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CHARACTERIZATION AND MEASUREMENT OF THE INDUSTRIAL ENVIRONMENT

MINERALOGY

Arthur M. Langer

NATURAL AGENTS OF DISEASE

Exploitation of metal ores and fossil fuels, and the quarrying and mining of nonmetallic rocks and minerals, are carried out primarily on and within the earth's continental crust which extends from the tidal zones along the ocean margins of land masses to the mountainous highlands and interior "shields" of continents. The lithological units constituting the earth's surface may range from unconsolidated beach sands to dense, crystalline rock massifs which often form the "spines" of many of the great mountain ranges of the world.

Those who work in these environments may be exposed by inhalation to powders arising from fragmented or comminuted rocks, minerals, and ores. Miners, millers, stone masons, quarry men, tunnel drivers, to name but a few, may develop pneumoconiosis and, in some instances, malignant neoplasms as the result of such exposures. These diseases are also evident among working populations which process or handle such materials in secondary capacities, e.g., nickel ore millers and processors and nickel smelter workers, who develop lung and sinus cancers; workmen who use these substances in a variety of applications, such as insulation workers who handle asbestos fiber and who suffer the asbestos diseases; and foundry workers who use molding sands and who develop silicosis.

An appreciation of the nature of the crust, its rock types and ores, and its specific mineral prevalence, distribution, and association, is essential to any fundamental comprehension of the nature, extent, and distribution of dust-related diseases. This is especially important where agents of disease are known and have been identified.

THE EARTH'S CRUST

On the basis of geophysical, geochemical, mineralogical, and petrological data, much is known concerning the physical/chemical nature of the crust. Geophysical data suggest its profile may extend from the surface down to a depth of some 60 km. It is thickest in continental regions where mountain building is still active. However, in other areas it may be thin, almost disappearing at the continent-ocean contacts. Variation and range in crustal depth are related to factors such as proximity to ocean basins or mountain ranges and location with "colliding" continental plates.

The concentration of exploited minerals and fossil fuels confines most human activities to the uppermost crust and surface. In some gold mining districts of the world, mine shafts with depths of four km. have been sunk. The depth limitations of these shafts are primarily due to the mine air temperature and humidity; the former may be near 50 °C (because of the geothermal gradient) and the latter at 100% "wet bulb," due to evaporating ground water and water coolants used on the mine drift walls. Therefore, human activities (direct mining) are carried out in the crustal "veneer," with most mining and exploitation operations confined to the upper several thousand feet (approximately 2 km.).

COMPOSITION OF THE CRUST

An understanding of minerals found in the crust requires some basic information regarding their chemistry. The chemical composition of the crust is uniform on the large scale, with only some 8 elements constituting almost 99% of its mass (Table I-1a). It is from these few elements that the overwhelming majority of minerals are formed. The two most abundant elements are oxygen and silicon; hence we have prolific supplies of silicate minerals and silica polymorphs, especially quartz. The ore minerals, those from which we extract most metals, metalloids, and other substances, are frequently nonsilicates which contain the less common elements ordinarily distributed as trace quantities. These have been concentrated sufficiently, by specific geological processes, to permit their exploitation as "ores." (Table I-1b).

The affinity of silicon for oxygen, together with its varietal bonding possibilities, results in many polymerization forms. This creates a variety of crystalline structures into which cations of differing species, size, and charge may fit. Six major structural types of silicate minerals result and the diversity of structural accommodations for differing cation species gives rise to the many silicate mineral forms that make up the earth's crust. The principles governing crystallization of minerals are outlined in the section on igneous rocks.

Table I-1a

CHEMISTRY OF THE EARTH'S CRUST

Major Elements Constituting the Crust

Element	Weight %	Atomic %	Volume %
Oxygen	46.6	62.6	93.8
Silicon	27.7	21.2	0.9
Aluminum	8.1	6.5	0.5
Iron	5.0	1.9	0.4
Calcium	3.6	1.9	1.0
Sodium	2.8	2.6	1.3
Potassium	2.6	1.4	1.8
Magnesium	2.1	1.8	0.3
	98.5	99.9	100.0

THE CLASSIFICATION OF CRUSTAL ROCKS

The earth's crust is comprised of rock types, which appear to vary greatly in mineral composition and physical character. Three generic rock types are recognized, with varietal classes based on the mode of origin. These are:

Igneous rocks, which form primarily through the crystallization of molten magma on or beneath the earth's surface.

Sedimentary rocks, which form primarily through the accumulation of erosional debris; floral and faunal deposits; some forms of volcanic ejecta; and the chemical precipitates. These materials were derived from the degradation products of pre-existing rocks and through the accumulation of crustal organisms.

Metamorphic rocks, which form through the change of pre-existing lithological units by recrystallization under superimposed new temperatures, pressures, and chemical processes. Mineral character is normally changed and textural relationships among minerals are altered.

Each rock type, in addition to its unique mode of formation normally possesses characteristic constituent minerals, structures, and textures. Each may act as a host for ore deposition. Some discussion of these characteristics will help define the nature and character of their mineral populations.

THE IGNEOUS ROCKS

Often considered "primary," igneous rocks (from the Latin stem *ignare,* meaning *fire*) are formed from the crystallization of molten magma, on or beneath the earth's surface. The resultant mineral species, and their textures (grain-size and geometric relationships) often reflect the parent magma and crystallization under specific conditions of temperature and pressure. The molten sources (magmas) of all igneous rocks are chemically referred to as silicate melts. Melts may vary in temperature and chemistry, kinds of cationic species present, amount of silica, water contents, etc. Such variation produces different end-product rocks and partly accounts for the observable igneous rock diversity.

Magmatic Crystallization

Magmatic melts may originate from numerous subcrustal zones, probably the lower crust or the earth's upper mantle, where preexisting rocks are heated by a variety of processes. After heating, melts develop ductility and are transported by tectonic or volcanic forces to places where they undergo crystallization. Deep within the crust, the melt may begin to crystallize and the process of igneous rock formation begins. However, while working their way to the surface—and depending upon local conditions (e.g., host rock types)—such high temperature silicate melts may remelt and assimilate surrounding in-place host rock units. This may profoundly alter the composition of the original melt and will yield much different rock types upon crystallization. Hence, although basaltic magmas (considered "primary" magma) should only produce a few rock types, other confounding factors are operative which produce complex rock and mineral suites.

The crystallization of silicate melts begins

Table I-1b

CHEMISTRY OF THE EARTH'S CRUST

Minor and Trace Elements in the Crust (Concentration in Parts Per Million)

Element	PPM	Element	PPM	Element	PPM	Element	PPM
Titanium	4,400	Rubidium	120	Lanthanum	18	Mercury	0.5
Hydrogen	1,400	Vanadium	110	Lead	15	Antimony	0.2
Phosphorus	1,180	Nickel	80	Gallium	15	Bismuth	0.2
Manganese	1,000	Zinc	65	Thorium	10	Cadmium	0.2
Sulphur	520	Nitrogen	46	Scandium	5	Silver	0.1
Fluorine	500	Cesium	46	Tin	3	Platinum	0.005
Strontium	450	Copper	45	Bromine	3	Gold	0.005
Barium	400	Yttrium	40	Beryllium	3	All others	
Carbon	320	Lithium	30	Arsenic	2	<0.005	
Chlorine	200	Neodymium	24	Uranium	2	(5 ppb)	
Chromium	200	Niobium	24	Tungsten	1		
Zirconium	160	Cobalt	23	Molybdenum	1		

in the molten state, as evidenced by recent studies of volcanic glasses (quenched melts) which demonstrate that crystalline domains (ordering) of silicon and oxygen and aluminum and oxygen, take place in materials which have been previously considered "glassy" (amorphous). Normally, the silicon-oxygen polymerization begins as silicon and oxygen complexes so that "bridging" increases, producing a progressive ordering of structure and a more stable thermodynamic unit.

As crystallization of a silicate melt proceeds, a number of chemical bridging events occur: single, isolated silica tetrahedra exist, forming structures only when joined together by cations; as temperature decreases, tetrahedra may share a corner oxygen to form double tetrahedral structures and eventually single infinite chains; with further temperature decreases, shared corners of silica tetrahedra form "double chains"; additional corner sharing of silica tetrahedra produces a two dimensional structure called a "sheet"; finally, the complete sharing of all tetrahedral apices forms a three-dimensional framework structure. During this process, the silicon to aluminum ratio decreases, the alkalies within the melt increase, the water and volatile contents of the melt increase, the fluorine and chlorine content of minerals increase, the unit cell volumes of the mineral species increase, and the mineral densities decrease (see Table I-2). These chemical trends reflect the chemical properties of the different atomic species in the melt. Included, as some of the important properties, are ionic radius, valence state, and electronegativity.

The first silicate mineral to crystallize is olivine. This phase then reacts with the melt (in which it has just crystallized) to form pyroxene. Pyroxene subsequently reacts to form amphiboles, and the amphiboles react to form micas. These reactions need not proceed to completion; consequently "survivor minerals" of the crystallization process are frequently observed in a variety of igneous rocks. Several mineral series may crystallize simultaneously (Table I-2). In addition to the ferromagnesium series, the feldspars crystallize at the same time. The calcium-aluminum varieties predominate at first, then change to the sodium varieties and end with those that are potassium rich. The potassic feldspars crystallize normally with the mineral quartz; the mica variety muscovite may end with zeolite and other "hydrothermal minerals."

Crystallization follows physical-chemical laws, one of which (the "phase-rule") implies that only a limited range of mineral phases may form at any one time. Almost 99% of the mineral composition of igneous rocks may be represented by 5 mineral groups and the silica phase quartz. The mineral groups and the common

Table I-2

PHYSICAL-CHEMICAL CHANGES ACCOMPANYING THE CRYSTALLIZATION OF BASALTIC MAGMA

Temperature of Melt During Crystallization

High temperature (~1250°C) → Low temperature (~750°)

Major Cations Incorporated in Minerals During Crystallization

$\mathrm{Mg} > \mathrm{Fe} \longrightarrow \mathrm{Fe} \cong \mathrm{Mg} \longrightarrow \mathrm{Fe} \gg \mathrm{Mg}$

$\mathrm{Ca} \gg \mathrm{Na,K} \longrightarrow \mathrm{Na,\ K} \cong \mathrm{Ca} \longrightarrow \mathrm{K} > \mathrm{Na} \gg \mathrm{Ca}$

$\mathrm{Si} \cong \mathrm{Al}$ —— (variable) → $\mathrm{Si} > \mathrm{Al}$

$-H_2O$ (anhydrous) → $+H_2O$ (hydrous)

-Volatiles → +Volatiles (F,Cl,B)

Polymerization of Silicon and Oxygen and Representative Minerals:

SiO_4 →	SiO_3 →	Si_4O_{11} →	Si_2O_5 →	SiO_2
nesosilicates	inosilicates	inosilicates	phyllosilicates	tektosilicates
(isolated tetrahedra)	(single chain)	(double chain)	(sheets)	(3-dimensional framework)
olivine(s)	pyroxene(s)	amphibole(s)	mica(s)	feldspar(s)

Physical Changes in Minerals

High density minerals → Low density minerals

Small unit cell dimensions → Large unit cell dimensions

Mineral Crystallization Sequences

Ferromagnesians:

Olivine → Pyroxene → Amphiboles → Mica

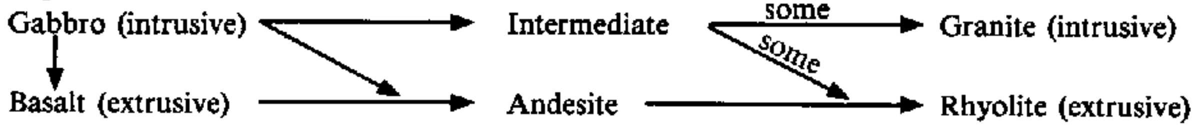
Feldspars:

Ca > Na Plagioclase > Potassic → Potassic > Na > Ca

Quartz:

None or little → Quartz-rich

Rock-type and Crystallization



← Serpentine deposits → Quartz-rich

← Talc deposits

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representative species within them are given in Tables I-3—I-8.

Rock-Forming Silicates

Often rock-forming silicates are described on the basis of their chemistry. Commonly, they are mixtures of different cationic species which substitute within the basic structure formed by bridged oxygen and silicon atoms. "Pure" mineral species, those made of single constituent cations, are rare. Rock-forming silicates tend to be composed of "solid-solutions" of representative end-member species. These end-members are also rarely found in nature and are in many instances hypothetical—used for chemical convenience. For example, the olivine minerals forsterite and fayalite, (Table I-3), are rarely observed in nature. Divalent iron and magnesium readily substitute for each other within silicate minerals, on the basis of their ionic radii, valence, and electronegativity. Therefore, most species of olivine consist of "mixtures" of the end-members, forsterite and fayalite. This concept may be carried forth to the pyroxene minerals (Table I-4) which are considered mixtures of wollastonite, enstatite, and ferrosilite; the amphibole minerals (Table I-5) which are further subdivided into a number of end-member groups, e.g., cummingtonite-grunerite, tremolite-actinolite, etc.; feldspars (Table I-6) e.g., the plagioclase series, albite-anorthite; and the rock-forming micas (Table I-7), with structural substitution based primarily on cationic charge in the octahedral structural layer.

Therefore, the crystallization of silicate melts produces a number of mineral species with specific structures and chemical constituents. Despite their large mineral diversity, these materials—the products of magmatic crystallization—produce only a limited number of mineral species. The average mineral content of crustal igneous rocks tends to be relatively small, yet varying proportions produce the varietal rock types (see Table I-9).

Crystallization and Trace Metals

The principles of crystal chemistry also apply for trace elements. Elemental coordination number or geometrical factors (the radius ratio effect) and electrical satisfaction (valence) together control distribution of trace metals in the minerals of igneous rock types. For example, on the basis of valence and size: nickel and cobalt occur in iron-magnesium minerals; strontium occurs in calcium minerals; rubidium occurs in potassium minerals; germanium occurs in silica minerals; gallium occurs in aluminum minerals. Therefore, one would anticipate concentrations of nickel in mafic rocks (high in ferromagnesian minerals) and concentrations of rubidium in potassic rich rocks (e.g., granitic in composition).

Table I-3

CRYSTAL CHEMISTRY OF THE
ROCK-FORMING OLIVINE MINERALS

Empirical Formula: X_2SiO_4

$X =$ divalent cations, Fe^{+2}, Mg^{+2}, Ca^{+2}
if $Mg = Mg_2SiO_4 =$ forsterite
if $Fe = Fe_2SiO_4 =$ fayalite

Pure Mg,Fe phases are uncommon

Most olivines are "mixtures" of Fe and Mg, expressed as mole percent Forsterite (Fo), Fayalite (Fa), e.g., olivine ($Fo_{80}Fa_{20}$)

Olivine is readily altered at and near the earth's surface to the serpentine minerals.

Classification of Igneous Rock by Mode of Occurrence and Resultant Texture

There are two broad categories of igneous rocks. *Intrusive* (plutonic) igneous rocks are those which form beneath the earth's surface; *extrusive* igneous rocks are those which form on or near the surface. In plutonic (intrusive) rocks, the magmatic crystallization is slow and individual mineral components grow to large dimensions, clearly visible to the unaided eye. Such is the case for intrusive (plutonic) rocks. On the other hand, those igneous rocks which form at the surface undergo rapid crystallization. The resulting mineral texture is fine-grained, so that individual mineral components are not visible to the naked eye.

Magmas of identical composition may form physically different rock-types based on mineral size (texture). Magma of basaltic composition, crystallizing beneath the surface, may form a coarse-grained rock which would be termed a gabbro; the same magma crystallizing on the surface would form a fine-grained equivalent termed a basalt (Table I-10).

By Outcrop Size and Relationship to Host Rock

In addition to textural characteristics, igneous rocks may be further classified according to outcrop dimension. Large mountain complexes (usually granite or granodiorite) are called batholiths. A mineralogically identical intrusive igneous body of smaller dimension may be termed a stock. In these cases, the field term would be modified by rock-type term. Also, the relationship of the intrusive with the surrounding host rock may determine nomenclature, e.g., if the igneous body conforms with the local structure, it may be termed a sill; if it is dicordant, it may be termed a dike. These terms are frequently encountered in the mining literature.

By Mineral Content (Composition)

Lastly, igneous rocks are classified on the basis of their mineral content. The final products of crystallization reflect, in essence, the chemistry of the melt. Specific mineral species produce specific rock types. For example, granite is commonly composed of potassic feldspars, minor amounts of sodic feldspars, quartz, and possibly some mica (either muscovite or biotite). Occasionally, amphibole minerals may occur as well. Gabbroic rocks contain feldspars which are calcic, pyroxenes, and occasionally olivine minerals. They normally do not contain quartz, micas, or amphiboles. These mineral suites are generalizations (see Table I-2, I-10).

The reader will likely be familiar with some names of common igneous rocks in Table I-10. It should be noted that granites and granodiorites, common plutonic rocks, tend to be quartz-poor.* The rocks named in Table I-10 range from varieties containing potassium, sodium, and calcium to those which contain high concentrations of iron and magnesium.

THE SEDIMENTARY ROCKS

Sedimentary rock types originate through a multitude of processes, which occur at or near the earth's surface, and under conditions normal to the earth's surface (relatively low temperatures and pressures). Pre-existing crystalline rocks, those of igneous and metamorphic origins, are basically unstable under conditions at the earth's surface. Because these were formed under high temperatures and pressures, their mineral components succumb easily to the chemical action of water, surface- and atmospheric-formed acids, and oxygen. Lithologies attacked in this manner may be further subjected to degradation through the mechanical effects of moving air and water in all its forms. The processes of physical-chemical weathering, erosion, transport, deposition, and diagenesis act in concert to create new rock types.

There have been a number of systems proposed for the classification of sedimentary rocks. All reflect the precursor material, the mode of formation, and other factors. Sedimentary rocks tend to be more varied and complex than other rock types: they arise from the products of erosion as diverse as the crust itself. There are two broad classes of sedimentary rocks:

1. The *Clastics* include mechanically deposited erosional debris from pre-existing surface lithologic units and in some instances, deposits of volcanic ejecta. Clastic rocks originate through the accumulation of single, discrete particulate debris, mechanically deposited as unconsolidated sediments. Most accumulation of nonclay-sized particles is brought about by settling processes, as the result of transport failure.
2. *Chemical precipitates* include rocks or materials formed through physical-chemical and organic processes (which account for the accumulation of mineral matter). The chemical precipitates include the carbonate lithologies (a major rock type on the crust of the earth), shells and hard parts of organism skeletons (for example, diatoms, coral, etc.), and saline deposits (which include evaporites and hot springs). These latter rock types form through chemical processes, mostly in water involved reactions, and are re-

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*Silicosis is more prevalent in workers exposed to dusts generated from the granite-type lithologies; silicosis is almost never seen in workers exposed to dusts generated from basalts.

Table I-4
CRYSTAL CHEMISTRY OF THE ROCK-FORMING PYROXENE MINERALS

Empirical Formula: $XY\ (ZO_3)_2 = Z_2O_6$
$X = Ca, Mg, Fe, Li, Mn, Na$
$Y = Fe^{+3}, Fe^{+2}, Mg, Al$
$Z = Al,\ Si$

Common pyroxene minerals are defined by mole percents of the phases: $CaSiO_3$ [Wollastonite (Wo)], $MgSiO_3$ [Enstatite (En)], $FeSiO_3$ [Ferrosilite (Fs)]

Orthorhombic pyroxenes:

Enstatite, $MgSiO_3$, ($En \gg Fs$), ± TrWo
Hypersthene, (MgFe) SiO_3 ($En > Fs$), ± TrWo

Monoclinic pyroxenes:

Diopside	$CaMgSi_2O_6$(Wo, $En > Fs$)
Hedenbergite	$CaFeSi_2O_6$(Wo, $Fs > En$)
Augite	(Series between diopside and hedenbergite as end-members)
Pigeonite	(En Fs^{+}Wo; calcium-rich E-Hy)
Aegerine	$NaFe^{+3}Si_2O_6$
Jadeite	$NaAlSi_2O_6$
Spodumene	$LiAlSi_2O_6$

—Al-rich varieties tend to originate under high-pressure conditions. XY positions acquire a plus (+) four charge. If Al^{+3} occupies the Y site, then a monovalent cation occupies the X site.

Table I-5
CRYSTAL CHEMISTRY OF THE ROCK-FORMING AMPHIBOLE MINERALS

Empirical Formula: $W_{0-1}X_2Y_5(Z_4O_{11})_2(O,OH,F)_2$
$W = Ca, Na, K$ as trace or minor element.
$X = Ca, Mg, Fe^2, Mn$
$Y = Fe^2, Mg, Ti, Al, Fe^3$
$Z = Si, Al$
As with pyroxenes, minerals may be expressed as mole percents of end-members

Orthorhombic amphiboles

Anthophyllite $(MgFe)_7Si_8O_{22}(OH)_2$NoCa
$W = O;\ X,Y = Mg, Fe(Mg \geqslant 6; Z = Xi, TrAl$

Gedrite $(MgFe)_7(AlSi_7O_{22})\ (OH)_2$NoCa
$W = O, X, Y = MgFe(Mg \geqslant 6); Z = Al, Si$

Monoclinic amphiboles

Cummingtonite-grunerite series $(Mg \rightarrow Fe)_7$NoCa
$W = O; X, Y = Mg, Fe; Z = Si$
Tremolite-actinolite series $Ca_2(Mg \rightarrow Fe)_5$; High Ca
$W = O, X = Ca; Y = Mg, Fe; Z = Si$
Hornblende series High Ca
$W = 0\text{-}1, Na_{0-1}K; X = Ca; Y = Mg, Fe, Al; Z = Al, Si$
Alkali amphibole series Na = 2 High Na
$W = O; X = NA; X, Y = Mg, Fe, Al; Z = Si$

e.g., Glaucophane = $Na_2Mg_3Al_2(Si_4O_{11})_2(OH)_2$
Riebeckite = $Na_2Fe_3^{+2}Fe_2^{+3}(Si_4O_{11})_2(OH)_2$

Table I-6
CRYSTAL CHEMISTRY OF ROCK-FORMING FELDSPARS

Empirical Formula: WZ_4O_8

$W = Na, K, Ca, Ba$

$Z = Al, Si$

Feldspars are generally grouped as two separate series on the basis of: major cation, structure, and geological occurrence.

Plagioclase: Solid solution series between anorthite ($CaAl_2Si_2O_8$) = An and albite (Na,Al,Si_3O_8) = Ab [produces 6 feldspars; all triclinic]

anorthite	An ≥ 90 Ab ≤ 10
bytownite	An 89-70
labradorite	An 69-50
andesite	An 49-30
oligoclase	An 29-10
albite	An ≤ 9 Ab ≥ 91

"Orthoclase group" commonly called K-spar or alkali series:

	$KAlSi_3O_8$ - All but microcline = *monoclinic*
sanidine:	monoclinic, high *T*, volcanic rocks
orthoclase:	mono, high *T*, plutonic rocks
microcline:	triclinic, low *T*, pegmatite rocks
adularia:	monoclinic, low *T*, authigenic origin
anorthoclase (Na):	triclinic, high *T*, volcanic rocks
celsian (Ba):	monoclinic, high *T*, volcanic rocks

Table I-7
CRYSTAL CHEMISTRY OF THE ROCK-FORMING MICAS

Empirical Formula: $W(X,Y)_{2-3}\ Z_4O_{10}\ (O,OH,F)_2$

$W = K, Na$

$X,Y = Al, Li, Mg, Fe^{+2+3}$

$Z = Si, Al\ (3:1)$

Micas are grouped according to number of sites filled in their octahedral layers (total charge per cell is $^{-6}$). If divalent cations occupy the site, then *three* are required to satisfy the valency, hence the micas are *trioctahedral*; if trivalent cations, *two* are required, hence, the micas are *dioctahedral.*

Dioctahedral	Muscovite	$KAl_2(AlSi_3O_{10})(OH)_2$
	Paragonite	$NaAl_2(AlSi_3O_{10})(OH)_2$
	Lepidolite	$KLi_2Al(Si_4O_{10})(OH)_2$
Trioctahedral	Biotite	$K(MgFe)_3(AlSi_3O_{10})(OH)_2$
	Phlogopite	$KMg_3(AlSi_3O_{10})(OH)_2$

Table I-8

CRYSTAL CHEMISTRY OF THE ROCK-FORMING SILICA POLYMORPHS

Empirical Formula:	XO_2	
	X=Si	
Quartz	SiO_2	Common
Cristobalite	SiO_2	Uncommon
Tridymite	SiO_2	Uncommon
Coesite	SiO_2	Rare: High pressure phase
Stishovite	SiO_2	Rare: High pressure phase
Opal	SiO_2	n H_2O: Major form of biogenic silica

"Amorphous" silica (SiO_2): X-ray amorphous—common

Other forms of silica exist in nature: e.g., silica glasses, (fulgurite). Silica phases exist as low- and high-temperature enantiomorphs and may occur with racemic varieties as well (quartz).

lated to environmental physical-chemical factors such as pH, ionization potential of constituent ions, reduction-oxidation potentials of elemental constituents, etc. Commonly, sedimentary rocks are composed of mixtures of rock-types, e.g., sandy limestones or calcareous sandstones.

Erosion

Exposed pre-existing rock units at the surface of the earth are subjected to erosion by a number of processes and forces: moving water (streams, wave action, glacial ice, underground waters); moving air; atmospheric radiation (heat fluctuation producing expansion and contraction of rocks); frost shattering; plant wedging; earthquake and volcanic forces; chemical weathering (oxidation, hydration, and hydrolysis); and atmospheric and organic acid attacks. These mechanisms attack component minerals and physically and chemically break down rocks. The resulting debris (single minerals, rock fragments, dissolved salts) may then be transported to another location where deposition occurs. The physical process of tumbling, saltation, particle impaction, abrasion rubbing, etc., tend to produce a general size reduction and "rounding" of debris constituents when particulates are transported in water.

The capacity of moving water to carry these erosional products is enormous, increasing exponentially as the velocity of the fluid doubles. Water volume, stream gradient (which determines velocity), nature of source debris, and physical-chemical character of water (temperature, pH, etc.) determine the amount of sediment transported, the degree of alteration of the carried debris, and the ultimate distance it is carried from the source material.

Erosion is a complex process involving interface between the atmosphere, the hydrosphere, and the rocks of the earth's crust. Erosion may be related to such large scale factors as climate (influencing both mean and extreme temperatures, rainfall), flora and fauna, mean elevation above sea level, and local topographic factors (especially slope), to name but a few. These general factors, considered in perspective with erosional processes, may produce vastly different degradation products originating from the same host rock.

A good example of complex factors in erosion can be illustrated by the physical-chemical degradation of limestone (calcium carbonate, $CaCO_3$). A limestone undergoing erosion in a wet, mountainous, hot climate would be readily affected by: rain acidified by atmospheric carbon dioxide (forming carbonic acid); the bicarbonate phase, which is some thirty times more soluble at the same temperature, pH, and volume of solute than the carbonate phase; high temperatures which would greatly enhance chemical reaction kinetics (the activity of some chemical reactions may double with increases of approximately 10°C); growth of flora and fauna which would increase the mechanical work of plant root systems into the carbonate soil and bedrock, increasing a *wedging effect*; the proliferation of soil organisms in the tropical environment which

Table I-9
AVERAGE MINERAL CONTENT OF CRUSTAL IGNEOUS ROCKS*

Mineral Species	% Occurrence (by weight)
Quartz (Silica)	12.0
Feldspars (K,Na,Ca)	59.5
Ferromagnesian minerals (amphiboles and pyroxenes)	16.8
Biotite (Mica)	3.8
"Ores" (sulfides, oxides)	1.5
Apatite	0.6
"Others" (including micas and clays)	5.8

*Based on an average of mineralogically characterized units cropping out on the continental surface.

can alter pH conditions of the soil and greatly increase acidity; and the mountainous topography (steep slopes) which can increase the activity of running water, its capacity for transporting sediment, its mechanical energy for erosion and transport, etc. Limestone will succumb under this condition readily. Yet, the same limestone existing under dry desert conditions would be essentially impervious to attack—as evidenced by the survival of the Egyptian pyramids, the bases of which are built entirely of limestone.

In addition to environmental factors, the chemistry of the rock type, the texture of the composite grains (spacial interrelationships), and structural characteristics (jointing, cleating, superimposed fissility) etc., have profound effects on erosion.

Deposition

The transport of sediment in a moving stream may end with deposition of clastic objects in accordance with their sizes and specific gravities. This may result in a form of "sorting." Major factors in such transport failure are reduction in stream velocity (gradient related) or reduction in water volume. Essentially, large heavy objects settle out first, followed by those of decreasing size and density. Clay particles of colloidal size settle out last. Normally, because of Brownian Motion, special conditions are required for clay settling, including slowing of water velocity to essentially zero, lowering of temperature to almost freezing (slowing the thermal motion of water molecules), and change in salinity (effecting cation concentration and thickness of the sorbed water layers on the particle's surface), etc. These processes may induce clay settling so that gravitational forces may overcome interparticle repulsion which maintains the particles in suspension.

If, after deposition, the clastic materials are well sorted (sizes fall within a narrow range), the nomenclature of rock-type is based on size rather than composition.

Minerals Constituting Clastic Particle Populations

The rock-forming silicate minerals succumb to weathering and erosional processes differently. Physical degradation of minerals may be related to such factors as cleavage, controlled by both its molecular structure and atomic species. Minerals with "good" or "excellent" cleavage tend to disappear in the environment more easily than minerals with "poor" or "no" cleavage. Chemical degradation of minerals is related to other factors, such as surface hydrolysis of cations. Based on a study of particle populations in sediments, it was observed that high temperature mineral species tend to succumb first during erosion and transportation (Table I-11). Mineral stability appeared to be the reverse of Bowen's crystallization series for igneous rocks. Minerals which crystallize first (e.g., olivine, pyroxene, etc.) are rare components of detrital sediments. Their prevalence in the environment is dependent upon these broadly related factors. Mineral survivor populations consist primarily of quartz, the potash feldspars, and muscovite. These form such rock types as sandstones, arkoses, siltstones, etc. (see Table I-11). Considering all rock types at the earth's surface (igneous, metamorphic, and pre-existing sedimentary units), mineral survival is well established (Table I-12).

Regardless of the mineral character, sedimentary rocks may be classified merely on the

Table I-10
COMMON IGNEOUS ROCKS

Intrusive (Plutonic) Individual mineral grains visible to unaided eye (phaneritic)		**Extrusive (Volcanic)** Individual mineral grains invisible to unaided eye (aphanitic)	
SiO_2: Saturated (+Quartz)	SiO_2: Undersaturated (−Quartz)	SiO_2: Saturated (+Quartz)	SiO_2: Undersaturated (−Quartz)
Acidic or Felsic			
Granite	Syenite	Rhyolite	Trachyte
Granodiorite	Diorite	Quartz Latite	
Tonalite	Diabase	Dacite	Andesite
Quartz Gabbro	Gabbro	Tholeiitic Basalt	Olivine Basalt
Basic or Mafic	*Ultramafic*		
	Peridotite		
	Dunite		

Other Common rock-types:
Volcanic tuffs, breccias, agglomerates (these are textural terms other than compositional), volcanic glasses including obsidian, pitchstone, perlite, pumice, etc.

basis of the particle size of the component grains (Table I-13). Large rock fragments form "gravels" (sizes greater than 256 mm) and when indurated, form rock types called "conglomerates," "breccias," "tillites," etc. Depending on the angularity of the components, their sources, etc., nomenclature may change (See Table I-13). Basically, very fine particles form sedimentary rocks called "shale," "siltstone," "mudstone," or "argillite." Sand-size grains form "sandstones," "arkoses," and "graywackes." Occasionally modifying terms may be used to indicate deposition in a standing body of water, a moving body of water, from volcanic ejecta, etc.

The above rock types may be further modified by mixtures, so that a silt-containing sandstone may be referred to as "silty/sandstone." It is also important to note that the composition of the particles may vary enormously. "Sand" sized particles may be quartz, feldspar, magnetite, garnet, ilmenite, or other minerals—reflecting different geological provenance, climate, transport and depositional history. Rock classification generally reflects size of components, not composition; yet the most common sandstone *is* composed of the mineral quartz.

The grain particles are considered "frameworks" which require an additional process or bonding agent to "hold them together." This general process is called "lithification" and is the result of consolidation, compaction, dewatering, cementation, and recrystallization. Clastic sediments are dewatered (if waterborne in origin) by overburden compaction; they then lose pore space, undergo reorientation of grains, and retain introduced substances which precipitate and/or crystallize in the interparticle voids to form an intergranular cement. Occasionally, sediments may begin some form of recrystallization.

In essence, sedimentary clastic rocks are classified on the basis of *texture* (particle size and shape) and *composition* of composite grains (and cementing agent if present). Texture determines major rock type name, e.g., sandstone, shale, etc. Structures of sedimentary clastic rock may include ripple marks, layering (stratification), mud cracks, etc. The variation in sedimentary rock nomenclature is also given in Table I-13.

The Chemically Precipitated Sedimentary Rocks

The process of weathering (the major process involved in the formation of precursor material for sedimentary rocks) is basically chemical. Although physical weathering pro-

Table I-11

GOLDRICH'S STABILITY SERIES
(RESISTANCE TO PHYSICAL-CHEMICAL WEATHERING)

Most resistant:

Quartz
Muscovite
Potash feldspars
Biotite = alkalic feldspars
Hornblende = alkalic-calcic plagioclase
Calcic—alkalic plagioclase
Augite (pyroxenes) = calcic plagioclase
Olivine

Least resistant:

↑ Deposited as survivor minerals to form sandstones, arkoses, siltstones, etc.

↓ At or near surface succumbs to attack. Tends to form serpentines when subjected to hydrothermal attack in upper crust.

Granites and sandstones are more durable at the earth's surface than gabbros and basalts. Conversely, ultramafic and mafic rocks containing magnesium silicate minerals tend to become serpentinized during degradation.

cesses (such as freezing and thawing of ice in joints and rock fractures) may be locally important, chemical weathering is universal. Surface rocks in contact with the earth's atmosphere expose minerals with unsatisfied surface valencies to the chemical components of the atmosphere. These mineral surfaces may react with atmospheric moisture with resultant surface hydration and hydrolysis. Cations such as calcium, magnesium, and potassium are removed as soluble hydroxides in the weathering process. The processes of degradation and erosion are essentially chemical as well. It is only climate which determines reaction kinetics. The major chemically derived sedimentary rocks are given in Table I-14.

Table I-12

MINERALS COMMONLY OBSERVED IN DETRITAL SEDIMENTS

Very Common	*Common*
Quartz	Andalusite
Feldspar (K,Na,Ca)	Augite and other pyroxenes
Muscovite	Epidote
Chlorite	Garnet
Biotite	Rutile
Apatite	Sphene
Hornblende	Staurolite
Zircon	Tourmaline
	Zoisite
	Calcite

Formation of detrital sediments includes high concentrations of quartz.

Chemistry and Mineralogy of Sedimentary Rock

The weathering of silicate minerals at the earth's crust and their subsequent erosion, removal, and deposition is largely controlled by chemical processes. Both chemical and physical degradation of pre-existing rocks produce sediments rich in quartz and feldspar and poor in olivine and pyroxene. Chemical breakdown also produces carbonates, the most common mineral form being calcite ($CaCO_3$). Under crustal conditions, almost all varieties of clays result from chemical weathering, with structural reorganization of pre-existing minerals. For example, chemical degradation of mica may produce a hydromica and then illite clay.

The importance of chemical processes has often been illustrated by the fact that the products of erosion and surface weathering form

Table I-13

NOMENCLATURE OF CLASTIC SEDIMENTARY ROCKS:* RELATIONSHIP OF PARTICLE COMMON NAME, PARTICLE SIZE AND SHAPE (TEXTURE), AND ORIGIN OF DETRITUS

			Indurated Lithological Units Based on Shape and Composition			
Components	**Size Range (mm)**	**Grabau Size-classification**	**Rounded**	**Angular**	**Volcanic**	**Common Rock Names****
Boulder (gravel)	≤256	Rudite	Conglomerate	Blocks	Bomb	Gravel, Till, Tillite, Talus, and others (specific instances)
Cobble (gravel)	256-64	Rudite	Conglomerate	Rubble Breccia	Bomb	Conglomerate Breccia
Pebble (gravel)	64-2	Rudite	Sandy Conglomerate	Rubble Breccia	Lapilli	Conglomerate Breccia
Sand	2-1/16	Arenite	Sandstone	Grit	Coarse Ash	Sandstone, Arkose, Graywacke Tuff
Silt	6/16-1/256	Arenite Lutite	Siltstone	Grit	Coarse Ash Fine Ash	Siltstone, Ignimbrite Ash
Clay	≤1/256	Lutite	Shale	—	Fine Ash	Shale, Argillite, Limestone

*Represents a general classification: see classification schemes, discussion of relationships in Pettijohn, 1957, p. 225 ff.

**Rock names may be modified by compositional terms, reflecting either component grains or cementing agent.

sedimentary deposits which may be generally characterized as chemical residues (Table I-15). Sedimentary deposits may be characterized on a chemical basis as follows: *Resistates* are deposits in which the minerals have resisted chemical degradation and are mechanically manipulated without loss of mineral character. Quartz and potash feldspars are good examples. These minerals tend to form sandstones, pebbles in conglomerates, and also rocks known as arkoses. *Hydrolysates* are deposits in which minerals are formed which contain aluminum and silicon. Basically, they are aluminosilicates or clays. Cations in the unsatisfied valencies at the mineral surface are removed from the mineral through hydrolysis to form cation-hydrate complexes, which recombine with hydrolyzed silica to form the clay minerals. These new clays form rocks such as shales. *Oxidates* are deposits which originate through oxidation reactions. Some cationic species are sensitive to slight variations in local pH conditions and may rapidly precipitate as oxide-hydroxide forms when specific chemical conditions have been met. These materials form important deposits of iron and manganese (banded iron-stones). *Carbonates* are deposits in which mineral salts containing carbonate or bicarbonate forms precipitate. Calcium carbonate is the dominant rock-type produced. Dolomites appear to be chemically modified calcium carbonate units, formed throughout the secondary introduction of magnesium-rich solutions. This accounts for a major sedimentary lithologic unit. *Evaporites* are deposits of salt minerals formed principally as a consequence of the concentration and precipitation which occurs through loss of solvent (water). A number of alkaline metals and earths—especially sodium, potassium, magnesium—concentrate in solution with halogens and complex anionic bases. Sulfates, borates, and chloride and bromide compounds form many evaporite deposits, when their concentrations exceed their solubilities. Salt deposits of various kinds are formed in this manner. *Reduzates* are deposits formed as the result of reducing environments. Fossil fuels—coal and petroleum—constitute the bulk of these materials.

Sulfur, phosphorous, and organic compounds with trace metals in a range of forms, accumulate in these deposits.

Amounts and Kinds of Sediments in the Crust

Sedimentary rocks constitute only about 5% of the volume of the earth's crust. However, some 75% of the total land surface area is covered with such materials. Therefore, most of the outer veneer of the earth's crust is of sedimentary rock. Of this material, three common varieties constitute almost 99% of all sedimentary rocks. These are shale, sandstone, and limestone in that approximate order of abundance (Table I-16). It is of great importance to note that the average mineral content of the three most common sedimentary rocks consists of the most stable minerals in the Goldich Stability Series. Quartz, feldspar, and fine mica (sericite) constitute the bulk of shales and sandstones. For all the sedimentary rocks, only five mineral groups make up over 90% of the bulk material (Table I-17). If the average mineral composition

Table I-14

MAJOR CHEMICALLY PRECIPITATED SEDIMENTARY ROCKS

Limestones (predominately $CaCO_3$ with trace silicates)

Dolomites (predominately $CaMg(CO_3)_2$ with trace silicates)

Bioherms (accumulated shells)

Coquinal limestones (accumulated shells)

Cherts, flints, and other cryptocrystalline silica precipitates (normally in another host, especially limestones)

Diatomaceous earth, radiolarian cherts and related organic derived precipitates

Phosphorite deposits (trace radioactive components)

Iron formations (predominately iron oxides, hydroxides, and silica)

Coal and similar fossil fuel deposits (Not chemically precipitated—*sensu stricto*)

Salines and evaporite deposits

Sulfur deposits (through bacterial action on sulfate precursors)

It is currently accepted that some metal-sulfide ore deposits may have originated through bacterial action. These are not included in the above list.

Table I-15

CHEMICAL CLASSIFICATION OF SEDIMENTS
(Based on Goldschmidt's Classification)

Group	Resistates	Hydrolysates	Oxidates	Carbonates	Evaporates	Reduzates
Major elements and compounds:	Si	Al,Si(K)* Hydrolyzed bases	$Fe(OH)_3$,Fe	Ca(Mg)* Carbonate Precipitates	(Ca)(K)(Mg)* Na Chlorides, sulphates, etc.	C,Fe^{+2},Mn^{+2} Heavy metals
Minerals:	Quartz Feldspars	Clay minerals	Minor clays	$CaCO_3$ $CaMgCO_3)_2$	NaCl $MgCl_2$	
Major Rock-types:	Sandstones Arkoses Siltstones	Shales	Iron-rich Sediments Shales	Limestones Dolomites	Saline Deposits	Fossil Fuels

*May be present in substantial quantities.

of crustal igneous rocks was compared with the average mineral content of crustal sedimentary rocks, one would see striking similarities. For example, based on six major oxide components of sedimentary and igneous rocks, the chemistry of the "average igneous rock" almost superimposes on the point of the "average crustal sedimentary shale"; the average composition of basaltic igneous rocks superimposes on the average chemical composition of carbonate rocks. Sedimentary rocks unacted upon by secondary geological processes are often "chemically fractionated" crystalline rocks.

METAMORPHIC ROCKS

Crustal processes, at temperatures and pressures in excess of those encountered in diagenesis and in association with altered chemical environments, may induce both physical and chemical changes in pre-existing rocks. These changes include recrystallization of mineral components, alteration of existing textures, and either introduction or removal of chemical constituents. These may occur in the solid state or, at elevated temperatures, include partial melting *in situ*. In the lower crust, where elevated temperature and pressures reach those encountered in the igneous regime, processes tend to merge so that these metamorphic products resemble igneous crystallization products.

The process of lithification of sedimentary rocks occurs post-depositionally. It involves formation of sedimentary rocks in indurated forms from previously loose and unconsolidated sediments. For example, during burial in a body of water, compaction, dewatering, reorientation of clays and other component grains, and subsequent cementation and partial recrystallization of components takes place. Further change in mineral texture or composition may rightfully be called metamorphism. In almost all cases, elevated temperatures and pressures are required for metamorphism. In orogenic belts, where tectonic forces are active, crustal movement along fault zones may induce changes in pre-existing lithological units through directed pressure. In areas of igneous activity, metamorphism may result through the effects of elevated contact temperatures. Usually, at the contact of igneous intrusions, elements may be mobilized and introduced to the host rock producing new mineral phases. Fluids escaping from such intrusions act as a medium to speed reactions. Water, carbon dioxide, acids of boron, chlorine, and fluorine, may also promote kinetics.

Each rock type responds to produce a range of new products. Under the influence of elevated temperatures, pressures, and fluids, the final product of a metamorphic process is an assemblage of minerals reflecting the original material and the superimposed environmental condition. Single rock types may yield vastly different products depending on the conditions of metamorphism. As with igneous crystallization, the number of mineral species created during metamorphism is limited by the constraints of chemical laws and thermodynamics. Given the pre-existing chemistry of the lithologic unit undergoing metamorphism, each new range of temperature and pressure will produce a limited number of mineral phases.

There are four major types of metamorphism recognized: cataclastic metamorphism, produced by the shattering and recrystallization of pre-existing units; contact metamorphism, produced by high temperature gradients at contacts with igneous bodies; regional metamorphism, produced on a large scale, involving elevated temperatures and pressures; and metasomatism, the production of new rocks by the introduction and translocation of elemental species (including pneumatolysis).

Cataclastic Metamorphism

Normally rocks located in proximity to a major fault zone in the crust of the earth are subjected to tectonic forces which bring about changes in the pre-existing mineral assemblage and rock fabric. Minerals may be reduced in size due to recrystallization or crushing; feldspars may be made to evolve phases (development of perthites); mineral crystal forms (e.g., "twins") may be bent, etc. These effects are usually local and may be traced directly to an active fault.

Contact Metamorphism

When igneous rocks intrude into pre-existing rock types, new mineral components are often formed in the host. This may be related to temperature; presence of volatiles and acids of various composition (water, fluorine, boron, carbon dioxide, etc.); and length of time the host is in contact with the intrusive. Other important factors which control the formation of new minerals include the texture and composition of the host rock, the highest temperature it was sub-

Table I-16

MINERAL CONTENT RANGE OF THE THREE MOST COMMON SEDIMENTARY ROCKS

Mineral Species	Major Sedimentary Rock Type		
	Shale	Sandstone	Limestone
Quartz	22—32	67—70	± 4
K + Na Feldspar	18—30	8—12	± 2
Sericite and clay minerals	25—28	6—8	± 1
Calcite-dolomite	6—7	±11*	93
Chlorite and related species	± 6 or less	± 1	0

*It should be noted that the presence of carbonate minerals in a rock type such as sandstone often reflects its occurrence as a "cementing agent," rather than as a discrete sand-size grain.

Table I-17

AVERAGE MINERAL CONTENT OF CRUSTAL SEDIMENTARY ROCKS

Mineral Species	% Occurrence
Quartz (and other silica polymorphs)	35
Feldspar (K,Na,Ca)	16
Ferromagnesian minerals (amphiboles and pyroxenes)	15
Micas	
"Others" (clays, carbonates, etc.)	34

The bulk chemistry represented by the average mineral content of crustal sedimentary rocks is very close to the bulk chemistry of granodiorites, the most common crustal igneous rock.

jected to during its previous history, the shape of the interface with the intrusive body, the composition of the intrusive, and the crustal depth at which the contact occurred. Here, at the contact, profound metamorphic changes may take place. For example, the metamorphic minerals produced in carbonate rocks (limestones) reflect the increasing temperature gradient at the contact. Specific minerals appear with "granite intrusives" as distinct from those which originate by contact with "basaltic intrusives" (Table I-18). The inclusion of "mineralizers" produces an additional mineral population characteristic of contact pneumatolysis.

Normally, one associates contact metamorphism with high temperatures and low pressures. Yet, significantly different mineral populations may be produced even during this "simple" metamorphic event. For example, the mineral assemblage produced in shale rock depends to a great extent on its initial composition as well. Normally, one can predict, on the basis of the chemistry, which mineral phases will occur if a specific metamorphic temperature and pressure were to be achieved; i.e., specific cations (represented as oxides) recombine at specific temperatures and pressures to produce specific mineral phases. The basic difference in the production of different mineral populations under different physical-chemical conditions is the different combination ratios. For example, the combinations of periclase (MgO) and quartz (SiO_2) will, in different proportions, produce minerals such as olivine (Mg_2SiO_4) or enstatite ($MgSiO_3$). These minerals form under different conditions and appear in different rocks depending on the temperature of metamorphism. This has been called the "facies concept" because for a given chemical system, there are limited numbers of mineral phases which can be formed (based on the physical-chemical constraints). The minerals formed will be dependent on their stability ranges (a function of temperature and pressure).

Based on this concept, contact metamorphic facies for shale produce mineral assemblages which reflect the original chemistry of the shale rock itself (Table I-19).

Regional Metamorphism

It has been said that regional metamorphism is "contact metamorphism on a regional scale." Basically, the temperatures to which the pre-existing rocks are subjected are elevated, as are the pressures. There are normally "several zones" of metamorphic terrains recognized (see Table I-20). These have been termed the low grade metamorphic zone; the medium grade metamorphic zone; and the high grade metamorphic zone. Again, using argillaceous rocks as a model, it has been shown that certain mineral species tend to characterize metamorphic rocks when temperatures and pressures increase (Table I-20). These may range from low temperature zeolite minerals to high temperature pyroxene and garnet rocks. Metamorphism can proceed to such an extreme that the rock partially melts *in situ*, granitization takes place, and "igneous" granite cannot be readily distinguished from metamorphic granite. It should be noted that most granites may have originated from melts derived from pre-existing rocks.

Diverse minerals are formed in metamorphic rocks: those commonly found in igneous rocks and those that represent additional phases produced by recrystallization and through introduction of new cation species. Their mineral characteristics are shown in Table I-21.

METASOMATISM AND PNEUMATOLYSIS

Occasionally, contact of host rock units with igneous intrusives containing large quantities of volatile fluids (both liquid and gas) produces deposits of new minerals in rich diversification (see Table I-18). In this environment, many of the semi-precious and precious gemstones are formed. Often, new mineral assemblages superimpose on the older host assemblage.Large quantities of quartz may be formed during the new crystallization phase. Metasomatism and pneumatolysis are both processes associated with contact metamorphism.

ROCKS AND MINERALS AS AGENTS OF DISEASE

It is obvious that the crust of the earth is a complex of interrelated rock types each of which has rich mineral diversity. As a result of this complexity, human exposure to rock and mineral dust is correspondingly complex. Yet, a common skein runs through the recognized disease patterns which suggests that only a limited number of these minerals and rocks are "dangerous!' As a good illustration, quartz (found as a mineral constituent in almost every important rock type in the crust) has produced the most prevalent pneumoconiosis, silicosis. Silicosis is recognized in a range of occupational settings (Table I-36).

There are a number of pneumoconioses which are thought to be induced by minerals other than quartz. However, on close examination of the geological setting, the agent suspected may only play a minor role in the disease process. Exploitation of clay minerals, coal of all ranks, abrasives, ores of many varieties, and building stones, to name but a few, carries with it the danger of silica exposure (Table I-36). In these instances, quartz (as well as the other silica polymorphs, cristobalite and tridymite) occurs as either a trace contaminant or in forms which tend to escape detection (e.g., submicroscopic particle sizes). In these cases, the disease pattern tends to differ from "classical silicosis" and the general term "mixed-dust pneumoconioses" is often used.

These difficult problems are observed in the field of mining. Here, superimposed on the host rock complexity, is exposure to a multitude of "ore minerals."

ECONOMIC GEOLOGY

Large-scale exploitation of the crust for mineral resources began with the advent of the industrial revolution. With the world-wide spread of industrial societies and the provocation of our "chemical age," the quantity of raw materials recovered in the 20th century exceeds by many orders of magnitude the total exploitation since the vestigial beginnings of civilization. The exploitation and redistribution of the earth's natural resources includes precious metals, industrial metals, nonmetallic substances of all

Table I-18

METAMORPHIC MINERALS PRODUCED IN CARBONATE ROCKS AND DURING PNEUMATOLYSIS—CONTACT METAMORPHISM

T °C		Mineral	Contact with mineralizers*
∼250°	↑ Contact with granite	Talc	Tremolite
270°		Tremolite	Phlogopite
300°		Forsterite	Scapolite(s)
410°		Diopside	Axinite
450°		Brucite	Sphene
560°		Periclase	Apatite
600°		Wollastonite	Danburite
			Topaz
	↓ Contact with basalt	Monticellite	Tourmaline
		Akermanite	Fluorite
∼700°		Tilleyite	Epidote
		Spurrite	
∼800°		Rankinite	
		Larnite	
		Merwinite	

*Primarily not temperature dependent.

Table I-19

EXAMPLES OF CONTACT METAMORPHISM OF ARGILLACEOUS ROCKS

Temperature	Facies	Composition	Resulting Mineral Assemblage
↓ Increasing	Pyroxene-Hornfels	Lime-poor	Hypersthene, cordierite, quartz andalusite, corundum
		Lime-rich	All above, w/o corundum + anorthite, grossularite, wollastonite, diopside, vesuvianite
	Sanidine	Lime-poor	Periclase, olivine, pigeonite, cordierite, quartz, sillimanite, mullite, spinel, corundum
		Lime-rich	Sillimanite, mullite, cordierite, pigeonite, periclase, wollastonite, anorthite

Table 1-20

CORRELATION OF COMMON SCHEMES OF CLASSIFICATION OF METAMORPHIC ROCKS, AS RELATED TO REGIONAL METAMORPHISM OF ARGILLACEOUS ROCKS (SHALES)

T °C	Metamorphic Facies		Isograds-Mineral Indicators of Metamorphic Grades	Metamorphic Grade	Metamorphic Zone	Packing Indices	Pressure
	Facies	*Subfacies*					
150°—200 °C	Zeolite		Zeolites Chlorite	"Low"	Epizonal (phyllites)	Glaucophane Schist Chlorite Schist	↓
200°—400 °C	Greenschist	sericite-chlorite biotite-chlorite	Biotite Epidote			Greenschist Albite Schist	
300°—500 °C	Epidote Amphibolite		Almandine garnet Staurolite	 "Medium"	 Mesozonal (Schists)	Mica Schist Amphibolite	
400°—600 °C	Amphibolite	cordierite-anthophyllite staurolite-kyanite sillimanite-almondine	Kyanite Sillimanite (S_1) Sillimanite (S_2)		 Katazonal (gneisses)	Garnet Schist Sillimanite Schist	
600°	Granulite (gabbro granutite)		Pyroxene-garnet	"High"			Increasing
↓	Eclogite	(v. high temperatures and pressure)	↓				
+800 °C	Ectinites	(partial melting, migmatites + complete recrystallization-*in situ* granitization)	*In situ* melting, recrystallization, ductile deformation				

Table I-21

COMMON MINERALS IN METAMORPHIC ROCKS BY GROUPS AND SPECIES

Silica Minerals
- Quartz

Aluminum Silicates
- Andalusite
- Staurolite
- Kyanite
- Sillimanite
- Cordierite

Micas, chlorites and other sheet silicates
- Chloritoid
- Muscovite
- Biotite
- Phlogopite
- Paragonite
- Talc
- Serpentine (including lizardite, antigorite, chrysotile)

Feldspars
- Plagioclase (almost all, especially anorthite, *bytownite* and labradorite in calcic metasediments; andesine, *oligoclase*, albite in metasediments)
- Orthoclase (and other high-temperature potash feldspars)
- Microcline (and perthite, antiperthite feldspars)

Pyroxenes and pyroxenoids
- Enstatite
- Wollastonite
- Diopside
- Augite
- Jadeite

Amphiboles
- Actinolite (including its asbestiform variety)
- Anthophyllite (including its asbestiform variety)
- Tremolite (including its asbestiform variety)
- Glaucophane
- Riebeckite (including its asbestiform variety, crocidolite)
- Cummingtonite
- Grunerite (including its asbestiform variety, amosite)
- Hornblende (all its chemical varieties)

Olivines
- Forsterite
- Monticellite

Garnets and related compounds
- Pyrope
- Almandine
- Grossularite
- Zoisite
- Clino-zoisite
- Epidote

varieties, fossil fuels, etc.

There are many geological processes responsible for the formation of mineral deposits: magmatic processes; magmatic emissions, including hydrothermal processes, sublimation, and contact metasomatism; concentration of ores by processes of sedimentation (e.g., changes in physical-chemical environment and the precipitation of iron and manganese); accumulation of chemical substances through evaporation; concentration of ores through depositional concentration (including residual concentration); enrichment of ores at the earth's surface through weathering processes (oxidation and supergene enrichment); and general conditions of metamorphism (with and without the introduction of new elements). In summary, any earth process involving physical and chemical mechanisms which mobilize and concentrate previously dispersed element, may form ore deposits. This exploitation has increased man's exposure to rocks and minerals with subsequent increase in disease. Agents of disease may include the host rock and its minerals.

The origins of mineral deposits of all varieties are often related to the inherent characteristics of crustal rocks. Structural planes (bedding, faults, joints, etc.) may control mineral localization; characteristics of the rocks themselves, including their composition and stratigraphic and textural characteristics, are also major factors which control ore deposition. In addition, the presence of certain species of anaerobic bacteria during lithification may play a major role in ore deposition (e.g., as with certain sulfide deposits which have been concentrated through bacterial reduction).

In the same geological time period, similar metals and materials are often concentrated in different geographic localities where similar conditions existed. Therefore, some mineral deposits have been correlated to worldwide changes in some of these conditions, e.g., climate. The precipitation of iron-rich sediments in the southern hemisphere in Pre-Cambrian time gave rise to deposits of asbestos which occur in South Africa, Australia, and South America.

Many exploitable metallic and nonmetallic mineral deposits are commonly restricted to local concentrations in crustal rocks. They contain cationic metals, which may or may not be chemically bound with other elements. These ore minerals may be juxtaposed or admixed with other minerals, or host rocks, which are essentially waste products of no economic value. These are called gangue. Common ore minerals listed according to the main metal for which they are exploited, are listed in Table I-22. It is not sufficient for these minerals to occur in a host rock for them to be considered "ore." This is dependent upon their concentration, their economic value in the world market, their cost of recovery, shipping, and processing, etc. As important as the ore minerals are, so are their common associated gangue minerals. Although not of direct economic importance, the forms of the gangue mineral, their chemical nature, and their uses as by-product source materials, as well as the cost of their disposal may also determine the value of an ore body. Often, the economic potential of an ore body may be determined by the nature of the gangue minerals associated with the ores. A partial listing of common gangue minerals is found in Table I-23.

METALLIC MINERAL DEPOSITS

There are thousands of important metal-producing mineral deposits in the continental United States and in Alaska and Hawaii. Many of these deposits are currently worked or were until recently worked.

Industrial Metals

1. **Iron**—Geological origins include those originating as sedimentary deposits, igneous segregations, and metamorphic concentrates. Principal producing areas are listed in Table I-24.
2. **Copper**—Most major deposits are located in the Southwest, associated as disseminated ore in a specific igneous rock type. Much copper is also recovered as one of many metals associated with lead-zinc ores in the Mississippi Valley. These deposits are listed in Table I-25.
3. **Lead-zinc**—Both lead and zinc are often by-product metals of copper and molybdenum and occur as primary metals in several major deposits in both the central and western United States. Important deposits are listed in Table I-26.

Precious Metals

In addition to the industrial metals, precious metal mining is also extensive in both the continental United States and in Alaska. Gold, silver, and platinum have all been recovered as both primary ores (mined specifically for these metals) and as associated "trace metals" in metal liferous deposits mined for other metal. With the increasing price of gold and silver, many of these secondary recovery operations have become the principal economic factor in a successful operation. Major precious metal deposits are listed in Table I-27.

Almost every metal required of an industrial society is mined in the continental United States (Table I-28). Although production of some of these metals does not meet national requirements in terms of total tonnage output, domestic deposits do exist which are competitive with world markets.

Ore deposits, and their ore minerals, rarely exist as single metal populations. Cationic species, on the basis of ionic radii, valence, and electronegativity, tend to coexist in the same geological environment. Therefore, there occurs in nature a number of common mineral associations (Table I-29).

NONMETALLIC MINERAL DEPOSITS

Of the important nonmetallic mineral deposits, the fossil fuels certainly head the list in terms of importance. Coal, of all ranks, oil, and gas provide most of the energy required by industrial societies.

Both coal and petroleum products originate in sedimentary rocks from pre-existing organic compounds, including plant and animal remains. Coal deposits are frequently admixed with gangue rock high in silica. Deposits of coal are extensive in the continental United States (Table I-30). The anthracite and bituminous coals of the Appalachian Field, the bituminous coals of the interior fields, and the vast sub-bituminous fields

Table I-22
COMMON ORE MINERALS

Metal	Common Ore Mineral	Composition
Aluminum	Bauxite	$Al_2O_2 \cdot 2H_2O$
Antimony	Stibnite	Sb_2S_3
Bismuth	Bismuthinite	Bi_2S_3
Chromium	Chromite	$FeCr_2O_4$
Cobalt	Smaltite	$CoAs_2$
	Cobaltite	$CoAsS$
Copper	Native copper	Cu
	Bornite	Cu_3FeS_4
	Brochantite	$CuSO_4 + Cu(OH)_2$
	Chalcocite	Cu_2S
	Covellite	CuS
	Cuprite	Cu_2O
	Enargite	$3Cu_2S + Ag_2S_5$
	Malachite	$CuCO_3 + Cu(OH)_2$
	Azurite	$2CuCO_3 + CU(OH)_2$
Gold	Native gold	Au
	Calaverite	$AuTe_2$
	Sylvanite	$(Au,Ag)Fe_2$
Iron	Magnetite	Fe_3O_4
	Hematite	Fe_2O_3
	Siderite	$FeCO_3$
	"Limonite"	$FeO + Fe(OH)_2$
	Goethite	$HFeO_2$
Lead	Galena	PbS
	Cerussite	$PbCO_3$
	Anglesite	$PbSO_4$
Manganese	Pyrolusite	MnO_2
	Psilomelane	$Mn_2O_3 \cdot nH_2O$
	Braunite	$3Mn_2O_3 \cdot MnSiO_3$
	Manganite	$Mn_2O_3 \cdot H_2O$
Mercury	Cinnabar	HgS
Molybdenum	Molybdenite	MoS_2
	Wulfenite	$PbMoO_4$
Nickel	Pentlandite	$(Fe,Ni)S$
	Niccolite	$NiAs$
Silver	Native Silver	Ag
	Acanthite	Ag_2S
	Ceragyrite	$AgCl$
Tin	Cassiterite	SnO_2
	Stannite	$Cu_2S \cdot FeS \cdot SnS_2$
Tungsten	Wolframite	$(Fe,Mn)WO_4$
	Huebnerite	$MnWO_4$
	Scheelite	$CaWO_4$
Zinc	Sphalerite	AnS
	Smithsonite	$ZnCO_3$
	Hemimorphite	$ZnSiO_3(OH)_2$
	Zincite	ZnO

Table I-23
COMMON GANGUE MINERALS

Silica forms	Quartz, amorphous silica
Carbonate minerals	Calcite, dolomite, siderite, rhodochrosite
Silicates	Feldspars, garnet, chlorite, clay minerals
Sulfates	Barite, gypsum
Iron oxide hydrate	Limonite minerals
"Others"	Host rock, fluorite, apatite
Sulfide phases	Pyrite, marcasite, pyrrhotite, arsenopyrite

of the Rocky Mountains and east Texas, are immense in terms of tonnage reserves. Although the likelihood of coal becoming the energy producing base for our nation is small, especially with the advent of nuclear energy (and energy in other forms), the organic compounds present in coal are of immense value to various portions of the chemical industry.

Oil and natural gas fields, both on and off the continental land mass, are also extensive (Table I-30). Although a great quantity of the petroleum requirements for the United States is currently imported, complete exploitation of the continental deposits here in North America has not yet been achieved. As an example, if shale oil could be economically extracted, it would provide the country with total petroleum needs for several centuries. Oil residues, composed of complex heavy hydrocarbons, tend to have chelated a number of heavy metals frequently observed in petroleum and its by-products. Each of these materials present different problems in terms of agents of disease.

Another important group of nonmetallic minerals, especially important to the chemical industry, are those which occur as evaporite deposits (Table I-31). Complex mineral assemblages consisting of important cations and anion complexes coexist as complex salt minerals in these deposits. Soda ash, potash minerals, and nitrite minerals, to name but a few, are derived from such deposits. Evaporites occur in the geological column (indicating a paleo-environment where evaporation exceeded water replenishment) as well as in current arid area deposits.

The variety of nonmetallic minerals and materials is enormous (Table I-32). Some of these substances are considered useless due to their crustal distribution. However, if concentrated so that mining them is economically profitable, they become "nonmetallic ores." Even limestone, when occurring with a specific amount of free silica and poor in alkali cations, may be quarried and recovered as cement rock. As with the ore minerals, nonmetal associations are common as well (Table I-33). Materials of like mineral composition, rock type, and mode of origin, are exploited separately yet occur within the same deposit.

Nonmetallic minerals and materials take on added complexity. For example, single materials may have multiple uses: limestone may be used as a building stone, a cement rock, a chemical source, etc. (Table I-34). Occasionally, the same application may be fulfilled by multiple materials. For example, bulk insulating properties may be satisfactorily found in any number of mineral and rock species: asbestos, diatomaceous earth, pumice, etc. This is also true of industrial material called "refractories" (Table I-34).

As a final illustrative example, even the rocks which constitute the crust of the earth may have economic value based on important, inherent characteristics. These often include both esthetic features and durability. For building purposes, granites, limestones of all varieties, marbles, etc., have been used in the United States (Table I-35). It is probably this final example which clearly demonstrates the close association man has had with the crust of the earth. He first used natural caves as his home, recovered materials of all types for a range of purposes, and exists today in an industrialized society actualized by energy-derived fossil fuels. However, he is paying a price for these manifold energy and technological benefits.

Table I-24

MAJOR IRON* DEPOSITS—BY STATES

State	Principal District—Mine
Alabama	Clinton iron-ore of Paleozoic age Principal Appalachian deposits of Hematite
Michigan, Minnesota, Wisconsin	Superior Upland of Pre-Cambrian age including: Cuyuna, Vermilion, Mesabi, Marquette, Menominee and Gogebic ranges. Hematite and magnetite—many pits.
Missouri	Iron Mountain deposit
Nevada	Ely
New Jersey	Dover
New Mexico	Fierro, Hanover
New York	Lyon Mountain
Pennsylvania	Cornwall
Texas	Northwest district (NW. Texas)
Utah	Iron Springs
Virginia	Oriskany deposits
Wyoming	Iron Mountain

*Iron occurs with manganese and titanium.

Table I-25

MAJOR COPPER* DEPOSITS—BY STATES

State	Principal District—Mine
Alaska	Kennecott District
Arizona	Ajo, Bisbee, Clay, Globe, Jerome, Magma-Superior, Miami-Inspiration, Morenci, Ray, United Verde
California	Plumas, Walker Mine
Colorado	San Juan
Minnesota-Michigan	Superior Upland District
Montana	Butte
Nevada	Ely, Rio Tinto
New Mexico	Chino, Santa Rita
Tennessee	Ducktown District
Utah	Tintic, Bingham
Washington	Holden

*Copper occurs with lead, zinc, molybdenum, tungsten, gold, and silver.

Table I-26

MAJOR LEAD-ZINC* DEPOSITS—BY STATES

State	Principal District—Mine
Arizona	Bisbee
California	Darwin, Inyo
Colorado	San Juan, Leadville, Red Cliff
Idaho	Coeur d'Alene district (include: Bunker Hill, Sullivan, Morning, Hecla mines)
Missouri, Oklahoma, Kansas	Southeast Missori district. Tristate district (SW. Missouri; NE. Oklahoma; SE. Kansas)
Nevada	Pioche, Goodsprings
New Jersey	Franklyn Furnace
New Mexico	Hanover, Magdalena
New York	Balmat-Edwards
Pennsylvania	Friedensville
Tennessee	Ducktown district (Include: Jefferson City, Mascot, Embree)
Utah	Bingham, Park City, Tintic
Virginia	Austinville
Wisconsin, Illinois	Southern Wisconsin (northern extension of Mississippi Valley deposit; Tristate extension)

*Lead-zinc occurs with copper and silver.

Table I-27

MAJOR PRECIOUS METAL DEPOSITS—BY STATES

State	Gold†	Silver*	Platinum
Alaska	Juneau, Treadwell, Yukon, White Channel, Klondike, Nome Creek, Seward, Fairbanks		Goodnews Bay
Arizona	Oatman		
California	Mother Lode area (Sierras), Grass Valley	Darwin	Mother Lode area (Sierras)
Colorado	Bull Domingo, Bassick, Cresson, Quartz Hill, Ouray, Camp Bird, Cripple Creek, San Juan	Quartz Hill, Georgetown, Leadville, San Juan San Juan	
Idaho		Couer d'Alene, Sunshine,	Stillwater
Montana	Golden Curry, Cable	Butte	
Nevada	Sierra Nevada range, Goldfield, Aurora, Tuscarora	Rochester, Virginia City, Tonopah (Comstock)	
Oregon			Plateau Basalt Area
South Dakota	Homestake, Black Hills		
Texas		Shafter	
Utah	Cactus, Gold Hill	Bingham, Silver Reef, Park City, Tintic, Emma	

†Includes: silver and copper.
*Includes: lead, zinc, copper, gold.

Table I-28

TWENTY ADDITIONAL METALS (OTHER THAN THOSE LISTED PREVIOUSLY)*

Metal	Principal Areas of Exploitation—By State**
Aluminum	Arkansas, Alabama, Georgia, Tennessee, Virginia, Mississippi, New Mexico
Antimony	Idaho, California, Nevada, Alaska
Arsenic	Primarily a by-product of copper processing (see Table I-25)
Beryllium	South Dakota
Bismuth	Arizona, Colorado, Nevada, Utah
Cadmium	Primarily a by-product of zinc processing (see Table I-26)
Chromium	California, Oregon, Maryland, North Carolina, Alaska
Cobalt	Missouri
Manganese	Arkansas, Colorado, Georgia, Montana, South Dakota
Mercury	California
Molybdenum	Arizona, Colorado, New Mexico, Utah
Nickel	Oregon, Montana, Alaska
Radium-Uranium	Colorado Plateau (New Mexico, Colorado, Arizona, Utah, Nevada, Montana, North Dakota, South Dakota, Wyoming)
Selenium-Tellurium	Primarily a by-product of copper processing (see Table I-25)
Tantalium-Colombium	South Dakota
Tin	Alaska
Titanium	New York, Florida, Virginia
Tungsten	California, Colorado, Idaho
Vanadium	Arizona, Colorado, Idaho, Utah, Wyoming
Zirconium	North Carolina, Florida

*Excluding rare earths and specialty metals.

**Primary sources listed. If major production comes as a "by-product," it is so indicated. Those metals with primary sources may also be produced as a "by-product," e.g., Mn, from iron-ore processing in the Superior Upland.

Table I-29

COMMON METAL ASSOCIATIONS

Common multiple metal mixtures:

Silver-Gold-Copper-Lead
Silver-Gold-Copper-Lead-Zinc
Silver-Tin-Lead-Zinc
Gold-Platinum-Copper-Nickel

Common binary metal associations:

Silver-Gold
Lead-Zinc
Copper-Gold
Iron-Manganese
Iron-Titanium
Nickel-Copper
Nickel-Cobalt
Chromium-Platinum
Tin-Tungsten
Molybdenum-Copper
Zinc-Cadmium

Common by-product metals, metalloids:

Arsenic
Antimony
Bismuth
Calcium
Selenium

HUMAN DISEASES ASSOCIATED WITH ROCKS AND MINERALS

Many effects have been described in humans exposed to rock and mineral dust generated during the recovery of crustal materials. Some of these are well known and receive much attention—e.g., silicosis, resulting from exposure to the silica polymorphs and the asbestos diseases, resulting from exposure to the asbestos minerals. Yet, most exposures in the crustal environment are not pure exposures: they involve exposure to a number of inorganic dust components. Such disease stigmata are either so complex as to be called "mixed dust pneumoconioses" with characteristics of several "pure exposures" or have been given the name of the principle dust alone. Some of these, and the associated complexities, are listed in Table I-36. Exploration of the biological effects of these materials is in its infancy.

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Table I-30

MAJOR FOSSIL FUEL DEPOSITS
COAL—BY FIELDS—ALL RANKS

Appalachian Field:*	Pennsylvania, Ohio, West Virginia, Virginia, Maryland, Kentucky, Tennessee, Georgia, Alabama
Interior Fields:	
Eastern	Illinois, Indiana, Western Kentucky
Western	Iowa to Arkansas (Great Plains States)
Southwest	Texas
Northern	Michigan
Rocky Mountain Field:	Montana to New Mexico
Pacific Coast Field:	Washington (+Alaska)

Oil and Gas Fields (On and Off Shore)

Appalachian Field
Mid-Continent Field
Gulf Coast Field (incl. East Texas)
Rocky Mountain Field
California and Pacific Coast
Alaskan Field (north slope)

Includes:
Alaska
Arkansas
California
Colorado
Illinois
Kansas
Louisiana
Michigan
Mississippi
New Mexico
Oklahoma
Pennsylvania
Texas
Wyoming

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*Tend to be anthracite and bituminous. Other fields (excluding local small deposits) tend to be bituminous and lower ranks.

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Table I-31

MAJOR EVAPORITE DEPOSITS

Product	Location
Alkali minerals (principally soda)	Owens Lake, Mono Lake, California; Soda Lakes of Nevada
Borate minerals	Owens Lake, Searles Lake, Borax Lake, California; Dry Lakes of Oregon and Nevada
Gypsum, anhydrite	New York; Great Salt Lake (Utah); Gulf Coast (Mississippi Valley)
Halite	New York; Ohio; Michigan; New Mexico; Gulf Coast; Great Salt Lake (Utah); Imperial Valley, California
Nitrate minerals	Searles Lake (and others) California; Dry Lakes of Utah and Nevada
Potash minerals	Searles Lake, Mono Lake, Death Valley, California; Moab, Utah; Columbia Marsh, Nevada
Sulfate minerals (excluding gypsum and anhydrite)	Soda Lake, Searles Lake, California; Downey Lake, Wyoming; Verde Lake, Arizona

Table I-32

SOME EXPLOITED NONMETALLIC MINERALS AND MATERIALS

Abrasives	Garnet, corundum, sand, tripoli, flint, emery	New York, Massachusetts, Virginia, North Carolina, New Hampshire, Idaho
Asbestos	Asbestiform silicate fibers, predominantly chrysotile	Vermont, Arizona, California
Barite, Witherite	$BaSO_4$, $BaCO_3$	Missouri, Georgia, California, Arkansas, Virginia
Building stone	All varieties, e.g., granite, limestone, sandstone	(See Table I-35)
Cement rock	Siliceous limestone	New York, Pennsylvania
Clay minerals	Kaolin, attapulgite, bentonite, ball and fire clays, estaurine clays, Fuller's earth	Indiana, Illinois, Maryland, New Jersey, North and South Carolina, Virginia, Wyoming, California, Connecticut, Delaware, Georgia, Kentucky, Tennessee, Pennsylvania, Ohio, Missouri, South Dakota
Coal	Anthracite to peat	(See Table I-30)
Diatomaceous earth	Amorphous opaline silica	California
Fertilizer	Potash from evaporite minerals and others	(See Table I-31)
Feldspars	Orthoclase, microcline	(See Table I-35)
Fluorspar	CaF_2	Illinois, Kentucky, Colorado, New Mexico
Gemstones	Mostly semi-precious, e.g., tourmaline	California, Maine
Glass	SiO_2 (quartz)	West Virginia, Pennsylvania, Illinois, Missouri
Graphite	Carbon	New York, California, New Mexico, Rhode Island, Alabama, Texas
Gypsum	$CaSO_4 \cdot 2H_2O$	(See Table I-31)
Halite	NaCl	New York, Michigan, California, Utah
Micas	Muscovite, biotite, vermiculite	Montana, Arizona, North Carolina
Phosphates	Phosphate minerals	Florida, North Carolina
Refractories	Aluminum silicates	California, Virginia, North Carolina, Georgia, South Dakota, Nevada
Sulfur	Sulfur	Louisiana
Talc, Soapstone Pyrophyllite	Magnesium silicate hydrate, Aluminum silicate hydrate	Vermont, Georgia, California, New York, Montana, North Carolina
Zeolites	Erionite, mordenite, others	Wyoming, Nevada, Utah

Table I-33

COMMON NONMETAL ASSOCIATIONS

Oil and natural gas	Fossil fuel reservoirs
Salt, potash, gypsum	Evaporite deposits
Feldspar and mica	Granite pegmatites
Soapstone and talc	Steatized Mg-rich rocks
Coal, fire clays, ball clays	Coal seams

Table I-34

EXAMPLES OF COMPLEXITY OF NONMETALLIC MINERALS AND MATERIALS

Single material with multiple uses	
e.g., "***Limestone***"	Building stone, trim stone, cement rock, chemical source (e.g., magnesium), fertilizer source (lime), lithographer's media
Multiple materials for single uses	
e.g., "***Bulk insulating material***"	Asbestos (primarily chrysotile) Diatomaceous earth Gypsum (calcined) Magnesium carbonate Perlite (calcined) Pumice Vermiculite
e.g., "***Refractories***"	Clays (pure, especially aluminum silicates (e.g., kaolin, dickite) Silica forms (e.g., quartz, diatomite) High alumina refractories (e.g., sillimanite, andalusite, kyanite, dumortierite) Zirconia (from zircon and baddeleyite) Graphite Rutile Beryllium compounds Titanium compounds Pyrophyllite and talc block Olivine in magnesia matrices

Table I-35

BUILDING STONES

Stone	Important Producing States
Dolerite (trap rock) and others	New Jersey, Connecticut, Massachusetts, Pennsylvania
Granite (including gneisses)	Vermont, Maine, Minnesota, Massachusetts, New Hampshire, Rhode Island, Wisconsin
Limestone	Florida, Indiana, Minnesota, Missouri, Texas
Travertine	Colorado, Montana
Marble	Georgia, Vermont
Sandstone	Connecticut, Kentucky, New York, Pennsylvania
Soapstone	Virginia

Table I-36

NATURAL MATERIALS ASSOCIATED WITH HUMAN DISEASE

ROCKS

Rock Type	Mineral Components	Comments
Coal	Anthracite Bituminous ±quartz	Coal workers' pneumoconiosis; "miner's consumption"; focal emphysema; anthracosis, silico-anthracosis; may be related to rank (anthracite >bituminous); "melanosis" or "black lung"; greater incidence of tuberculosis; may progress to "massive fibrosis."
Fullers earth	Butonites and related montmorillonites ± quartz + free silica	Pneumoconiosis without massive fibrosis and nodules (diffuse); mottled x-ray appearance; some related silicosis
Diatomaceous earth	Opaline diatom fragments	Some lung scarring developed; much greater in processing when calcined (conversion of opal to cristobalite); silicosis with progressive massive fibrosis.
Granite Quartzite Sandstone Slate	All with large amounts of quartz.	Silicosis; silico-tuberculosis; nodular silicosis; fibrosis; enlarged and hardened lymph glands. Silicotic nodules in spleen
Pumice	Volcanic glass, some devitrification to quartz	Resembles silicosis; some linear scarring.

Table I-36

NATURAL MATERIALS ASSOCIATED WITH HUMAN DISEASE (Continued)

ROCKS

Mineral Name	Major Uses	Comments
Limestone	Calcite ± quartz	Some bronchitis; some emphysema, some scarring reported; when calcined for industrial purposes, toxicity increases; caustic burns; dermatitis; ulceration of skin; injury to conjunctiva and cornea.
Marble	Calcite ± quartz	
Dolomite	Dolomite ± quartz	
Gypsum	Gypsum ± evaporites	Some bronchitis; when calcined for industrial purposes, toxic effect to skin increases some irritation to eyes, nose, and pharynx
Anhydrite	Anhydrite ± sulfur	
Bauxite	Hydrated aluminum oxides	Some reports of lung scarring
	SILICATE MINERALS	
Amosite	Used as asbestos	A major asbestos mineral; asbestosis lung cancer; cancer of the gastrointestinal tract; pleural and peritoneal mesothelioma; possible increase in other malignancies.
Anthophyllite	Used as asbestos	See amosite
Biotite	Insulation and filler	Pulmonary fibrosis; silicosis; strong association with free quartz, likely a major factor in producing fibrosis.
Chalcedony	Pottery and grinding material (abrasive)	Silicosis; "potters' asthma"; "potters' consumption"; silicotic nodules in spleen; silico/tuberculosis; progressive pulmonary fibrosis.
Chert	See chalcedony	See chalcedony
Chrysotile	See anthophyllite	See anthophyllite; this mineral is the asbestos type which accounts for over 90% of asbestos consumption in the United States.
Cristobalite	By-product produced	See chalcedony; cristobalite is more fibrogenic than quartz
Crocidolite	See amosite	See amosite

Table I-36

NATURAL MATERIALS ASSOCIATED WITH HUMAN DISEASE (Continued)

SILICATE MINERALS

Mineral Name	Major Uses	Comments
Diatomaceous earth (Opal)	See chalcedony	See chalcedony; the opaline composition is altered when the earth is processed; it is often converted to cristobalite, in whole or in part.
Feldspar (K,Na spar)	Ceramics	Silicosis; often attributed to the included quartz content of the pegmatite-derived mineral.
Flint	See chalcedony	See chalcedony
Fluorite	Industrial flux	Fluorosis; silicosis; the latter is often attributed to the associated quartz
Graphite	Crucibles; high temperature facings; electrodes; paints	Graphite pneumoconiosis; tuberculosis; resembles silicosis
Kaolin	Ceramics; filler	Some lung scarring observed, but only in areas associated with free quartz.
Kyanite	Ceramics	Some lung scarring observed.
Muscovite	See biotite	See biotite
Nepheline	Industrial uses	Nephelosis; some lung scarring.
Olivine	Industrial uses	Silicatosis; some lung scarring.
Phlogopite	See biotite	See biotite
Pumice (obsidian and scoria)	Abrasive; insulation	Silicosis
Quartz	Abrasive; industrial uses	See chalcedony; this material is likely responsible for a number of diseases attributed to other minerals.
Sericite	Impurity associated with other minerals	Some fibrosis observed in men exposed to sericite dusts; however, attributed by some to the admixed free quartz.
Sillimanite (mullite)	See kyanite	See kyanite
Talc	Industrial uses; filler	Talcosis; talc pneumoconiosis
Tridymite	See cristobalite	See chalcedony; also, more fibrogenic than quartz.

Table I-36

NATURAL MATERIALS ASSOCIATED WITH HUMAN DISEASE (Continued)

ORE MINERALS

Metal	Mineral	Comments
Aluminum	Bauxite ore Corundum	Aluminosis; some lung scarring; corundum grinders may suffer a severe pneumoconiosis; emphysema; free silica (quartz) associated with corundum deposits, some scarring attributed to this.
Arsenic	Cobaltite Enargite Realgar Orpiment Arsenopyrite Smaltite	Local skin and mucous irritant; carcinogen; anemia (hemolytic agent); hemoglobinuria; most severe reactions are observed during the smelting of arsenic-containing ores; miners of the ore are reported to have "excess" lung cancers although published accounts are few; also, many of the ores are admixed with other materials which confound the data and represent "mixed dust pneumoconioses."
Beryllium	Beryl Chrysoberyl Bertrandite	Berylliosis; chronic lung disease; pulmonary lesions; acute poisoning; granuloma; pneumonitis; most severe reactions are observed in ore processing; ore minerals are associated with quartz-rich rocks which add a "mixed dust pneumoconioses" effect.
Cadmium	Greenockite	Most effects are related to mineral processing and recovery; generally a by-product of Pb and Zn smelting; no pneumoconiosis reported for the mineral dust itself; renal and pleural involvement.
Chromium	Chromite	Some reports of lung cancer among chromite miners, but most of the effects are among the "chromite workers" who process the ore; the ore also includes a number of other active mineral substances such as serpentine phases (chrysotile).
Cobalt	Smaltite Linnaeite Cobaltite Erythrite	Some reports of excess deaths due to lung cancer and cancer of the main bronchus; "hardmetal disease"; excess cancer among the cobalt ore processors.
Iron	Hematite Magnetite	Siderosis; scarring of the lung increases as the quartz content of the ore increased; some reports of increased lung cancer among taconite ore miners of Newfoundland; some experimental work supports this observation.

Table I-36
NATURAL MATERIALS ASSOCIATED WITH HUMAN DISEASE (Continued)
ORE MINERALS

Metal	Mineral	Comments
Lead	Galena Cerussite Anglesite	Some reports of pneumoconiosis among the miners of galena, likely produced by associated mineral dusts; most of the severe reactions are observed among the processors and users of the by-products; diseases of the central nervous system; nephritis; "plumbism"; anemia; Pb content of ambient air in smelting towns is generally high.
Manganese	Pyrolusite Braunite Manganite Hausmanite Rhodochrosite	Some reports of pneumoconiosis among miners of manganese ores, but most effects are observed among ore processors; affects the central nervous system (Parkinsonism syndrome); unusually high rate of pneumonia among ore processors.
Mercury	Cinnabar	A range of systemic diseases are recognized among miners and processors; nephrosis (renal lesions); "salivation"; "vertigo"; "paralysis"; "Hatters shakes"; erethism; stomatitis; "mercury poisoning"; perforation of nasal septum.
Nickel	Pentlandite Niccolite Millerite Garnierite	Some pneumoconiosis observed among miners but generally attributed to the admixed gangue minerals; some observations indicate a higher than normal lung cancer rate among miners of Ni in "hard rock areas"; higher incidence of lung and nasopharynx cancer amongst Ni smelters.
Phosphorus	Apatite	Some x-ray changes of lungs with minor scarring; some neurological disorders induced in men who process mineral for P recovery; phosphine and pesticide forms toxic-to-lethal.
Platinum	Platinum Sperrylite	No disease associated with water-worked placer deposits; direct mining in mafic rocks generally associated with serpentine minerals, some lung scarring observed which resembles asbestosis.
Selenium	Tiemannite Guanajuatite Clausthalite Naumannite Eucairite Chalcomenite	Pneumoconioses observed are to admixed gangue minerals; some observed in hard-rock mining of Pb, Cu, Hg, Ag, ores; most adverse effects observed in ore processors; severe irritation of nose and eyes; gastro-intestinal disorders; dental caries.

Table I-36

NATURAL MATERIALS ASSOCIATED WITH HUMAN DISEASE (Continued)

ORE MINERALS

Metal	Mineral	Comments
Silver	Silver Acanthite	Some x-ray changes of lungs but attributed to the admixed gangue minerals; some disease observed in men processing ore; argyria—discoloration of the skin to a pale gray or blue-gray.
Tellurium	Montanite Emmonsite Durdenite Tetradymite	As in the case of selenium, the pneumoconioses observed are attributed to the admixed gangue minerals; some scarring in areas of hard rock of mining of Bi, Pb, Ag, Hg. Most adverse effects are observed in ore processors; gastrointestinal disorders; renal disorders (impairment or death).
Tin	Cassiterite	Severe x-ray changes in miners; tin pneumoconiosis; some associated silicosis when quartz admixed in as gangue.
Titanium	Rutile Sphene Ilmenite	Severe lung scarring, titaniosis; scarring regardless of the nature of the gangue minerals.
Tungsten	Wolframite Tungstite	Lung scarring observed among miners of tungsten pneumoconiosis; ore often associated with cobalt minerals—the suspect causative agent.
Uranium	Uraninite Carnotite Pitchblende Thorium ores Vanadium ores	Some silicosis reported for sandstone deposits of uranium; excess lung cancers reported for the Colorado Plateau.
Vanadium	Vanadinite Carnotite	Some permanent lung scarring; immediate reaction is a respiratory irritant; irritant to eyes; susceptibility to pneumonia.
Zinc	Sphalerite	Shortness of breath; some minor lung changes; some deaths reported from pneumoconiosis.