U. S. DEPARTMENT OF THE INTERIOR

U. S. GEOLOGICAL SURVEY

REMOTE SENSING AND AIRBORNE GEOPHYSICS IN THE ASSESSMENT OF NATURAL AGGREGATE RESOURCES

by

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ABSTRACT

Natural aggregate made from crushed stone and deposits of sand and gravel is a vital element of the construction industry in the United States. Although natural aggregate is a high volume/low value commodity that is relatively abundant, new sources of aggregate are becoming increasingly difficult to find and develop because of rigid industry specifications, political considerations, development and transporation costs, and environmental concerns, especially in urban growth centers where much of the aggregate is used. As the demand for natural aggregate increases in response to urban growth and the repair and expansion of the national infrastructure, new sources of natural aggregate will be required. The USGS has recognized the necessity of developing the capability to assess the potential for natural aggregate sources on Federal lands; at present, no methodology exists for systematically describing and evaluating potential sources of natural aggregate. Because remote sensing and airborne geophysics can detect surface and near-surface phenomena, these tools may useful for detecting and mapping potential sources of natural aggregate; however, before a methodology for applying these tools can be developed, it is necessary to understand the type, distribution, physical properties, and characteristics of natural aggregate deposits, as well as the problems that will be encountered in assessing their potential value.

There are two primary sources of natural aggregate: (1) exposed or near-surface igneous, metamorphic, and sedimentary bedrock that can be crushed, and (2) deposits of sand and gravel that may be used directly or crushed and sized to meet specifications. In any particular area, the availability of bedrock suitable for crushing is a function of the geologic history of the area - the processes that formed, deformed, eroded and exposed the bedrock. Deposits of sand and gravel are primarily surficial deposits formed by the erosion, transportation by water and ice, and deposition of bedrock fragments. Consequently, most sand and gravel deposits are Tertiary or Quaternary in age and are most common in glaciated areas, alluvial basins, and along rivers and streams.

The distribution of potential sources of natural aggregate in the United States is closely tied to physiography and the type of bedrock that occurs in an area. Using these criteria, the United States can be divided into 12 regions: western mountain ranges, alluvial basins, Columbia Plateau, Colorado Plateau and Wyoming basin, High Plains, nonglaciated central region, glaciated central region, Piedmont Blue Ridge region, glaciated northeastern and Superior uplands, Atlantic and Gulf coastal plain, Hawaiian Islands, and Alaska. Each region has similar types of natural aggregate sources within its boundary, although there may be wide variations in specific physical and chemical characteristics of the aggregates within a region.

Conventional exploration for natural aggregate deposits has been largely a ground-based operation (field mapping, sampling, trenching and augering, resistivity), although aerial photos and topographic maps have been extensively used to target possible deposits for sampling and testing. Today, the exploration process also considers other factors such as the availability of the land, space and water supply for processing purposes, political and environmental factors, and

distance from the market; exploration and planning cannot be separated.

There are many physical properties and characteristics by which aggregate material is judged to be acceptable or unacceptable for specific applications; most of these properties and characteristics pertain only to individual aggregate particles and not to the bulk deposit. For example, properties of crushed stone aggregate particles such as thermal volume change, solubility, oxidation and hydration reactivity, and particle strength, among many others, are important considerations for the aggregate used for concrete highway paving. Standards and testing methods for properties and characteristics important to aggregate quality are available from the American Society for Testing and Materials (ASTM) and the American Association of State Highway and Transportation Officials (AASHTO).

The application of remote sensing and airborne geophysics to the detection and mapping of potential aggregate sources, however, is based on a limited number of intrinsic bulk physical properties and extrinsic characteristics of the deposits that can be directly measured, derived from measurements, or interpreted with remote sensing and geophysical data. The important physical properties include electrical resistivity, spectral reflectance, thermal emissivity, thermal inertia, radioactivity, porosity, and permeability. Characteristics that are often associated with potential aggregate deposits include landform, drainage pattern and density, vegetation, texture (surface roughness), land use, and geologic setting.

Remote sensing and airborne geophysical methods have been used to detect and map exposed bedrock units and surficial deposits and, consequently, should be applicable to studying the location and distribution of potential natural aggregate deposits. Geophysical techniques, such as gamma-ray spectrometry and aeromagnetics, have been used to map the distribution of bedrock units and should also be useful for tracing some bedrock units that can be used for crushed stone. Airborne resistivity surveys have been used to map surficial deposits based on variations in resistivity controlled by porosity, permeability, and the contained fluids. Applications of remote sensing measurements made from aircraft and satellites in the visible, near-infrared, thermal infrared, and microwave (radar) portions of the electromagnetic spectrum to the detection and mapping of bedrock geology and surficial deposits are well documented in the literature. The information derived from these measurements includes both compositional information based on physical properties (spectral reflectance, thermal emissivity, etc.) and spatial information describing the surface characteristics (landforms, drainage network, etc.). Remote sensing systems collect digital measurements that can be processed, analyzed, and interpreted using computer techniques, and easily incorporated into Geographic Information System databases.

The manner in which airborne geophysics and remote sensing are applied to the assessment of potential natural aggregate resources will depend on the assessment process. At present there is no systematic methodology for assessing natural aggregate resources, and several factors will make the easy integration of natural aggregate into the USGS three-part assessment procedure highly unlikely. For example, the concept of aggregate deposit grade is nearly meaningless because there is no single commodity upon which to base the value of a deposit or to compare different deposits. Furthermore, there is no uniform price structure for aggregate materials; cost of aggregate is highly variable regionally and locally and is dependent on a variety of factors including local availability, distance from the market (which can change), processing costs controlled by regional and local specifications, and reclamation costs.

Extensive research and careful thought will be required to develop an effective and systematic procedure for assessing potential natural aggregate resources. Identifying those properties and characteristics of natural aggregate deposits that are essential to the assessment process should be given immediate attention. Airborne geophysics and remote sensing techniques can provide information pertinent to the recognition and characterization of natural aggregate deposits and should, therefore, be a useful source of information in the assessment process.

I. INTRODUCTION

Natural aggregate derived from crushable stone and deposits of sand and gravel is a vital element in public works projects, residential, commercial, and industrial construction, as well as many other industries in the United States, and accounts for nearly half of the nonfuel mining volume in the country. In 1990, the gross value of aggregate production in the United States was nearly twice the value of the precious metals produced (Langer and Glanzman, 1993). Because aggregate is produced and used in every State, the health and vitality of the aggregate industry is important to both local and national economies.

The USGS has recognized the need to be able to assess for potential natural aggegate deposits on Federal lands and to provide planners and managers with the resource information necessary for making wise land-use decisions. The development of a systematic and objective methodology for assessing natural aggregate resource potential is in its infancy, but it is already clear that a wide variety of data can contribute to the assessment process.

Regional to local remote sensing and airborne geophysical data provide a variety of information about the near-surface environment in which potential sources of natural aggregate occur. This report surveys the capabilities of remote sensing and airborne geophysical methods in terms of the properties and characteristics of sand and gravel deposits and sources of crushed stone and describes data and analysis techniques that have been used to study surficial deposits. To provide a context for the survey, the different types of aggregate deposits and their distribution in the United States are discussed, as well as the conventional methods that have been used to explore for sources of natural aggregate. No attempt has been made to provide a complete description of natural aggregate or the aggregate industry, and the reader is encouraged to consult more definitive treatments, such as *The Aggregate Handbook* (Barksdale, 1991) and *Concrete Manual* (U.S. Department of Interior, 1981), for a more complete perspective; *Natural Aggregate - Building America's Future* (Langer and Glanzman (1993) provides an excellent overview of natural aggregate and the aggregate industry.

The purpose of this report is to discuss those aspects of natural aggregate deposits that are most amenable to remote sensing and airborne geophysical exploration techniques so that research can be focused on the development of data analysis and interpretation techniques providing the most useful information to the resource assessment process. The possible extension of natural aggregate to the USGS three-part mineral resource assessment procedure (Singer, 1993) is also examined.

II. TYPES OF AGGREGATE DEPOSITS

There are two principal types of aggregate sources: (1) crushed stone and (2) sand and gravel. In 1991, a total of 1.1 billion short tons of crushed stone (58 % of total aggregate production) were produced in the United States (Tepordei, 1993b), while 780 million short tons of sand and gravel (42 % of total aggregate production) were produced (Tepordei, 1993a). The relative proportions of crushed stone and sand and gravel (fig. II-1) produced in various geographic regions of the United States largely reflects the occurrence and accessibility of sand and gravel deposits, which generally require less processing and are correspondingly cheaper to produce. The availability of sand and gravel (or absence of sand and gravel) is closely tied to the regional geologic history of each region.

Naturally-occurring aggregate deposits, whether sand and gravel or source rock for crushed stone, are formed by a variety of geologic processes. Volcanoes, earthquakes, glaciers, rivers and streams, and marine processes have each contributed to the formation of the materials we use as aggregate. Consequently, the key to locating suitable deposits and assessing the potential for new aggregate sources is understanding the geologic processes that form them and the geologic settings in which they occur.

Crushed Stone

Crushed stone is "The product resulting from the artificial crushing of rock, boulders, or large cobblestones, substantially all faces of which have resulted from the crushing operation" (Langer, 1988 as paraphrased from Americal Society for Testing and Materials, 1980). More crushed stone is produced in the United States than any other mineral, mainly for uses in the construction industry, and as noted by Tepordei (1993b, p. 1), "Despite the relative low value of its basic products, the crushed stone industry is a major contributor to and an indicator of the economic well-being of the Nation".

In addition to the size and shape of the particles, crushed stone is also classified according to the type of rock from which it was produced. Bedrock is broadly classified on the basis of its origin into three main groups: sedimentary, igneous, and metamorphic. Crushed stone is produced from each of the three rock groups as summarized below. More detailed discussions of the rock types are contained in Tepordei (1993b) and Dunn (1991).

It should be noted that, in reporting aggregate production, the aggregate industry does not strictly adhere to a common petrological classification to describe the source rocks for crushed stone. For example, a "limestone" may refer to a limestone, a dolomite, or a marble that does not take a polish. On the other hand, the term "marble" may refer to a true metamorphic marble or to a limestone or dolomite that takes a polish. Similarly, the coarse-grained, dark-colored mafic intrusive rock called gabbro may be identified as "traprock" or "black granite" by the aggregate industry; however, the term "traprock" is also used to describe any fine-grained, dark-colored extrusive igneous rock such as basalt and andesite. The informal nomenclature used by the aggregate industry will inhibit the application of

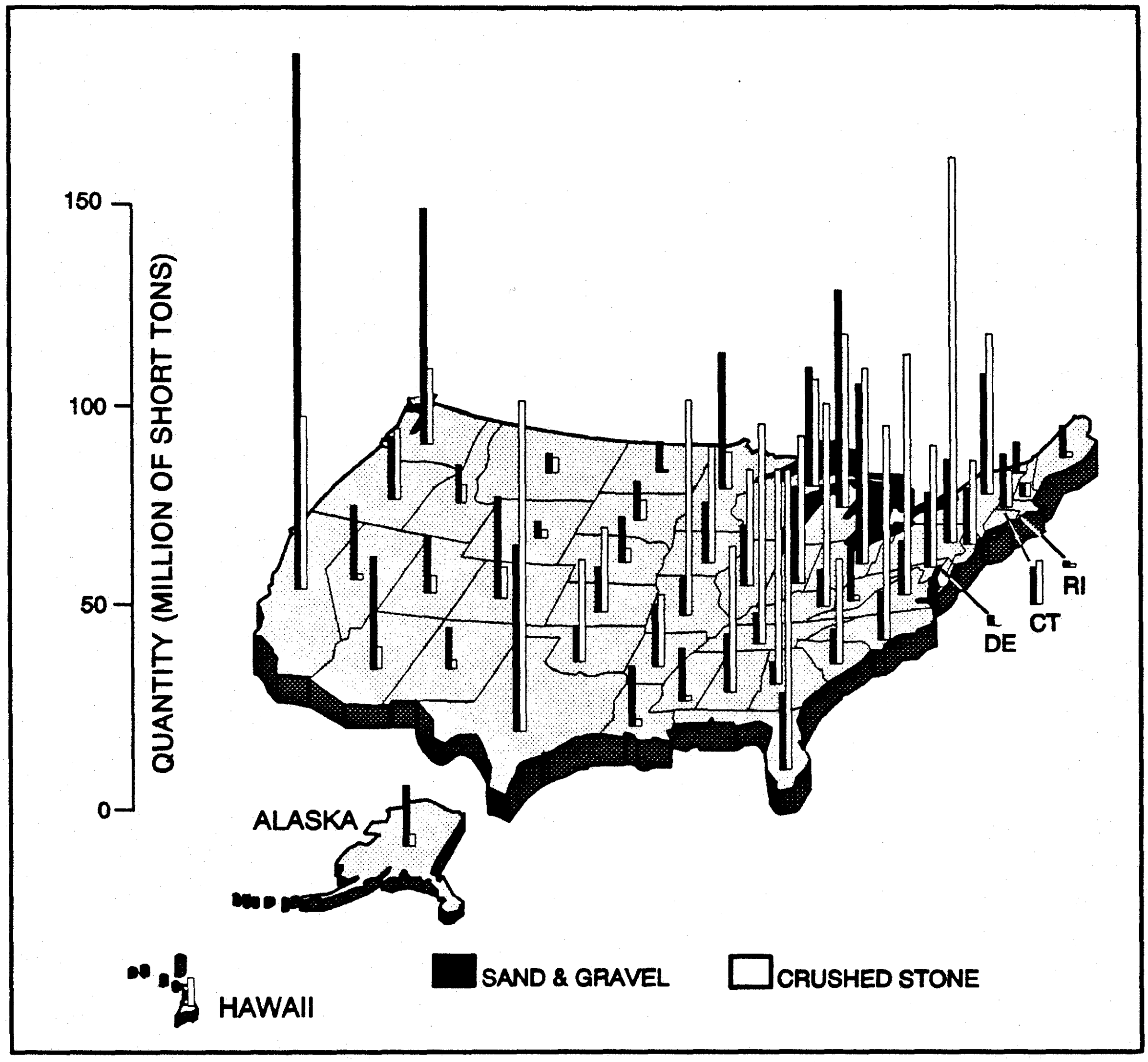

Figure II-1. Production of crushed stone and sand and gravel in the United States in 1991 (from Langer and Glanzman, 1993).

production data for deposit characterization and modeling studies.

Sedimentary Rocks

Sedimentary rocks result from the consolidation of loose sediment by chemical or biochemical or mechanical processes. The sediments may be derived from the weathering and transportation of older bedrock by water, wind, ice, and gravity (clastic) or they may result from the concentration of the carbonate or siliceous shells or skeletons of marine organisms. The sediments are cemented by carbonate, silica, or iron oxide minerals to produce an indurated rock. Less commonly, sedimentary rocks are formed directly from chemical precipitation.

Of the chemically or biochemically deposited sedimentary rocks, hard dense limestones and dolomites, composed of carbonates, generally make good sources of crushed stone and make up approximately 71 percent of crushed stone production (Tepordei, 1993b, Table 3). However, some limestone and dolomite may be soft, absorptive, and friable, which results in poor quality aggregate. Chert and flint are composed of silica that has been precipitated from water by organisms such as sponges, radiolarians, and diatoms. These rocks may be used as crushed stone; however, they may cause adverse chemical reactions with alkali when used as concrete aggregate.

Clastic (mechanically deposited) sedimentary rocks are classified according to the grain size of individual particles. Rocks that consist predominantly of pebbles and larger size fragments are called conglomerates; rocks that consist primarily of sand-sized particles are called sandstones, and rocks that consist primarily of silt- or clay-sized particles are called siltstones and shales, respectively. Of these rocks, sandstone, when hard and dense, is usually the only type that is considered for use as crushed stone and is a major source of aggregate in some areas. Even so, sandstone makes up less than 3 percent of the total U.S. production (Tepordei, 1993b, Table 3).

Igneous Rocks

Igneous rocks solidify from molten or partly molten silicate melt called magma generated in the earth's crust or upper mantle. As the magma cools, silicate minerals crystallize into an interlocking network. Consequently, igneous rocks commonly are hard, tough, and dense, and make an excellent source of crushed stone. Unlike a rigorous petrological classification of igneous rocks based on mineralogy, the aggregate industry identifies igneous rocks based primarily on grain-size and color. Unfortunately, the industry may apply a well-established petrologic rock type name to a broad range of rocks with differing mineralogies and origins. In addition, the same rock type may be classified differently by different producers.

Intrusive igneous rocks have solidified within the earth and are coarsely crystalline because the magma cooled slowly. Referred to under the general term 'granite' by the aggregate industry, these rocks include a range of generally light-colored specific rock types including granite and diorite (14 % of total crushed stone production) (Tepordei, 1993b. Table 3); the dark-colored, coarse-grained mafic rock called gabbro is sometimes also referred to as either 'black granite' or 'traprock'. In addition, coarse-grained metamorphic gneisses are also termed 'granite'.

Extrusive igneous rocks (volcanic rocks) are formed at or very near the earth's surface and are moderately to finely crystalline due to relatively rapid cooling of the magma; when cooling is extremely rapid, no crystals can form before the magma solidifies as a glass (obsidian). A broad compositional range of generally dark-colored common extrusive igneous rocks, including andesite and basalt (and sometimes rhyolite), are referred to under the general term 'traprock' by the aggregate industry (8 % of total crushed stone production) (Tepordei, 1993b, Table 3). Light-colored, fine-grained volcanic rocks like rhyolite and trachyte may be termed 'traprock' or 'granite' by different producers. Volcanic cinders and scoria are also used as sources for crushed stone, but together they make up only about 0.2 percent of the total crushed stone production (Tepordei, 1993b, Table 3).

Although most igneous rocks make good sources of crushed stone, there are some exceptions. Certain extrusive rocks, especially those with a high silica content, are too porous to make good aggregate. Other igneous rocks with a very high content of silica tend to chemically react with alkali when used as aggregate in cement concrete.

Metamorphic Rocks

Preexisting rocks subjected to heat and pressure within the earth recrystallize into metamorphic rocks. Common metamorphic rocks include slate, schist, gneiss, marble, and quartzite. Of these, only schist appears to have little or no use as aggregate. Marble accounts for 0.34 % of the total crushed stone production and slate for 0.14 % (Tepordei, 1993b); however, rocks identified by the producers as marble may include some limestones and dolomites that take a polish. Metamorphic quartzite physically resembles sedimentary silica-cemented quartz sandstone and the two are not separated in reported production figures. Similarly, gneiss has many physical characteristics that are similar to intrusive igneous rocks and aggregate producers usually apply igneous terminology to these rocks. Consequently, reported production figures include a substantial amount of gneiss under the granite catagory.

Sand and Gravel

Sand and gravel deposits are the result of the erosion of bedrock and the subsequent transport, abrasion, and deposition of the weathered fragments. The principal geologic agents that affect the distribution of deposits of sand and gravel are ice and water. Consequently, most gravel is found in areas that were glaciated, in alluvial basins, or as fluvial deposits near rivers and streams. Gravity has a minor influence on the formation of sand and gravel through downslope movement of material and the gradation of fragments of similar size and density along an alluvial system. Windblown deposits are confined to fine-grained materials and are, commonly, of little importance as natural aggregate except possibly as blending sands.

Unlike sources of crushed stone, which may be any age, sand and gravel deposits are mostly Pleistocene or younger in age, although some Tertiary sand and gravel is mined as aggregate. Consequently, most sand and gravel deposits are surficial deposits and are amenable to study using remote sensing and airborne geophysical techniques.

Glacial Deposits

Much of the sand and gravel occurring in the northern latitudes or high altitudes of the United States are the products of either continental or alpine glaciation. As glaciers advance over the landscape, they erode the bedrock at the base of the overriding ice. As the glacier recedes by melting, meltwater flows from on top of, within, and underneath the ice. The rock particles that had been carried by the ice are picked up and transported by the meltwater. As the material is transported, it is subjected to the abrasion and sorting actions of the streams. Angular fragments are rounded, and weak materials are broken down into smaller particles. Fine materials are carried away and deposited in quiet waters (glaciolacustrine deposits), whereas the coarser sands and gravels are deposited in and along the stream channels (glaciofluvial deposits).

Glaciofluvial deposits occur in a wide variety of topographic situations. Streams flowing within or on top of the ice may deposit material as sinuous ridges called eskers or ice-channel fillings. Where the materials are deposited adjacent to the ice as mounds or terraces, they are called kames or kame terraces. All of these deposits are collectively referred to as ice-contact deposits, which tend to contain a high percentage of coarse material, and tend to be poorly sorted. The materials that were transported further away from the ice before being are deposited are commonly referred to as outwash deposits. They tend to have fewer coarse particles, and also tend to be better sorted. The processes involved with glacial erosion and deposition are extremely complex and dynamic. Hourly, daily, seasonal, and longer term temperature and climatic changes affect the generation of meltwater. Because of this, the character of glaciofluvial deposits varies greatly, both areally and with depth.

Alluvial Fans

In the arid western part of the United States, large valley basins are filled with thick unconsolidated alluvial material. Alluvial fans are most common in, and characteristic of, regions with arid and semiarid climate, although some fans occur in more humid environments as well. In arid regions the material in these fans is derived from erosion of the adjacent mountains, then transported by infrequent but torrential floods (typical of desert environments) down steep-gradient streams towards the basins. Once reaching the flat, lowland areas the sudden change in gradient combined with infiltration of water creates a loss of carrying power which causes the streams to deposit their sediment load as alluvial fans. Generally, the coarsest material is deposited adjacent to the mountains. The material commonly gets progressively finer toward the center of the basins. In time, the fans formed by adjacent streams coalesce to form continuous, thick bahada deposits.

During glacial periods, the climate of many arid regions was significantly different than it is today. Rainfall was more abundant and mountain streams and meltwater from mountain glaciers sustained numerous freshwater lakes. Terraces and beaches found on mountainsides in these areas are remnants of the lakes that filled the valleys during wetter climatic periods.

Stream Channel and Terrace Deposits

Sand and gravel deposits are widely distributed throughout the United States as channel or terrace deposits. In hilly or mountainous areas, bedrock is chemically and mechanically weathered, progressively breaking down eroded fragments into smaller and smaller particles. Less resistant minerals are dissolved or altered into clays; the more resistant minerals remain as rock fragments. Depending on the composition and structure of the bedrock, and on the climate, land cover, and topography, the remaining soils may range in thickness from almost nonexistent to tens of meters, and range in composition from nearly all clay, through mixtures of clay, silt, sand, and gravel, to nearly all sand and gravel. Gravity, sheetwash, and small tributary streams move some of this material downslope into valleys of relatively high-gradient streams. Once in the stream channels, rock fragments are subjected to abrasion, rounding, and sorting processes of the stream.

Erosion can alter an already established floodplain. If the river or stream incises its channel, the older channel and floodplain deposits may be preserved as terraces. Repeated downcutting can result in the formation of a series of terraces or terrace remnants, each of which may contain material suitable for sand and gravel production.

Marine Deposits

Deposits of sand, silt, and clay form along shorelines (beaches) and submarine bars where sediments transported by streams are deposited and reworked by wave and current action. At the mouths of larger streams, large deltas may be formed, but the sediments are mostly sand, silt, and clay. However, where vigorous streams draining nearby mountains empty into the sea, deltaic deposits may contain a gravel component (Dunn, 1991). Although marine deposits provide a very small proportion of sand and gravel production, they could become more significant as other sources are depleted, and if economic, regulatory, and environmental concerns can be adequately addressed.

III. DISTRIBUTION OF AGGREGATE DEPOSITS IN THE U.S.

To concisely describe the occurrence of natural aggregates, it is necessary to divide the United States into specific regions (fig. III-1 and Table III-1). Each division reflects the type and availability of bedrock in a region and reflects the origin, general distribution, and abundance of sand and gravel in a region. Because the occurrence of bedrock suitable for use as crushed stone, and the origin and occurrence of sand and gravel deposits are related to physiography, the divisions selected for this report are based in general on physiography.

Generally, each region has similar occurrences of aggregate within its boundaries, but is fairly distinct from other regions. However, there are also significant differences within regions, specifically concerning physical and chemical characteristics of the aggregates. Where possible, these differences are discussed in the text.

Western Mountain Ranges

The Western Mountain Ranges occupy parts of western Washington and Oregon, large parts of Idaho, eastern Montana, western Wyoming, central Colorado, northern and eastern California, and small parts of South Dakota and New Mexico. The region includes Sierra Nevadas in California and Nevada, Coast Ranges and Cascade Mountains in Oregon and Washington, northern Rocky Mountains in Idaho and Montana, Bighorn Mountains in Wyoming, Wasatch and Uinta Mountains in Utah, Black Hills in South Dakota, and Southern Rocky Mountains in Wyoming, Colorado, and New Mexico. The general physiography is tall, massive mountains alternating with relatively narrow, steep-sided valleys. The summits and slopes of the mountains consist of bare or thinly covered bedrock only a few meters thick. Cover is thicker along the base of the slopes. The narrow valleys are underlain with relatively thin, coarse, bouldery alluvium. Larger valleys may have higher terraces.

Most of the region is underlain with granitic and metamorphic rocks, flanked by consolidated sedimentary rocks including some limestones. The same bedrock is also a source for glacial, stream-channel, or terrace deposits.

Alluvial Basins

The Alluvial Basins consist of two areas: the main area occupies most of Nevada, western Utah, large parts of California, Arizona, and New Mexico, and small parts of Idaho, Colorado, and Texas; a smaller part occupies the Puget Sound and Willamette Valley of Washington and Oregon. The region has alternating basins or valleys and mountain ranges. The summits of the mountains commonly consist of bare or thinly covered bedrock only a few meters thick. The mountain ranges are commonly underlain with granitic, metamorphic, and consolidated sedimentary rocks. The basins are generally filled with thick (several hundred to several thousand meters) unconsolidated fluvial material with alluvial fans along the margins. Although the region commonly has abundant supplies of sand and gravel, some

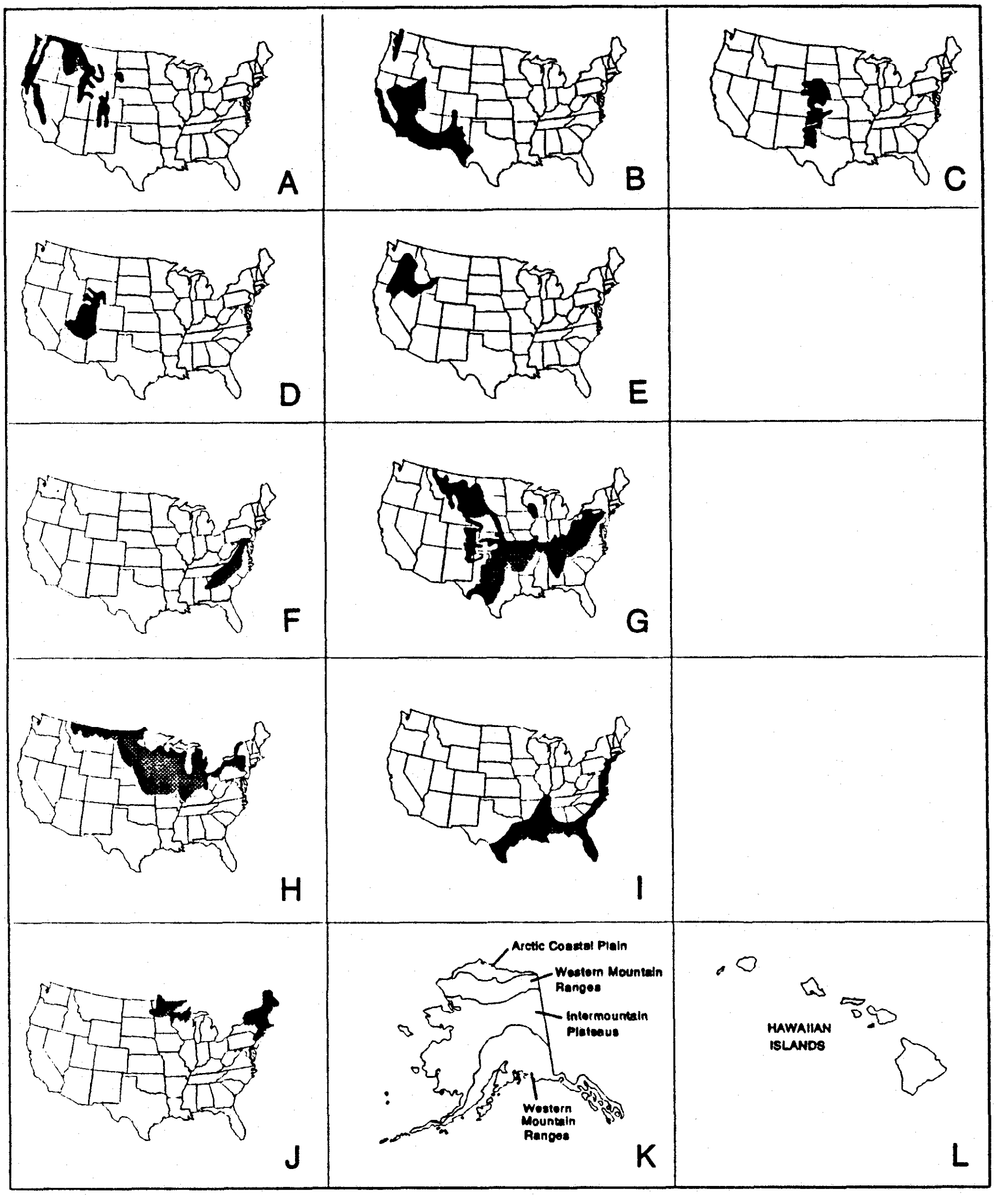

Figure III-1. Index map of broad natural aggregate regions of the United States (after Langer and Glanzman, 1993). See Table III-1 for the key to specific regions.

	REGION	BRIEF DESCRIPTION
A	WESTERN MOUNTAIN RANGES	Mountainous areas underlain with bedrock generally suitable for use as crushed stone. Sand and gravel commonly restricted to stream and terrace deposits and limited glaciofluvial deposits.
B	ALLUVIAL BASINS	Mountain ranges underlain with bedrock generally suitable for use as crushed stone. Large alluvial basins filled with extensive deposits of poorly sorted sand and gravel.
C	HIGH PLAINS	Gently-sloping plain underlain with unconsolidated or semiconsolidated bedrock unsuitable for use as crushed stone. Sand and gravel of variable quality commonly restricted to upstream sections of major river and terrace deposits.
D	COLORADO PLATEAU AND WYOMING BASIN	Flat plateau underlain with bedrock generally unsuitable or marginally suitable for use as crushed stone. Sand and gravel of variable quality commonly restricted to stream and terrace deposits.
E	COLUMBIA PLATEAU	Flat plateau underlain with bedrock generally suitable for use as crushed stone. Sand and gravel of variable quality commonly restricted to stream and terrace deposits.
F	PIEDMONT BLUE RIDGE REGION	Areas of thick saprolite underlain with bedrock generally suitable for use as crushed stone. Sand and gravel commonly restricted to stream and terrace deposits.
G	NONGLACIATED CENTRAL REGION	Areas of residuum underlain with bedrock of variable suitability for use as crushed stone. Sand and gravel of variable quality commonly restricted to stream and terrace deposits.
H	GLACIATED CENTRAL REGION	Areas underlain with bedrock of variable suitability for use as crushed stone. Thickness of overburden limits accessibility of bedrock in large areas. Sand and gravel commonly is available as glaciofluvial deposits and as stream and terrace deposits.
I	ATLANTIC AND GULF COASTAL PLAIN	Gently-sloping plain underlain with thick unconsolidated sediments generally unsuitable for use as crushed stone. Consolidated bedrock generally is inaccessible. Sand and gravel is of variable quality and is limited in occurrence, commonly being restricted to upstream sections of major rivers and terrace deposits.
J	GLACIATED NORTHEASTERN AND SUPERIOR UPLANDS	Areas underlain with bedrock generally suitable for use as crushed stone. Sand and gravel commonly is available as glaciofluvial deposits and as stream and terrace deposits.
K	ALASKA	Physiographically complex area of mountains, plateaus, and coastal plains underlain by igneous, meatmorphic, and sedimentary rocks of varying suitability for use as crushed stone. Sand and gravel commonly is available as glaciofluvial deposits and as stream and terrace deposits.
L	HAWAIIAN ISLANDS	Volcanic islands underlain with bedrock generally suitable for use as crushed stone. Sand and gravel is of variable quality and is limited in occurrence, commonly being restricted to stream, terrace, and beach deposits.

Table III-1. Key to broad aggregate regions of the United States shown in Figure III-1.

areas, such as a large area surrounding the Salton Sea in southern California, are deficient in sand and gravel.

Columbia Plateau

The Columbia Plateau region occupies parts of southeastern Washington, eastern Oregon, southern Idaho, northeastern California, and northern Nevada. The region is underlain with a thick sequence of extensive lava flows separated by soil zones and interbedded sediments. These lavas are mantled in places by alluvial, glacial, and windblown deposits. The northern part of this region commonly is underlain with basalts. The southern part is underlain with basaltic and acidic rocks.

Sand and gravel, partly formed by present streams, and partly of glacial origin is well distributed throughout much of the Washington part of the region. However, in places, enormous floods that occurred during Pleistocene time, stripped the surface soils, leaving bare scablands or cutting deep valleys such as Grand Coulee. In the rest of the region sand and gravel is rather limited, commonly being restricted to river and stream terraces.

Colorado Plateau and Wyoming Basin

The Colorado Plateau and Wyoming Basin region occupies parts of Wyoming, eastern Utah, western Colorado, northern Arizona, and northwest New Mexico. The region consists of high plateaus with deeply incised canyons, mountains, deserts, and badlands. The region is underlain with flat to gently dipping sedimentary rocks. Erosion has produced extensive, prominent cliffs that commonly are capped with resistant sandstones. There are large expanses of exposed bedrock or areas of thin rocky soil. Surficial deposits are of relatively minor importance in the region.

This region is generally underlain with poorly consolidated to consolidated sandstones, shales, and limestones, with the sandstones and shales being most prevalent and most extensive. In places the rock units contain significant amounts of gypsum or halite.

Thin deposits of alluvium or glacial deposits occur along parts of the valleys of major streams especially adjacent to the mountain ranges in the northern and eastern parts of the region. In the remainder of the region sand and gravel is generally limited to stream or river terraces.

High Plains

The High Plains region extends from South Dakota in the north through Nebraska, Wyoming, Colorado, Kansas, Oklahoma, to New Mexico and Texas in the south. The High Plains are a remnant of a great alluvial plain built by streams that flowed east from the Rocky Mountains. Stream erosion has removed a large portion of the plain, however, in large areas the original depositional surface of the plain is almost unmodified, and forms a flat, gently eastward-sloping tableland. Significant topographic features include sand dunes, which are especially prevalent in central and northern Nebraska; wide valleys of braided streams that flow from the Rocky Mountains eastward across the plain; and numerous circular depressions called playas, that intermittently contain water after heavy rains.

The region is underlain by thick, semiconsolidated bedrock that ranges from silt to sand and gravel, with sand being most abundant, and clay occurring in only a few areas. Gravels occur haphazardly throughout the region, usually in small deposits.

The major source of aggregates is alluvial deposits from major rivers and their tributaries.

Nonglaciated Central Region

The Nonglaciated Central region extends from the Rocky Mountains on the west to the Appalachian Mountains on the east. The part of the region in eastern Colorado and northeastern New Mexico is separated from the remainder of the region by the High Plains. The nonglaciated region also includes the "Driftless " area in Wisconsin, Minnesota, Iowa, and Illinois. The region is topographically complex and includes central lowlands and plains as well as hilly and mountainous areas.

Most of the northern part of the region (in Montana, North Dakota, South Dakota, Wyoming, and Nebraska) and the part of the region flanking the Rocky Mountains is underlain with sedimentary rocks that consist mostly of sandstones, shales, and conglomerates. Most of the region in the south-central and eastern United States is underlain with limestones and dolomites. Sand and gravel deposits occur as alluvial or terrace deposits.

Glaciated Central Region

The Glaciated Central region extends from the northern part of the Great Plains in Montana to the Catskill Mountains in New York, and south to the limit of Pleistocene glaciation. The eastern part of the region (New York and Pennsylvania) is characterized by rolling hills and low rounded mountains. The western part of the region is flat to gently rolling. The entire region is underlain with consolidated sedimentary rocks which in turn are overlain with glacial deposits. The sedimentary rocks consist primarily of sandstone, shale, limestone, and dolomite and are most prevalent in southern Minnesota and Wisconsin, Iowa, northern Illinois, Missouri, Indiana and western Ohio, and are less prevalent in Pennsylvania and New York. The parts of the region in Montana, North Dakota, South Dakota, and most of Nebraska generally lack limestones or dolomites.

Piedmont Blue Ridge Region

The Piedmont Blue Ridge region extends from Pennsylvania in the north, southward through Maryland, Virginia, North Carolina, South Carolina, Tennessee, Georgia and Alabama.

The Piedmont part of the region consists of low, rounded hills and long, rolling northeast-southwest trending ridges situated between the Coastal Plain to the east and the Blue Ridge to the west. The Blue Ridge is mountainous, and contains the highest peaks east of the Mississippi. The mountains are bordered by low-gradient streams flowing in relatively narrow valleys. The entire region is underlain by igneous, metasedimentary, and metaigneous bedrock (granite, gneiss, schist, quartzite, slate, marble, and phyllite). Near the surface the rocks are weathered to saprolite, a clay-rich, unconsolidated material developed in place primarily from the chemical weathering. The valleys are underlain with relatively thin, moderately-sorted alluvium with sand and gravel deposits occurring as alluvial or terrace deposits.

Glaciated Northeastern and Superior Uplands

The Glaciated Northeastern and Superior Uplands region occupies two separate areas. The Northeast Upland includes nearly all of New England, the Adirondack Mountains, and the Lake Champlain valley. The Superior Uplands encompasses most of the northern parts of Minnesota and Wisconsin adjacent to the western end of Lake Superior. The entire region is characterized by rolling hills and low mountains. Although some of the higher mountains have large expanses of exposed rock, most igneous and metasedimentary bedrock of the region is overlain by unconsolidated deposits laid down by ice sheets that covered the area during the Pleistocene, and by gravel, sand, silt, and clay laid down by meltwater streams and in lakes that formed during the melting of the ice.

The thickness of the unconsolidated deposits range from a few meters to more than 100 m in some of the valleys. The most extensive glacial deposit is till. In most of the valleys and other low areas, the till is covered by glacial outwash consisting of interlayered sand and gravel. The major sources of sand and gravel are glaciofluvial deposits and stream channel and river terrace deposits.

Atlantic and Gulf Coastal Plain

The Atlantic and Gulf Coastal Plain region extends along the Atlantic Coast from Cape Cod, Massachusetts south to Florida, and along the Gulf Coast from Florida to the Rio Grande, Texas. The topography of the region ranges from extensive, flat, coastal swamps and marshes to rolling uplands near the inner margin of the region. The region is underlain with extensive deposits of sand, silt, clay, and gravel that vary in thickness. Depending on location, they are either of marine or fluvial origin.

Consolidated bedrock generally is inaccessible in the Coastal Plain region, except near the inner margin, and in southeastern Florida, which is underlain by semiconsolidated limestones.

The predominant surficial material of the coastal plain is sand. Near the inner edge of the Coastal Plain are deposits of sand and gravel. Present-day streams cutting through these deposits transport gravels downstream as much as 80 km. These terrace and stream gravels are limited in occurrence. Coarse materials are so limited in this region that shells are commonly substituted for gravel in coastal areas. The quality of the gravels vary in accordance with the types of rocks from which they originated.

Hawaiian Islands

The Hawaiian Islands are the tops of volcanoes that rise from the ocean floor. Each island was formed by lava that issued from one or more eruptive centers. The islands have a hilly appearance resulting from erosion that has carved valleys into the volcanoes and built relatively narrow plains along parts of the coastal areas.

Each of the Hawaiian Islands is underlain with lava flows. Andesitic and basaltic lava flows are commonly used as a source of crushed stone. In addition, clinker from the tops of lava flows and cinders from cinder cones are used as stone aggregate.

In some areas, alluvium of older and modern terraces and alluvial fans contain poorly sorted sand and gravel of variable quality. In coastal areas a thin layer of alluvium consisting of coral and shell fragments, volcanic debris, and clay form discontinuous beach deposits. Alluvium, terrace deposits, and beach deposits may all be used as aggregate if they meet the required specifications.

Alaska

The Alaska region can be divided into four distinct areas; the Arctic Coastal Plain, the Rocky Mountain System, the Intermontane Plateaus, and the Pacific Mountain System.

Alaska is underlain by a diverse assemblage of rocks. The principal mountain ranges have cores of igneous and metamorphic rocks. These are overlain and flanked by sedimentary and volcanic rocks. The sedimentary rocks include carbonates, sandstones, and shales.

Approximately half of Alaska, including the mountain ranges and adjacent parts of the lowlands, was covered by glaciers during the Pleistocene. Glaciofluvial deposits in these areas commonly contain sand and gravel. In the Intermontane Plateaus, sand and gravel commonly occurs in river channels and floodplains, terrace deposits, and placer-mine tailings. The Arctic Coastal Plain consists of silt, sand, and gravel, with the northeastern part having moderate to high potential for sand and gravel. The Arctic Coastal Plain, as well as most of the Rocky Mountain System and part of the Intermontane Plateaus are areas of continuous permafrost. Here, and to a lesser degree elsewhere in Alaska, much of the aggregate is frozen and requires drilling and blasting.

IV. PHYSICAL PROPERTIES AND CHARACTERISTICS

Physical properties are intrinsic properties of a material that are generally measured and expressed in SI units or units derived from SI units. Density (g/cm^3), electrical conductivity (mhos/m), seismic velocity (km/sec), and thermal conductivity (cal/cm sec ^{o}C) are examples of common physical properties of interest to geologists and geophysicists. Some physical properties are expressed as dimensionless proportions of a known value, such as reflectivity, which is expressed as the proportion of the light reflected from a surface (radiance) to the light incident on the surface (irradiance); both irradiance and radiance are measured in units of watts per square meter steradian (W/m^2· sr). The important factor in distinguishing a physical property of a material from other useful characteristics is the intrinsic nature of the physical property, that is, the value of the physical property applies to any portion of the material.

A characteristic of a material is an extrinsic property that may be expressed qualitatively or quantitatively. For example, the drainage texture developed on a gravel deposit can be expressed as course, medium, or fine or it can be expressed quantitatively as the length of the drainage lines per unit area (for example, km/km^2). Drainage texture, however, only exists on the exposed surface of the deposit and is not intrinsic to the gravel. Characteristics are often more useful or practical for identifying materials in nature than are physical properties.

The capability of determining physical properties and interpreting characteristics of various deposit types forms the basis for detecting and mapping areas containing potential deposits of sand and gravel and sources of crushed stone using remote sensing and airborne geophysical techniques. Physical properties and characteristics are also very important to the aggregate industry in determining the quality and potential usefulness of aggregate for specific construction uses. Table IV-1 lists the properties and characteristics of aggregate that are considered significant by the aggregate producers and users; detailed descriptions of these properties are in Marek (1991, p.3-3 - 3-17) and Langer (1988, p.12-14). Ideally, these physical properties and characteristics would be measurable by airborne geophysical or remote sensing techniques, but most of the properties and characteristics in Table IV-1 must be determined by detailed physical and chemical laboratory testing, mostly on individual particles. In addition, the physical properties and characteristics of aggregate (sand and gravel and sources of crushed stone) that define its quality and usefulness are determined after mining and processing (crushing, washing, and grading) and are mostly different from the bulk properties of the in-situ deposits before mining and processing. Remote sensing and airborne geophysical techniques may be useful for evaluating, in a qualitative way, some physical properties and characteristics critical to defining the quality and usefulness of sand and gravel and sources of crushed stone, but their primary application will be for mapping bulk properties and characteristics that differentiate potential sources of aggregate from other materials.

Table IV-1. Properties and characteristics that define the quality and usefulness of aggregate for construction uses (Marek, 1991, p. 3-3 - 3-17).

PHYSICAL	
Particle Shape	**Thermal Conductivity**
Maximum Particle size	**Integrity During Heating**
Particle Surface Texture	**Electrical Conductivity**
Pore Structure	**Reflection**
Absorption	**Glare**
Porosity	**Color**
Permeability	**Volume Change - Wetting and Drying**
Specific Gravity	**Resistance to Wetting - Drying**
Particle Grading	**Resistance to Freezing - Thawing**
Voids in Aggregate Mixture	**Deleterious Substances**
Thermal Volume Change	
CHEMICAL	
Solubility	**Resistance to Attack by Chemicals**
Slaking	**Chemical Compound Reactivity**
Base Exchange	**Oxidation and Hydration Reactivity**
Surface Charge	**Organic Material Reactivity**
Coatings	**Chloride Content**
MECHANICAL	
Particle Strength	**Resistance to Degradation**
Mass Stability	**Particle Shape of Abraded Fragments**
Particle Stiffness	**Resilient Modulus**
Wear Resistence	

As discussed above, sand and gravel deposits are unconsolidated clastic sedimentary deposits formed in several different geologic environments: glacial (till, esker, kame, moraine, etc.), fluvial (channel, terrace, alluvial fan), marine (beach, bar, delta), and eolian (dune) (Dunn, 1991, p.4-2 - 4-48). The deposits are at or very near the present surface and most are younger than Tertiary. The chemical and mineral composition of the deposits are highly variable and depend on the composition of the source material and the subsequent history of the deposits after formation. The different types of deposits are also highly variable in grain size, grading, and sorting characteristics. Surface expression is often a key factor in identifying areas of potential sand and gravel deposits, but even similar types of deposits can appear quite differently in different geographic/climatic areas. Consequently, it is currently impossible to construct a single descriptive model for sand and gravel deposits and no single physical property or characteristic can be universally applied to the definition of potential sand and gravel deposits using airborne geophysical and remote sensing techniques. Nevertheless, numerous physical properties and characteristics that can be measured, derived, or interpreted from remote sensing and airborne geophysical data can provide useful clues to the possible existence of potential sand and gravel deposits.

Unlike naturally occurring sand and gravel, crushed stone is composed of well indurated bedrock, mostly extracted from surface quarries, which has been crushed into irregular fragments or ground into specific particle sizes, washed, and screened for specific applications (Tepordei, 1993b). Since the search for potential sources of crushed stone involves the identification of appropriate types of bedrock (ignoring zoning and transportation questions), those remote sensing and airborne geophysical techniques that are useful for geologic mapping should also be applicable to identifying potential sources of crushed stone.

Physical Properties

No remote sensing or airborne geophysical system directly measures physical properties. The instruments detect and measure parameters that can be used, with appropriate assumptions, to calculate apparent values of the bulk physical property. Maps and images made from the reduced data can be interpreted in terms of the apparent values and their geometrical patterns and how they relate to known properties and characteristics of sand and gravel deposits.

Electrical resistivity (conductivity)

Electrical resistivity (ρ), is the resistance a material presents to the passage of an electrical current and is expressed in ohm - centimeters (Ω-cm) in the cgs system and ohm-meters (Ω-m) in the mks system. The electrical conductivity (σ) of a material is the reciprocal of the resistivity ($1/\rho$). Resistivities of sand and gravel deposits at or near the surface are mostly a function of the porosity of the deposit and the composition and concentration of fluids contained in the pores; the lithology of the clasts has little effect on the bulk resistivities (Dobrin, 1960, p. 340; Hoover and others, 1992, p. 44). Similarly, resistivity measurements provide information on the fracture permeability and fluid content of potential sources of crushed stone.

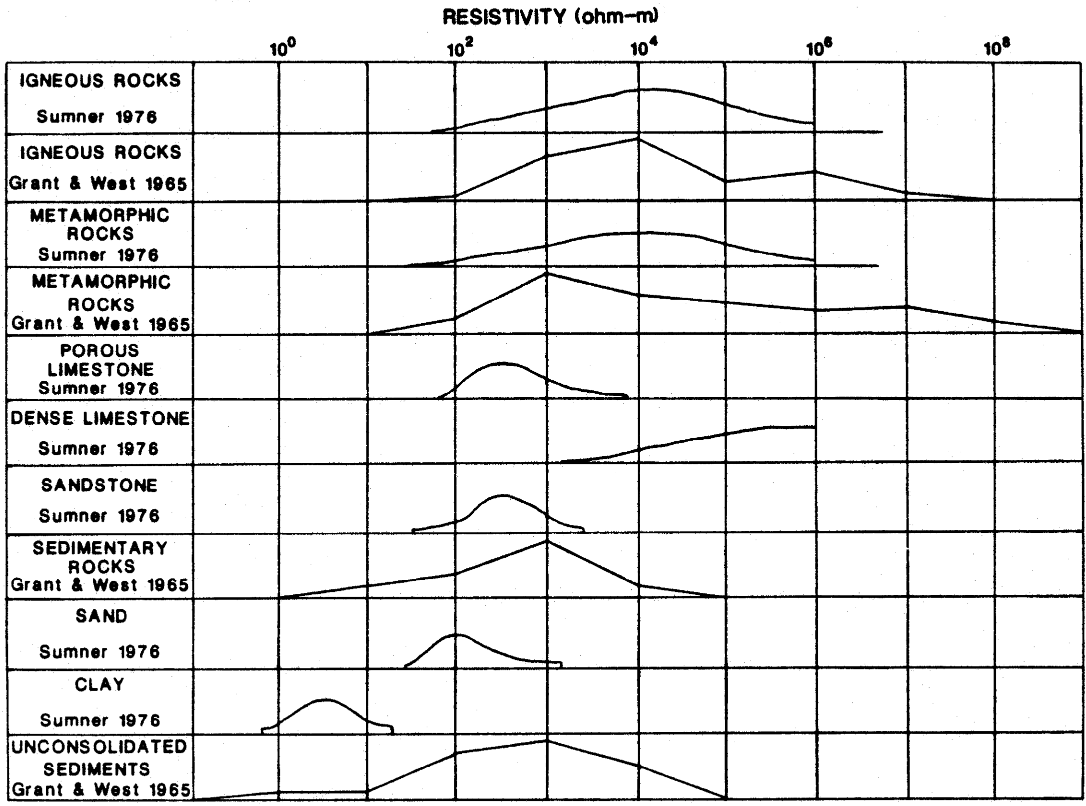

Figure IV-1. Distribution diagrams of resistivities of common rocks and sediments as compiled by Hoover and others (1992) from Sumner (1976) and Grant and West (1965).

Resistivities measured on a broad range of rocks, compiled by Hoover and others (1992, p.48), shows magnitudes ranging form 10^{-1} to 10^{9} ohm-m, a range of 10 orders of magnitude (Fig. IV-1); however, the upper four decades represent laboratory measurementson low porosity or dry samples that are not representative of in-situ bulk resistivities that generally do not exceed 10^{5} ohm-m (Hoover and others, 1992, p.47).

Although there is considerable overlap between the resistivity ranges of sand and unconsolidated sediments and igneous, metamorphic, and sedimentary rocks (Fig.IV-1), unconsolidated sediments and sand tend to be less resistive than most igneous and metamorphic rocks and less than or equivalent to sedimentary rocks; clay is the least resistive (most conductive) of the materials because of its normally high water content. Unconsolidated Quaternary and Tertiary terrestrial sediments, a major source of potential sand and gravel deposits, have resistivities less than 10^{2} ohm-m (Keller and Frischknecht, 1966), providing good resistivity contrasts with most other materials. The application of ground-based resistivity studies for delineating the extent of sand and gravel deposits and estimating the distribution and thickness of overburden (Dunn, 1991) and early experiments using airborne VLF to study sand and gravel deposits (Middleton, 1977) suggest that airborne resistivity surveys may be useful in the regional assessment of sand and gravel potential.

Spectral reflectance and albedo

Electromagnetic radiation incident on a surface can be absorbed by the material, transmitted into or through the material, or reflected from the surface such that,

$$\alpha + \tau + \rho = 1, \qquad (1)$$

where

α = absorptivity,
τ = transmissivity, and
ρ = reflectivity.

For most naturally occurring materials at the earth's surface, the transmissivity is 0, so that,

$$\alpha + \rho = 1. \qquad (2)$$

Reflectance is the ratio of the electromagnetic radiation reflected from a surface within a certain wavelength range (radiance) to the radiation incident on the surface in the same wavelength range (irradiance); the incident radiation that is not reflected is absorbed. The radiation reflected and absorbed is a function of the elemental and molecular composition of the material, and both reflectance and absorptance are sensitive to the wavelength of the incident radiation, that is, they are spectral properties. The relationship between spectral reflectance and spectral absoptance is then,

$$\alpha(\lambda) + \rho(\lambda) = 1. \qquad (3)$$

Because reflectance is a spectral property, the measure of reflectance as a function of wavelength produces data that is characteristic of the material. Spectral reflectance curves (fig. IV-2) show reflectance as a function of wavelength. Local minima (troughs) in the curves represent wavelengths at which absorption occurs and the wavelength, size and shape of the absorption features are often characteristic or diagnostic of the material. Hunt (1980) gives an excellent discussion of the interaction of electromagnetic radiation with matter and the spectral properties of rocks and minerals.

Albedo is the total radiant reflectance of natural materials illuminated by the sun (Janza, 1975, p. 79-80). That is, albedo represents the total reflectance integrated across the entire solar spectrum compared to the incident radiation from the sun. In application, albedo is often used in a general way to indicate the relative brightness or darkness of an object on aphotograph or image. For example, limestones are considered to have a high albedo (bright), while basalts generally have a low albedo (dark); this usage, although useful, is not exactly correct because only the visible portion of the spectrum is considered.

Fresh exposures of sand and gravel deposits are relatively rare. Consequently, the bulk spectral reflectance properties of these deposits will probably not play an important part in defining new sources. Nevertheless, recognition of selected minerals or mineral groups, such as gypsum, calcite, clay minerals, and iron oxides (Fig. IV-2), in the soils developed over the deposits may provide qualitative information on the overall quality that will be useful for evaluating the favorability of potential new sources. Understanding the significance and spectral reflectance characteristics of materials developed in the near-surface environment over deposits of sand and gravel, such as soils and selective vegetation growth, is important for effectively applying remote sensing data from the visible and near-infrared portion of the electromagnetic spectrum to the detecting and mapping of potential new sources.

The spectral properties of potential sources of crushed stone are a function of the mineral content of the rocks. Some common monomineralic sources of crushed stone, such as limestone and dolomite, can be identified by characteristic absorption features in spectral curves. Other bedrock sources are more difficult to identify, although spectral reflectance characteristics can be used to map their distribution by enhancing the spectral contrasts with other rocks using image processing techniques. The spectral characteristics of lithologically-controlled soils and vegetation may also provide important indirect indicators of the distribution of potential sources of crushed stone.

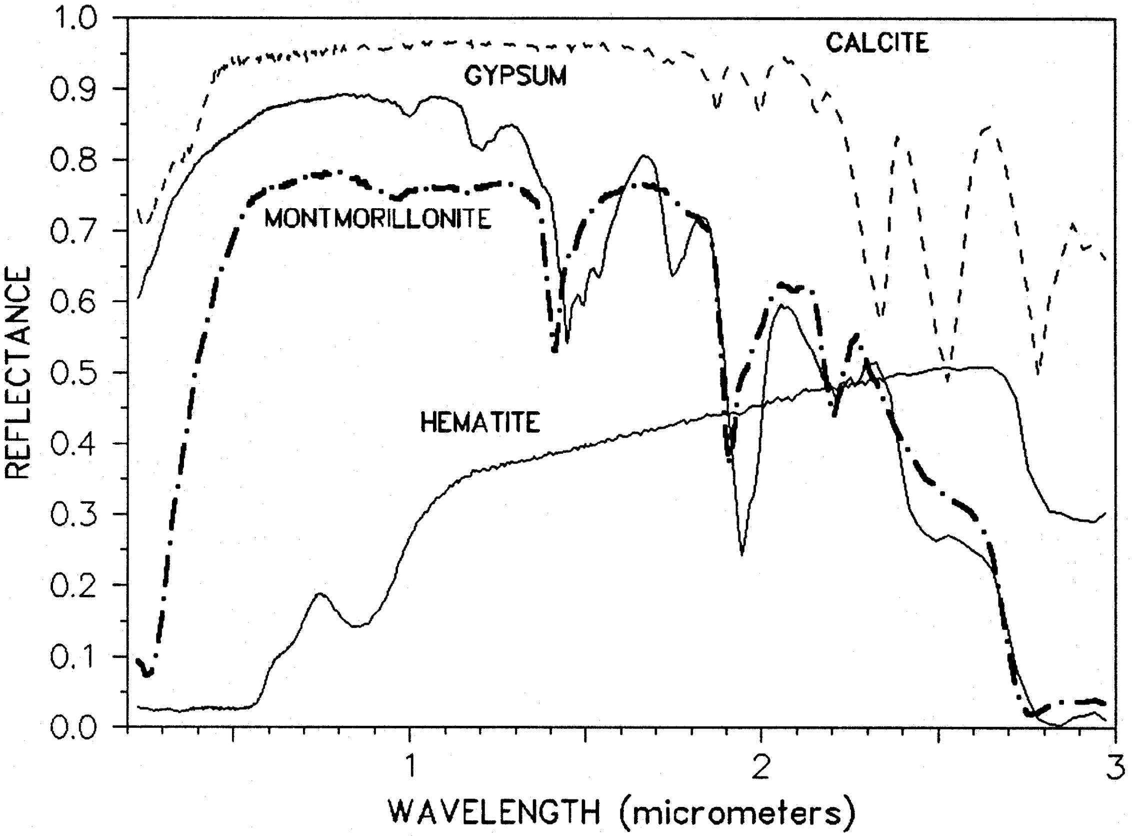

Figure IV-2. Spectral reflectance curves of some common rock-forming minerals.

Thermal Emissivity

Any body of material at a specific temperature emits radiation in the thermal infrared region of the spectrum (8-14μm). Spectral emissivity ε is a physical property of materials that can be estimated from measured spectral radiance R(λ) at wavelength λ divided by the blackbody radiance B(λ,T) at temperature T and wavelength λ. Simply written without atmospheric terms:
B(λ,T) is given by the Planck function:

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where C_1 and C_2 are the radiation constants. The unknowns in these equations are the emissivities and the temperature. However, if the radiances R(λ)'s are measured at two times in the diurnal cycle (optimally at the maximum and minimum temperatures in the heating cycle) and if it is assumed that emissivity is temporally invariant, then it is possible to solve for the emissivities (Watson, 1992a; Watson, 1992b).

Emissivity is a dimensionless quantity with values less than one. This is due to materials emitting only a fraction of the energy emitted from a blackbody at the equivalent temperature. Typical values for various materials range from .82 for granite to .99 for water at thermal infrared wavelengths as published in the Manual of Remote Sensing (Colwell, 1983). (These values were compiled from the work of Buettner and Kern (1965), Lillisand and Kiefer (1979), and Underwood, Houston, and Hazard (1980).)

Most well-sorted sands and gravels are fluvial deposits, either in the form of stream-channel deposits and valley fills or as alluvial fans. For these surficial deposits, the spectral emissivity can be diagnostic of favorable sand and gravel material. Emissivity is sensitive to changes in soil moisture; wet soil has a higher (0.95) emissivity than dry soil (0.92) (Lillisand and Kiefer, 1979). Surficial as well as shallowly buried deposits will exhibit different drainage patterns than the surrounding materials. Studies by Huntley (1978) and Heilman and Moore (1981) show that predawn thermal data do detect shallow aquifers. Thus potential deposits can be identified by thermal emissivity calculations as well as variation in thermal patterns on infrared images.

Thermal Inertia

Thermal inertia is a physical property of materials and is a measure of the resistance of materials to changes in temperature. Thermal properties cannot be measured directly but must be inferred from measurements of the temperature variation during the diurnal cycle in combination with models of the heating process which occur during the cycle (Watson, 1971, 1975; Kahle, 1977; Pratt and Ellyett, 1979). Thermal inertia is dependent upon several physical properties. For a homogeneous material, thermal inertia can be expressed by $(K\rho c)^{1/2}$, where K is the thermal conductivity, ρ is the density, and c is the specific heat. Another way of expressing thermal inertia is the conductivity (K) divided by the square root of the diffusivity (κ).

Thermal conductivity is a measure of the rate at which heat will pass through a material and its units in $(W\ m^{-1}\ {}^{o}K^{-1})$ equal $(418.54\ cal\ cm^{-1}\ s^{-1}\ {}^{o}C^{-1})$. The density of a material is the mass (weight) of a known volume compared to the mass of an equal volume of water. Its units of measurement are $(kg\ m^{-3})$ which is equal to $(1000\ gm\ cm^{-3})$. Specific heat is defined as the quantity of heat necessary to raise the temperature of unit mass of the material one degree. The units for this quantity are $(W\ s\ kg^{-1}\ {}^{o}K^{-1})$, which is equal to $(4185.4\ cal\ gm^{-1}\ {}^{o}C^{-1})$. And diffusivity denotes the rate of temperature change in the material; its units are $(m^{2}\ s^{-1})$ or $(10^{-4}\ cm^{2}\ s^{-1})$.

Starting with the diffusion equation and assuming appropriate boundary conditions, Watson (1975) developed a simple theoretical model to estimate thermal inertia. This algorithm requires measuring the maximum day and the minimum night temperatures, computing the temperature difference, and dividing this quantity by (1-A), where A is the albedo. Because the skin depth of the diurnal wave is small, information is limited to the upper decimeter of the ground. Carr and Blakely (1966) established that both sand and gravel, and clay till could be effectively mapped by measuring the diurnal temperature change at a depth of 0.3m below the ground surface (Pratt, 1978).

The units for thermal inertia are $(W\ m^{-2}\ {}^{o}K^{-1}\ s^{½})$ or 1 thermal inertia unit (TIU). The cgs unit is $(cal\ cm^{-2}\ {}^{o}C\ s^{-½})$ and if multiplied by 4.1854×10^{4} equals 1 TIU. The Manual of Remote Sensing (Reeves, 1975) shows a table of typical thermal inertia values for common rocks (Table IV-2). The values range from loose, dry pumice at 400 TIU to quartzite at 3000 TIU. Of particular interest for this study, sandy soil is 1000 TIU; gravel is 1400 TIU; moist clay is 1750 TIU; and sandy gravel is 2100 TIU. (Carslaw and Jaeger (1959) is also a good source of typical values of thermal properties of some common substances.) These values are all approximate and will vary with the particular sample.

Additionally, thermal mapping is most sensitive to differences between consolidated and unconsolidated materials and between wet and dry soils. Thermal inertia of soils is dependent primarily on bulk density and moisture content; the specific heat is nearly the same for most soil minerals (Kilmer, 1982). Miller and Watson (1977) found a rough linear relationship between thermal inertia and density for dry materials. The addition of moisture

THERMAL PROPERTIES OF SELECTED ROCKS,
SEDIMENTS, AND WATER

	K	ρ	C	κ	P
GRANITE	0.0075	2.6	0.16	0.016	2176
RHYOLITE	0.0055	2.5	0.16	0.014	1967
WELDED TUFF	0.0028	1.8	0.20	0.008	1339
OBSIDIAN	0.0030	2.4	0.17	0.007	1465
SYENITE	0.0077	2.2	0.23	0.009	1967
BASALT	0.0050	2.8	0.20	0.009	2218
GABBRO	0.0060	3.0	0.17	0.012	2302
PERIODOTITE	0.0110	3.2	0.20	0.017	3516
LOOSE, DRY PUMICE	0.0006	1.0	0.16	0.004	377
DOLOMITE	0.0120	2.6	0.18	0.026	3139
LIMESTONE	0.0048	2.5	0.17	0.011	1883
QUARTZ SANDSTONE	0.0120	2.5	0.19	0.013	2260
SHALE	0.0042	2.3	0.17	0.008	1423
QUARTZITE	0.0120	2.7	0.17	0.026	3097
MARBLE	0.0055	2.7	0.21	0.010	2344
SERPENTINE	0.0063	2.4	0.23	0.013	2637
MOIST CLAY SOIL	0.0030	1.7	0.35	0.005	1758
GRAVEL	0.0030	2.0	0.18	0.008	1381
SANDY GRAVEL	0.0060	2.1	0.20	0.014	2093
SANDY SOIL	0.0014	1.8	0.24	0.003	1004
WATER 0^{O}C	0.0013	0.9987	1.0074	0.0013	1542
WATER 20^{O}C	0.0014	0.9982	0.9988	0.0014	1580
WATER 40^{O}C	0.0015	0.9922	0.9980	0.0015	1613

Table IV-2. Selected thermal properties of common rocks, sediments, and water (after Reeves, 1975, p.83-85). **K**, conductivity; ρ, density; **C**, conductivity; κ, diffusivity; and **P**, inertia. **K**, ρ, **C**, and κ in cgs units; **P** in thermal inertia units (TIU).

to dry soil results in a rapid increase in thermal inertia. For example, dry sand has a thermal inertia of 600 TIU, and wet sand (8% moisture) has a thermal inertia of 1020 TIU. Thus, thermal inertia, when combined with the other geophysical data sets, shows promise of being a good reconnaisance tool for locating sand and gravel deposits.

Radioactivity

The radioelements potassium (K), uranium (U), and thorium (Th) are present in many rocks and minerals and, consequently, may become incorporated into sand and gravel deposits. In addition, uranium is very mobile in the near-surface oxidizing environment and can become concentrated in deposits of secondary minerals, such as carnotite and uranophane, when reducing conditions are encountered (Hoover and others, 1992, p.66-69). Gamma-ray spectrometry records the number of gamma-rays detected per unit time at specific energy levels diagnostic of potassium, uranium, and thorium. From these measurements, the approximate concentrations of these elements can be calculated. Potassium concentration is normally expressed as a percentage, while uranium and thorium concentrations are expressed as parts per million (ppm).

The radioelement content of sand and gravel deposits is largely dependent on the radioelement content of the individual clasts (source rocks); Table IV-3 shows the radioactive element content measured for a variety of rock types in the section on physical properties of potential sources of crushed stone below lists the ranges of many common rock types. Variations shown by these data indicate the potential for airborne gamma-ray spectrometry for lithologic discrimination that may be applicable to detecting and mapping sand and gravel deposits as well. Ratios between the various radioelements provide data that is especially powerful for lithologic mapping (Hoover and others, 1992) and should be useful for mapping potential sources of crushed stone.

Porosity and Permeability

Porosity is a measure of the amount of pore space, or interstices, contained in a rock or sediment and is usually expressed as a percentage of the total bulk volume of the material (Meinzer, 1923, p. 19; Gary and others, 1972, p.558). In unconsolidated sand and gravel, porosity is about 35 percent (Holmes, 1965, p. 414), but porosities in some unconsolidated materials can range up to nearly 90 percent (Hoover and others, 1992, p. 33). Bedrock porosities and permeabilities are significantly lower than sand and gravel deposits and other unconsolidated sediments (fig. IV-3). Hoover and others (1992, p.29-32) present a useful discussion of the porosities and permeabilities of common rocks and sediments.

Permeability is the capacity of rock or sediments to allow fluids to move though it (Holmes, 1965, p. 413), and is measured in units of darcies. One darcy of permeability occurs when 1 cm^2 of surface releases 1 cm^3 of fluid in 1 second under a pressure differential of 1 atmoshpere per cm (Krumbein and Sloss, 1963, p. 121). Unlike porosity, permeability is highly dependent on particle size, sorting, shape, and packing. Unconsolidated sand and gravel deposits are very permeable; coarser grain size, a high degree of sorting, and loose packing all favor high permeability.

Although no airborne geophysical or remote sensing system directly measures porosity or permeability, these factors are extremely important in controlling other bulk physical properties of sand and gravel deposits and potential sources of crushed stone in the near surface environment that may be calculated or deduced from remote measurements. For example, porosity and permeability influence the amount of water contained at any particular time by controlling the rate of infiltration and drying during and after storms. Decreasing the amount of water contained from saturated to dry may decrease density by 0.5 gm/cm^3 and increase resistivity several orders of magnitude (Hoover and others, 1992, p. 31). In addition, permeability is especially influential in controlling the texture of drainage lines developed at the surface (high permeability-course drainage texture) and influences the type of vegetation growing over bedrock and sediments. These indirect indicators can be detected and measured using remote sensing techniques.

Characteristics

The recognition and mapping of potential sand and gravel deposits and sources of crushed stone on remote sensing images and photographs employs a combination of the well-established principles of photogeology and an understanding of the spectral reflectance characteristics of rocks, soils, vegetation, and other materials at the earth's surface. Photogeologic interpretation is a powerful tool for studying and correlating geological features on both local and regional scales. Miller and Miller (1960, p.81) summarize the photogeologic interpretation process:

> The process of identifying, mapping, correlating, and interpreting geology from aerial photographs is an extremely complex one. It requires patience, judgment, and the ability to evaluate the significance of many different types of information.
>
> Therefore, photography must be approached with the full realization that geologic interpretation can only be accomplished if close attention is paid to all of the following elements: outcrop appearance and distribution, structural details, landform, drainage, vegetation, soil, and occasionally such cultural features as land utilization and population selectivity. The photogeologist must be at least conversant with the allied sciences of pedology (soils), botany, and geography.

The power, and the difficulty, of geologic image interpretation stems from the combination of deductive and inductive reasoning, based on the principle of cause and effect, that the interpreter must perform to make full use of the data. For example, a terminal moraine is often easily recognizable on an image, and it can be inductively concluded that the area has under gone glaciation. With this information, less distinct features on the image or photograph may be deduced to be some other type of glacial deposit, and from that deduction

RADIOELEMENT CONTENT OF SELECTED ROCK TYPES

K=potassium U=uranium Th=thorium

ROCK TYPES	K%	U ppm	Th ppm
GRANITE	4.43	4.5	18.0
GRANITE (G-1)	4.45	3.4	50.0
GRANODIORITE (GSP-1)	4.50	2.0	104.0
QUARTZ DIORITE - GRANODIORITE	2.05	2.1	8.3
NEPHYLINE SYENITE (STM-1)	3.54	9.1	27.0
GABBRO-DIABASE	0.56	0.6	1.8
PERIDOTITE-PYROXENITE	0.012	0.03	0.08
PERIDOTITE (PCC-1)	0.001	0.005	0.01
RHYOLITE (RGM-1)	3.49	5.8	13.0
RHYOLITE	3.87	4.7	19.0
DACITE	2.20	2.5	10.0
QUARTZ LATITE (QLO-1)	2.90	5.8	13.0
ANDESITE	1.66	1.2	4.0
ANDESITE (AGV-1)	2.35	1.9	6.4
BASALT-DIABASE	0.55	0.7	2.3
BASALT (BCR-1)	1.38	1.7	6.0
MICA SCHIST (SDS-1)	2.71	3.1	11.4
GRAVEL-CONGLOMERATE	--	2.4	9.0
SANDSTONE-SILTSTONE	1.07	2.9	10.4
AVERAGE SANDSTONE	1.07	1.7	5.5
CLAY-ARGILLITE	2.66	4.0	11.5
AVERAGE SHALE	2.66	3.7	12.0
LIMESTONE	0.27	1.6	1.8
DOLOMITE	0.27	3.7	2.8
AVERAGE CARBONATE	0.27	2.2	1.7

Table IV-3. Radioelement content measured in some common rock types as compiled by Hoover and others (1992) from Vavilin and others (1982) and Van Schmus (1984). Sample identifications shown in parentheses refer to USGS rock standards measured by Van Schmus (1984).

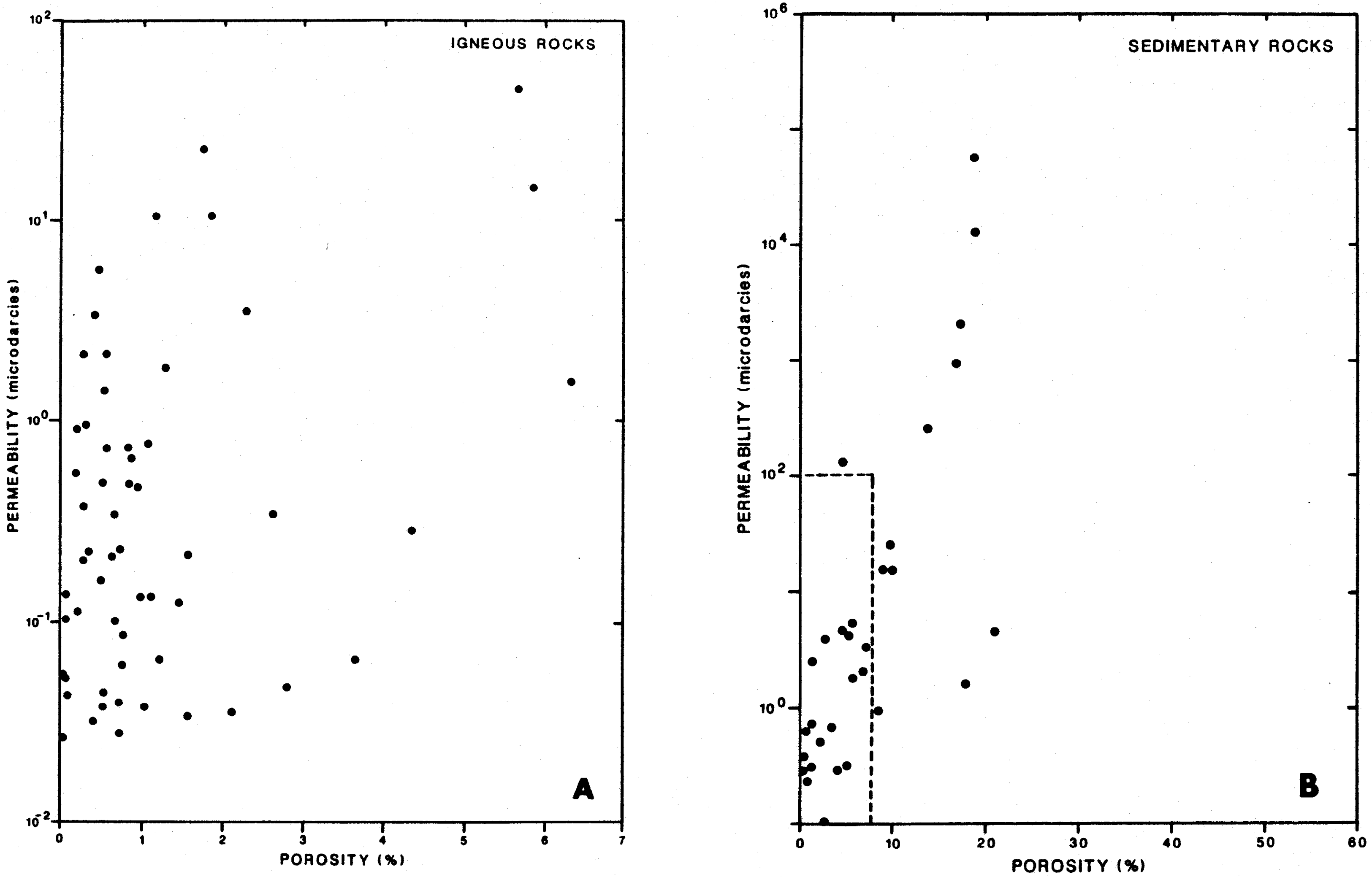

Figure IV-3. Measured porosities and permeabilities of common igneous (A) and sedimentary (B) rocks as compiled from Hoover and others (1992) from Johnson (1983). Notice that the two plots are at different scales; the dashed line on the plot for sedimentary rocks (B) would contain all of the measurements for igneous rocks (A).

the nature of the material in the deposit can be deduced or inferred (Ray, 1960, p.5). The results of photointerpretation may be combined with the measurements of apparent values of one or more of the physical properties discussed above to refine or check the interpretations.

Several broad catagories of characteristics could provide useful information on the existence and distribution of potential sand and gravel deposits and sources of crushed stone: landform, drainage pattern and density, vegetation, texture (surface roughness), landuse, and geologic setting.

Landform

The identification of landforms often identifies the process that formed it: alluvial fan (fluvial), cinder cone (volcanism), moraine (glaciation), hogback (tectonic uplift and erosion) (Ray, 1960, p.34). Sand and gravel deposits are transported materials that are usually associated with a diagnostic constructional landform (moraine, esker, alluvial fan, terrace, etc.), although very thin veneers of alluvium or colluvium and very small erosional remnants of terraces or pediment deposits may be difficult to detect and identify on photos or images. In addition, large expanses of glacial drift in the north-central United States may not be associated with a diagnostic landform, although other surface characteristics may be used to infer its presence (Ray, 1960, p.17). In addition, aggregate-bearing regions in the Coastal Plain have subdued topography and coarse materials within major fluvial systems may be entirely buried.

Recognition of selected landforms not only helps to identify potential sources of sand and gravel, but also provides a crude evaluation of the type of aggregate that may be present in the deposit (Table IV-4). Grain size is major factor in determining the potential value of an aggregate deposit. Consequently, recognition of landforms will play an important part in the development of aggregate deposit models.

Drainage Texture

In addition to the obvious relationship between many occurrences of sand and gravel and major drainages, the texture of drainage lines can be useful for locating potential deposits of sand and gravel. Drainage texture is a qualitative term used to describe the relative spacing between drainage lines; drainage density is a more quantitative measure of the total length of the streams in an area divided by area. Another quantitative measure of drainage texture is stream frequency, which is the total number of streams in an area divided by the area (Thornbury, 1969).

Although climate and precipitation influence the texture of an evolved drainage pattern, the most important factor is permeability. In general, fine drainage textures (high drainage densities and stream frequencies) are associated with impermeable materials and course drainage textures (low drainage density and stream frequency) with highly permeable

LANDFORMS AND GRAIN SIZE

LANDFORM	*GRAIN SIZE*
BEACH	**Sand (Gravel)**
FLOOD PLAIN TERRACE	**Silt and Clay**
CHANNEL TERRACE	**Sand and Gravel (Clay)**
GLACIAL OUTWASH CHANNEL	**Sand and Gravel (Clay)**
DELTA, MEANDERING RIVER	**Silt and Clay (Sand)**
DELTA , VIGOROUS STREAMS	**Sand and Gravel close to mouth; finer away from mouth**
ESKER	**Sand and Gravel (Clay)**
KAME	**................Sand and Gravel (Clay)**
ALLUVIAL FAN	**Bouldery Gravel and Sand**
DRUMLINS, LODGEMENT TILL	**Compacted Silt and Clay with Gravel and Boulders**

Table IV-4. Association of landform with the type of aggregate (grain size) to be expected (modified from Dunn, 1991, table 4.2). Parentheses indicate minor components.

materials. As discussed above, sand and gravel deposits generally have higher permeabilities than most other materials and could be expected to develop coursely-textured drainage networks. In fact, Thornbury (1969, p.126) noted that "areas covered by such permeable materials as sands and gravels may practically lack surface drainage lines".

Vegetation

Type and distribution of vegetation can provide important information on the nature of the underlying substrate. However, many factors can influence vegetation, including soil type, slope and aspect, climate, and water availability (permeability), so interpretation of images and photographs can be difficult (Ray, 1960). Nevertheless, recognition and identification of plant types can be used to deduce conditions that may indicate the presence or absence of potential sand and gravel deposits. For example, willows indicate wet soil conditions, while poplar indicates much dryer ground; these species, therefore, indirectly suggest permeability conditions in the soils that may be interpreted in terms of the presence or absence of potential sand and gravel deposits. In some areas the presence of jack pine is correlated with sand and gravel deposits (Belcher, 1945).

Selective vegetation growth may provide useful information for delineating areas of potential crushed stone sources. Just as with geologic mapping, inferences about bedrock type and distribution can be made based on vegetation patterns on images and photographs. Vegetation density, and especially variations in vegetation density, are often characteristic of certain rock types within a region. For example, in the Canon City, Colorado, area trees grow only on shale units. Limestones and ultramafic rocks in otherwise highly vegetated areas are often conspicuous because of sparse vegetation density probably due to pH factors, although in other areas limestones may support abundant vegetation (Raines and Canney, 1980). Clearly, vegetation patterns are complicated and the interpretation of vegetation patterns on images and photographs is usually combined with other physical properties and characteristics to deduce probable rocks, soils, and transported surficial deposits in the near-surface environment.

Geologic Setting

The geologic setting of potential deposits of sand and gravel may provide useful information on the probable character and quality of the deposits. For example, an alluvial fan mapped on images or photos could be at the foot of an uplift cored by crystalline rocks or along an excarpment in stratified sedimentary rocks. The nature of these alluvial fan deposits could be expected to be quite different and their usefulness as aggregate would depend on the specific intended use and the overall availability of aggregate in the region.

Geologic maps are usually available for determining the geologic context of potential sand and gravel deposits mapped on images or photographs. In unmapped or poorly mapped areas, the images or photographs themselves may be interpreted to to determine the geologic setting using standard photogeologic mapping techniques.

V. CONVENTIONAL AND TRADITIONAL EXPLORATION

Although the tools and methods used to prospect for natural aggregate deposits are much the same as those used to explore for metals, oil, and natural gas, one important factor distinguishes aggregate exploration from the search for other types of mineral deposits. Metals and petroleum are concentrated into deposits by very special processes operating under unusual circumstances; consequently, metal deposits are relatively rare and are often buried and difficult to find. Sources of natural aggregate, on the other hand, are mostly surficial deposits that are relatively common, abundant, and widespread. Most sand and gravel deposits and sources of crushed stone that have been produced were well exposed, associated with a characteristic landform, and easy to find. In many areas the location of additional deposits is well known and there is little need for exploration to find new sources. Instead, exploration and development is more concerned with identifying those deposits that meet specific criteria and can be produced at a competitive price. In other areas, particularly in urban areas, sources of aggregate have been depleted or built over and exploration becomes essential to satisfy current and future demands (Bottge and others, 1965a).

In most of the United States where aggregate is in heavy demand, exploration and planning are inseparable. Many factors determine whether a deposit can be produced including the location of the deposit, the quality and quantity of the material, the availability of the deposit for production, and the means for transporting the aggregate to market. If a problem is encountered in any of these factors, an otherwise excellent deposit of sand and gravel or a source of crushed stone may be essentially worthless. Although the search for new aggregate deposits begins with locating a potential source, the exploration process must constantly consider the economic, social, political, regulatory, and transportation aspects of development and production of the potential deposit (Dunn, 1991, p. 4-19).

Where Are the Potential Deposits?

The key to locating potential sources of aggregate is an understanding of the geology of the region: mostly the surficial geology and Pleistocene and Holocene geologic history for deposits of sand and gravel, and the complete stratigraphy, origin, and structural history of the region for sources of crushed stone. Geologic maps serve as a primary source of information for beginning the search for new sources of aggregate (Dunn, 1991, p.4.23). The mapped distribution of surficial deposits restricts the area in which sand and gravel deposits are likely to occur, while the distribution of bedrock units suitable for crushed stone, such as granite, limestone, dolomite, and basalt, shown on geologic maps is sufficient for identifying the general areas where the target stone type is at or near the surface (Bottge and others, 1965b). Nevertheless, available geologic maps may lack sufficient detail to confidently select potential targets, and additional reconnaissance or detailed mapping may be necessary to further restrict the areas in which more detailed examination will be conducted.

Aerial photographs are a valuable tool for identifying landforms associated with sand and gravel deposits and sources of crushed stone, although detailed topographic maps are also used. In addition, aerial photos provide an excellent means for preparing reconnaissance geologic maps when none exist or existing maps are too generalized (Schwochow and others, 1974).

Analysis of existing geologic and topographic maps and the interpretation of aerial photos, along with reconnaissance field work, are used to identify one or more sites that are likely to contain useful deposits. The next step is to evaluate the quality of the material at each site and determine how much material is available for production.

What are the Quality and Quantity of Potential Deposits?

The incentive for establishing a new source of aggregate stems from the recognition of a market for the material. To be economic, a deposit of sand and gravel or a source of crushed stone must have characteristics that meet the requirements of the intended market (Marek, 1991). Consequently, detailed exploration includes extensive sampling and testing.

Samples from sand and gravel deposits can be obtained from outcrops, test pits and trenches opened by bulldozers or backhoes, cuttings from power augers, and drill cores (Langer and Glanzman, 1993; Dunn, 1991). Samples of potential sources of crushed stone can be obtained by grab samples from outcrops or quarry walls, rock blasted from outcrops or existing quarries, and drill core. Samples of the potential deposit must then be tested to determine if the physical, mechanical, and chemical characteristics of the material meet the specifications required for the intended use (see Table IV-1).

National specifications exist for sand and gravel and crushed stone used for various applications; however, specific requirements are determined by the users of the material, including federal, state, county, and city governments and the ASTM (American Society for Testing and Materials). Aggregate used in road building and concrete construction are subject to very rigorous specifications, but these specifications, as well as the specifications for other applications, can vary from area to area; U. S. Department of Interior (1981), Barksdale (1991), and American Society for Testing and Materials (1980) describe many of the tests and factors that must be considered for concrete aggregate. The lack of standardization of specifications poses a significant problem for aggregate producers providing material from the same operation to users with different specifications (Tepordei, 1993a; 1993b). Consideration of the possibility and cost of meeting varying specifications is an important economic factor that is an integral part of exploration. The areal variations in specifications and the differing specifications for different applications are also factors that must be considered in the quantitative modeling of potential aggregate deposits for regional assessment and planning purposes.

Having established a potential source of aggregate that meets the specifications of the intended application (market), it must be determined if the quantity of the potential source is sufficient to merit production. Calculating the reserves of a sand and gravel deposit or a source of crushed stone involves determining the three-dimensional extent (volume) and variability (yield of usable material) of the deposit. Dunn (1991, p. 4-37 - 4-44) describes the geologic information required to calculate reserves, the methods for calculating various types of reserve information, and the critical nature of the reserve information in evaluating the economic risk of subsequent permitting and production processes.

Estimating the volume of a deposit, particularly a sand and gravel deposit, is a complex process that involves determining the configuration of the deposit. Drilling, coring, augering, and trenching are routine methods for determining the thickness of the deposit and overburden, as well as the vertical variation in the deposit required for accurate reserve estimates. Seismic, ground-based resistivity, ground-penetrating radar, and electromagnetic measurements are especially useful supplements for extrapolating the lateral extent and vertical variation of the deposit between drill holes, pits, and trenches (Odum and Miller, 1988, p. 2-3; Dunn, 1991, p. 4-39). Detailed geologic cross sections and isopach maps derived from the various data provide the primary information necessary for calculating reserves.

Are the Potential Deposits Available?

Exploration involves not only identifying suitable deposits for specific markets, but identifying suitable deposits that may be available for production. Numerous factors can render an otherwise excellent aggregate deposit worthless: zoning, regulatory and political factors, ownership, social and environmental concerns, reclamation requirements. Consequently, these factors must be addressed as a part of the exploration process concurrently with the evaluation of the quantity and quality of the potential deposit. These factors must also be addressed in the preparation of quantitative models for assessing the regional potential for future aggregate development.

What Type of Processing is Required?

Depending on the characteristics of a particular deposit, some processing is required before the material mined from a deposit is suitable for use. Processing may involve crushing, screening, sorting, washing, and, blending of particle sizes for specific applications (Langer and Glanzman, 1993). Some of these processes require substantial amounts of water that must be available on site. In addition, land must be available near the site to accommodate the processing plant; planning for the processing yard is an integral part of exploration.

Getting the Aggregate to Market

The area of exploration for new sources of aggregate, whether sand and gravel or crushed stone, is limited by the location of the market for the aggregate. Because aggregate is a low value-high volume product, the economic viability of a deposit is strongly controlled by the cost of transporting aggregate to the market (Dunn, 1991, p. 4-20). Indeed, transportation costs alone may exceed the value of the aggregate, doubling or even tripling the cost of the aggregate at the quarry site (Tepordei, 1993a, 1993b; Bottge and others, 1965a, p. 108). Although costs for haulage are difficult to determine in the early phases of exploration, planning for moving the aggregate to market must be an integral part of the exploration process.

VI. AIRBORNE METHODS

With the exception of aerial photos, airborne geophysical and remote sensing methods have not been routinely used in the exploration for sand and gravel or sources of crushed stone. Nevertheless, airborne methods have been used for geologic mapping and the study of surficial materials, and the results of these studies indicate that airborne geophysical and remote sensing techniques could have significant application to the exploration and assessment of potential aggregate sources on local and regional scales. In addition, several studies have tested remote sensing and airborne geophysical techniques for detecting and mapping various types of sand and gravel deposits in different geologic environments.

Geophysics

Contrasts in physical properties detectable by geophysical techniques form the basis for methods of exploring and assessing the potential for sand and gravel deposits and sources of crushed stone. The high porosity and permeability of sand and gravel deposits creates highly conductive materials when the open spaces are filled with fluid (water) and low conductivities when filled with air or the water is frozen. These conductivity contrasts with underlying bedrock are generally detectable by airborne resistivity measurements. Geophysical techniques applicable for detecting and mapping sources of crushed stone are the same techniques used to supplement geologic mapping: airborne resistivity, magnetics, and gamma-ray spectrometry.

Resistivity

Ground-based resistivity measurements have been used for many years to define the depth of overburden and the thickness and lateral extent of sand and gravel deposits. The utility of ground-based data suggested that resistivity measurements obtained from an airborne platform might allow much larger areas to be surveyed, including areas with difficult access, with a potential cost savings to the exploration process. By 1964, a system operating at VLF (very low frequency) frequencies was commercially available (Paterson and Ronka, 1971), and by 1969 several commercial airborne VLF systems were being flown, mostly to search for buried sulfide orebodies (McNeill and Labson, 1991).

In the early 1970's, the potential of airborne VLF surveys for detecting and mapping buried gravel deposits was tested in Saskatchewan, Canada (Culley, 1973). High resistivity anomalies corresponding to ground-based anomalies, checked by power augering a series of 25-foot-deep holes, identified shallowly-buried sand and gravel. The high resistivities associated with the deposits were due to interstitial water being frozen in the -20° to -30°F temperatures during the February survey or because the deposits were well drained.

At about the same time, the Ontario Department of Mines and Northern Affairs conducted numerous airborne VLF surveys of selected townships in the Matheson and Toronto areas to map the Pliestocene geology, particularly the overburden, bedrock topography, and gravel deposits (Middleton, 1977). To test different depths of penetration, surveys were flown at both 17.8 kHz VLF (200 ft [60m] penetration) and 1010 kHz broadcast (25 ft [8 m] penetration) frequencies in the Torono area. Results of these surveys suggested that areas of well-drained sand and gravel deposits could generally be outlined by high resistivity anomalies. However, decreasing the 300-m-flightline spacing to 200 m was suggested to obtain the resolution necessary to detect many small, but potentially economic deposits, in the region (Middleton, 1977). These studies, as well as numerous other Canadian studies (Edwards and Chao, 1989), have demonstrated that airborne resistivity studies have a definite place in the exploration and assessment of sand and gravel resources in Canada. The same approach should be effective in portions of the United States as well.

Although airborne resistivity studies are more expensive than aerial photo or topographic map analysis, the added cost may be more than compensated for by the added capability of airborne resistivity studies to detect the presence of sand and gravel deposits buried by up to 30 m of overburden (Culley, 1974; Middleton, 1977; Fraser, 1978; Edwards and Richardson, 1989). In areas lacking surficial deposits or where surficial deposits have already been depleted, the capability of finding buried gravel deposits may be critical to maintaining a continued supply.

Aeromagnetics

Airborne magnetic surveys are not normally flown for the purpose of mapping surficial deposits, although placer magnetite deposits can be found using airborne data (Hoover and others, 1992). To the contrary, airborne magnetic measurements are primarily used to detect and map the distribution of bedrock lithologies based on their magnetic properties (Cady, 1989). For example, aeromagnetic maps are a powerful tool for mapping the subsurface extent of exposed plutons and finding buried plutons (Grauch and others, 1988). This capability may have application in the identification and mapping of bedrock suitable as a source of crushed stone or as a method for tracing the extent of a known source beneath surficial cover and overburden.

Radiometrics

Airborne gamma-ray measurements obtained with scintillometers or multichannel spectrometers detect the presence of radioactive potassium, uranium, and thorium within approximately 50 cm of the surface. The primary use of airborne gamma-ray surveys has been in the exploration for uranium, with secondary uses for coal, lignite, radioactive heavy metal, and phosphate exploration. In addition, data from airborne gamma-ray surveys have proved useful for detecting and mapping radioelement haloes around hydrothermal mineral deposits, especially the distribution of potassic alteration, and in differentiating between felsic (more radioactive) and mafic igneous rocks (Hoover and others, 1992). These capabilities may have applications in the tracing of known sources of crushed stone based on their radioactivity and in helping to identify surficial deposits derived from different sources, which may have implications for deposit quality estimates.

Airborne radiometric data were acquired for the entire United States at either 1, 2, 3, or 6 mile flightline spacing as part of the NURE program. A national digital data set grid at a 3 kilometer grid spacing (Phillips and others, 1993) is available for analysis as part of regional aggregate potential assessment investigations. Alternatively, data from all or part of individual NURE 1^o x 2^o quadrangle surveys could be reprocessed and analyzed to obtain additional detail in some areas.

Remote Sensing

Remote sensing instruments measure reflected or emitted radiation in the visible, near-infrared, thermal infrared, or microwave portions of the electromagnetic spectrum to obtain information about the earth's surface from a distance. A few of the instruments measure a profile of the reflected or emitted radiation along a line on the ground; however, most modern instruments are scanners that acquire the data in an image format consisting of an array of picture elements (pixels) that covers a certain geographic area dependent on the instrument and the data acquisition parameters. The information derived from remote sensing observations consists of two types: (1) information dependent on the physical properties (composition) of the surface materials (spectral reflectance, thermal emissivity, dielectric constant, etc.) and (2) indirect spatial information about the surface configuration (landforms, geologic structures, distribution of surface materials, etc.). Both types of information may be useful for studying potential sand and gravel deposits and sources of crushed stone. Descriptions of many geologic applications of remote sensing data are in Watson and Knepper (in press).

Modern remote sensing systems acquire data from two types of platforms: airborne and satellite. Data are collected in three primary spectral bands: (1) visible and near-infrared, (2) thermal infrared (mid-infrared), and (3) microwave. Most modern data is collected in digital form and can be processed and analyzed using computer techniques (Table VI-1). Watson and Knepper (in press) describe the characteristics of current airborne and satellite systems and their data and discuss systems that are in development and will be available in the future.

Visible and Near-Infrared

Aerial photographs are the acknowledged remote sensing data of choice in the aggregate industry for reconnaissance geologic mapping to determine the distribution of potential sand and gravel deposits and sources of crushed stone (Dunn, 1991; Langer andGlanzman, 1993; Tepordei, 1993a). Photogeologic methods and techniques for interpreting aerial photos are applicable to the interpretation of digital airborne and satellite images as well; however, the digital form of the data and the multiple bands of spectral information allow computer processing and analysis to extract additional information not available in aerial photographs. While the relatively high resolution of aerial photos favors their use for detailed site studies, the digital format, multispectral form, and uniform regional

SATELLITE SYSTEMS		
Status	Spectral region	**Systems**
Operational	visible and near-infrared	Landsat-MSS,TM SPOT *AVHRR*
	thermal infrared	Landsat-TM (day) *AVHRR*
Experimental	thermal infrared	*HCMM (day,night)* Landsat-TM (night)
	microwave (radar)	Seasat SIR-A,SIR-B
	visible and near-infrared	Soyuzkarta photography
Future	visible and near-infrared & thermal infrared	*JERS* *MODIS-EOS*
	visible and near-infrared	HIRIS-EOS (spectrometer)
	microwave (radar)	Radarsat SAR-EOS
AIRBORNE SYSTEMS		
Programmatic (operational)	visible and near-infrared	NHAP (photography)
	microwave (radar)	USGS Radar Program
Experimental	visible and near-infrared	AIS,AVIRIS (spectrometers)
	visible and near-infrared	TMS
	multispectral thermal infrared	TIMS
Commercial	visible and near-infrared	GERIS (spectrometer)
	multispectral thermal infrared	Geoscan,Daedalus
	visible and near-infrared & thermal infrared	Daedalus (TMS)

Table VI-1. Remote sensing systems with possible applications for detecting and mapping sand and gravel deposits and sources of crushed stone. Modified from Watson and Knepper (in press, Table 1). Systems only producing data with greater than 100 m ground resolution are shown in italics.

coverage of some airborne and satellite data are attractive for the more regional approach used in mineral resource assessments.

In an early study to locate construction materials for a road across 650 km of the Kalahari Desert in the Republic of Botswana, Beaumont (1979) successfully used Landsat multispectral scanner (MSS) data to rapidly identify potential calcrete deposits over a very large area along the route. Both black-and-white images of the single bands and color composites formed by projecting three registered single band images with red, green, and blue filters (optical processing) were analyzed for tonal and color variations indicative of calcrete on or immediately below the surface; the color composite images were best for detecting differences in sand color that are associated with calcrete. The MSS images also provided a means for rapidly evaluating landforms and geomorphological relationships (terraces and paleodrainages) associated with calcrete over the entire region. Because of the synoptic view provided by the MSS images, the satellite data were also instrumental in selecting and plotting the route for the new road.

Shortly after the study by Beaumont (1979), the need for an additional 1000 km of feeder roads in Botswana was recognized and a project using aerial photographs and Landsat MSS images to locate calcrete deposits for road construction along the selected routes was initiated by the government (Henry, 1989). At 1980 prices, the cost of computer compatible tapes (CCT) of the 29 Landsat MSS scenes necessary to cover the project area was too high, so off-the-shelf negatives of the standard false color composite images (bands 7, 5, and 4 color-coded red, green, and blue, respectively) were used to make 1:250,000-scale color prints to use for interpretation. The results of the study showed that using satellite images and aerial photos is more effective and rapid than ground-based prospecting. Toward the end of the project, an additional 500 km of new route needed to be quickly evaluated for calcrete deposits and digital Landsat Thematic Mapper (TM) data were available for the study area. The TM data were computer processed to enhance tonal boundaries and emphasize the spectral characteristics of known calcrete deposits. The enhanced TM images improved the interpretation of features that were not resolved on the MSS images (80 m ground resolution compared to 30 m resolution of the TM data), although aerial photo analysis was necessary to map some of the smaller features. The synoptic view provided by the satellite images was invaluable because many of the discovered calcrete sources occur outside the area of previous searches.

In a study to apply Landsat MSS image data to the search for more conventional gravel deposits, West and others (1976) tested digital classification techniques on data from three seasons to identify the gravel-rich areas within the Shelbyville terrace along the Wabash River north of Terre Haute, Indiana. Non-supervised classification techniques produced the best results based on follow-up drilling and resistivity studies. They conclude that the application of MSS data, combined with available geologic, soil, and photographic information, can locate areas with a high potential for gravel deposits and that this combined approach should save time and expense compared to conventional methods alone.

Digitally classifying Landsat MSS image data of north-central Indiana into 11 spectral classes, Peterson and others (1975) recognized a 40-mile strip of dark soils that defines an east-trending buried Pleistocene river valley. These valleys are important sources of groundwater and sand and gravel deposits in this region. Paleochannels of the ancient Danube River near Budapest, Hungary, containing large commercial deposits of sand and gravel are expressed as lineaments on digitally enhanced Landsat MSS images (U.S. Geological Survey, 1981).

In northwestern Alberta, Canada, Gorecki and others (1989) investigated the spectral characteristics of gravel deposits on Landsat TM image data as a function of cover type to devise a means of exploring for new deposits. Supervised classifications, based on numerous known but undisturbed deposits, were conducted on principle component data and the single band data. The areas outlined by visual interpretation on the classification images were studied with aerial photos to better delineate the boundaries, and available topographic and vegetation maps, along with the air photos, were used to assist in judging whether the potential for aggregate in the classified areas is low, medium, or high. Gorecki and others (1989) emphasize that, although their methods were successful in locating gravel deposits, additional research on alternative image classification schemes and image enhancement techniques is necessary to increase the overall effectiveness of the exploration process. In addition, they recognize the need to integrate all available information (air photos, geologic maps, geophysical data, drill hole data, vegetation and landuse maps, radar imagery, etc.) into the process, preferably in a GIS system, to allow data manipulation and modeling.

The addition of water to particulate material lowers the albedo of the material. Using the Hapke bidirectional reflectance model, measured radiance from TM band 4 data from wet and dry times of year, atmospheric parameters measured during the satellite overpass, and a digital elevation model, Skirvin (1991) computed the single scattering albedo (SSA) for the Whetstone Mountains, Arizona, for wet and dry seasons to look for areas of high soil moisture related to groundwater movement along pediment surfaces. After accounting for changes in the SSA between wet and dry times of year caused by differences in atmospheric characteristics, illumination, and vegetation, an SSA difference map was prepared to show areas where the change in SSA between wet and dry seasons was significant at the 0.05 level by the Student T-test. These areas of significant SSA change are interpreted as indicating areas of groundwater movement shown by elevated soil moisture (reduced albedo) during the wet season. This concept could also be applied to searching for low soil moisture changes due to rapid infiltration often associated with sand and gravel deposits.

Working under the hypothesis that shallowly buried gravel deposits in the Chatham, Ontario, Canada, area will have better drained soils developed over them, George and others (1986) attempted to identify and map tonal anomalies caused by the drainage phenomenonon on standard color infrared photos and on digital multispectral image data in the visible and near-infrared obtained from an airborne scanner. Most of the mapping was done on the color infrared photos, but analysis of the multispectral imagery was useful for enhancing tonal boundaries that were only partly discernable on the photos. Excellent discrimination of surficial materials was obtained from color composites made from 3 of the 8 available bands of mulstispectral data (456-518 nm, 522-735 nm, and 793-893 nm) and 3 band ratios (522-735 nm/793-898 nm, 522-735 nm/751-787 nm, and 456-518 nm/751-787 nm).

Remote sensing methods applicable to the detection and mapping of potential sources of crushed stone are those methods that address the problem of bedrock geologic mapping. Studies that test, develop analytical methods, and apply digital airborne and satellite remote sensing data in the visible and near-infrared portion of the spectrum to bedrock geologic mapping are abundant in the remote sensing literature. Watson and Knepper (in press) present a general overview of the capabilities, limitations, and future trends of remote sensing in the visible and near-infrared for geologic and lithologic mapping. Abrams (1980) and Colwell (1983, p. 1763-1777) discuss geologic and lithologic mapping theory and methods, as well as the results from numerous investigations; the reader is directed to the abundant references in these publications for additional reading on specific topics.

The currently emerging tool of imaging spectrometry, not thoroughly discussed in the above overviews, deserves some additional discussion. Imaging spectrometer systems (i.e. Airborne Visible and Infrared Imaging Spectrometer - AVIRIS) acquire radiance data in many spectral bands in the visible and near-infrared (224 for AVIRIS) for each pixel on the ground. With these data calibrated to spectral reflectance, spectral curves of near-laboratory quality can be prepared and analyzed for each pixel on the ground. The data have the spectral resolution necessary for identifying the diagnostic absorption bands that characterize many specific mineral species and vegetation types and the spatial resolution (less than about 20 m) required for reasonably detailed mapping (Goetz and others, 1985; Clark and others, 1990). Consequently, imaging spectrometer data may have applications in the search for specific rock types for use as crushed stone and for the detection and mapping of potential sources of sand and gravel. In addition, the capability of detecting specific mineral species may be useful in evaluating the possible quality of potential deposits (for example, the mineralogy of carbonate units or the presence of deleterious material). Airborne imaging spectrometer data are currently only available for selected local sites within the United States and a satellite-borne instrument with the ground resolution necessary for mapping potential sources of aggregate is not planned for at least another decade; commercial airborne data can be acquired, but the cost is probably prohibitative for most current mineral assessment projects. Nevertheless, research using available data to develop analysis and interpretation techniques for application to the assessment of potential for sand and gravel deposits and sources of crushed stone should be pursued so that when these potentially powerful data are more regionally available they can be quickly integrated into the assessment process.

Thermal Infrared

Studies in central Indiana demonstrating the existance of diurnal temperature differences between sand and gravel deposits (outwash plain, kame, esker, and valley-train terrace) and adjacent clay till (Carr and Blakely, 1966; Carr and Webb, 1967) provide the rationale for the application of airborne thermal infrared data to the detection and mapping of exposed and shallowly buried sand and gravel deposits. Temperatures measured by thermister probes at 30 cm depth at several sites over both sand and gravel deposits (outwash plain) and clay till during a period of months (May 1965-February 1966) showed that mean diurnal temperature differences over that clay till were consistently greater (95 percent certainty) than over the sand and gravel deposits, although it was impossible to distinguish one material from the other by a single set of temperature measurements taken at any particular time of day (Carr and Blakely, 1966). Diurnal temperature measurements at 30 cm depth made in August 1966 (kame and esker) and October 1966 (terrace) between sand and gravel deposits and adjacent clay till revealed dirunal temperature changes over the sand and gravel deposits to be consistently greater than over the clay till (Carr and Webb, 1967). The sites in both studies were selected to minimize the effects of vegetation cover, ground surface color, and topographic position and measurements were taken to minimize the effect of solar radiation (clear days with little wind).

The opposite results obtained by these two studies is attributed to differences in the thermal diffusivity of the sand and gravel deposits and the clay till due to soil moisture content; high soil moisture content reduces the thermal diffusivity and lowers the diurnal temperature changes that occur. High soil moisture content of the sand and gravel of the outwash plain due to a high water table caused relatively small changes in the diurnal temperatures compared to the clay till, while the well-drained (low water table) sand and gravel of the esker, kame, and terrace deposits produced large changes in the measured diurnal temperatures relative to the clay till (Carr and Webb, 1967). The differences in the thermal properties of the sand and gravel and the clay till in these studies as expressed by the dirunal temperature differences suggest that airborne thermal infrared data might be useful for locating potential sand and gravel deposits.

The application of airborne thermal infrared data to detecting and measuring differences in soil moisture at the surface is well documented in the literature (Chilar and others, 1977; Idso and others, 1975; Schmugge and others, 1980; Jackson and others, 1978 and many others). Water has a much larger affect on the thermal properties of soils than does the mineral composition of the soil. Consequently, the surface temperatures measured by airborne thermal infrared data may be related to soil moisture. All things being equal, high soil moisture increases the thermal inertia of the soil so that diurnal temperature differences are smaller than for comparable soils with less soil moisture. However, things are not always equal and interpretation of airborne thermal infrared temperature measurements also must consider a variety of additional influencing factors such as solar radiation history (slope effects), wind, humidity, air temperature, vegetation cover, precipitation history, and the time of day the data were acquired.

Singhroy and Barnett (1984) tested whether differences in soil and drainage textures developed over shallowly buried gravels and clay tills would produce different rates of infiltration that could be detected as temperature differences due to soil moisture differences on airborne thermal infrared data. Daytime airborne thermal infrared data were acquired 12 hours after a 6 cm rainfall over an area in southern Ontairo, Canada, containing complex surficial deposits including glacial and glacial outwash gravels. Analysis of the thermal infrared imagery, corroborated by ground geophysical studies, drill hole data, and temperature measurements during the acquisition of the thermal infrared data , showed that the outline of shallowly buried gravel deposits could be delineated on the thermal infrared imagery by the warmer temperatures of the well-drained soils developed over the gravels.
Gravels in stream channels and active alluvial fans in Death Valley, California, can be discriminated from surrounding materials on daytime and nighttime airborne thermal infrared images and Landsat 4 thermal images (Sabins, 1984). The temperature differences between the gravels and the surrounding materials is probably due to the lower density (higher porosity) of the gravels and relatively low soil moisture in the arid climate, but no information is available on the surface conditions during the data acquisition or the short-term meteorological conditions prior to data collection.

In addition to lithologic discrimination based on temperature differences on broadband thermal infrared image data, laboratory emission spectra of rocks (Lyon, 1965; Lyon and Patterson, 1966; Vickers and Lyon, 1967) revealed that mafic rocks could be broadly separated from felsic rocks based on the wavelength position of emission minima (reststrahlen minima) in the thermal infrared due to differences in silica content (fig. VI-1). Regional satellite data from the NOAA-7 Advanced Very High Resolution Radiometer (AVHRR) and the Nimbus 5 Surface Composition Mapping Radiometer

(SCMR) were used by Blodget and others (1984) to prepare multiple channels of coregistered thermal infrared image data to test the utility of multispectral thermal data for geologic applications. On color composite, ratio, principle component, and unsupervised classification images broad areas of sand, gravel, or limestone could be discriminated from the surrounding materials; however, the 1 km ground resolution makes these data unsuitable for most assessment applications.

Studies of data from a higher resolution (10-30 m) airborne multispectral thermal infrared scanner, the NASA Thermal Infrared Multispectral Scanner (TIMS), suggest possible applications to assessing potential aggregate sources; Kahle and Goetz (1983) provide an overview of the 6-band TIMS system and the potential for obtaining mineralogic information from multispectral thermal infrared data.. Scholen and others (1985) concluded that 30-m TIMS data could be used to locate buried gravel deposits on National Forest land in Louisiana by processing the data to detect pixels exhibiting a quartz signature associated with the gravels. Analysis of color composite images prepared from principal component, hue-saturation-intensity, and decorrelated 12 m TIMS data of the Lunar Craters area, Nevada, lead MacDonald (1991) to conclude that enhanced TIMS data have good potential for discriminating surficial sediment types and basalts and related Quaternary volcanic rocks, as well as carbonate rock units. Using 6 bands of thermal infrared data (6 m resolution) from another airborne multiband scanner, the Geoscan Mk II, Lyon and Honey (1991) demonstrated that three-band color composites prepared from the raw data could define quartz-rich areas from garnet-pyroxene areas and that quartz-rich areas could also be easily found using simple band-difference images.

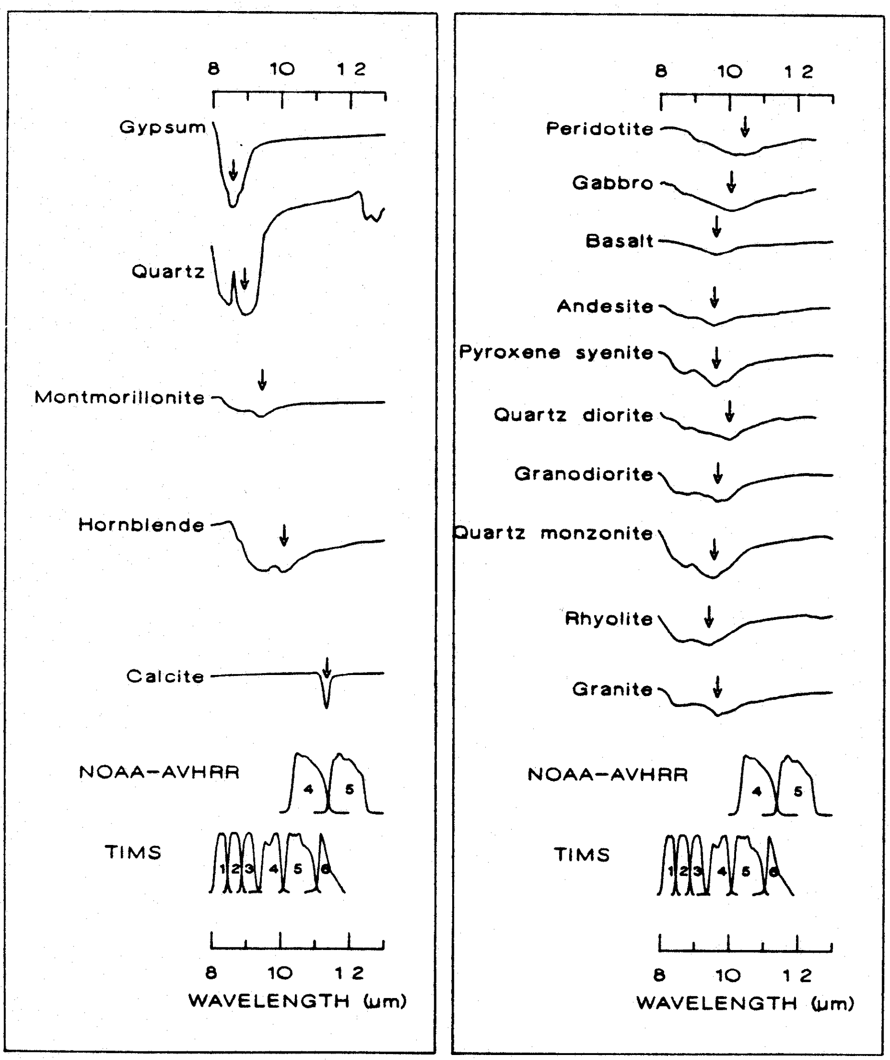

Figure VI-1. Laboratory emission spectra of some common minerals and igneous rocks (from Watson and Raines, 1987). Arrows indicate emission minima that can be used to broadly discriminate between the different materials. Curves are offset vertically to more clearly display the emission minima. Detector responses for the different bands on the NOAA-AVHRR and TIMS thermal infrared imaging systems are shown below the spectra.

While the data from the airborne multispectral thermal infrared scanners seems to hold some potential for applications in the assessment of potential aggregate sources, both sand and gravel and sources of crushed stone, the rather restricted geographic coverage of existing data puts some limits on current use. Multispectral thermal infrared image data from the ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) system, scheduled for launch on a National Aeronautics and Space Administration's Earth Observing System (EOS) satellite in 1998, will provide worldwide 90-m resolution data that may hold some potential for the study of natural aggregate deposits (National Aeronautics and Space Administration, 1991, p. 55).

Microwave (Radar)

The practical application of airborne or satellite-borne remote sensing systems operating in the microwave portion of the electromagnetic spectrum to studies of potential sources of aggregate is limited to side-looking radar systems. Although microwave (radar) energy is sensitive to the dielectric constant of the surface materials, other effects dominate the measured radar return to the extent that little true compositional information is directly available from radar imagery. On flat surfaces, radar return is strongly controlled by the texture (surface roughness) of the surface materials; generally, fine textures produce low radar returns and coarse textures produce higher returns (Singhroy, 1992). In general, tonal differences on radar images of sparsely vegetated flat terrain may, therefore, be interpreted in terms of possible gravels (bright) as opposed to more clay-rich surficial materials (dark). In areas of more relief, the shadowing effect due to topography makes radar images useful for mapping subtle to strong landforms associated with gravel deposits (terraces, alluvial fans, glacial and glacial outwash features, etc.), as well as other features related to geologic structures and the surface expression of bedrock lithologic units.

To study the effects of surface roughness on radar backscattering, Schaber and others (1976) analyzed L-band (25 cm) airborne side-looking radar images of the salt flats and gravel fans of Death Valley, California; the radar data were acquired at 45^o- 90^o depression angle to reduce radar shadowing and increase the signal-to-noise ratio of the data. Qualitative measurements of radar backscatter based on the gray tones on the image film (high backscatter is bright) showed several surficial geologic units of differing roughness characteristics. The three brightest units (highest backscatter) are massive salt, salt-rich silty sediments, and silt and sand lake deposits impregnated with carbonate salts that are rough because of the presence of irregular solution cavities in each of the units. Loose varnished and unvarnished gravels of pebble to cobble size on the giant alluvial fans produce an intermediate radar return, and a transitional zone at the base of the one fan from darker to lighter gray on the radar image corresponds to a distinct size gradation of the gravel from finer to coarser toward the head of the fan. The oldest of the fan gravels are fitted together and form a desert pavement that produce a low radar return (smooth). Floodplain deposits along present streams are the smoothest surfaces in the region and produce the lowest radar returns.

Airborne L-band multipolarization radar image data of the Death Valley region were combined with Landsat Multispectral Scanner (MSS) image data by Daily and others (1979) to increase the discrimination of surficial materials. A color composite image was prepared from (1) a Landsat MSS total intensity image using the four MSS bands (red), (2) the L-band VV (vertical transmit/vertical receive) image (green), and (3) the L-band VH (vertical transmit/horizontal receive) image (blue). The total intensity MSS image discriminates materials based on their overall reflectance in the visible and near-infrared. The L-band VV image is sensitive to the size of the scatters (boulders on the gravel surfaces), while the L-band VH image is mostly effected by the density of the scatters on the surface. The combination of the Landsat MSS data with the L-band radar data provides complementary information. For example, gravel surfaces lacking desert varnish on alluvial fans of two ages appear the same on the Landsat MSS total intensity image, but the roughness of the fan surfaces are easily detected on the L-band radar images. Conversely, fan surfaces with different degrees of desert varnish are easily discriminated on the MSS total intensity image even though the roughness characteristics of the fans are identical.

Landsat MSS image data were also combined with coregistered Seasat SAR (synthetic aperture radar) satellite data by Merifield and others (1984) to map alluvial deposits in the eastern Mojave Desert. The most useful combination was a color composite formed from Landsat MSS band 4 (red), Landsat MSS band 7 (green), and Seasat data (blue). The results indicate that the color composite allowed the mapping of more surficial units, based on both reflectance and roughness characteristics, than could be mapped on either of the individual data sets.

Singhroy and others (1989) evaluated C-band airborne side-looking radar images with HH polarization and 6-meter ground resolution for mapping Quaternary glacial and associated deposits at sites in Ontario and Manitoba, Canada. Using radar images acquired in the spring, tonal differences in areas of exposed soils could be interpreted in terms of soil moisture differences controlled by the texture of the deposits, allowing the nature of the deposits to be inferred. In the rougher terrain, the interpretation of tonal differences on the radar images was less effective; however, a color composite image combining stretched radar data, Landsat Thematic Mapper band 4, and the first principal component of all the visible and near-infrared bands of TM data permitted the delineation of sand-silt till, glaciolacustrine silt and clay, and beach sand and gravel. This color composite image was also useful in delineating units in forested terrain where vegetation is associated with the type of surficial deposits. The most reliable information extracted from the radar images was the interpretation of landforms from which the nature of the surficial deposits could be indirectly inferred.

VII. NATURAL AGGREGATE AND THE USGS ASSESSMENT PROCESS

The manner and effectiveness of integrating remote sensing and airborne geophysics into the exploration and assessment for natural aggregate resources is tied to the types of information that are required. To many geologists and aggregate industry producers, the exploration for new or expanded sources of natural aggregate is a relatively simple and straightforward process. The widespread occurrence of sand and gravel deposits or suitable bedrock sources for crushed stone in many parts of the United States, and the easily recognizable landforms associated with these deposits, makes this viewpoint understandable. In many areas, the locations of these natural aggregate sources are already well known by the industry and producers may simply look at nearby abandoned pits and exposed deposits that have never been developed. Identification of new sources to produce consists mainly of airphoto analysis, drilling and trenching, and ground geophysics to determine the volume of material present and sampling and testing to evaluate the deposit characteristics and composition in terms of the market specifications. Social and political aspects also contribute to the potential availability of otherwise exploitable sources, and the cost of transporting the aggregate to the users is a major factor in deciding whether a deposit can be economically produced.

In other areas of the United States, sources of natural aggregate, particularly coarse materials, are very rare, or non-existent, and the search for new sources is extremely difficult. Some deposits are buried or lack any characteristic landform; these deposits require the use of many of the techniques and methods used to explore for metallic mineral deposits. The absence of local sources of natural aggregate requires that remote sources be transported to the local market, usually at considerable expense, or that inferior or man-made materials be employed.

The availability of natural aggregate to the construction industry at a reasonable cost is a vital factor in both local and national economies, and as current supplies are consumed, new supplies must be found. To ensure a continued flow of aggregate, there is a growing need to plan for the intelligent use of existing sources. Planning requires a knowledge of the distribution and quality of potential aggregate sources such as might be gained through the use of mineral resource assessment techniques like the three-part quantitative assessment method used by the USGS (Singer and Mosier, 1981; Singer, 1993; Cox and Singer, 1986).

The USGS three-part quantitative assessment method consists of (1) delineation of areas permissive for the occurrence of a specific type of deposit based on a descriptive model of that deposit type, (2) statistical representations of the grade and tonnage of known deposits of the specific type (grade and tonnage models) that provide a means for determining a value of the resource, and (3) the estimation of the number of undiscovered deposits of the specified type within the permissive areas. This type of analysis can presently be done only for the 69 mineral deposit types (mostly base and precious metal deposits) for which descriptive and grade and tonnage models have been developed (Cox and Singer, 1986; Bliss, 1992). There are presently no descriptive or grade and tonnage models for natural aggregate deposits and, because of some fundamental differences between natural aggregate and metallic mineral deposits, the three-part

USGS methodology cannot be directly translated to natural aggregate. Significant modifications to the procedure will be necessary to accomodate the nature of natural aggregate deposits and the aggregate industry.

Delineating Permissive Areas

The identification of areas that are permissive for the occurrence of a specific type of mineral deposit is based on the descriptive model for that type of deposit. There are no fewer than eleven types of deposits in which gold is a major commodity and each of the deposit types has a descriptive model that is used by mineral resource assessors to delineate areas that are permissive for that type of deposit (Cox and Singer, 1986). The first task involved in integrating natural aggregate deposits into the USGS three-part assessment procedure is the identification of different types of natural aggregate deposits and the preparation of descriptive models for each type.

This will not be a trivial task because criteria for describing how deposits differ have not been established. Clearly, bedrock sources of crushed stone are fundamentally different from sand and gravel deposits, but within each of these major groups of natural aggregate sources, the characteristics that both distinguish one type of deposit from another and are important to the aggregate industry and resource assessment must be identified.

The rigid format of the descriptive models in Cox and Singer (1986) is poorly suited for distinguishing between different types of natural aggregate deposits (Table VII-1A). While the major catagories might be applied to natural aggregate deposits, the subheadings under **Geological Environment** and **Deposit Description** are mostly inappropriate. For example, the subheadings *Rock Types* and *Textures* under the major heading **Geological Environment** refer to the host rocks of the deposit, and there are no host rocks for sand and gravel deposits; the rocks are the deposit in most sources of crushed stone. Other subheadings, such as *Alteration*, *Ore Controls*, and *Geochemical Signature*, seem to have little value for distinguishing different types of natural aggregate deposits. The formats of the descriptive models contained in Bliss (1992) seem to be more flexible, but even the model for a sedimentary deposit (oolitic ironstone; Maynard and Van Houten, 1992) contains descriptive catagories that are of little or no value in describing natural aggregate deposits (Table VII-1B).

If natural aggregate is to be integrated into the USGS three-part mineral resource assessment process, a high priority must be placed on (1) identifying the geologic criteria that distinguish different types of deposits and (2) developing descriptive models that are suitable for defining areas that are permissive for those deposits.

DESCRIPTIVE MODEL FORMATS

A.
General
Cox and Singer (1986)

APPROXIMATE SYNONYM

DESCRIPTION

GENERAL REFERENCE

GEOLOGICAL ENVIRONMENT

- *Rock Types*
- *Textures*
- *Age Range*
- *Depositional Environment*
- Tectonic Setting(s)
- *Associated Deposit Types*

DEPOSIT DESCRIPTION

- *Mineralogy*
- *Texture/Structure*
- *Alteration*
- *Ore Controls*
- *Weathering*
- *Geochemical Signature*

EXAMPLES

B.
Oolitic Ironstones
Maynard and Van Houten (1992)

BRIEF DESCRIPTION

- *Synonym*
- *Description*
- *Typical Deposits*
- *Relative Importance*
- *Distinguishing Features*

Commodities

- *Other Commodities*

Associated Deposit Types

REGIONAL GEOLOGIC ATTRIBUTES

- *Tectonostratigraphic Setting*
- *Regional Depositional Environment*
- *Age Range*

LOCAL GEOLOGIC ATTRIBUTES

- *Host Rocks*
- *Associated Rocks*
- *Ore Mineralogy*
- *Gangue Minerals*
- *Structure and Zoning*
- *Ore Controls*
- *Isotopic Signatures*
- *Structural Setting*
- *Ore Deposit Geometry*
- *Alteration*
- *Effect of Weathering*
- *Effect of Metamorphism*
- *Geochemical Signatures*
- *Geophysical Signatures*
- *Overburden*

Table VII-1. Major and minor topics covered in representative descriptive mineral deposit model formats used by the USGS (Cox and Singer, 1986; Bliss, 1992).

Grade/Tonnage Models

Grade and tonnage models are prepared for each mineral deposit type that is defined by a descriptive model. The grade and tonnage models are statistical representations of the variation in the deposit size and the quantity of mineral commodity based on production and reserve figures for well explored deposits that fit the descriptive model (Singer, 1993). Grade and tonnage models exist primarily for base and precious metal deposits (Cox and Singer, 1986; Bliss, 1992) and a few selected industrial mineral deposits (Orris and Bliss, 1992).

The concept of grade of a deposit (the relative quantity or percentage of the mineral commodity contained in the ore), along with the size of the deposit (the number of tons of ore), is useful for comparing the value of different mineral deposits producing the same commodity because the final product from each deposit is the same and because a dollar value is easily assigned to the final product. For example, the final product from a gold mining operation, after mining, milling, smelting, etc., is a bar of gold containing a known number of ounces of gold (flasks of mercury, pounds of copper, etc.); it is relatively simple to compare the number of gold bars (or the number of ounces of gold) being produced by different mining operations. Furthermore, the value of each ounce of gold is set by a worldwide market and does not vary greatly from day to day or from area to area; the value of an ounce of gold can be obtained from the business section of any major newspaper. The gold derived from the mining operation can then used in a variety of applications (jewelry, money, electronics, dentistry, etc.), but the basic value of the gold in those products is always tied to the current market.

There is no standard final product derived from a sand and gravel operation or a stone quarry upon which to base an estimate of grade. The ore (the stone at the quarry or the in- situ sand and gravel) is processed by some combination of washing, crushing, screening, and blending to produce a variety of products required by the local market (or for export in some cases). These products vary from area to area in response to local demands and may even vary with time within a single area according to the nature of changing demands. In addition, the price of comparable products varies wildly across the nation as a function of local supply and demand. For example, the at-source price of a ton of 0.75"-1.5" gravel cost $4.85 in Atlanta, Georgia, and $15.80 in Kansas City, Missouri, in January of 1993 (Engineering News Record, 1993). Consequently, the estimation of the value of a potential source of aggegate presents new problems to resource assessment that must be considered in developing an effective assessment procedure or integrating aggregate into the USGS three-part assessment method.

Estimating the volume (tonnage) of the raw materials (ore) in many potential crushed stone sources or sand and gravel deposits should only pose modest problems, assuming that descriptive models are available to allow the deposits and their geometries to be recognized. Bliss (1993) has taken some preliminary steps in modeling the volume of selected alluvial fan deposits as a function of the area covered by the deposits. Even so, the lack of a standard(s) for attaching a valuation to the estimated volume of raw material hinders an objective assessment of the potential resource.

Perhaps as specific deposit types are identified and descriptive models for these deposits are prepared, some characteristics will be found to be unique to each specific deposit type (or have an identifiable range), such as volume (tonnage), size, shape, and gradation of particles, mineral composition, and chemical reactivity, that can be compared to a set of standard products produced in the geographic area of the deposit to yield some estimation of the potential value of the deposit. Then, again, perhaps some other approach will be required. Clearly, considerable research and careful thought will be required to develop a rational and scientifically sound approach to assessing potential aggregate resources. The approach may incorporate many of the elements of the USGS three-part method, but significant departure from the method should be anticipated to account for the differences between natural aggregate and metallic deposits and industries. It is important that the types of information required to assess potential aggregate resources be defined as soon as possible, so that applications of remote sensing and airborne geophysics to gather the appropriate kinds of information can be developed.

Estimating Undiscovered Resources

The most subjective element in the USGS three-part assessment procedure is estimating of the number of undiscovered deposits in the areas identified as permissive for the occurrence of a specific deposit type (Ludington and others, 1992; Singer, 1993). Numerous methods are used as guidelines for making these estimates, but the final estimates are made subjectively by a small group of scientists (economic geologists, geochemists, geophysicists) that are knowledgeable on the specific deposit type and are experts on the mineral deposits of the region (Singer, 1993). Using this procedure assures that the wealth of geologic information and experience possessed by these "experts" is factored into the assessment process.

There are two major problems in estimating the number of undiscovered deposits of natural aggregate. First, there is a shortage of "experts". Although there are numerous excellent surficial geologic mappers within the USGS, most are not tuned to thinking of the deposits as a potential mineral commodity and they lack a detailed understanding of the aggregate industry. In addition, the number of surficial geologists with an understanding of the USGS three-part mineral resource assessment process is extremely limited.

Secondly, there is a fundamental question as to what constitutes a single deposit. For example, should a bajada of coalesced alluvial fans be considered a single deposit or should each alluvial fan be considered a single deposit? Should a fluvial system with isolated gravel terraces be considered a single deposit? This problem should become less perplexing as descriptive models for natural aggregate deposits are developed; however, even in the more highly evolved base and precious metal assessment procedure there are questions as to whether it might be more correct to evaluate possible mineral districts containing deposits associated with a single genetic process rather than the individual deposits. Perhaps it will be necessary to develop an entirely new concept of "potential deposits" to accomodate the nature and characteristics of natural aggregate.

Adaptation or New Directions?

From the above discussion, it seem reasonably clear that incorporating natural aggregate into USGS mineral resource assessments will not involve a straightforward extension of the three-part methodology to a new family of deposits. The nature and characteristics of natural aggregate, and the aggregate industry, indicate that considerable modification to the three-part procedure would be necessary or that perhaps an entirely new approach will be required. The answer to this question will only come with extensive research and careful thought.

New research is clearly needed on several fronts. First, the types of deposits that constitute potential sources of natural aggregate need to be identified and characterized; descriptive geologic models need to be developed. Second, a sound method(s) of determining the value of potential sources of natural aggregate needs to be developed in a manner that is both useful and understandable to the aggregate industry and other potential users of the mineral resource assessment information. Third, methods need to be developed for applying a variety of available data, such as remote sensing and airborne geophysics, to the characterization of potential aggregate resources, particularly in areas where existing geologic maps do not satisfactorily discriminate between various types of surficial deposits (the Qal problem). The need for additional research directions will undoubtedly be recognized as new information and ideas are explored.

VIII. REFERENCES

Abrams, M.J., 1980, Lithologic mapping, *in* Siegal, B.S., and Gillespie, A.R., eds., Remote Sensing in Geology, New York, John Wiley and Sons, p. 381-418.

American Society for Testing and Materials, 1980, Annual book of ASTM standards, pt. 14, Concrete and mineral aggregates: Philadelphia, Pa., 878 p.

Barksdale, R.D., ed., 1991, The Aggregate Handbook: Washington, D.C., National Stone Association, 16 chapters numbered separately.

Beaumont, T.E., 1979, Remote sensing for the location and mapping of engineering construction materials in developing countries: Quarterly Journal of Engineering Geology, v. 12, no. 3, p. 147-158.

Belcher, D.J., 1945, The engineering significance of soil patterns: Photogrammetric Engineering, v. 11, no. 2, p. 115-148.

Bliss, J.D.,ed.,1992, Developments in mineral deposit modeling: U.S. Geological Survey Bulletin 2004, 168 p.

Bliss, J.D., 1993, Modeling sand and gravel deposits--initial strategy and preliminary examples: U.S. Geological Survey Open-File Report 93-200, 31p.

Blodget, H.W., Andre, C.G., Marcell, Richard, and Minor, T.B., 1984, Multispectral thermal infrared satellite data for geologic applications: Proceedings, International Symposium on Remote Sensing of Environment, Third Thematic Conference, Remote Sensing for Exploration Geology, Ann Arbor, Michigan, Environmental Research Institute of Michigan, p. 917-928.

Bottge, R.G., McDivitt, J.F., and McCarl, H.N., 1965a, Prospecting for natural aggregates, Part 1: Rock Products, v. 68, no. 5, p. 108-153.

______________________________________, 1965b, Prospecting for natural aggregates, Part 2: Rock Products, v. 68, no. 6, p. 93-95.

Buettner, K. J. K. and Kern, C. D., 1965, The determination of infrared emissivities of terrestrial surfaces: Jour. Geophys. Res., v. 70, p. 1329-1338.

Cady, J.W., 1989, Geologic implication of topographic, gravity, and aeromagnetic data in the Northern Yukon-Koyukuk Province and its borderlands, Alaska: Journal of Geophysical Research, v. 94, no. B11, p. 15821-15841.

Carr, D.D., and Blakely, R. F., 1966, Temperature variation at a depth of 30 cm in clay till and outwash sand and gravel: Proceedings, 4th Symposium on Remote Sensing of Environment, p. 203-214.

Carr, D.D., and Webb, W.M., 1967, Sand and gravel exploration by thermal sensing of soil, *in* Angeno E.E., and Hardy, R.G., eds, Proceedings of the Third Forum on Geology of Industrial Minerals, State Geological Survey of Kansas Special Distribution Publication 34, p. 32-38.

Carslaw, H. S., and Jaeger, J. C., 1959, Conduction of Heat in Solids (2nd ed.): New York, Oxford Univ. Press., 497 p.

Chilar, J., Somerfeld, T., and Paterson, B., 1977, Soil water estimation in fallow fields from airborne thermal scanner measurements: Canadian Journal of Remote Sensing, v. 5, no. 1, p.18-32.

Clark, R.N., Gallagher, A.J., and Swayze, G.A., 1990, Material absorption band depth mapping of imaging spectrometer data using a complete band shape least-squares fit with library reference spectra: Proceedings of the 2nd Airborne Visible Infrared Imaging Spectrometer (AVIRIS) Workshop, Jet Propulsion Laboratory, Publication 90-54, p. 176-186.

Colwell, R. N., ed., 1983, Manual of Remote Sensing (2nd ed.), Falls Church, Va., American Society of Photogrammetry, 2440 p.

Cox, D.P, and Singer, D.A., 1986, Mineral deposit models: U.S. Geological Survey Bulletin 1693, 379 p.

Culley, R.W., 1973, Use of airborne resistivity surveys for gravel location: Canadian Mining and Metallurgical Bulletin, v. 66, n. 733, p. 70-74.

___________, 1974, Evaluation of an airborne resistivity system (E-Phase) for gravel location: Saskatchewan Department of Highways, Technical Report 21, 41 p.

Daily, M.I., Farr, T., Elachi, C., and Schaber, G., 1979, Geologic interpretation from composited radar and Landsat imagery: Photogrammetric Engineering and Remote Sensing, v. 45, p. 1109-1116.

Dobrin, M.B., 1960, Introduction to geophysical prospecting: New York, McGraw-Hill, 446 p.

Dunn, J.R., 1991, Chapter 4 - Geology and Exploration, *in* Barksdale, R.D., ed., The Aggregate Handbook: Washington, D.C., National Stone Association, p. 4-2 - 4-45.

Edwards, W.A.D., and Chao, D.K., 1989, Bibliographic index and overview of aggregate resource publications: Alberta Research Council Internal Report, 93 p.

Edwards, W.A.D., and Richardson, R.J.H., 1989, Remote sensing techniques used for sand and gravel exploration by the Alberta Geological Survey: Proceedings, Seventh Thematic Conference on Remote Sensing for Exploration Geology, Calgary, Alberta, Environmental Research Institute of Michigan, p. 151-165.

Engineering News Record, 1993, Monthly market quotations: January 4, 1993, p. 47.

Fraser, D.C., 1978, Resistivity mapping with an airborne multicoil electromagnetic system: Geophysics, v. 43, no. 1, p. 14-172.

Gary, Marrgaret, McAfee, Robert, Jr., and Wolf, C.L., 1972, Glossary of geology: Washington, D.C., American Geological Institute, 857 p.

George, H., Dusseault, M.B., and Keslik, A.B., 1986, Exploration for buried aggregates by remote sensing techniques - An assessment: Ontario Geological Survey Miscellaneous Paper 130, p. 155-160.

Goetz, A.F.H., Vane, Gregg, Solomon, J.E., and Rock, B.N., 1985, Imaging spectrometry for earth remote sensing: Science, v. 228, p. 1147-1153.

Gorecki, R.C., Schmidt, B.J., and Smith, D.G., 1989, The application of satellite remote sensing to aggregate exploration in northwestern Alberta: Proceedings, Seventh Thematic Conference on Remote Sensing for Exploration Geology, Calgary, Alberta, Canada, Environmental Research Institute of Michigan, v. II, p. 701-712.

Grant, F.S., and West, G.F., 1965, Interpretation theory in applied geophysics: McGraw-Hill, 584 p.

Grauch, V.J.S., Blakely, R.J., Blank, H.R., Oliver, H.W., Plouff, Donald, and Ponce, D.A., 1988, Geophysical delineation of granitic plutons in Nevada: U.S. Geological Survey Open-File Report 88-11, 7 p., 2 plates (1:1,000,000).

Heilman, J. L., and Moore, D. G., 1981, HCMM detection of high soil moisture areas: Remote Sens. Environ., v. 11, p. 73-78.

Henry, C.J., 1989, Exploration for construction materials for Botswana roads:Proceedings, Seventh Thematic Conference on Remote Sensing for Exploration Geology, Calgary, Alberta, Canada, Environmental Research Institute of Michigan, v. I, p. 603-614.

Holmes, Arthur,1965, Principles of geology:New York, Roland Press, 1288 p.

Hoover, D.B., Heran, W.D., and Hill, P.L., 1992, The geophysical expression of selected mineral deposit models: U. S. Geological Survey Open-File Report 92-557, 129 p.

Hunt, G.L., 1980, Chapter 2, Electromagnetic radiation - The communication link in remote sensing, *in* Siegal, B.S., and Gillespie, A.R., eds., Remote Sensing in Geology: New York, John Wiley and Sons, p. 5-45.

Huntley, D., 1978, On the detection of shallow aquifers using thermal infrared imagery: Water Resources Research, v. 14, p. 1075-1083.

Idso, S.B., Schmugge, T.J., Jackson, R.D., and Reginato, R.J., 1975, The utility of surface temperature measurements for the remote sensing of soil water status: Journal of Geophysical Research, v. 80, p. 3044-3049.

Jackson, R.D., Cihlar, J., Estes, J.E., Heilman, J.L., Ralke, A., Kanemasu, E.T., Millard, J., Price, J.C., Wiegand, C., 1978, Soil moisture estimation using reflected solar and emitted thermal radiation: Chapter 4, Soil Moisture Workshop, NASA Conference Publication 2073, 219 p.

Janza, F.J., ed., 1975, Chapter 4: Interaction mechanisms, *in* Janza, F.J., ed., Manual of Remote Sensing: American Society of Photogrammetry, p. 75-179.

Johnson, G.R., 1983, Rock property measurements and analysis of selected igneous, sedimentary, and metamorphic rocks from world-wide localities: U>S> Geological Survey Open-File Report 83-736, 36 p.

Kahle, A. B, 1977, A simple thermal model of the Earth's surface for geologic mapping by remote sensing: Jour. Geophys. Res., v. 82, p. 1673-1680.

Kahle, A.B., and Goetz, A.F.H., 1983, Mineralogic information from a new airborne thermal infrared multispectral scanner: Science, v. 222, p. 24-27.

Keller, G.V., and Frischknecht, F.C., 1966, Electrical methods in geophysical prospecting: Pergamon Press, 523 p.

Kilmer, V. J., ed., 1982, Handbook of Soils and Climate in Agriculture: CRC Press, Inc., p. 144.

Krumbein, W.C., and Sloss, L.L., 1963, Stratigraphy and sedimentation: San Francisco, W.H. Freeman and Company, 660 p.

Langer, W.H., 1988, Natural aggregates of the conterminous United States: U. S. Geological Survey Bulletin 1594, 33 p.

Langer, W.H., and Glanzman, V.M., 1993, Natural aggregate - Building America's Future: U. S. Geological Survey Circular 1110, 39 p.

Lillisand, T.M., and Kiefer, R. W., 1979, Remote Sensing and Image Processing: John Wiley and Sons, 396 p.

Ludington, Steve, Orris, G.L, and Cox, D.P, 1992, Methods of resource assessment, *in* U.S. Geological Survey and Servico Geologico de Bolivia, Geology and mineral resources of the Altiplano and Cordillera Occidental, Bolivia: U.S. Geological Survey Bulletin 1975, p. 218-219.

Lyon, R.J.P., 1965, Analysis of rocks by spectral infrared emission (8-25μm): Economic Geology, v. 60, p. 715-736.

Lyon, R.J.P., and Honey, F.R., 1991, Extraction of thermal exitance spectra (TIR) from Geoscan Mk II scanner imagery - Spectra derived from airborne (mobile) and ground (stationary) imagery compared with spectra from direct exitance spectrometry: Proceedings, Eighth Thematic Conference on Geologic Remote Sensing, Ann Arbor, Michigan, Environmental Research Institute of Michigan, p. 117-130.

Lyon, R.J.P., and Patterson, J.W., 1966, Infrared spectral signatures - a field geological tool: Proceedings, Fourth Symposium on Remote Sensing of Environment, Ann Arbor, Michigan, University of Michigan, p. 215-230.

MacDonald, M.C., 1991, Phenomenology and exploitation of enhanced thermal infrared multispectral scanner data (TIMS) for geologic mapping applications in the Pancake Mining District, Northern Nye County, Nevada: Proceedings, Eighth Thematic Conference on Geologic Remote Sensing, Denver, Colorado, Environmental Research Institute of Michigan, p. 701-707.

Marek, C.R., 1991, Chapter 3 - Basic Properties of Aggregate, *in* Barksdale, R.D., ed., The Aggregate Handbook: Washington, D.C., National Stone Association, p. 3-2 - 3-67.

Maynard, J.B., and Van Houten, F.B., 1992, Descriptive model of oolitic ironstones, *in* Bliss, J.D., ed., Developments in mineral deposit modeling: U.S. Geological Survey Bulletin 2004, p. 39-40.

McNeill, J.D., and Labson, V.F., 1991, Geological mapping using VLF radio fields, *in* Nabighian, M.N., ed., Electromagnetic methods in applied geohysics, v. 2, Part B: Society of Exploration Geophysicists, p. 521-640.

Meinzer, O.E., 1923, Outline of ground-water hydrology: U.S. Geological Survey Water-Supply

Paper 494, 71 p.

Merifield, P.M., Hazen, R.S., and Evans, D.L., 1984, Discrimination of desert surficial materials for engineering/environmental geology applications utilizing coregistered Landsat MSS and Seasat SAR data: Proceedings, Third Thematic Conference , Remote Sensing for Exploration Geology, Colorado Springs, Colorado, Environmental Research Institute of Michigan, p. 487-496.

Middleton, R.S., 1977, Ground and airborne geophysical studies of sand and gravel in the Toronto region: Ontairo Geological Survey Study GS18, 37 p.

Miller, V.C., and Miller, C.F., 1960, Photogeology: New York, McGraw-Hill, 248 p.

Miller, S. H., and Watson, Kenneth, 1977, Evaluation of algorithms for geological thermal-inertia mapping: Proceedings, 11th International Symposium on Remote Sensing of Environment, Environmental Research of Michigan, p. 1147-1160.

Ntaional Aeronautics and Space Administration, 1991, EOS Reference Handbook: NASA Goddard Space Flight Center, 147 p.

Odum, J.K., and Miller, C.H., 1988, Geomorphic, seismic, and geotechnical evaluation of sand and gravel deposits in the Sheridan, Wyoming, area: U.S. Geological Survey Bulletin 1845, 32 p.

Orris, G.J., and Bliss, J.D., 1992, Industrial mineral deposit models; grade and tonnage models: U.S. Geological Survey Open-File Report 92-437, 83 p.

Paterson, N.R., and Ronka, V., 1971, Five years of surveying with the very low frequency-electromagnetic method: Geoexploration, v. 9, p. 7-26.

Peterson, J.B., Goodrick, F.E., and Melhorn, W.N., 1975, Delineation of the boundaries of a buried pre-glacial valley with Landsat-1 data: Proceedings, NASA Earth Resources Survey Symposium, First Comprehensive Symposium on the Practical Application of Earth Resources Survey Data, Houston, Texas, NASA TM X-58168, v. I-A, p. 97-103.

Phillips, J.D., Duval, J.S., and Ambroziak, R.A., 1993, National geophysical data grids: gamma-ray, gravity, magnetic, and topographic data for the conterminous United States: U.S. Geological Survey Digital Data Series DDS-9, 1 CD-ROM.

Pratt, D. A., 1978, A study of the remote determination of thermal inertia for hydrogeological and geological mapping: PhD thesis for the University of Newcastle, N.S.W. , 192 p.

Pratt, D. A., and Ellyett, C. D., 1979, The thermal-inertia approach to mapping of soil moisture and geology: Remote Sens. Environ., v. 8, p. 151-168.

Raines, G.L., and Canney, F.C., 1980, Chapter 12 - Vegetation and geology, *in* Siegal, B.S., and Gillespie, A.R., eds., Remote sensing in geology: New York, John Wiley and Sons, p. 365-380.

Ray, R.G., 1960, Aerial photographs in geologic interpretation and mapping: U.S. Geological Survey Professional Paper 373, 230 p.

Reeves, R. G., ed., 1975, Manual of Remote Sensing, First Edition, American Society of Photogrammetry, Falls Church, Va., 2144 p.

Sabins, F.F., 1984, Geologic mapping of Death Valley from Thematic Mapper, thermal infrared, and radar images: Proceedings, International Symposium on Remote Sensing of Environment, Third Thematic Conference, Remote Sensing for Exploration Geology, Ann Arbor, Michigan, Environmental Research Institute of Michigan, p. 139-152.

Schaber, G.G., Berlin, G.L., and Brown, W.E., Jr., 1976, Variations in surface roughness with Death Valley, California: Geologic evaluation of 25-cm radar images: Geological Society of America Bulletin, v. 87, p. 29-41.

Schmugge, T.J., Jackson, T.J., and McKim, H.L., 1980, Survey of methods for soil moisture determination: Water Resources Research, v. 16, no. 6, p. 961-979.

Scholen, D.E., Clerke, W.H., and Luepke, D.E., 1985, Locating subsurface gravel with thermal imagery, *in* Kahle, A.B., and Abbott, Elsa, eds., The TIMS Data User's Workshop, NASA Jet Propulsion Laboratory, JPL Publication 86-38, p. 59.

Schwochow, S.D., Shroba, R.R., and Wicklein, P.C., 1974, Sand, gravel, and quarry aggregate resources, Colorado Front Range counties: Colorado Geological Survey, Department of Natural Resources Special Publication 5-A, 43 p.

Singer, D.A., 1993, Basic concepts in three-part quantitative assessments of undiscovered mineral resources: Nonrenewable Resources, v. 2, no. 2, p. 69-81.

Singer, D.A., and Mosier, D.L., 1981, A review of regional mineral resource assessment methods: Economic Geology, v. 76, p. 1006-1015.

Singhroy, V.H., 1992, Radar geology: Techniques and results: Episodes, v.15, no. 1, p.15-20.

Singhroy, V.H., and Barnett, P.J., 1984, Locating subsurface mineral aggregate deposits from airborne infrared imagery (reflected and thermal) - A case study in southern Ontario: Proceedings, International Symposium on Remote Sensing of Environment, Third Thematic Conference, Remote Sensing for Exploration Geology, Colorado Springs, Colorado, Environmental Research Institute of Michigan, p. 523-539.

Singhroy, V.H., Kenny, F.M., and Barnett, P.J., 1989, Radar imagery for Quaternary geological mapping in glaciated terrains: Proceedings, Seventh Thematic Conference on Remote Sensing for Exploration Geology, Calgary, Alberta, Canada, Environmental Research Institute of Michigan, p.591-600.

Skirvin, S.M., 1991, Use of processed Landsat Thematic Mapper data to detect surface soil moisture over mountain pediments, southeastern Arizona: Proceedings, Eighth Thematic Conference on Geologic Remote Sensing, Ann Arbor, Michigan, Environmental Research Institute of Michigan, p. 145-157.

Sumner, J.S., 1976, Principles of induced polarization for geophysical exploration: Elsevier, 277 p.

Tepordei, V.V., 1993a, Construction sand and gravel - 1991: U.S. Bureau of Mines Annual Report, 19 p.

____________, 1993b, Crushed stone - 1991: U.S. Bureau of Mines Annual Report, 43 p.

Thornbury, W.D., 1969, Principles of geomorphology (2nd ed.): New York, John Wiley and Sons, Inc., 594 p.

Underwood, S. A., Houston, A. G., and Hazard, W. R.,1980, Performance Evaluation: Estimates of structural heat loss from interpretation of aerial thermography, 1 p.

U. S. Department of Interior, 1981, Concrete manual: Water and Power Resources Service Technical Publication, 627 p.

U. S. Geological Survey, 1981, Geological Survey Research 1981: U.S. Geological Survey Professional Paper 1275, p. 252.

Van Schmus, W.R., 1984, Radioactivity properties of minerals and rocks, *in* Carmichael, R.S., ed., CRC Handbook of Physical Properties of Rocks, p. 281-293.

Vavilin, L.N., Vorob'ev, V.P., Efimov, A.V., Zelenetskiy, D.S., Mateyev, A.V., and Filimonov, V.V., 1982, Aerogamma-spektrometriya v geologii (airborne gamma-spectrometry in geology): Nedra, Leningrad, 271 p.

Vickers, R.S., and Lyon, R.J.P., 1967, Infrared sensing from spacecraft - a geological interpretation: American Institute Aeronautics and Astronautics, Thermophysics Specialist Conference Proceedings Paper no. 67-284, 10 p.

Watson, K, 1971, A computer program of thermal modeling for interpretation of infrared images: U. S. Geol. Surv. Rep. PB 203578, Washington, D. C.

__________, 1975, Geologic applications of thermal infrared images: Proc. of the IEEE, v. 63, p. 128-137.

__________,1992a, Spectral ratio method for measuring emissivity: Remote Sens. Environ., v. 42, p. 113-116.

__________,1992b, Two-temperature method for measuring emissivity: Remote Sens. Environ., v.42, p. 117-121.

Watson, Kenneth, and Knepper, Daniel H., Jr., eds, in press, Airborne remote sensing for geology and environment - Present and Future: U.S. Geological Survey Bulletin 1926.

West, T.R., Mundy, S.A., and Moore, M.C., 1976, Evaluation of gravel deposits using remote sensing data, Wabash River valley north of Terre Haute, Indiana: Proceedings, Twenty Seventh Annual Highway Geology Symposium, Orlando, Florida, p. 199-214.

Watson, Ken, and Raines, G.L., 1987, Exploration remote sensing - A look to the future, *in* Garland, G.D., ed., Proceedings of Exploration '87, Third Decennial International Conference on Geophysical and Geochemical Exploration for Minerals and Groundwater: Ontario Geological Survey Special Volume 3, p. 78-87.