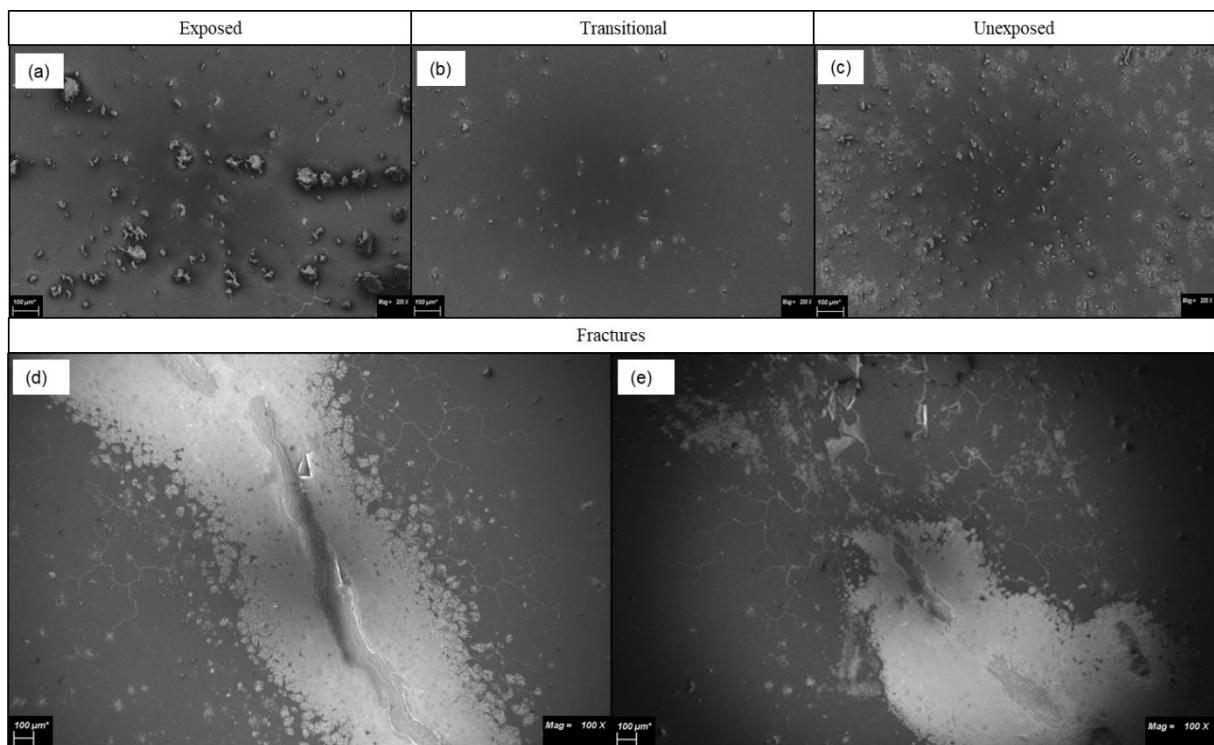


Figure 4-19: SEM images of exposed (a), central (b), unexposed (c) regions with the shale sample at 200x magnification, and (d-e) showing fracturing at 100x magnification.

4.4. X-Ray Diffraction Results: Mineralogical Composition of Rock Samples

The results presented in this section are derived from X-Ray Diffraction (XRD) analyses (Section 8.1.2), which were crucial for identifying the crystalline minerals within the samples. The XRD results have been graphically represented in Figure 4-20. The mineral composition analysis led to the classification of the igneous rock samples as quartz-diorite and granite. Additionally, the shale sample was identified as a silica-dominated mudstone based on its high quartz content, as illustrated by the QAP and ternary diagrams in Figure 4-21. This identification is essential for understanding the relationship between mineralogy and the weathering indices, which will be discussed in the subsequent sections.

The XRD results showed that shale had the highest quartz content (52.8%), followed by granite with 32.8% quartz. Quartz-diorite contained the lowest percentage of quartz at 10.1%. Granite had the highest percentage of orthoclase (35.8%), whereas shale had the lowest percentage of orthoclase at 0.8%. Quartz-diorite also showed a low orthoclase content of 2%.

Quartz-diorite contained 1.7% actinolite, which is an amphibole silicate mineral. Actinolite is not durable in the weathering environment, and can transform into secondary clay minerals, or goethite. Quartz-diorite also contained 19.4% biotite which has a high susceptibility to weathering (Grotzinger, et al., 2014) and transforms into goethite during the process of weathering (Laukamp et al., 2013).

The quartz-diorite sample had the highest plagioclase content at 66.8%, followed by the granite sample with 31.5% plagioclase. The shale contained no plagioclase; however, it did contain 14.0% kaolinite.

Muscovite was present in both granite and shale, however granite showed minimal amounts (less than 1%), whereas shale showed an approximate 30% muscovite content.

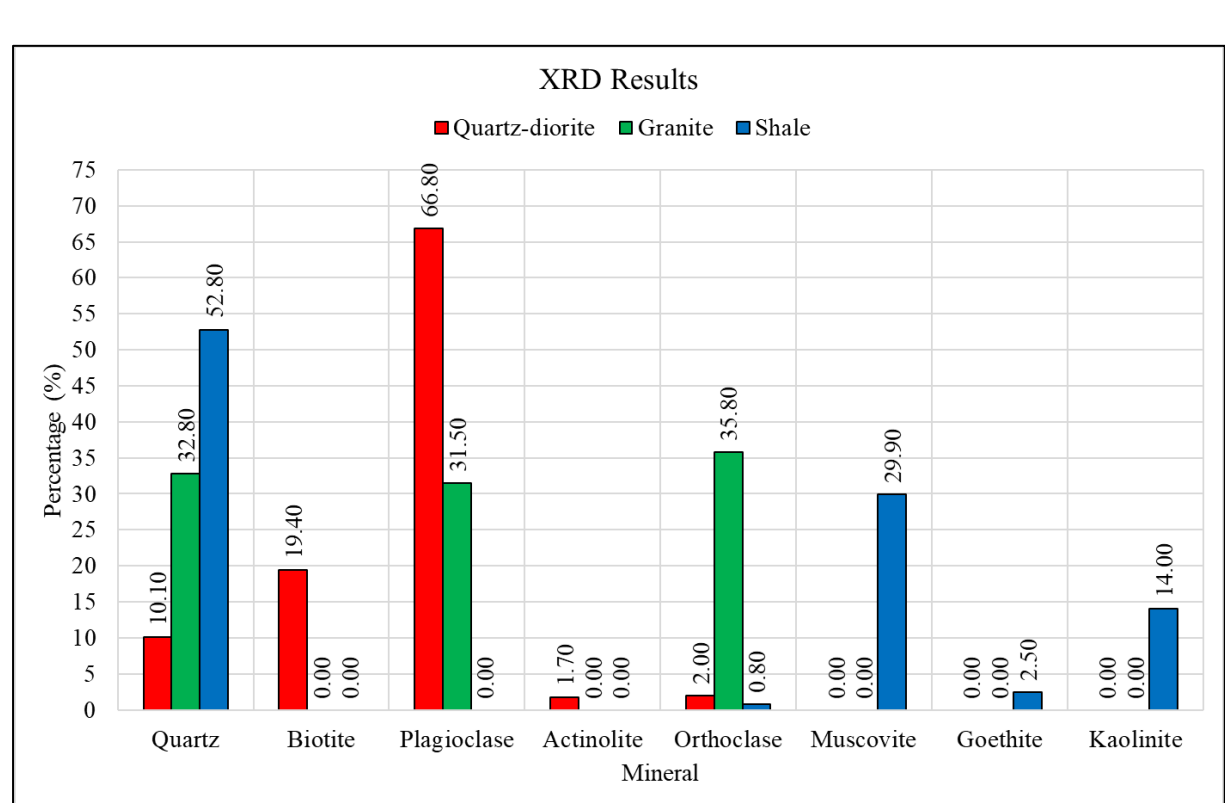


Figure 4-20: XRD Results per sample.

Based on the XRD results the igneous rock samples were identified as quartz-diorite and granite using the QAP- diagram shown in Figure 4-21(a). Figure 4-21(b) shows a ternary diagram in which shale plots within the Silica-dominated mudstone region due to the high quartz content.

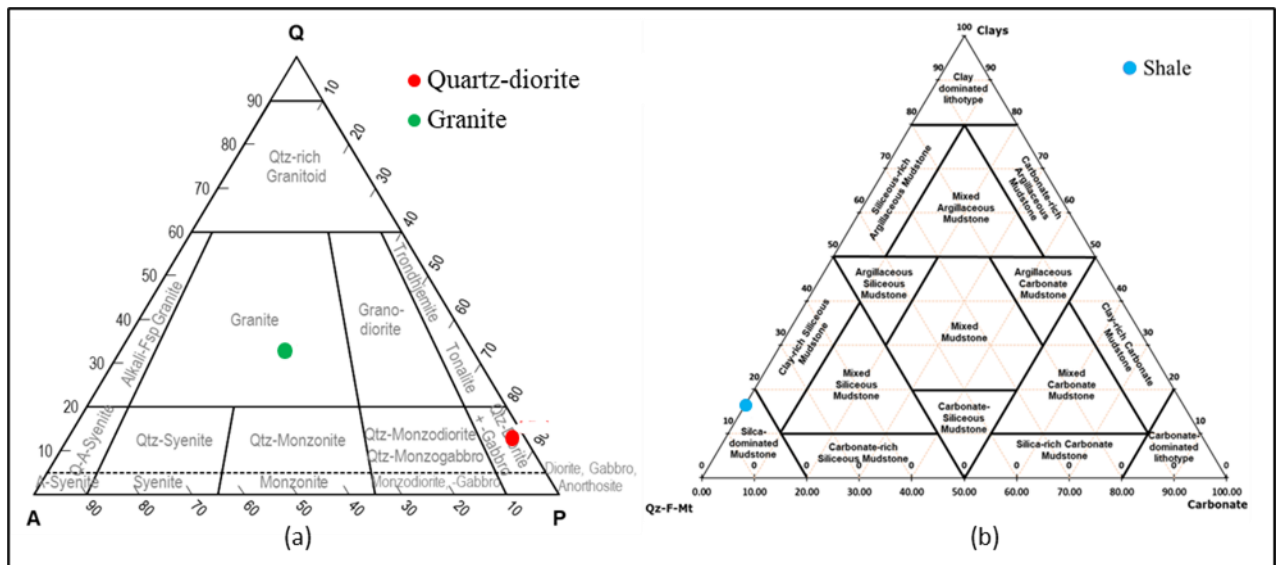


Figure 4-21: (a) QAP plot for Igneous rock samples quartz-diorite and granite. (b) Ternary Diagram for classification of mudstones (Miao et al., 2023).

4.5. X-Ray Fluorescence Results: Chemical Composition of Rock Samples

The analysis of X-Ray Fluorescence (XRF) results is important for understanding the elemental composition and weathering characteristics of the rock samples. This section presents detailed findings on the major oxides present in quartz-diorite, granite, and shale, highlighting significant variations in chemical weathering among these rock types. By examining relationships between key oxides such as SiO_2 , Al_2O_3 , and TiO_2 , the type of sedimentary rock can be confirmed (i.e. whether the sample is a sandstone or mudstone) and assess the degree of weathering. A ternary diagram was used to determine the chemical index of alteration (CIA), specifically. The influence of propagating weathering on the water holding capacity of a rock material is also illustrated in this section by analysing the loss of ignition (L.O.I) measured during the XRF analysis. The loss of ignition (L.O.I) percentage is also described as a sound indicator of weathering (Kagonbé et al., 2021). The implications of these findings on the geochemical processes at play in the studied samples will be discussed in detail. (a) QAP plot for Igneous rock samples quartz-diorite and granite. (b) Ternary Diagram for classification of mudstones (Miao et al., 2023).

The X-Ray Fluorescence results showed that the bulk of each sample consisted of SiO_2 , with granite containing the most at 74.41 (wt%). The highest percentages of Al_2O_3 and Fe_2O_3 were present within the shale sample. Following shale was quartz-diorite. When comparing the amount of Al_2O_3 and Fe_2O_3 present within the two igneous rock samples, quartz-diorite showed a higher degree of weathering compared to granite. Upon analysis, it was determined that shale exhibited the highest H_2O^- content, followed by quartz-diorite, with granite displaying the lowest levels. Furthermore, Loss on Ignition (LOI) assessments revealed that shale contained the greatest proportion of volatile components, including water, organic matter, and carbonates. Among the igneous rock samples, quartz-diorite demonstrated a higher volatile content compared to granite (Figure 4-22).

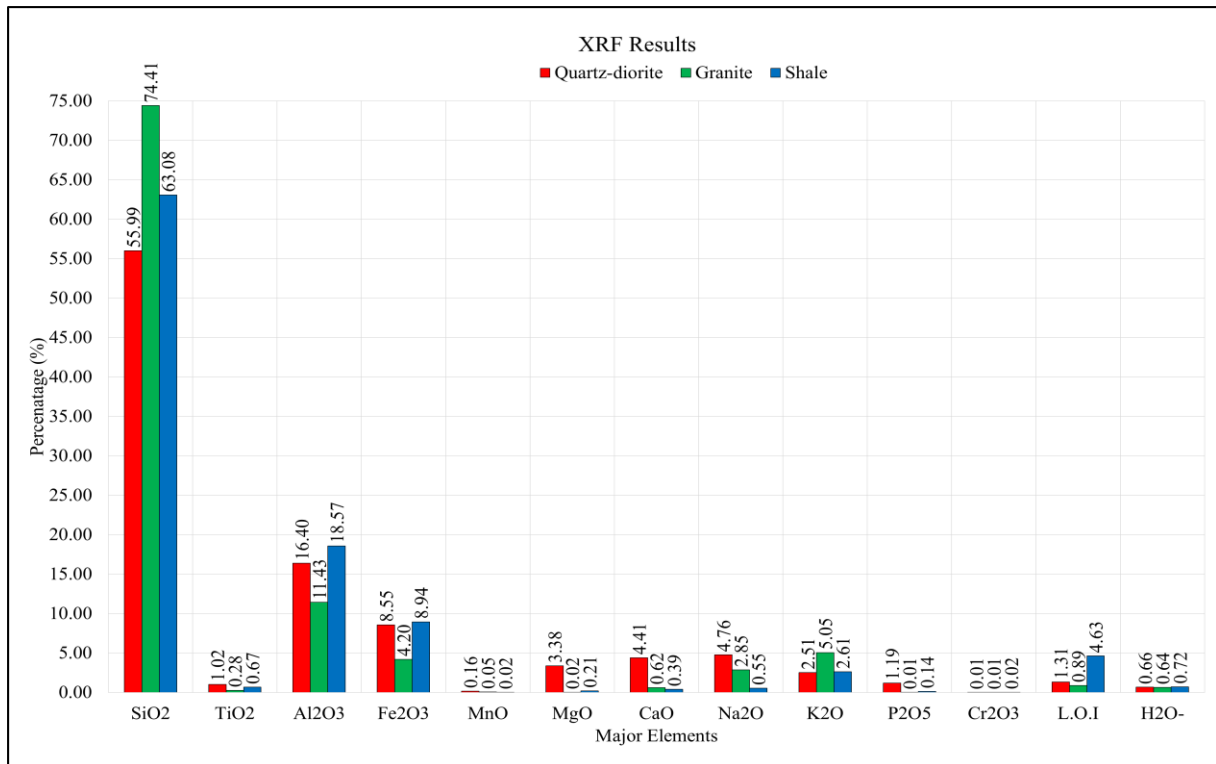


Figure 4-22: Major Element percentage in quartz-diorite, granite, and shale.

The relationship between the Al₂O₃ (%) and TiO₂ (%) is shown in Figure 4-23. This relationship is utilised to determine whether the sedimentary rock classifies as a mudstone or a sandstone, specifically focusing on the shale sample in this study. Elevated levels of Al₂O₃ and TiO₂ are indicative of mudstone, reflecting a higher concentration of clay minerals and fine-grained components. Conversely, lower concentrations of Al₂O₃ and TiO₂ suggest the sample is more likely a sandstone, characterized by a coarser grain size and a predominance of quartz over clay minerals. According to Figure 4-23, which considers the weight percentages of Al₂O₃ and TiO₂, shale plots outside the sandstone and mudstone regions, however due to the high Al₂O₃ content and fine-grained nature of the sample, this sample was considered as a mudstone with a high quartz content. This relationship confirms what is shown in Figure 4-21(b).

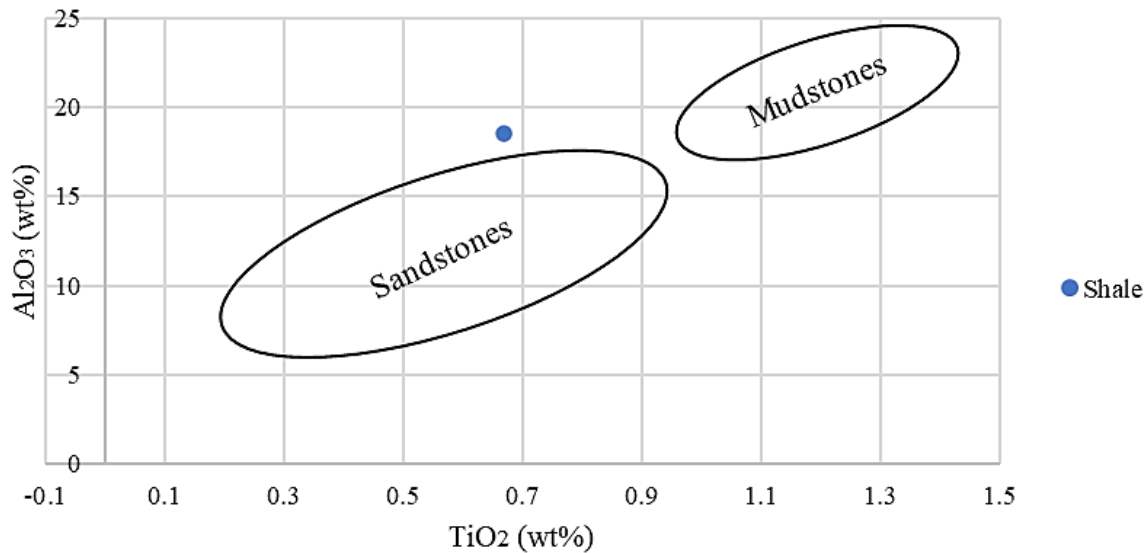


Figure 4-23: Al_2O_3 vs TiO_2 (Moore, 1992).

The correlation between K_2O and Al_2O_3 (Figure 4-24 (a)) serves as an indicator of the degree of weathering within the rock sample. Higher K_2O content typically reflects less weathering of feldspar minerals. In contrast, the ratio of $\text{Fe}_2\text{O}_3/\text{SiO}_2$ vs $\text{Al}_2\text{O}_3/\text{SiO}_2$ (Figure 4-24 (b)) provides insight into the mineralogical composition, particularly highlighting the relative abundance of iron oxides and silicate minerals. These ratios can reveal changes in mineralogical phases and geochemical processes affecting the rock (Miao et al., 2023).

In Figure 4-24(a), quartz-diorite and shale plots in the central region of the binary plot, thus reflecting moderate weathering. Shale, however, shows a higher Al_2O_3 content compared to that of quartz-diorite. Granite plots well within the feldspar region, indicating weak weathering. Granite is thus the least weathered based on the relationship between Al_2O_3 and K_2O . The results from this analysis coincide with the XRD results. Quartz-diorite contain relatively high proportions of biotite, clays (Al_2O_3) and iron-oxides (Fe_2O_3), thus coinciding with the XRD results, whereas granite contains a relatively high proportion of quartz (SiO_2) (Figure 4-24(b)), this was observed in the XRD results as well. The high quartz content of granite points to a high resistance to weathering and thus indicated high durability.

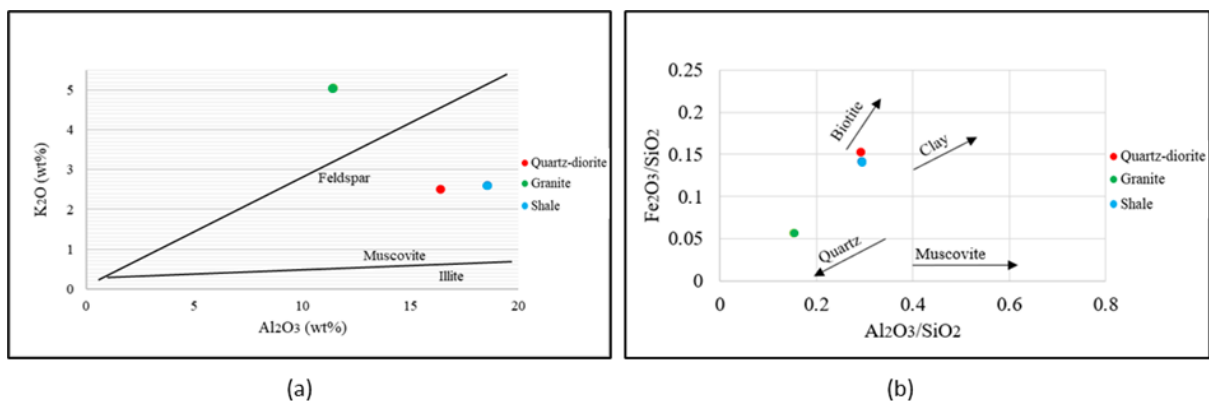


Figure 4-24: (a) K_2O vs Al_2O_3 for all samples (Alqahtani et al., 2021). (b) $\text{Fe}_2\text{O}_3/\text{SiO}_2$ vs $\text{Al}_2\text{O}_3/\text{SiO}_2$ for all samples (Alqahtani et al., 2021).

Figure 4-25 indicates the ternary diagram of Al_2O_3 -($\text{CaO}+\text{Na}_2\text{O}$)- K_2O , which was used to establish the degree of weathering for quartz-diorite, granite, and shale with the CIA shown on the vertical axis. Both quartz-diorite and granite fall within the weak weathering zone, however quartz-diorite places slightly higher within the tertiary diagram. Shale plots within strong weathering zone due to the high Al_2O_3 content.

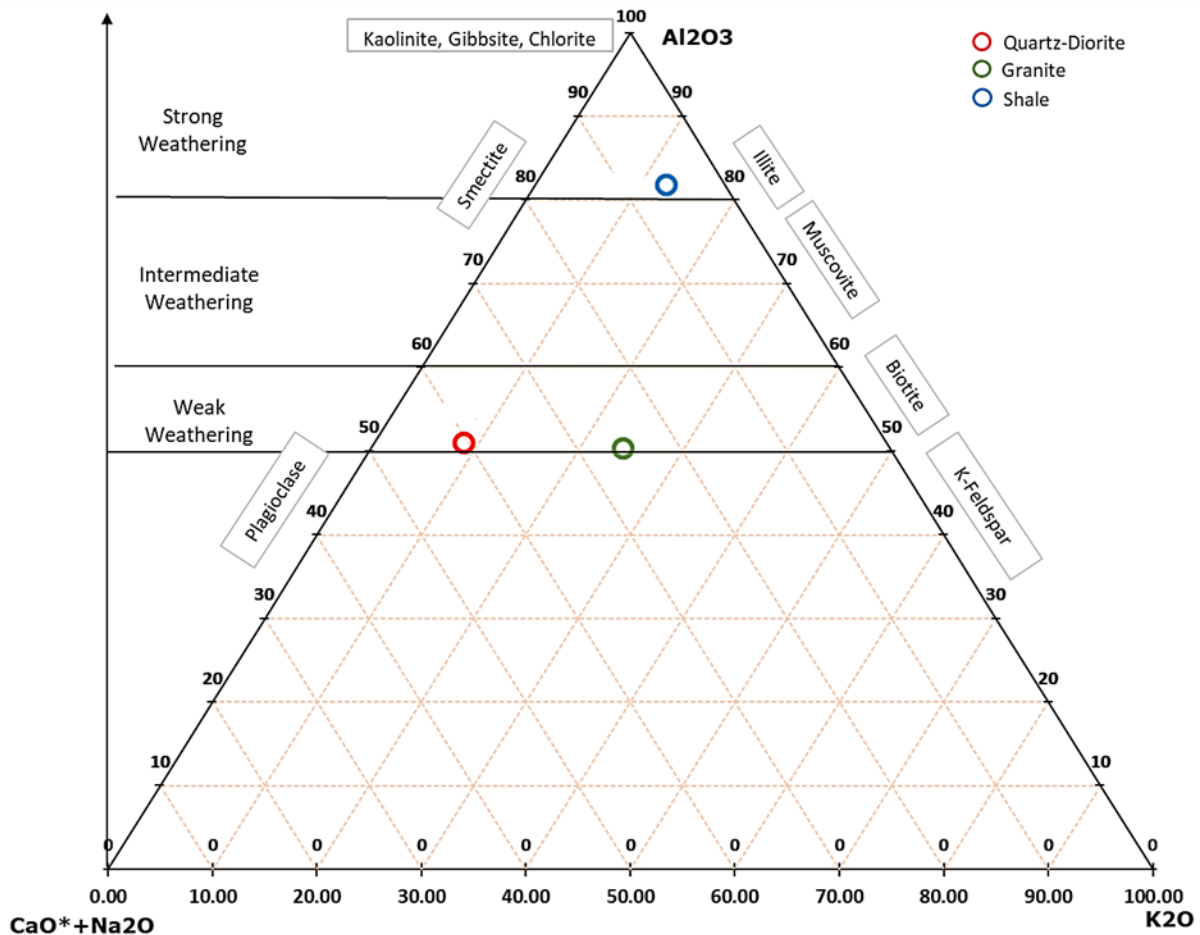


Figure 4-25: Ternary diagram of Al_2O_3 -($\text{CaO}+\text{Na}_2\text{O}$)- K_2O to obtain the degree of weathering for quartz-diorite, granite, and shale with the CIA shown on the vertical axis (Alqahtani et al., 2021).

The X-Ray Fluorescence results were used to establish the weathering indices for each sample. These weathering indices included the Chemical Index of Alteration (CIA), Mineralogical Index of alteration (MIA), Chemical Index of Weathering (CIW), and the Plagioclase Index of Alteration (PIA). The weathering indices are shown in Table 4-1.

The Chemical Index of Alteration (CIA) produces values between 50 and 100. Values between 50 and 60 indicate an early stage of weathering, which was observed for both quartz-diorite and granite. Shale, however, presented a high CIA of 81.93. The high CIA percentage within the shale indicates that the sample was composed of highly weathered raw material and shows the influence that grain size and sediment provenance have on the CIA (Krissek & Kyle, 2001). Due to this influence, the CIA value calculated for shale was not representative of its weathering degree but only a reflection of its fine-grained nature and sedimentary origin, which tends to amplify chemical weathering indicators.

The Mineralogical Index of alteration (MIA) produces values between 0 and 100. The values of 2.13 for quartz-diorite and 0.80 for granite showed a low degree of mineralogical weathering, thus indicating

a low transformation ratio between the primary minerals into their equivalent secondary minerals. The MIA values of 2.13 and 0.80 indicate that 2.13% and 0.80% of the Na₂O content was utilised during the creation of secondary minerals from albite, and the remaining percentages represents unaffected primary minerals. Shale showed a MIA of 63.85, indicates a significant amount of secondary minerals present within the sample (Voicu et al., 1997).

The Chemical Index of Weathering, also known as the CIW, produces high values (> 85) for rocks that are rich in K-feldspars (Orthoclase), regardless of the degree of weathering, which can be misleading (Fedo et al., 1995). This explains the intermediate CIW value of 66.40% for granite.

The Plagioclase Index of Alteration (PIA) excludes the influence of K-enrichment, which can occur during burial and diagenesis (Mangold et al., 2019). As a result, PIA values typically show little variation from Chemical Index of Alteration (CIA) values, except in cases where significant diagenetic alteration has occurred, such as in shales. Shales, being sedimentary rocks formed through burial and diagenesis, are particularly susceptible to K-enrichment, which can lower CIA values relative to PIA.

Table 4-1: Calculated CIA, PIA, CIW, MIA percentages for all samples.

Parameter	Quartz-diorite	Granite	Shale
CIA (%)	51.06	50.40	81.92
PIA (%)	51.28	50.77	92.53
CIW (%)	55.78	66.40	93.59
MIA (%)	2.13	0.80	63.85

4.6. Strength and Degree of Weathering on Rock Samples

The difference in strength between the weathered (material adjacent to joint/exposed surface) and the unweathered portion of the rock samples was assessed through the use of a Schmidt hammer test. The average R-values for each of the regions tested in each sample were calculated and compared. The Schmidt Hammer tests revealed that the R-value or hardness of the rock material was lower, closer to the weathered surface compared to that of the unweathered portion of the rock specimens.

When comparing the R-values from the fresh portion of the samples to the R-values from the rock material adjacent to the exposed surfaces a decrease in the R-values was observed for all the samples. Quartz-diorite showed the greatest difference between the fresh and adjacent R-values and shale showed the lowest difference. The outcome of this comparison points to shale being the least affected by propagating weathering regarding the hardness of the adjacent material.

The difference between the R-values for the fresh rock and the rock material adjacent to the joint is shown in Table 4-2, indicating the average R-values for the weathered and unweathered portions of the rock sample as well as the difference in the R-values. The average R-values were calculated from ten (10) Schmidt hammer tests performed within each portion of the samples. The test data for each sample can be found in the Appendices, in Section 8.1.1. The hardness of the unweathered portion of the rock is greater than that of the material adjacent to the joint surface for all rock samples. The relationship between the degree of weathering and the reduction in hardness due to the process of propagating weathering is shown in Table 4-2.

Table 4-2: Summary of Schmidt hammer results (R-values) for fresh intact rock and rock material adjacent to joint/exposed surface.

Rock Type	Quartz -diorite		Granite		Shale	
Weathering Degree	Unweathered	Weathered	Unweathered	Weathered	Unweathered	Weathered
R-Value	59.56	25.56	29.56	14.13	21.30	14.01
Hardness Decrease (Value)	34.00		15.44		7.29	
Hardness Reduction (%)	57.09		52.20		34.23	

In summary, the analysis presented in this chapter has provided a comprehensive overview of the mineralogical, chemical, physical, and engineering properties of the rock samples, highlighting the distinctions between weathered and unweathered regions. These findings serve as the foundation for a deeper understanding of how propagating weathering influences the properties of the material. This will be discussed in the following section.

5. Discussion

The following discussion will delve into the relationships between the mineralogical, chemical, physical, and engineering properties of the rock samples, with a particular focus on the hardness variations between weathered and unweathered areas. Additionally, the mineralogical and chemical compositions of each rock type will be examined to identify how the degree of weathering is reflected through the changes in mineral content, as indicated by the presence of certain minerals and the depletion of others. By exploring these trends and comparing the depth of weathering with the chemical composition, the discussion will clarify the specific effects of weathering on rock properties, and how the inherent properties of the rock prior to weathering have influenced the propagation of the weathering process itself.

5.1. Propagation of weathering from the joint surface to the rock material

The classification of a rock or rock mass forms an essential part in determining the safe and sound design of any engineering structure. The accuracy of the weathering classification is thus of the utmost importance to ensure long term stability for any structure. During this study, three rock samples were analysed to assess the propagation of weathering from the exposed surface (joints or other exposed surfaces) into the unexposed surface (intact rock material). The material adjacent to the joint was examined in detail to determine the effects of weathering propagation and create a weathering classification system specific to each rock type.

In this proposed weathering classification scheme, schematics are presented which indicate the exposed, transitional, and unexposed regions as observed in each rock sample (Figure 5-1). This classification scheme is adapted from Amin et al. (2000) and Barton et al. (1977); however, the proposed classification system includes concepts of visual observations, chemical (petrology) and mechanical properties of the rock samples. The boundary between the fresh and weathered material was established by determining the point at which discolouration of the sample had ceased completely.

The quartz-diorite showed a clear progression of weathering from the joint opening to the intact rock material. The zoning within the quartz-diorite sample is illustrated in Figure 5-1 (a). The light-yellow

colour represents the weathered joint surface, which was observed to possess yellowish-brown staining characterised by extensive fracturing, both on the surface and between the grains. Near the joint opening (exposed region), pronounced weathering effects along the actinolite and biotite grain boundaries measured to be 676 μm were observed. In contrast, the quartz grains, averaging 422.50 μm , showed minimal signs of alteration in this zone. However, in the transitional phase, discolouration and fracturing were less pronounced on the rock sample compared to the exposed region. The visible effects of weathering diminished gradually. While signs of alteration were apparent for both actinolite and biotite, the quartz remained unaffected during this phase. In the unexposed region, classified as fresh intact rock, the effects of weathering, such as discolouration, were less visible and there was an increase in grain size for biotite and actinolite, ranging from 931 μm to 2012 μm , with quartz averaging 547.67 μm . The average joint compressive strength reflected a notable disparity, as indicated by the rebound numbers that revealed a considerable decrease from the unexposed to exposed regions. The average joint compressive strength for the area-ranges tested are represented by the R-values. The weathered portion showed an average of less than half of the average R-value obtained for the fresh region. This indicates that the rock sample has been severely affected by the process of propagating and shows the negative impact on the strength (hardness) of the material, specifically a 57% decrease from the R-value of the unexposed region. This places the sample within an intermediate weathering phase.

Granite shows a gradual decrease in the degree of weathering intensity from the exposed joint surface into the intact rock material Figure 5-1 (b)). The rock material adjacent to the joint surface consists of loose particles. Additionally, the surface is stained with iron-oxides resulting in a rust-like appearance at and near the exposed surface. The feldspar grains show significant alteration in the form of discolouration and fracturing. In contrast, the quartz grains in the exposed surface showed high stability and minimal alteration with Fe-oxides present along the grain boundaries, which indicates progressive migration of Fe-bearing solutions along mineral interfaces. The transitioning zone within the granite was marked by the shift from yellowish-brown discoloured zones along the fractures to a region only showing discolouration and alteration near Fe-oxides. This gradual decrease in weathering degree created zones of varying levels of weathering, resulting in three discoloured zones with some overlapping between these zones. In the exposed intact rock material, the granite sample showed a reduction in pore size and quantity with increasing distance from the exposed surface. The average R-values for weathered zone, showed a hardness of less than half the strength of the fresh region of the sample, specifically 48% of the R-value obtained from the fresh (unexposed) region of the sample. This indicates a weakening in the rock material adjacent to the joint opening. The propagation of weathering thus caused a decrease in the strength (hardness) of the rock material adjacent to the joint and results in the sample being classified as intermediately weathered.

As weathering moves deeper into the intact rock material from the exposed surface, the shale sample displayed a clear zoning pattern (Figure 5-1 (c)). For the exposed region, the shale sample exhibited weathering concentrated along fracture walls. Dissolution pores were observed in this section of the sample, indicating the presence of water. The process of dissolution resulted in increased pore connectivity (Khan et al., 2022). The joint surface and adjacent material showed a loose and powdery appearance with the majority of this zone comprising of kaolinite and minor Fe-oxide staining. The properties of this zone indicated a highly weathered material. In the transition phase, shale displayed significant fracturing, especially near the exposed surface and along major fractures, which facilitated both physical and chemical weathering. The larger fractures showed substantial weathering, with iron-oxide minerals (limonite) forming along the fracture surfaces. The limonite, a product of weathering iron-bearing minerals, created a protective layer that inhibited further propagation of weathering from the specific fracture surfaces, acting as a barrier to additional chemical alteration. However, microfractures extended beyond this protective layer, allowing weathering to continue deeper into the

adjacent material. The combined effects of physical fracturing and chemical changes, particularly in Fe-sulphides, iron carbonates, and silicates, decreased the shale's overall durability, making it more susceptible to weathering over time. For the unexposed region there was a noticeable absence of pore spaces and a distinct darkening in colour. This suggests a lesser degree of weathering.

The observed zoning can be attributed to the inherently low permeability of the shale, which significantly slows the ingress of water and other reactive fluids. This limited permeability restricts the diffusion of weathering agents, causing the rock material near the joint surface to undergo more intense chemical and physical alteration. Due to the slow propagation of fluids and associated reactions into the interior, the material near the joint surface weathers more thoroughly before further progression takes place. This results in discrete weathering boundaries being created, with minimal transitional overlap between the zones. This suggests that the low permeability of the shale not only controls the rate of weathering but also contributes to the development of well-defined alteration boundaries. These distinct weathering zones reflect varying degrees of rock alteration, strongly influenced by the slow rate of propagation through the low-permeability material. The average R-value for the weathered region of the sample was approximately 66% of the average R-value obtained for the fresh region, indicating that the propagation of weathering had minimal impact on the strength of the material adjacent to the joint opening, and thus leading to the sample classifying as slightly to intermediately weathered. The shale sample exhibited the smallest difference, in terms of strength, between the fresh and weathered material near the joint, which can be attributed to its high quartz content and low permeability.

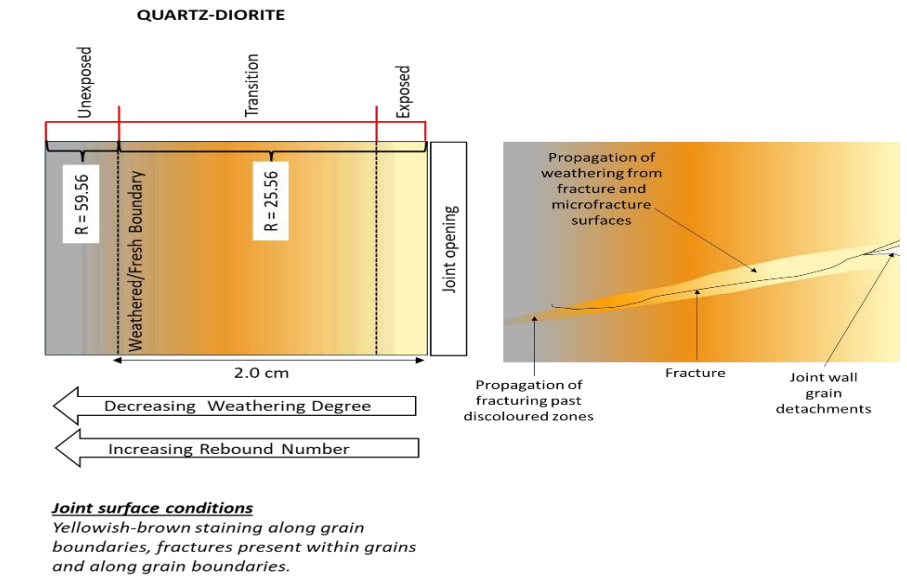
In all the rock samples it was observed that fractures protruded into the fresh zone without exhibiting visible signs of chemical weathering, which can obscure the boundary between fresh and weathered material. The fractures create pathways for future chemical weathering, potentially leading to the underestimating of the weathering degree for the material. In the shale sample, some fractures contained a black-coloured coating or infilling, which acted as a protective layer, thus limiting the propagation of weathering from the fracture surfaces and reducing both discolouration and depth of alteration. Fracturing can speed up the process of propagating weathering by serving as pathways that allow weathering processes to progress more rapidly. This results in a greater degree of weathering, less distinct zoning, and greater penetration of weathering process. The latter indicates that fractures play a major role in the propagation of weathering from the exposed surface and further into the intact rock material. Fractures are formed at both the macro and micro scales (Hencher, 2004). Thus, not all fractures are visible to the naked eye.

The classification system can be summarised as follows:

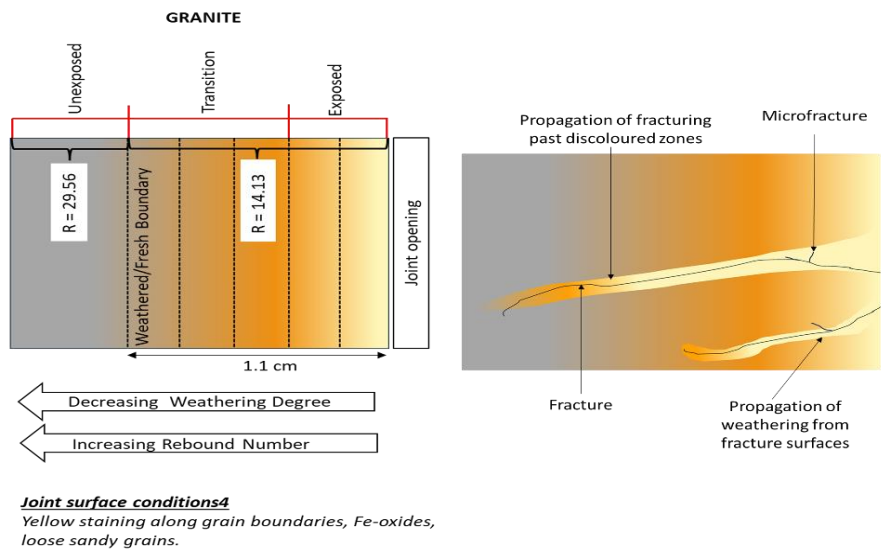
- Exposed region/ joint surface: the rock samples exhibited distinct characteristics within the exposed regions. These characteristics include weathering initiated by fractures originating at the exposed surfaces, which acts as pathways for further propagation of weathering. Fracturing is prominent at the exposed surface and extends deeper into the material adjacent to the exposed surface. Both micro-and macro-fractures were observed. A decrease in grain sizes was observed throughout all samples compared to the grain sizes within the unexposed regions. Large pore spaces were observed at and near the exposed surfaces, which facilitated the infiltration of water, thus leading to the propagation of weathering processes. Finally, discolouration was present along fractures and in between grain boundaries. The minerals near the exposed surfaces showed more pronounced signs of alteration.
- Transition zone: The transitioning zones within each sample indicated that the fracturing (macro and micro) served as the primary conduits for weathering propagation. The fracturing extended beyond the visible zones of discolouration, which leads to further weathering into the

unexposed regions of the samples. Fracturing thus dictates the movement of propagating weathering within the rocks.

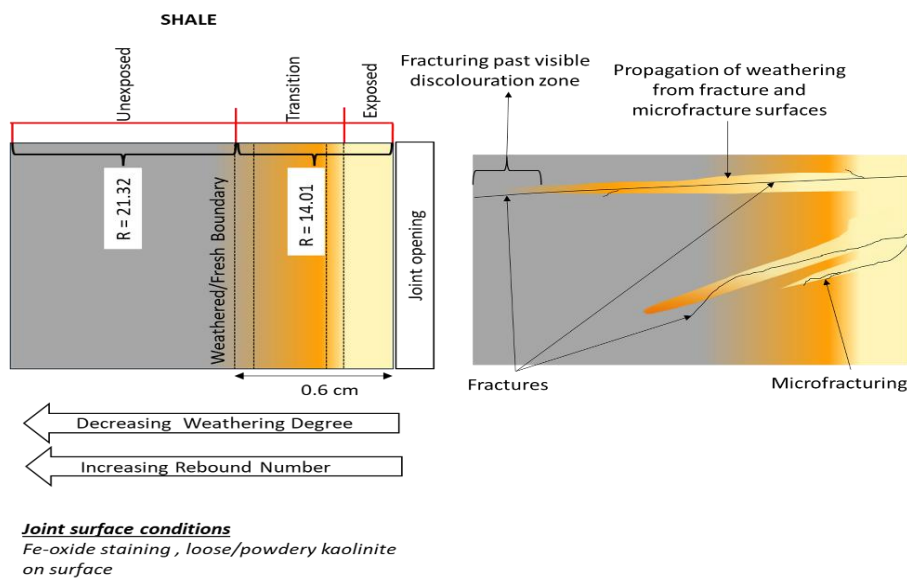
- Unexposed regions / intact rock material: The unexposed or fresh regions of the rock samples showed minimal signs of weathering. Alteration in this region focussed in and around minerals that are more susceptible to weathering. All samples exhibited a decrease in the number of pore spaces and fracturing with increasing distance from the exposed sections, thus indicating that the weathering degree is greater, closer to the surface of the joint.
- Fracturing: Fracturing was observed to originate at the surface of the joints, driven by grain detachment and/or dissolution. This process gradually widens the joint openings. As weathering propagates from these fracture surfaces, weathering degrees and discolouration zones overlap, with the material further from the main joint opening, which often results in a higher degree of weathering. This suggests that fracturing accelerates the rate of weathering propagation.



(a)



(b)



(c)

Figure 5-1: Joint weathering classification scheme for rock samples.

5.2. Physical and engineering properties of a rock as indicators of the degree of chemical alteration

The classification of the samples (in Section 5.1) was largely based on the percentage decrease in the strength (hardness) of the unexposed material of the samples as well as the depth of visible discolouration and fracturing. Assuming that the absence of visible discolouration in the material adjacent to a joint corresponds to negligible hardness reduction, a direct relationship can be established between the depth of discoloration and the percentage decrease in hardness for each rock sample (Figure 5-2). Thus, the greater the depth of propagating weathering, the higher the weathering degree will be. This phenomenon is confirmed when comparing the CIA (%) with the depth of discolouration, specifically in that of the igneous rock samples, when assuming that an unweathered sample will show no sign of discolouration (Figure 5-3). A linear relationship was also observed between the reduction in hardness of the material adjacent to a joint and the CIA (%), for the igneous rock samples (Figure 5-4), thus further establishing the relationship between chemical, physical and engineering properties of a rock and how the propagation of weathering impacts these properties.

Figure 5-2 indicates the rate (slope) at which the hardness of the material adjacent to joints decreases relative to the depth of discolouration. When comparing the gradients of the igneous rock samples (quartz-diorite and granite) it was revealed that quartz-diorite experiences a slower rate of strength (hardness) reduction compared to granite in terms of depth of propagation of weathering. Thus, in the case that a granite and a quartz-diorite rock experiences the same depth of discolouration within the material adjacent to the joint, for example, 1cm, the adjacent material in the granite would show a 47.5% decrease in strength, whereas the adjacent material in a quartz-diorite would show a decrease in strength of approximately 26%.

An Assumption made by Amin et al. (2000) is that the propagation of weathering takes place at the same rate on both sides of the joint. Thus, creating a similar zoning pattern on both sides. This may differ due to the presence of fracturing and microfracturing, as well as the water content present within the joint walls. It is thus not a guarantee that both joint walls will be affected by propagating weathering to the same degree. The side wall affected to a greater degree (greater depth of discolouration and lower rebound numbers), will thus govern the weathering degree classification for the material at and near the joint opening.

Each rock type reacted differently to the process of propagating weathering. The igneous rock samples showed a more gradual change in physical and chemical properties from the exposed surface towards the unexposed surface within the material adjacent to the joint. Whereas the sedimentary rock sample (shale) showed a more abrupt reaction to the propagating of weathering from the exposed surfaces and into the material adjacent to the joint. The textural changes observed can be attributed to an increase in porosity and permeability from the unexposed to the exposed regions of the sample. These changes lead to decreased density of the rock material (Hencher, 2004). The density, which is directly proportional to the porosity of the material, plays an important role in the strength of the material. This was seen in the decreased rebound number results when comparing the results from the unexposed regions to that of the exposed regions in each sample as an indirect relationship exists between the apparent porosity of the material and the uniaxial compressive strength (Gu et al., 2020). The higher porosity developed due to propagating weathering, leads to greater weatherability, thus resulting in lowered durability of the rock (Bell, 2014, and Mulenga, 2015). Additionally, the texture of the rock samples exerted significant control over its resistance to weathering effects in that the fine-grained sedimentary rock showed less propagation of weathering compared to that of the igneous rock samples. Momeni et al. (2017) asserts that the durability of a rock is also largely influenced by its mineralogical composition.

Consequently, rock samples with the higher quartz content indicated a greater degree of durability. In contrast, the rock samples with a higher percentage of high-reactivity (unstable) minerals showed a greater degree of weathering penetration, these samples were the igneous rock samples. The sedimentary rock sample, shale, which contained a large percentage of low-reactivity (stable) minerals showed less weathering penetration compared to the igneous rock samples. This observation aligns with that of Israeli et al., (2018) in which a non-linear relationship was identified between the amount of stable and unstable minerals present within a rock and the rate at which weathering takes place.

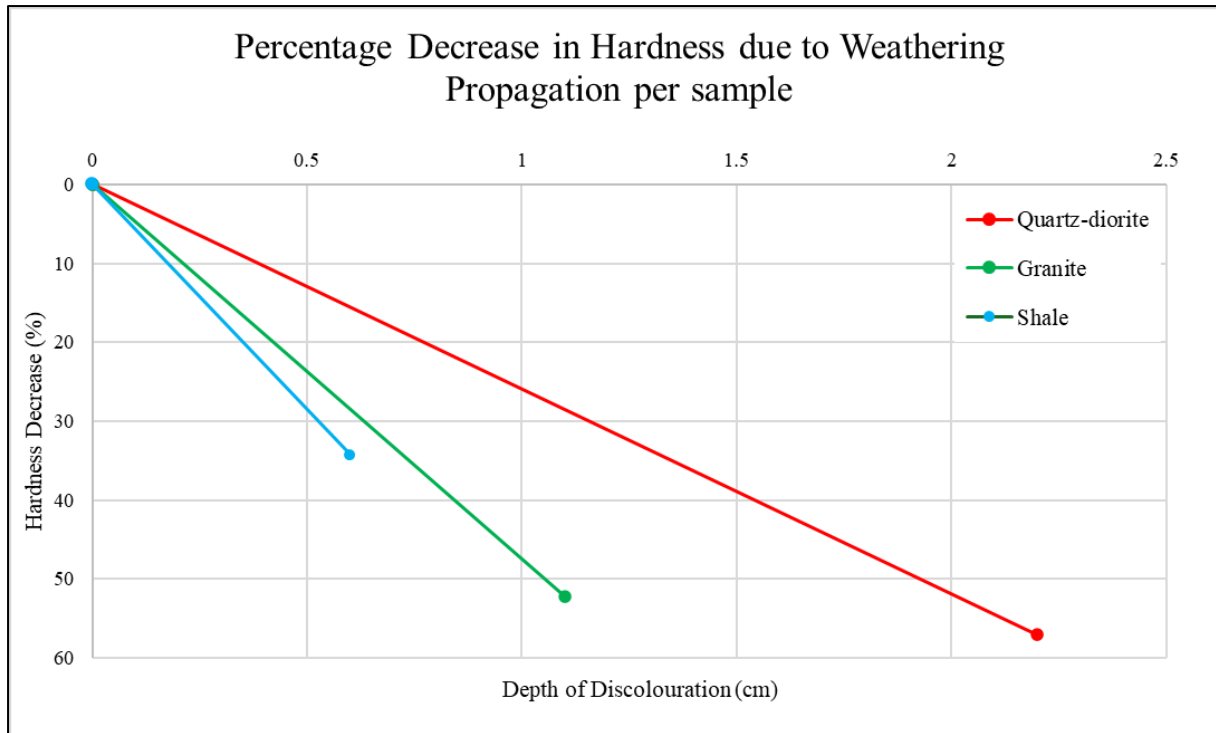


Figure 5-2: Relationship between percentage hardness decrease and depth of discolouration.

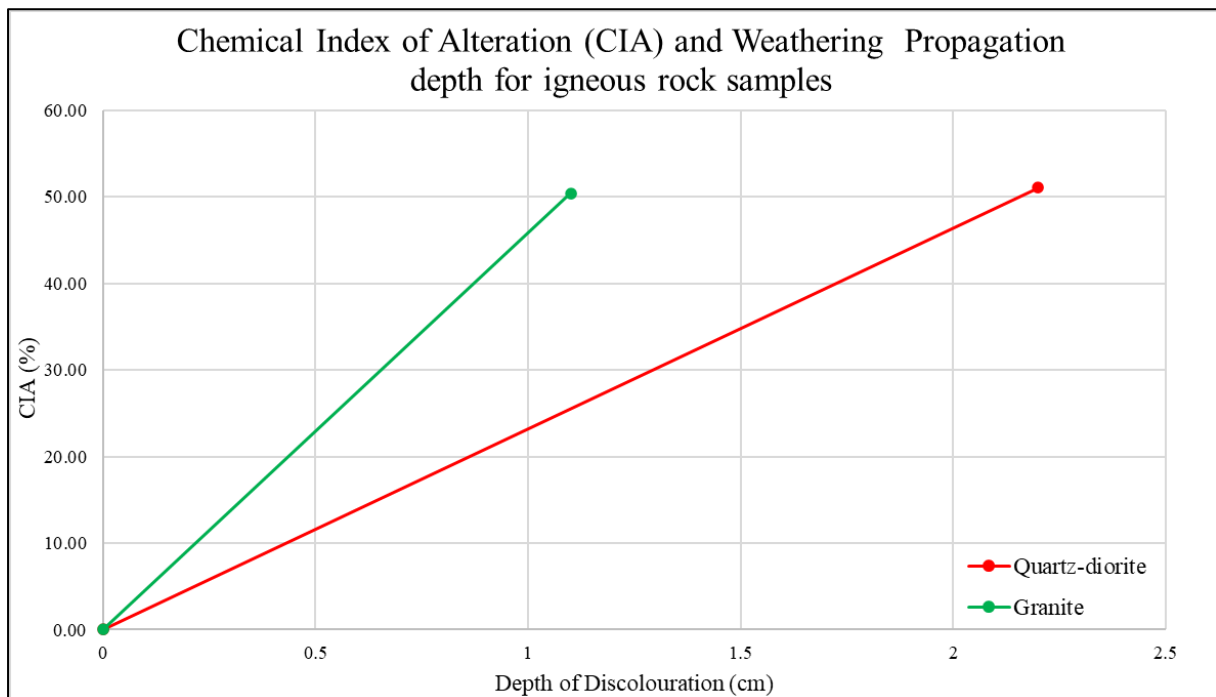


Figure 5-3: Relationship between CIA % and the depth of discolouration.

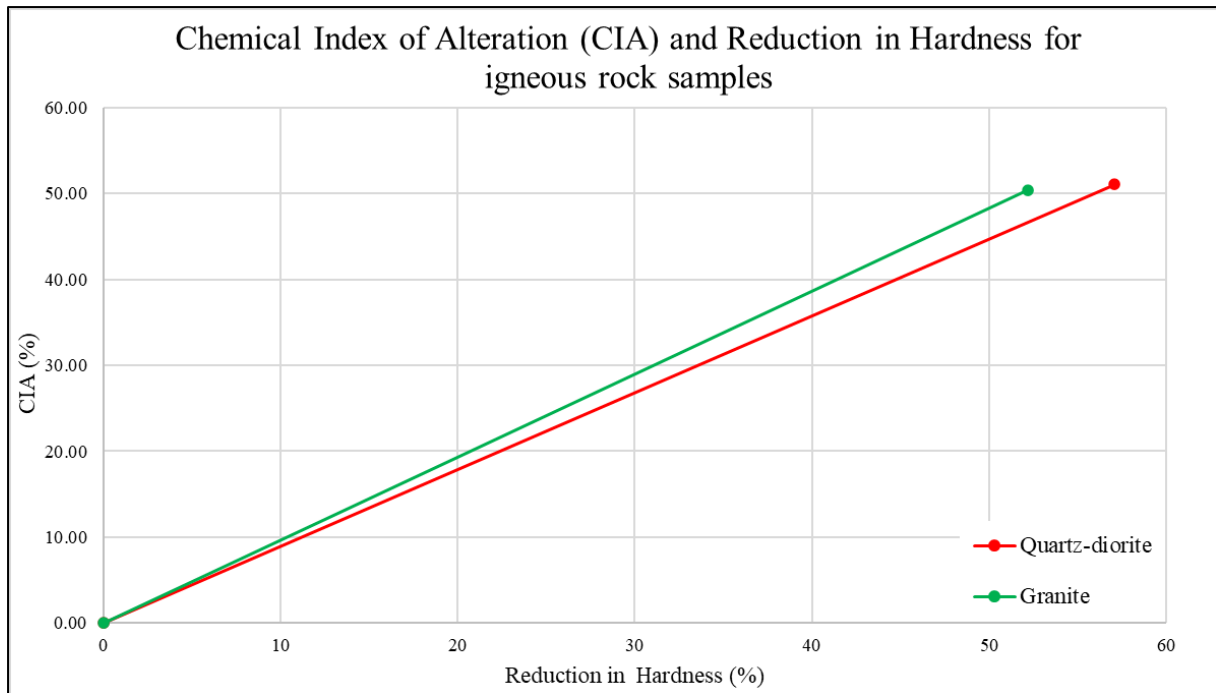


Figure 5-4: Relationship between the degree of weathering (CIA %) and the reduced hardness within the material adjacent to the joint surface.

5.3. Mineralogy and weathering indices of rock samples

This analysis highlights the varying degrees of weathering experienced by each rock type. Special attention is given to how the chemical composition and the weathering degree are related. The influence of the chemical composition on the propagation of weathering is also established during this section. The XRD and XRF results are analysed and compared to the effects of propagating weathering on the samples.

X-ray diffraction (XRD) analyses were conducted on the three rock samples (shale, granite and quartz-diorite). The XRD results showed the mineralogical compositions of each rock type. The main mineral responsible for the resistance to weathering is quartz (Momeni et al., 2017). In this study, shale exhibited the highest quartz content at 52.8%, followed by granite with 32.8% and finally, quartz-diorite at 10.1%. The low quartz content in quartz-diorite indicated a lower resistance to weathering compared to granite. The high quartz content in the shale indicated a high resistance to weathering, specifically chemical weathering. The fine-grained nature of the shale remains a primary driver for high weatherability (Israeli, 2018). Quartz-diorite contained actinolite, which is an amphibole silicate mineral that is highly susceptible to weathering, often transforming into secondary clay minerals or goethite. Additionally, the presence of biotite in quartz-diorite, a mineral with high susceptibility to weathering (Grotzinger et al., 2014), further weakens the rock as it transforms into goethite during the weathering process (Laukamp et al., 2013). These minerals contribute to the chemical instability of quartz-diorite, making it more prone to accelerated weathering compared to rocks with more stable mineral compositions. The quartz-diorite also had the highest plagioclase content, followed by granite. During the process of chemical weathering, plagioclase transforms into kaolinite (Laukamp et al., 2013), which is chemically more stable compared to that of plagioclase but lacks the hardness of its primary mineral (plagioclase), thus future weathering and further physical weakening of the quartz-diorite sample is certain. The shale contained the non-swelling clay minerals, known as kaolinite, which is a chemically stable mineral, thus indicating that further chemical breakdown of this mineral is unlikely to occur in the short term.

(Grotzinger et al., 2014). The presence of kaolinite on or near the exposed surfaces of the shale samples suggests that it was formed through the process of propagating weathering.

Muscovite was present in both granite and shale, with shale containing the higher amount. The resistance of muscovite to weathering contributes to the chemical stability of these rocks, making them less prone to chemical breakdown. The high muscovite content in shale indicated greater chemical stability, suggesting a lower likelihood of significant future weathering of the rock material over time (Grotzinger et al., 2014).

The XRD and XRF analyses exhibit a strong correlation in terms of mineralogical and chemical compositions. For instance, while the quantitative percentages differ, both techniques consistently indicate that granite samples contain higher amounts of quartz and SiO₂ compared to quartz-diorite samples. The XRF analysis also revealed the presence of biotite in the quartz-diorite samples, which is consistent with the XRD results. This consistency underscores the complementary nature of XRD and XRF in providing a well-rounded understanding of sample composition. Furthermore, petrographic examination through thin-section analysis corroborates these findings, as the observed mineral assemblages align with the results obtained from both XRD and XRF analyses. This multi-faceted approach enhances the reliability of the compositional interpretations. The minerals identified during the XRD analysis were also identified in the thin sections of each sample, however, no iron-oxides were mentioned during the XRD analysis for the igneous rock samples (quartz-diorite and granite), and amphibole grains were identified in the granite thin section, which was not picked up by the XRD analysis. This phenomenon can be attributed to sample size, preferential orientation of the thin section, and the low concentrations of these minerals within the samples, making the minerals difficult to identify during the XRD analysis (Fewster, 2023; Holder et al., 2019).

The weathering indices determined during this study included the CIA, MIA, PIA, and CIW. All weathering indices showed similar results, thus only a single weathering index was used as a comparative parameter to provide insight into the relationship between the weathering grade of a material and other physical and chemical characteristic. The chemical index of alteration (CIA) quantifies the extent of chemical weathering in rocks. In addition to this, Goldberg (2010) indicated that the degree of chemical weathering is directly proportional to the chemical index of alteration (CIA), with higher percentages indicating a higher degree of weathering. Moreover, the most prominent influence of propagating weathering on the rock samples was discolouration, originating at the exposed surface, with the degree of discolouration becoming less intense as the distance from the exposed surface increased, indicating a decrease in weathering processes and the effects thereof (Mulenga 2015; Yildiz et al. 2009; Hencher 2004). Therefore, the depth of discolouration was measured for each sample and compared to the chemical index of alteration (Table 5-1).

Based on the chemical index of alteration results (Table 5-1), shale had the highest CIA percentage. This phenomenon can be attributed to the fine-grained nature of the sedimentary rock and is thus not representative of the degree of weathering for the sample. The high CIA for the shale does not indicate a high degree of chemical weathering within the sample, only that the sample consists of a high proportion of weathered products derived from igneous, metamorphic, or other sedimentary rocks (Krissek & Kyle, 2001). This observation aligns with the notion that sedimentary rocks typically consist of minerals that experienced considerable chemical alterations (i.e. chemically stable minerals), as a result, shale demonstrates a higher chemical stability compared to the igneous rocks (Bell, 1992). Shale also showed a shallower extent of weathering propagation from the exposed (joint surface) into the unexposed (rock material) surface. The quartz-diorite and granite showed a deeper propagation from the exposed into the unexposed region of the rock. This, together with the lower degree of chemical

alteration observed in the igneous rock samples, render these samples susceptible to further propagation of weathering in the future, which is a concern since this indicates further weakening of the material over time.

Table 5-1: Weathering degree based on chemical index of alteration values.

Parameter	Quartz-diorite	Granite	Shale
Chemical index of alteration (%)	51.06	50.40	81.92
Weathering Degree (see Figure 4-25)	Low degree	Low degree	High degree
Depth of weathering propagation	2.00	1.10	0.60

Furthermore, oxides (SiO_2 , Al_2O_3 , Fe_2O_3 , and H_2O -), determined from the X-ray fluorescence results, indicate the weathering and chemical stability of a rock (Grotzinger et al., 2014; Bell, 1992). The L.O.I. percentage is indicative of the volatile substances (H_2O - and H_2O +, organic material, and carbonates) present within the samples (Ündül and Tuğrul, 2011). Thus, these weight percentages were analysed alongside the CIA (%) values, the depth of weathering propagation, and the percentage decrease in hardness for each sample. Figure 5-5 illustrates the chemical variation between each sample in terms of oxides present, and L.O.I, and indicates how weathering has affected the different samples in terms of weathering degree (CIA), depth of propagating weathering (discolouration), and decreased hardness, which is directly related to the decrease in compressive strength caused by propagating weathering (Katuwal, 2019, Ismail et al., 2019). Granite, with the highest SiO_2 content (74.41%), suggesting a high quantity of silica-rich minerals (e.g. quartz) present, which correlates with durability and resistance to degradation, had the lowest CIA percentage (50.40%), as well as the lowest L.O.I percentage (0.89%). In contrast, quartz-diorite, which contained the lowest amount of SiO_2 had the higher CIA percentage (51.06%) between the igneous rock samples and showed a higher L.O.I percentage (1.31%). An inverse relationship was thus observed between the amount of Silica and both the L.O.I and degree of weathering (CIA) for the igneous samples. The amount of H_2O -, which forms part of the L.O.I percentage, increased with L.O.I and thus also shows elevated percentages for greater chemically weathered samples. Since shale is a sedimentary rock, a comparison between all rock samples was not possible, however, a similar trend can be seen for the shale sample as well, during which the L.O.I increased with the CIA%.

Comparing the depth of propagation between the igneous rock samples, indicated that the combination of a greater percentage of SiO_2 and a lower percentage of L.O.I, such as was the case for the granite, resulted in less propagation of weathering. The percentage decreased hardness comparison between the igneous rocks yielded that granite had a lower percentage decrease in strength (hardness), caused by the propagation of weathering, compared to that of the quartz-diorite sample. Thus, indicating that granite, which contained a higher proportion of SiO_2 and a lower percentage of L.O.I, possessed a lower degree of weathering, and had been less affected by the process of propagating weathering. This aligns with findings by Momeni et al. (2017), who observed that higher quartz content (silica-rich mineral) generally correlates with lower degradability, contributing to the rock's long-term durability.

The Al_2O_3 and Fe_2O_3 represent clay and other secondary minerals present with a rock and are thus correlated with weathering processes taking place within the rock (Irmak et al., 2007). Shale, which contained the highest levels of Al_2O_3 (18.57%) and Fe_2O_3 (8.94%), showed the greatest CIA percentage between all the tested samples, whereas granite contained the least amount of Al_2O_3 (11.43%) and Fe_2O_3 (4.20%), and showed the lowest CIA percentage. When comparing the igneous rock samples, a similar trend was established between the weight percentages of Al_2O_3 and Fe_2O_3 present within the rock and the CIA percentage. Thus, a greater percentage of clay and other secondary minerals, such as iron-

oxides, indicated a greater degree of chemical weathering (CIA) in igneous rock samples, however, since the shale sample is naturally composed of weathered materials, its baseline composition already reflects a higher degree of alteration. Therefore, the Chemical Index of Alteration (CIA) may not effectively distinguish the extent of weathering in shale samples compared to igneous rocks. The relationship between the CIA% and the weight percentages of Al_2O_3 and Fe_2O_3 , still remain the same throughout all rock samples tested.

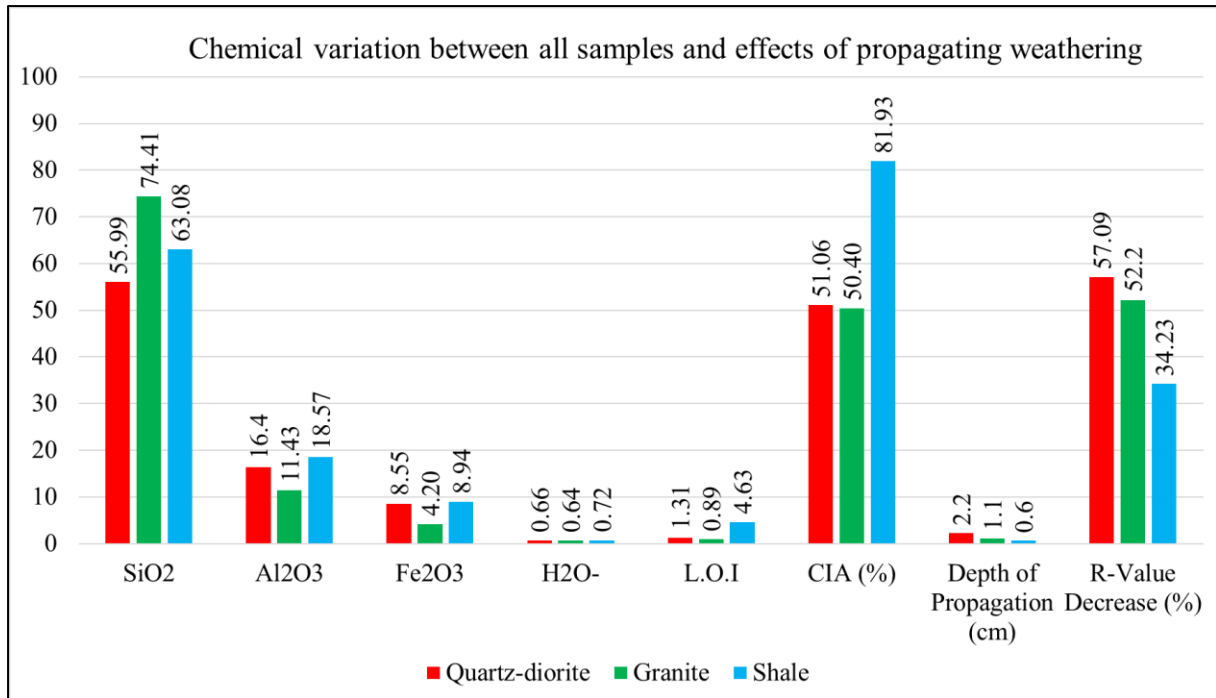


Figure 5-5: Weight percentages of SiO_2 , Al_2O_3 , Fe_2O_3 , H_2O , and compared to CIA, depth of weathering propagation, and the percentage decrease in hardness for each rock sample.

Analysing the XRF results from a purely chemical perspective, thus not rock type specific, a relationship between the degree of weathering (represented by the CIA) and the L.O.I of each sample is presented in Figure 5-6. The graph shows an exponential relationship between L.O.I. and the Chemical Index of Alteration (CIA), with the assumption that L.O.I. will rarely reach a value of 0.00%. With the knowledge that L.O.I. is partially indicative of the free water present within a sample, it can be assumed that the water content also increases as the weathering degree (CIA%) increases (Fakunle, 2016).

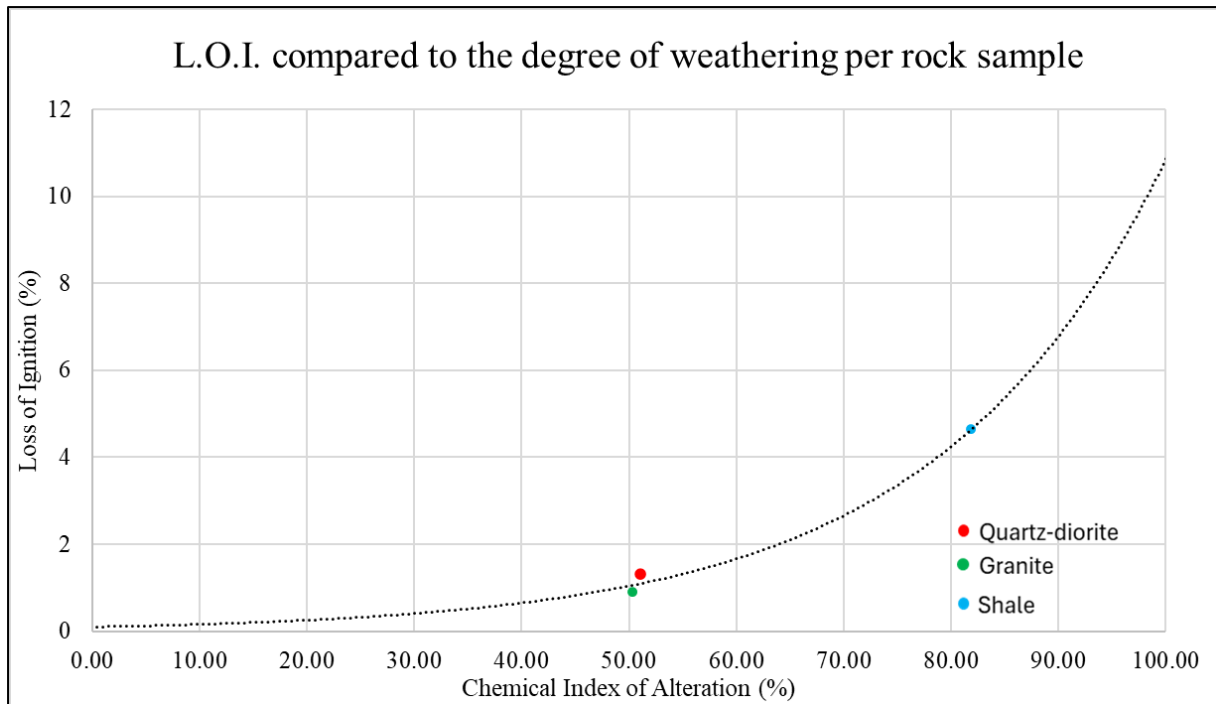


Figure 5-6: Exponential Relationship between the L.O.I and Chemical Index of Alteration.

In summary, quartz-diorite and granite indicated similar trends with regards to chemical composition, degree of weathering (CIA), depth of propagation (discolouration), decreased hardness, and loss of ignition (L.O.I.). A high percentage of chemically stable silica-rich minerals, combined with a low percentage of clay, and/or iron-oxides, and minimal L.O.I., were indicative of rock samples that have undergone a low degree of chemical weathering as well as limited propagation of weathering into the intact rock, and little difference in hardness between the exposed and unexposed regions of the sample. The shale sample displayed similar results in terms of the CIA, however the depth of propagation into the intact rock was less than that of the igneous rock samples. This phenomenon can be attributed to textural differences between the samples. This analysis also indicated an exponential relationship between the L.O.I. and the degree of chemical weathering. The key features from the comparison between the igneous rock samples (granite and quartz-diorite) was that a higher percentage of chemically stable minerals, and a lower percentage of volatile substances, such as free water, are indicative of a material not greatly affected by the process of weathering. This nuanced understanding of each rock type's durability under weathering can inform stability assessments and support decisions in engineering and construction.

5.4. Comparison of Current Weathering Classification Schemes and a Proposed Weathering Classification Procedure

The preliminary degree of weathering was determined for each sample through the use of a number of different weathering classification schemes (Table 5-2). Comparing different weathering classification schemes for the same rock sample is valuable because it offers multiple benefits. First, cross-validation between schemes enhances the reliability of the results by confirming consistency or identifying discrepancies, since different authors describe weathering differently. It also provides a more holistic understanding, as each scheme highlights different aspects of weathering, such as chemical, mineralogical, or physical changes. Additionally, it improves the accuracy of interpretations, as some schemes are better suited to specific conditions. Finally, this comparison helps make more reliable predictions about the long-term stability of the rock in geotechnical applications. By cross-referencing these results, geotechnical engineers can better predict how weathering will progress over time, helping

1701 to anticipate potential changes in strength, permeability, or structure. This analysis aids in developing
1702 more accurate models for the behaviour of rocks under future weathering scenarios.

1703 The results of this analysis indicated that granite displayed a greater overall degree of weathering.
1704 However, when comparing this finding with the XRF and XRD analyses, a slight discrepancy emerged.
1705 Quartz-diorite exhibited the most pronounced effects of propagating weathering, particularly in its
1706 mineral composition and chemical alterations. This suggests that while granite may show more
1707 extensive surface-level weathering, the quartz-diorite sample has undergone deeper, more structurally
1708 significant weathering processes, making it the most affected in terms of overall rock stability and
1709 composition.

1710 Table 5-2: Weathering degree of rock samples according to different classification schemes for each rock sample.

Weathering Degree Classification							
Rock Mass Classification Scheme	Description	Quartz-diorite		Granite		Shale	
		Classifier	Grade	Classifier	Grade	Classifier	Grade
Fakunle (2016)	Slight discolouration, slight weakening to Considerably weakened, penetrative discolouration. Large pieces cannot be broken by hand (Slightly). Considerably weakened, penetrative discolouration. Large pieces cannot be broken by hand. (Moderately)	Slightly to Moderately Weathered	II to III	Moderately Weathered	III	Slightly to Moderately Weathered	II to III
Bell (2014)	Fractures are stained or discoloured and may contain a thin filling of altered material. Discolouration may extend into the rock from the fracture planes to a distance of up to 20% of the fracture spacing (i.e., less than 40% of the core is discoloured).	Slightly Weathered	-	Slightly Weathered	-	Slightly Weathered	-
Price (1993) and Martin, et al. (1986)	Problems of Excavation stability: Limited impact of weathering on the engineering properties of the rock mass must be considered in the design, due to weathering resulting in reduced shear strength of discontinuities.	Significantly Weathered	Class B	Significantly Weathered	Class B	Significantly Weathered	Class B
Amin et al. (2000)	Zone I: Slightly weathered with highly discoloured joint surfaces and in material closer to the joint (Stage 2). Between Zone I and approaching Zone II, with moderately and highly decomposed/disintegrated friable material in the joint aperture (Stage 3).	Stage 2 to 3	Block: I Joint: III OR Block: I-II Joint: III	Stage 2	Block: I Joint: III	Stage 2	Block: I Joint: III
Barton, et al. (1977)	A slow reduction in the JCS in the case that the joints are water-conducting. The JCS, thus becomes less than the UCS of the little to unweathered intact rock (Stage 2). The intermediate stage, in which the joints are considered weathered, and water-conducting. The rock blocks are defined as impermeable. The JCS at this stage is only a fraction of the UCS of the intact rock material (Stage 3).	Stage 2	-	Stage 2 To Stage 3	-	Stage 2	-

1711

Understanding the degree of weathering in rock masses is essential for accurate geotechnical assessments and the design of stable engineering structures. This section introduces a comprehensive weathering classification procedure that integrates various analytical methods to evaluate key properties such as strength, porosity, permeability, depth of discolouration, mineralogy, and degree of fracturing. Engineering properties like permeability, strength, and durability significantly influence the rate of weathering, which in turn affects the engineering behaviour of rock masses. The proposed methodology systematically covers field data collection and detailed laboratory analyses to provide a robust framework for classifying weathering degrees and predicting the engineering behaviour of rock masses. By addressing the interconnected influence of chemical, physical, and mechanical properties on weathering processes, this procedure ensures a thorough and precise assessment of rock stability.

Therefore, the proposed weathering classification procedure (Figure 5-7) is based on the findings from this study and summarises the proposed steps to accurately classify the weathering degree of the material adjacent to a joint as follows:

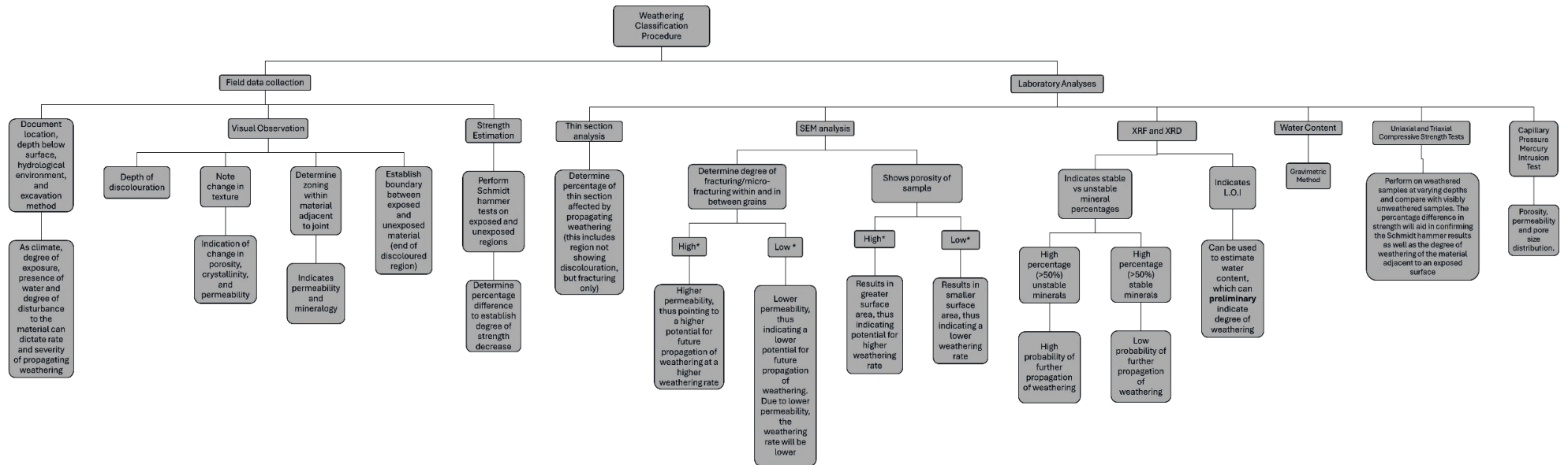
1. Field Data Collection

- Record the location, depth, hydrological setting, and excavation method.
- Conduct **visual observations** by assessing discoloration, texture changes, permeability indicators, and defining the boundary between weathered and unweathered material.
- Estimate **strength** using Schmidt hammer tests and calculate the percentage decrease to assess weathering impact.

2. Laboratory Analyses

- **Thin Section Analysis:** Identify micro-fractures and determine the percentage of the section affected by weathering.
- **SEM Analysis:** Examine porosity and micro-fracturing to infer permeability and potential weathering rates.
- **XRF and XRD:** Determine stable vs. unstable mineral percentages, indicating susceptibility to further weathering.
- **Water Content Analysis:** Use the gravimetric method to estimate water retention and infer the degree of weathering.
- **Strength Testing:** Perform uniaxial and triaxial compressive strength tests to confirm field observations.
- **Capillary Pressure Mercury Intrusion Test:** Assess porosity, permeability, and pore size distribution. An important note regarding the differentiation between primary porosity, secondary porosity, and fracturing is that a reference point will be put in place to determine the primary porosity of the sample (fresh or unweathered samples). This reference point will serve as the pristine condition in which the propagation of weathering has not affected the porosity. Weathered samples will then be tested to establish the degree of change (secondary porosity and fracturing) caused by the process of weathering.
- **Interpret Results**
- Compare findings across methods to classify the weathering degree accurately.

- 1751 ○ Use results to predict further weathering potential and its implications for engineering or
1752 geological assessments.



1753 Figure 5-7: Proposed weathering classification procedure.

1754 *Degree of fracturing and/or porosity must be compared to a pristine rock sample representing the unweathered specimen. A reference sample must thus be put
 1755 in place in order to compare samples. Generally, an unweathered igneous rock sample, like granite, will show a porosity and/or fracturing percentage of <1%,
 1756 whereas a slightly weathered sample will possess a porosity and/or fracturing percentage of 1% to 5%. A moderate to highly weathered rock sample will have
 1757 a porosity and/or fracturing percentage of greater than 5% (Staněk et al., 2019).

6. Conclusion

The intricate interplay between weathering processes and rock mass stability is a cornerstone of geological engineering. Petrological analysis, including thin section examination, discolouration assessment, and fracturing analysis, has unveiled the effects of weathering on various rock types. Methods such as Schmidt hammer tests, X-ray fluorescence (XRF) analysis, X-ray diffraction (XRD), scanning electron microscopy (SEM), polarized light microscopy, and establishing weathering indices have been employed to highlight the critical role of fractures and joints as primary pathways for weathering propagation. Discolouration serves as a visible indicator of these weathering processes. This study underscores the necessity of understanding these weathering mechanisms to ensure the long-term stability of structures. By examining the depth of weathering propagation, chemical composition through weathering indices, hardness reduction, and loss on ignition (L.O.I.), invaluable insights into the resilience of different rock types are gained. These findings pave the way for developing more tailored and precise weathering classification schemes, essential for informed decision-making in geotechnical projects. As evolving environmental conditions are navigated, this research provides a robust foundation for predicting rock behaviour and enhancing structural stability in diverse geological settings.

Petrological analysis revealed clear weathering effects at the rim and adjacent rock material of the samples. The maximum weathering propagation depth, indicated by discolouration, was approximately 2 cm in the quartz-diorite sample. The shale samples exhibited the shallowest weathering propagation, likely due to its low permeability. Fractures, originating at the exposed surfaces, are attributed to weathering processes, with further discolouration and weathering advancing along these fractures, highlighting its role as primary pathways for weathering propagation.

The thin sections revealed a decline in discolouration with increasing distance from the exposed surface. However, fracturing persisted along grain boundaries and mineral surfaces beyond the discoloured region. This suggests that weathering propagation extended further into the unexposed portion of the rock, undetectable to the naked eye. A gradual decrease in grain size as weathering propagated further into the intact rock material was observed.

The weathering indices indicated that granite was the least weathered, followed by quartz-diorite, and shale, respectively. It is important to note that the CIA value is significantly influenced by the grain size of the sample and the provenance of the sediment, which explains the high CIA value for shale. Due to this influence, the CIA value calculated for shale was not solely representative of its weathering degree but also a reflection of its fine grain size and sedimentary origin, which tend to amplify chemical weathering indicators.

Quartz-diorite and granite demonstrated comparable trends in chemical composition, weathering intensity (CIA), depth of weathering propagation (discolouration), hardness reduction, and loss on ignition (L.O.I.). High silica content, low proportions of clay and iron oxides, and minimal L.O.I. were indicative of limited chemical weathering, shallow propagation into intact rock, and little difference in hardness between the exposed and unexposed regions of the sample. While shale exhibited similar CIA values, the weathering propagation depth was less pronounced, likely due to its finer texture. An exponential relationship between L.O.I. and chemical weathering degree was identified. These findings underscore that mineralogical stability and low volatile content contribute to reduced weathering effects, providing critical insights for stability assessments in engineering and geotechnical applications. Granite contained the most quartz out of all three (3) rock samples and showed a lower reduction in hardness compared to that of quartz-diorite. With the assumption that the absence of visible

discoloration in the material adjacent to a joint corresponds to negligible hardness reduction, a direct relationship was established between the depth of discoloration and the percentage decrease in hardness for each rock sample. The relationship between the percentage decrease in hardness and the depth of weathering propagation revealed that as the depth of weathering propagation increased, the greater the decrease in hardness of the rock material adjacent to the joint. Comparing the gradients of the igneous rock samples (quartz-diorite and granite) revealed that quartz-diorite experiences a slower rate of strength reduction compared to granite as weathering depth increases. A clear relationship was observed between the Chemical Index of Alteration (CIA) percentage and the depth of discolouration in these samples. Additionally, a linear correlation was identified between the reduction in hardness near joints and the CIA percentage, highlighting the interconnected influence of chemical, physical, and engineering properties on the impact of weathering propagation.

Each rock type showed distinct joint zoning patterns caused by the propagation of weathering, which indicates that each rock reacted differently to the propagation of weathering and were affected in different ways. This highlights the importance of recognising that not all rocks react to weathering in the same way and that a single classification system is inadequate for accurately classifying diverse rock types. Understanding these variations is essential for developing more tailored and precise weathering classification schemes.

Building upon the findings of this study, future research should focus on several critical areas to enhance the understanding of weathering propagation and its implications for geological engineering. Understanding fluid flow dynamics in weathered rock is another crucial aspect, requiring both experimental and numerical modelling approaches to assess how propagating weathering affects fluid velocity and distribution patterns. This research could inform water management strategies in mining, tunnelling, and other subsurface engineering projects. Furthermore, gravimetric water content analysis would aid in confirming the relationship between moisture levels and chemical weathering, strengthening the knowledge of how water influences rock mass behaviour over time. Expanding the sample base to include a wider variety of lithologies and exposure histories would also enhance the applicability of the findings across different geological settings.

Future studies should investigate the role of exposure time in weathering progression, determining weathering rates under various environmental conditions. This would enable long-term predictions of engineering behaviour and inform sustainable design strategies. A multidisciplinary approach integrating geochemical, mineralogical, and mechanical data with advanced modelling techniques—could provide a comprehensive framework for assessing rock mass stability. Additionally, exploring the broader implications of weathering relationships in engineering design, such as using propagation depths as a non-destructive method to estimate material strength and hardness, could have practical applications in excavation support and slope stabilisation.

Given the growing impact of climate change, examining how different climatic conditions influence weathering propagation will be crucial for designing resilient infrastructure. These efforts will bridge the gap between theoretical insights and practical applications in engineering geology, ensuring a stronger foundation for predicting rock behaviour and improving long-term structural stability. By addressing these knowledge gaps, future research will contribute to safer and more sustainable engineering practices in diverse geological settings.

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8. Appendices

8.1.1. Rebound Numbers

Table 8-1: Schmidt hammer results (R-values) for fresh intact rock and rock material adjacent to joint for Joint sample quartz-diorite.

R-Value for fresh/Unweathered Rock	R-Value for rock material adjacent to joint surface
59.0	19.0
62.0	25.0
60.5	33.5
59.5	18.0
59.5	24.5
56.5	17.0
59.5	32.0
60.0	35.5
Average: 59.56	Average: 25.56

Table 8-2: Schmidt hammer results (R-values) for fresh intact rock and rock material adjacent to joint for granite.

R-Value for fresh/Unweathered Rock	R-Value for rock material adjacent to exposed surface
19.5	11.0
35.0	11.5
27.5	23.0
36.5	17.5
26.0	13.5
29.5	11.0
35.0	15.0
27.5	10.5
Average: 29.56	Average: 14.13

Table 8-3: Schmidt hammer results (R-values) for the fresh intact rock and the rock material adjacent to the weathered surface for shale:

R-Value for fresh/Unweathered Rock	R-Value for rock material adjacent to the exposed surface
22.5	15.5
20.5	12.5
22.0	13.7
21.6	14.0
22.0	12.5
19.5	15.5
22	16.0
20.5	12.4
Average: 21.3	Average: 14.01

8.1.2. X-Ray Diffraction (XRD)

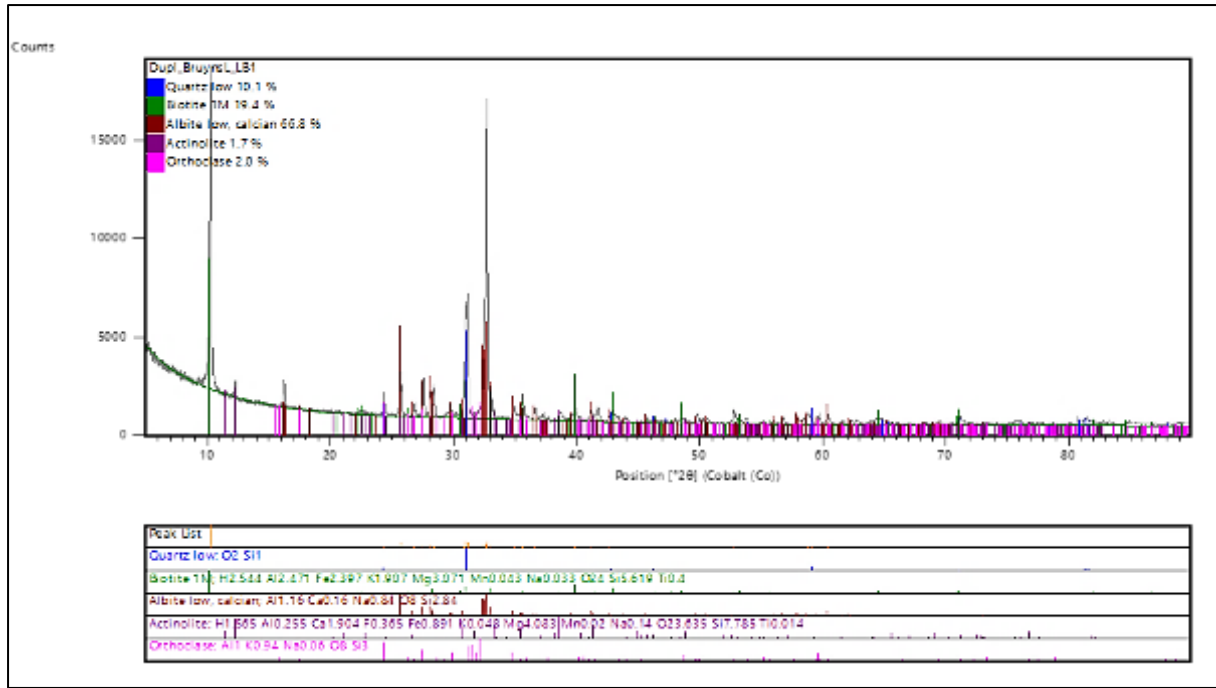


Figure 8-1: X-Ray Diffraction analysis for quartz-diorite.

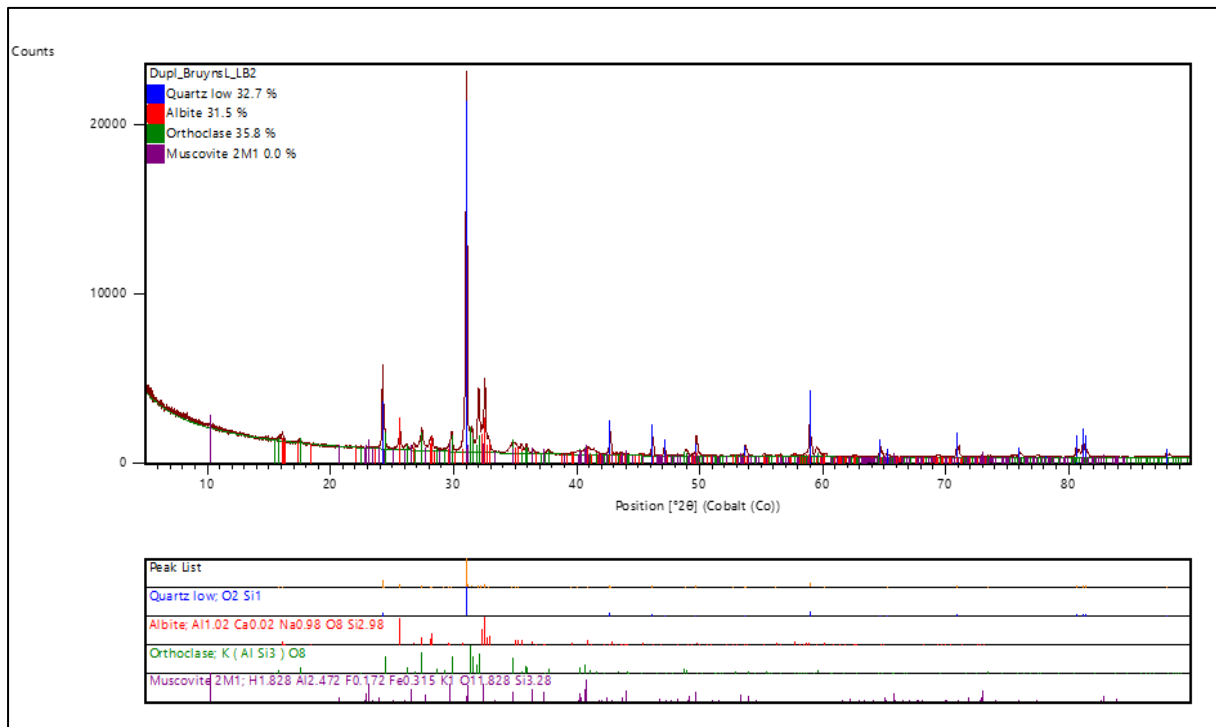


Figure 8-2: X-Ray Diffraction analysis for granite.

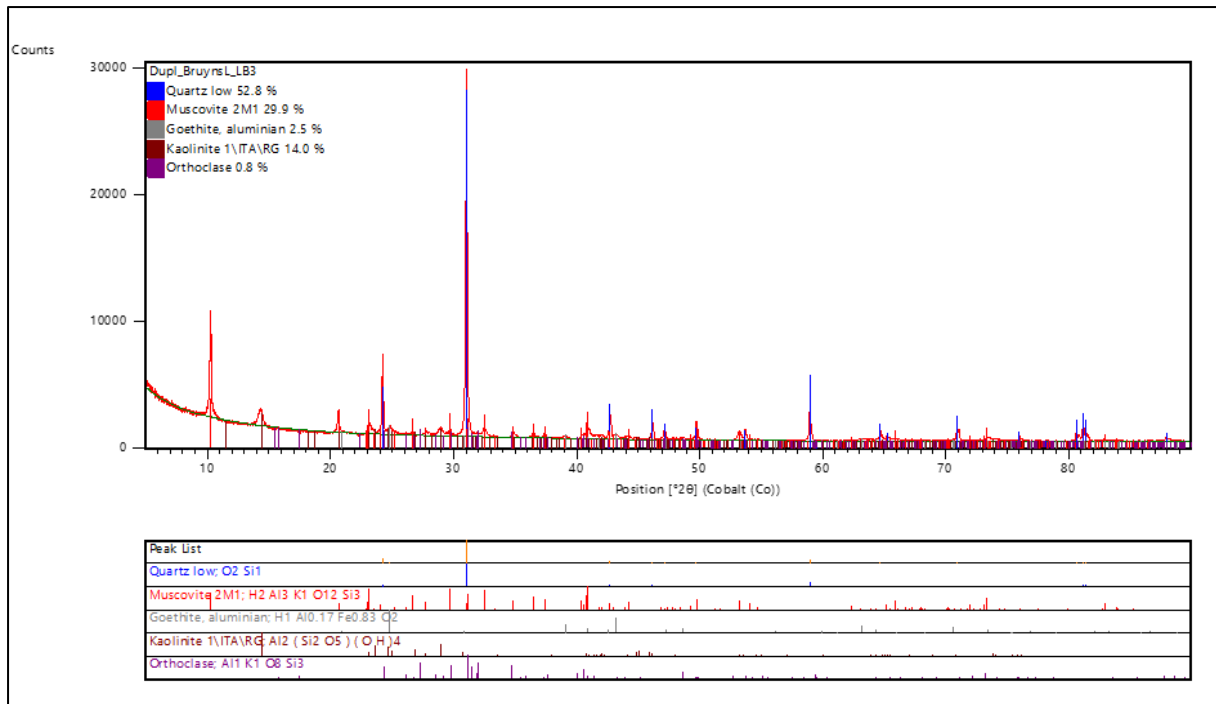


Figure 8-3: X-Ray Diffraction analysis for shale.