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The Time of Sands: Quartz-rich Sand Deposits as a Renewable Resource

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Sand is a common material critical to the manufacture of many modern technologies. It occurs everywhere in nature and society. We use millions of tons of sand each year in a multitude of materials and manifestations (Figure 1). Sand use has a long history and a bright future. Fortunately sand is produced in prodigious amounts by natural processes and distributed widely by geologic agents. Sand is ubiquitous in the natural world, our manmade universe, even in human literature. Who has not had sand in their shoes, known a strong-willed person with "sand" or grit, or heeded biblical advice to avoid building upon shifting sands or modern advice to get one's head out of the sand? This article will help the reader understand more about sand and, as suggested by turn of the (last) century British poet and artist William Blake, "to see the universe in a grain of sand." It will discuss this common but vital material that has existed since the beginning of our Earth and that can even be considered a renewable resource. The reader will learn about what sand is, where it originates, some of its many uses, its importance as a natural resource that helps build our society, and its renewable nature.

We are not the first culture to rely on quartz. The very first hominids in Africa used quartz-rich rocks for their tools some 2.5 million years ago. Earliest Americans shaped a variety of quartz called chert into tools for hunting, household chores, and protection (Figure 2). Today quartz rendered into silicon, glass, and chemicals provides the basics of our modern communication, computing, as illustrated by the chip (Figure 3). Great quantities of sand are used in the construction industries. Glass production, including fiberglass, requires very pure quartz sand that is melted and can be recycled into other products.

Buddhist monks or Navajo Shamans works sand grains into beautiful and philosophically meaningful mandalas. Some Buddhist sand paintings emphasize the meaninglessness of time. One such mandala is ironically used on this clock face (Figure 4). After completion these complex icons of nature guided by human intellect and skill are destroyed and cast into a body of water to further emphasize the transience of human existence. The order of the art is gone but the sand remains with its intrinsic character intact just as it behaves in nature.

What is Sand?

Sand is generally known as loose, gritty particles of worn or disintegrated rock usually deposited along shores of water bodies, in river beds, or desert dunes. Geologists define sand more specifically as a natural loose, granular material made of separate mineral or rock particles from 0.0625 to 2.00 millimeters (mm) in size. Larger particles are granules, pebbles, cobbles, or boulders (>256 mm) and smaller grains are silt (0.0625-0.00 mm) or clay (<0.004 mm). Particle size is measured by passing samples through a series of screens with various sizes of openings (Figure 5). Sand is a product of weathering and transport of preexisting rocks. Sand and its solidified form, sandstone, are both very important geologic products that have undergone extensive research (Pettijohn, 1975). Publications written for the general public such as *Sand* (Siever, 1988) have also been well received. Forces that produce sand and sand parent materials occur all over the Earth and so sand is found in all parts the globe. Sand grains can be a part of soil but soil also contains fine-grained, plastic clay minerals, organic materials, oxide minerals, and poorly defined mineraloids.

Sand is the final product of rock weathering (Figure 6) which is an important part of the rock cycle. The weathering of any quartz-bearing rock creates sand: igneous, sedimentary, or metamorphic. It is involved in a continuous cycle of rock formation and erosion that started with the Earth’s formation and continues today. Weathered grains become separated from inter-grown or cemented minerals that make up hard rocks. Grains are transported mainly by water on an oft-interrupted quest for the sea. As they travel, weaker minerals are removed and resistant grains become smaller in size, become more equant or rounded in shape, and their surfaces are modified by constant abrasion or chemical attack. The longer times that grains travel the more mature they become. Many sand grains are very well rounded indicating several cycles of deposition and transport. Very mature sands make the most chemically pure, most ideally round, and best sorted sand deposits. Scientists study mineral compositions, grain size distribution, measures of grain roundness, statistics of particle sorting and other details to unfold a sediment’s history. These features are also of critical importance to a sand deposit’s suitability for human uses (Carr, 1971; Zdunczyk & Linkous, 1994).

Numerous physical characteristics of sand are measured to help define its origins, histories, and potential uses. The term sand is used to define particle size, the quartz-rich sediment, geologic deposits, or a mined product. The U.S. Geological Survey uses several terms interchangeably as reflected in this quote:

"Industrial sand and gravel, often termed "silica," "silica sand," and "quartz sand," includes high SiO_2 content sands and gravels." (Bolen, 1996, p. 715)

The glossary provides exact definitions and readers should be guided by contexts of the term.

Sands can be made of many different minerals but industrial sand deposits are made mainly of the mineral quartz. White tropical beaches can be made of carbonate minerals while some beaches are composed of green olivine, dark ferromagnesian minerals, resistant black oxide minerals, or whatever minerals are available near the deposit. But almost important sand deposits are composed of the mineral quartz with varying types and amounts of other minerals.

Quartz

Many sands and all the highest quality sand deposits are made of quartz (Figure 7). Quartz is the most common mineral in the crust of the Earth comprising an estimated 35% of all rocks. A mineral is "a naturally occurring inorganic element or compound having a periodically repeating arrangement of atoms and characteristic chemical composition, resulting in distinctive physical properties." (Jackson, 1997, p. 410) The crystal structure controls physical properties of minerals. In quartz the element silicon (Si) is completely surrounded by four oxygen atoms to form a tetrahedron-rather like an equidimensional pyramid (Figure 8A). Silica (SiO_2) in combination with a variety of other oxides forms a number of minerals known as silicates which have structure based on different arrangement of the silica tetrahedral. In quartz each oxygen atom is shared between two silicons in a tight three-dimensional framework (Figure 8B) giving rise to a mineral that is very stable chemically and mechanically (*The Mineral Gallery*, 2004).

The two most abundant chemicals on Earth, Si (28%) and O (47%), combine to form quartz (Table 1). Both elements are born in the final stages of nucleosynthesis of red giant stars and scattered to the universe when such stars explode. Differentiation of chemicals during planet formation results in separations of chemical species with most silica being concentrated in the outer crustal rocks. Rocks or sediments melt when buried deep in the Earth where geologic forces of plate tectonics plunge existing rocks deep into the mantle. Great heat is produced where faulting or metamorphic conditions occur, or at localized "hot spots" of upwelling hot mantle materials. Quartz and other minerals form when molten rock that is rich in silica solidifies into igneous rocks. Mineral grains grow together into an interlocking mosaic as magma cools.

Quartz is the most abundant mineral on Earth. Quartz and its closely related mineral relatives in the feldspar group make up the bulk of most igneous rocks. These minerals form when silica-rich melts or magmas cool and solidify into one of the most common rocks, granite. Granites rich in quartz comprise about 40% of crustal rocks. They are especially prominent in mountain ranges. Minerals form in a definite sequence – the Bowen Reaction Series – that depends on temperatures and melt compositions. Minerals that form at high temperatures such as olivine are less stable at the Earth's surface than late formed minerals such as quartz. The so called Goldich Stability Series (a mirror image of the Bowen series, Figure 9) shows the relative stability of minerals in the weathering environments at the surface.

Sand on the Move

Weathering and Transport

The mineral mosaics of rocks degrade and fall apart once subjected to surface conditions that mount a complicated assault of chemical and physical forces collectively known as weathering. Temperature changes, wetting and drying, sunlight, microorganisms, and most importantly freezing and thawing of ice or crystallization of other minerals produce repeated mechanical forces that force originally interlocking mineral grains apart. Chemical reactions especially those involved with water further liberate and modify mineral grains. Weathering is especially severe in high mountains. Over time high mountain ranges are virtually flattened by weathering (Ritter, 1986).

Rock and mineral fragments, once liberated from their igneous origins, move by gravity, ice, water, even air currents toward the lowest points on Earth usually the sea floor. Erosion and transport of grains result in destruction of physically weak minerals as they cascade down mountains, crash into boulders, and grind against each other. The constant jostling reduces sizes of mineral grains, grinds off corners and eliminates unstable or weaker minerals. The aggregate of weathered and transported grains are called sediments.

Sediments, like humans, reflect the rigors of their experiences. Mineral grains that have traveled far have more refined compositions, shapes, sizes, and companions. Mature sediments are those which have long experience in traveling. Silica sand deposits are usually mature or supermature. Geologists employ sophisticated measurements to characterize sediments. One of the most common is grain size which is determined by the screening process as discussed earlier. Natural deposits contain a range of shapes and grain sizes from fine (Figure 10) to coarse (Figure 11).

Particles that are immature generally are angular in shape (Figure 12), but they become more rounded with transport and maturity. Many sand consumers prefer very round grains (Figure 13) because they flow easily and react completely, but for some uses such as foundry molds, angular grains are preferred because they form a more stable body. Abrasive producers also prefer angular sands. More mature sands are well sorted meaning that they have a relatively limited size range and sedimentologists use sophisticated statistics to quantify size, angularity, and sorting of grains.

Mature sands tend to be made dominantly of one mineral, quartz. Younger sediments often contain relatively unstable minerals such as mica or feldspar or even individual rock fragments containing several different minerals. Very long travel times or multiple transport events can lead to deposits of remarkable purity. Super mature sands often are more than 95% quartz with some natural deposits containing 98% quartz. These high-purity sands have numerous economic applications and are required for glass manufacture (Table 2).

Sediments deposited by glaciers are almost never pure enough nor of proper sizes to be used as industrial sands but most can be used for construction purposes. Moving water or air are great media for sorting and refining raw sand materials.

Stops Along the Way

Water currents easily move sediments, especially sand-size grains. Even slow currents will make sand move downhill and faster currents can move larger grains, even large boulders. Many rivers are brown in color due to suspended fine sediments and clays. During floods one can hear a constant crashing and grinding of boulders bashing into each other in the strong current. Geologists have performed many experiments that relate differing grain sizes or currents to forms of ripples or other sedimentary features seen in rivers. Rivers themselves move as shifting currents that make numerous sand bars and other features constantly remakes their channels. The land itself can rise or fall allowing rivers to cut rapidly into their bedrock beds or leaving old stream deposits as terraces far above the new river levels.

Rivers, waves, longshore currents, and winds are the most efficient movers of sediments. Large particles move by being pushed along the bottom of a stream as bedload by river currents and grains of a certain size move by bounding or saltation. Very fine materials can be suspended in turbulent waters as evidenced by muddy rivers (Figure 14A). Sediment sizes that can be transported depend on fluid velocity, turbulence, viscosity, and roughness of the bottoms. Sand grains can move in suspension constantly floating in air or water currents, by traction or slipping along the bottom, or a process called saltation where grains bounce along (Figure 14B). Many times sand congregates into ripples in water or dunes if on land. In ripples or dunes, sand goes up a gently sloping backside and cascades over the top onto a steep leeward slope or slip face. These forms move and change as fluid motion changes. Huge amounts of quartz sediments move from the land to the sea with billions of tons deposited in seas each year.

As fluid velocity slows upon entering quiet water, sediments may cease traveling, fall to the bottom, and become deposited, at least temporarily. Rivers have complex water motions and sand deposits are constantly being reworked, moved, and re-deposited. Rivers meander sideways across their floodplains (Figure 14C) generating wide sheets of sand deposits or downcut leaving terrace deposits at levels high above current water level. Sand and gravel are often mined along rivers or even in active channels. Some sand mining relies on continuous renewal of deposits by traveling sediments. Finally rivers build large deltas of sands into lakes or oceans. Deltas grow as long as rivers bring sediment but even large deltas can die if the river's channel changes path.

Once deposited in water body sand still moves either through wave motion or wave generated longshore drift. When waves hit a beach at angle sand is forced sideways along the coast and broad beaches are built or destroyed by so-called longshore currents that move "rivers of sand." Large storms can completely obliterate beaches, offshore shoals or even entire islands. Off-shore mining, man made structures, or dredge projects dramatically affect ocean sand movement. Governments routinely commit tens of millions of dollars to dredge sand from shipping channels, to replenish sand beaches, or make sand bypassing projects in order to preserve structures and protect recreation industries. Underwater sand mining is common on coasts throughout the world and some mining companies find that sand is noticeably replenished by natural sand movement sometimes in periods as short as a year or two.

In high, cold mountains and rarely on low lying but huge areas, glaciers made of ice move sediments but the ice movement itself does almost no sorting of grains and so rarely produces sand deposits. Melt waters rushing from dying glaciers often rework sediments of all sizes winnowing away fine-grained clays or silts and leaving well-graded (Figure 15) sand deposits along their paths.

Sediments spend a lot of their travel time in river-related deposits but some are also stopped in lake deposits. Waves often form well-sorted deposits along lake shores as do winds that form dune fields. In the Eastern and Midwestern U.S., unconsolidated sand deposits are almost all related to rivers, melt water channels, lake deposits, or dunes. Rivers and lakes are generally short lived and most sediments ultimately reach the ocean.

By the Sea – The Beautiful Sea

Once the energy of movement is spent, grains fall by gravitational settling to the lake floor, or sea bed to form large deposits of sands. Larger fragments settle first near shore while fine-grained and platey clay grains can travel far to sea. At the edge of the coast wave motion and longshore currents winnow and transport huge amounts of sand, often sorting by size and specific gravity.

Once sand grains reach the ocean their travels do not cease. Sediments build up near river mouths often in deltas but much material is moved along the shore by wave action and a process called longshore drift. Normal longshore currents due to everyday wave motion move sand constantly, but really dramatic changes are wrought by strong storms that can obliterate barrier islands and redistribute enormous quantities of sand reshaping islands, beaches, shoals, and many minor near-shore deposits. Waves, currents, and drift build beaches, barrier islands, offshore shoals, spits, dunes, and many coastal deposits from sand. These features are very changeable, as any beach lover knows. Entire islands are worn away and deposited elsewhere. Inlets through islands or shoals form and man builds a variety of facilities along the coast. Table 3 summarizes selected data about beach sediment movement.

Beaches are where the land meets the oceans. These areas make up less than 1% of Earth’s landmass, but are incredibly important because almost half all human population lives within 100 kilometers of a coast. Commerce, shipping, and recreation require relatively stable coasts and huge amounts of money and effort are spent on fighting the effects of sand movement. Sand grains have been shown to move several kilometers in just one day. Huge volumes of sand travel naturally and millions of tons of sand are rearranged by coastal engineers to keep channels open, to stabilize beaches, or shore up facilities each year.

Sand was often mined from beach areas in the past. This activity still occurs in many countries but very rarely in the U.S. Most sea sand mining is done from offshore deposits. Extensive research on such mining has shown that mined areas often fill in with new sand sometimes in a period of years under normal conditions. Hurricanes, large storms, and other natural disasters can mobilize sand in unimaginable quantities.

Sand in the Air

Where abundant sand materials, dry conditions, and sufficient wind combine, air currents in dune forms will deposit sands. Some of these areas are known as sand seas that cover thousands of square kilometers. Wind is an especially good agent for sorting fine sand grains. Some of the dunes can be hundreds of meters high. These dunes move with the wind, sometimes at fast rates. Builders often wage war with encroaching sand. One study showed dune migrations of 3.8 to 7.5 miles per year (Tsoar, Blumberg, & Stoler, 2004). This represents a huge amount of sand movement over a large area and could easily replenish mined areas.

Frequently sand is piled up in dunes landward of beaches by wind action. Inland dunes are formed by strong directional winds that transport sand in generally arid areas. Some of the most pure sands are found in dunes and dune sand mining used to be common. In the United States mining of sand dunes is severely restricted, but dune mining still occurs in many parts of the world. One of the concerns about dunes is that they move as the wind blows. Large inland areas of dunes such as Imperial Dunes, or the Sahara, march along overtopping vegetation, oases, buildings, and all in their paths. Desertification by dune movement can cause severe disruptions to human activity, but it also shows the Earth’s ability to replenish sand deposits.

Sand and Man

Silica Sand Uses

Common sand is also a critical material for all manner of building applications from making cement, aggregates in concrete and mortar, flooring, roofing, and resins. Amazing amounts of sand and gravel are used each year to build roads, buildings, and all manner of facilities public or private.

Silica sand is a very important raw material for many modern materials. The main use is for making glass (>35%). Different kinds of glass require different levels of purity and grain size (Table 4). Glass fiber used for reinforcing, insulation, and textiles are made of very pure silica. Special materials such as fiber optic cables require exceptionally pure sands.

Nature first made mineral glass in volcanoes. Glass was made in Mesopotamia more than 4,000 years ago. It was prized by Egyptians, Romans, and other early cultures, but glass making was perfected in Europe during the twelfth century. Modern glass making is a multibillion dollar industry based on quartz sands. Mineral or glass wool is the leading thermal and acoustic insulating material. Mineral wool is made of igneous rock such as basalt and fluxing agents melted at 1,400 to 1,600 oC. Glass wool or Fiberglass is made of silica sand with other raw or natural material. The raw material is melted at about 1,100 oC and made into fibers by forcing the melt through centrifugal spinners aided by jets of air or steam. Many fiberglass plants are in the eastern U.S. with clusters in the Georgia and Alabama areas of the southeast. Production also occurs in Texas, Kansas, and California. Fiberglass is an environmentally friendly material. It is easily made, is readily recycled, is essential for energy conservation, and is made mostly from an abundant, renewable mineral resource – sand.

Pure quartz sands are known as industrial sand, silica sand, high quartz sand or simply silica by industries. Carefully sized quartz sand is used extensively for filtering water. Raw, angular quartz sand is mixed with clays to make heat-resistant molds or cores for casting metal parts. Fine sand is used for precision coatings such as jewelry, high precision parts, or dental devices. Ceramic items depend on quartz for toughness and resilience, and for their glazes. Quartz is used to make refractory (temperature resistant) bricks for lining furnaces, limited specialized niches, and fused quartz can be made into many complex shapes for laboratory devices.

Refined quartz produces a huge range of silicon chemicals used in drugs, cleaners, and pharmaceuticals and also the silicon chips that power our computerized world. Quartz can provide silicon metal or ferrosilicon which is an alloying agent for various metals. Silicon carbide, an important abrasive made from quartz and natural quartz, both have been used for a myriad of abrasive tasks such as sandpaper. Quartz sand is used as a filler or extender for such products as paints, plastics, gels, and other suspensions. It imparts considerable toughness to rubber or plastics, and can provide some temperature resistance. Coarse, spherical sand grains introduced into oil-bearing geologic formations increase permeability of certain rock units by propping open fractures, thus allowing for easier and more complete production of oil. Quartz has use in farming, forestry, and animal husbandry for soil conditioning, as a carrier for farm chemicals, and as additives for animal feed. Quartz sand is even used in recreation such as golf, volleyball, and other sports. In short, we depend on quartz every bit as much as our ancient ancestors and probably even more due to its importance in chemicals and computers. Table 5 summarizes the many uses of silica sand.

Sand Production

The U.S. Geological Survey states that

"Identified resources of silica sand are virtually inexhaustible, and reserves are very large in relation to demand. Known deposits can satisfy national demands at reasonable cost for centuries." (Ketner, 1973, p. 579)

Sand deposits occur under many geographic and geologic conditions. Industrial sands are less common than construction sands and may require more exploration. Geologists find deposits by searching existing records or air photos, then drilling, trenching, sampling, and analyzing samples to confirm a deposit's extent and character. Common sand is produced from unconsolidated deposits or hard, consolidated rocks. Sandstones and quartzites are the most common hard rock sources, but a few operations produce specialty quartz from igneous rocks.

Figure 16 shows industrial sand and gravel production for the United States. The U.S. produced 29.7 million metric tons in 2004 at a value of $685 million. Worldwide production was 115 million metric tons. The U.S. produces nearly 30% of total world production from more than 150 operations and about three-fourths of production is from the central U.S. (Dolley, 2004a). Silica sand production in the United States has averaged 28 million mt per year for several years and the average dollar price per ton has risen from $19.58 per ton in 2000 to $22.28 per ton in 2004. Employment in silica sand mining stands at about 1,400 and major producing states are Illinois, Texas, Michigan, Wisconsin, North Carolina, California, New Jersey and Oklahoma. The U.S. supplies all its glass sand needs and even exports minor amounts of sand. Slovenia, Germany, Belgium, France, Spain, Australia, Japan are also major producers (Dolley, 2004a, 2004b).

Most silica sand production is from unconsolidated units, but the St. Peter and Ottawa Sandstones of Illinois, the Oriskeny Sandstone in New Jersey and New York, or the Oil Creek in Oklahoma are major bedrock producing units. Identified resources of silica sand are nearly inexhaustible according to the U.S. Geological Survey (USGS) (Ketner, 1973) . Glass sand deposits of North America were reviewed by E. William Heinrich who emphasized the diversity of geologic occurrences and ages of these deposits, especially consolidated rocks (Heinrich, 1981). Known deposits could satisfy U.S. needs for centuries. World resources are similarly immense. U.S. and world natural sand resources are more than adequate to supply current and projected needs. Modern processing can upgrade marginal deposits.

Sand Processing

Nature separates and purifies sand to a great degree but further processing is needed to produce sand sufficiently pure for modern uses. Current processing technology can upgrade sand deposits that are not naturally pure enough for glass making. Consistency is of paramount importance for most sand uses. Chemical purity and particle size are the most important parameters. Main contaminants are iron (Fe_2O_3), alumina (Al_2O_3), and titanium dioxide (TiO_2). Figure 17 shows several contaminant materials. If feldspars are present lime (CaO), soda (Na_2O) and potassium (K_2O) can also be important impurities. Rare heavy minerals can be deleterious even when present in only very low levels.

Iron is a strong colorant and must be carefully controlled. Alumina affects the viscosity and density of glass. Alkalis affect melting temperatures, certain refractory heavy minerals (usually silicates or oxides) in parts per million levels are counted as number of grains. Even one or two grains of chromite in 500 grams of material can eliminate a sand from glass use. Thus raw materials are usually processed by methods noted below to remove minerals that contain contaminants.

The most common and easiest processing technique is simple washing. Water is added to the sand then the slurry is pumped to a cyclone separator. Movement of the slurry and grain-to-grain rubbing is enough to loosen clays and fine contaminants. Scrubbing with specialized equipment can be used if clays or films are tightly bound to quartz grains. A process called desliming removes <100 micron materials. Such small minerals are generally clays. Cyclone separators are used if clays are low (<3%) and hydrosizers using kindred settling techniques are efficient if clay contents are >74%. Heavy minerals and iron oxides can be removed by gravity separation using spiral separators in which lighter particles are pushed to the outside of spiral pans. Flotation techniques can also remove undesirable minerals including micas. Strong rare-Earth magnets or electromagnetic cells remove certain slightly magnetic minerals and certain minerals can be separated based on their electrical charges by turboelectric methods.

Particle size is very critical for glass making. Sizing of larger grains is done by screening to remove oversize >1 mm grains assuming that most grains are about 0.5 microns. Screening is very efficient; one screen can separate 250 tons per hour. Screens are generally stacked for efficiency. Some applications require very fine sizes of quartz, thus grinding methods are used to produce ground silica. Grinding is accomplished in large mills that use flint or alumina ceramics as liners and grinding media. Strict size control is achieved using special air classifiers. All glass sand is dried prior to shipping. Drying can be the most expensive stage of sand processing. Simple beneficiation can enlarge already huge and growing sand resources.

Sand as a Renewable Resource

Quartz sands, at least those in unconsolidated deposits, can be considered a renewable, even rapidly renewable resource in certain cases (*Federal Register*, 1995, p. 50724). Most people do not consider minerals as renewable but there are special cases in which certain resources do reform after mining. In the Great Salt Lake and other southwestern saline lakes, evaporate minerals such as halite continuously grow from evaporation of water. Early American colonists extracted iron from concentrations of iron minerals known as bog iron that formed in swampy areas. These bog ores could be re-harvested every few years. Settlers in the Midwest often extracted nitrate minerals such as saltpeter from cave deposits that grew anew after mining. Even earlier Native Americans harvested sulfate minerals such as epsomite and even aragonite from cave deposits that reformed quite rapidly. Renewal of quartz sand deposits depends on chemical and physical processes that free quartz by weathering.

Geologists measure the combined effects of weathering as denudation rates reported as average thickness of rocks removed in millimeters per year. Values range from less than 1 mm to more than 20 mm per year and are highly variable depending on climate, rock type, topography, and land use. Because of the large areas involved immense amounts of material are continually being removed from the parent rock. Once liberated as fragments or individual mineral grains, weathered materials become sediments that are transported by rivers, glaciers, even the air.

Sediment transport or sediment discharge rates measure amounts of sediment moved in a given time and are measured by weight or volume of sediment that passes a section of stream or discharges into the ocean. Hay reviewed sediment transport and concluded that rivers supply about 20 x 10 9 metric tons of detrital sediments to the oceans each year or about 0.226 kg/m 2/year (Hay, 1988).

Glacial transport contributes about 0.8 x 10 9 metric tons as 0.05 kg/m 2/year and wind transports 0.9 x 10 9 total tons or 0.45 kg/m 2/year. Summary tables in Patrick show that annual sediment discharge from major rivers in the United States alone exceeds 603 million tons or about 245 tons per square mile (Patrick, 1995). Worldwide values exceed 8 billion total tons or 520 tons/square mile. Other estimates (i.e. Hay) are much higher but all studies indicate that sediment is generated and transported in billion plus ton amounts each year. Some of this sediment is separated by geologic processes to minable glass sand deposits.

Hundreds of millions of tons of sediments including sand size materials move from high areas to the sea each year as seen in Table 6. The Mississippi River alone carries between 280 and 300+ million tons of sediment each year (Ritter, 1986). Holeman estimates 5 x 10 9 tons of sediment are generated per year (Holeman, 1981). Local transport depends on climate, rock types, relief, and land uses. Drainage areas with fast weathering, high topographic relief, weak rocks, and little vegetation cover produce the most sediments. Regions that have undergone glaciation are also prolific producers. Even a small, low-gradient stream can transport hundreds of tons of sand in a single flood (Figure 18).

Sediment transport can even renew mined areas in streams as noted by the California Assessors' Handbook:

"Some commercial aggregate deposits are located in or close to existing stream channels. As a result, there are no stable physical reserves. The movement of water may bring in or remove material with changing seasonal water levels. Keeping track of the reserves in such a situation is difficult not only for the operator, but for the appraiser as well. Instead, most operators of such properties know from experience that the reserves will ultimately be replenished, although there have certainly been cases of long years of drought where that has not been the case. Accordingly, it is the Board's position that such properties receive a base year value, in conformance with procedures established for other mining properties with the following exceptions:

No allowance shall be made for depletion
No new reserves shall be added unless the property is expanded in size or some other mining method is utilized.

Obviously, if new material is typically brought into the site naturally, the typical depletion does not occur. Therefore, no allowance for depletion should be made."

(California State Board of Equalization 1997, chapter 6, pp.14-15)

Miners have known that certain riverine sand deposits replenish themselves by trapping some of the moving sediments in mined pits. Langer noted that aggregates can be skimmed off sand bars when subsequent high river flows can replenish deposits (Langer, 2003, p. 14). Mining in river systems can cause adjustments in channels but careful mining can actually stabilize channels if extraction does not exceed sediment influx (Sandecki, 1989). Removal of gravel from the Fraser River was thought to have lessened aggradation and so reduced flood potential (Church, 1999). Many other reports of sand replenishment in rivers are known, and the unceasing action of running water carrying sediments assures abundant sand deposits.

Activities by humans affect sediment transport. Construction of dams decrease sediment delivery (Kondolf, 1997), but other activities such as logging and farming increase sediment transport (Wilkinson, 2005).

Numerous estimates of sediment discharge to the oceans have been made. Many of these were summarized by Holeman (1968) and updated by Millimann and Meade (1983), Ritter (1986), and Meade, Yuzyk, & Day (1990). Worldwide sediment discharge rates range from 13.5 to 18.3 billion tons per year. North America alone contributes from 1.5 to 1.8 billion tons each year (Table 7). While much of the sediment is fine-grained mud or silt a substantial amount is made up of sand size materials. There is even more sediment produced by weathering that is sorted and stored in rivers or lakes along the way. Probably 5 to 10 times the ocean discharge tonnages are in river storage. As much as 90 percent of eroded sediments exist in storage along rivers or lakes. Sediments delivered each year to the Great Lakes alone are ten times the total annual industrial sand production (Meade et al., 1990). Clearly much more raw sand is generated annually than is used by man.

Publications of the USGS, which monitors mineral production and resources, clearly state that quartz sands are in plentiful supply in the United States and elsewhere. There will be resources for many years even without renewal, but renewal will certainly continue. Sandstone, quartzite, tripoli, chert, and other consolidated sources of quartz are deemed by the USGS to be adequate for many years. Even though deposits do not occur everywhere and some deposits are not available for political or economic reasons, quartz sand supplies should be readily available for centuries.

As we have seen quartz mineral grains formed along with other minerals in igneous rocks are liberated by weathering processes. During transportation toward the sea quartz is reduced in size and separated from other minerals into various deposits by geologic agents of gravity, water movement, air currents, longshore drift, or waves. In rivers, beaches, offshore islands, shoals, or sand dunes, sand can be replenished via sediment transport after or even during mining. Huge volumes of sand and other sediments are in motion all the time. Previous discussions provide some idea of the amounts. The 28+ million metric tons of silica sand mined each year could easily be replaced many times over by normal geologic processes.

Current Consumption

Americans consume huge amounts of natural resources. Per capita consumption of nonfuel minerals exceeds several tons each year. The most used commodity is sand and gravel at 9,000+ pounds per person (Figure 1). Sand is produced in every state and some states have hundreds of individual mines. Most sand is used with limited processing for construction projects as fill material, fine aggregate in concrete, or as a component of asphalt. Such sands are bulk materials with relatively low costs.

A special category of high purity sands known as high quartz sand, silica sand, industrial sand, or glass sand is essential for making glass and a large number of high value products. The silica sands command much higher prices but must meet demanding specifications. They are produced in much smaller quantities and from more limited areas. U.S. apparent consumption of industrial sand and gravel in 2004 was 26.9 million metric tons which was an increase of 6% over 2003 (Dolley, 2004b). Apparent consumption is defined by the U.S. Geological Survey as production plus imports minus exports. Industrial sands have a myriad of uses as seen above.

Many examples exist of sand deposits that become renewed by moving sands. The reserve of sand is not static, but it is very large and grows due to weathering and processing improvements. The U.S. Geological Survey states that:

"Development of more efficient mining and processing methods is expected to continue. This will encourage the mining of lower grade silica sand deposits that are located closer to markets but are not presently mined. Such developments are expected to increase silica sand reserves ." (Dolley, 2002).

The USGS estimates that known deposits of silica sand can satisfy expected demand for centuries (Davis & Tepordei, 1985). In essence silica sand resources are "virtually inexhaustible." So we should have adequate sands for all time.

Summary and Conclusions

Quartz is one of the most abundant minerals and is made of the most common chemical elements on earth.

Geologic processes continuously form, liberate, transport, sort, clean, and concentrate huge tonnages of quartz.

Quartz sands are raw materials for a large number of vital building, chemical, glass, or industrial materials.

Millions of tons of quartz sand are mined each year.

Quartz sands are very abundant and widespread. Known deposits could last for hundreds of years.

New deposits of sand are generated in the hundreds of millions of tons each year by normal, ongoing geologic processes.

Low grade deposits can be upgraded by well known beneficiation processes.

The time of sands is with us and will be for any foreseeable future.

The Earth undergoes constant changes. Certain igneous processes form the abundant mineral quartz which is very stable both chemically and physically. Weathering and transport liberates quartz and other minerals from preexisting rocks, reduces the sizes of grains, modifies grain shape, sorts grains by size, and reduces contaminating materials to form economic deposits of pure quartz sands known as industrial sands. Quartz in various forms is used in large quantities (millions of tons) for construction, glass, fiberglass, and in lesser amounts for numerous products or processes.

The United States used about 28 million metric tons of industrial sand in 2004, (1,736 thousand metric tons is fiberglass alone), and worldwide consumption exceeded 115 million metric tons. Enormous amounts of quartz sand are generated so the resource is renewed. Some deposits renew themselves annually or almost annually due to floods, storms, or other acts of nature that move large volumes of sand. Others may require many years. The good news is that abundant resources of industrial sand exist in the U.S. and worldwide, enough to satisfy human needs for hundreds of years. In addition to great existing resources new or renewed deposits of sand are being produced continuously.

Silica sand is one of man’s oldest, most important, and most abundant raw materials. It has served us well and shows no signs of running out. Indeed some geologic situations replenish sand deposits making it one of the few renewable or even rapidly renewable geologic resources. The time of sands, as the early geologist James Hutton might say, shows no vestige of a beginning, nor any prospect of an end.

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Glossary of Terms

glass sand – A sand that is suitable for glassmaking because of its high silica content (93-99+ %) and its low content of iron oxide, chromium, cobalt, and other colorants (Jackson, 1997, p. 272).

industrial mineral – Any rock, mineral, or other naturally occurring substance of economic value, exclusive of metallic ores, mineral fuels, and gemstones; one of the nonmetallics (Jackson, 1997, p. 324).

quartz – (a) Crystalline silica, an important rock-forming mineral: SiO 2. It is, next to feldspar, the commonest mineral, occurring either in transparent hexagonal crystals (colorless, or colored by impurities) or in crystalline or cryptocrystalline masses. Quartz is the commonest gangue mineral of ore deposits, forms the major proportion of most sands, and has a widespread distribution in igneous (esp. granitic), metamorphic, and sedimentary rocks. It has a vitreous to greasy luster, a conchoidal fracture, an absence of cleavage, and a hardness of 7 on the Mohs scale (scratches glass easily, but cannot be scratched by a knife); it is composed exclusively of silicon-oxygen tetrahedra with all oxygens joined together in a three-dimensional network. It is polymorphous with cristobalite, tridymite, stishovite, coesite and keatite. Symbol: Q. Abbrev: qtz; qz. Etymol: German provincial *Quarz.* Cf: *tridymite; cristobalite; coesite; stishovite*. (b) a general term for a variety of noncrystalline or cryptocrystalline minerals having the same chemical composition as that of quartz, such as chalcedony, agate, and opal (Jackson, 1997, p. 525).

quartzite – A very hard but unmetamorphosed sandstone, consisting chiefly of quartz grains that have been so completely and solidly cemented with secondary silica that the rock breaks across or through the grains rather than around them; an *orthoquartzite*. The cement may grow in optical and crystallographic continuity around each quartz grain, thereby tightly interlocking the grains as the original pore spaces are filled (Jackson, 1997, p. 525).

sand – (a) A detrital rock fragment or mineral particle smaller than a granule and larger than a coarse silt grain, having a diameter in the range of 1/16 to 2 mm (62-2000 micrometers, or 0.0025-0.08 in., or a size between that in the lower limit of visibility of an individual particle with the unaided eye and that of the head of a small wooden match). In Great Britain, the range of 0.1-1 mm has been used. (b) A loose aggregate of unlithified mineral or rock particles of sand size; an unconsolidated or moderately consolidated sedimentary deposit consisting essentially of medium-grained clastics; The material is most commonly composed of quartz resulting from rock disintegration, and when the term “sand” is used without qualification, a siliceous composition is implied; but the particles may be of any mineral composition or mixture of rock or mineral fragments, such as "coral sand" consisting of limestone fragments. Also, a mass of such material, esp. on a beach or a desert or in a stream bed. (c) *sandstone* (Jackson, 1997, p. 565).

sandstone – (a) A medium-grained clastic sedimentary rock composed of abundant rounded or angular fragments of sand size with or without a fine-grained matrix (silt or clay) and more or less firmly united by a cementing material (commonly silica, iron oxide, or calcium carbonate); the consolidated equivalent of sand, intermediate in texture between conglomerate and shale. The sand particles are predominantly quartz, and the term "sandstone", when used without qualification, indicates a rock containing about 85-90% quartz (Kynine, 1940). The rock varies in color, may be deposited by water or wind, and may contain numerous primary features (sedimentary structures and fossils). Sandstone may be classified according to composition of particles, mineralogic or textural maturity, primary structures, and type of cement. (b) A field term for any clastic rock containing individual particles that are visible to the unaided eye or slightly larger (Jackson, 1997, p. 566).

silica sand – An industrial term for a sand or an easily disaggregated sandstone that has a very high percentage of silica (quartz). It is a source of silicon and a raw material of glass and other industrial products (Jackson, 1997, p. 593).

weathering – 1) Destructive processes by which rocky materials on exposure to atmospheric agents at or near the Earth's surface are changed in color, texture, composition, or form. 2) Physical disintegration and chemical decomposition of rock (Jackson, 1997, p. 711).

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Figure 1.Annual per person use of industrial minerals in the U.S.

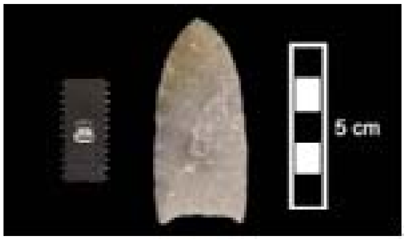


Figure 2. Silicon as chert made arrowheads and other early tools. It is critical to today's microchips.

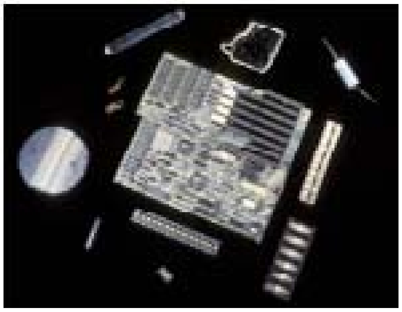


Figure 3. Modern computers contain many forms of silicon derived from manmade quartz. Upper left is a man-made crystal.

Figure 4. Colored grains of sand are used to make fantastic but ephemeral mandalas in Buddhist and other cultures.

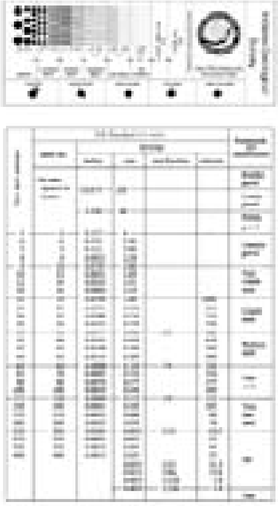
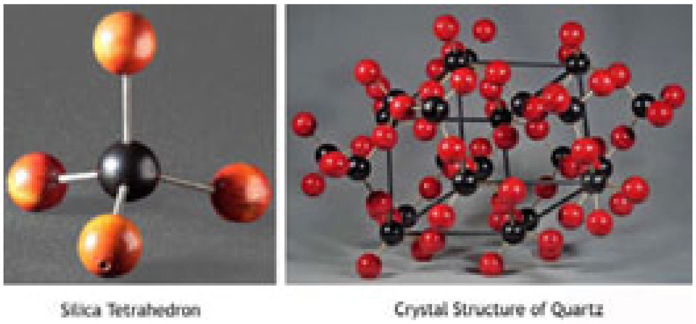


Figure 5. Sieves define sand sizes. Shapes of grains are also important.

Figure 6. Rocks are formed from minerals.They undergo constant recycling through the rock cycle.

Figure 7.Well formed natural crystals of the mineral quartz (SiO2).


Silica Tetrahedron

Crystal Structure of Quartz

Figure 8. Quartz basic structure begins with a silica tetrahedron where one silicon atom (black) is surrounded by oxygen atoms (red). A) Tetrahedra are arranged to form the very stable atomic arrangement shown in B) where the black bars outline the unit cell.

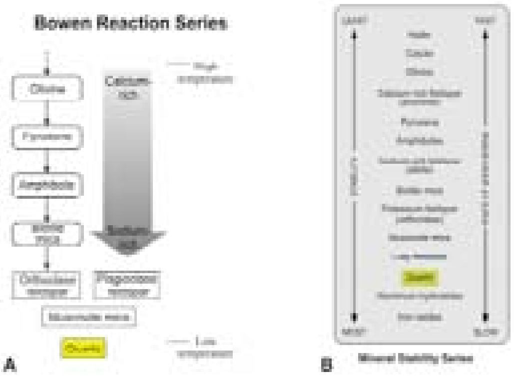


Figure 9. Bowen Reaction Series of mineral formation from magmas.

Figure 10. Fine-grained quartz sand.These are approximately 0.25 mm.

Figure 11. Coarse-grained quartz sand.These are approximately 1 mm.

Figure 12. Immature sediment with angular fragments, mixture of sizes, various minerals, even mineral fragments.

Figure 13. Pure, well rounded and sorted quartz grains are especially valued.

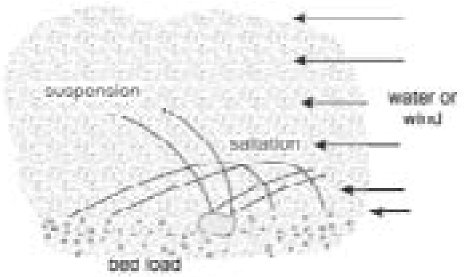


Figure 14a Sediments move as bed load by sliding, jumping by saltation, or are continuously suspended.

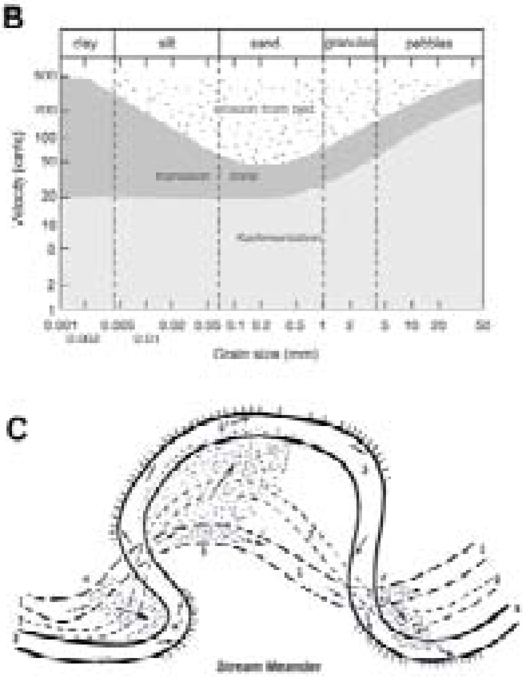


Figure 14b Velocity of fluids is an important factor in moving grains.Velocity can also affect river bottoms and cause erosion.

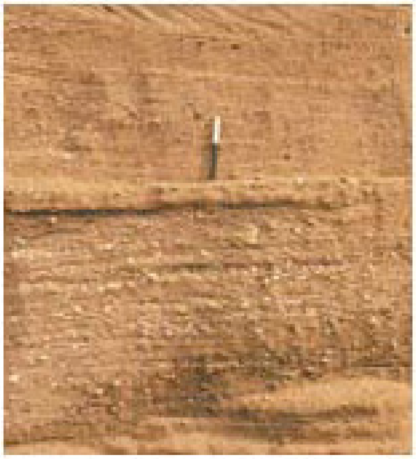


Figure 15.Well sorted, bedded sand with minor gravel reflect good sorting by water movement

Figure 16. Industrial sand and gravel production (A) and value (B) has been stable to slightly growing for many years in the United States.

Figure 17. Even small amounts of impurities such as magnetite, ilmenite, hematite, or many others drastically affect final products and so must be removed during processing.

Figure 18.Many tons of sand were deposited in this forest during one flood event on a small low gradient stream in the Midwest.

Table 1. Abundance of chemical elements in Earth's crust.

Element	**Percent of Earth's Crust (by weight)**
Oxygen (O)	46.60
Silicon (Si)	27.72
Aluminum (Al)	8.13
Iron (Fe)	5.00
Calcium (Ca)	3.63
Sodium (Na)	2.83
Potassium (K)	2.70
Magnesium (Mg)	2.09
TOTAL	98.70

Table 2. Specifications for the chemical composition of glass sand, from Carr (1971).

Quality	**SiO_2 Minimum (percent)**	**Al_2O_3 Maximum (percent)**	**Fe_2O_3 Maximum (percent)**	**CaO + MgO Maximum (percent)**
First quality, optical glass	99.8	0.1	0.020	0.1
Second quality, flint glass containers and tableware	98.5	0.5	0.035	0.2
Third quality, flint glass	95.0	4.0	0.035	0.5
Fourth quality, sheet glass, rolled and polished plate	98.5	0.5	0.060	0.5
Fifth quality, sheet glass, rolled and polished plate	95.0	4.0	0.060	0.5
Sixth quality green glass containers and window glass	98.0	0.5	0.300	0.5
	95.0	4.0	0.300	0.5
Seventh quality, green glass	98.0	0.5	1.000	0.5
Eighth quality, amber glass containers	95.0	4.0	1.000	0.5
Ninth quality, amber				

Table 3. Longshore sediment transport rates at various coastal sites, from Johnson (1956)

Location	Transport Rate (m^3/yr)	Predominant Direction	Years of Record
U.S. Atlantic Coast			
Suffolk Co., NY	255,000	W	1946 – 1955
Sandy Hook, N.J	377,000	N	1885 – 1933
Sandy Hook, N.J.	334,000	N	1933 – 1951
Asbury Park, N.J.	153,000	N	1922 – 1925
Shark River, N.J.	255,000	N	1947 – 1953
Manasquan, N.J.	275,000	N	1930 – 1931
Barnegat Inlet, N.J.	191,000	S	1939 – 1941
Absecon Inlet, N.J.	306,000	S	1935 – 1946
Ocean City, N.J.	306,000	S	1935 – 1946
Cold Springs Inlet, N.J.	153,000	S	--
Ocean City, Md.	115,000	S	1934 – 1936
Atlantic Beach, N.J.	22,600	E	1850 – 1908
Hillsboro Inlet, Fla.	57,000	S	--
Palm Beach, Fla.	115,000-172,000	S	1925 – 1930
Gulf of Mexico			
Pinellas Co., Fla	38,000	S	1922 – 1950
Perdido Pass, Ala.	153,000	W	1934 – 1953
Galveston, Texas	334,700	E	1919 – 1934
U.S. Pacific Coast			
Santa Barbara, Calif	214,000	E	1932 – 1951
Oxnard Plain Shore, Calif.	756,000	S	1938 – 1948
Port Hueneme, Calif.	382,000	S	1938 – 1948
Santa Monica, Calif.	207,000	S	1936 – 1940
El Segundo, Calif.	124,000	S	1936 – 1940
Redondo Beach, Calif.	23,000	S	--
Anaheim Bay, Calif.	115,000	E	1937 – 1948
Camp Pendleton, Calif.	76,000	S	1950 – 1952
Great Lakes			
Milwaukee Co., Wis.	6,000	S	1894 – 1912
Racine Co., Wis.	31,000	S	1912 – 1949
Kenosha, Wis.	11,000	S	1872 – 1909
Ill. State line to Waukegan	69,000	S	--
Waukegan to Evanston, Ill.	44,000	S	--
South of Evanston, Ill.	31,000	S	--
Outside of the U.S.			
Monrovia, Liberia	383,000	N	1946 – 1954
Port Said, Egypt	696,000	E	--
Port Elizabeth, South Africa	459,000	N	--
Durban, South Africa	293,000	N	1897 – 1904
Madra, India	566,000	N	1886 – 1949
Mucuripe, Brazil	327,000	N	1946 - 1950

Table 4. Physical and chemical specifications of special-purpose sands, from Carr (1971)

Sand Uses	**Physical Properties**			**Chemical Properties**			
	Size Range of Particles (U.S. Standard)	**Roundness of Particles**	**Desirable Degree of Sorting**	**Percentage Range SiO_2**	**Percentage Range Al_2O_3**	**Percentage Range Fe_2O_3**	**Others**
Abrasives:							
Blasting	4 to 100	Round or angular	Well sorted	High	Low	Low	Low in debris
Scouring powder	Silica flour; 99 percent less than 200 sieve	Angular or subangular	Well sorted	High	Very low	Very low	Very low; whiteness important
Stone sawing	30 to 100	Round or angular	Well sorted	High	Low	Low	Low in soft particles and materials that stain
Glass and chemical:							
Glass	30 to 140	Round to angular	Moderately well sorted	Very high	Low	<1	<0.5 percent
Porcelain	30 to 140	Round to angular	Moderately well sorted	Very high	Low	<1	Low
Silicon carbide	20 to 100	Round to angular	Moderately well sorted	>99.0	Low	Low	Low
Sodium silicate	20 to 100	Round to angular	Moderately well sorted	>99.3	<0.25	<0.35	Low
Metallurgical:							
Metallurgical pebble	3/8 in. to 8 in.	Round to angular	Moderately well sorted	Very high	<0.4	<0.2	Base oxides, <0.3 percent; phosphorus and arsenic not permitted
Refractory:							
Core	30 to 140	Round to angular	Moderately well sorted	High	Low	Low	Low in debris
Furnace bottom	3 to 200	Round to angular	Moderately sorted	High	Some desirable	--	--
Ganister mix	50 to 200	Round to angular	Moderately sorted	High	Some desirable	--	--
Molding	70 to clay	Round to angular	Moderately sorted	Variable	Variable	--	--
Refractory pebble	40 to 2 in.	Round to angular	Moderately sorted	High	<0.4	<0.4	Opaline silica, <0.5 percent; CaO, <1.0 percent; alkalies, <0.5 percent; TiO_2, very low
Miscellaneous:							
Engine	16 to 100	Angular to subangular	Well sorted	High	Low	Low	Low in debris
Filtering							
Water filtering	3/32 to 3½ in.	Round to subround	Well sorted	High	Low	Low	--
Sewage trickling	1 in. to 3 in.	Round to subround	Well sorted	High	Low	Low	--
Sludge filtering	4 to 50	Round to subround	Well sorted	High	Low	Low	--
Hydraulic fracturing	4 to 70	Round	Well sorted	>98	Low	Low	Clay, silt, and soft-particle content <0.5 percent

Table 5. Industrial sand and gravel sold or used by U.S. producers in 2004, by major end use,[1] Modified from Dolley (2004b).

Major Use	Quantity (thousand metric tons)	Value (thousands)	U.S. Total[2] Value (dollars per ton)
Sand:			
Glassmaking:			
Containers	4,560	$77,900	$17.08
Flat, plate and window	3,410	57,400	16.84
Specialty	817	19,600	23.95
Fiberglass, unground	1,040	17,300	16.64
Fiberglass, ground	696	28,300	40.62
Foundry:			
Molding and core, unground	5,360	83,600	15.61
Molding and core, ground	(4)	(4)	77.61
Refractory	186	4,070	21.84
Metallurgical:			
Silicon carbide	(4)	(4)	29.70
Flux for metal smelting	19	134	7.10
Abrasives:			
Blasting	784	27,400	34.91
Scouring cleaners, ground	(4)	(4)	46.78
Sawing and sanding	(4)	(4)	37.32
Chemicals, ground and unground	771	17,100	22.17
Fillers, ground, rubber, paints, putty, etc.	462	31,100	67.28
Whole grain fillers/building products	2,460	70,900	28.89
Ceramic, ground, pottery, brick, tile, etc.	192	10,600	55.16
Filtration:			
Water, municipal, county, local	410	17,500	42.73
Swimming pool, other	64	4,310	66.96
Petroleum industry:			
Hydraulic fracturing	3,280	135,000	41.26
Well packing and cementing	165	7,890	47.72
Recreational:			
Golf course, greens and traps	887	16,900	19.07
Baseball, volleyball, play sand, beaches	240	5,770	24.08
Traction, engine	137	2,680	19.60
Roofing granules and fillers	266	6,230	23.41
Other, ground silica	XX	XX	XX
Other, whole grain	XX	XX	XX
Total or average	28,700	668,000	23.31
Gravel:			
Silicon, ferrosilicon	570	9,840	17.27
Filtration	55	2,320	42.22
Nonmetallurgical flux	W	W	9.20
Other uses, specified	447	4,410	9.87
Total or average	1,070	16,600	15.47
Grand total or average	29,700	685,000	23.03

W Withheld to avoid disclosing company proprietary data; for sand, included with “Other, ground silica” or “Other, whole grain;” for gravel, included with “Other uses, specified.”

XX Not applicable

-- Zero

[1] Data are rounded to no more than three significant digits, except for values per metric ton; may not add to totals shown.

[2] Calculated by using unrounded data.

Table 6. Suspended-load denudation in basins of different size in the United States. Modified from Ritter (1986).

Basin	**Location**	**Area (mi^2)**	**Average Annual Suspended Load (tons x 10^3)**
Mississippi	Louisiana	1,243,500	305,000
Colorado	Arizona	137,800	149,000
Columbia	Washington	102,600	10,300
Rio Grande	New Mexico	26,770	9,420
Sacramento	California	27,500	2,580
Alabama	Alabama	22,000	2,130
Delaware	New Jersey	6,780	998
Yadkin	North Carolina	2,280	808
Eel	California	3,113	18,200
Rio Hondo	New Mexico	947	545
Green	Washington	230	71
Alameda	California	633	221
Scantic	Connecticut	98	7
Napa	California	81	63