Long-Term Survivability of Riprap for Armoring Uranium Mill Tailings and Covers: A Literature Review

Prepared by C. G. Lindsey, L. W. Long, C. W. Begej

Pacific Northwest Laboratory
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Prepared for
**U.S. Nuclear Regulatory
Commission**

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SUMMARY

Pacific Northwest Laboratory (PNL) is investigating the use of a rock armoring blanket (riprap) to mitigate wind and water erosion of an earthen radon suppression cover applied to uranium mill tailings. The purpose of this earthen cover is to reduce radon-222 exhalation from the tailings and to provide long-term stability for the tailings impoundments. Because of the length of time the cover must remain intact (up to 1000 years or longer), the soil must be protected from natural erosional forces, hence the need for a long-term mitigation technique such as a riprap blanket. At the same time, this rock blanket must itself withstand natural weathering processes that promote deterioration of the rock. Should weathering cause the riprap to fail, the radon suppression cover would be exposed to erosional forces and its effectiveness thereby reduced. An early task in this study is to review current state-of-the-art information on rock weathering and riprap durability. This report, prepared for the U.S. Nuclear Regulatory Commission, is designed to provide an introduction to topics in geology relevant to weathering processes and to describe methods currently used to evaluate rock durability.

Information for this report was taken from a review of the literature describing chemical and physical weathering processes, rock characteristics related to durability, climatic conditions affecting the degree and rate of weathering, and testing procedures used to measure weathering susceptibilities. Additional information is presented in a report by Dr. Richard Jahns of Stanford University, which can be found in Appendix A.

As this study evidences, the ability of many rock types to survive 1000 years of weathering is highly uncertain. Numerous failures of riprap dams and other manmade stone structures on much shorter time scales have been attributed to weathering. Thus, proper rock sampling and testing is needed to reach a judgment on riprap durability. Physical rock properties, such as mineral composition, texture, specific gravity, and porosity, need to be evaluated. A rock's susceptibility to chemical weathering processes, including hydrolysis, hydration, oxidation, solution, and acid attack, must be considered. Likewise, mechanical weathering agents, including ice action, salt crystallization, hydration, temperature fluctuations, and stress relief by unloading should be studied. Riprap durability tests are designed mostly to evaluate the effects of physical weathering agents. Although these tests have demonstrated a measure of reliability, their ability to predict rock durability for the long term is uncertain. This uncertainty is related to the lack of corroborative evidence between laboratory studies and actual field performance, and to the current use of riprap for projects with comparatively short life expectancies.

The best available information to date indicates that certain rock types may be suitable for mill tailings armoring, including varieties of igneous rocks (e.g., rhyolites and granites), metamorphic rocks (e.g., quartzites and granitic gneiss), and perhaps a few sedimentary rocks (e.g., limestones). The ability of these rocks to protect the mill tailings will depend on the weathering conditions to which they are exposed. In turn, these conditions depend on climatic conditions and lithologic factors, which usually require site-specific evaluations.

ABSTRACT

Pacific Northwest Laboratory (PNL) is investigating the use of a rock armoring blanket (riprap) to mitigate wind and water erosion of an earthen radon suppression cover applied to uranium mill tailings. Because the radon suppression cover and the tailings must remain intact for up to 1000 years or longer, the riprap must withstand natural weathering forces. This report is a review of information on rock weathering and riprap durability. Chemical and physical weathering processes, rock characteristics related to durability, climatic conditions affecting the degree and rate of weathering, and testing procedures used to measure weathering susceptibilities have been reviewed. Sampling and testing techniques, as well as analyses of physical and chemical weathering susceptibilities, are necessary to evaluate rock durability. Many potential riprap materials may not be able to survive 1000 years of weathering. Available techniques for durability testing cannot adequately predict rock durability for the 1000-year period because they do not consider the issue of time (i.e., how long must riprap remain stable). This report includes an Appendix, which discusses rock weathering, written by Dr. Richard Jahns of Stanford University.

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1.0 INTRODUCTION

Uranium mill tailings are potential sources of radioactive and toxic materials, which if released into the environment could adversely affect environmental quality and human health. A number of investigations have been conducted and are currently underway to develop and evaluate long-term methods for preventing the redistribution of these materials to the air, soil, and water. Because "long term" may imply time periods up to or longer than a 1000 years, applied mitigation techniques must be evaluated in light of natural forces that could reduce their effectiveness.

A promising technique to prevent the release of hazardous substances in the tailings (e.g., radon-222 gas) is the application of several meters of natural soil to the surface of the tailings. However, this radon suppression cover must itself be protected from naturally occurring destructive forces such as wind and water erosion. Investigations (Bander 1980; Walters and Skaggs 1980) have shown that wind and water action could produce sufficient denudation of the soil cover to render it ineffective. Nelson and Shepherd (1978) discuss a variety of natural phenomena that could destabilize the soil cover and underlying tailings (on time scales of a few hundred to several tens of thousands of years).

One possible mechanism to prevent the removal of the soil overburden is the installation of a rock armoring cover, or riprap, on the tailings piles. Riprap covers have been used successfully to absorb and redirect erosional forces on earthen dams, roadway embankments, and stream channels. Documentation of the uses and durability of riprap, however, is limited for the most part to applications since the turn of the century. Before riprap is to be used on tailings impoundments, rock durability (i.e., the ability to withstand chemical and physical weathering agents) must be evaluated for a much longer time scale. The purpose of this report is to document the findings of an initial survey of publications in fields of geology related to rock weathering and durability (e.g., petrology, geochemistry, geophysics, geomorphology, and riprap engineering) to provide state-of-the-art information on factors influencing rock weathering. Such information should provide a foundation for the proper selection of riprap and of methods for estimating its durability. This document is one in a series of reports being prepared by PNL concerning long-term stabilization. These studies are addressing questions of wind erosion, water erosion, riprap engineering, and recommended guidelines for the selection and application of riprap to uranium mill tailings.

Ample evidence exists of the complete deterioration of many rock types in a matter of tens to a few hundreds of years. Obviously, rocks that fail at this rate would not insure the long-term stability of uranium tailings piles. Characteristics of the rock selected for use as riprap, the environment in which that rock is placed, and the weathering agents acting in that environment all affect the rock's durability and are discussed in the following sections.

Analyses of rock weathering are difficult because weathering processes:

- occur on a variety of spatial scales, from the molecular level to large geographical regions
- occur on temporal scales from a few minutes to hundreds of thousands of years
- operate in conjunction with each other as a function of rock characteristics and climatic factors.

More to the point, few studies exist that examine the long-term durability of rocks used as riprap. Therefore, the approach taken in this report is to look at rock weathering from a general viewpoint (bearing in mind that long-term durability is our objective), taking into account chemical, dynamic, and thermodynamic processes, and how these processes affect various rock types. Examples of rapid deterioration are given to indicate inherent weaknesses in some rock types or to indicate the forcefulness of certain weathering agents. Available information on riprap durability is cited, particularly in instances where failures are known to have occurred as a result of weathering. Thousands of citations on rock weathering exist; the attempt here has been to refer to works of prominent authors who have summarized the efforts of their predecessors. Thus, this document is not a final statement on a very complicated topic; rather, it is a means of introducing the problems associated with geologic durability.

A basic introduction to the concepts of mineral and rock formation and characteristics, and a broad overview of rock properties and their relationships to rock weathering are given in this report. Chemical and physical weathering phenomena and their correlation with rock survivability are discussed. The report reviews testing procedures currently used to estimate rock durability, and discusses experimental investigations of some of the more prominent weathering processes. Finally, the relationship between weathering, climate, and rock durability is examined, with the objective of presenting a preliminary procedural model for determining durability.

Appendices to this document include a glossary of terms, and a report prepared by Dr. Richard Jahns of Stanford University. The latter report provides additional coverage of geologic topics relevant to long-term riprap durability evaluations.

2.0 CONCLUSIONS AND RECOMMENDATIONS

The durability of a rock is defined in this report as its resistance to weathering. Because all rocks exposed at the earth's surface are experiencing attack by various weathering agents, the question pertinent to riprap durability is how long will the rocks remain in a suitably sound and stable state. The answer to this question depends on three factors:

- mineral composition, and associated chemical properties
- physical rock properties
- climatic conditions to which the rock is exposed.

Mineral composition relates to the assemblage of inorganic crystalline compounds that makes up individual rock types. Minerals are classified as either of igneous, sedimentary, or metamorphic origin, the distinction being whether the minerals form directly from the cooling of a magmatic melt (igneous), from the deposition and lithification of previously weathered minerals (sedimentary), or from the alteration of existing rocks and minerals by chemical and thermal processes (metamorphic). Different minerals weather at different rates, depending on the environment in which they were formed and the weathering conditions that they experience at the earth's surface. Minerals formed under conditions of high temperature and pressure generally tend to be less stable than those formed under less extreme conditions because an environment of low temperature and pressure more closely resembles weathering conditions at the earth's surface.

The most common igneous minerals are the feldspars and ferromagnesian silicates, the former having a more complex crystal structure and stronger bonding characteristics and thus more resistance to weathering than the latter. The silicate content of igneous rocks is an indicator of their durability. Acidic igneous rocks (e.g., granites) contain high proportions of silica, whereas basic igneous rocks (e.g., basalts) contain less silica and more ferromagnesian. Silica is resistant to chemical weathering and abrasion, whereas ferromagnesian are softer and tend to oxidize readily under surface conditions.

Sedimentary minerals include primarily silicates, carbonates, sulfates, and oxides. Although the minerals themselves tend to be quite stable, the rocks they form (e.g., limestone, sandstone, shale) may be very susceptible to weathering from attack on the cementing (lithifying) material. Calcareous material generally is less stable than siliceous material, particularly in a humid environment.

Metamorphic minerals form during the alteration and recrystallization of existing rock material. In some cases, the parent minerals are simply recrystallized and undergo little or no chemical or physical change. Metamorphism usually produces completely new minerals (e.g., garnet, talc, or staurolite). Common metamorphic rocks include gneiss, schist, slate, marble, and quartzite. Like igneous rocks, the susceptibility of metamorphic rocks to weathering is influenced by mineral content, the environment of mineral formation, and

weathering conditions. Mineral segregation and textural features produced during dynamic metamorphism can influence weathering rates by promoting differential weathering.

Physical rock properties that are relevant to durability include specific gravity, density, porosity, strength, and texture. Measurements of these characteristics help to define a rock's susceptibility to weathering. High values of specific gravity and density may indicate sufficient rock strength to resist attack by ice, salts, water, and temperature fluctuations that tend to establish high internal disruptive pressures. Likewise, rock porosity serves as a measure of a rock's ability to sorb water and promote free drainage. High sorption values generally are undesirable unless the water can readily drain from pores and capillaries. Grain texture is another measure of weatherability; coarse-grained rocks usually are less durable.

Climatic conditions determine the weathering environment to which the rock will be exposed. Precipitation, temperature, wind, and airborne pollutants all contribute to defining this environment. Weathering proceeds on two levels: chemical and physical. Water, a significant driving factor for both processes, serves as the medium for the dissolution of organic and inorganic compounds that promote chemical attack, particularly by acidic solutions. The freezing of water in rock pores, the hydration and dehydration of soluble salts and rock minerals themselves, and the physically abrasive properties of water contribute to rapid weathering. The rate of chemical reactions is a function of temperature. Solar insolation and fire may produce differential expansion and contraction of mineral grains and promote fracturing, cracking, and spalling. Windblown particles serve as abrasive agents, and wind-driven water is known to produce rapid deterioration of riprap used on earthen dams. The airborne transport and deposition of the oxides of sulfur, nitrogen, and carbon, and the formation of their acidic counterparts, serve to promote chemical attack on rocks. Sulfuric and carbonic acids are noted for their effects on both silicate and carbonate rocks.

Chemical weathering is a slow, but continuous, weathering phenomenon that usually occurs in the presence of water. Chemical weathering can be described by five different processes: hydrolysis, hydration, oxidation, solution, and acidic degradation. Igneous rocks are most commonly weathered by hydrolysis from reactions involving the dissociation of water. Clays and evaporites are subject to hydration and its accompanying swelling pressures. Oxidation removes iron from mineral structures when oxygen and iron combine to form a ferric oxide crust soluble only by acids. Solution leaches alkaline metals from mineral structures, and acidic degradation alters minerals to more soluble salts.

Mechanical weathering is a process leading to disintegration of the rock without chemical alteration. The role of water during physical weathering may be either direct or indirect, but few mechanical agents do not include water as a mechanism of deterioration. The most prevalent physical weathering phenomena are:

- frost action and freeze/thaw activity
- salt crystallization, migration, and hydration
- water sorption (adsorption and absorption)
- mineral hydration
- wetting and drying cycles
- a abrasion by wind, water, and mechanical means
- temperature-induced expansion and contraction of mineral grains.

Quarrying practices can accelerate rapidly the weathering of any rock type by introducing internal stresses resulting from improper blasting techniques and by promoting stress relief in previously buried rock masses.

Several tests are available to estimate the durability of rock to be used as riprap, including examinations of physical properties (e.g., specific gravity, sorption, porosity, and strength), and accelerated weathering tests to determine freeze/thaw, wetting/drying, and abrasion susceptibilities. These tests have several serious limitations, particularly because 1) few attempts have been made to correlate laboratory data with field observations and experience, and 2) the tests attempt to determine the rock's ability to survive on time scales of less than 100 years (i.e., the life expectancy of most riprap projects), which may be too short a time period when considering riprap durability on tailings piles.

This report does not recommend the use of a specific rock type for the tailings piles armoring cover; rather, it reviews factors that influence durability. The inherent differences in rock weatherability (even within particular rock types), as well as our inability to predict which rock types will be available for use, preclude such a recommendation. Care must be exercised during the sampling and testing phase of rock selection to consider all the variables that influence rock durability, including climatic parameters. A rock that works well under one set of conditions may fail under a different set of circumstances. The determination of the cause of that variability requires more information than is currently available. Climatic conditions probably play a role, but slight differences in mineral composition, texture, porosity, and other parameters also may provide the reasons. A great deal of work remains to be done to correlate laboratory data with field performance. In spite of these restrictions, some guidelines can be suggested for determining rock durability, and these are reported in Sections 6.0 and 7.0. Rocks susceptible to very rapid deterioration probably can be eliminated during the testing phase. Making a categorical determination of suitability for many rock varieties will be difficult, given the time requirements for rock stability applicable to tailings pile protection, unless new testing procedures or a better understanding of the current procedures become available.

3.0 MINERALS AND ROCKS: AN OVERVIEW OF TOPICS RELEVANT TO ROCK SURVIVABILITY

Rock classifications and environments of formation are important issues because weathering rates can vary substantially among rock types. Rock classifications are based on mineral composition and mode of occurrence. In a broad sense, any mineral, alone or combined with other minerals, defines a rock; the environment of formation determines if it is igneous, sedimentary, or metamorphic.

Igneous rock-forming environments involve primary mineral crystallization from a magma. Sedimentary and metamorphic rocks form by removal and redeposition or alteration of primary igneous minerals. The following sections briefly outline the common rock-forming minerals and general rock-forming environments.

3.1 MINERAL FORMATION

Minerals are inorganic chemical compounds with definite crystalline structures which are formed in various ways. Igneous minerals crystallize from a magma and constitute a significant proportion of the common rock-forming minerals in all three rock types (igneous, sedimentary, metamorphic). Nonigneous minerals can form as lower-temperature chemical precipitates or through alteration of primary minerals by surface weathering or by heat and pressure at depth. These nonigneous rock-forming minerals are restricted to sedimentary and metamorphic rock types.

3.1.1 Crystallization of Igneous Minerals

Various minerals form in a reaction series as temperatures drop within a mass of igneous magma. To maintain equilibrium between solid and liquid phases as the melt cools, early crystals react with the liquid, changing in composition to form new minerals. This reaction series can produce a continuous or discontinuous suite of igneous rock-forming minerals, and proceeds until the liquid is depleted.

During the continuous series of fractional crystallization, one mineral is converted to another mineral of the same mineral group by changing the ratio of cation end members. The plagioclase feldspar group is a classic example of continuous crystallization, as high temperature calcic anorthite ($\text{CaAl}_2\text{Si}_2\text{O}_8$) changes to sodic albite ($\text{NaAlSi}_3\text{O}_8$) as temperatures decrease.

Certain ferromagnesian minerals form in a discontinuous series. Specifically, as the temperature cools, early high-temperature minerals become unstable and react with the liquid to form new minerals of different crystal structure.

This reaction series, first described by Bowen (as cited in Leet and Judson 1971), is presented in Figure 3.1. More detailed discussions on crystallization of igneous rock-forming minerals are available in the literature (Jackson 1970; Krauskopf 1979).

FIGURE 3.1. Reaction Series of Igneous Mineral Formation

The complexity of a mineral's crystal structure and its bonding strength also depend on temperature of formation, and can have important implications in the stability and weathering of rocks. The basic building block of igneous minerals is SiO_4 tetrahedra, where four oxygen ions surround a single silicon ion. High temperature minerals (e.g., olivine) are formed as metal cations combine with single SiO_4 groups. However, as temperature decreases, the SiO_4 tetrahedra share an oxygen and "polymerize" to form multiple groups, single and double chains, sheets, and three-dimensional lattice structures (Deer, Howie and Zussman 1966). Increasing complexity in crystal structure increases stability and inhibits weathering.

3.1.2 Secondary Mineralization

Secondary mineralization as discussed in this report encompasses all processes whereby existing minerals and other inorganic compounds are converted to more thermodynamically stable forms. These processes include the alteration of weathered igneous minerals (e.g., to form clays and soils); the evaporation/precipitation from solution of inorganic compounds such as calcium carbonate or halite (rock salt); and the production of new minerals by metamorphic processes involving chemically or thermally active solutions.

Secondary mineralization may proceed through a number of cycles: igneous minerals may become sedimentary minerals that are subjected to deposition and lithification and then altered by metamorphic processes or they may be subjected to normal weathering actions to re-enter the mineralization cycle. Thus, sedimentary and metamorphic minerals may have experienced a number of transformations, with each in general being more stable (i.e., resistant to weathering) than the preceding stage.

3.2 COMMON ROCK-FORMING MINERALS

Although many different minerals occur in rocks, only a few are common rock-forming minerals. Certain assemblages of common rock-forming minerals are characteristic of igneous, sedimentary, and metamorphic rocks. These are discussed in the following sections.

3.2.1 Igneous Rock-Forming Minerals

The most common rock-forming minerals among igneous rocks crystallizing from a melt are those described by Bowen's reaction series. Generally, these minerals include silica-rich quartz and alkali feldspar, silica-intermediate plagioclase feldspars and micas, and silica-poor ferromagnesian minerals (see Table 3.1).

TABLE 3.1. Common Igneous Rock-Forming Minerals

<u>Mineral Group</u>	<u>Anion Silicate Structure</u>
<u>Ferromagnesian</u>	
Olivine	Single SiO_4 structure
Amphiboles	Chains of SiO_3
hornblende	
riebeckite	
Pyroxenes	Chains of SiO_3
augite	
hypersthene	
Biotite mica	Sheets of aluminum silicates
<u>Feldspathoids</u>	Frameworks of aluminum silicates
leucite	
nepheline	
<u>Feldspars</u>	Frameworks of aluminum silicates
plagioclase feldspar	
alkali feldspar	
<u>Quartz</u>	Frameworks of pure silicate

Although igneous minerals crystallize in an ordered reaction series, the mineral assemblages found in any given igneous rock depend on chemical composition of the original magma. If the magma is high in silica, quartz and

feldspars dominate. Silica-poor magmas will produce darker ferromagnesian minerals like pyroxene, amphiboles, or olivine. However, because feldspars crystallize over a wide temperature range, they are generally the most abundant minerals of igneous rocks.

Mineral assemblages in igneous rocks will commonly be a matrix of one or more feldspar with smaller amounts of ferromag-silicates, feldspathoids, or quartz. Extreme end-members, such as olivine and quartz, rarely occur together.

3.2.2 Sedimentary Rock-Forming Minerals

The predominant minerals of sedimentary environments can be divided into three groups: carbonates, sulfates, and oxides and hydroxides. One of the most common minerals is calcite (CaCO_3), a carbonate formed by precipitation of supersaturated solutions. Calcite forms massive beds of limestone and is the cement of many sedimentary rocks. Other common carbonates include dolomite [$(\text{Ca},\text{Mg})\text{CO}_3$] and siderite (FeCO_3).

The two major sulfates are the evaporites, gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) and anhydrite (CaSO_4). Gypsum is often formed from the hydration of anhydrite during diagenesis. Both form beds of evaporite deposits in sedimentary rock sequences.

The most predominant oxide found in sedimentary deposits is hematite (Fe_2O_3). The oxidized (ferric) iron lends its red color to many deposits even when present in small concentrations. Limonite ($2\text{Fe}_2\text{O}_3 \cdot 3\text{H}_2\text{O}$) and goethite form iron deposits, coat clastics, or act as cements. Additional information on sedimentary minerals may be found in Blatt, Middleton and Murray (1972), and Prinz, Harlow and Peters (1978). Silica minerals also can form as precipitates in sedimentary environments, frequently appearing as cements in sedimentary rocks.

3.2.3 Metamorphic Rock-Forming Minerals

Metamorphic rocks are igneous or sedimentary rocks that have been transformed by heat and pressure. Therefore, many minerals found in the parent rock will also occur in metamorphic rocks; these minerals have often simply recrystallized.

High-grade metamorphism produces minerals not commonly formed in silica melts or sedimentary environments. Like igneous minerals, metamorphic mineral assemblages depend on the composition of the parent rock. If the parent material has a wide variety of minerals, or if impurities are introduced through contact metamorphism, a variety of new minerals can form.

Low-grade metamorphism of granitic rocks will lead to the transition of biotite and hornblende to chlorite (magnesian hydroxide), and then at higher grades to almandine (iron garnet). Biotite can also be transformed into pyroxene. An igneous intrusion into limestone will often produce grossularite (calcium garnet) and wollastonite (calcium silicate). High-grade metamorphism

of igneous or sedimentary rocks can produce mica schists consisting primarily of quartz and mica, but also containing garnet, staurolite (iron aluminum silicate hydroxide), kyanite, and sillimanite (aluminum silicate). Regional metamorphism of mafic igneous rocks such as basalt can result in pyroxenes recrystallizing into chlorite, amphiboles, and quartz. Chlorite in turn can go to almandite and biotite, depending on the degree of metamorphism.

In all stages of metamorphism, the minerals present tend to recrystallize into something stable in that particular environment. Therefore, the more extreme stages of metamorphism will tend to produce minerals that are the least stable at surface conditions. For further discussion of metamorphic processes see Jackson (1970) and Williams, Turner and Gilbert (1954).

3.3 ROCK TYPES AND CHARACTERISTICS

The three broad categories of rock types (igneous, sedimentary, and metamorphic) have numerous subdivisions. Minerals crystallize from an igneous magma to form igneous rocks that weather to form sedimentary rocks. In the ideal rock cycle, both igneous and sedimentary rocks can then be transformed into metamorphic rocks or can be melted to form new magma. This rock cycle is depicted in Figure 3.2. Although disruptions and interactions make the actual rock cycle far from ideal, this simplified model provides insight into the nature of rocks in general. Because each rock type has a unique mineralogy and texture, each weathers at a different rate. The following sections provide a general description of rock types and characteristics that affect weathering rates.

FIGURE 3.2. The Cycle of Rock Formation

Igneous Rocks

Igneous rocks have crystallized directly from liquid magma and are usually homogeneous in all directions, with interlocking crystals that display a low porosity and permeability. Numerous schemes have been proposed for the classification of igneous rocks, based on parameters such as mineral content, silica content, mode of occurrence, texture, or color. Many of these classifications are contradictory and some try to name minor variants of common rocks. The most widely accepted classification for igneous rock is based on a combination of silica content, type and amount of feldspar present, and texture. Figure 3.3 shows a simplified version of this classification.

Igneous rocks with a high-silica content appear on the left side of the classification in Figure 3.3; low-silica rocks are on the right. High-silica rocks are generally light in color and weight (felsic), whereas low-silica rocks are darker in color and heavier in weight because of the iron and magnesium content (mafic). The texture of igneous rocks varies widely, depending on the environment of formation. Texture is determined by:

FELDSPAR	QUARTZ > 5 PERCENT		NO QUARTZ; NO ROCKS WITH PATHOIDS		NEPHELINE OR LEUCITE > 5 PERCENT	
	COARSE	FINE	COARSE	FINE	COARSE	FINE
• POTASH FELDSPAR > PLAGIOCLASE	GRANITE	RHYOLITE	SYENITE	TRACHYTE	NEPHELINE SYENITE LEUCITE SYENITE	PHONOLITE LEUCITE PHONOLITE
PLAGIOCLASE > POTASH FELDSPAR	GRANODIORITE	QUARTZ LATITE	MONZONITE	LATITE		
PLAGIOCLASE (OLIGOCLASE OR ANORTHITE)	TONALITE	DACITE	DIORITE	ANDESITE	NEPHELINE DIORITE	
PLAGIOCLASE (LABRADORITE TO ANORTHITE)	QUARTZ GABBRO		GABBRO	BASALT	NEPHELINE GABBRO	TEPHRITE (-OLIVINE) BASANITE (+OLIVINE)
NO FELDSPAR			PERIDOTITE (OLIVINE DOMINANT) PYROXENITE (PYROXENE DOMINANT) HORNBLANDITE (HORNBLANDITE DOMINANT)		DIJOLITE	NEPHELINITE (-OLIVINE) NEPHELINE BASALT (+OLIVINE)

UNDER POTASH FELDSPAR ARE INCLUDED ORTHOCLASE, MICROCLINE, ANORTHOCASE, MICROPERTHITE

FIGURE 3.3. General Classification of Igneous Rocks as a Function of Silica Content (across), Feldspar Content (down), and Texture (coarse versus fine grained)

- ratio of large crystals to groundmass (matrix)
- size of crystals
- relative arrangement of crystals.

Coarse-grained (granular) rocks typically form in deep, igneous masses that cool slowly enough for large crystals to grow. When molten rock is extruded at the surface and cools rapidly, microscopic crystals form to produce fine-grained (aphanitic) rocks such as basalt. If crystallization begins at depth and the magma is suddenly extruded, the rocks will have a fine-grained matrix enclosing coarse crystals (porphyritic). A glassy texture is formed when magma or lava cools so rapidly that few crystals have time to form. Volcanic glass is a supercooled solution with no crystal structure.

The ideal igneous rock for use as a riprap cover would be composed of felsic minerals with low temperatures of formation and a dense fine-grained texture. Igneous rocks that may satisfy these criteria include rhyolite, trachyte, and phonolite. Coarse-grained igneous rocks such as granite or syenite, if composed of light-colored, low-temperature minerals, may be more suitable than fine-grained rocks such as andesite or basalt that contain unstable high-temperature mafic minerals. The least stable riprap would be coarse-grained mafic rocks such as gabbro or peridotite.

3.3.2 Sedimentary Rocks

Gregor (1980) attributes 74% of the weathered rock materials in the world to sediments and metasediments and 26% to true crystalline rocks. Sedimentary rocks are divided into two classes: detrital (clastics) and chemical. Clastics are lithified deposits of rock fragments derived from the weathered surfaces of older rocks; chemical rocks are formed by the precipitation/evaporation of inorganic or biochemical compounds such as calcium carbonate or calcium sulfate.

Typical clastic sedimentary rocks are quartzite, sandstone, siltstone, shale, conglomerate, and coquina. Quartzite is a siliceous-cemented sandstone. Sandstone, siltstone, and shale are rock types defined by grain size (i.e., sand-, silt-, and clay-sized, respectively). Conglomerate is composed of large, rounded gravels and cobbles in a matrix of finer material. Coquina is a generic term for densely fossiliferous carbonates.

Three common types of chemical rocks are: limestone, evaporites, and siliceous oozes. Limestone and evaporites are formed during supersaturation of a solution with a solid phase (e.g., calcite, halite, or sulfate salts), with subsequent precipitation, deposition and lithification. Siliceous oozes and some limestone precipitates are formed from accumulations of marine life. Radiolarians and diatoms form siliceous oozes; comminuted and colloidal calcite from calcareous marine organisms form limestone precipitates. Evaporites are deposited on the shores of warm, shallow seas or in the vadose zone of arid deserts. Gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) is the predominant evaporite, although thick deposits of anhydrite (CaSO_4) and halite (NaCl) are found in localized regions.

Other common chemical rocks include dolomite and travertine. Dolomite is a limestone with over 40% of the calcium replaced by magnesium. Travertine refers to a heterogeneously banded limestone formed at geothermal springs or at cold lakes and streams. Additional information on sedimentary rocks may be found in Gilluly, Waters and Woodford (1968); Blatt, Middleton and Murray (1972); Krumbien and Sloss (1963); and Prinz, Harlow and Peters (1978).

Sedimentary rocks may be a suitable choice for riprap if they are sufficiently durable in the particular environment. The optimum sedimentary rock would be a massive bedded quartzite with siliceous cementation; however, a massive carbonate such as limestone or dolomite could be adequate in areas of low rainfall. Parameters to consider when choosing a sedimentary rock for armoring are the extent and durability of the cement, the durability of the clastic minerals in the environment, the packing or intergrowth of crystals and the resulting porosity, and the presence of radically different planes of strength.

3.3.3 Metamorphic Rocks

Igneous and sedimentary rocks can be altered to metamorphic rocks by heat, by pressure, and by chemical reactions that produce changes in texture, structure, and mineralogy. Metamorphosed rocks are generally stronger, with a coarser crystalline structure than the parent material. New minerals may or may not form; however, recrystallization always occurs.

Metamorphism caused by the weight of overburden rock is static and tends to produce metamorphic rocks that remain massive and without structure. Uneven compressive forces (e.g., those associated with mountain building) cause rocks to fracture or flow plastically during the process of dynamic metamorphism. Contact metamorphism occurs when heated liquids and gases from a magmatic intrusion produce chemical and mineralogical changes in the nearby rocks.

Because metamorphic rocks do not lend themselves to well-defined classifications, most are grouped by chemical composition and by the physical conditions of metamorphism. All metamorphic rocks (regardless of composition) that have been metamorphosed within certain broad limits of temperature and pressure constitute a particular metamorphic facies. Each metamorphic facies is characterized by an assemblage of minerals that forms within the temperature and pressure limits. Metamorphic rock texture and structure are determined by the type of process that has occurred (i.e., dynamic metamorphism, static metamorphism, or contact hydrothermal metamorphism). Each facies will produce rocks with different weathering rates. The significance of weathering rates is addressed in later sections of this document.

Based on mineral stability and texture, several metamorphic rocks can be considered well suited for riprap material. Metamorphic quartzite is composed of recrystallized quartz and is extremely resistant to weathering. Slates may also make good rock armoring covers because their density and fine-grained texture would inhibit weathering agents. Metamorphic rocks that may not be suited for riprap include those with unstable high-grade metamorphic minerals or foliated texture. For further description of metamorphic facies see Williams, Turner and Gilbert (1954) and Jackson (1970).

4.0 ROCK PROPERTIES

Physical properties and mineral composition can greatly influence weathering rates of rocks and are important considerations in rock durability studies. Because most of the common rock-forming minerals crystallized in an environment vastly different than surface conditions, they are out of equilibrium. Weathering is simply a process to reach a more stable state.

Physical rock properties such as texture or porosity also influence weathering rates by determining area and rate of exposure to weathering agents. Discussions on mineral stability and physical properties of rocks are presented below as a background for later sections on rock weathering. Appendix A provides additional information.

4.1 MINERAL COMPOSITION

Rocks weather because their constituent minerals are unstable in their current environment. Igneous and metamorphic minerals crystallize under reducing conditions at higher-than-atmospheric temperatures and pressures. The most readily weathered component of sedimentary rocks is often the cement.

Silicate minerals are the most abundant minerals found in igneous and metamorphic rocks. The end-minerals of the discontinuous reaction series, olivine and biotite, form at 1900°C and 900 to 1100°C, respectively. The plagioclase continuous reaction series is formed between 1100 to 1500°C. Quartz forms between 500 to 900°C. The crystal structure of silicates becomes more complex with decreasing temperature of formation, as silica tetrahedra (SiO_4) polymerize into chains, rings, sheets, and three-dimensional lattice structures. Minerals with high crystallization temperatures usually weather faster than lower-temperature minerals (Table 4.1). This is caused by the higher bonding strength of the more complex crystal lattice and the smaller temperature difference between the earth's surface and the environment of crystallization.

Dark-colored minerals of the discontinuous reaction series have magnesium and iron as the predominant cations. Iron and magnesium oxidize on contact with free oxygen in the atmosphere. This, in conjunction with their higher temperature of formation and simpler silicate structures, causes them to be least resistant to weathering.

Light-colored minerals of the plagioclase continuous reaction series have the alkali metals as the predominant cations and weather predominantly through solution. Physical and electrical properties of sodium and calcium make these ions more soluble than potassium, silicon, and aluminum. This supports observations that plagioclase feldspars are more susceptible to weathering than alkali feldspar and quartz.

TABLE 4.1. Silicate Rock-Forming Minerals (in order of decreasing weathering rates)

<u>Dark Minerals</u>	<u>Light Minerals</u>
Olivine	Calcic plagioclase
Pyroxenes	Sodic plagioclase
Amphiboles	Potassium (Orthoclase)
Biotite	Muscovite
	Quartz

Quartz and calcite are the predominant minerals of sedimentary rocks and their metamorphic counterparts. Quartz is usually found as a clastic mineral (e.g., sand) and is occasionally present as a cement. **It** has a higher, more unstable free energy ($\Delta G = -204.75 \text{ kcal mole}^{-1}$) than calcite, but is much less soluble in water. Calcite is the most common sedimentary precipitate. **It** has a high free energy ($\Delta G = -270.18 \text{ kcal mole}^{-1}$) and is unstable in the presence of water. Calcite readily combines with water to form the particularly soluble bicarbonate complex; weathering of the bicarbonate frees additional surfaces for weathering. Calcite is more susceptible to mechanical weathering, as **it** has a hardness of 3 on the Moh's mineral hardness scale; quartz has a hardness of 7 (Leet and Judson 1971).

Cement is the most important characteristic to consider when comparing the weathering behavior of sedimentary rocks (Chorley 1969). Large amounts of cement in the rock composition increase the durability of the rock. Cementation can be defined as contact, pore, and basal. Contact cement forms an interconnecting rind on the clastics, whereas pore cement also fills the voids between closely packed sediments. A rock has basal cement **if** the rock fragments appear to be floating in the cement (Winkler 1975).

Silica, carbonate, iron, and clay cements **lithify** sedimentary rocks. Because a rock cemented with silica will break across (rather than around) grains (providing fewer weathering surfaces), silica cements are the most resistant to weathering. Siliceous cements may be crystalline, cryptocrystalline, or amorphous. Smaller crystal sizes **fill** more pores to make a more resistant rock. Carbonate cement (calcite-- CaCO_3) is the dominant cement found in sedimentary rocks. Like siliceous cements, carbonate cement is classified by grain size. Because calcite is prone to weathering from dissolution (see Section 5.1), **it** is not a strong cement in areas with high rainfall. Iron cements are composed of siderite (FeCO_3), hematite (Fe_2O_3), goethite (FeOOH), and limonite ($\text{Fe}_2\text{O}_3 \cdot 2\text{H}_2\text{O}$). Iron cement is usually an incomplete pore or contact cement with low strength and poor weathering resistance (Winkler 1975). Clay cements are found in lithified alluvial or beach deposits and are moderately stable in regions of low rainfall (Blatt, Middleton and Murray 1972).

4.2 TEXTURAL FEATURES

Rock weathering rates and rock textures are linked primarily by grain size and mineral spatial associations. A short description relating texture to weathering rates of each of the three general rock types is presented here as background to later sections.

4.2.1 Igneous Rock Texture and Weathering

Texture in igneous rocks refers to the features of size, shape, and arrangement of the component mineral grains (Williams, Turner and Gilbert 1954). Differences in texture between igneous rocks can influence weathering in a number of ways. Spatial arrangements between stable and unstable minerals can lower rock integrity through differential weathering. For example, if coarse-grained pyroxene and calcic plagioclase crystals interlock with quartz and alkali-feldspar, the high-temperature minerals will break down first and leave a weak and porous rock. Local concentrations of unstable minerals can weather, leaving large voids in a rock.

Grain size and mineral association can also influence mechanical weathering processes. As temperatures in the weathering environment fluctuate, different minerals expand and contract by varying degrees. If a rock's texture is such that two interlocking minerals have greatly different coefficients of thermal expansion, diurnal temperature changes may lead to physical separation at the grain boundaries. This physical weathering makes the rock more permeable and leads to accelerated chemical weathering.

Grain size alone can become a factor in chemical weathering by influencing the rate of advance of weathering agents. Fine-grained rocks are generally less permeable than coarse-grained rocks of equal density. Increased permeability in coarse-grained rocks will usually accelerate weathering.

4.2.2 Texture in Sedimentary Rocks

Texture in sedimentary rocks refers to the clastic's grain size and shape, and the resulting packing. Grain size is reflected by the rocks' generic names: sandstone, siltstone, claystone. Sand consists of particles ranging from 0.0625 mm to 2.0 mm; silt consists of particles ranging from 0.0039 mm to 0.0625 mm; and clay consists of particles less than 0.0039 mm (Wentworth 1922). Clay-sized particles are frequently mineralogical clays and resist further crystalline transformation from chemical weathering; yet clays are substantially softer than other minerals and are subject to mechanical weathering. The intergrowth of grains is inherently related to durability. Chemical precipitates frequently have intergrown crystals that decrease the porosity and make the rock more resistant to weathering. Grain shape reflects the weathering that the particle has been through and is described by rounding (i.e., the number of sharp edges a mineral has). Well-rounded clastics probably are composed of weathering-resistant minerals. Grains of equal size and shape pack with greater porosity than grains of different sizes and shapes. Packing also determines the quantity of cement required for lithification (Figure 4.1).

KIND OF CONTACT	SYMBOL	DIAGRAMMATIC APPEARANCE	CLASS NO.
FLOATING	F		0
TANGENT	T		1
LONG	L		2
COMPLETE	C		3
SUTURED OR SERRATED	S		4

FIGURE 4.1. Grain Packing (Griffiths 1967)

Both fabric and structure are related to texture in sedimentary rocks. The fabric of sedimentary rocks describes the orientation of the detrital material. Parallel arrangement of particles causes differing planes of strength and may increase permeability along some axes, thus enhancing weatherability. Structure describes the thickness of bedding units. Sedimentary rocks are formed by the parallel superposition of weathering products. Laminated beds are <1 m thick, flags are 6 to 10 m thick, and massive structures are >100 m thick (Winkler 1975). In general, thin-bedded deposits are subject to greater weathering than massive units.

4.2.3 Texture in Metamorphic Rocks

Because metamorphic rocks are crystalline with interlocking grain boundaries, textural factors described for igneous rocks in Section 4.2.1 generally apply. However, some textural features are unique to metamorphic rocks.

During the process of dynamic metamorphism, minerals are often segregated into bands and recrystallized to form new rocks (e.g., gneiss). Metamorphic rocks with distinct bands of contrasting mineral assemblages are subject to differential erosion. When those segregated bands alternate between light and dark minerals, which is often the case, the rock is particularly susceptible to differential weathering.

Mineral orientation in metamorphic rocks and mineral segregation characteristics may affect weathering rates. Dynamic metamorphism often results in preferred orientation of grains parallel to the longest axis. This nonrandom association of mineral grains can increase permeability and permit a greater penetration of weathering agents.

4.3 ENGINEERING PROPERTIES OF ROCKS

In addition to mineral composition and texture, engineering properties are important considerations in rock weathering studies. Among the more important engineering properties are specific gravity, porosity, sorption, and strength characteristics (Krynine and Judd 1957).

4.3.1 Specific Gravity and Porosity

Specific gravity is a function of a rock's weight, grain porosity, and water sorption. The specific gravity is defined as follows:

$$\text{Specific Gravity} = \frac{W_0}{W_w - A - W_s}$$

where

W_0 = dry weight of rock

W_w = weight of water-saturated rock

W_s = weight of rock while suspended in water

A = weight of water filling the rock pores.

However, a more commonly used measure is the apparent specific gravity:

$$\text{Apparent Specific Gravity} = \frac{W_0}{W_w - W_s}$$

where W_0 and W_s are the same as defined above.

Porosity is the percentage pore space in a rock, or the ratio of void volume to total volume. The value of porosity can be expressed as follows:

$$\text{Porosity} = \frac{W_w - W_0}{V} \times 100$$

where V is total volume and W_w and W_0 are as defined in the specific gravity calculation.

Studies have shown that a relationship exists between porosity and specific gravity and a rock's mode of origin (Griffith 1937). Crystalline igneous and metamorphic rocks that were formed at high temperature and pressure tend

to have low porosity and high specific gravity. Sedimentary rocks tend to have higher porosities and lower specific gravities. Typical specific gravities and porosities of various rock types are presented in Table 4.2.

4.3.2 Water Sorption

The degree of pore filling by water determines the rock's surface area exposed to chemical weathering agents. Percent sorption is a ratio of rock volume to the volume of sorbed water, and can be expressed as follows:

$$\text{Percent sorption} = \frac{W_w - W_0}{W_0} \times 100$$

where W_0 and W_w equal dry weight and wet weight, respectively.

Water sorption, or the degree of saturation, can be inhibited by trapped air or by expanding clay material in pore spaces. Whether water is attracted to the pore wall or remains "free" also influences sorption rates. Sorption properties of rock specimens presented in Table 4.2 show that sedimentary rocks generally sorb more water than igneous or metamorphic rocks.

4.3.3 Rock Strength

Strength characteristics that determine a rock's rate of failure under stress include: compressive resistivity to volume changes and resistance against shear forces. Compressive strength is a measure of the force per area a rock can withstand when unconfined at the sides. Typical ranges of compressive strength of different rock types are presented in Table 4.3.

Correlations have been observed between rock texture and compressive strength (Windes 1949; Obert and Duvall 1945). These studies show that coarse-grained crystalline rocks are weaker than fine-grained crystalline rocks. Sedimentary rocks with the highest compressive strength are those that have been silicified (i.e., cemented with silica).

Degree of water sorption in rock pores has an inverse effect on strength, (i.e., as the percent of sorption increases, the compressive strength decreases). Studies show that wet conditions can decrease strength in granites by 10%, and by 10% to 20% in layered sandstones, limestones, and slates (Kessler, Insley and Sligh 1940; Obert, Winde and Duvall 1946).

Shear stress is the component of stress that acts tangentially to any given plane of a rock. Generally shear is thought of as the product of vertical compression and tangential force, and can be expressed as:

$$S = P \times \tan \phi + C$$

TABLE 4.2. Specific Gravity, Porosity, Sorption, and Unit Weight of Various Rocks (Griffith 1937)

Rock Type	No. of Specimens	Apparent sp. gr.	Porosity, %	Sorption, %	Dry Unit Wt., pcf
Igneous:					
Andesite	4	2.22	10.77	4.86	174.3
		2.70	0.72	0.28	168.5
		2.79	0.10	0.05	138.8
Aplite	1	(2.50) (a)	(4.11)	(1.67)	(156.1)
Basalt	4	(2.77)	(22.06)	(9.97)	(172.9)
		2.75	1.10	0.13	171.6
		2.21	0.22	0.66	138.2
Dacite	1	(2.46)	(3.50)	(1.44)	(153.6)
Diabase	2	2.95	0.17	0.06	184.4
		2.82	1.00	0.38	176.0
Gabbro	3	3.00	0.00	0.00	187.3
		2.86	0.29	0.13	178.4
		2.72	0.62	0.25	169.6
Granite	17	2.67	3.98	1.55	166.6
		2.60	1.11	0.44	162.7
		2.53	0.44	0.20	158.2
Granite	1	(2.99)	(1.67)	(0.58)	(186.6)
Granodiorite	1	(2.70)	(0.50)	(0.19)	(168.5)
Quartz Syenite	1	(2.63)	(1.54)	(0.62)	(164.1)
Rhyolite	1	(2.49)	(4.13)	(1.67)	(155.2)
Sedimentary:					
Breccia (syenite)	1	(3.10)	(0.78)	(0.27)	(193.3)
Breccia (limestone)	1	(2.28)	(18.73)	(8.26)	(142.1)
Chert	1	(2.48)	(4.10)	(1.69)	(155.1)
Coquina	1	(1.19)	(45.70)	(47.80)	(74.0)
Coral	2	2.66	1.06	0.41	166.2
Limestone	7	(2.54)	(4.36)	(1.73)	(158.9)
		2.67	1.70	0.65	166.8
		(2.72)	(0.27)	(0.12)	(169.7)
Limestone (dolomitic)	2	2.69	2.08	0.80	167.9
Limestone (oolitic)	3	2.66	1.06	0.42	166.3
Sandstone	6	(2.58)	(1.62)	(0.66)	(160.9)
		2.35	9.25	4.12	147.2
		1.91	26.40	13.80	119.5
Sandstone (calcareous)	1	(2.31)	(11.85)	(5.14)	(144.5)
Sandstone (clayey)	1	(2.48)	(6.10)	(2.48)	(155.1)
Travertine (onyx)	2	2.63	1.07	0.42	164.7
Metamorphic					
Gneiss	5	3.12	2.23	0.84	195.0
		2.66	0.78	0.30	166.1
		2.61	0.30	0.12	162.9
Marble	7	2.73	2.02	0.77	170.2
		2.61	0.62	0.23	163.1
		2.49	0.31	0.13	155.5
Marble (dolomitic)	2	2.84	0.60	0.21	177.2
Quartzite	3	2.64	0.46	0.17	164.7
Slate	3	(2.77)	(0.00)	(0.00)	(173.0)
		2.74	1.06	0.40	171.5

(a) Values in parentheses are results of tests on only one rock specimen. Where three values are given for one rock type, the middle value is the average for that particular physical property. However, the highest and lowest values shown were not used in computing the average value.

TABLE 4.3. Compressive Strength of Various Rocks
(Von Moss and deQuervian 1948)

<u>Rock Type</u>	<u>Strength, psi</u>
Diabase and some basalts and quartzites	Over 40,000
Fine-grained granite, diorite, basalt, quartzite, well-cemented sandstone and limestone	25,000 to 40,000
Average sandstone and limestone, coarse-grained granite and gneiss	10,000 to 25,000
Porous sandstone and limestone, shales	5,000 to 10,000
Tuff, talc, siltstone, very porous sandstone	Under 5,000

where

S = shear stress

P = compressive force

ϕ = angle of shearing resistance

C = cohesion.

Shear stress in riprap could result from elastic rebound within rocks freshly excavated from a deep quarry or from surface loading of other rocks. Plastic flow by gravity can also lead to failure from shear if rocks are large and not well supported.

5.0 ROCK WEATHERING AND DURABILITY

As an introduction to the following discussion of weathering agents and processes, the term "weathering" and other related concepts are more specifically defined here. In its simplest terms, weathering is a process of moving from an unstable to a stable state. Minerals and rocks are formed under a variety of environments: under high temperatures and pressures, under the influence of chemically and thermally active solutions, or from sediment deposition and chemical precipitation. At the time of formation, the rocks and mineral assemblages are in equilibrium with these environments, or rather, a thermodynamically stable set of conditions exists. When the environment changes, however, these materials are in a state of disequilibrium (instability). Thus, weathering represents the mechanisms whereby this instability is transformed to a new, stable set of conditions. In Winkler's (1975) words: "the process of weathering is merely the adjustment, or readjustment of minerals and rocks to conditions prevailing at the earth's surface, by conversion of existing minerals to minerals of higher stability towards the atmosphere." Other authors include the hydrosphere and biosphere as part of the new environment. Thus, the study of weathering lends itself to the tools of chemistry, physics, and thermodynamics.

Commonly, chemical weathering and physical weathering are treated as separate processes, although such a distinction is not always clear. Such a demarcation is convenient, however, because physical weathering is a process of disintegration, whereas chemical weathering is one of decomposition. Disintegration implies physical breakdown of the rock into its component materials without considerable change to the minerals themselves; decomposition involves chemical alteration of the minerals to form new minerals. Disintegration promotes an increase in surface area of the parent rock, thereby allowing accelerated chemical attack. Decomposition may remove the more reactive materials in the rock, leading to accelerated physical weathering.

5.1 CHEMICAL WEATHERING PROCESSES

Chemical weathering is a function of the availability of water and the thermodynamic properties of the solid. Water and its hydrogens are the critical reactants for any of the chemical weathering reactions: hydrolysis is a reaction in which water dissociates and hydrogen unites with the predominant anion of a mineral; hydration occurs when water either becomes part of the crystal lattice or is absorbed into it; oxidation uses oxygen from air and water molecules; solution centers around the solvent characteristics of water; and all acid reactions require hydrogen ions from water.

Water is an effective solvent because of its unique combination of chemical properties. As an ionic molecule with a high dipole moment, the water molecule has polar properties which allow it to cluster around charged ions with opposing electrical forces. Water is considered the universal solvent because dipolarity weakens the electrical field within a solid, eventually resulting in dissociation. Water's strong ionic nature accounts for its high surface tension and strong capillarity forces.

The stability of a mineral will dictate its resistance to chemical weathering. A mineral's stability is characterized by its free energy of formation (ΔG_f^0) and its inverse solubility (see Table 5.1). Stable minerals have low free energies and are difficult to break apart. However, the kinetics rate of a dissociation reaction determine whether the mineral will dissociate. For instance, a mineral could have a high energy of formation, but the kinetics of dissolution could be so slow that the reaction would not occur.

Parker (1970) proposed a weathering index for silicates based on the amount of energy required to break the bond between the alkali and alkaline earth metals and oxygen. It is defined by the expression

$$\left(\frac{(\text{Na})_a}{(\text{Na}_2\text{O})_b} + \frac{(\text{Mg})_a}{(\text{MgO})_b} + \frac{(\text{K})_a}{(\text{K}_2\text{O})_b} + \frac{(\text{Ca})_a}{(\text{CaO})_b} \right) \times 100 = \text{Weathering Index} \quad (5.1)$$

where

a = atomic properties of element $\left(\frac{\text{atomic percentage}}{\text{atomic weight}} \right)$

b = bond strength of oxide.

The above expression reduces to:

$$\left(\frac{(\text{Na})_a}{0.35} + \frac{(\text{Mg})_a}{0.9} + \frac{(\text{K})_a}{0.25} + \frac{(\text{Ca})_a}{0.7} \right) \times 100 = \text{Weathering Index} \quad (5.2)$$

TABLE 5.1. Energies of Formation of Selected Minerals
(Lindsay 1979)

Mineral	Formula	ΔG_f^0 , kcal/mole ⁻¹
Olivine	(Mg,Fe)SiO ₄	-460.08
Pyroxene	CaAl ₂ SiO ₆	-756.13
Albite	NaAlSi ₃ O ₈	-886.15
Microcline	KAlSi ₃ O ₈	-894.71
Muscovite	KAl ₂ (AlSi ₃ O ₁₀)(OH)	-1339.15

Parker generated the following table of weathering index values (Table 5.2) from published weathering profiles and found that rocks with the highest values were most likely to weather.

TABLE 5.2. Application of Weathering Index to Chemical Analyses of Weathered Rock Profiles (Parker 1970)

Profile ^(a)	Values of the Index							Rock Type	
	Fresh Rock -----					→ Weathered Rock			
S-1	78.2	71.8	68.3	43.3	34.6	30.3			Granite
S-2	76.0	77.5	68.5	52.7					Granite
T-1	82.7	76.0	75.2	62.9	52.9	49.5			Granite
T-2	80.0	76.3	74.7	70.8	43.4	47.2			Granite
E-1	75.9	65.2	67.2	69.7	37.7	22.4			Granodiorite
Windy	77.8	43.7	20.3	13.4	8.8				Hypersthene-Andesite
Cohasset	70.0	50.9	6.7	2.3	2.1				Olivine-Andesite
Kiama	93.5	62.8	30.4	20.4	15.7	19.8			Latite
Bathurst	87.7	64.7	4.7	4.5	4.5	4.5	5.6	13.6	Basalt
Inverell	81.9	13.8	11.9	6.8	6.0	3.1			Basalt
Casino	106.0	85.4	45.5	30.3	16.8	9.7			Basalt
Guyra	89.4	78.0	29.6	27.6	19.7	18.8	28.1		Basalt
Murrundi	87.6	60.6	62.3	32.5	46.8	46.0	27.2	17.2	Basalt

(a) The profiles below are specific samples described in Parker (1970).

5.1.1 Hydrolysis

Hydrolysis is the dominant chemical weathering process for igneous rocks (Chorley 1969) (see Appendix A). Water dissociates and the hydrogen ions join with anions from the minerals, for instance:

Hydrolysis produces an alkaline weathering solution with the formation of the hydroxide radical (OH⁻). The hydroxides are available for the production of clays, the ultimate chemical weathering product. However, hydrolysis may be slowed by the formation of hard weathering rinds on the rocks if the weathered silicates and clays (if not removed by water) form relatively insoluble crystalline skins (Krauskopf 1979; Fritz and Ragland 1980; Appendix A includes a more detailed discussion of this process).

5.1.2 Hydration

Hydration is a chemical weathering process with mechanical weathering implications because hydration frequently involves a change in volume. The end products of this type of chemical weathering are either altered hydration products or hydrated minerals (usually clays). The two most basic hydration reactions are the conversion of anhydrite to gypsum and of hematite to limonite:

Clays easily hydrate because they have very open crystal lattices. Montmorillonite, beidellite, and montronite are clays that swell tremendously in the presence of water (Loughlin 1931; Grim 1968). Gauri (1978) reported a case of hydration weathering that occurred during stabilization work on a

monument. Iron rebars were used for reinforcement. The oxidation and hydration of the iron resulted in the formation of limonite, which swelled during periods of high humidity causing the monument to break apart.

5.1.3 Oxidation

Oxidation is a primary weathering reaction for rocks with large amounts of iron, sulfur, or manganese. The black and dark red surfaces of many rocks reflect weathering from oxidation. The chemical reaction involves the loss of an electron of an element to oxygen and the acquisition of a positive charge. The two sources of oxygen are atmospheric oxygen and oxygen from the hydrolysis of water.

Much of the iron in primary minerals is in the ferrous (+2) state. Weathering through oxidation forms relatively insoluble ferric (+3) hydroxides.

The oxidation of ferrous and ferric silicate minerals may well approach the corrosion rates of iron. Conductive minerals (pyrite, marcasite, and hematite) if present in water may be subject to electro-chemical corrosion attack (Winkler 1975). Corrosion studies have detailed the weaknesses as a result of the oxidation of iron, including a decrease in fatigue strength, stress corrosion cracking, and embrittlement. Weaknesses imposed by oxidation may be adequate to cause the disintegration of a rock or to allow greater susceptibility to forces of mechanical weathering.

The surface coatings formed by the oxidation of iron oxides can protect the rock from further weathering if the coatings are homogeneous and impermeable, preventing the migration of oxygen to fresh surfaces (Loughlin 1931; Larrabee and Mathay 1963). Hydrated iron oxides are soluble in acids, and the greater concentration of acids in today's environment could increase leaching of iron from weathered surfaces.

5.1.4 Solution

Solution reactions occur when a mineral has a high solubility. Independently, solution is a very minor weathering process for most minerals and rocks. However, the chemical precipitates, limestone, dolomite, and gypsum,

are very susceptible to solution weathering (Jackson 1970). As in other chemical reactions, solubility increases with an increase in temperature and a decrease in ionic strength (Winkler 1975).

Much of the laboratory work on weathering has examined solution by leaching rocks and minerals with distilled water over long periods of time (Goldrich 1938; Pedro 1961; Keller, Balgoard and Reesman 1963). Some general conclusions may be drawn about the solubility and resistance of different elements. All the alkali metals will leach out quickly, while Si, Fe, Al, and Ti will maintain or increase their concentration in comparison to other elements in the solid (see Figure 5.1). Water and CO₂ will increase in the mineral structure.

A number of different models have been developed to describe the extent of solution weathering. Simple Si:Al ratios were used to rate rocks, based on the assumption that the Si was mobile and the Al insoluble. Reiche (1943) and Ruxton (1968) point out that this will be invalid when examining rocks from semi-arid savannahs where iron and silica precipitate in the weathering zone or in regions where the ferromagnesian-rich smectite and vermiculite are the initial weathering products. Reiche (1943) developed a potential weathering index (PWI) based on the ratio of easily leached oxides to the resistates.

$$\frac{100 (CaO + Na_2O + MgO + K_2O + H_2O)}{SiO_2 + Al_2O_3 + Fe_2O_3 + TiO_2 + FeO + CaO + MgO + Na_2O + K_2O} = PWI \quad (5.3)$$

The formation of insoluble ferric hydroxides was taken into account in the modified potential weathering index [White and Sarcia (1978) after Reiche (1943)]:

$$\frac{-(CaO + Na_2O + MgO + K_2O) + (Fe_2O_3 - 1/2 FeO) + \text{Combined Water}}{(\text{combined } SiO_2 \text{ and all the oxides})} = \text{Modified PWI} \quad (5.4)$$

5.1.5 Acid Attack

Acid attack of stone has always been an active weathering process, but its importance has increased substantially since the Industrial Revolution. High concentrations of pollutants (specifically, carbon dioxide, sulfur oxides, and nitrates) combine with hydrogen from the hydrolysis of water to form acids. The average composition of carbon dioxide in air is 0.034%, but heavily industrialized cities sometimes have as much as 0.27% from the incomplete burning of hydrocarbons. Sulfate and chloride concentrations have doubled in the last fifty years in Lakes Erie, Ontario, and Michigan (Winkler 1970). The combustion of coal with sulfur concentrations ranging from 1.5% to 8% is the largest source of sulfates (Winkler 1975).

FIGURE 5.1. Subtraction Diagram Showing the Relative Rates of Loss of the Various Components of the Average Granite, Assuming **it** to be Leached by the Average Ground Water.

As acid attack can occur only in the presence of water, **it** is a formidable weathering process in regions of high rainfall. Acid-forming materials cannot break down rocks and minerals without the hydrogen ion from the hydrolysis of water. Undersaturation, or dilution makes acids more corrosive (Larrabee and Mathay 1963).

Carbonation

The carbonation reaction is an important acidic weathering process because of the rapid dissolution of CaCO_3 and the formation of carbonic acid. Carbon dioxide is readily soluble in water, and depending on the availability of hydrogen ions, reacts to form the weakly acidic carbonic acid or the soluble bicarbonate ion.

or

The soluble bicarbonate formed from the dissolution of calcite, limestone, and marble is easily washed away, freeing other surfaces for weathering.

Temperature, the availability of carbon dioxide, and vegetation determine the solubility of CO_2 in water. Solubility decreases as the temperature decreases. Rainwater at 0°C usually has 95 ppm calcite in a rural area, 120 ppm in urban areas, 140 ppm in industrial areas, and 700 ppm in soils. More than 60% of the CO_2 found in urban areas comes from automobiles and the combustion of hydrocarbons; heavy industry contributes the rest. In soils, intense metabolism from living organisms within a closed system increases the concentration substantially (Winkler 1975). Carbonation is thus the most active weathering process occurring around buried materials.

The saturation of solutions with carbon dioxide strongly affects their weathering capacity. Hard waters, or solutions that are saturated with bicarbonate and other ions (e.g., Cl , SO_4 , Ca , Mg) are less likely to weather rocks through acid attack than are soft waters with lower concentrations of bicarbonate. Undersaturated soft waters are thus very corrosive (See Figure 5.2). Arid areas of the west have very hard waters and carbonation is not as active a weathering process as it is in the east.

A number of calculations on the weathering of carbonates have been performed (Loughlin 1931; Miller 1952; Keller, Bagoard and Reesman 1963; Winkler 1975). Keller, Balgoard and Reesman (1963) leached common silicate minerals with distilled water and CO_2 -charged water and observed doubled leaching rates for Ca , Mg , Na , and K in the CO_2 -charged waters. Measurements on limestone buildings and monuments in the midwestern United States with 75 to 100 cm of annual rainfall indicated that limestone would weather 30 mm in 1000 years; similar studies in England showed potential weathering rates of 6 mm/year (Winkler 1975).

Acids from Sulfur Compounds

Sulfur enters the atmosphere from ocean spray, gypsum dust, desert flats, and volcanic activity, but principally from the burning of coal, oil, or

FIGURE 5.2. Approximate Solubility Equilibrium of Calcium Carbonate

natural gas. Carbon monoxide and sunlight serve as catalysts for the transformation of sulfur dioxide (SO_2) to sulfite (SO_3^{2-}) (Winkler 1975). Sulfur and its oxides then combine with hydrogen to make sulfuric and sulfurous acid.

Acids from sulfur are present in greater amounts at high relative humidity or when diluted with large amounts of water; 0.6 kg H_2SO_4 can be dissolved

at 50% humidity whereas 4.5 kg H₂SO₄ can be dissolved at 98% humidity (Winkler 1975). Larrabee and Mathay (1963) suggest that sulfuric acid is moisture absorbing, and thus self-diluting.

Sulfuric acid alters carbonates (e.g., limestone) to sulfates and dissolves other rocks through hydrolysis. The rapid denudation of limestone buildings in urban areas such as London and Chicago are being attributed to this process:

Other Inorganic Acids

Chlorides and nitrites also form acids. Chlorides enter the atmosphere through ocean spray, through eolian dispersion of chloride evaporite deposits, and from industrial activities. A small fraction of nitrates enters the atmosphere from lightning and from organic decay in soils, but most comes from the oxidation of hydrocarbons. Nitric acid is slightly more corrosive than hydrochloric acid (Lindsay 1979). Nitrogen behaves like sulfur with multiple oxidation states that can be used to both oxidize and hydrolyze rocks.

5.2 MECHANICAL WEATHERING FACTORS

To a first approximation, the physical weathering processes leading to disintegration of rocks exposed at the earth's surface can be divided into two categories: internal forces acting within the rock material itself, and external forces acting on the surface of the rock. For the most part, differential pressure forces constitute the internal forces that produce cracking, spalling, sloughing, fracturing, and the removal of individual grains, a few of the common forms of disintegration. These pressure forces can result from a variety of mechanical processes, including expansion and contraction of mineral grains during changes in temperature, the growth of ice crystals within pores and cracks, the growth of other secondary minerals (including the formation and transport of soluble salts), hydration, and unloading pressures produced by the quarrying and exposure of buried rock masses.

External forces acting on rock surfaces are of a dynamic (abrasive) nature (e.g., wind and water action, where suspended material transported by these media scours the rock surface). Wave action has deleterious effects on riprap used for protection of banks on earthen dams because of a process known as cavitation, discussed below. The quarrying, transport, and placement of rock used for riprap can produce extreme abrasive forces, which can lead to disintegration.

As with chemical and physical weathering processes, factors influencing mechanical wear are interdependent and can proceed in conjunction with or

separate from each other. Thus, a number of rock characteristics need to be examined before the weatherability of a rock type can be determined (see Appendix A).

5.2.1 Frost Action and Freeze/Thaw Cycles

Frost damage to rocks is one of the primary causes of disintegration. When water freezes, a spontaneous volume expansion of approximately 9% occurs. As Schaffer (1932) and others point out, water that is completely confined in the pore spaces and capillaries of rocks, and that subsequently freezes, can exert tremendous pressures, producing weathering features on a variety of scales. The degree of disintegration can range from the removal of individual mineral grains, to the development of cracks and fractures, to the complete breakdown of the original rock into smaller-sized fragments. The rate and degree of disintegration caused by frost action depends on climatic factors such as temperature variations and amount of precipitation, and on certain characteristics of the rock itself (e.g., porosity, pore size, and sorption properties--Winkler 1975).

As reported by Winkler (1968, 1975), water freezes at 0°C and 1 atm while expanding from a density of about 1.000 to 0.9165, but under conditions of confined freezing the pressure will increase 1750 psi for each 1°C decrease in temperature. With the aid of a pressure-volume-Temperature (p-v-T) diagram for water at temperatures below freezing, Winkler (1975) explains that ice confined in rock pores can achieve a pressure of 610 atm at -5°C, 1130 atm at -10°C, and 2115 atm at -22°C. At this last temperature and pressure, the "triple point" of water with density (d) = 1.086, Ice II with d = 0.948, and Ice III of d = 1.1459 is achieved; thus, subsequent increases in pressure are much less significant. To put the disruptive forces associated with these pressures into perspective, Findlay [(1923), as reported by Schaffer (1932)] reported a pressure of 2115 kg/cm² for the "triple point" of water, Ice II, and Ice III, whereas the tensile strength of most construction grade stone is 7 to 104 kg/cm² (Hirschwald 1912).

Hudec (1978a, 1978b) reports that many rock types that appear to be sensitive to ("frost" weathering actually tend to saturate by adsorption (water molecules adhering to the walls of pores and capillaries) rather than by absorption, and that adsorbed water is generally unfreezeable. In these cases, the disintegration that appears to be caused by frost formation is actually caused by the expansion of the rock as the water is adsorbed. In this instance, "wetting and drying" is a more accurate descriptor of the process causing weathering. Hudec (1978a) and Dunn and Hudec (1966) point out that sound rocks that are susceptible to frost action are characterized by open porosity and large pore size, which in turn allows the absorption of bulk, freezeable water. Swihart (1979) examined the premise of the role of adsorbed versus absorbed water in granites and concluded that in cold regions the freezing of water within rock pore spaces is the prime weathering agent. Both studies, however, draw a distinction between fresh rock and rock that had already experienced some degree of weathering. The latter displayed greater weight losses when subjected to simulated frost activity.

Saltzman (1975) reports on Winkler's (1975) description of three mechanisms whereby ice formation may lead to the disintegration of rock:

- a "hydraulic pressure" (after Powers 1955), whereby still unfrozen water confined in pore spaces is further compressed by the advancing ice front, so that increased pressures produced by this mechanism, in conjunction with the expansive pressures produced by freezing water, cause bond rupture and disintegration
- a "temperature-dependent volume change of adsorbed water," which is a recount of Dunn and Hudec's (1966) efforts summarized above
- "dual mechanism theory," whereby the actions of hydraulic pressure, adsorbed water, and ice pressure combine to produce disruption (after Larsen and Cady 1969).

Schaffer (1932) reports that temperature fluctuations across the freezing point that produce alternate freezing and thawing are more disruptive than the forces associated with frost action when the temperature remains below 0°C. Winkler (1975), Saltzman (1975), and Larsen and Cady (1969) report a critical mean pore diameter of 5 microns, below which water will remain trapped in the rock during alternating cycles of freezing and thawing, but above which water may be able to drain out freely. However, Hudec (1978b) points out that smaller pore size will result in smaller amounts of freezeable water being absorbed. A 5-micron pore size appears to be the critical limit that balances these two processes.

Freeze/thaw testing is a common exercise to determine the durability of riprap. The most resistant rocks (based on test results) appear to be dense, fine-grained igneous rocks (e.g., rhyolite), whereas many sedimentary rocks, particularly porous or jointed carbonates (e.g., limestone), show rapid disintegration. However, as will be seen in Section 6.0, caution must be exercised when interpreting the results of such tests.

5.2.2 Temperature

Temperatures above 0°C are known to produce many of the same types of rock weathering as ice action, although different processes are at work. Cracking, fracturing, spalling, and grain removal are common weathering features. Two sources of heat are responsible for temperature-induced disintegration: solar insolation and fire. Both forces produce thermal expansion of rocks, but proceed at different rates. Fire damage to rocks will induce relatively immediate consequences, whereas damage to rocks exposed to normal variation of atmospheric and surface temperatures will require more time to appear (Schaffer 1932). For the purposes of this report, physical weathering phenomena associated with the wetting and drying of exposed rocks are included in this section because of the relationship between temperature, humidity, and evaporation.

Schaffer (1932) summarized two processes whereby temperature fluctuations can cause rock disintegration:

- stresses induced within the rock by unequal expansion and contraction of the component materials
- stresses induced by the expansion and contraction of the surface layers relative to the underlying material.

Crystal structures of rock-forming minerals exhibit different coefficients of expansion in different directions. Thus, changes in temperature may induce cracks in the surface that allow attack by other weathering agents. Schaffer points out, however, that thermal expansion alone may not account for the deleterious effects seen in various rock types, because the thermal gradients set up by the heating of the surface are not capable of inducing sufficient stress in all cases. Saltzman (1975) supports this thesis by referring to the works of Reiche (1950), Sparks (1973), Tarr (1915), and Griggs (1936); who discuss the role of water in contributing to rock disintegration by thermal expansion. Winkler (1975) and Dunn and Hudec (1966) point to adsorbed water as a disruptive force because this "ordered" water can remain in the liquid state to temperatures of -40°C and can expand sufficiently to produce disruptive pressures. Winkler discusses the role of ordinary sorbed water, which can expand sufficiently when heated to induce rapid disintegration. As an example, he makes use of the p-v-T diagram for water above 0°C (Winkler 1975). He points out that at 60°C , unconfined water expands 1.5% by volume, whereas granite expands only about 0.15%. If small pore spaces containing water prevent expansion of the water (i.e., the water is completely confined), a pressure of -360 atm (5000 psi) will be induced within these pores. This is sufficient to cause disruption of the granite. Furthermore, in arid or semi-arid desert climates, intense solar insolation is capable of heating the surfaces of rocks to 60°C and higher. Rapid disintegration can result in a few years time due to the expansion of moisture in rocks in this type of environment (Griggs 1936).

The intense heating produced by fires in forested areas can have severe consequences on rock survivability. A complete summary of the effects of fire can be found in Winkler (1975). Here, he reports on the findings of Kieslinger (1954), Tarr (1915), and Boyd and English (1960), who demonstrate that the response of quartz minerals to extreme temperatures ($\sim 500^{\circ}\text{C}$) is the determining factor for fire-induced disintegration because quartz expands several times more than other common rock-forming minerals. Increases in volume in quartz at about 500°C can establish internal pressures of 1000 to 2500 atm, although many rocks will crack sooner. Basic igneous rocks appear least susceptible to the effects of fire because of their lower quartz content. Cracking and spalling (exfoliation) will occur along planes of weakness within the rock (e.g., joints and secondary mineral veins) and can produce fragments from flake size to complete separation of the rock into two or more pieces [Blackwelder (1926), as cited by Ollier 1967]. Pritchett, Riney and Nayfeh (1974) summarize experimental findings on the production of cracks in heated granite and other rocks when the heated area is struck by a water jet.

Technically speaking, disintegration by the wetting and drying cycle process does not require temperature variations because the damage is caused by the expansion of rock as it sorbs water and the subsequent contraction when the water evaporates. Hudec (1978a) argues that the effects of wetting and drying are similar to those for freeze/thaw weathering, and the ability of adsorbed water to remain unfrozen to very low temperatures is the primary agent for this type of disintegration. The chief source of moisture is not necessarily rainfall or surface water, but rather atmospheric water vapor, which condenses as dew on rock surfaces (Winkler 1975). Carbonate rocks appear to be most susceptible to this form of weathering, although some granites also may disintegrate in a few years (Hudec 1978a).

5.2.3 Salt Action and Moisture

Salt action, in conjunction with moisture, in rock may be the cause of the most severe and rapid disintegration found in nature. The crystallization of soluble salts, particularly the sodium, calcium, and potassium sulfates, and the hydration and dehydration of these salts, can induce significant pressures within the pore and capillary spaces of rock used for riprap.

Two processes of crystallization are described in the literature. Efflorescence describes the crystallization of salts that have migrated from within the rock to the surface. There they form layers of a hard crust that can spall easily, removing layers of the parent rock material (Sleater 1977). As a result, fresh rock surfaces are exposed to the attack of new weathering agents. Subflorescence, or in Schaffer's (1932) words "cryptoflorescence," describes the crystallization of salts within the body of the rock. These two processes can occur simultaneously or separately. "Florescence" is a term frequently used to describe both processes when a distinction between the two is unnecessary or unclear.

Evaporation and the pore and capillary properties of the rock appear to influence the role of salts in rock disintegration (Schaffer 1932). Temperature, humidity, and wind velocity control evaporation rates and the drying of rock, and thus influence the hydration/dehydration of soluble salts, as well as their movement through the rock. The physical properties of the rock influence capillary transport of the dissolved salts because the suction forces within the rock depend on the size and distribution of open channels for moisture migration. Schaffer (1932) discusses the theoretical considerations of moisture transport in capillary systems. These two properties are interrelated, as water will migrate to areas where the rate of evaporation is the greatest, and because crystallization will occur only under conditions of supersaturation [Correns (1949) as cited by Winkler (1975)].

Sources of soluble salts include salts present within the rock that migrate into the rock before quarrying (e.g., halite); salts migrating into the rock from the upward migration of ground water after the rock is placed as a protective blanket (particularly calcium, magnesium, and sodium sulfates, and sodium and calcium chlorides); and salts transported as atmospheric pollutants (some sulfates and sea-salts)--(Sleater 1973; Winkler and Wilhelm 1970; Schaffer 1932).

As described by Winkler (1975), salts may migrate through rock by ionic diffusion, capillary motion, or ionic osmosis. Crystallization of these salts at the rock surface produces a softening and crumbling of the rock, which is especially pronounced in carbonate rocks (Mamillan 1968; Winkler 1975) but also is found in much denser stone.

The disruptive influences of salt action can be attributed to osmotic pressure, crystallization pressures, hydration pressure, and differential thermal expansion of salts. Winkler (1975, 1980a) argues that hydration pressures are the most damaging. He demonstrates that maximum osmotic pressures are insufficient to cause disintegration other than surface flaking. In addition, Schaffer (1932) points out that crystallization pressures are insufficient to exceed the compressive and tensile strengths of most construction grade stones, citing the efforts of Correns (1926) and Nacken (1928), which support the same conclusion.

Several publications point to salt hydration pressure as the force responsible for the disintegration of even the hardest rocks on a time scale of several years (Winkler 1970, 1975, 1980b; Mortensen 1933; Schaffer 1932; Saltzman 1975; Sleater 1973, 1977). The hydration/dehydration of several common salts in response to changes in atmospheric temperature and humidity can produce pressures within confined pore spaces of up to 2800 atm (42,000 psi). As Winkler (1975) discusses, the compressive strength of many rock types used for construction, including riprap, is on the order of 5,000 to 10,000 psi, but their tensile strength is much lower, on the order of one-third to one-tenth the compressive strength. Hydration pressures, therefore, can rapidly rupture all but the strongest material. Salt hydration was blamed as the force that nearly destroyed a granite obelisk (Cleopatra's Needle) in New York in less than a year. This monument had survived virtually unscathed in the Egyptian desert for 4000 years but weathered rapidly when placed in the humid New England environment (Winkler and Wilhelm 1970; Winkler 1980a).

Cooke and Smalley (1968) note that salt crystals exhibit differing thermal properties; thus, differential expansion and contraction of these secondary minerals may contribute to disintegration. For example, when the temperature of granite is raised from 0°C to 60°C (as might occur in a desert climate), halite (NaCl) expands 0.5% as compared to a 0.2% expansion of the granite.

5.2.4 Hydration

Chorley (1969) points to the uptake of water by clay minerals within rocks as a cause of physical disintegration. The volume expansion associated with the hydrated minerals can produce pressures capable of fracturing the rock. Similarly, the leaching of soluble ions by chemical weathering agents permits the hydration of the crystal lattices of the silicate minerals found in most rock types (Winkler 1975). These processes are most pronounced during extended periods of wetting and drying cycles. Chorley observed that the Mancos Shale formations of the Colorado Plateau (the site of several uranium tailings piles) are particularly susceptible to hydration pressures.

Unloading

Saltzman (1975) concludes that unloading (stress relief) combined with crystal growth (e.g., ice and salts) represent the most damaging physical weathering agents for riprap. Unloading describes the process whereby rock expands when compressional, tensional, or shear stresses to which the rock has been subjected are allowed to dissipate (Winkler 1975). These stresses may result from natural phenomena, such as the confining pressures experienced by deeply buried rock, or they may be artificially induced by quarrying operations, particularly blasting (Lienhart and Stransky 1981). In either case, the expansion of the rock accompanying the removal of these stresses can produce a wide range of physical deformities. Examples include the faulting of large blocks, the development of massive exfoliation (sheeting) in granites, the spheroidal weathering of boulders in hard igneous rocks, jointing, fracturing, and cracking. These features are most likely to develop in and around quartz grains because of their greater expansion characteristics (Ollier 1967; Fookes, Dearman and Franklin 1971; Winkler 1975; Lienhart and Stransky 1981).

The implications of these phenomena for riprap durability are two-fold. First, the physical disintegration that accompanies unloading can produce significant material loss. Second, and perhaps most important, the development of fractures and cracks promotes the infiltration of water, exposing the rock to attack by other chemical and physical weathering agents. Unloading reduces the strength of the rock, alters its physical properties, and thus promotes more rapid disintegration (Winkler 1980b).

Winkler (1975) provides a qualitative and quantitative description of stress relief. In short, he emphasizes the fact that rock "in its natural setting has established a temporary equilibrium with the external forces of erosion and weathering." When buried rock is exposed at the surface by natural weathering/erosional processes, or by man's activities associated with quarrying, a new equilibrium must be established. The accompanying redistribution of stresses may take only minutes, or may require several hundred years. Unless an onsite determination of stress conditions and lithology is made at the quarry before removal of the rock, estimating how the rock will respond to stress relief once it is applied as a protective blanket is very difficult (Lienhart and Stransky 1981).

Proper blasting techniques are critical for producing suitable rock for riprap. Lienhart and Stransky (1981) outline the procedures to be followed to insure that residual stress from the blasting is quickly dissipated. Once the rock is removed, it should be "cured" ("aged") by stockpiling for a period of time (these authors recommend six months) to allow water to drain from the rock and to allow stress relief to occur. Curing also promotes "case hardening," the formation of layers of hard crust on the rock surface promoted by the movement of moisture to the surface. Such crusts may provide protection against attack by weathering agents, particularly in an arid environment if

calcite is a component of the material (Winkler 1975). Freeze/thaw and wetting/drying susceptibilities of riprap have been attributed to the failure to allow for a proper curing period.

Restricting production time to summer months also appears desirable. Disintegration is accelerated during the winter months, partly because of the expansion of frozen pore water in the freshly quarried rock.

5.2.6 Abrasion

Four abrasive processes can be identified that promote disintegration of riprap: wind action (scouring), water action (scouring and cavitation), animal and plant activity (boring and root penetration), and mechanical abrasion occurring during the quarrying, transport, and placement of riprap.

Wind-blown particles can have serious consequences for rock durability, although erosion rates are difficult to quantify (Schaffer 1932). Desert climates, where wind velocities may be high and where an abundant supply of material exists that can be suspended and carried along by wind action, tend to promote disintegration by scouring (Winkler 1975). Geologic displays such as those found in Chicago's Field Museum of Natural History contain samples of rock that have experienced significant material loss due to wind abrasion on a time scale of a few tens of years to a few centuries. "Soft" rock such as some sandstones and loosely compacted sedimentary rocks are most susceptible to scouring. Wind erosion of exposed rock increases surface area and thus promotes attack by other weathering agents (Leet and Judson 1971).

Flowing water that carries suspended sediments may produce effects similar to wind scouring, but the primary forces of water-induced disintegration are associated with cavitation. De Puy (1965), De Puy and Ensign (1965), and Saltzman (1975) discuss the role of cavitation on the failure of rock used for riprap on earthen dams. Cavitation describes the process of the formation and rupture of vapor and gas bubbles in a liquid medium. When these bubbles are in contact with a material surface and subsequently burst, pressures in the range of 10^4 psi can be exerted on the material, producing pitting and scouring (Saltzman 1975). The above authors have concluded that the rapid disintegration of riprap near the waterline on earthen dams is caused by wave action and the resulting cavitation phenomena. Riprap used on tailings piles probably will not be subjected to this type of weathering.

Little information exists on the physical weathering processes associated with animal and plant activity (at least not on a time scale of more than a few years). Boring and root wedging are known to promote disintegration, but perhaps their most important role is to expose and widen cracks and other openings in rock, allowing the subsequent infiltration of moisture (Stembridge 1973).

The mechanical abrasion of rock probably will not be a factor once riprap is installed on the tailings pile if proper engineering and construction practices are followed. Abrasion and material loss occurring during quarrying, transport, and placement will indicate weakness in the rock (e.g., poor

cohesion and fracturing--DePuy and Ensign 1965). Proper screening and selection of the rock to be used as riprap should limit abrasive losses. Rock that is unsuitable because of weight loss by abrasion will be susceptible to rapid disintegration by other weathering processes.

6.0 DURABILITY TESTS

Rock durability in this report refers to the ability of rocks to resist the forces of disintegration (physical weathering) and decomposition (chemical weathering) on a time scale comparable to the expected service life of the armoring blanket used on tailings piles. All rocks exposed at the surface are subjected to weathering phenomena leading to a final equilibrium state as residual soil or displaced sediments. Therefore, the suitability of a rock type for use as riprap will depend on the rate at which it succumbs to weathering agents, which in turn depends on a number of factors, including the physical and chemical characteristics of the rock and the environment to which the rock is exposed.

Several testing procedures have been devised and are in use by organizations such as the U.S. Bureau of Reclamation for evaluating riprap and building stone durability. These tests are divided into two groups: procedures for determining the physical characteristics of the rock (e.g., density and porosity) and investigations of the effects of accelerated weathering phenomena, particularly freeze/thaw and wetting/drying susceptibilities.

Although the reliability of these tests is acceptable for many short-term applications, several shortcomings should be emphasized here:

- Quantitative analysis of rocks is limited to determination of susceptibility to physical weathering agents. Little mention exists in the literature of methods for evaluating the chemical weatherability of rocks, and most investigations have relied on reaction chemistry theory and field observations (Winkler 1975; Curtis 1976).
- The final determination of a rock's suitability for use as riprap is often based on a qualitative judgment by the examiner, who relies on a petrographic examination of the rock's physical properties and mineral composition (De Puy 1965; De Puy and Ensign 1965; Klein^(a)).
- Proper sampling procedures are critical for reliable results because Samples of rock taken from the same quarry may show large variations in weathering tendencies (Lienhart and Stransky 1981).
- Current testing procedures use small samples of the rock under investigation and the preparation of the samples (e.g., crushing and cutting) frequently masks properties relevant to durability prediction (Klein and Oliverson^(b); Lienhart and Stransky 1981).

(a) Personal communication from Peter Klein of the U.S. Department of the Interior, Bureau of Reclamation, Denver, Colorado, on October 28, 1981.

(b) Personal communication from Peter Klein and Jim Oliverson of the U.S. Department of the Interior, Bureau of Reclamation, Denver, Colorado, on October 28, 1981.

How well artificial accelerated weathering tests simulate actual environmental conditions is uncertain (De Puy 1965; De Puy and Ensign 1965).

- Little corroborative evidence exists between durability tests and actual field performance because of the short history of testing procedures (Saltzman 1975).
- The testing of riprap and other aggregate stone is based on the premise that this material will be used in projects that have a service life of perhaps 100 years and that will be subjected to routine maintenance (e.g., dams and roadways). Such assumptions are not valid for the purposes of this discussion, as the protection of tailing piles must be insured for much longer periods.

Although all of the above points are critical to an understanding of the merits of the procedures currently used to evaluate rock durability, the last two best reflect the problems associated with identifying rocks to be used as tailings piles armoring. The lack of corroborative evidence and the time requirements for tailings pile stability imply that 1) supporting evidence must be acquired and better test procedures developed, or 2) the determination of riprap durability will have to rely on empirical evidence and qualitative judgments.

6.1 EVALUATION OF ROCK PROPERTIES

The following discussion summarizes the test procedures currently used to evaluate physical rock properties and mineral composition. The reader is referred to the works of De Puy and Ensign (1965), De Puy (1965), Saltzman (1975), and Winkler (1975) for a more complete comparison and theoretical evaluation of these analyses, as well as for a description of procedures to be followed in conducting the tests. Schaffer (1932) presents a historical perspective on materials testing, and discusses procedures for interpreting results, as well as the pitfalls to be avoided.

6.1.1 Specific Gravity [American Society of Testing Materials (ASTM) C-97-47, 1958]

Bulk specific gravity, the ratio of the mass of the rock to an equal volume of water, is considered a good indicator of rock quality because it is a measure of the compactness of a rock, which implies strength. When used in conjunction with porosity and sorption characteristics, specific gravity can provide data on the ability of rock to withstand cycles of freezing/thawing and wetting/drying. Transportation costs are affected by specific gravity.

6.1.2 Porosity

Porosity is volume of pore space in the rock in relation to its total volume, expressed as a percentage. Pore volume and capillary size determine the sorption characteristics of rock, and thus indirectly define the ability of water and salts to cause disruption. The bulk density and porosity of some common rocks are given in Table 6.1

TABLE 6 - Bulk Density and Porosity of Some Common Rocks.
(Winkler 1975)

<u>Rock</u>	<u>Bulk Density gm/cm³</u>	<u>Porosity, %</u>
Granite	2.6 to 2.7	0.5 to 1.5
Gabbro	3.0 to 3.1	0.1 to 0.2
Rhyolite (felsite)	2.4 to 2.6	4.0 to 6.0
Andesite (felsite)	2.2 to 2.3	10.0 to 15.0
Basalt	2.8 to 2.9	0.1 to 1.0
Sandstone	2.0 to 2.6	5.0 to 25.0
Shale	2.0 to 2.4	10.0 to 30.0
Limestone	2.2 to 2.6	5.0 to 20.0
Dolomite	2.5 to 2.6	1.0 to 5.0
Gneiss	2.9 to 3.0	0.5 to 1.5
Marble	2.6 to 2.7	0.5 to 2.0
Quartzite	2.65	0.1 to 0.5
Slate	2.6 to 2.7	0.1 to 0.5

6.1.3 Water Sorption (ASTM C-97-47, 1958; ASTM C-127-68, Modified, 1949)

Although the results of this test are usually interpreted in terms of absorbed water, actually, both adsorbed and absorbed water are being measured. Sorption by itself is not a good indicator of freeze/thaw durability because rocks with high sorption values but good drainage characteristics have proved very durable. Nevertheless, low absorption is a desirable property of riprap to prevent rapid disintegration by salt action and mineral hydration.

6.1.4 Hardness

Hardness is a measure of the rock's resistance to permanent deformation, which is an important consideration for quarrying practices and the effects of abrasion. Several accepted tests are available for evaluating rock hardness. Scratch, indentation, abrasion, rebound, and impact hardnesses are measured separately or in combination, depending on the intended use for the rock.

Scratch hardness for rocks is similar to Moh's hardness for minerals (see Figure 6.1). Indentation hardness is a measure of the load required to create a permanent indentation in the rock and reflects the hardness of the hardest mineral present. The Vickers Diamond Hardness and Knoop Hardness tests are two of the preferred procedures for evaluating indentation hardness. Abrasive hardness (ASTM C-241-51, 1958), on the other hand, depends on the average

ROCK TYPE	RANGE OF MOH'S HARDNESS								
	1	2	3	4	5	6	7	8	9
GRANITE, GNEISS						—			
BASALT, FELSITE					—				
SHALE		—							
SANDSTONE		—							
LIMESTONE, MARBLE			—						
DOLOMITE			—						
SLATE			—						
QUARTZITE							—		

Figure 6.1. Scratch Hardness of Selected Rock Types
Based on Moh's Relative Mineral Hardness
Scale: 1 (least resistant) to 9 (most
resistant) (after Winkler 1975)

hardness of all minerals present. Rebound hardness is a measure of the elastic properties (compressive strength) of a rock, which may be important to a rock's ability to survive cycles of expansion and contraction. The Shore scleroscope and Schmidt hardness tests are commonly used for performing this test on riprap.

Rock impact hardness (ASTM D-3-13, 1942) is a measure of resistance to sudden impacts such as those aggregate used in roadways might experience. Intergranular bonding appears to influence both a rock's rebound and impact hardness, which serve as a measure of a rock's brittleness.

6.1.5 Strength

The relationship between compression and tensile strength and rock behavior during cyclic expansion and contraction was discussed in Section 5. Compressive strength is the load per unit area that causes the shearing or splitting of a block sample. Winkler (1975) and others distinguish between unconfined (uniaxial) and confined (triaxial) strength. The uniaxial compressive strength test (ASTM C-170-50, 1958; ASTM D-2938-71) is used as a measure of rock durability for riprap, although wide scatter in the data has proved troublesome in the past (Figure 6.2).

TERM	psi	kg/cm	ROCK MATERIALS
VERY WEAK	<1,000	<70	
WEAK	1,000-3,000	70-200	
MEDIUM STRONG	3,000-10,000	200-700	
STRONG	10,000-20,000	700-1,400	
VERY STRONG	>20,000	>1,400	

FIGURE 6.2. Ranges of Uniaxial Compressive Strength for Selected Rock Types (after Winkler 1975)

Tensile strength, from one-third to one-tenth the compressive strength, is a measure of the ability of rock to resist a pulling force (Brazilian Splitting Tensile Test--U.S. Army Corps of Engineers 1980). This measurement is important when considering the ability of rock to resist differential pressures and when estimating the blasting force required to quarry the material. The tensile strength depends on the strength of both the individual mineral grains and the cementation material, as cracks and fractures apparently begin at the boundaries between individual grains.

6.1.6 Sonic Velocity

Sonic velocity measurements are made by recording the time required for a short duration stress pulse to travel through a prepared rock specimen. These measurements are used to compute elastic constants for the rock, such as the modulus of elasticity (E), which define the stress-strain relationships of the rock. Such relationships, in turn, help to quantify the strength of the rock, although directly relating velocities to rock strength has proved difficult in practice.

6.1.7 Petrographic Analysis

A detailed petrographic examination of rocks considered for use as riprap has been a standard procedure and is highly recommended by the U.S. Bureau of Reclamation (De Puy and Ensign 1965). This examination (ASTM C-295-54) identifies rock types by mineral composition and describes certain salient features of the sample, including clay veins, cracks and fractures, and unsound sections. The Bureau of Reclamation uses petrographic examinations as the standard against which other tests are rated. Its limitations are that a final estimate of the rock's durability is based on the qualitative judgment of the examiner rather than on quantitative test values, and that careful

attention must be given to obtaining a representative sample of the rock from the quarry. The latter can prove to be a formidable task because of the variations inherent in rock types even within the same seam or outcrop.

6.2 ACCELERATED WEATHERING TESTS

The tests described below are commonly performed to simulate physical weathering agents in the laboratory. Procedures for conducting these tests, and their ability to reproduce environmental conditions in an accelerated time frame, are discussed by Hudec (1978a,b), Harvey et al. (1978), Saltzman (1975), De Puy (1965), De Puy and Ensign (1965), Lienhart and Stransky (1981), Wiman (1963), and Schaffer (1932).

6.2.1 Freeze/Thaw

Freeze/thaw durability, perhaps the most frequently performed weathering test, is conducted by subjecting pre-cut samples of rock immersed in water to alternate cycles of temperature above and below 0°C. The U.S. Bureau of Reclamation executes this test for 250 cycles at a rate of 8 cycles per day, thus requiring 5 weeks to complete a single run. Other testing laboratories may follow different procedures, for example, using a water-alcohol immersion bath to promote absorption, and allowing for a greater or lesser number of cycles.

This procedure is probably most effective on microporous and absorptive rocks that are not free-draining (e.g., limestone and dolomite), but is of little use in determining freeze/thaw susceptibilities on dense, porous rocks such as some igneous varieties.

Rock durability is measured in terms of the percent weight loss in the sample, based on before and after weighings. However, the form of weight loss usually is not specified; that is, no distinction is made between a 50% loss of material that is reduced to individual grains (rubble) and the same weight loss that is due to the sample merely splitting into two equal halves.

Freeze/thaw tests have produced extensive disintegration in samples of rock that in practice appear to perform quite well, whereas other samples have shown little weight loss during the test only to disintegrate rapidly when applied as riprap. Furthermore, determination of the number of temperature cycles representative of actual environmental conditions complicates the assessment of disintegration rates. Riprap placed in a high altitude alpine climate may experience only a few such cycles annually, whereas a desert wintertime climate may produce diurnal cycles of freezing and thawing. Lienhart and Stransky (1981) report that an attempt is being made to correlate the number of laboratory-induced cycles with those occurring in nature at locations throughout the continental U.S., but this information was unavailable for this report.

6.2.2 Sodium Sulfate Soundness Test

The sodium sulfate soundness test, a measure of a rock's resistance to differential pressures produced by the growth and expansion of secondary mineral crystals, is frequently employed in lieu of, or in conjunction with, the freeze/thaw test. Although attempts have been made to correlate the results with empirical evidence of salt action, it generally is assumed that this test simulates the fracturing and crumbling associated with ice action.

The test (ASTM C-88, 1973) requires alternately soaking a rock sample in a sodium sulfate (Na_2SO_4) solution and then drying the specimen in an oven. Crystal growth occurs in the pores, producing flaking and rupture as the water evaporates. Harvey et al. (1978) provide a concise description of the theoretical aspects of this test. The primary drawback is that this procedure produces the greatest deterioration in rocks with an extensive pore system, which in nature are the ones least susceptible to frost action because they are free-draining. Conversely, microporous rocks, which should be most affected by freeze/thaw weathering, display minimal deterioration.

6.2.3 Wetting/Drying

The purpose of the wetting/drying test is to examine the effects of alternate wetting and drying such as might be experienced during summertime conditions (Lienhart and Stransky 1981). Whether this test simulates the weathering conditions associated with pressures within the rock arising from alternate absorption and subsequent evaporation, or the conditions produced by hydration/dehydration of the minerals themselves, is unclear. Nevertheless, the previously cited authors state that this test is very effective for selecting suitable rock types for use as armoring stone.

The test is conducted by soaking samples in water at 10°C for six hours, and then drying them under heat lamps that produce realistic surface rock temperatures (e.g., 60°C). Before and after weighings determine the percent weight loss.

6.2.4 Los Angeles Abrasion Test

The LA abrasion test (ASTM C-535-69, ASTM C-131), designed to determine the resistance to mechanical wear of large-size aggregates, is frequently used for testing riprap, although restrictions placed on the grading of the samples prevents testing rocks of the same size as those commonly used in protective blankets. The test is conducted by crushing the samples to conform to size requirements and then rotating these pieces in a drum for a specified number of revolutions. Weighing and sieving of the material determines the percent weight loss.

Resistance of the rock to this type of mechanical wear is related to rock quality, but not necessarily to rock durability (e.g., freeze/thaw or wetting/drying susceptibility). The test does indicate the lack of cohesion, or

"softness" of the rock, and provides a relatively reliable test for material loss caused by erosive forces such as wave action. Currently, no way exists to correlate the results of the LA abrasion test with actual field performance in terms of specifying a timetable for abrasive disintegration.

6.2.5 Ultrasonic Cavitation Test

When first developed during the mid-1960s, the ultrasonic cavitation test was considered a breakthrough as a procedure for determining rock durability. It is performed by attaching a sample of rock to a small piezoelectric transducer that operates at 20,000 cycles per second. The sonic vibrations produced by the transducer induce mechanical vibrations in the rock that are believed to simulate the cavitation phenomena discussed in Section 5. As a result, pores and cavities in the rock are quickly enlarged and defects quickly detected.

Although cavitation is associated with water action on riprap on earthen dams, results of this testing procedure have provided good indications of overall rock durability. However, the test alone is not sufficient for ascertaining rock quality, but should be used in conjunction with other procedures. It requires a very small rock sample that must be carefully prepared before conducting the test. Also, a final determination of rock durability may require a qualitative judgment based on a visual examination of the specimen.

6.2.6 Test Standards and Comparisons

Criteria for determining the suitability of rock for use as riprap based on the results of the aforementioned tests are given in Table 6.2. These values are recommended by the U.S. Bureau of Reclamation (De Puy and Ensign 1965), but the life expectancy requirements for Bureau projects is, in general, much shorter than those that will have to be met by tailings pile armor-ing rock. Table 6.3 presents the criteria suggested by the Bureau for interpreting the results of the ultrasonic cavitation test in terms of a visual inspection of the sample, and Table 6.4 presents a different set of criteria for this test (and others) based on weight loss, as determined by Saltzman (1975).

The relative merits of these tests are reflected in the results of a study performed by the Bureau, which are summarized in Table 6.5. However, the ability of the tests to evaluate rock durability are based on a benchmark comparison with petrographic analyses of the rocks studied, not with actual field performance. Qualitative and quantitative results of these tests on various rock types, as measured by the Bureau, are given in Tables 6.6 and 6.7. The poor performance of the granite sample is attributable to the severely weathered sample chosen for comparative purposes.

TABLE 6.2. U.S. Bureau of Reclamation Standards for Judging Riprap Durability (De Puy and Ensign 1965)

Test	Quality		
	Poor	Fair	Good
Ultrasonic cavitation rating	0 to 5	5 to 7	7 to 10
Bulk specific gravity	2.5	2.5 to 2.65	2.65
Absorption, %	1.0	0.5 to 1.0	0.5
Freeze-thaw weight loss, %(a)	5	0.5	0 to 0.5
Na ₂ SO ₄ weight loss, %	10	5 to 10	5
Los Angeles abrasion loss, %(b)	10	5 to 10	5
Schmidt impact hammer	40	40 to 60	60
Scleroscope	30	30 to 50	50
Coefficient of restitution(c)	0.5	0.5 to 0.7	0.7
Tensile strength, psi	500	500 to 1,000	1,000
Compressive strength, psi	15,000	15,000 to 20,000	20,000
Sonic velocity, ft/sec	15,000	15,000 to 17,000	17,000

(a) 250 cycles

(b) 100 revolutions

(c) rebound hardness

TABLE 6.3. U.S. Bureau of Reclamation Criteria for Judging Results of Ultrasonic Cavitation Test Based on Visual Examination (De Puy and Ensign 1965)

Numerical Durability Rating	Amount of Cavitation Damage
0	Sample completely broken up before 1 minute
1	Sample broken up by end of 1-minute test
2	Severe deterioration
3	Severe general erosion
4	Severe pitting
5	Moderately severe pitting
6	Moderate pitting
7	Minor pitting or some intergranular erosion
8	Some minor intergranular erosion
9	Very slight pitting
10	No visual damage

TABLE 6.4. Criteria for Judging Results of Ultrasonic Cavitation Test Based on Weight Loss and Durability Ratings for Selected Additional Tests (Saltzman 1975)

Name of Test	Excellent Acceptability	Conditional Acceptability	Not Acceptable
Ultrasonic cavitation test, total weight loss in mg	0 to 20	20 to 90	>90
Schmidt value	>40	35 to 40	<35
Los Angeles abrasion (modified), % weight loss ^(a)	<20	20 to 40	>40
Freeze-thaw (% weight loss) ^(b)	<20	20 to 30	>30

(a) 1000 revolutions

(b) 20 cycles using water-alcohol solution

TABLE 6.5. Comparative Rating of Selected Riprap Durability Tests for Determining Rock Quality. The ability of a test to accurately predict rock quality is rated against a determination of rock quality using petrographic examination (De Puy 1965)

Rating	Test Method	Percent Agreement With Rock Quality
1	Petrographic examination	85
2	Tensile strength	84
3	Specific gravity	80
4	Schmidt hammer	79
5	Absorption	75
6	Freeze-thaw	70
6	Compressive strength	70
6	Scleroscope	70
6	Sulfate soundness	70
10	Coef. restitution	65
11	Pulse Velocity	60
11	Cavitation	60
13	L. A abrasion	50

TABLE 6.6. Qualitative Results of U.S. Bureau of Reclamation Tests for Riprap Durability (De Puy and Ensign 1965)

Rock Type	Sample No.	Petrographic Evaluation	Bulk Sp G	Absorption	Freeze-thaw	Na ₂ SO ₄ Soundness	L.A. Abrasion	Schmidt Impact Hammer	Scleroscope	Coefficient of Restitution	Compressive Strength	Tensile Strength	Sonic Pulse Velocity	Ultrasonic Cavitation
Limestone and Calcareous	M-4855	Good	Good	Good	Good	Good	Fair	Good	Fair	Good	Fair to Good	Fair to Good	Good	Fair
	M-4851	Good	Good	Good	Fair	Poor	Fair	Fair	Good	Good	Poor to Good	Poor to Fair	Good	Poor to Good
	M-4876	Good	Good	Good	Good	Fair	Fair	Good	Good	Good	Good	Fair to Good	Good	Fair
Sandstone	M-4746C	Fair	Poor	Poor	Fair	Poor	Poor	Poor	Poor	Fair	Good	Poor	Fair	Poor
	M-4634B	Poor	Fair	Poor	Fair	Poor	Fair	Poor	Good	Good	Poor	Fair	Fair	Poor
	M-4611C	Poor	Fair	Poor	Poor	Poor	Fair	Fair	Fair	Good	Poor to Fair	Fair	Fair	Poor
	M-4879B	Poor	Poor	Poor	Fair	Fair	Fair	Poor	Poor to Good	Poor to Good	Poor	Poor	Fair	Fair
	M-4077	Poor	Poor	Poor	Poor	Poor	Fair	Poor	Poor	Fair	Poor	Poor	Fair	Poor
Quartzite	M-4299C	Good	Good	Good	Good	Good	Good	-	Good	Good	Good	Fair to Good	Good	Good
Sandstone	M-4762	Good	Fair	Poor	Good	Fair	Fair	-	Good	Good	Good	Fair to Good	Poor	Fair
	M-4652C	Fair to Good	Poor	Fair	Good	Poor	Fair	Good	Good	Good	Fair	Poor to Good	Fair	Good
	M-4759	Fair	Poor	Poor	Poor	Fair	Poor	-	Good	Good	Fair to Good	Fair to Good	Poor	Poor
	M-4802	Poor	Poor	Poor	Fair	Poor	Poor	Poor	Poor	Fair	Poor	Poor	Poor	Poor
Gabbro	M-4743	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good
Gneiss	M-4300	Good	Good	Good	Good	Good	Fair	-	Good	Good	Good	Good	-	Good
Andesite	M-4810	Good	Good	Poor	Good	Good	Fair	Fair	Good	Good	Poor to Good	Fair to Good	Fair	Fair
	M-4799	Good	Fair	Poor	Good	Good	Fair	Good	Good	Good	Fair to Good	Fair to Good	Fair	Fair
Basalt	M-4624	Good	Fair	Fair	Good	Good	Fair	Good	Good	Good	Poor	Fair to Good	Good	Fair
Tuff	M-4623	Fair to Poor	Poor	Poor	Poor	Fair	Fair	Good	Good	Good	Poor	Fair	Poor	Fair to Poor
Granite	M-3448-3		Poor	Poor	Poor	Poor	Poor		Fair to Good	Good	Fair to Poor			

6.3 EXPERIMENTAL AND OBSERVATIONAL EVIDENCE OF ROCK WEATHERING

As in all branches of science, information on the geochemical and geophysical aspects of rock weathering is derived from experimentation and observation. Because of the complexities of chemical and mechanical geologic processes, however, geologists and petrologists have had to rely heavily on field observations of weathering phenomena, which have proved difficult to duplicate in the laboratory. To review all of the evidence that supports the theories and conclusions presented in previous sections is beyond the scope of this report. For the purpose of clarity, though, some conspicuous examples of rock weathering are documented.

6.3.1 Observation: Monuments, Tombstones, Buildings, and Dams

Manmade structures are frequently studied as victims of weathering because of the engineering and architectural significance of preventing their decomposition and deterioration, because they provide quantitative indications of weathering rates, and because of the relative ease with which samples of weathered material can be obtained. Evidence of rock weathering in monuments, tombstones, and buildings is important for riprap engineering because similar types of rock frequently are used for both.

Observations of chemical attack by acidic solutions derived from aqueous dissolution of atmospheric gases have been made for a number of years in urban environments. Limestones and sandstones are particularly susceptible to attack by carbonic and sulfuric acids. Limestone weathers by the dissolution of calcium carbonate and the formation of hard surface skins which exfoliate. Sandstone, if cemented by carbonaceous material, will deteriorate rapidly as the cement is removed, leaving behind the individual sand grains. Schaffer (1932) presents photographs of such deterioration in London buildings and tombstones which, on a time scale of a few tens of years to a few hundred years, have weathered sufficiently to require major renovation to maintain structural integrity and appearance. Winkler (1975) presents photographs of a sandstone sculpture in Germany which between 1702 and 1908 displayed little wear, but between 1908 and 1968 was destroyed almost completely. He attributes this remarkable decomposition to the increase in urban CO₂ and SO₂ concentrations. Loughlin (1931) observes that chemical attack is minimal on igneous rocks containing mostly quartz, feldspars, hornblends, pyroxines, and some micas. However, igneous varieties that consist of secondary minerals produced by below-ground weathering (pale green micas, green micaceous chlorite, green epidote, calcite and other carbonates) may be subject to severe weathering.

Winkler (1975) considers the possibility that the weathering of ferrous-ferric oxides and silicate minerals by oxidation may occur at rates similar to the corrosion of manmade iron structures. Drawing on Larrabee and Mathay's (1963) observations of corrosion rates for openhearth iron specimens, Winkler reports weight losses on 2 x 4 x 118-inch specimens of from 0.16 g/year to 70.5 g/year, which vary as a function of climate. The former value is observed in a dry inland climate and the latter in a coastal marine environment.

TABLE 6.7. Quantitative Results of U.S. Bureau of Reclamation Tests on Rocks Used for Riprap, see Table 6.6 for durability ratings (after De Puy and Ensign 1965)

Rock Type	Sample No.	Petrographic Evaluation		Bulk Specific Gravity	Percent Absorption	% Wt loss	Cycles Freeze-Thaw	Na ₂ SO ₄ Soundness	L.A. Abrasion % wt Loss		Compressive Strength, psi	Tensile Strength psi Splitting Method	Sonic Pulse Velocity Longitudinal Wave, ft/sec	Hardness		Coefficient of Restitution	Extent of Cavitation	Cavitation Numerical Rating
		Description	Physical Quality						100 Revolutions	500 Revolutions				Schmidt Hammer	Scleroscope			
Limestone	M-4855	Hard, dense, pink	Good	2.74	0.5	0	250	3(a)	7.0(a)	31.7(a)	14,699 to 24,000	500 to 1,200	22,800	64	44	0.79	Moderate	6
	M-4851	Hard, brittle, fractured, brown	Good, but rock contains many fractures	2.65	0.4	0.4	250	10.9	5.6	24.3	13,000 to 21,000	315 to 600	22,300	47	50	0.79	Variable, slight to severe	3-8
	M-4634B	Moderately hard, buff to yellow, brittle fractured	Poor	2.50	1.6	70, severe disintegration	100	18.8(a)	5.4(a)	22.6(a)	8,000 to 16,000	600	-	34	70	0.87	Severe pitting, fracturing	4
	M-4611C	Finely porous	Poor	2.52	1.7	60	100	35.4(a)	6.5(a)	28.4(a)	15,500	500 to 800	16,750	58	43	0.77	Sample completely broken up	0
	M-4077	Soft, absorptive, chalky	Poor	2.42	5.3	50	20 to 42	18.7	9.3	39.6	-	-	-	-	20	0.54	Severe deterioration	2
Limy Sandstone	M-4876	Hard, dense	Good	2.67	0.4	0	250	5.7	6.4	28.6	20,200	500 to 1,060	19,400	60	69	0.81	Minor pitting, one corner broken off	7
	M-4746C	Weathered, porous	Fair	2.25	4.6	1	250	36.4(a)	12.9(a)	50.0(a) 5,000 to 12,000	Variable	360	15,000	39	25	0.64	Severe erosion	
	M-4879B	Weathered, porous	Poor	2.36 to 2.14	3.6 to 7.1	2	250	6.9(a)	10.7(a)	46.4(a)	1,000 to 6,000	160	15,700	34	24 to 55	0.44 to 0.77	Moderate enlargement of pores, heavy erosion on one edge	5
	M-4652C	Well cemented, firm	Fair to Good	2.36	0.6	0	250	15.4	9.8	39.5	17,000	340 to 1,050	16,300	61	80	0.93	Some intergranular erosion	8
Sandstone	M-4762	Firm, well cemented, fine-grained, red	Good	2.50	2.2	0.1	290	5.4	6.3	28.2	25,000	700 to 1,400	13,300	-	68	0.81	Moderately severe pitting	5
	M-4759	Similar to M-4762, but is slightly friable, somewhat weathered	Good	2.40	2.7	0.8, minor surface scaling	250	21.6	11.6	48.0	14,000 to 21,700	440 to 1,260		-	60	0.83	Severe pitting	4
	M-4802	Crossbedded, porous, poorly cemented, mediumgrained	Fair to Poor	2.20	4.0	0.6	250	40.4	50.3	95.7 6,000 to 11,000	Variable	200	12,100	27	27	0.67	Severe erosion	3
Quartzite	M-4299C	Very hard, contains many small, tight microfractures	Good	2.66	0	0	270	0.2	4.8	21.3 av 27,000	20,000 to 48,900	600 to 2380	18,700(a)		90	0.89	Some minor spalling and splitting along microfractures	8-9
Tuff	M-4623	Moderately hard and firm, well indurated, glassy	Fair to Poor	2.33	2.3	Variable 2 to 17	250	9.6	7.0	30.0	11,200	760	14,300	65	84	0.88	Variable, moderate to severe pitting	4-6
Andesite	M-4799	Vesicular, glassy, hard, dark gray	Good	2.59	1.1	0.2, very minor	250	1.9	5.4	23.9	18,500 to 20,500	530 to 1,200	16,900	60	85	0.89	Enlargement of vesicles, moderate pitting	6
	M-4810	Finely vesicular, hard, gray-black	Good	2.66 to 2.81	0.6 to 1.5	0	250	1.1	5.9	27.5	12,000 to 25,000	680 to 1,500	16,900	43	76	0.87	Moderate pitting	6
Basalt	M-4324	Vesicular, hard, black	Good	2.58	0.7	0.1	250	1.5	6.1	26.5 av 13,500	6,000 to 15,000	800 to 1,300	18,900	60	85	0.89	Moderate pitting	6
Granite	M-4624	Weathered, somewhat weakened, but moderately firm, contains intergranular fractures	Poor	2.41	24	Variable 0.6 to 36	170	12.3	14.4	51.7	14,800	350	-	-	45-75	0.76	Severe deterioration	2
Gneiss	M-4300	Mediumgrained, hard	Good	2.76	0	0	270	0.7	5.9	25.7	35,000	800 to 1,400	-	-	85	0.87	Some intergranular erosion	8
Gabbro	M-4743	Mediumgrained, hard	Good	3.10	0	0	250	0.8	2.7	12.2	50,000	2,000	22,300	73	94	0.94	Minor intergranular pitting	9

(a) Test results on sample containing some rock varying from described rocks; however, results are considered a reasonable approximation.

A classic example of salt action on stone is the previously mentioned deterioration of Cleopatra's Needle in New York. Salt action has been observed in all types of rock, but appears to be most damaging to sedimentary varieties. Research indicates that whereas the porosity of igneous rocks promotes salt crystallization, the strength of these denser materials serves to inhibit rapid deterioration.

Spheroidally weathered granite boulders may reflect the damage produced by unloading and frost action, although Ollier (1967) claims that chemical attack in the absence of volume expansion is responsible for this phenomenon. Dunn and Hudec (1966) believe that the freezing and thawing of a salt solution is more damaging than that induced by pure water, and Winkler (1975) points to the disintegration of a 100-year-old dolomite wall in Wisconsin as a possible example supporting their claim. Observations of rock from a limestone quarry show that moist quarry-fresh stone appears to be more susceptible to freeze/thaw weathering than cured stoned (Winkler 1975).

A study of the causes of failure of riprap dams in the western U.S. points to several weathering agents that produced rapid disintegration in numerous rock types (Esmiol 1967). Of 149 dams constructed since 1906, 46 displayed moderate to complete failure of the riprap. Of these, only three were classified as having failed as a result of means other than weathering agents. Abrasion produced by wind and water action caused the greatest number of failures, followed by "temperature variations," ice action, and water sorption. Fire, salt action, and plant root growth also were found to contribute to riprap failures. Sedimentary rocks (sandstone, shale, and limestone) were the most susceptible, with temperature variations being the primary cause of disintegration. Basic igneous rocks (basalt and andesite) showed the second highest rate of failure, where temperature, ice, fire, and salts were agents of weathering. Acidic igneous rocks (rhyolite and granite) were rated as having performed quite well.

6.3.2 Experimentation: Laboratory Analyses

During laboratory experiments of rock weathering, the investigator must find means to accelerate the weathering rate without altering the fundamental processes he is attempting to reproduce. Time and cost restraints dictate this approach. Nevertheless, experimental evidence has provided much of the data needed to determine the factors influencing the durability of rock.

Experiments simulating the attack of acidic gases on carbonate rocks have been able to reproduce weathering effects remarkably well. The dissolution of calcium carbonate in limestone by carbonic acid has demonstrated the role of atmospheric CO_2 on limestone leaching. Similarly, experiments using SO_2 and H_2SO_4 have been able to produce rapidly the crustal skins found on several carbonate rocks, and to promote the decomposition of calcareous sandstone (Schaffer 1932). Such experiments have provided evidence that the degree of decomposition depends on the periodicity of exposure to these agents. Continual exposure appears to produce results that correlate favorably with conditions observed in nature, whereas intermittent exposure followed by drying appears to retard the weathering process.

Experiments on the chemical weathering of silicate rocks indicate that sodium-plagioclase feldspars are leached faster than potassium-orthoclase feldspars, agreeing in principle with the theory of the Bowen series. The leaching of common rock-forming silicate minerals has been reproduced by the use of both distilled and CO₂-charged water. White and Sarcia (1978) report on removing appreciable amounts of silica from an olivine basalt using demineralized water. The silica dissolved initially (SiO₂) and subsequently precipitated as a siliceous gel, which is a common indicator of silicate weathering found in nature. Winkler (1975) recommends careful testing of basalt to be used for construction purposes, because many basalts have exhibited rapid weathering caused by chemical attack of the mineral analcite, which has produced rapid decomposition on a time scale of a few years. Acidic igneous rocks (e.g., granites) appear to weather much slower than sedimentary rocks or some varieties of metamorphic rocks.

Duplicating physical weathering processes in the laboratory has proved somewhat easier. Much of the literature focuses on water, salt, and ice attack on rock and stone.

The p-v-T diagram of water above freezing, referred to in Section 5.2.2, is reproduced in Figure 6.3. Contours depicting equal pressure of confined water as a function of temperature are indicated, as is the volume expansion of granite as a function of temperature. As can be seen, extreme disruptive

FIGURE 6.3. p-v-T Diagram of Water for Temperatures greater than 0°C (Winkler 1975)

pressures are produced by the confined expansion of water at temperatures well within normal environmental ranges measured in rock. Dunn and Hudec (1966) draw on data of this type to support their argument for the role of sorbed water as a major cause of deterioration in carbonate rocks. Alternate wetting and drying without a change in temperature was studied by Hockman and Kessler (1950; as reported by Winkler 1975). The effects of solar insolation and the alternate expansion and contraction of rock subjected to cycles of wetting and drying were studied by Griggs (1936; as cited by Winkler 1975). Dry granite subjected to a simulated 244 years of diurnal temperature changes displayed little wear, whereas a moist granite began deteriorating rapidly after only 2-1/2 years of simulated exposure.

Rock disintegration by salt action appears to be caused by crystallization, hydration, and differential thermal expansion pressures. Table 6.8 presents crystallization pressures of some common salts that were calculated from the theoretical discussions of Correns (1949; as reported by Evans 1969, in Winkler 1975) and which agree favorably with laboratory evidence. As mentioned earlier, a condition of supersaturation is required for crystallization. As the ratio of the solute concentration during crystallization to the saturation concentration (C/C_s) decreases, crystallization pressures decrease. Note, also, that increasing temperature is associated with higher pressures.

The p - T diagram for water/ice at temperature below freezing is presented in Figure 6.4 (see Section 5.2.1 for a discussion of these data). Wiman (1963) summarizes Tricart's (1956) experimental findings on freeze/thaw weathering, and his discussion of three types of frost weathering:

- macro-gelivation producing boulders, where fracturing occurs along cleavage and bedding planes
- macro-gelivation producing grains, where crystals are removed by disruption of the grain cement
- micro-gelivation, where deterioration occurs along microscopic cracks and fissures but does not appear to depend on obvious features of structure and texture.

Wiman's own experiments on frost weathering, although somewhat inconclusive, imply that slates, mica schists, and porphyritic granites weather to a greater extent than granites, metamorphic quartzites, or gneisses. Porosity, moisture content, and the number of freeze/thaw cycles appear to influence the rate and degree of weathering. The distinction between the roles of unfreezeable adsorbed water and bulk freezable water is still debated (see Section 5.2.1) and requires further investigation.

6.4 ROCK WEATHERING CLASSIFICATION

Observation and experimentation to analyze rock weathering has led geologists to advance methods for standardizing degrees of deterioration. Several such methods allow the engineering geologist to estimate rock durability

TABLE 6.8. Crystallization Pressures of Some Common Salts Found in Rocks and Stone.
C/Cs is the ratio of solute concentration to saturation concentration
(Winkler 1975).

Salt	Chemical Formula	Density, gms/cm ³)	Molecular Weight, gms/mole	Molecular Volume, cm ³ /mole	Crystallization Pressure, atm					
					C/C _s = 2		C/C _s = 10		C/C _s = 50	
					0°C	50°C	0°C	50°C	0°C	50°C
Anhydrite	CaSO ₄	2.96	136	46	335	398	1120	1325	1900	2262
Bischofite	MgCl ₂ · 6H ₂ O	1.57	203	129	119	142	397	470	675	803
Dodecahydrate	MgSO ₄ · 12H ₂ O	1.45	336	232	67	80	222	264	378	450
Epsomite	MgSO ₄ · 7H ₂ O	1.68	246	147	105	125	350	415	595	708
Gypsum	CaSO ₄ · 2H ₂ O	2.32	127	55	282	334	938	1110	1595	1900
Halite	NaCl	2.17	59	28	554	654	1845	2190	3135	3737
Heptahydrate	Na ₂ CO ₃ · 7H ₂ O	1.51	232	154	100	119	334	365	568	677
Kieserite	MgSO ₄ · H ₂ O	2.45	138	57	272	324	910	1079	1543	1840
Mirabilite	Na ₂ SO ₄ · 10H ₂ O	1.46	322	220	72	83	234	277	397	473
Natron	Na ₂ CO ₃ · 10H ₂ O	1.44	286	199	78	92	259	308	440	524
Tachhydrite	2MgCl ₂ · CaCl ₂ · 12H ₂ O	1.66	514	310	50	59	166	198	282	336
Thenardite	Na ₂ SO ₄	2.68	142	53	292	345	970	1150	1650	1965
Thermonatrite	Na ₂ CO ₃ · H ₂ O	2.25	124	55	280	333	935	1109	1590	1891

FIGURE 6.4 p-T Diagram of Water/Ice at Temperatures Below 0°C and Isolines of Water Density (Winkler 1975)

based on field examination of exposed rock masses. Generally, these techniques require the trained observer to examine both the parent rock and the residual soil, and to look for evidence of rock quality by studying crystal structure, fracturing, discoloration, and strength. Portable devices are available to test rock strength.

Fookes, Dearman and Franklin (1971) discuss several weathering classification systems and present one of their own that has proved very satisfactory for estimating the suitability of a rock type for construction. This method is presented in Table 6.9. The index value reported in the first column is derived from the work of Weinert (1964) and is used by the South African National Institute for Road Research (N.I.R.R.) for evaluating igneous rocks used for roadstone. The index is computed from the study of three rock properties: luster, hardness and consistency, and state of crystallization. Index values of 1 to 4 are assigned to each category and summed to obtain a rock quality total index value, where higher numbers indicate advanced weathering (see Table 6.10). The authors recommend that in applying a

TABLE 6.9. Engineering Classification of Rock Weathering for Rocks Suitable for use in Construction (Fookes, Dearman and Franklin 1971)

Index Value	N.I.R.R. Classification ^(a)	Grade	Degree of Decomposition	Field Recognition		Engineering Properties (after Little 1969)
				Soils (i.e., Soft Rocks)	Rocks (i.e., Hard Rocks)	
12	Residual soil	VI	Soil	The original soil is completely changed to one of new structure and composition in harmony with existing ground surface conditions.	The rock is discolored and is completely changed to a soil in which the original fabric of the rock is completely destroyed. There is a large volume change.	Unsuitable for important foundations. Unstable on slopes when vegetation cover is destroyed, and may erode easily unless a hard cap present. Requires selection before use as fill.
11						
10	Badly weathered	V	Completely weathered	The soil is discolored and altered with no trace of original structures.	The rock is discolored and is changed to a soil, but the original fabric is mainly preserved. The properties of the soil depend in part on the nature of the parent rock.	Can be excavated by hand or ripping without use of explosives. Unsuitable for foundations of concrete dams or large structures. May be suitable for foundations of earth dams and for fill. Unstable in high cuttings at steep angles. New joint patterns may have formed. Requires erosion protection.
9		IV	Highly weathered(b)	The soil is mainly altered with occasional small lithorelicts of original soil. Little or no trace of original structures.	The rock is discolored; discontinuities may be open and have discolored surfaces and the original fabric of the rock near the discontinuities is altered; alteration penetrates deeply inwards, but corestones are still present.	Similar to Grade V. Unlikely to be suitable for foundations of concrete dams. Erratic presence of boulders makes it an unreliable foundation for large structures
8						
7	Weathered	III	Moderately weathered(c)	The soil is composed of large discolored lithorelicts of original soil separated by altered material. Alteration penetrates inwards from the surfaces of discontinuities.	The rock is discolored; discontinuities may be open and surfaces will have greater discoloration with the alteration penetrating inwards; the intact rock is noticeably weaker, as determined in the field, than the fresh rock.	Excavated with difficulty without use of explosives. Most crushes under bulldozer tracks. Suitable for foundations of small concrete structures and rockfill dams. May be suitable for semipervious fill. Stability in cuttings depends on structural features, especially joint attitudes.
6						
5		II	Slightly weathered	The material is composed of angular blocks of fresh soil, which may not be discolored. Some altered material starting to penetrate inwards from discontinuities separating blocks.	The rock may be slightly discolored; particularly adjacent to discontinuities which may be open and have slightly discolored surfaces; the intact rock is not noticeably weaker than the fresh rock.	Requires explosives for excavation. Suitable for concrete dam foundations. Highly permeable through open joints. Often more permeable than the zones above or below. Questionable as concrete aggregate.
	Fresh					
3		I	Fresh rock	The parent soil shows no discoloration, loss of strength or other effects due to weathering.	The parent rock shows no discoloration, loss of strength or any other effects due to weathering.	Staining indicates water percolation along joints; individual pieces may be loosened by blasting or stress relief and support may be required in runnels and shafts.

(a) The N.I.R.R. Classification is given for comparative purpose and the Grade Figures given throughout the text are those in the third column.

(b) Total Index Value is obtained by adding the index value for luster, hardness and consistency, and state of crystallization.

(c) The ratio of original soil or rock to altered material should be estimated where possible.

TABLE 6.10. N.I.R.R. Rock Weathering Index for Igneous Rocks Used in Roadway Construction. See Table 6.9 for a comparison of this method with a more general classification scheme (Fookes, Dearman and Franklin 1971).

Property	Method of Determination	Description of Condition	Index Value										
Luster	From general impression; hand lens not used	Shiny, flickering when turned; dense cementing matrix (if present) looks greasy, iron oxide only as film on fissures.	1										
		Luster generally dull; natural color and luster of fresh rock partly retained; light-colored crystals may still reflect light but not dark ones; dense cementing matrix (if present) looks dull.	2										
		Dull yellowish; dull light grey or dull light brownish	3										
		Earthy red; earthy black when wet or earthy grey when dry.	4										
Hardness and consistency	Whole sample; not one surface only	Hard; rings when struck with hammer; breaks into sharp chips. Blasting required.	1										
		Still hard but breaks along natural cracks (often with flat surfaces) which are strongly stained with iron oxide; fresh cores surrounded by a clearly visible layer of weathering material. Picked with difficulty; blasting required in places.											
		Breaks easily into small pieces (sugar) many of which are loose crytals; friable; crystals and rock pieces break off when rubbed slightly with finger. Picked easily.	3										
		Soft; earthy; gravelly with grain diameter less than 1 cm; shoveled easily.	4										
State of crystalli- zation	By hand lens and steel needle	Crystals well defined with sharp boundaries between; up to 10 of the crystals may be oxidized, brittle or powdery; dense cementing matrix (if present) contains excellently shaped crystals. If no scattered crystals in the matrix, give sample same index value as allotted for 'luster'.	1										
		Most crystals are well defined; 10 to 50 of crystals oxidized, brittle or powdery; dense cementing matrix with or without loose crystals.	2										
		More than 50 crystals oxidized or powdery; original shape may be largely retained (light colored crystals, if present stand out clearly).	3										
		No crystals except quartz detectable.	4										
<div>Total Index Value = Luster Index Value + Hardness Index Value + Crystallization Index Value</div> <table><tr><th>Index Value</th><th>Classification</th></tr><tr><td>12, 11</td><td>Residual soil</td></tr><tr><td>10, 9, 8</td><td>Badly weathered</td></tr><tr><td>7, 6, 5</td><td>Weathered</td></tr><tr><td>4, 3</td><td>Fresh</td></tr></table>				Index Value	Classification	12, 11	Residual soil	10, 9, 8	Badly weathered	7, 6, 5	Weathered	4, 3	Fresh
Index Value	Classification												
12, 11	Residual soil												
10, 9, 8	Badly weathered												
7, 6, 5	Weathered												
4, 3	Fresh												

classification test to determine rock quality, the investigator should avoid using rock pieces lying loosely in a quarry or outcrop, and should attempt to evaluate freshly exposed rock surfaces.

The above methods represent but one weathering classification approach to evaluating rock durability. Ollier (1969) and Little (1969) have reviewed others that may prove desirable for ascertaining riprap durability.

7.0 CLIMATE AND WEATHERING: A PRELIMINARY MODEL OF RIPRAP DURABILITY

In the preceding sections we discussed the major weathering agents that attack stone and a number of geological concepts pertinent to rock durability. The type and degree of weathering that occurs depends on several environmental features, notably moisture availability and temperature. At the same time, a rock's response to the weathering agents depends on certain inherent properties such as mineral composition, porosity, and strength. This relationship between climate and lithology is examined to help determine the causes of rock deterioration and to guide a riprap durability evaluation.

7.1 ENVIRONMENTAL CONDITIONS

Water and temperature are two of the parameters that describe weathering climates. A more complete list appears below:

- moisture availability
- temperature
- solar insolation
- organic matter production
- source of hydrogen ions (H^+)
- vegetation
- topography
- wind.

Implicit in this list is the element of time. For our purposes (i.e., riprap durability for mill tailings armoring) the time interval is up to, or longer than, 1000 years. Although such a broad temporal scale is difficult to simulate in the laboratory, it is a very small fraction of geologic time (10^9 years); thus, we can dismiss many long-term weathering phenomena such as mountain building and lowering. Furthermore, we can observe certain datable weathering processes within this time frame, for example, weathering of the pyramids of Egypt, monuments such as Cleopatra's Needle (see Section 5.2.3), or some cathedrals of Europe. The rate of weathering of building/construction-grade stone appears to decrease exponentially with time. That is, the most vigorous attack occurs early in the weathering process and then proceeds more gradually (Winkler 1975).

The role of most of the above climatic factors in rock weathering was discussed in previous sections (see also Appendix A). Organic matter production (and, in part, vegetative cover) is relevant because of the production of organic acids that cause rock decay; topography (and, again, in part, vegetation cover) is included because relief features control water runoff and infiltration, and thus the availability of water. Topography also determines the role of gravity and the removal of weathering products, although this may be more important to soil development and sediment transport than to riprap durability.

The relationship between climatic factors and rock weathering frequently is discussed in terms of energy input/output models (Trudgill 1976). This is a convenient approach because rock weathering is really a series of energy transformations between kinetic, chemical, and thermodynamic energy forms (Curtis 1976). Freeze/thaw weathering is an example of thermodynamic and kinetic energy exchange processes. Chemical weathering proceeds by a series of commonly exothermic reactions to convert unstable mineral assemblages to more stable compounds (greater negative free energy--Keller 1978). If the preceding list of climatic factors represents sources of energy for rock weathering processes, in theory we should be able to identify the type and rate of weathering that will occur in a given geographical location by determining the magnitude of the energy inputs. However, weathering processes are so complicated that such an approach probably will only provide general guidelines for identifying weathering phenomena. These guidelines are discussed below.

When examining the relationship between climate and weathering, macroenvironment-, mesoenvironments, and microenvironments are discussed (Keller 1978; Hudc 1978b). Macroenvironments cover broad geological or geographical regions. Figure 7.1 presents one representation of the relationship between rainfall, temperature, and large-scale environments. Different weathering processes probably occur as a function of the type of climate experienced in such areas. Figure 7.2, for example, presents information on the degree of chemical weathering as a function of latitude, temperature, and water availability. There is a correlation among high moisture availability, high temperatures, and extensive chemical weathering. Likewise, Trudgill (1976) reports that chemical weathering may be accelerated as much as ten-fold when high levels of organic acids are available, which may explain the high degree of weathering in the tropics, and the comparatively lesser degree of weathering in tundra environments.

On the macrolevel, the relationship between chemical and physical weathering is determined in part by fluctuations of energy inputs. Notably, a stable environment of persistently high moisture availability and high temperatures (such as in tropical rain forests) should favor chemical weathering. Conversely, an environment characterized by less water, greater periodicity in the water supply, and large temperature fluctuations (such as in desert or high alpine environments) should favor mechanical weathering agents. These concepts have been used to identify global weathering zones and to explain broad geomorphological features. Our suggestions for relative weathering as a function of climatic variables are presented in Figure 7.3. The wide ranges of climatic conditions indicate that examination of such information on the macroscale can provide only a guideline for determining weathering conditions. Meso- and microenvironmental conditions require more definitive evaluation.

Mesoenvironments represent geographical features on a scale of tens to hundreds of square kilometers, or geological features such as soil horizons or deposition beds in a lake (Keller 1978). Differences in the type of weathering expected to occur on the mesoscale are probably not as important as

FIGURE 7.1. Relationship Between Climate and Vegetation.
 Symbols: r - character of rainfall
 t - temperature
 t_s - summer temperature
 t_w - winter temperature (Jackson 1970)

FIGURE 7.3. Variation in Temperature, Precipitation, and Organic Matter from the Pole to the Tropics--Related to the Depth of Chemical Weathering (Leet and Judson 1971)

FIGURE 7.3. Proposed Macroscale Relationship Between Climatic Variables, Environments, and Rock Weathering Agents: Occurrence of Weathering as a Function of Climate

differences in the rate of weathering. If two mesoenvironments are selected from the same general macroenvironment, similar types of weathering should be observed, but variations in the energy inputs may be sufficient to induce more rapid weathering in one area. For example, Colman and Pierce (1981) report on their findings of weathering rind thickness on basalts at various sites in the Pacific Northwest. At two sites near West Yellowstone, Montana, an elevation difference of only 30 m and a slightly different position relative to storm tracks produced large differences in snow pack depth and thus ground moisture. As a result, weathering was much more extensive at the site with the greater snowfall.

Mesoscale topographic features influence precipitation rates, temperature fluctuations, vegetative cover, and organic matter production. Evaluation of the influence of these variations on weathering generally requires site-specific studies. Observations of weathering of similar materials should reveal both the types and rate of weathering that can be expected at different locations. Relating the development of soils (e.g., clays vs humus) to precipitation and temperature has proved useful (McLaughlin 1955). The guidance of a professional consultant should be sought for such studies.

Microenvironments are defined by processes operating on scales as small as the molecular level. The weathering of a calcium carbonate crystal by CO₂-charged rainwater would represent microscale conditions, as would the freezing of pore water, or mineral hydration. Much of the discussions of Sections 3, 4, and 5 focus on the geochemical and geophysical aspects of molecular level weathering. At this level the relationship between climatic factors and lithological properties becomes most important because the ultimate concern is how a given rock will weather under specific environmental conditions. Rock properties are important when considering macro- and mesoscale environmental factors and subsequent weathering, but the processes at work are too complicated to allow us to draw any definite conclusions on durability (unless identical rock types are studied, which rarely will be the case). Therefore, to depart from purely climatic considerations and to examine the interaction between rocks and weathering agents is appropriate.

7.2 LITHOLOGY, CLIMATE, AND WEATHERING

A rock's response to weathering agents is determined in large measure by certain bulk properties of the material: mineral composition, porosity, sorption, strength, specific gravity, and hardness. These parameters have been reviewed in Sections 3, 4, and 6, as have tests designed to quantify and rate these properties in terms of their ability to predict durability. On the microscale, the dominant properties that interact with climatic conditions and thus determine durability probably are mineral composition, texture, and porosity (Jackson 1970; Hudec 1978b).

If chemical weathering processes are active in an area (i.e., an area with high rainfall and temperature), mineral composition is particularly

important for rocks that are at least partly made up of unstable primary igneous minerals. Such minerals are the first to weather and thus weaken the rock, exposing it to even more vigorous weathering. In regions where mechanical agents dominate, mineral composition is important in determining rock strength and elastic properties.

Texture is a measure of the number, size, and distribution of pathways for the penetration of weathering agents (Jackson 1970). Coarse-grained rocks frequently tend to weather more extensively than fine-grained rocks under similar environmental conditions. Fractures and cracks also tend to promote more rapid weathering.

Water is a primary weathering agent. Rock porosity and permeability determine the ability of water to penetrate the stone. As Hudec (1978b) argues, internal surface area and pore size determine a rock's response to weathering by the actions of water. He points out that rocks with a small number of large pores or a large number of small pores can have equal porosity, but in the latter case the internal surface area is much larger and this promotes greater weatherability. Water initially enters the rock and adheres in a thin film to the **internal** surfaces (adsorbed water) where salt action or the introduction of H^+ ions can take place. As more water is sorbed, bulk freezeable water becomes available for **freeze/thaw** or hydration weathering. Thus, Hudec argues, in cold climates, physical disintegration will proceed by salt action, hydration pressures, and **freeze/thaw** weathering. In warm, humid climates, chemical weathering will proceed by hydrolysis and acidic decay. Small pore sizes and high porosity allow greater penetration of adsorbed water and thus promote greater weathering.

As a result of the above discussion and those of previous sections, our preliminary estimates of desirable rock properties as a function of climatic factors and weathering conditions are given in Table 7.1. These should serve as a guideline when selecting durable **riprap** or attempting to evaluate the durability of available stone. As Hudec (1978b) argues, rocks that weather rapidly under physical weathering conditions probably will weather rapidly in the presence of environmental conditions favorable for chemical weathering. This explains the similarities of the durable and nondurable characteristics for chemical and physical weathering given in Table 7.1.

7.3 SUGGESTIONS

Although many questions remain concerning our ability to categorically define rock durability for any given combination of rock type and environmental conditions, the following outline may prove helpful in the selection of **riprap** for mill tailings armoring.

1. Define "failure" of the rock: This depends on the intended application. Because the purpose of the armoring is to prevent wind and water erosion of the radon suppression cover, certain levels of force must be resisted by the **riprap** (e.g., maximum possible flood discharge, maximum wind velocity). These levels of force determine the amount of **riprap** needed,

TABLE 7.1. Weathering Resistance and Susceptibility Related to Weathering Type and Rock Properties

	Chemical Weathering		Physical Weathering	
	Durable	Nondurable	Durable	Nondurable
Mineral Composition	<ul style="list-style-type: none"> - Uniform mineral composition - High silica content (quartz, stable feldspars) - Low metal ion content (Fe-Mg), low biotite - High orthoclase, Na feldspars - High aluminum ion content 	<ul style="list-style-type: none"> - Mixed/variable mineral composition - High CaCO₃ content - Low quartz content - High calcic plagioclase - High olivine - Unstable primary igneous minerals 	<ul style="list-style-type: none"> - High feldspar content - Calcium plagioclase - Low quartz content - CaCO₃ - Homogeneous composition 	<ul style="list-style-type: none"> - High quartz content - Sodium plagioclase - Heterogenous composition
Texture	<ul style="list-style-type: none"> - Fine grained dense rock - Uniform texture - Crystalline - Clastics - Gneissic 	<ul style="list-style-type: none"> - Coarse grained igneous - Variable textural features (porphyritic) - Schistose 	<ul style="list-style-type: none"> - Fine grained (general) - Uniform texture - Crystalline, tightly packed clastics - Gneissic - Fine grained silicates 	<ul style="list-style-type: none"> - Coarse grained (general) - Variable textural features - Schistose - Coarse grained silicates
Porosity	<ul style="list-style-type: none"> - Large pore size, low permeability - Free draining - Low internal surface area 	<ul style="list-style-type: none"> - Small pore size, high permeability - Poorly draining - High internal surface area 	<ul style="list-style-type: none"> - Low porosity, free draining - Low internal surface area - Large pore diameter permitting free draining after saturation 	<ul style="list-style-type: none"> - High porosity, poorly draining - High internal surface area - Small pore diameter hindering free draining after saturation
Bulk Properties	<ul style="list-style-type: none"> - Low absorption - High compressive and tensile strength - Fresh rock - Hard 	<ul style="list-style-type: none"> - High absorption - Low strength - Partially weathered rock (oxide rings, pitting) - Soft 	<ul style="list-style-type: none"> - Low absorption - High strength with good elastic properties - Fresh rock - Hard 	<ul style="list-style-type: none"> - High absorption - Low strength - Partially weathered rock (grus, honeycombed) - Soft
Structure	<ul style="list-style-type: none"> - Strongly cemented, dense grain packing - Siliceous cement - Massive 	<ul style="list-style-type: none"> - Poorly cemented - Calcareous cement - Thin bedded - Fractured cracked - Mixed soluble and insoluble mineral components 	<ul style="list-style-type: none"> - Minimal foliation - Clastics - Massive formations - Thick bedded sediments 	<ul style="list-style-type: none"> - Foliated - Fractured, cracked - Mixed soluble and insoluble mineral components - Thin bedded sediments
Representative Rocks	<ul style="list-style-type: none"> - Igneous varieties (acidic) - Metamorphics (other than marbles, etc.) varieties - Crystalline rocks - Rhyolite, granite, quartzite (metamorphic), gneisses - Granitic gneiss 	<ul style="list-style-type: none"> - Calcareous sedimentary - Poorly cemented sandstone - Limestones, basic igneous, clay-carbonates - Slates - Marble, dolomite - Carbonates (other) - Schists 	<ul style="list-style-type: none"> - Fine grained granites - Some limestones - Diabases, gabbros, some coarse grained granites, rhyolites - Quartzite (metamorphic) - Strongly cemented sandstone - Slates - Granitic gneiss 	<ul style="list-style-type: none"> - Coarse grained granites - Poorly cemented sandstone - Many basalts - Dolomites, marbles - Soft sedimentary (poorly cemented) - Schists

the size, specific gravity, and other factors to be discussed in a later report.^(a) Failure of the riprap can then be defined in terms of loss of ability to resist these forces (specified by, for instance, percent weight loss or decrease in rock size as a result of surface denudation).

2. Determine weathering conditions:
 - Identify macroenvironmental factors. Data on precipitation, temperature, and other factors can be used in estimates of the relative importance of physical vs chemical weathering agents. Observations of large-scale weathering events can be instructive for determining the roles of various weathering agents. Soils are good indicators of the climatic control of weathering. Warm, temperate climates will promote chemical weathering, producing stable products such as clays, oxides, and hydroxides. Arid or alpine climates will yield mechanically weathered residue consisting of unstable minerals, silt, sand, and coarse particles (Jackson 1970).
 - Identify mesoenvironmental factors. Local variations in precipitation, temperature, and vegetation demonstrate relative rates of weathering. Observations of weathering products by trained personnel are critical at this stage. Fresh rock outcrops should be examined for weathering, as well as nearby deposits of previously weathered material. Samples of the various rocks and soils should be taken for later analysis.
 - Identify microenvironmental factors. Analyze rock and soil samples taken in areas where riprap will be used to estimate the severity of weathering and rock response.
3. Identify available sources of rock for use as riprap: quarries and mines in the area.
4. Quantify bulk properties of rock samples taken from available sources of riprap:
 - Qualified personnel should be consulted during all phases of the analyses; proper sample collection and execution of tests are necessary.
 - Section 6 provides an overview of the various tests available.
 - Current procedures may not be suitable for the long-term durability evaluation required for mill tailings armoring; until and unless such procedures are verified as valid indicators of long-term durability, relying on field observations of weathering of the rock and petrographic examinations may be necessary.

(a) Walters, W. H. 1982. Rock Riprap Design Methods and Their Applicability to Long-Term Protection of Uranium Mill Tailings Impoundments (to be published).

5. Determine/specify durability; this may be a two-fold process. A type of rock best suited to resist the weathering conditions in an area should be specified. If such a rock type is unavailable, the durability of available rocks should be evaluated. Accelerated weathering tests, mineral composition, and porosity can serve to estimate durability (see Section 6 and Appendix A).
6. Perform cost/benefit analysis to select the "best" available rock for riprap. (Criteria for this phase will be discussed in a later report to be written as part of this research.)
7. Select and apply riprap using good riprap engineering practices (to be discussed in later reports)^(a).

(a) Walters, W. H. 1982. Rock Riprap Design Methods and Their Applicability to Long-Term Protection of Uranium Mill Tailings Impoundments (to be published) and G. B. Parker. 1982. Interim Guideline (to be published).

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APPENDIX A

WEATHERING AND LONG-TERM DURABILITY OF ROCK MASSES

APPENDIX A

WEATHERING AND LONG-TERM DURABILITY OF ROCK MASSES

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INTRODUCTION

The following is a brief review of accumulated information on the responses of various rock types to conditions of natural weathering, with particular emphasis on the nature, causes, and rates of rock disruption and decay. The review is intended for preliminary evaluation of the long-term durability of rock types that might be used for stabilizing riprap blankets over the clay or soil covers of uranium tailings piles. According to specifications provided by the Pacific Northwest Laboratory of Richland, Washington such riprap emplacements must remain stable for a period of at least one thousand years to insure the required integrity of the tailings installations.

Included in the following pages are summaries of weathering characteristics, factors that influence the nature and rate of weathering and the relative weatherability of various rock types under contrasting conditions of exposure. Some estimates of weathering rates are noted, and suggestions are offered for further research on long-term durability of several common rock types. The general objective has been to outline the current state of knowledge in these areas, with appropriate reference to published sources of information. To this end, a literature review of wide-ranging scope has been reviewed and annotated. Kathryn M. Hess of the Department of Applied Earth Sciences, Stanford University, contributed substantially to this work, which was in part computer-assisted. The literature search was supplemented by examination of notes and other records from the writer's files.

For briefness and clarity, much of the information in the following pages is presented in outline or tabular form, with specific comments appended wherever necessary for qualification or explanation. No claim can be made here for in-depth coverage of rock weathering, the central subject, or of the factors that govern weathering rates. The coverage is nonetheless extensive, and it deals with the most significant factors to be reckoned with in the selection of suitable natural riprap materials. The list of selected references at the end of this paper, though lengthy, represents only a fraction of the many hundreds of published works that were considered.

RESISTANT ROCK TYPES

Many kinds of rocks are relatively resistant to weathering, and hence have relatively high survivability when exposed over lengthy periods of time. Most

of these rocks have long been used by man, at various levels of success, for constructional, protectional, monumental and exterior decorative purposes. The principal types that have been so used are:

- plutonic rocks--
 - Granitic rocks (granites, monzonites and quartz monzonites, granodiorites, tonalites)
 - Syenites and nepheline syenites
 - Diorites
 - Diabases (trap rocks) and gabbros; ultramafic rocks (peridotites, pyroxenites, anorthites, etc.)
- volcanic rocks--
 - Silicic rocks (rhyolites, latites and quartz latites, dacites)
 - Trachytes and phonolites
 - Felsites
 - Basic rocks (andesites, basalts)
 - Glassy rocks (obsidians, perlites, etc.)
 - Fragmental rocks (agglomerates, volcanic breccias, etc.)
- sedimentary rocks--
 - Sandstones and arkoses
 - Conglomerates and breccias
 - Limestones and dolomites
- metamorphic rocks--
 - Quartzites
 - Marbles (calcitic, dolomitic)
 - Slates
 - Phyllites and argillites
 - Schists
 - Gneisses
 - Amphibolites
 - Serpentinites.

Notably absent from this list of relatively durable natural materials are common rocks that are soft or weak (e.g., shales, mudstones, marls, chalks, many tuffs), highly porous (e.g., pumice, scoria), or readily soluble in water (e.g., gypsum, halite). Moreover, inclusion of a given rock type in the list does not necessarily indicate superior durability for all of its occurrences.

SOURCES OF INFORMATION ON ROCK WEATHERING AND DURABILITY

The scientific and technical literature on rock weathering and durability derives from many sources and represents many different interests and constituencies. Individual publications range from comprehensive volumes to brief papers dealing with specific reactions or mineral phases, from treatments of regional stone resources to descriptions of single quarrying districts, from broad geomorphologic analyses to appraisals of ancient monuments, and from

specifications for test methods and rock properties to reports on experimental investigations. It is convenient here to sort out the most broadly useful parts of the published record in terms of a few major categories, and to provide typical examples of individual contributions:

- relatively comprehensive or general treatments of rock weathering--
 Brunsden (1979); Carroll (1970, esp. Table 40, p. 175-187); Chernyakhovskii, Gradusov and Chizhikova (1976); Keller (1957, 1978); Kieslinger (1932), Loughnan (1969), Ollier (1969); Reiche (1950); Schaffer (1932); Shore (1957); Winkler (1975, 1978a, 1978b)
- discussions of weathering in geomorphologic and climatic contexts--
 Carroll (1970); Embleton and Thornes (1979); Goudie (1978); Loughnan (1969); Ollier (1969); Peltier (1950); Prescott (1949); Ravina and Zaslavsky (1974); Scheidegger (1970); Strakhov (1967); Thornbury (1954); Visser (1945)
- general treatments of commercial stone--
 Barton (1968); Bowles (1939); Currier (1960); Merrill (1898); Winkler (1975)
- regional treatments of commercial stone--
 Georgia--(Watson 1912); Indiana--(Loughlin 1929); Maryland--(Keyes 1895b); Minnesota--(Bowles 1918; Thiel and Dutton (1935); Missouri--(Buckley and Buehler 1904); Nevada--(Reid 1904); New England states--(Dale 1923); North Carolina--(Watson, Laney and Merrill 1906; Council 1954); Pennsylvania--(Miller 1925; Stone 1932); Southeastern Atlantic states--(Watson 1910); Washington--(Moen 1967); Wisconsin--(Buckley 1898); Great Britain--(Shore 1957)
- standard specifications and tests for commercial stone--
 American Society for Testing and Materials (1980); Hawkes and Mellor (1970); Hockman and Kessler (1950); Ingram (1963); Kessler, Insley and Sligh (1940); Kessler and Sligh (1932); Obert, Windes and Duvall (1946); Winkler (1975)
- observations of weathering damage to manmade structures--
 Barton (1916); Emery (1960); Geike (1880); Julien (1884, 1893); Kieslinger (1932); Mattias (1967); Rahn (1971); Reid (1904); Voûte (1963, 1969); Winkler (1965; 1975, p. 87-89, 126-132, 140-151, 172); Winkler and Singer (1972).

Publications included in the foregoing lists represent a period of more than a century. Those of early vintage should not be discounted out of hand, as they record many careful observations and thoughtful interpretations (e.g., Geike 1880; Julien 1884; Buckley 1889; Dale 1923; Loughlin 1929). Moreover, some of them provide early checkpoints for quantitative appraisals of relative and absolute rates of weathering. For recent summary coverage of rock

properties and durability, including bibliographic materials specially pertinent to this review, the works of Winkler (1975, 1978b) are strongly recommended.

Additional publications are cited in the following sections to provide more direct correlation with specific topics. Some of the cited works deal with soil-forming processes, but the field of soils science is not treated systematically here because it represents stages of rock degradation not directly pertinent to this review.

NATURE AND COMMON EXPRESSIONS OF WEATHERING

Rock weathering ordinarily results from 1) disintegrative processes that can involve impacting, prising, wedging, or other stress-induced rupture and separation over a very wide range of scales; 2) direct removal of original constituents by solution; and 3) decompositional processes of many kinds. A single process, physical or chemical, can be effective in reducing or altering a rock, but in most natural occurrences some combination of causal processes can be identified or reasonably inferred. Rocks that initially are quite fresh can be recognizably weathered over time periods ranging from years to millennia, depending in highly complex ways on indigenous features of composition, texture, and structure, and on the physical, chemical, and biological conditions of exposure.

Physical weathering is variously expressed on exposed rock surfaces by cracking, flaking or scaling, spalling, pitting, blistering, bloating, and roughening (see Carroll 1970, p. 85-88; Dragovich 1967; Heidecker 1968; Johnson 1980; Julien 1884; Merrill 1895; Ollier 1969, p. 5-26; Winkler 1965, 1968; Yaalon 1970). Related separation on large scales is indicated mainly by certain kinds of fractures and fissures. Disintegration typically progresses inward from exposed surfaces and, given sufficient time, can reduce the affected rock to an accumulation of small fragments, or grus. Physical weathering is most vigorous in areas with dry and very cold or very hot climates, and it can be especially effective in attacking hard, quartz-bearing rocks such as granites, granitic gneisses, and some quartzites and sandstones. The quartz in such rocks, though very hard and resistant to ordinary abrasion, is brittle and commonly is traversed by numerous fractures that can provide access for agents of rupture (see Dale 1923, p. 26-36; Jahns 1943; Nur and Simmons 1970; Peng and Johnson 1972). Serpentinites and other rocks that already have been intimately fractured or sheared also are susceptible to attack by processes of physical weathering.

Several rock-forming minerals, most notably calcite, dolomite, and gypsum, can be taken into solution without residue by soft, neutral, or acid waters. In addition, nepheline, olivine, and a few other silicates gelatinize under long-term exposure to acid waters, and quartz can be effectively dissolved by some highly saline waters. Solution weathering (see Carroll 1970, p. 97-103; Gordon, Tracey and Ellis, 1958; Harder 1949; Kaye 1957; Kieslinger 1962;

Loughlin 1929; Murata 1943; Winkler 1975, p. 137-145) is a widespread phenomenon generally expressed on rock surfaces as fissures, niches, grooves and pits, and broader indentations separated by irregular ridges with rounded to very sharp crests. Various tubes, channels, and irregular caverns*can be developed within the rock masses. Common rock types most seriously affected by solution weathering are limestones, dolomites, marbles, and bedded salts.

Most of the common rock-forming silicates are not in equilibrium with aqueous and atmospheric solutions under ambient pressure-temperature conditions at the earth's surface; hence, they are liable to chemical attack and alteration. Rocks that contain such minerals are gradually decomposed. Various combinations of oxidation, reduction, acidification, hydrolyzation, and ion-exchange reactions are involved. The rates of decomposition can vary enormously, but in general they are most rapid for feldspathic, feldspathoidal, and mafic rocks in areas with warm, humid climates. With the onset of decay, exposed rock surfaces ordinarily become dull and lusterless, are roughened in various ways, and are spotted, stained, or otherwise discolored, mainly by oxides of iron and manganese. Water, air, and other agents of attack increasingly penetrate beneath the surfaces along fractures, grain boundaries, and mineral cleavage or twinning cracks, and the rocks become progressively softened and leached. Dissolution and alteration of original constituents lead to formation of clay minerals and other decay products, typically resulting in soil development. Residual concentrations of clays, bauxite, and iron ores are end products in some situations. The diverse processes, expressions, effects, and products of chemical weathering have been described and analyzed in a host of published works (e.g., Andersson and Wiklander 1975; Bain and Russell 1980; Baynes and Dearman 1978; Behre 1931; Berner and Holdren 1979; Brunsden 1979; Carroll 1970, p. 81-128; Chernyakhovskii, Gradusov and Chizhikova 1976; Conyers, Wilding and McLean 1969; Dale 1923, p. 66-73; Fung, Bird and Sanipelli 1979; Eggleton and Busek 1980; Jackson and Sherman 1953; Keller 1957; Keyes 1895a; Loughnan 1969; Marshall 1941; Marshall and Jeffries 1946; Moore and Gribble 1980; Nixon 1980; Ollier 1969, p. 27-37, 53-63; Parker 1970; Ramspott 1965; Siever and Woodford 1979; Suttner et al. 1976; Watson 1902, p. 299-333; Wilson 1970; Wilson and Farmer 1970).

Relatively hard weathering crusts are formed on the surfaces of many porous rocks, chiefly sandstones, limestones, tuffs, and perlites. Though generally more resistant to weathering than the underlying rocks, such crusts rarely remain intact for very long periods of time. Well-defined, typically softer weathering rinds often are found on the faces of fine-grained basic rocks such as andesites, basalts, and diabases. Some silicic tuffaceous rocks become casehardened to depths of inches or even feet, with attendant increases in durability, when they are exposed to saline combinations of air and water. In most occurrences of casehardening, however, thin and well-defined crusts, generally consisting of a calcerous, siliceous, or ferruginous sinter, form a no-more-than-temporarily protective blanket over partly weathered stone beneath. Or, more commonly, the crusts are discontinuous, with crudely regular distribution that leads to use of terms such as boxwork, honeycomb, ring, frame, cameo, and intaglio weathering to characterize the surfaces on which

they appear. Weathering rinds and various expressions of casehardening have been widely investigated in both natural exposures and man-made structures (see Anderson and Anderson 1981; Behre 1929; Colman 1981; Colman and Pierce 1981; Kieslinger 1959; Knetsch and Refai 1955; Ollier 1969, p. 174-179, 192-195; Voûte 1963; Winkler 1975, p. 129-132).

WEATHERING SUSCEPTIBILITY AND DEGREE OF WEATHERING

The gross effects of rock weathering in any given environment of exposure are fundamentally related to the respective weathering susceptibilities, or weatherabilities, of the constituent minerals originally present. Quartz is one of the most chemically resistant rock-forming phases, but it is a leading contributor to physical rupture and breakdown of many rock types. Comparable quartz-free rocks tend to be more resistant to disintegrative forces, though not necessarily more resistant to chemical decay.

Differences among inherent tendencies toward chemical breakdown led Goldich (1938) to suggest a weathering stability series for the principal rock-forming silicate and aluminosilicate minerals. Presented as a Y-shaped diagram, this two-limbed series is remarkably similar to the well-known reaction series of Bowen (1928, p. 54-62), which deals with crystallization and reaction phenomena in igneous systems. From relatively low to relatively high weathering stability (resistance to chemical breakdown), the sequences are olivine-pyroxene-amphibole-biotite and calcic feldspar-calc-alkalic feldspar-albite, orthoclase, with muscovite and quartz shown as the most stable phases in the stem of the Y. Notes on relative weatherability and weathering rates for these and other minerals are presented further on.

With preferential dissolution and alteration of rock-forming minerals, some of the constituent elements tend to be removed from the system more rapidly than others. This process, aptly termed chemical winnowing by Carroll (1970, p. 103), generally favors more rapid removal of alkali and alkaline-earth elements than removal of iron, silicon, and aluminum (see Carroll 1970, p. 97-115; Correns 1941, 1963; Garrels, Dryer and Howland 1949; Jackson and Sherman 1953; Keller 1957; Keller, Balgord and Reesman 1963; Loughnan 1969, p. 28-64; Moore and Gribble 1980). To represent sequences of removal, Reiche (1943, 1950) proposed application of the weathering potential index, a parameter calculated for a rock or mineral constituent from its chemical analysis. Like other empirically derived expressions for weathering susceptibility and sequence, this index is useful for both descriptive and some predictive purposes. It does not provide, however, an explanation of the complex processes of chemical weathering, nor is it in accord with all mineral relationships observed in weathered rocks.

Discussions of chemical weathering processes, including summaries of broad scope, are included among the references cited in the preceding section of this paper. Various petrographic and experimental studies, many of them addressed to soil-forming processes have led to numerous additional publications (e.g., Adams, Evans, and Abdulla 1971; Aires-Barros 1978; Aires-Barros,

Graca and Velez 1975; Andersson and Wiklander 1975; Boyle, Voight and Sawhney 1974; Clemency and Lin 1981; Conyers, Wilding and McLean 1969; Correns 1963; Ismail 1969; Lancaster and Behre 1930; Lin and Clemency 1981; Siever and Woodford 1979; Wilson and Farmer 1970).

The degree to which a given rock mass has been weathered is important in appraising its durability and in estimating, from occurrences where its period of exposure is known, the rate at which its fresh counterparts might be weathered in the future. Effects of physical or mechanical weathering ordinarily can be identified and measured on exposed rock surfaces, with supplementary microscopic examination and study of selected specimens where appropriate. Thus the nature, distribution, orientation, and abundance of cracks, fissures, and larger-scale breaks can be evaluated. It is not always possible to distinguish readily between those openings that represent weathering and those formed by other processes, but such genetic ambiguity need not be important in the context of further weathering, as openings of any kind can be hosts for fluids that promote solution, decomposition, and further disintegration.

The earliest stages of chemical weathering can be recognized in many rock types, especially where expressed by solution pits, mineral staining, or general loss of luster or hardness. Even subtle differences are evident when comparisons with perfectly fresh rock are possible. The quarryman, for example, has no difficulty in sorting out and discarding the most faintly weathered granite that is hard and strong yet slightly "sappy" in appearance. Oxidation of ferrous iron and subsequent effects of dissolution, leaching, and alteration generally can be recognized through careful examination under the petrographic microscope, supplemented by X-ray, spectrographic, or other analyses to identify and estimate the abundance of clay minerals and other alteration products. In many instances, accurate quantitative determinations are not easily made; therefore, several alternative methods have been employed in attempts to appraise the degree of weathering, especially for silicate rocks. These include:

- determination of abrasion pH for estimating content of clay minerals in the rock (Grant 1969)
- a use of "standard-cell" calculations, from chemical analyses of the rock and its fresh counterpart, for determining cation losses (Barth 1948)
- comparison of silica/alumina ratios from chemical analyses of the rock and its fresh counterpart (Ruxton 1968)
- various methods using index minerals or chemical composition of the non-clay fraction in a soil or highly weathered rock (Marshall 1941; Carroll 1970, p. 70-79)--in general not applicable for purposes here.

Degree of rock weathering also can be inferred by means of various tests for hardness, toughness, strength, porosity, and other bulk properties.

Moreover, the results of different kinds of tests, when considered in combination, can provide useful insights into the factor of long-term durability. Standardized test methods and specifications for natural building stones are available for such properties as abrasion resistance, absorption and bulk density, color, compressive strength, flexural strength, tensile strength, shearing strength, modulus of rupture, pulse velocities and ultrasonic elastic constants, thermal and moisture expansion, and weather resistance (American Society for Testing and Materials 1980, p. 1-77, 391-478; Hockman and Kessler 1950; Kessler, Insley and Sligh 1940; Obert, Windes and Duvall 1946; Walker et al. 1969; Winkler 1975, p. 68-86). Another significant property subject to bulk measurement is drillability (see Paone and Bruce 1963; Proctor 1970), which variously reflects toughness, compressive strength, and abrasion and percussion hardness. An excellent review of bulk properties and some of their relationships has been provided by Winkler (1975, p. 27-50, 68-86).

FACTORS THAT INFLUENCE THE NATURE AND RATE OF WEATHERING

Air and water are the prime agents of rock weathering. The atmosphere serves as an oxidizer, a transporter of abrasive and corrosive materials, a source of water, and a reservoir of carbon dioxide and numerous impurities that can acidify water with which it is in contact. Water, present on rock exposures and in fractures, pores, and other openings within the rock, is effective as a solvent, a medium for material transfer, an agent for mineral dissolution and alteration, and a source of local rock stresses. Moreover, it is an important element in organic processes that also can contribute to rock weathering. Given the presence of air and moisture, the nature, rate, and effects of rock disintegration and decay depend on many possible combinations of 1) indigenous rock features such as texture and mineral composition, and 2) various conditions and processes that in effect are superimposed on the originally fresh rock. The most significant factors are outlined in the following two sections, with emphasis on their respective influences on weathering susceptibility and rate.

INDIGENOUS FEATURES--MINERAL CONSTITUENTS

Relative weatherabilities, in most circumstances corresponding in a general way to relative weathering rates, are here noted from published observations of rocks and from results of experimental studies of minerals and rocks, supplemented by observations of the writer. The minerals and rocks are listed in order of decreasing weatherability.

Physical Weathering

Rupturing, the prime mechanism of physical rock weathering, is associated mainly with pore water, either directly or through its role as a concentrator of salts within the rocks. As described in later sections, the most potent and widespread disintegrative processes derive from crystallization, hydration,

and thermal-expansion pressure of salts, and from thermal-expansion pressures and other effects of water. The effectiveness of such processes is in part dependent on hardness, toughness, brittleness, cleavage, and other basic properties of the rock-forming minerals. On this score, the following general comparisons can be drawn for some common constituents of rocks (listed in order of decreasing mechanical weatherability--i.e., increasing mechanical durability):

- Quartz > muscovite > feldspars
- Quartz > feldspars > hornblende
- Quartz > nepheline
- Quartz > calcite
- Na plagioclase > Ca plagioclase
- Feldspars > hornblende

Thus, for some of the common rocks:

- Granites > syenites
- Quartz monzonites > monzonites
- Granitic rocks > most basalts > gabbros > diabases
- Dolomites > limestones

Sample references: Dale (1923, p. 17-26); Dunn and Hudec (1965, 1966); Ernst (1960); Hockman and Kessler (1950); Nur and Simmons (1970); Peng and Johnson (1972); Tarr (1915); Winkler (1975, p. 27-67, 169-181).

Chemical Weatering

The rates of chemical weathering are strongly influenced by fundamental properties of the rock-forming minerals, although other kinds of influences can be of equal or greater importance. Thus, carbonate rocks in humid regions ordinarily are reduced by solution more rapidly than adjacent silicate rocks, which can be chemically or mechanically weathered, whereas in many desert regions the carbonate rocks are more resistant to weathering than granites and other common silicate rocks that are relatively susceptible to disintegration. General comparisons of chemical weatherabilities among common rock-forming minerals can be useful, however, if they are considered in terms of all pertinent factors. Some of the most weatherable constituents, even where present at low levels of abundance, commonly are significant because their early alteration or removal yields salts that act as weathering agents and also provides additional avenues for chemical or mechanical attack on adjacent minerals. The following general comparisons among minerals and some related rocks (listed in order of decreasing weatherability) are grouped into four categories of chemical weathering:

Simple solution:

- Halite >> gypsum > anhydrite >> calcite > dolomite > siderite >> common silicate minerals
- Calcareous slate > noncalcareous slate
- Calcareous slate > dolomitic slate
- Pyritic limestone >> sulfide-free limestone

Simple oxidation (rusting):

- Pyrite, marcasite > magnetite > siderite
- Pyrite, marcasite > biotite

Biotite >> hornblende, pyroxene > actinolite > chlorite
 Mg, Fe olivine > Fe olivine
 Biotite, allanite >> hornblende
 Allanite > biotite
 Allanite > magnetite

Incongruent dissolution and chemical winnowing:

Calcic plagioclase > sodic plagioclase > orthoclase > microcline >> quartz
 Biotite, phlogopite > muscovite > lepidolite
 Mafic minerals > feldspars > muscovite > quartz
 Olivines > pyroxenes > biotite
 Olivine > augite > hornblende > biotite
 Nepheline > feldspars
 Olivine > K-feldspars, albite, leucite > tremolite > muscovite
 Fe hornblende > Mg hornblende
 Andesine > phlogopite > muscovite > albite > augite > hornblende
 (neutral conditions in closed experimental system)
 Hornblende > muscovite > phlogopite > augite > andesine > albite
 (acid conditions in closed experimental system)
 Ca > Mg > Na > K > Si > Al (typical order of winnowing mobility)

Chemical decay in general:

Olivines > pyroxenes > some amphiboles > biotite > nepheline >
 plagioclases > K feldspars > muscovite >> quartz
 Plutonic rocks -- ultrabasic > basic > intermediate > alkaline > granitic
 Volcanic rocks -- basalts > andesites, diabases > latites > rhyolites
 Metamorphic rocks -- marbles > most schists > amphibolites,
 serpentinites > gneisses > slates, phyllites > pure quartzites
 Laniprophyre > nepheline syenite > granite
 Clay-bearing carbonate rocks > clay-poor carbonate rocks

Sample references: Aires-Barros (1978); Aires-Barros, Graca and Velez (1975); Andersson and Wiklander (1975); Behre (1931); Berner et al. (1980); Berner and Holdren (1979); Boyle, Voight and Sawhney (1974); Carl and Amstutz (1958); Carroll (1970, p. 89-115); Correns (1963); Dale (1923, p. 66-70); Ismail (1969); Jackson and Sherman (1953); Keller (1957); Keller and Reesman (1963); Keller, Balgaard and Reesman (1963); Kieslinger (1932); Kirkman and McHardy (1980); Leonard and Weed (1970); Loughlin (1929); Nixon (1980); Parker (1970); Pearce (1976); Ramspott (1965); Siever and Woodford (1979); Suttner et al. (1976); Wilson (1970); Wilson and Farmer (1970); Winkler (1975, p. 138-145, 164-168).

INDIGENOUS FEATURES--CHEMICAL COMPOSITION

For a given set of exposure conditions, the bulk chemical composition of a rock can serve as a general guide for estimating its weatherability. Correlations should be made with some caution, however, for polymineralic rocks that contain one or more phases with high weathering susceptibility.

Physical Weathering

High-silica rocks > carbonate rocks
High-silica rocks > low-silica rocks
Salic rocks > femic rocks

Chemical Weathering

Bedded salts > gypsum rocks > anhydrite >> carbonate rocks >>
silicate rocks
Low-silica rocks > high-silica rocks
Femic rocks > salic rocks
Andesitic glasses > latitic glasses > trachytic glasses > rhyolitic
glasses

INDIGENOUS FEATURES--TEXTURE, STRUCTURE, AND POROSITY

Several elements of texture can affect rock weatherability, chiefly through their influences on bulk strength and porosity:

- crystallinity, ratio of mineral grains to glass, cementing matter, or already existing alteration products
- sizes and phases of grains
- nature of grain boundaries
- specific types of fabric (e.g., directive, oolitic, ophitic, poikilitic, and reaction textures)
- fluid inclusions in grains or quartz and other relatively brittle minerals.

Similarly significant structural features include:

- clastic structures
- bedding, flow layering, foliation, schistosity
- fractures, ranging from microcracks to extensive joints and shear zones
- inclusions and segregations
- special features (e.g., ripple marks, stylolites, and amygdaloidal, columnar, miarolitic, perlitic, spherulitic, and vesicular structures).

Porosity and permeability ("effective porosity"), as defined by combinations of textural and structural features, are important in providing avenues of entry and circulation for the fluid agents of weathering. Typical porosity values are compared below (e.g., basic plutonites have smaller values of porosity than granites):

Low (0.1% to 1.5%) -- basic plutonites < dense basalts, diabases < slates, quartzites < granitic plutonites, gneisses < some marbles, dolomites
Moderate (1.5% to 4.0%) -- some granites < some marbles, dolomites < most dolomites < some schists
High (>4.0%) -- rhyolites, trachytes, most felsites < limestones (wide range) < sandstones (wide range) < many basic volcanic rocks

Some general relationships between weathering susceptibility (in decreasing order) and elements of texture, structure, and porosity are:

Fine-grained rocks > coarse-grained counterparts with equal porosity and hardness

Coarse-grained hard silicate rocks > fine-grained hard silicate rocks

Rocks with great textural variations > uniformly-textured counterparts

Thin-bedded rocks > thick-bedded or massive rocks

Schistose rocks > relative massive rocks

Poorly cemented rocks > well-cemented rocks (clastic sedimentary rocks)

Moderately porous rocks > rocks with low or high porosity

Very highly porous rocks > rocks with lower porosity

Rocks with small mean pore size > rocks of similar porosity but with larger mean pore sizes

Marbles > unmetamorphosed counterparts

Sample references: Brace (1964); Brace, Paulding and Scholz (1966); Carroll (1970), p. 85-88; Dennen and Anderson (1962); Hoek (1965); Jaeger and Cook (1976); Nur and Simmons (1970); Peng and Johnson (1972); Winkler (1975, p. 1-29); standard petrology texts.

INDIGENOUS FEATURES--BULK PROPERTIES

Abrasion Resistance, Hardness, Toughness

High values ordinarily indicate superior resistance to physical weathering, but detailed correlations with long-term durability are not yet possible. Test values range widely, but in general:

Gabbros > diorites (i.e., gabbros are more resistant to abrasion than are diorites) > basalts, diabases > some serpentinites > quartzites > granites > slates, well-cemented sandstones > sound carbonate rocks.

Compressive Strength, Tensile Strength

High values correlate with superior hardness, toughness, and resistance to rupture. Direct comparisons should be made only between rocks of the same general kind. Some rocks are distinctly anisotropic in their strength properties (e.g., schists, phyllites, slates, thin-bedded sedimentary types).

In general :

Sound quartzites > gabbros, dense basalts (i.e., sound quartzites generally have greater strength properties than gabbros) > granites and granitic gneisses > some serpentinites > slates (across cleavage) > some well-cemented sandstones and arkoses > marbles (wide range) > dolomites, limestones, many sandstones (wide ranges).

Flexural Strength, Shearing Strength

As parameters that indicate resistance to failure under high bending stresses or local stress concentrations, flexural strength and shearing strength can be important in predicting the performance of stone in typical riprap use, especially in installations where the load is large.

General relationships from extensive tests of flexural strength are:

Slates >> some serpentinites (i.e., slates have greater flexural strength than some serpentinites) > gabbros > dense basalts, diabases > granites > marbles (wide range) > dolomites, limestones (wide ranges > sound sandstones.

For shearing strength:

Gabbros > dense basalts, diabases > granites > slates > marbles (wide range) > dolomites, limestones, sound sandstones (wide ranges).

Bulk Density (Specific Gravity), Absorption

The workability of a stone is related to its bulk density, which in turn reflects its composition and porosity (see earlier sections). Bulk density, in dry weight per unit volume, averages near 180 lb/cu ft for gabbros, basalts, and diabases, 174 for slates, 172 for marbles, 170 for serpentinites, 167 for quartzites, 165 for granites and granitic gneisses, and 145 for limestones and sound sandstones.

Water absorption, a very important factor in weathering processes, is related to porosity, or the difference between bulk dry-rock density and true density. Typical absorption ranges for fresh, sound rocks, in weight percent of water, are 0.04 to 0.20 for gabbros, basalts, and diabases, 0.01 to 0.60 for slates, 0.06 to 0.45 for marbles, 0.09 to 0.40 for granitic rocks, 0.1 to 2.0 for quartzites, and 2.0 to 15.0 for sandstones. Most rocks with water absorption values above these respective ranges are already somewhat weathered and show unusually high water-transmission rates. Rocks with more than 16% absorption generally are too weak for most construction purposes.

Thermal Expansion

Near-surface rupture of stone can be prompted by rapid temperature changes, as in exposure to fire or to a great many cycles of heating and cooling. High local stresses are most commonly produced under such conditions by marked differential thermal expansion of quartz, and also of calcite and dolomite.

Sample references: American Society for Testing and Materials (1980, p. 1-77); Brace (1964); Hawkes and Mellor (1970); Hockman and Kessler (1950); Kessler, Insley and Sligh (1940); Kessler and Sligh (1932); Moen (1967); Winkler (1975 p. 27-45).

INDIGENOUS FEATURES -- STRAIN ENERGY

The continuity of rock masses is commonly interrupted by faults, shears, and joints that bespeak the relief of accumulated strain. Most surfaces of differential movement actually are zones along which the rock has been much disturbed mechanically and, in many occurrences, significantly decomposed as well. Joint surfaces also can provide ready access for weathering agents, especially where the ruptures are complicated by branching fractures, conchoidal or feather markings, or other irregularities (see Dale 1923; Hodgson 1961a, 1961b; Roberts 1961; Winkler 1975, p. 51-53).

Many large masses of relatively unbroken rocks, such as thick-bedded sandstones and quartzites, limestones, and various plutonites, have retained significant amounts of strain energy. Ordinarily this represents some combination of residual stresses and imposed tectonic stresses. In the highly asymmetric stress field that characterizes the near-surface environment, failure by exfoliation tends to occur, generally in the form of scaling, slivering, or larger-scale sheet fracturing (see Blackwelder 1925; Dale 1923, p. 26-36; Farmin 1937; Jahns 1943; Johnson 1980, Watson 1910, p. 23-25; Winkler 1975, p. 58-61). Such rupture, in effect a self-induced kind of disintegration, is most common and widespread in quartz-bearing rocks and in some carbonate rocks. The quartz of granites and other massive rocks generally is cut by countless microfractures that can propagate from one mineral grain to another in achieving stress relief, forming larger-scale breaks and increasing the rock porosity (see Adams 1910; Gray 1965; Hoek 1965, Hoek and Bieniawski 1965; Jaeger and Cook 1976; Obert 1962; Nur and Simmons 1970; Peng and Johnson 1972).

SUPERIMPOSED CONDITIONS AND PROCESSES-CLIMATE

Climate profoundly influences the nature and rate of rock weathering. The most significant factors on this score are 1) amount, temporal distribution, and acidity of precipitation, 2) ratio of precipitation to evaporation, 3) ratio of precipitation to surface runoff, 4) frequency and density of cloudiness and fog, 5) mean temperature and temperature range, 6) frequency of freezing temperatures, 7) amount of solar radiation on horizontal surfaces, 8) frequency and intensity of winds, and 9) long-term consistency among these factors. As noted earlier, warm and humid climates accelerate rock solution and decay, whereas very hot or very cold, dry climates accelerate mechanical weathering. Investigators have variously identified contrasting types and zones of climate, often in attempts to correlate them with differences in rock weathering processes, but a review of such work is not pertinent here (see Carroll 1970, p. 9-18; Loughnan 1969, p. 67-71; Ollier 1969, p. 103-119; Peltier 1950; Prescott 1949; Ravina and Zaslavsky 1974; Strakhov 1967; Visser 1945).

Small but significant differences between urban and rural climates have been noted by Lowry (1967). Winkler (1975, p. 132-134) has made a comparison between stone weathering in urban humid areas and in desert areas, finding them "strikingly similar." In the following section of this paper, attention is focused on high, arid to semi-arid nonurban parts of the western United States, where combinations of physical and chemical weathering are characteristic.

SUPERIMPOSED CONDITIONS AND PROCESSES -- TEMPERATURE CHANGES

Fire

Rocks that are strongly heated by forest fires, brush fires, or burning structures tend to rupture and exfoliate, especially when cooled suddenly by rain or directed hosing of water. The effects, local but often drastic, are most serious for quartz-bearing rocks, some feldspathic rocks, and carbonate rocks (Blackwelder 1927; Emery 1944; Tarr 1915; Winkler 1975, p. 167-175).

Insolation

Diurnal changes in rock temperature, as related to solar radiation, have been suggested as an important cause of flaking, spalling, and large-scale exfoliation of hard rocks (see Ollier 1969, p. 14-19; Rice 1976, Wolters 1969). Although some surprisingly high rock-surface temperatures have been measured (see Smith 1977), strong effects of insolation cannot extend far beneath the outcrop. Most investigators have dismissed insolation as a cause of exfoliation, or have considered it as a possible cause of rupture only in the outermost parts of rock masses that contain moisture (e.g., Blackwelder 1925, 1927, 1933; Farmin 1937; Griggs 1936; Hockman and Kessler 1950; Jahns 1943; Peltier 1950; Reiche 1950; Roth 1967; Winkler 1977; Yaalon 1970).

Other Effects

Solar radiation and temperature changes are important in the surface evaporation of water and in the establishing of temperature gradients within rock-pore systems. The effects are noted further on, in connection with actions of water and salts.

SUPERIMPOSED CONDITIONS AND PROCESSES -- ABRASION

Wind Action

Strong winds can detach and remove loose particles from exposed rock surfaces and, if charged with particles of quartz and other hard minerals, such winds can effect strong abrasion of in-place materials (see Ollier 1969, p. 23-24, 62-63; Suzuki and Takahashi 1981). Most readily affected by wind abrasion are carbonate rocks and loosely cemented arenaceous rocks, as well as micas, feldspars, amphiboles, and other minerals with good cleavage. At localities where natural sandblasting is vigorous and frequent, even the hardest and freshest rock surfaces can become visibly sculptured.

Water Action

Loose materials are readily removed by impacting or flowing water, and grinding, gouging, or plucking of rock surfaces can become significant if the water contains suspended solids. The abrasion process is slow, however, unless the affected rock is relatively soft or the attack is frequent.

Gravity Abrasion

Fragments of hard rocks that are moving in response to gravity, as in rockfalls, landslides, and rock glaciers, can reduce the surfaces over which they travel. The effects of such impact and mechanical grinding ordinarily are shallow and local.

SUPERIMPOSED CONDITIONS AND PROCESSES -- WATER IN ROCKS

Water enters near-surface rock domains from the atmosphere as precipitation and condensation, from adjacent ground by flow and capillary movement, and from subjacent ground mainly by capillarity. It occupies the rocks by partly or completely filling the many kinds of openings that are available, thus forming extremely complex, intimately penetrating fluid networks that are neutral to acid in most occurrences. Some of the water commonly is immobilized as thin films of ordered water (adsorbed or "non-freezeable" water) that are electrostatically attached to grains of clays and other minerals (Dunn and Hudec 1965, 1966; Ruiz 1962). Most of it, however, remains as common pore water that is highly mobile.

Absorbed water fills many roles in the weathering of a rock:

1. It delivers atmospheric oxygen and dissolved salts into the rock.
2. It is a solvent for some common rock-forming minerals.
3. It is an agent for ion exchanges and for incongruent dissolution, alteration, and leaching of other common rock-forming minerals.
4. It is a constituent of important newly formed alteration minerals.
5. It is a capillary transporter of dissolved matter and also serves as a medium through which such matter is transferred by diffusion (see Garrels, Dreyer and Howland 1949).
6. It is a fundamental participant in various osmotic processes.
7. It is an agent of rock disruption, mainly in response to temperature changes.
8. It is an important part of organic systems that in turn exercise influences over rock weathering.

SUPERIMPOSED CONDITIONS AND PROCESSES -- RUPTURE BY WATER

Wet-Dry Cycles

Disintegrative effects of cyclic wetting and drying of rocks are significant, both at constant temperature and when combined with heating and cooling of the system. They are most readily developed when many cycles are rapidly repeated (Hockman and Kessler 1950). Bulk expansion, cracking, and spalling can result from the wetting and drying of granites, basalts, limestones, and other common rocks. The effects may be due in part to accumulation of ordered water that attaches to mineral-grain surfaces in the rocks (Ollier 1969, p. 20-23); ordinary absorbed water probably also is involved.

Thermal Cycles

Thermal expansion of absorbed water with increase in temperature above 4°C typically exceeds the thermal expansion of the containing rock. If confined, the water can exert considerable disruptive pressure. Cracking has been developed in granite test specimens subjected to thermal and wet-dry cycles (Kessler, Insley and Sligh 1940, p. 203-205). This process could be effective in some natural occurrences, especially for dark-colored rocks warmed by insolation (Smith 1977; Winkler 1975, p. 110-111).

Freeze-Thaw Cycles

Rupture of rocks by freezing of absorbed water can be a potent disintegrative process under favorable conditions of saturation and pore properties (Loughlin 1929; Matthias 1967; Thorn 1979; Winkler 1975, p. 176-181). Fine-grained rocks with 1 to 5% of absorbed water are generally most frost-sensitive, and a mean pore size of about 5µm may well be critical for freeze-thaw response (Walker et al. 1969).

Disruptive pressures in freezing are ascribable to various combinations of the water-to-ice volume increase, expansion of the ice at lower temperatures, hydraulic pressure of water displaced by the advancing ice front, volume increases in converting absorbed water to adsorbed (ordered) water, and expansion of unfrozen adsorbed water (see Dunn and Hudec 1966; Larsen and Cady 1969; Powers 1955).

SUPERIMPOSED CONDITIONS AND PROCESSES -- RUPTURE BY SALTS

Disintegration by actions of salts is variously known as salt rupture, salt weathering, salt erosion, and salt fretting. It is one of the most potent and rapid processes of rock weathering (see Cooke 1979; Evans 1969-70; Goudie 1974; Goudie, Cooke and Evans 1970; Knetsch and Refai 1955; Voûte 1963; Winkler 1975, p. 111-129).

Crystal-Growth Pressure

Confined crystallization of salts in the pores of rocks can generate pressures sufficiently high to cause rupture on many scales (see Chapman 1980, Correns 1949; Evans 1969-1970; Kessler, Insley and Sligh 1940, p. 201-205; Kwaad 1970; Wellman and Wilson 1963; Winkler and Singer 1972; Yaalon 1970). The highest pressures are generated by growth of halite crystals; anhydrite and thenardite also can exert pressures high enough to rupture many strong rocks. The chief expressions of rupture, scaling, and spalling commonly are associated with salt efflorescence and subflorescence (see Laury and Milne 1926).

Salt-Hydration Pressure

Pressure sufficiently high to rupture hard, strong rocks also can be generated by the hydration of some salts in response to changes in temperature and humidity (see Winkler 1965; Winkler and Wilhelm 1970). The change from anhydrite to gypsum, for example, can be both a rapid and a potent disintegrative factor, especially at low temperatures and high relative humidities.

Thermal Expansion of Salts

Differences in thermal expansion between confined pore salts and their host rocks also can cause rupture. Among the common salts, halite probably is most important on this score (Cooke and Smalley 1968).

SUPERIMPOSED CONDITIONS AND PROCESSES -- BIOLOGICAL PROCESSES

Plants and animals contribute to both physical and chemical weathering (see Brunsdon 1979; Carroll 1970, p. 117-128; Jacks 1953; Ollier 1969, p. 46-52). In this role, they can:

- a affect air and water circulation
- provide organic acids and other agents of dissolution and leaching
- a add carbon dioxide to the rock system
- a enter into cation exchange reactions
- facilitate, through chelation, dissolution and leaching under nonacid conditions
- impose root pressures in host rocks.

References: Brenner 1951, 1954; Boyle, Voight and Sawhney 1974; Gill and Bolt 1955; Keller 1957; Keller and Frederickson 1952; Schatz et al. 1954; Stolzy and Barley 1968; Taylor and Burnett 1964; Taylor and Ratcliff 1969).

Experimental exposure to chelators has led to removal of K from orthoclase (Perkins and Purvis 1954), leaching of granite and other rock types (Schatz et al. 1954), and dissolution of several rock-forming minerals (Goldberg and Arrhenius 1958, p. 160).

Among the microorganisms (Webley, Henderson and Taylor 1963) found in the early-weathering environment and capable of rock attack are:

- bacteria that include calcite-dissociating, iron-oxidizing, sulfur-oxidizing, and uranium-leaching types (Drzal and Smyk 1968; Harrison, Gow and Iverson 1966; Kauffmann 1960; Millot et al. 1967; Silverman and Ehrlich 1964; Voûte 1969)
- algae and fungi (Drzal and Smyk 1968; Henderson and Duff 1963; Silverman and Munoz 1970; Weed, Davey and Cook 1969)
- lichens and mosses (Henderson and Duff 1963; Keller and Frederickson 1952; Rudolf 1966).

MEASUREMENTS OF WEATHERING RATES

Many different methods have been applied, in both the field and the laboratory, to the problem of measuring long-term weathering rates, but in few studies has it been possible to establish more than two points for control of the curve that relates degree of weathering to time. A linear rate commonly has been assumed, perhaps justifiably for many instances of solution weathering and for those unusual situations in which a steady state among all contributing factors is achieved early and then maintained. Most weathering rates, however, probably decrease with time, tending to become asymptotic to certain relatively low values (see Cernohouz and Solc 1966; Colman 1981; Ollier 1969, p. 242-252; Ruxton 1968). Under some conditions, weathering rates can increase with time, especially during early or intermediate stages of the overall process (Ollier 1969, p. 198-216, 242-252; Rodrigues 1978).

Rates of weathering generally have been estimated via one or more of the following approaches:

- studies of age-dated expressions of weathering, such as altered volcanic glass, weathering rinds on rocks, and soil sections (c.f., Anderson and Anderson 1981; Caine 1979; Colman 1981; Colman and Pierce 1981; Morrison and Wright 1967; Owens and Watson 1979) studies of old buildings, monuments, and other man-made structures of known date (see Dragovich 1979; Geike 1880; Julien 1884; Heizer and Fenenga 1948; Kaiser 1929; Millot et al. 1967; Winkler 1965)
- laboratory tests or experiments designed to simulate natural weathering, generally at an accelerated rate (see American Society for Testing and Materials 1980; Kessler, Insley and Sligh 1940, p. 198-206).

Because of the present focus on riprap use and a minimum time parameter of 1000 years, only the second category above is briefly reviewed here for "closest-fit" comparison. The structures that have been examined by competent investigators include monuments in Egypt (Barton 1916; Emery 1960; Voute 1963; Winkler 1965); cathedrals, castles, and tombstones in Europe (Cernohouz and Solc 1966; Geike 1880; Kauffmann 1960; Mamillan 1968; Millot et al. 1967; Winkler 1965); and buildings, monuments, and tombstones in the eastern United States (Judson 1968; Julien 1884, 1893; Matthias 1967; Rahn 1971). The rock types represented among these structures include granite, syenite, granitic gneiss, marble, limestone, dolomite, schist, arkosic sandstone, and basalt.

Salt damage is by far the most widely cited expression of weathering for these structures, which range in age from about 100 years to more than 4800 years. Much damage also is attributed to frost action, to solution effects on carbonate rocks, and in only a few instances, to chemical decay. Among the reported rates of weathering, expressed in terms of maximum damage penetration per century, are 0.5 mm for basalt, 1 cm for marble and limestone, 6 mm for arkosic sandstone, and 0.5 mm to 1 cm for granite. These and many other reported values are not susceptible to detailed comparisons because they do not represent identical techniques of weathering measurement, nor do they represent the same time spans, histories, and conditions of exposure for the rock types that were studied. On the other hand, the results of such studies do support the following useful generalizations with respect to weathering of initially sound rocks during centuries of exposure:

- In areas with humid and warm to temperate climates, limestones and other carbonate rocks are markedly reduced by solution, in general at average rates that differ from one locality to another.
- Accompanying sandstones, other clastic sedimentary rocks, and micaceous schists in such areas are physically and chemically reduced at similar to somewhat lesser average rates.
- Accompanying granites and other plutonic rocks, hard volcanic rocks, slates and phyllites, quartzites, gneisses, amphibolites, and serpentinites in such areas are physically and chemically reduced at considerably lesser average ratios.
- In areas with arid to semi-arid climates that are temperate to very hot or very cold, granitic and many other plutonic rocks, sandstones, schists, gneisses, and serpentinites are significantly reduced by frost action, salt weathering, and other disintegrative mechanisms; reduction tends to be most rapid in relatively coarse-grained rocks that contain abundant quartz.
- Accompanying carbonate rocks in such areas are reduced mainly by solution, at similar, greater, or lesser average rates.

- Accompanying silicic volcanic rocks, basalts, diabases, phyllites, and amphibolites in such areas are reduced at similar or lesser average rates.
- Accompanying quartzites and slates in such areas are reduced at markedly lesser average rates.
- For relatively hard and massive rocks in such areas, the factors of grain size, quartz content, and exposure to salt actions and temperature changes appear to be very important in governing rates of weathering.

ANALYSIS AND CONCLUSIONS

Many contrasting factors, both indigenous and superimposed, influence the nature and rate of rock weathering, as indicated in the foregoing pages. These factors are interrelated in such highly complex ways that they constitute, in effect, a sort of polydimensional matrix not readily susceptible to overall analysis. Certainly this matrix cannot be expressed in any simple graphic or tabular form that would reliably indicate a long-term weathering rate for a given rock type under a given set of exposure conditions. The objective of rate estimation at least can be approached, however, through use of a step-by-step procedure that reduces the matrix to fewer dimensions and thereby reveals the most promising avenues for specific investigation of controlling factors.

The procedure repeatedly used in the present analysis of available data comprises the following steps:

- Specify the time span of weathering and the general climatic conditions of exposure.
- Specify the rock type to be considered.
- Characterize this rock type in terms of its mineral and chemical composition and its physical properties.
- Correlate each factor of composition and each physical property with the anticipated effects of each agent and each process of weathering that could be expected to operate under the specified climatic conditions of exposure.
- Identify the correlations of greatest probable influence on overall weathering of the rock type.
- Calibrate the expected weathering rate of the rock type insofar as possible, mainly through comparison of measured, estimated, or inferred weathering rates reported for rocks of the same type under similar conditions of exposure.

- Repeat this procedure for other specified rock types in order to rank them in terms of weatherability or weathering rate for the specified time span under the specified general climatic conditions of exposure.

Given the overall requirement of stability in riprap use for a period of at least 1000 years under arid to semi-arid high-altitude climatic conditions in the western United States, the writer is confident that satisfactory natural rock materials can be found. Under the indicated conditions of exposure, both physical and chemical weathering can be anticipated, with disintegrative processes ordinarily more effective than solution or decay for silicate rocks, and with solution more effective than disintegration for carbonate rocks (except at very high altitudes). Biological weathering processes could be locally significant, but in general their effects would be distinctly subordinate to those of other processes.

Rocks that meet the specifications of superior building stone for exterior use (American Society for Testing and Materials 1980) should be relatively resistant to weathering, and from these and other considerations the following priority groups of rock types are suggested as a preliminary focus for future investigation.

- Group 1 -- Quartzites, noncalcareous slates, fine- to medium- grained felsic granites or granitic gneisses
- Group 2 -- Coarser-grained granites or gneisses, dense basalts/ or diabases
- Group 3 -- Marbles, limestones, dolomites.

Given sound, fresh, and unaltered masses for comparisons, the rock types assigned to these three groups can be individually ranked in various ways, according to the criteria emphasized. The quartzites, granites, and gneisses of Group 1, for example, are hard, strong, and resistant to abrasion. Pure quartzites also are highly resistant to solution and decay, the leucocratic granites and gneisses somewhat less so. All these rocks tend to have low porosity, but they are relatively brittle and hence are more liable to rupturing and spalling than many other rock types. Thus their principal mode of weathering is mechanical, given the climatic conditions emphasized in this study, and the disintegration is effected mainly by wetting and drying, freeze-thaw cycles, and actions of interstitial salts.

Most noncalcareous slates are highly resistant to both physical and chemical weathering. They have very low porosity, high compressive strength, and very high flexural and shear strength. They rank below quartzites and most granites in hardness and abrasion resistance, and their structural anisotropy can lead to some splitting and spalling in response to frost and salt actions.

The relatively coarse-grained granites and gneisses of Group 2 yield more readily to weathering than their finer-grained counterparts, but they have lower weathering rates than monzonitic, dioritic, and other medium- to coarse-grained plutonites with higher percentages of plagioclase and dark minerals. Dense varieties of basalt and diabase are favored by superior hardness,

toughness, and strength, as well as by low porosity, but they are much more susceptible to chemical weathering than the other rocks of Groups 1 and 2.

The principal carbonate rocks are assigned to one of the foregoing priority groups despite their relative softness and long-term solubility, because some sound, compact varieties have moderately high compressive strength, flexural strength, and resistance to physical weathering. In general, dolomites and dolomitic marbles are less soluble than limestones and calcite marbles, but they are somewhat more easily ruptured.

Plutonites of intermediate to ultrabasic composition, most sedimentary and volcanic rocks, and metamorphic rocks such as phyllites, schists, amphibolites, and serpentinites are not included among the suggested priority groups because in most occurrences they do not have superior resistance to long-term weathering. This can be variously attributed to characteristics such as softness, low strength, unfavorable porosity, weak cementation, marked textural irregularities, widespread fractures, abundant glass or minerals liable to rapid alteration, or combinations of these and other unfavorable features.

Some perspective on long-term durability of Group 1 rock types is provided by numerous observations in the northeastern United States and adjacent parts of Canada, where Holocene climatic conditions have approximated those emphasized in the present study. The most pertinent of these observations are:

- Among buildings, monuments, and markers in both urban and rural areas, most filigree decorations and inscriptions on slates are well preserved after as much as three centuries of exposure; polished surfaces on some granites are essentially unaffected but surficial cracking and local flaking or spalling has occurred on other granites during a century of exposure, and the surfaces of carbonate rocks have been reduced at apparent rates of 1 to 8 mm per century.
- Among the accumulations of coarse waste materials that have been exposed for a century or more at old mines and quarries, blocks of originally fresh slates and granites have retained sharp corners and edges; blocks of limestones and marbles have been recognizably pitted and in part edge-rounded; blocks of sandstones and schists commonly have been spalled, split, or rounded, and blocks of sulfide-bearing schists and gabbros have been softened, broken, and heavily stained by iron oxides.
- Similar weathering contrasts can be recognized among different rock types in the coarse debris of postglacial talus accumulations, in which the most resistant rock types are granites with slightly spalled or flaky surfaces and quartzites and slates that show even lesser weathering effects after many centuries of exposure.
- Glacial striae, grooves, and some polish are locally well preserved on surfaces of slates, phyllites, quartzites, and granitic rocks that have been essentially unprotected for decades to centuries, and such features also can be recognized on the discolored and slightly weathered surfaces of diabbases that evidently have been exposed for millennia.

- a Many large, isolated glacial erratics in northern New England and eastern Canada are blocks of granitic rocks that have retained much of their original joint-bounded form despite the erosional effects of ice transport and subsequent exposure to weathering for a time span on the order of 10,000 years.
- a Postglacial exfoliation in and near New England granite quarries has developed at low rates that evidently have varied according to strain-energy levels in the stone; typical ranges among estimated average rates are 1 to 6 mm/5000 years for depth of flaking and 1 to 3 mm/5000 years for development of new sheet fractures, generally within 20 cm of the postglacial outcrop surface.

OUTLINE OF SUGGESTED STRATEGY FOR INVESTIGATION

REVIEW OF AVAILABLE INFORMATION

- a further review of published descriptions and data pertinent to rock weathering
- a contacts with organizations having relevant responsibilities or research programs [e. g., American Society for Testing and Materials, Geophysical Laboratory, National Bureau of Standards, University of Arizona, University of California (Berkeley), Colorado School of Mines, Georgia Institute of Technology, Massachusetts Institute of Technology, University of Minnesota (Minneapolis), University of Missouri (Rolla), University of Notre Dame, Pennsylvania State University, Purdue University, Stanford University, Texas A and M]
- a review of geologic maps and reports for the areas or region under consideration for uranium tailings piles.

FIELD WORK

- a reconnaissance of selected areas for appraising distribution and accessibility of candidate rock types for riprap use
- a detailed examination of in-place candidate rocks for comparison of lithologic and structural features, outcrop characteristics, and styles and relative degrees of weathering
- a examination of candidate rocks in talus accumulations, rock glaciers, and old mine and quarry dumps
- a study of old petroglyphs, monuments, cemetery markers, and buildings or other structures for comparisons with candidate rock types in terms of weathering styles and rates.

LABORATORY WORK

- standard bulk testing, especially for compressive strength, modulus of rupture, and water absorption, in part for preliminary appraisal of soundness and freshness of candidate rock types
- petrographic study of both fresh and weathered rock samples
- use of "accelerated-weathering" tests, including abrasion-percussion, acid solution, wet-dry and thermal cycling, freeze-thaw cycling, and salt-rupturing tests.

SITING AND DESIGN CONSIDERATIONS

- consider balance among factors of weatherability, location, and accessibility of candidate rock types
- consider tailings sites with topography, drainage
- characteristics, and aspects of exposure most favorable for long life of protective installations
- consider design of protective installations most favorable for long-term durability of the riprap cover (e.g., low cross-sectional exposure to moisture- or salt-carrying winds, isolation from saline surface waters and ground waters, good internal drainage, possible composite design involving riprap rock types with contrasting response to different weathering agents and mechanisms.

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APPENDIX B

GLOSSARY

GLOSSARY

Absorption	In "solids," the taking up or incorporation of liquids.
Acidic Rocks	A term applied loosely to any igneous rock composed predominantly of light-colored minerals and having a low specific gravity; silica contents generally exceed 70%.
Adsorption	Adhesion of gaseous or liquid molecules to the surface of solid bodies with which they are in contact.
Albite	Sodium (Na^+) feldspar; a plagioclase feldspar.
Alkali Feldspar	A group of feldspars whose cation end members are potassium or sodium.
Alluvial	Pertaining to any sediments or rock fragments deposited by a stream or running water.
Amphibole	A group of Fe^+ , Mg^+ silicate minerals characterized by double chains of SiO_4 tetrahedra.
Andesite	A plagioclase/Fe-Mg igneous rock containing little or no quartz or orthoclase; fine-grained.
Anhydrite	Dehydrated gypsum, or calcium sulfate: CaSO_4 .
Anion	Any ion with an overall negative ionic charge.
Basalt	An igneous rock; dark colored, fine-grained, consisting primarily of plagioclase feldspars and Fe-Mg silicates.
Basic Rocks	A term applied to igneous rocks low in silica content (less than 50%) and generally rich in iron, magnesium and/or calcium; often synonymous with dark igneous rocks.
Biotite	Rock-forming Fe-Mg silicate forming late in discontinuous branch of reaction series; dark green or brown; black mica.
Boulder Size	Volume equivalent of sphere of diameter greater than 256 mm.

Bulk Modulus	Numerical expression of force required to produce a specific elastic change in the volume of a material; a measure of resistance to elastic volume deformations.
Calcareous	Any rock or sedimentary material that contains calcium carbonate (CaCO_3).
Calcic Rocks	A term applied to igneous rocks in which the silica percentage is greater than 61% by weight and the weight percent of CaO and $\text{K}_2\text{O} + \text{Na}_2\text{O}$ are equal.
Calcite	A precipitate mineral, calcium carbonate: CaCO_3 .
Capillary Action	The action by which water is drawn up in small pore spaces as a result of surface tension.
Capillary Size	Tubes of diameters in range of 0.0025 to 0.25 cm.
Carbonates	A group of minerals containing the carbonate (CO_3) anion.
Case Hardening	Formation of crusts on outer surfaces of rocks resulting from moisture movement within the rock to the surface and the subsequent crystallization of soluble minerals as evaporation occurs.
Cation	Any ion with a positive overall ionic charge.
Cavitation	Erosional process caused by the sudden bursting of vapor bubbles in water against a rock surface.
Cementation	The process whereby unconsolidated deposits of weathered rock material are joined together by the precipitation of a binding agent into the spaces between the fragments. The most common cementing agents consist of calcareous or siliceous material.
Clastics	Rocks or sediments composed of broken fragments derived from pre-existing rocks or minerals that have been transported some distance from their place of origin.
Clay Minerals	Weathering products of feldspars, pyroxenes, amphiboles, etc., consisting of crystalline silicates; most clays fall into the kaolinite, montmorillonite, or illite groups.
Clay Size	Volume equivalent of sphere of diameter less than 0.004 mm

Cleavage	<p>a) Mineral: planes of weakness in mineral crystal structures where breakage will occur; determined by atomic configuration.</p> <p>b) Rock: property of breaking along planes of weakness, which are usually parallel, such as in slate.</p>
Cobble Size	Volume equivalent of sphere of diameter greater than 64 mm and less than 256 mm
Colloidal	Between 0.0002 mm and 0.001 mm
Continuous Reaction Series	As described by Bowen, the progressive formation of minerals as a melt cools without sudden phase changes between the constituent minerals; the plagioclase feldspars series.
Crystalline Structure	The arrangement of atoms within a crystal which determines the mineral shape, form, etc. The six crystal systems for rock-forming minerals are isometric, tetragonal, orthorhombic, monoclinic, triclinic, and hexagonal (see Leet and Judson 1971 in References).
Curing	The stockpiling of freshly quarried rock to allow moisture drainage casehardening and relief of stresses induced by blasting, etc.; highly recommended for riprap.
Density	Mass per unit volume; a measure of concentration of matter (e.g., kg/m ³).
Diatoms	Microscopic single-celled organisms growing in marine or fresh water that secrete a hard silica shell.
Differential Weathering	An uneven surface that develops on rock surfaces resulting from more-resistant material weathering slower than adjacent less-resistant material.
Dionite	An igneous rock; coarse-grained equivalent of ardesite; little or no quartz or orthoclase; primarily plagioclase feldspars and Fe-Mg silicates.
Discontinuous Reaction Series	As described by Bowen, the progressive formation of minerals as a melt cools, where abrupt phase changes occur between each stage of mineral formation; the Fe-Mg series: olivine, augite, hornblende, biotite (black mica).
Dolomite	A sedimentary rock composed chiefly of carbonate materials, CaMg (CO ₃) ₂ .

Dust Size	Volume equivalent of sphere of diameter less than 0.06 mm
Elasticity	Resistance to deforming forces in terms of complete recovery of original dimensions after removal of the force. Elasticity is the ratio of stress/strain.
Exfoliation	A weathering process whereby plates or sheets of rock are removed from larger rock masses; volume changes within the rock are responsible for differential pressure forces which cause outer layers of rock to exfoliate.
Extrusive Rock	Rock formed by magma which solidified at the earth's surface.
Facies	A particular part of a rock body as differentiated from other parts of the same rock body by appearance, mineral composition or structural features.
Felsic	A general term applied to light colored rocks containing feldspar, quartz, feldspathoids and muscovite.
Feldspar	A group of common rock-forming minerals of the general formula $M,Al(Al,Si)_3O_8$ where $M = K, Na, Ca, Ba, Rb, Sr, Fe$. Feldspars are widely distributed and constitute 60% of the earth's crust.
Feldspathoids	A group of aluminosilicate rock-forming minerals similar to feldspars but having too little silicate to form feldspars.
Ferromagnesian Silicates	A general term applied to dark rock-forming silicate minerals that contain iron and magnesium.
Fractional Crystallization	The separation of an igneous melt into a liquid and solid phase with different minerals crystallizing as the temperature changes.
Gabbro	An igneous rock; the coarse-grained equivalent of basalt.
Garnet	A family of metamorphic silicate minerals with positive ions of iron, magnesium, aluminum, calcium, manganese, and chromium.

Geomorphology	The study of geology and physiography that deals with configuration of the earth's surface and evolution of landforms.
Gneiss	A metamorphic rock usually derived from granite; a rock with gneissic cleavage.
Granite	Igneous rock composed of orthoclase (~50%), quartz (~25%), and combinations of feldspars and Fe-Mg silicates. The majority of intrusive igneous rocks are granites or granodiorites (as opposed to extrusive igneous rocks, e.g., basalts). Coarse grained, light colored.
Granodiorite	An igneous rock with mineral composition between granite and diorite; coarse grained, semi-dark.
Graywacke	A type of sandstone consisting of quartz and feldspar grains intermixed in a clay lattice; dark colored and relatively hard.
Gypsum	Common mineral, relatively soft, composed of calcium sulfate: $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$. Frequently occurs in conjunction with calcareous sedimentary rocks such as limestone and shales.
Halite	Rock salt, NaCl ; a precipitate mineral forming sedimentary rocks.
Hematite	Iron oxide mineral, Fe_2O_3 . Predominant iron ore mineral.
Hornblende	A double-chained Fe^{+} , Mg^{+} silicate mineral; member of the amphibole group.
Hydration	A natural process that incorporates water into the crystal lattice of a mineral.
Hydrolysis	A chemical process in which water is broken up into H^{+} and OH^{-} and reacts with other components of the solution.
Hydroxides	A group of minerals that contain the hydroxyl (OH) anion.
Igneous	Origin of any rock or mineral that has solidified from molten or partly molten material (i.e., from a magma).

Illite	A family of hydrous Al^{+} silicate clays similar to montmorillonite except for greater presence of aluminum, which significantly reduces sorption and subsequent swelling characteristics.
Intrusive Rock	Rock formed by magma that solidified within the earth's crust but did not reach the surface.
Kaolinite	A hydrous aluminum silicate clay mineral as $Al_4Si_4O_{10}(OH)_8$. Little substitution of ions takes place as occurs in other clay groups, producing a more stable mineral structure.
Lithify	To turn to rock from consolidation of sediments or crystallization from a magma.
Mafic Rocks	A term applied to dark-colored igneous rocks composed chiefly of one or more ferromagnesian minerals.
Magma	Naturally occurring molten rock material liquified by heat within or below the earth's crust.
Marble	A metamorphic rock composed of calcite or dolomite; limestone frequently parent material.
Metamorphic	Any rock derived from pre-existing rock by mineralogical, chemical, and structural changes resulting from heat, pressure, or stress.
Metasediments	Sedimentary rocks that have undergone partial metamorphism.
Mohs Hardness	A scale (1 to 10) of relative hardness of 10 minerals based on the ability of a given mineral to scratch all minerals below it on the scale. The scale is as follows: 1) talc, 2) gypsum, 3) calcite, 4) fluorite, 5) apatite, 6) orthoclase, 7) quartz, 8) topaz, 9) corundum, 10) diamond.
Montmorillonite	A family of hydrous Al^{+} silicate clays bonded in sheets; easily sorbs water, producing appreciable swelling and weakening of bonds.
Muscovite	A potassium/aluminum sheeted silicate: white mica.
Olivine	A rock-forming ferromagnesian silicate mineral that forms early in Bowen series during melt cooling; darker color, less stable than later formed minerals $(Mg,Fe)_2 SiO_4$.

Orthoclase	Potassium (K^+) feldspars: $K(AlSi_3O_8)$
Oxidation	The process of any element or mineral combining with oxygen.
Oxides	A group of minerals or compounds that form when a cation combines with an oxygen anion.
Pebble Size	Volume equivalent of sphere of diameter greater than 4 mm and less than 64 mm.
Permeability	A measure of the ease of flow of a liquid through a rock via interconnected pore spaces.
Petrology	The study of the origin, occurrence, structure, and history of rocks.
Plagioclase Feldspar	A common rock-forming mineral series ranging from the composition $NaAlSi_3O_8$ to $CaAl_2Si_2O_8$.
Plastic Deformation	Response to deforming force; the permanent change in dimensions of a material, which continues once started without an increase in the force and without rupture.
Porosity	The property of a rock containing pore spaces or voids between individual grains. The ratio of void volume to total volume.
Pressure	Force per unit area.
Pyrite	Sulfide mineral, FeS_2 .
Pyroxene	A group of Fe^{+} , Mg^{+} silicate minerals characterized by single chain of SiO_4 tetrahedra (e.g., augite).
Quartz	Rock-forming silicate composed exclusively of SiO_2 tetrahedra; many varieties, determined by impurities that produce spectacular colorations.
Quartzite	A metamorphic rock derived from sandstone, composed chiefly of quartz grains; no rock cleavage; very durable.
Radiolarians	Marine protozoans that possess complex internal silica skeletons.
Rhyolite	An igneous rock; the fine-grained equivalent of granite.

Riprap	Broken rock used for revetment and the protection of structures exposed to weathering elements.
Sand Size	Volume equivalent of sphere of diameter greater than 0.0625 mm and less than 2.0 mm.
Sandstone	Detrital sedimentary rock composed primarily of sand (quartz) grains cemented by calcareous or siliceous material.
Schist	A regionally metamorphosed rock possessing schistose cleavage.
Sedimentary	Pertaining to rocks formed from the consolidation of rock particles or chemical precipitates laid down in successive layers either in water or on land.
Shale	A sedimentary rock composed of detrital deposits of clay and silt; fine grained.
Siliceous Ooze	A soft sedimentary slime composed mainly of silica skeletal remains of microscopic marine organisms.
Silt Size	Volume equivalent of sphere of diameter greater than 0.0039 mm and less than 0.0625 mm.
Slate	Fine grained metamorphic rock produced by low-grade metamorphism of shale.
Spalling	The chipping, fracturing, or fragmentation and outward flaking of a rock caused by weathering forces.
Specific Gravity	Ratio of weight of material of given volume to equal volume of water at 4°C.
Spherical Weathering	A weathering process whereby chemical agents induce pressures within a rock mass, resulting in concentric shells of outer layers being spalled off.
Staurolite	A metamorphic silicate mineral with Fe^+ and Al^+ as positive ions.
Strain	The response of a material to stress; the change in dimensions of the material.
Strength	A measure of resistance to stress at the point of initiation of brittle or plastic deformation.
Stress	A force which when applied to a material causes changes in the material's dimensions.

Sulfates	The group of minerals or compounds that contain a sulfate (SO_4) anion.
Talc	Magnesium silicate metamorphic mineral, also known as soapstone; very soft.
Tetrahedra	A crystal form having four faces each with equal intercepts on all three axes.
Texture	The general appearance of a rock described in terms of the size, shape, and orientation of the minerals which the rock contains. Each rock type--igneous, sedimentary, metamorphic--has texture classifications.
Vadose Water	Subsurface water above the zone of saturation and within the zone of evaporation.
Vugs	A rock cavity, often with a mineral lining of different composition than that of the surrounding rock.

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16. ABSTRACT (200 words or less) Pacific Northwest Laboratory (PNL) is investigating the use of a rock armoring blanket (riprap) to mitigate wind and water erosion of an earthen radon suppression cover applied to uranium mill tailings. Because the radon suppression cover and the tailings must remain intact for up to 1000 years or longer, the riprap must withstand natural weathering forces. This report is a review of information on rock weathering and riprap durability. Chemical and physical weathering processes, rock characteristics related to durability, climatic conditions affecting the degree and rate of weathering, and testing procedures used to measure weathering susceptibilities have been reviewed. Sampling and testing techniques, as well as analyses of physical and chemical weathering susceptibilities, are necessary to evaluate rock durability. Many potential riprap materials may not be able to survive 1000 years of weathering. Available techniques for durability testing cannot adequately predict rock durability for the 1000-year period because they do not consider the issue of time (i.e., how long must riprap remain stable). This report includes an Appendix, which discusses rock weathering, written by Dr. Richard Jahns of Stanford University.					
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