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Modeling sand and gravel deposits--initial strategy and preliminary examples

by

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PREFACE

Models are an integral part of quantitative mineral resource assessment for use in planning future infrastructure development and renewal. This report is primarily concerned with an initial strategy for modeling sand and gravel deposits. Models for only three sand and gravel deposit variables are given--volume, area, and thickness. The models, both those given here and to be developed, can be used to predict qualities expected in sand and gravel deposits both undiscovered or incompletely defined. These models are an initial attempt to characterize sand and gravel deposits; revisions of the models are expected and additions, corrections, or comments on the strategy or on the preliminary models are welcome and should by directed to Jim Bliss, U.S. Geological Survey, 210 E. 7th St., Tucson, AZ 85705-8454.

Sand and gravel is a low-unit-value commodity used in enormous tonnages in construction with production estimated at 2.9 billion dollars in 1991 (U.S. Bureau of Mines, 1992a). The production ranks third among industrial commodities produced in the United States. Only portland cement (3.7 billion dollars) and crushed stone (4.2 billion dollars) were more valuable. The value of sand and gravel generally has varied from 15 to 17 percent of industrial mineral production from 1986 to 1991 based on reporting in the U.S. Bureau of Mines mineral commodity summaries.

INTRODUCTION

To date, models used in quantitative mineral resource assessment have been largely focused on metals. The largest compilation of descriptive and grade and tonnage models is found in Cox and Singer (1986). Additional models can be found in Bliss (1992). These models are used in a three-part quantitative resources assessment (Singer and Cox, 1988; Singer and Ovenshine, 1979). Computer simulation using results of three-part assessments provides a measure of the quantity of materials remaining in undiscovered deposits at different levels of certainty (Root and others, 1992; Spanski, 1992). The U.S. Bureau of Mines also uses assessment results in their analysis of economic potential of future mineral development within an area (e.g., the East Mojave National Scenic Area, California (U.S. Bureau of Mines, 1992b) and Kootenai National Forest, Idaho and Montana (Gunther, 1992)).

Model development for industrial minerals including sand and gravel deposits has only recently begun in earnest. Efforts to date include the compilation of descriptive models (Orris and Bliss, 1991) and grade and tonnage models (Orris and Bliss, 1992) for industrial minerals. Models for industrial minerals include not only the grade and tonnage model common to metallic deposits but also require contained-material, impurity, and deposit-specific models (Orris and Bliss, 1989).

Two models have been developed for sand deposits and sandstone/quartzite deposits that are used as a source of silica (Orris, 1992a, 1992b). These models are for deposits which are silica rich (i.e., greater than 75 percent). These deposits lack gravel-sized clasts; they are well-sorted glass sands with essentially no clay size fraction (G. Orris, oral commun., Nov. 25, 1992). Sandstone/quartzite deposits are found in lithified stratigraphic sections some of which can also be exploited for sand and gravel. Like the sand deposit, the sand/quartzite deposit lacks gravel-sized clasts and has essentially no clay-size fraction. These two models describe deposits that are specialized types of sand and gravel deposits.

The distribution of deposits by area can be described using spatial models. A type of spatial model has been developed specifically to assist in the three-part quantitative assessment procedure (Bliss and Menzie, in press). A simple measure used in this type of spatial modeling is the mineral deposit density or deposits per a standard unit area. Mineral deposit densities have been calculated for a number of metallic deposit types and some initial ones were calculated for sand and gravel deposits as well.

DEFINITIONS AND MECHANICS IN MODELING

The definition of a mineral deposit model as given by Cox and Singer (1986, p. 2) is "the systematically arranged information describing the essential attributes (properties) of a class of mineral deposits. A model may be empirical (descriptive), in which instance, the various attributes are recognized as essential even though their relationships are unknown; or it may be theoretical (genetic), in which instance, the attributes are interrelated through some fundamental concepts."

The economic characteristics of mineral deposits can be empirically modeled using size (or volume), grade, contained materials, impurities, and deposit-type-specific attributes. Estimates should be made of tonnage (or volume) at the lowest reported cut-off grades or highest level of impurities allowed. Models are presented in graphical format (plots) for ease of display and to enable comparison with other models (Cox and Singer, 1986; Bliss, 1992). The plots show grade, tonnage, or selected attributes on the horizontal axis and the cumulative proportion of deposits on the vertical axis. The units are metric and a logarithmic scale is used in most cases. Each point on a plot represents a individual deposit. The deposits are cumulated in ascending attribute value. Smoothed curves, representing percentiles of a lognormal distribution that has the same mean and standard deviation as the observed data are plotted through the points. Intercepts for the 90th, 50th, and 10th percentiles of the lognormal distributions are identified. A detailed description of how these plots are generated is found in Singer and Bliss (1990).

For sand and gravel deposits, the volume of the deposit is the size attribute to be modeled. A variety of deposit-type specific features of sand and gravel deposits may also need to be modeled. In place of grade, investigators and reporters on sand and gravel deposits commonly use either minimum volume, minimum thickness, or other conditions to define deposits.

DEFINITION OF SAND AND GRAVEL DEPOSITS

Sand and gravel deposits consist of rock or mineral fragments in loose, non-cohesive bodies. They are the result of sedimentary processes including fluvial, lacustrine, marine, eolian, and glacial. Langer (1988) defines sand and gravel deposits as a mixture of sand and gravel in which gravel is 25 percent or more by weight. Sand and gravel are natural aggregate that include crushed stone. Natural aggregates are defined as any "material composed of rock fragments which are used in their natural state except for such operations as crushing, washing, and sizing" (McLaughlin and others, 1960, p. 16-4).

The distribution of the size of the fragments is important. Sand and gravel deposits are best when they contain little silt. However, terminology varies greatly regarding the diameter of fragments in sand and gravel deposits. This is to be expected because naturally occurring fragment sizes have a continuous range in size from fine to coarse. This inconsistency is one of the important variables that must be taken into account.

In contrast to other mineral deposit types, minor renewal of sand and gravel deposits may occur. Sand and gravel deposits, too thin or too small to be worked at their present location are moved down stream where they collect in larger workable deposits. Replenishment to the deposits may be more likely during spring flooding (Yeend, 1973).

Nearly all deposits in the United States are Quaternary. Some Paleocene and Eocene conglomerates are worked in southern California (Goldman, 1968) and elsewhere. These older deposits may require a different modeling strategy from that used for the younger surficial sand and gravel deposits under consideration here.

Empirical modeling of deposit attributes is always dependent on the level of reporting in the literature. Evaluation of the volumes of sand and gravel deposits in published compilations inevitably is focused on the total size of the deposit, <u>not</u> the size of pits or workings in the deposit. Commonly, sand and gravel deposit size is estimated based on the geology and morphology of the deposit rather than on data gathered by drilling. The deposit sizes are at a level of confidence of a resource, not a reserve. Whether a deposit will continue to be worked, or worked at all is dependent on economic, political, and social criteria beyond the scope of this study. As a rule of thumb, I have treated sand and gravel bodies as part of the same deposit if separated by a distance of 1.5 km or less. One exception is where alluvial fans and the stream beds upstream from the alluvial fans are treated separately. Some assessments have grouped bodies separate by distances greater than 1.5 km, others more closely. In some cases, the published assessments are about single bodies divided into adjoining blocks. Some data for deposits in or adjacent to urban areas may lead to an underestimate of deposit volumes because developed areas are excluded from size estimates. This situation occurs frequently in the United Kingdom.

Data compiled for sand and gravel deposits in this report must be qualified as the result of a variety of inconsistencies because of different reporting standards used by different investigators. These inconsistencies include: overburden requirements, minimum thickness, minimum volume, maximum fines, and maximum thickness. For some deposits, thickness was not reported but was estimated from depth of workings. Commonly, past production data are not reported. These factors will tend to underestimate the sand and gravel resource in some deposits.

Following are examples of some of the standards used by reporters. Cameron and others (1977) considered only those deposits with a overburden ratio of 1:1 or greater. Cameron and others (1977), McAdam (1977, 1978) and Browne (1977) required a minimum thickness of 2 meters of sand and gravel; Squirrell (1974) considered deposits with 1 meter or more. Goldman (1961, 1964, 1968) was unconcerned with thickness but required that the deposit contain more than 50,000 cubic yards (38,000 cubic meters) of material. Goldman's inventories included only deposits which were within 50 miles (80 km) of markets. Deposits above and below water table were often reported separately; I have combined figures when appropriate. For some deposits, gravel below water tables was explicitly excluded by some reporters. Some deposits in Goldman (1964) are above the summer water table. Squirrell (1974) considered deposits with overburden thickness to sand and gravel thickness ratios of 3:1 or less, with the proportion of fines (0.0625 mm) not to exceed 40 percent. Squirrell (1974) also noted that sand and gravel extraction seldom exceeds depths of 24.4 m and set a maximum depth of drilling of 18.3 meters if the hole was still in overburden. California sand and gravel deposits (particularly alluvial fan types) have been considered as possible resources to depths of 95 m (Goldman, 1968).

SAND AND GRAVEL DEPOSIT TYPES

Data for modeling was collected from a wide range of sand and gravel deposit types. Locally, tailings from gold placering are used as a source of sand and gravel and data from these deposits are included in this compilation. Sand and gravel deposits include those found in stream beds, in stream terraces (common to the California data set), glacial terraces, outwash plains, eskers, kame terraces, beaches both modern and raised (common to the United Kingdom data). All of these depositional environments are found for deposits in the data used; many deposits involve several environments. A few Tertiary gravels in California worked for sand and gravel were also included but may be excluded in future modeling.

STRATEGY

General Issues

Modeling of sand and gravel deposits must take into account the range of: (1) deposit volumes and geometry; (2) size distribution of material in the deposits; (3) physical characteristics of the material; and (4) chemical composition and chemical reactivity of the material. Extracting this information from the literature is complicated--variables measured and the type of test used are dependent on the expected application. A host of tests and specifications for sand and gravel deposits have been developed by the American Society for Testing and Materials (ASTM). All government agencies from Federal to local, that have been involved in highway construction have also been involved in preparation of specifications. Tepordei (1989) notes that the proliferation of standards have evolved to address local soil, climatic, and material characteristics.

Model attributes dependent on data generated under these conditions can be expected to contain variability related to the standards and procedures used in the analysis. Several trends in modeling sand and gravel variables can be anticipated: (1) some variables will be modeled in a very general way, (2) some variables will be modeled with a specific end use in mind, (3) some variables will be modeled for local applications only, and (4) some variables are so poorly characterized that they can not be modeled. Engineering geologists, civil engineers, and others have attempted to predict properties of earth materials for a wide variety of specific applications and it is expected that modeling can take advantage of this.

Modeling deposit geometry

Models can be developed concerning the geometry of sand and gravel deposits. Mineral deposits, including sand and gravel deposits, can have an explicit surface area. Because sand and gravel deposits have, as a first approximation, the form of an uneven blanket, the deposit volume can be approximately calculated using area and average thickness.

Sometimes sand and gravel deposits are dissected into several parts and when the segments are treated as part of the same deposit, the area involved includes a portion without sand and gravel. While it would be ideal to treat each sand and gravel remnant as a separate deposit, the level of resolution varies from one data source to the next. Most publications used as data sources treat sand and gravel resources in a regional fashion, not by individual bodies. Because of this, I have grouped remnants into deposits. The resulting area is called a mineral deposit target area; it is treated separately from deposit areas described previously. Modeling mineral deposit target areas has been successfully used (Bliss and others, 1991) and will be developed in future modeling of sand and gravel deposits. Both deposit areas and deposit target areas can be used to assist in mineral resource assessment.

Modeling deposit volume

Sand and gravel deposit volumes can be modeled in the same way as deposit tonnage. As noted in the previous section on deposit geometry, deposit area and average thickness are independent variables and can be used to calculate deposit volume. Future research will be need to determine if volume is related to other sand and gravel attributes.

Modeling size of particulates

A first-order model for size distribution in sand and gravel deposits would provide the distribution of percent gravel, percent sand, and (or) percent fines. A problem with this scheme is that size classification used to define gravel, sand, and fines are not standardized. Different units are used as well. In this summary, the units (including sieve size) used in the source document are given first followed in parenthesis in terms of either metric and (or) English units and sieve size. Pettijohn and others (1973) reported that the distinction between sand (or very fine sand to coarse silt) varies from 0.05 mm (U.S. Standard Sieve No. 45) used by the U.S. Department of Agriculture) to 0.10 mm (U.S. Standard Sieve No. 140) as suggested by Boswell (1919). Goldman and Reining (1983) noted that sand defined in commercial usage in the United States consists of unconsolidated or poorly consolidated fragments retained on a No. 200 sieve (0.074 mm openings) and that pass through a No. 4 sieve (4.76 mm openings); this is also the ASTM definition (Tepordei, 1989). The Wentworth scale defines sand as those fragments passing a No. 10 sieve (2 mm) and gravel as the retained material. There is not an upper size boundary for gravel in the Wentworth scale. ASTM sets an upper size for gravel at 3 inches (76.2 mm) (Dutro and others, 1989). The upper part of the grain-size scale used by engineers include cobbles between 3 and 12 inches (305 mm), and boulders are larger than 12 inches (305 mm) (Dutro and others, 1989).

A number of statistics have been applied to grain-size distributions. These parameters may need to be modeled if they are found to be useful in distinguishing among sub-types of sand and gravel deposits. These include measures of central tendency (mean, mode, median), bimodality, skewness, and kurtosis (Pettijohn and others, 1973).

Modeling physical and chemical variables

The separation of physical variables from the chemical ones is somewhat arbitrary. Desirable deposits contain clean, uncoated, properly shaped particles which are sound and durable (Goldman and Reining, 1983). Perhaps some type of model can be devised to characterize the various populations of particle shapes for a deposit. The external coating of particulates might be modeled given data on percent of particulates and type of coating involved. Coating types would include calcium carbonate, clay, silt, opal, iron oxide, manganese oxide, and gypsum among others (Goldman and Reining, 1983).

Sand and gravel become less suitable for certain applications with the presence of undesirable material which has certain physical or chemical properties. These undesirable materials can be characterized using impurity models. Impurities that need to be modeled (either separately or as a group) includes mica, clay, silt, organic matter, fissile shale, friable sandstone and other weak rock type fragments (Harben and Bates, 1984). The percentage of impure material tolerated needs to be modeled as well. An ASTM test noted in Goldman and Reining (1983) uses heavy liquids to test for organic matter. The amount of material which makes a deposit totally unsuitable needs to be defined and may be used as cut-off grades are used in metallic deposit types. It is expected that the grade will vary with intended application. ASTM tests include ones for measuring hardness and durability, soundness, specific gravity, cleanness, lack of soft or friable fragments, and toughness (Goldman and Reining, 1983).

Modeling of chemical variables is primarily concerned with magnitude of chemical reaction between the aggregate and either portland cement or bituminous mixtures. ASTM tests include ones for potential chemical reactivity (Goldman and Reining, 1983). Materials which may be deleterious due to chemical reactivity includes gypsum, zeolite, pyrite, opal, chalcedony, and volcanic glass (Goldman and Reining, 1983).

The following characteristics are being considered for modeling (some overlap is possible). Not all characteristic have been covered in the previous discussion. Items flagged with (*) may be applicable to coarse aggregate only. The characteristics are:

volume	deposit geometry	particle sizes
particle geometry	external coating	impurity
specific gravity	sand equivalent	mineralogy
bulk density	soundness	flakiness*
hardness & durability	soft/friable fragments	toughness
cleanness	hydration	alkali-silica reactivity
chemical reactivity	solubility/leaching	thermal incompatibility
moisture content	weathering susceptibility	polish*
freeze/thaw response	water absorption*	shrinkage*

Data of relatively uniform quality and the results of reasonably compatible testing procedures must be available from a large number of sand and gravel deposits before modeling could proceed.

DEPOSITS

A list of deposits and locations used in this preliminary model follows. The locality abbreviations are: UKSC--United Kingdom, Scotland; UKWL--United Kingdom, Wales; USCA--United States, California. Underlined deposit names are for sand and gravel deposits in alluvial fan or alluvial plains and have a separate volume model.

Alameda Creek	USCA	Butte Creek	USCA
Allanton-Stane	UKSC	Cache Creek, North Fork	USCA
Allt Osda	UKSC	Cache Creek-Brooks	USCA
American River	USCA	Cache Creek-Rumsey	USCA
American River tailings	USCA	Calaveras Creek	USCA
Antioch sand dunes	USCA	Calaveras River	USCA
Ardnacross	UKSC	Caldermill	UKSC
Ardyne & Toward	UKSC	Callander-Dunblane	UKSC
Arroyo de la Cruz	USCA	Cammerlaws-Bedshiel	UKSC
Arroyo Seco	USCA	Campbeltown	UKSC
Arroyo Seco	USCA	Carmel River	USCA
Baddinsgill	UKSC	Carradale	UKSC
Bathgate (north)	UKSC	Carstairs	UKSC
Bathgate (south	UKSC	Carwood	UKSC
Battle Creek	USCA	Castaic Creek	USCA
Bavelaw	UKSC	Causewaybank	UKSC
Bear Creek (1)	USCA	Chalone Creek	USCA
Bear Creek (2)	USCA	Cherokee tailings	USCA
Bear River	USCA	Chili Gulch Creek	USCA
Big Maria Mountain	USCA	Churn Creek	USCA
Big Rock Creek	USCA	Claughearn Lodge	UKSC
Big Sur River	USCA	Clear Creek	USCA
Big Tujunga River	USCA	Clyde-Cumbusnethan	UKSC
Biggar	UKSC	Coldstream	UKSC
Birgham	UKSC	Correl Hollow Creek	USCA
Blackwood Creek	USCA	Cottonwood Creek	USCA
Blue Tent Creek	USCA	Cottonwood Creek	USCA
Blyth Bridge	UKSC	Crystal Rock	USCA
Borthwick and Tyne River	UKSC	Cucamonga Creek	USCA
Boyn Hill and Taplow	UKEN	Cuddy Creek	USCA
Bron's Hill	UKSC	Dailly	UKSC
Broomdykes	UKSC	Davis Creek	USCA

Day Creek	USCA
Derwyn Fwr (E)	UKWL
Dibble Creek	USCA
Donner Lake	USCA
Douglas	UKSC
Douglas buried channel	UKSC
Douglas Muir	UKSC
Douglas Water bur. channel	UKSC
Draffan	UKSC
Drumelzier-Barns	UKSC
Drumpellier	UKSC
Dry Creek	USCA
Dry Creek	USCA
Drymen and Finnich Glen	UKSC
Duddingston	UKSC
Dunbar-Oldhamstock	UKSC
Duns-Chirnside	UKSC
Dunsyre-Dolphinton	UKSC
East Fortune	UKSC
East Linton	UKSC
Easthouse	UKSC
Eastwood Distict	UKSC
Eaton Creek	USCA
Eddleston Water	UKSC
Ednam north	UKSC
Ednam south	UKSC
El Paso Mountain	USCA
Elibank	UKSC
Elsrcke	UKSC
Ettrick Water-Yarrow Water	UKSC
Fairmilehead	UKSC
Falkirk District	UKSC
Feather River tailings	USCA
Ford	UKSC
Forth Valley	UKSC
Garcia River	USCA
Garrauld Farm esker	UKSC
Gerrards Cross drifts	UKEN
Gerrards Cross SE	UKEN
Giespin	UKSC
Gilmanscleuch	UKSC
Glamis	USCA
Glandhouse-Carrington	UKSC
Glen Eachaig	UKSC
Glendaruel	UKSC
Glengravel Water	UKSC
Gorgie	UKSC
Greenhorn Creek	USCA
Greenock Mains	UKSC
Guadalupe Creek	USCA
Gullane	UKSC
Halls	UKSC
Harperrig	UKSC
Hospital Creek	USCA
Howgate	UKSC
Hunterston	UKSC
Huntleywood-Hexpath	UKSC
Indio Hills	USCA
Irvington gravel	USCA
Jacalitos Creek	USCA
Jackrabbit Trail	USCA
Joyland Creek	USCA
Kaweah River	USCA
Kelsey Creek	USCA
Kern River	USCA
Kibowie	UKSC
Kidlaw Region	UKSC
Kiel Croft	UKSC
Kilfinan	UKSC
Kilmartin	UKSC
Kilmore	UKSC
King River	USCA
Kingledoors	UKSC
Kirkoswald-Straton	UKSC
Ladykirk	UKSC
Laggan Bay	UKSC
Lagunitas Creek	USCA
Laigh Flakefield	UKSC
Lake of Menteith	UKSC
Lamberton	UKSC
Lanak-Sandilands	UKSC
Larkhall	UKSC
Legerwood	UKSC
Lindo Channel	USCA
Linlithgow (south part)	UKSC
Little Morongo Creek	USCA
Little Panoche Creek	USCA
Little Rock Creek	USCA
Loch Etive	UKSC
Loch Gorm	UKSC
Loch Gruninarh-Loch Indaal	UKSC
Loch Katrine	UKSC
Loch Voil	UKSC
Lone Pine Creek	USCA
Long Gulch	USCA
Los Banos Creek	USCA
Los Gatos Creek	USCA
Loudou Hill & Allanton Plains	UKSC
Lower Cache Creek	USCA
Lytle Creek	USCA
Lytle-Cajon Creeks	USCA
Mad River	USCA
Magee Creek	USCA
Makerstoun-Roxburgh	UKSC
Merced River	USCA
Merced River-El Portal	USCA

Mill Creek	USCA
Mojave River	USCA
Mokelumne River	USCA
Monterey sands-Monterey	USCA
Monterey sands-Pacific Grove	USCA
Moore Creek	USCA
Morebattle-Kirk Yetholm	UKSC
Mount Lothian	UKSC
Mt. Shasta	USCA
Muirkirk	UKSC
Needles	USCA
Nether Wellwood	UKSC
New Cumnock	UKSC
Newberry Mts.	USCA
Newbigging	UKSC
Newbridge	UKSC
Newcastleton	UKSC
Newmilns	UKSC
North Darvel	UKSC
Orestimba Creek	USCA
Ormiston	UKSC
Oro Grande	USCA
Otay River	USCA
Otter Ferry	UKSC
Owens River	USCA
Pacacho Creek	USCA
Pant Glas (D)	UKWL
Peebles	UKSC
Peebles-Traquair	UKSC
Peel	UKSC
Pencaitland-Humbie-Fala	UKSC
Penygroes-A	UKWL
Penygroes-C	UKWL
Pit River	USCA
Polmont	UKSC
Pool of Muchart (1)	UKSC
Pool of Muchart (2)	UKSC
Putach Creek	USCA
Putah Creek	USCA
Redbank Creek	USCA
Reston-Eyemouth	UKSC
Rhunahaorine	UKSC
River Avon	UKSC
River Clyde (Glasgow)	UKSC
River Clyde (Hamilton)	UKSC
River Clyde terraces (Biggar)	UKSC
River Colne & Mishbourne	UKEN
River Euchar	UKSC
River Kelvin	UKSC
River North Esk	UKSC
River Teviot	UKSC
Rommanno-Leadbin	UKSC
Russian River	USCA
Russian River	USCA
Rutherford	UKSC
Sacramento R., Anderson Bench	USCA
Sacramento R., Bloody Island	USCA
Sacramento R., Chadam Bar	USCA
Sacramento R., Hatch Ranch Bar	USCA
Sacramento R., Saron F.C. Bar	USCA
Sacramento River Sloughs	USCA
Saddell	UKSC
Salinas River-Atascadero	USCA
Salt Creek	USCA
Salton Sea dunes (1)	USCA
Salton Sea dunes (2)	USCA
Sam Joaquin River	USCA
San Antonio Creek	USCA
San Benito River	USCA
San Diego River	USCA
San Dieguito	USCA
San Emigdio	USCA
San Gorgonio River	USCA
San Grabriel River	USCA
San Luis	USCA
Sandur No. 14	UKWL
Santa Ana River	USCA
Santa Clara River	USCA
Santa Rosa	USCA
Santa Rosa plain	USCA
Santa Ynez River	USCA
Santiago Creek	USCA
Sisquoc River	USCA
Skirling	UKSC
South Darvel	UKSC
Spanish Creek	USCA
St. Boswells	UKSC
Stanislaus River	USCA
Stillwater Creek	USCA
Stonehouse	UKSC
Stoneypath	UKSC
Stony Creek	USCA
Stratblaine Water	UKSC
Strathaven	UKSC
Strathfillian	UKSC
Sweetwater River	USCA
Sycamore Canyon	USCA
Temescal Creek	USCA
Ten Mile River	USCA
Thankerton esker	UKSC
Thornyless	UKSC
Tia Juana River	USCA
Toftcombs	UKSC
Torphichen	UKSC
Torran Dubh	UKSC
Touch Hill	UKSC

Trabuco Creek	USCA	West Dunbar	UKSC
Tule River	USCA	West Linton Area	UKSC
Twentynine Palms Mts.	USCA	Weston	UKSC
Uddington	UKSC	White Water Wash	USCA
Unnamed buried channel	UKSC	Whitkirk	UKSC
Upper Truchee River	USCA	Woodhall	UKSC
Uvas Creek	USCA	Yuba dredge field	USCA
Van Dusen Creek	USCA	Zapato Creek	USCA
Ventura	USCA		
Walker Creek	USCA		
Walkerburn	UKSC		

DATA ANALYSIS AND PREPARATION

Data are either from California or the United Kingdom. While the overall surfical geology hosting sand and gravel deposits of these two areas is quite different, it will be shown that the sizes of sand and gravel deposits are not. Before discussing the model, several issues must be addressed concerning the data.

The largest sand and gravel deposits are of the alluvial fan type (including one alluvial plain deposit) found in the data set from California; however, some of these sand and gravel deposits have volumes which are the same as some of the smaller-sized deposits (fig. 1). Sand and gravel deposits in California were classified into two groups--alluvial fan type and all other types. Both groups were found to be not significantly different from lognormal (at the 1 percent level) using the skewness and kurtosis goodness-of-fit tests (Rock, 1988). The alluvial fans in California have a geometric mean size of 41 million cubic meters; all other sand and gravel deposits in California have a geometric mean size of 6.2 million cubic meters. The hypothesis that the two means are equal was rejected using the t-test (at the 1 percent level). Therefore the volume of sand and gravel deposits in alluvial fans needs to be modeled separately.

Sand and gravel deposits in the United Kingdom have a distribution not significantly different from lognormal (at the 1 percent level) using the skewness and kurtosis goodness-of-fit tests (Rock, 1988). The volumes of United Kingdom deposits overlap with those from California (fig. 2). Is the geometric mean of 4.8 million cubic meters for the United Kingdom significantly different from the geometric mean size of 6.3 million cubic meters for California sand and gravel deposits excluding alluvial fans? The hypothesis that the two means are equal was not rejected by the t-test (at the 1 percent level). Therefore, the volumes of California and United Kingdom sand and gravel deposit are modeled together.

VOLUME MODELS AND APPLICATIONS

Introduction

Models of sand and gravel deposits can be applied in two different circumstances: (1) poorly known or described regions where deposits are suspected to be present but not yet identified and (2) reasonably well-examined regions with known sand and gravel deposits or with clear indication of deposits as seen in outcrop and in other geologic evidence.

Poorly-known regions

Two volume models can be used to characterize sand and gravel deposits in poorly-known regions. One volume model is for sand and gravel deposits in alluvial fans and one other for all other deposit types. Analysis of deposit volume data compiled to date do not reveal any statistically significant differences in sizes among other genetic types. The two models, area and thickness, described in the following section on well-examined regions should be consulted to assist in making subjective estimates of numbers of undiscovered deposits.

Data for 275 deposits were used in the general volume model of sand and gravel deposits (fig. 3). About 45 percent of the deposits for the model are from California; the balance of the data are from the United Kingdom--predominantly from Scotland although a few are from Wales and England. The median sand and gravel deposit is 5.4 million cubic meters in size.

Data for 18 deposits are used in the model for sand and gravel deposits in alluvial fans (fig 4). The deposits for the model are predominantly from California although data on two fans from the United Kingdom were also included. The median sized deposit in alluvial fans is 35 million cubic meters--over 6 times larger than the median size expected for other types of sand and gravel deposits. Sand and gravel deposits in alluvial-fans usually vary in thickness between 6 and 99 meters; the typical or median deposit is 12 meters thick or over two times thicker than the median of the typical sand and gravel deposit.

Application of the volume models in quantitative mineral resource assessment requires a subjective estimate of the number of undiscovered sand and gravel deposits in the assessed region. Keep in mind that suspected sand and gravel bodies which are within 1.5 km are treated as parts of the same deposit for modeling purposes and this proximity rule will also need to be followed in the estimate of number of undiscovered deposits. Note that alluvial fans are treated separately. The estimates of number of undiscovered deposits can be used with the volume models in a Monte Carlo simulation to provide the probable range of volumes of sand and gravel in undiscovered deposits in the assessed region.

Well-examined regions

In many areas the surficial nature of sand and gravel deposits usually insures that they are likely identified or partially worked. For these deposits, the models of area and thickness of each deposit may be used to predict additional sand and gravel resources. It is necessary that subjective estimates of areas underlain with sand and gravel deposit be made before these models can be used in computer simulation.

As part of developing the area and thickness models, estimated volumes calculated from average thickness and area were compared to the reported volumes. About 77 percent of the data compilation for modeling sand and gravel deposits also includes thickness and area in addition to volume. For about two-thirds of these deposits the volume calculated from average thickness and area is within 10 percent of the reported volume; for 4 out of 5 deposits the calculated volume is within 25 percent of the reported volume. These results suggest that estimating volume using area and average thickness yields reasonable volume estimates despite the considerable complexity in geometries that sand and gravel deposits may exhibit. Of course, some investigators have used area and average thickness to calculate some of the reported volumes which probably increases the level of agreement between the calculated and reported figures.

A model of the areas of sand and gravel deposits (fig. 5) has a distribution not significantly different from lognormal (at the 1 percent level) using the skewness and kurtosis goodness-of-fit tests (Rock, 1988). Areas in this model are between 3 and 11,000 hectares (ha[1]). The model provides a guide to estimating areas. Since area, along with thickness, is frequently used to compute sand and gravel deposit volumes, area is clearly not independent of volume and the positive correlation (R^2 = 0.85, N = 256) (at the 1-percent level of significance) between area and volume is a case of spurious self-correlation (fig. 6).

For an assessment an estimate of the range of areas for <u>each</u> sand and gravel deposit is required. The uncertainty (or range) in the estimate is considered to have a normal distribution. In order to use these estimates in computer simulation, two parameters are needed, a mean and variance of the estimate. The best estimate will be treated as the mean. The uncertainty in the best estimates is obtained from estimates of the minimum area and the maximum area underlain with sand and gravel. The estimates need to be symmetrical about the best estimate of area. For example, if the estimated minimum area is 120 ha and the maximum area is 400 ha, the best estimate will be 260 ha. The estimates (best, minimum, maximum areas) should be made in different sequences to arrive at a final set of figures. The estimates of minimum and maximum areas will be defined as containing 99 percent of the area under the normal distribution curve or 2.6 times the standard deviation. (This means that there is one chance in a 100 that the actual area is either smaller or larger then the limits provided.) Also needed to evaluate each sand and gravel deposit is a single estimate of area worked (or volume removed by mining).

A general model of the thickness of sand and gravel deposits (fig. 7) has a distribution significantly <u>different</u> from lognormal (at the 1 percent level) in terms of both the skewness and kurtosis goodness-of-fit tests (Rock, 1988). The reason for the difference from lognormality is unknown. No transformation was found to give data which fit any standard distribution type. While it would be desirable to used a standard distribution, the empirical frequency distribution of thickness can be used in computer simulation. Therefore, the percentiles (90th, 50th, and 10th) in fig. 7 are for the data and not for a fitted distribution which is the case in other models given here. Deposit thickness varies between 0.4 and 65 meters; the typical or

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[1]One hectare is equal to 2.47 acres; 1 square miles is equal to 259 ha.

median deposit is 4.6 meters thick. There is a small, but significant, positive correlation ($R^2 = 0.038$, N = 230) (at the 1-percent level of significance) between thickness and area (fig. 8). Therefore sand and gravel thickness and area are not quite independent variables but only weakly correlated. For the type of application envisioned, these two variables can be treated as independent. While one may speculate about the range of deposit areas, this may not be so easy to do for deposit thickness. However one may also make thickness estimates using the strategy described for estimating deposit area. Otherwise, the general model of sand and gravel deposit thickness can be used in simulation.

Since thickness, along with area, is frequently used to compute sand and gravel deposit volumes, thickness is clearly not independent of volume and the positive correlation ($R^2 = 0.30$, N = 230) (at the 1-percent level of significance) between thickness and volume is a case of spurious self-correlation (fig. 9).

Monte Carlo simulation using these models and estimates for area and (or) thickness can provide the probable range of volumes of sand and gravel in known deposits in the region. The calculated range in volumes is due to uncertainty in areas and thickness of deposits in the area under investigation and not the uncertainty in number of undiscovered deposits.

ESTIMATING AREAS MINED FOR ROAD CONSTRUCTION

A useful estimator for planning is the size of area disturbed by a predetermined volume of sand and gravel needed in some application. An estimate can be made by simply dividing the needed volume by the median thickness of 4.6 m for most sand and gravel deposits.

Langer (1988, table 4) who tabulates data by Schenck and Torries (1975) gives approximate estimates of consumptive tonnage of coarse aggregate needed per mile of roadway (including a six-lane interstate, a four-lane interstate with and without bridges and interchanges). A variety of assumptions are given concerning concrete thickness, subbase thickness, presence or absence of paved shoulders, etc.

In the case of a four-lane interstate with bridges and interchanges, approximately 65,000 tons of coarse aggregate are needed per mile of construction (Langer, 1988). This is equal to 59,000 metric tons or about 29,000 cubic meters. This is the volume of gravel needed if the coarse aggregate is to be supplied from sand and gravel deposits. The estimated median gravel content of 36 sand and gravel deposits is 53 percent. In order to obtain 29,000 cubic meters of gravel, about 55,000 cubic meters of a sand and gravel deposit must be mined. Dividing this volume by 4.6 m suggests that this could be supplied by working 1.2 ha of a typical sand and gravel deposit. This indicates that the gravel extracted alone to build 216 miles of this type of road will disturb one square mile of land. Given details of the type of aggregate needed for other applications, this procedure can also be used to make estimates of areas to be disturbed by sand and gravel extraction. Of course there are regions (e.g., the seaward sections of the Atlantic and Gulf coast areas of the United States) where gravel is completely absent and this estimate does not applied.

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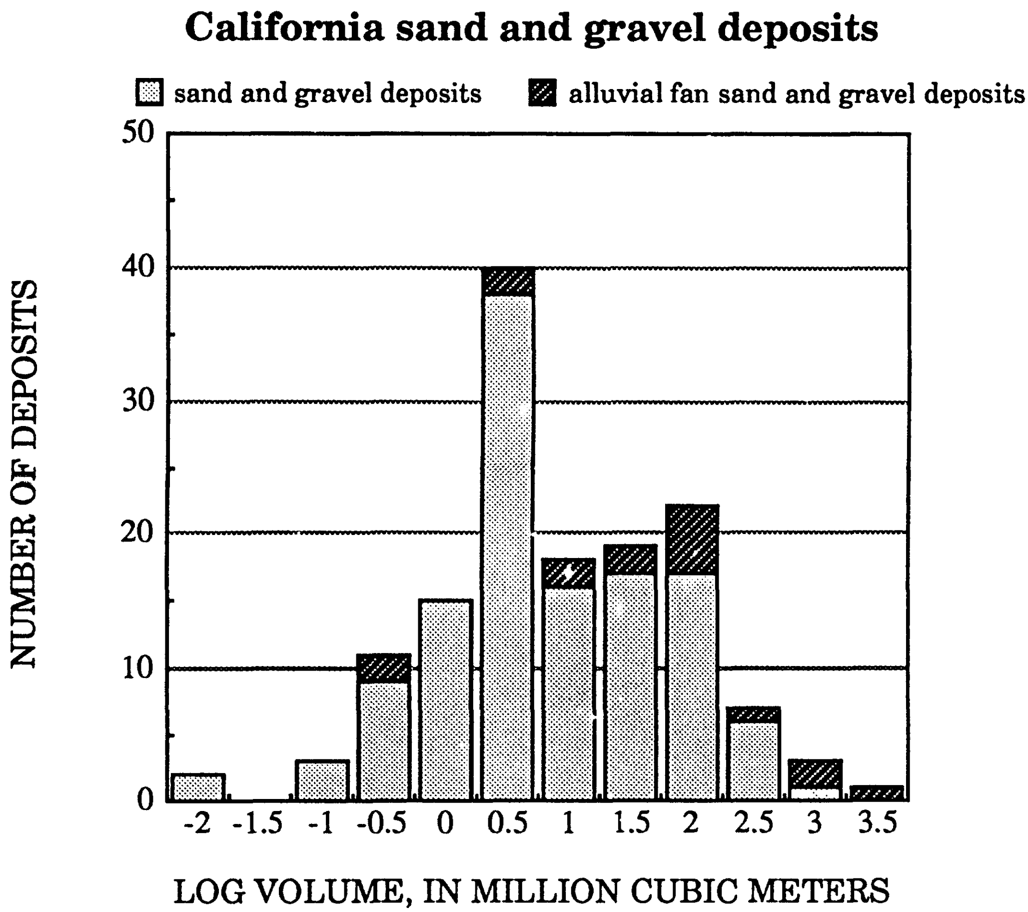

Figure 1. Histogram of sand and gravel deposits in California.

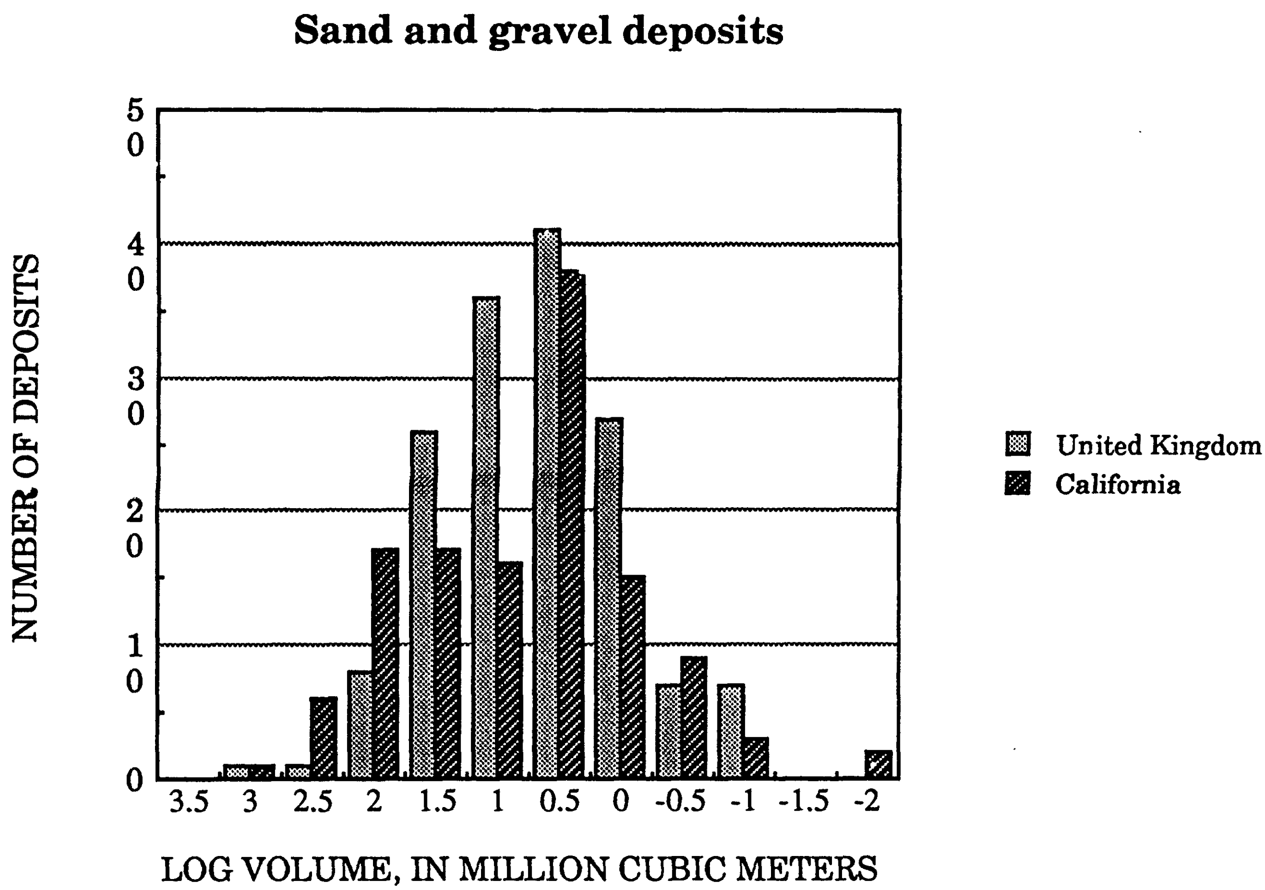

Figure 2. Histogram of sand and gravel deposits in California and in the United Kingdom.

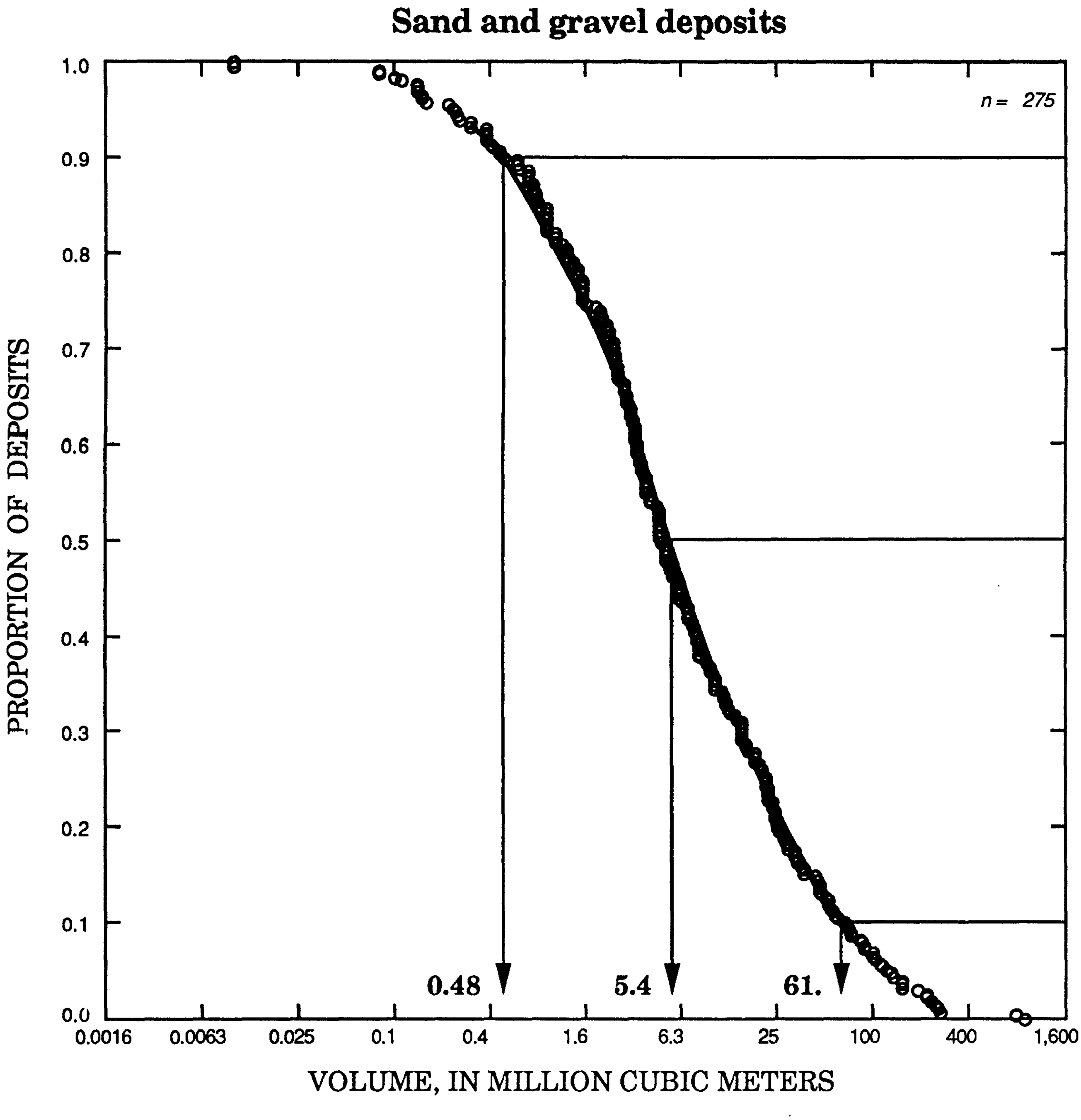

Figure 3. General volume model of sand and gravel deposits.

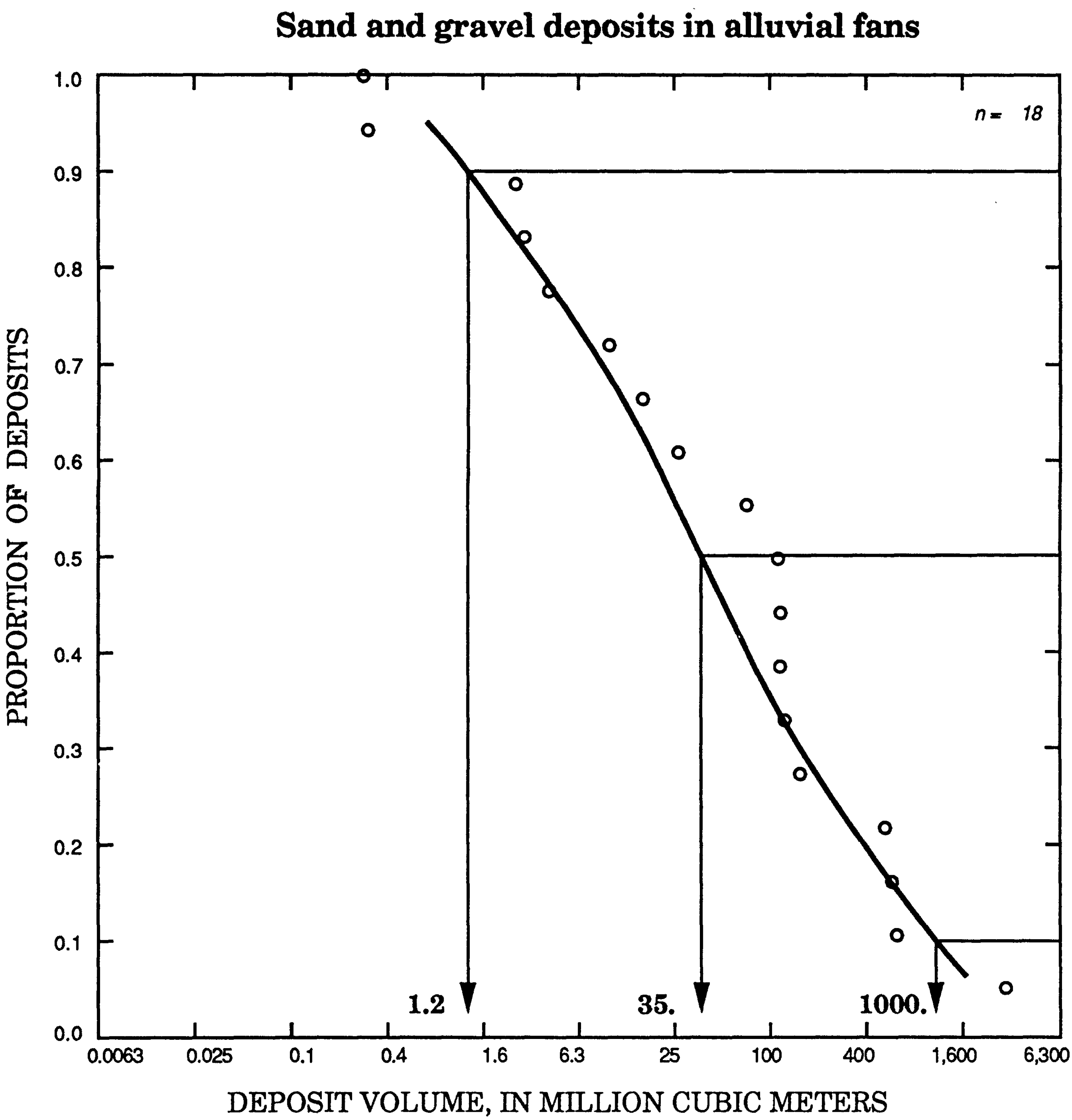

Figure 4. Volume model of sand and gravel deposits in alluvial fans.

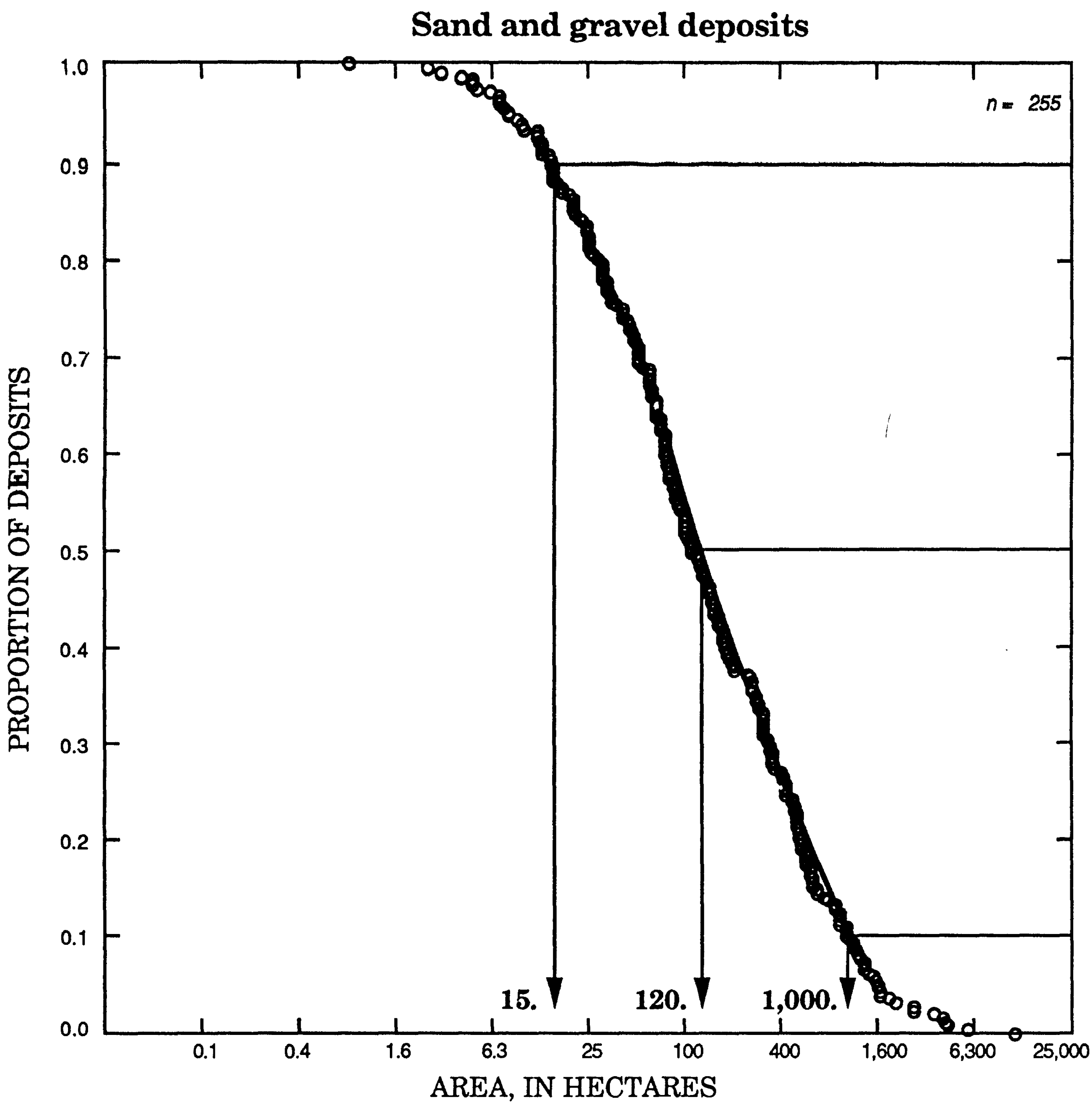

Figure 5. General area model of sand and gravel deposits.

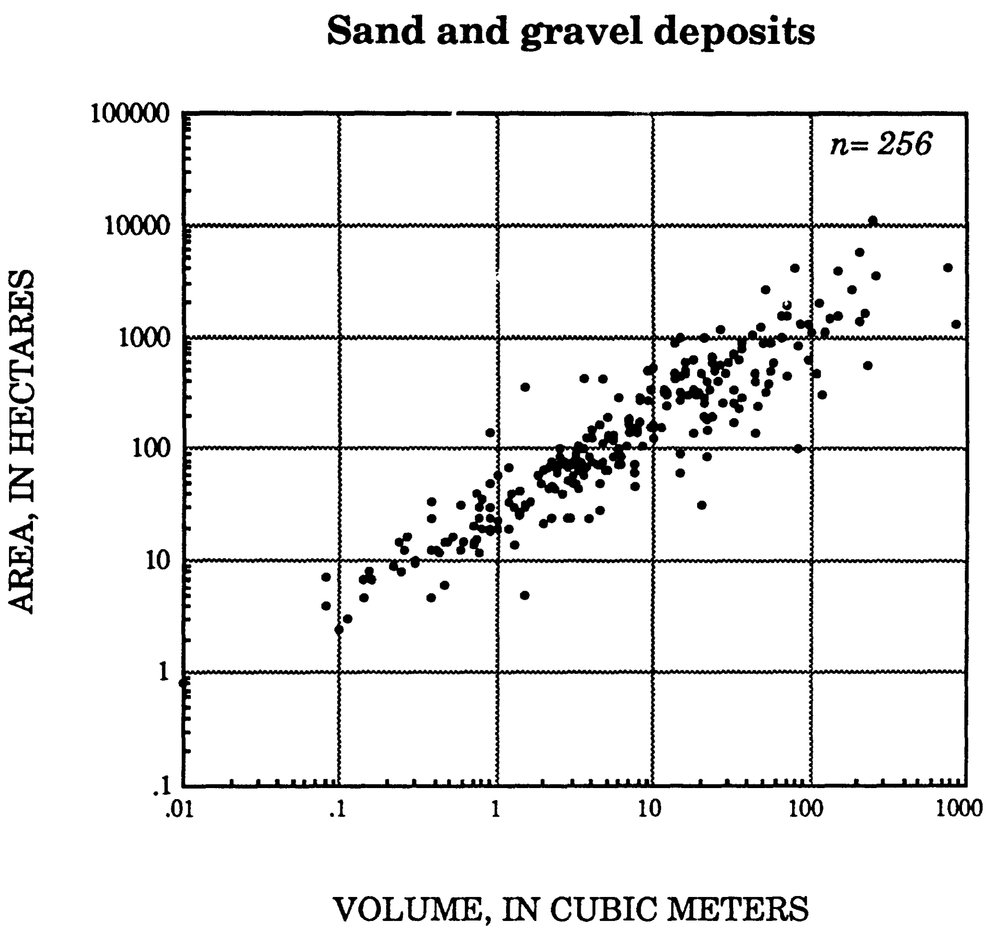

Figure 6. Scatter plot of area (hectares) and volume (cubic meters) of sand and gravel deposits.

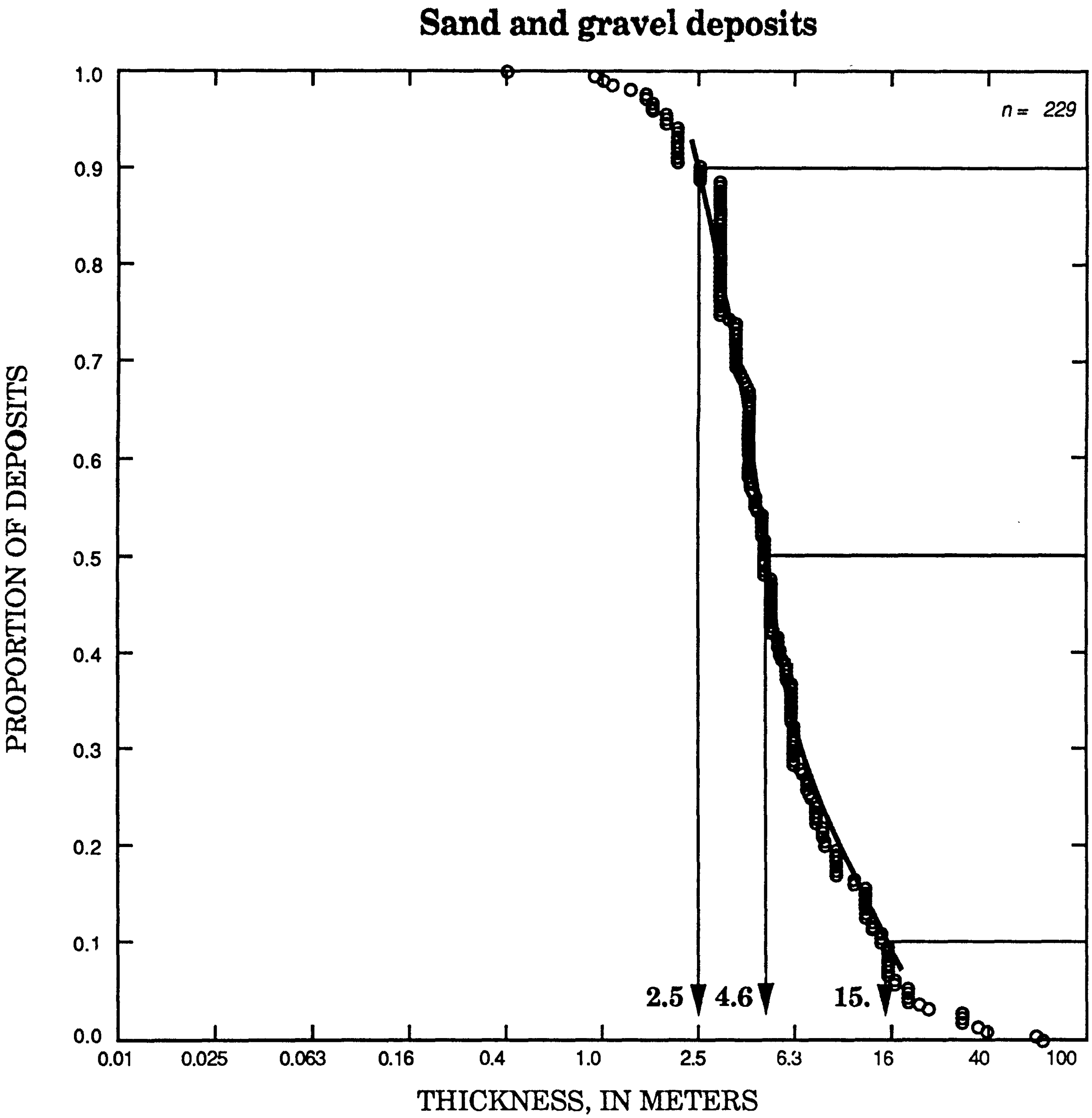

Figure 7. General thickness model of sand and gravel deposits.

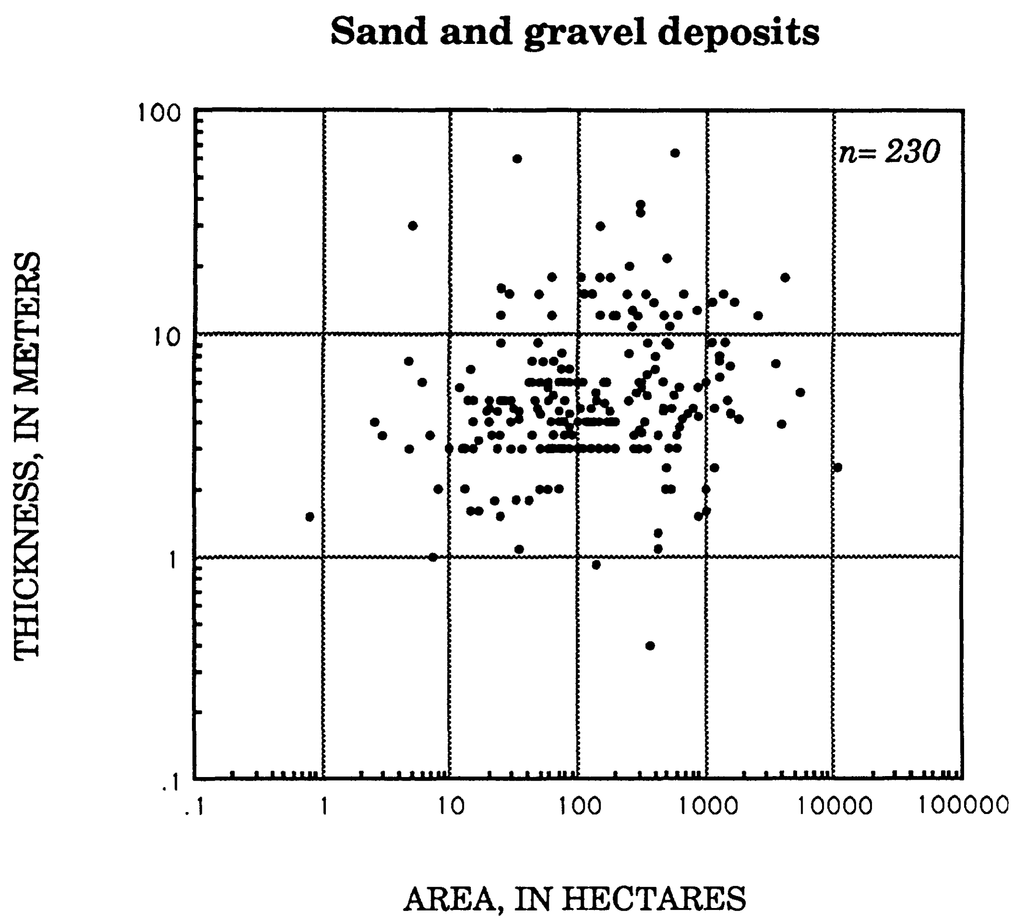

Figure 8. Scatter plot of thickness (meters) and area (hectares) of sand and gravel deposits.

Sand and gravel deposits

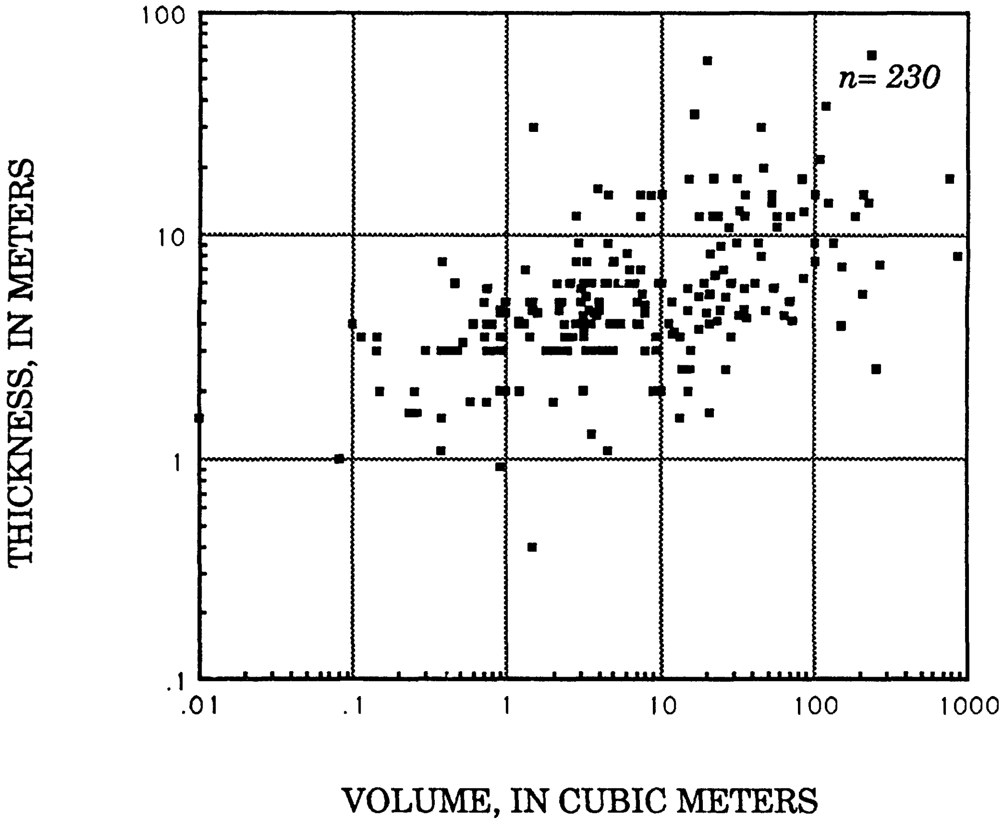

Figure 9. Scatter plot of thickness (meters) and volume (cubic meters) of sand and gravel deposits.