

ROCK WEATHERING AND SOIL FORMATION

by
Gary S. Brierley* — Member

Abstract

The phenomenon of rock weathering is described in simplified but complete terms. The contribution of mechanical, biological and chemical processes are delineated; with a thorough description and discussion of the role played by chemical processes. The relative contributions of climate, topographic relief, and rock composition and structure to the process of weathering are discussed and the overriding importance of climate and topographic relief is demonstrated. The paper concludes with a description of typical soil profiles that develop in North American climates.

I. Introduction

The primary purpose of this paper is to describe how the forces and agents of nature can change relatively dense, solid rock materials into relatively loose, fragmented soil materials and how the composition and structure of the rock compares with the composition and structure of the resulting soil. An understanding of the processes and products of weathering is very important for anyone concerned with the uses of soil and rock. Keller³ goes as far as to say that "Weathering is the geologic process which is the most important and closest to the life of man!" He goes on to describe how food is grown in the soil, which is a direct product of weathering, and how many of our fossil fuels and important ore deposits result from weathering. Some people would consider soil to be the most important natural resource of a country. Others state how weathering fits into the study of geologic processes since it is the principal producer of unconsolidated materials which become available for erosion, transportation and deposition. In addition, a knowledge of the products and processes of weathering can assist geologists in many ways such as providing clues about the type of underlying rock or about climatic changes for long periods of time. Weathering is important to soil engineers because it occurs virtually everywhere within the scope of engineering projects and because it can cause substantial and erratic changes in the permeability, strength and compressibility characteristics of the parent material.

Weathering is the response of materials in the lithosphere to conditions at or near its contact with the hydrosphere and/or the atmosphere and the biosphere. The activity in these areas of contact causes many interactions and changes to take place in each "sphere", but it is the changes in the lithosphere which is the primary topic of this paper. The kinds and rates of

*Assistant Project Engineer, Haley & Aldrich, Inc., Cambridge, Mass.

changes in the lithosphere depend on the intensity of the process, which is largely a function of climate, and on the susceptibility of the material to alteration, which is largely a function of its composition and structure. Another factor that interacts with the climate, composition and structure is the topographic relief.

Climate is a significant but elusive factor in the process of weathering. In general, the macroclimate, or the climate of the atmosphere, controls the average temperature, the amounts of precipitation and evaporation and the distribution of plants and animals. Significant small scale variations, however, referred to as the microclimate, occur in the climate at or near the ground surface and the specific effects of climate on weathering are largely a function of these small scale changes. Large differences can occur between the two climates with respect to temperature, moisture content, air composition and wind velocity, as for instance, on the north and south sides of a boulder, which can be important to a depth of 2.0 ft. or more. A difference in temperature of only 10°F, for example, can cause a change in the rate of a chemical reaction of 2 or 3 times.

The composition of the materials subjected to weathering is somewhat easier to quantify than climate; at least on a continental scale. It is known that approximately 95 percent of the upper 10 miles of the crust is composed of igneous rocks, but that 75 percent of the material at the surface is composed of sedimentary rocks. In addition to this distribution, many of the surface rocks are covered by the transported soils such as glacial, fluvial or eolian deposits, and it is the soil that is most readily available for weathering.

Chemical analyses of all these classes of material have shown that the actual number of abundant elements and minerals present near the surface of the earth is very limited. The eight most common elements in their order of abundance are oxygen, silicon, aluminum, iron, calcium, magnesium, sodium and potassium, and these combine to form the eight most common minerals that comprise approximately 90 percent of the outermost 10 miles of the crust. Given below is a listing of the most common minerals and their relative abundance:

Feldspar	30%	Carbonate	9%
Quartz	28%	Iron Oxide	4%
Clay Minerals		Pyroxene	
and		and	
Mica	18%	Amphibole	1%

It is these materials, therefore, that will usually be involved in the weathering process.

Rock structure is another highly variable factor in the rate of weathering. Large features such as joints, foliation, bedding planes, and faults, and small features such as texture and grain contacts are all important for determining the accessibility of rock to weathering agents. The internal

stress regime and stress history, although less obvious, can also cause changes in the rate of weathering.

Topographic relief can affect weathering indirectly by changing the microclimate or directly in many important ways. The three most important direct effects of topography are the rate of runoff vs. infiltration, the rate of subsurface drainage and the rate of removal of the weathered products. The rates of infiltration and subsurface drainage control to a very large degree the rate of chemical weathering. Erosion determines how quickly fresh material is exposed to weathering.

With these four factors in mind — climate, composition, structure and topographic relief — a more thorough discussion of weathering will be presented in the following sections. Weathering is commonly divided into mechanical, biological and chemical processes, but this is mostly for convenience since all of the processes of weathering are intimately interrelated. Biological processes, especially, can be easily divided into mechanical and chemical effects. These three divisions, however, will form the basis for the following sections with pertinent cross references as the need arises.

II. Mechanical Weathering

Mechanical weathering is defined as those forces in nature that cause a reduction in particle size without chemical alteration. The two most important effects of a reduction in particle size are that the material becomes more susceptible to erosion and to chemical weathering. Most geology texts have a complete discussion of mechanical weathering, and the important aspects of the process are listed here in outline form only.

Impact and Abrasion — Many particles are reduced in size simply by falling and being shattered upon impact. Particle impact during transportation by wind, water and ice will also cause a reduction in particle size by abrasion. These processes are so important, in fact, that they are usually treated as a separate branch of geology.

Frost Wedging — Freezing water can generate large forces due to an increase in volume. If the water is enclosed in cracks in the rock, the forces are sufficient to cause the rock to break. The amount of breakage has been found to be more closely related to the number of freeze-thaw cycles than to the intensity of a single freezing episode.

Thermal Expansion and Contraction — Ordinary diurnal temperature variations are not thought to be a significant cause of rock breakage except in the presence of water, and then the water probably causes more chemical than physical alteration. Temperatures generated in forest fires, however, may cause rock fracturing.

Pressure Relief — Substantial pressure relief by erosion can cause cracks in the rock to form on a large scale. Exfoliation and joints are two common examples of this mechanical breakage.

Tectonic Forces — Mountain building forces result in folding and faulting of rock materials that can cause considerable rock deformation and

breakage. These forces also very often make the rock available for other types of weathering processes.

Volume Changes — Chemical weathering will cause an increase in volume of the parent material which is sufficient to create large forces in a material that is not weathering uniformly throughout. These differential stresses can cause the rock to disintegrate and release the most resistant particles unaltered.

III. Biological Weathering

Biological activity and accumulation of organic matter is common in the zone of weathering. The effect of living organisms is somewhat different than other agents and forces in the environment because living organisms are able to utilize the energy of the sun directly through metabolism to drive their life-giving reactions. In addition, living and dead organisms add many complex organic molecules to the environment. Some of the more important aspects of biological weathering are given below in outline form. Much of what is given below will be expanded in the next section on chemical weathering.

Root Wedging — The turgid pressure of plant roots reaching out to find water and nutrients is sufficient to loosen soil and even to break rock. The actual contribution of this process to mechanical breakage of rock is probably quite small, but it can be locally important.

Mixing — Although not directly related to particle disintegration, many rodents and insects move vast quantities of soil up and down the soil profile every day. This activity continually makes fresh material available for weathering and provides additional access for other weathering agents to materials that were not disturbed.

Redox Potential — Organic materials are powerful reducing agents, combining readily with oxygen to form carbon dioxide. This can have an important effect on the "mobility" of some ions in the environment.

Colloidal Activity — Small particles of organic matter are chemically active with several exterior exchange positions available for cations that may be present in the environment. If the cation happens to be hydrogen, the organic matter will become a colloidal acid. Changes in the pH can have many effects on other reactions.

Acid Production — Besides retaining hydrogen ions in the environment, the carbon dioxide produced by decomposing organic matter combines readily with water to produce carbonic acid. Although not a powerful acid, carbonic acid seems to have widespread effects due to its great abundance.

Chelation — Certain organic compounds are capable of surrounding a cation and isolating it from the environment. These compounds are commonly produced in nature and are capable of removing important cations from participation in secondary mineral recrystallization. Chelation is also another method whereby plants may obtain their food.

IV. Chemical Weathering

Chemical weathering results from a change in the chemical environment. The change usually occurs when rock formed deep in the lithosphere under conditions of high temperature and pressure is exposed near the surface and brought in contact with water, oxygen, carbon dioxide and other elements and compounds. With this change, the process of weathering begins and new minerals are produced that are relatively more stable in the new environment.

The process of chemical weathering can be divided into three phases. The first phase is the breakdown of the existing minerals. Several common exothermic (heat releasing) chemical reactions are involved with the breakdown of the minerals which proceed spontaneously to equilibrium while changing the properties of the parent material. This equilibrium would be the end of the process if it were not for the second phase, the removal of soluble constituents.

Many of the products produced by the breakdown of the parent material are continuously removed from the chemical environment so that the chemical reactions hardly ever reach an equilibrium. The two most important mechanisms for removal are leaching and the use of constituents by plants. This removal is the real driving force of chemical weathering. A large part of the understanding of chemical weathering, therefore, is to understand what the "mobility" of the various products of breakdown are in different chemical environments.

The third phase consists of the recrystallization or reorganization of the remaining products into new, more stable minerals. The composition and type of new minerals depends to some degree on the composition and type of parent material and to a very large degree on the constituents selectively removed by leaching and by plants.

To understand the breakdown of parent materials, it is necessary to know something about the composition and structure of these materials. As stated in the Introduction only a relatively few minerals exist in the outer crust. Of these, clay minerals and iron oxide are largely the *result* of weathering processes. Those remaining are composed mostly of silicates, and to a much lesser degree, carbonates.

The basic building block of a silicate is the silicon tetrahedron, which is a silicon atom surrounded by four oxygen atoms in a tetrahedral configuration. The manner in which the tetrahedra are connected together is a good method for classifying the various silicate minerals. An abbreviated example of this classification system is presented below with brief descriptions.

Nesosilicates (SiO_4 Group) — No polymerization, individual silica tetrahedra bonded together by cations. Aluminum substitution for the silica in the tetrahedron is rare. Olivine, zircon, garnet and topaz are examples of this class. Susceptibility to weathering is variable.

Sorosilicates (Si_2O_7 Group) — Polymerization of two silica tetrahedra by a single oxygen bond.

Cyclosilicates (Si_6O_{18} Group) — Tetrahedra arranged in hexagonal rings with each tetrahedron sharing two oxygen with adjacent units. Rings bonded together by cations. Examples are beryl and tourmaline. Relatively resistant to weathering.

Inosilicates (Si_2O_6 and Si_4O_{11} Groups) — In the Si_2O_6 group, tetrahedra are in single chains with all the tetrahedra pointing in the same direction. Each tetrahedron shares two oxygen with adjacent tetrahedra and the chains are linked together by cations. Limited substitution of aluminum for silicon in the tetrahedra in some of the more complex members. Cleavage at 93° . Pyroxene is the common name. Highly susceptible to weathering.

In the Si_4O_{11} Group, the tetrahedra are formed into double chains by polymerization. Hydroxyl ions present in the cavities between the chains. Chains bonded together by cations. Cleavage at 56° and 124° . Amphibole is the common name. Highly susceptible to weathering.

Phyllosilicates (Si_4O_{10} Group) — Tetrahedra further polymerized into continuous sheets with the tetrahedra all pointing in the same direction. Sheets form an hexagonal pattern with hydroxyl ions in the pockets of the hexagons. Sheets bonded together by cations. Variable substitution of aluminum atoms in the tetrahedra up to 25 percent of the silicon. Well developed parallel cleavage. Biotite, muscovite and talc are common examples. Highly susceptible to weathering with specific exceptions such as muscovite.

Tectosilicates (SiO_2 Group) — Complete polymerization with all the oxygen atoms shared by silica to form a three-dimensional network. Quartz and feldspar are included in this group. Quartz is a complete network of silicon tetrahedra which is highly resistant to chemical weathering. Feldspar has up to 50 percent substitution of aluminum in the tetrahedra for silicon and associated cations to balance the charges. Feldspar has distinct cleavage and is moderately susceptible to chemical weathering.

The most direct effect of mineral structure on weathering is the relative stability of the atomic bonds in the mineral. The silicon-oxygen bond is the most stable followed in order by the aluminum, potassium, sodium, ferrous iron, magnesium and calcium bonds with oxygen to name a few of the more common cations.* An analysis of the bonding energy for the above groups of silicates shows that the energy increases regularly from the nesosilicates to the tectosilicates. This means that each group in order from the nososilicates releases more energy during crystallization and requires more energy for breakdown.

Closely related to this phenomenon is the coordination number, which is a measure of how tightly packed various atoms can be due to their actual

*Only oxygen bonds are considered here because oxygen is by far the most common anion. Other anions in the ocean and on land are chloride, bromide, sulfate, borate, carbonate, and bicarbonate.

physical size. Atoms that can fit more closely together will usually have higher bonding energies and be more resistant to weathering.

The coordination number also has an important bearing on the susceptibility of molecules to isomorphous substitution during crystallization and to ionic exchange during weathering. Cations of similar coordination number may replace one another in the silicate structure. Substitution depends not only on the actual size of the atom, but on the difference in charge, which may be as great as one valence unit, and on the overall mineral structure. An example of substitution is in the mineral olivine where ferrous and magnesium atoms can replace each other in a continuous series.

Another type of mineral structure is associated with sedimentary and metamorphic carbonate rocks such as limestone, dolostone and marble. These materials are composed primarily of calcium carbonate, with magnesium substitution common in dolomite, and variable through small amounts of other substances such as quartz. Although these minerals are crystalline, crystal structure is not well developed because the carbonates can exist in several different configurations and because "impurities" interrupt crystal growth.

The four chemical reactions described below: Hydrolysis, Oxidation, Carbonation and Ion Exchange, are the most important for disrupting silicate and carbonate structures.

Hydrolysis is the separation of the water molecule into hydrogen and hydroxyl ions and the interaction of these ions with other reactants to form new compounds. The separation is accomplished when the water molecule is subjected to an electric force sufficient to break its internal bond. This is a very important reaction in chemical weathering.

Oxidation of a substance occurs when one of its constituent atoms loses electrons and becomes positively charged. Oxidation in nature usually occurs when a weathering material loses electrons to elemental oxygen which has become ionized. Other elements such as sulphur and chlorine can also cause oxidation. This is usually the first noticeable reaction because it generally is accompanied by a change in color.

Carbonation is the combination of carbonate or bicarbonate ions with a weathering material. Calcium, magnesium and, to a lesser degree, iron bearing rocks can be weathered by carbonation. Carbonate and bicarbonate ions are produced in nature principally by the combination of water and carbon dioxide to form carbonic acid.

Ion Exchange occurs whenever positive or negative ions replace other ions of similar charge in a substance without series rearrangement or change of structure. This is possible because not all ions have the same affinity for inclusion in a given substance. Whether or not the substitution actually occurs depends on the relative affinities, the composition and concentrations of other chemical compounds that may be present and the atomic structure of the substance. Hydrogen ions are particularly effective in ion exchange reactions because of their small size and high

charge-to-size ratio. In silicate minerals the exchanged ions can be rejected from the mineral and/or various silica polyhedra and lost to the environment.

Although the response of various minerals to the four chemical reactions listed above is complex and almost infinitely variable, a simple model for the mechanism of breakdown of the minerals will be given here. In general, the silicate minerals weather by hydrolysis and cation exchange, iron-bearing minerals by oxidation and carbonate minerals by carbonation and solution.

When a silicate comes in contact with water, the water is polarized to such an extent that the hydrogen and hydroxyl ions are dissociated and become bonded to exposed anions and cations at the minerals surface. Simultaneously, the hydrogen may displace cations at the mineral surface causing the pH of the liquid to become alkaline. This reaction would quickly reach an equilibrium, with just as many cations entering and leaving the mineral structure, unless some of the released cations are removed from the system. With removal the hydrogen ion becomes very effective in disrupting the crystal structure and causing the release of monomeric or polymeric silica to the environment.

Iron-bearing minerals are susceptible to weathering by oxidation. In greatly simplified terms, iron in the crystal structure is oxidized to form a stable mineral with oxygen and is removed from its crystal bonding function. The removal of iron in this way causes the crystal to become electrically unstable and to break up in order to become balanced again. Since oxidation is exothermic, the reaction proceeds spontaneously.

The mechanism of breakdown of carbonate rocks is quite straightforward. Although calcium carbonate is nearly insoluble, it reacts readily with acid to form calcium bicarbonate which is highly soluble. As the carbonate is removed by solution, the impurities in the rock become relatively concentrated in the environment and, depending on their composition, may be further broken down by hydrolysis, ion exchange and oxidation.

As the mechanism of breakdown proceeds a residue is produced that contains silica, displaced ions, oxygen, carbon dioxide, water and many other substances. The silica may have been reduced to monomeric form (molecularly dispersed) or it may retain much of the structure of the parent material in polymeric form. All of these materials are now available for use or removal by the environment. The relative ease or difficulty with which these materials are removed will determine to a large degree the final composition of the residue and the types of new minerals which form from the residue.

One of the most important factors affecting the rate of removal is the pH, which is the logarithm of the reciprocal of the concentration of hydrogen ions. A low pH is a high concentration of hydrogen ions and usually a low concentration of other exchangeable ions while a high pH is a low concentration of hydrogen and an abundance of other exchangeable ions. A pH

of 7.0 corresponds to distilled water and is called neutral. Substances with a pH less than 7 are acid, and those with a pH greater than 7, alkaline. Most natural soil materials have a pH between 4 and 9.

It should be noted that the pH is a measure of the degree of acidity but not the total amount. Different substances with the same pH may have more or fewer hydrogen ions. In addition, the pH can be highly variable in a multiple phase system: being one value in the solids, another in the liquid and so on. It is the average pH that is of importance with respect to chemical weathering.

The relationship between average pH and the solubility of common soil constituents is shown in Figure 1. The diagram shows that for the common natural range of pH between 4 and 9 Ca(OH)_2 , Mg(OH)_2 , and the alkalis* (not shown) are completely soluble, and Fe(OH)_3 and Al_2O_3 are completely insoluble. The solubility of molecularly dispersed silica** though low in this range is constant and relatively unaffected by pH. Hence, the compounds whose mobilities are most affected by natural changes in pH are CaCO_3 and Fe(OH)_2 .

Changes outside the normal range can cause dissolution of Al_2O_3 and precipitation of Mg(OH)_2 if alkaline, and dissolution of Al_2O_3 and Fe(OH)_3 , if acidic. An example of this latter case is illustrated in Figure 2 for two soil profiles that are well leached and contain similar clay minerals. In this case, the low pH (acidic condition) of the organic matter at the top of the podsollic soil causes the Al_2O_3 to be dissolved and reprecipitated lower in the profile where the pH is higher.

Changes in the pH are caused by changes in the concentration of hydrogen ions which are made available by dissociation of water molecules. Common sources for hydrogen ions are hydrolysis, the oxidation of sulfide minerals to form carbonic acid, the action of plant roots, and extraneous sources. Hydrolysis was explained earlier and the production of sulfuric and carbonic acids are straight-forward chemical phenomena. The action of plant roots is somewhat less obvious, but it seems that plants are able to utilize the energy of the sun to maintain a highly acidic condition. The hydrogen ions are exchanged for other cations that the plant needs for food. Hydrogen ions from extraneous sources such as mining and industrial activities and not important on a large scale, but can have significant local effect.

The production of the ions is only the first part of the process, however. In order for the pH to become low the ions have to be retained and concen-

*Alkali and alkaline earth ions are referred to frequently in this report. Alkali ions are those in Group IA of the periodic table that easily form singly charged cations. Alkaline earth ions are those in Group IIA that easily form doubly charged cations. Common examples of alkali ions are sodium and potassium and common examples of alkaline earth ions are magnesium and calcium.

**Quartz is approximately ten times less soluble than monomeric silica.

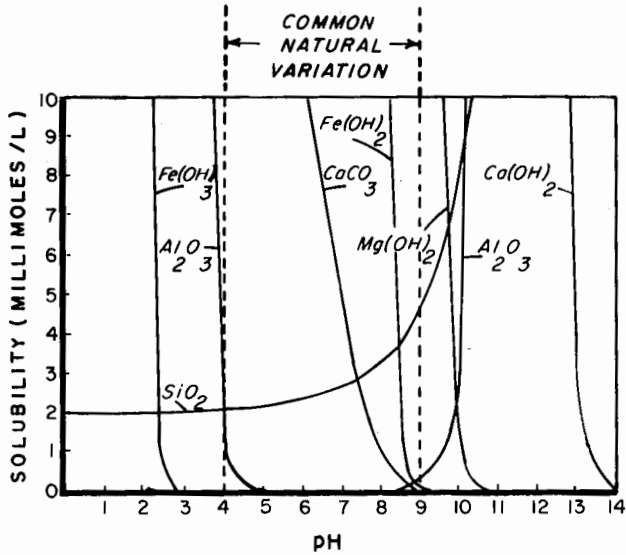


FIGURE 1

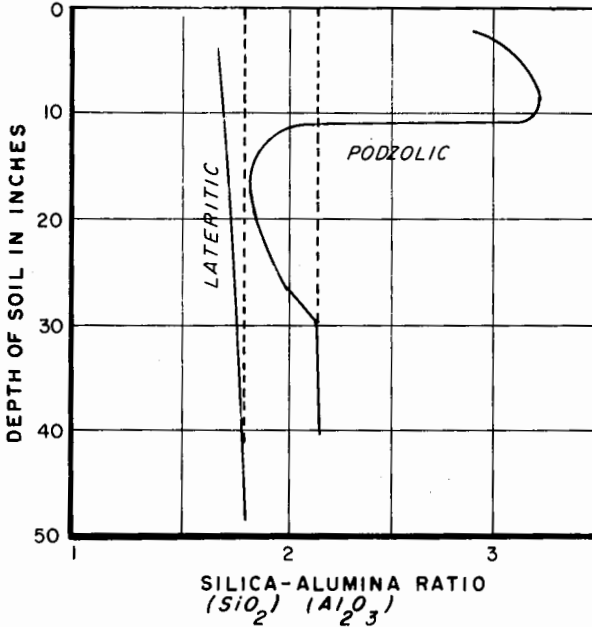


FIGURE 2

trated in the environment. A major factor in the retention and concentration of hydrogen is the colloidal activity of clay minerals and organic matter. These classes of material are capable of retaining many cations, including hydrogen, at exchange positions on their exterior surfaces.

Alkaline environments are created by the accumulation of alkali and alkaline earth ions which have been released from the parent material or have been introduced by extraneous sources. Ions from the parent material are released mostly during exchange reactions with hydrogen. Other sources of salts, alkali, or alkaline earths are materials dissolved or washed from the atmosphere, deposited by the groundwater or intentionally added to the ground. Materials washed from the atmosphere include salts near the ocean and pollutants near large cities. Many cations can be concentrated by the groundwater in any natural basin from a swamp to an ocean. Intentionally created alkaline environments occur frequently in farming areas.

The second factor that can affect the rate of removal of some of the soluble constituents is the redox potential or Eh. As shown in Figure 1 iron is capable of existing in more than one valence state and the solubility characteristics of the two states are quite different. Iron is particularly important in this respect because it is common and because its oxidation potential for the transition of ferrous (+2) to ferric (+3) falls within the range of natural environments.

The actual redox potential in natural environments is difficult to determine. It depends primarily on the availability of atmospheric oxygen, the presence or absence of organic matter, and the pH. Oxidation (removal of electrons) tends to proceed spontaneously above the zone of permanent groundwater saturation with reducing conditions below this level. Organic matter, however, is a powerful reducing agent and may create a reducing environment even above the water table. Reducing environments are also induced with respect to iron by a low pH or acidic conditions.

The third factor, which is particularly important with respect to the mobility of potassium, is called fixation. Fixation refers to the containment of an atom in a very stable crystal structure. The phenomenon is related to the concept of the coordination number where the geometric fit is so good that it is difficult to force the atom out of its position. Such a good fit occurs readily for potassium in muscovite and in many clay minerals. Containment of the potassium atom in this way is apparently the reason why muscovite is so resistant to weathering. It is also the reason for the immobility of potassium and for its scarcity in the ocean basins.

The last important factor with respect to the mobility of various cations is chelation. Chelation refers to the ability of an organic compound to form a ring structure around a cation and to isolate it from the environment. Organic compounds with this property are referred to as complexing agents and are supplied to the environment by root secretions and by the accumulation of dead organic matter. The total contribution of this mechanism to mobility is not fully understood, however.

The destruction of the parent material and the selective removal of soluble constituents leaves a residue that is available for reformation into new, relatively more stable minerals. The composition of the residue is almost infinitely variable, but for "normal" ground conditions it consists of resistant parts of the parent material, monomeric and polymeric silica, atmospheric substances and relatively insoluble or fixed cations. Recrystallization of the residue usually results in the formation of clay minerals or stable oxides of silicone, iron and aluminum which are referred to as the secondary minerals.

Secondary minerals are sometimes called the end products of chemical weathering, but it is important to realize that these substances are also subjected to weathering at a somewhat reduced rate. It is not uncommon, for example, for clay minerals to change from one type to another. A discussion of the weathering of the secondary minerals is beyond the scope of this paper, however.

Some of the more resistant minerals that appear in the residue and that are commonly found in sedimentary rocks are quartz, zircon, tourmaline, garnet and muscovite. Sodium plagioclase is also resistant compared to calcium plagioclase and can be found in silt sized particles in some heavily weathered soil profiles.

The clay minerals are nearly all phyllosilicates with the three most common types being kaolinite, illite and montmorillonite. Kaolinite is somewhat in a class by itself because it has a crystal structure different than the other two types and because it is nonexpanding. Illite and montmorillonite are both expanding clay minerals with similar crystal structure. The essential differences between these two minerals are in the amount of charge deficit and in the nature of the sorbed cations. More information about the distribution and occurrence of the clay minerals is given in the next section. For a more complete description of the clay minerals the reader is referred to Loughman⁷.

V. Soil Formations

This section deals briefly with the composition of different types of soil profiles that result when rock is acted upon by the weathering processes. Soil profiles are very often classified according to the prevailing climate in their area of formation. Climate was given in the Introduction as one of four factors, together with composition, structure and topographic relief, that control the kinds and rates of weathering processes. Over long periods of time, however, it appears that climate is the most important factor because it has been observed that similar soils will develop in rocks of vastly different composition and structure in the same climate. Topographic relief is probably of secondary importance but it is more variable and difficult to use for classification on a large scale.

Five different climates, will be discussed in the following sections: temperate-wet, temperate-dry, temperate, tropical, and arctic. This selection is arbitrary and not all-inclusive. Climate, of course, is infinitely variable and

any division is somewhat arbitrary, but the five climates listed above include large areas of the North American Continent.

Temperate-Wet Climate

Precipitation — greater than 25 in. per year

Temperature — Moderate

Leaching — Moderate

Organic Matter — Present

A temperate-wet climate is characteristic of the eastern half of the United States. Soils in this area are referred to as pedalfers and are leached at the top with accumulations of iron and clay lower in the profile. The pH is generally acid due to the presence of organic matter. The redox potential can be either oxidizing or reducing depending on the local conditions and the position of the water table.

In general, the alkali and alkaline earth ions are removed by leaching along with some of the silica. Alumina and ferric iron ions are concentrated. Kaolinite is a familiar clay mineral in the clay fraction.

A particular form of pedalker soil is a podzol which is a pedalker that has been leached by solutions rich in humic acid. The humic acid causes the iron and aluminum to be leached out relative to the silica and to be deposited deeper in the profile. Podzolic soils occur most often in moist, heavily forested areas.

Temperate-Dry Climates

Precipitation — less than 15 in. per year

Temperature — Moderate

Leaching — Slight

Organic Matter — Absent or sparse

Soils in this climate are called pedocals and are characteristic of much of the western half of the United States although pedalfers exist in many of the wetter regions in the mountains. The pH is generally alkaline due to the slight leaching, high evaporation and lack of organic matter. The redox potential is oxidizing. Chemical weathering is slow despite the relatively high temperatures due to the lack of removal of weathering by-products by leaching or plants.

Pedocals are immature soils and usually reflect the composition and structure of the parent material. Iron is immobilized in the ferric state and tends to coat the soil grains giving a varnished appearance. High evaporation causes the carbonates to be deposited in the upper soil to the point that in extreme cases a solid, almost impervious layer called caliche is formed. Illite, montmorillonite and other expanding clay minerals are common in the clay fraction.

Temperate Climate

Precipitation — Between 15 and 25 in. per year

Temperature — Moderate
 Leaching — Moderate
 Organic Matter — Abundant

Intermediate between the pedalfers and the pedocals are transitional soils of the midwestern prairies. Enough leaching occurs in this area to remove lime from the A and B horizons, but, if present in the parent material it can usually be found in the C horizon. Acidity is not sufficient to induce leaching of iron and aluminum as it does in podzolic soils. Retention of the alkali and alkaline earth ions is sufficient to favor the formation of expanding clay minerals, especially illite. The soil profile consists of a thick, dark, organic-rich A horizon and a yellow or light brown B horizon.

Tropical Climates

Precipitation — Greater than 50 in. per year
 Temperature — Hot
 Leaching — Intense
 Organic Matter — Sparse, rapidly destroyed

Tropical climates are characterized by abundant rainfall and intense leaching. Chemical weathering is intense with a moderately low pH and an oxidizing redox potential. Organic matter is rapidly removed by bacteria that thrive in the hot climate.

Laterite is a very common soil type in this region consisting of a concentration of hydrated oxides of aluminum and ferric iron as compared to silica and a lack of clay minerals. Clay particles are predominantly kaolinite. Humic acid is not available to leach iron ions as in podzolic soils and the acid environment is not concentrated due to the lack of clay minerals. Laterites are most readily formed from basalt, gneiss, schist, sandstone or limestone in areas of heavy rainfall, good subsurface drainage and strongly oxidizing environments.

Soils formed under climatic conditions similar to those above, but with an abundance of feldspar in the parent material are called bauxite. Bauxite consists of aluminum hydroxides such as gibbsite, boehmite and diaspore. If present in sufficient quantity, laterite and bauxite can be valuable sources of iron and aluminum, respectively.

Arctic Climate

Precipitation — Variable
 Temperature — Cold
 Leaching — Slight
 Organic Matter — Sparse

Soils in the arctic regions are poorly developed due to the very slow rate of chemical activity. Drainage and leaching are poor because of permafrost and a high water table which favors reducing conditions and the formation of marshy areas in the warmer months. The pH varies from mildly alkaline to highly acidic in the marshy areas.

Mechanical weathering related mostly to frost action is the predominant soil forming mechanism. Hence, the soils are stony and continually disturbed by frost or glaciation. Clay minerals are scarce and are mostly of the illite, montmorillonite or mixed layer varieties.

VI. Summary

The preceding discussions have indicated that although pH, Eh, fixation and chelation play important roles, the extent and results of weathering are largely determined by the availability of water and the degree of leaching. Water is a significant contributor to mechanical and biological weathering and is the most important initiator of chemical weathering due to the active nature of the hydrogen ion. The mobility of the various products of weathering in water also determines what substances will be available for recrystallization into secondary minerals.

The most important factor relative to the availability of water is the macroclimate. With time, the soil profile in an area will be largely a function of the climate for a wide variety of different parent materials.

Topography and composition probably share significant secondary importance. Topography contributes to the amount and rate of subsurface drainage and leaching which was shown to be very important. Topography also controls the rate of removal of the weathering products. Composition is important for determining the characteristics of the soil if the soil is young or immature or if the minerals in the rock are relatively rare and contain rare elements.

Structure is least important in the vast majority of cases with its most significant contribution being to the rate of weathering.

VII. Acknowledgments

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