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Kentucky Geological Survey
Donald C. Haney, State Geologist and Director
UNIVERSITY OF KENTUCKY, LEXINGTON

Sand *and* Gravel Resources

Along the Ohio River Valley

in Boone, Gallatin, and Carroll Counties, Kentucky

Eugene J. Amaral
With Contributions by **Warren H. Anderson**

Series XI, 1994

Report of Investigations 8

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SAND AND GRAVEL RESOURCES ALONG THE OHIO RIVER VALLEY IN BOONE, GALLATIN, AND CARROLL COUNTIES, KENTUCKY

Eugene J. Amaral

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ABSTRACT

Glacial outwash sand and gravel from three northern Kentucky counties in the Ohio River Valley have been analyzed in order to characterize their particle size, composition, morphology, and surface alteration and to determine the geologic significance of lateral and stratigraphic variations in these sediment properties. The late Wisconsinan-age deposits, actively mined in terraces along the Ohio River, are composed of moderately sorted sand and a poorly sorted, bimodal mixture of sand and gravel. A systematic pattern of regional grain-size variation was found to be associated with the confluence of the Great Miami River, a major meltwater sluiceway entering the Ohio River Valley. This area contained the greatest amounts of large-pebble gravel. Downstream from this area, the maximum and modal gravel size and the total gravel percentage decreases, the total sand percentage increases, but essentially no change takes place in modal sand size. Sediment sorting is generally poor, with no apparent downstream variation. Over these broad, regional trends are superimposed local textural variations that correlate with hydraulic gradients created by meander bend geometry. Stratigraphically older outwash located in adjacent upland areas is much coarser grained and more poorly sorted than outwash in the Ohio River Valley.

Outwash particle composition is related to grain size, stratigraphy, and location. Approximately 75 percent of the gravel to coarse sand sizes are composed of dolomite and limestone, with the remaining 25 percent made up of quartz, chert, sandstone, igneous, and metamorphic rock fragments. Rock fragment percentages, in general, decrease from coarse pebble to fine sand sizes, as individual mineral percentages increase in the sand fractions. Chert and quartz sandstone are most abundant in the fine pebble sizes.

Stratigraphic differences in sand and gravel composition, reported for ice-laid tills of the region, were used to differentiate between subsurface samples of outwash in the Ohio River Valley. Limestone/dolomite ratios greater than 5:1 and an abundance of chert and sandstone characterize older outwash units, while a limestone/dolomite ratio less than 1:1 typifies the youngest unit. Regional composition changes along the Ohio River Valley include a downstream decrease in carbonate rock pebbles and an increase in chert, sandstone, igneous, and metamorphic rock pebbles. Local variations in pebble composition are found in low-energy depositional environments where clay, chert, and coal pebbles accumulated.

Pebble shape varies little with respect to particle size or stratigraphy, but it is distinctive in certain rock types. Axial ratio plots show very platy and elongated pebbles are composed mostly of limestone and sandstone. On average, outwash pebbles are rounded to well rounded, but significant variations in roundness occur with respect to lithology, grain size, and stratigraphy. Roundness variations among lithologies reflect differences in their hardness or resistance to abrasion. Having traveled a greater distance from their glacial source, pebbles in the youngest outwash are more rounded than pebbles in older stratigraphic units. Because of their longer exposure to abrasion, smaller pebbles are more rounded than larger ones.

Pre-Illinoian and Illinoian Pleistocene outwash, located on uplands bordering the Ohio River Valley, are unfavorable as a source of aggregate because of the abundance of deeply weathered, unsound particles and the large amounts of deleterious sandstone and chert. Younger Wisconsinan outwash deposits within the Ohio River Valley, in contrast, contain the largest concentrations of sound, coarse and fine aggregate with the least amount of deleterious materials.

INTRODUCTION

Nationwide demand for natural aggregate—crushed stone, sand, and gravel—will be nearly 2.5 billion short tons a year by the year 2000, according to U.S. Bureau of Mines predictions (Langer, 1988). Of the Nation's total aggregate production of 1.8 billion tons in 1991, Kentucky contributed 60 million tons (U.S. Bureau of Mines, 1992). Sand and gravel, making up about 15 percent of the aggregate produced in Kentucky, represent a finite, nonrenewable resource essential for the construction and maintenance of structures and highways. Because sand and gravel are relatively low-value, high-bulk commodities at the point of origin, mine sites must be located near the consuming market to keep transportation and construction costs economical.

Sediment-laden, glacial meltwaters flowing down the Ohio River Valley during late Pleistocene time deposited Kentucky's major source of high-quality sand and gravel. Terrace remnants along the valley containing these sediments are of agricultural, urban, and industrial interest because these sand and gravel deposits form an important regional aquifer and provide a convenient, economical source of construction material. Expansion of urban centers and construction of residential tracts, industrial parks, and power plants on the high terraces, however, have been removing potential high-quality aggregate from Kentucky's resource base. Competition for this limited land area, therefore, compels responsible agencies to formulate long-range plans for sequential, multiple land use that will permit the recovery of this valuable resource.

A well-designed plan for sequential land use requires adequate characterization of an area's natural resources. Because little has been published about Kentucky's sand and gravel in the Ohio River Valley, a thorough description of this resource is needed. The purposes of this investigation are to (1) quantify the physical and chemical properties of sand and gravel deposits in a three-county area of northern Kentucky, (2) determine any lateral or stratigraphic variability in these properties, and (3) explain the significance of these variations.

Location

The study area covers approximately 600 square miles of the Ohio River Valley and its upland margin in Boone, Gallatin, and Carroll Counties in northern Kentucky (Fig. 1). These three counties were selected because they contain (1) the most complete Pleistocene stratigraphic section in the region, (2) the discharge site of a major glacial meltwater sluiceway entering the Ohio River Valley from glaciated terrain to the north, and (3) the greatest concentration of sand and gravel pits in Kentucky.

Previous Studies

As part of North America's southern glacial boundary, the Pleistocene deposits of Kentucky have long been discussed and debated because they hold important clues to the region's glacial history and geomorphology (Wright, 1890; Leverett, 1899, 1902, 1929; Durrell, 1961; Teller, 1970, 1973; Ray, 1974). The region's two principal types of glacial deposits, collectively termed *drift*, consist of unsorted, nonstratified ice-contact sediments called *till* and stratified meltwater sediments called *outwash*. The quality of these deposits has been described by Leverett (1929) and personnel of the U.S. Geological Survey–Kentucky Geological Survey joint mapping program (Gibbons, 1972, 1976; Swadley, 1969, 1971, 1972, 1973, 1976). Thorough, quantitative descriptions of the region's glacial tills have been carried out by Ray (1957), Gooding (1963, 1966, 1973), Leighton and Ray (1965), and Teller (1970, 1972), but outwash sand and gravel have received much less attention. Outwash studies include chemical and mechanical analyses of a few sand samples from Carroll County (Richardson, 1920, 1927), petrographic and stratigraphic descriptions of sand and silt deposits from Kenton and Campbell Counties (Schaber, 1962; Teller, 1962), measurement of outwash thickness and depth to bedrock along the Ohio River Valley (Walker, 1957; Price, 1964a–b), and petrographic and geochemical analysis of calcite cement in several coarse sands from western Boone County (Paxton, 1980). The outwash between Lawrenceburg, Indiana, and Jeffersonville, Indiana, which is adjacent to the present study area (Fig. 1), has been described thoroughly by Webb (1970).

GEOLOGIC SETTING

Regional Geology and Geomorphology

Local and distant bedrock, eroded and redistributed by glacial-fluvial processes during the last million years, was the source of northern Kentucky's sand and gravel deposits. Most sand and gravel were derived from the bedrock and rocky soils of southern Ohio and Indiana, but regional bedrock as far north as Canada also contributed (Fig. 2).

The bedrock lithology of the north-central United States is composed of a thick sequence of carbonates and clastic rocks such as limestones, dolomites, sandstones, shales, and coastal swamp coals. These rocks accumulated in the subsiding Michigan, Illinois, and Appalachian Basins 570 to 250 million years ago during the Paleozoic Era. These basins are separated by the

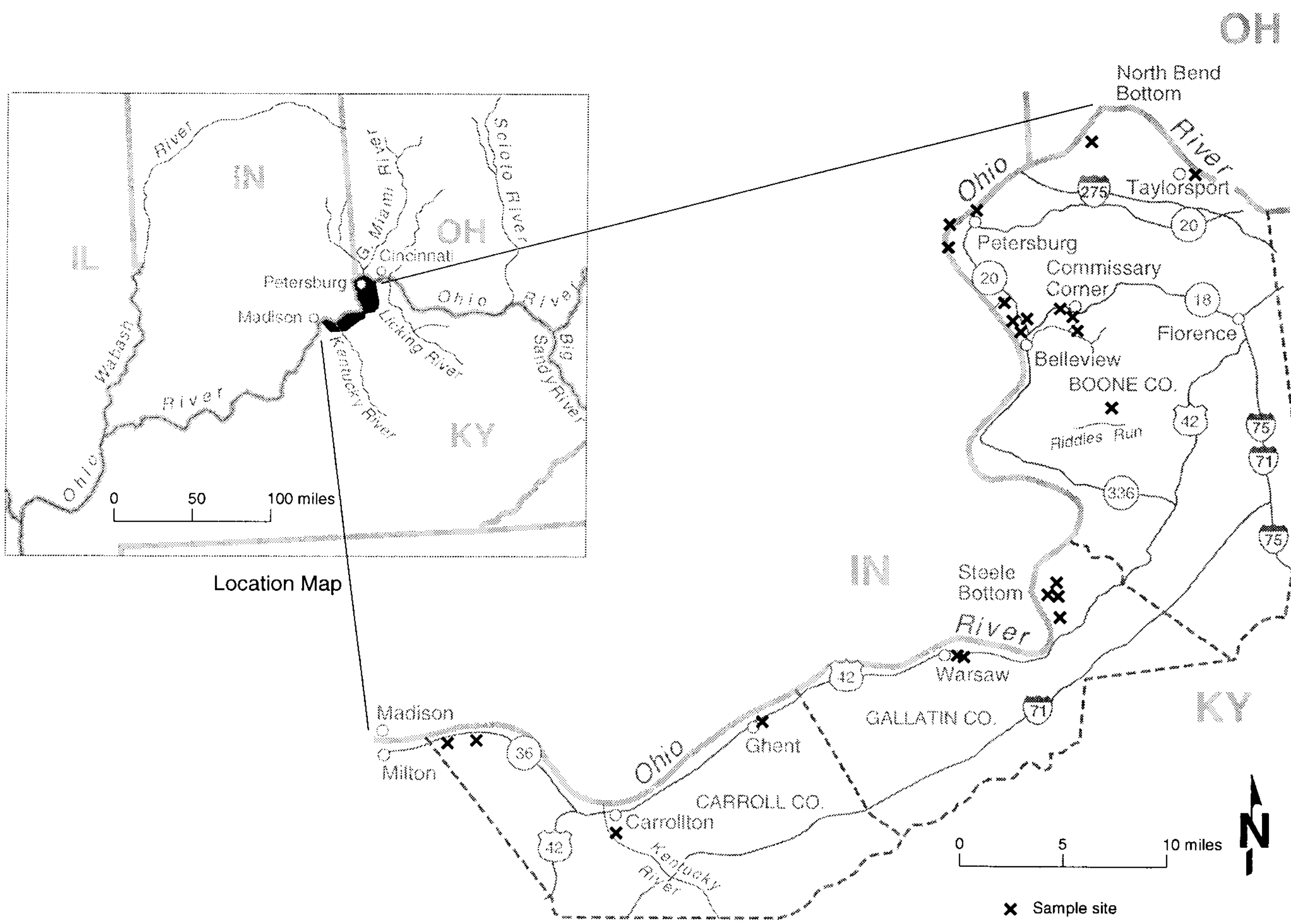

Figure 1. Location of study area and sample sites.

Cincinnati, Findlay, and Kankakee Arches, which extend across Indiana, Ohio, and central Kentucky into middle Tennessee (Fig. 2). In northern Kentucky, Late Ordovician bedrock of interbedded limestone and shale dips very gently from the axis of the Cincinnati Arch into the adjoining Illinois and Appalachian Basins (Fig. 2). Arranged in broad bands along the arch are successively younger rock units: Silurian and Devonian shale, dolomitic limestone, dolomite, and bituminous shale; Mississippian shale, siltstone, sandstone, and limestone; and Pennsylvanian and Permian shale, sandstone, and coal.

Erosion of upper Paleozoic rocks exposed lower to middle Paleozoic rocks in the central parts of Indiana, Ohio, and Kentucky (Fig. 2). By late Tertiary time the region had been beveled to a plain of low relief traversed by sluggish, meandering rivers. Gradual, widespread uplift of this gently rolling plain during Pliocene–Pleistocene time (1 to 5 million years ago) resulted in drainage entrenchment 50 to 100 feet below the regional surface. Preserved remnants of this old, entrenched drainage system are found today as high-level fluvial deposits scattered across the uplands in many parts of Kentucky.

During preglacial Pliocene–Pleistocene time, the main east–west trunk stream draining the eastern, Midcontinental region was the Teays River. Originating in the Appalachians near the present-day Virginia–North Carolina border (Tight, 1903), the Teays River avoided the highest structural part of the Cincinnati Arch by following a northwestern course to what is now central Ohio, where it turned west and flowed across north-central Indiana and Illinois to the Mississippi River (Fig. 3). The ancestral Kentucky, Licking, and Big Sandy Rivers, whose northerly courses were controlled by the north–south alignment of variably resistant bedrock strata, drained into the Teays River. The upper Ohio River Valley, as known today, did not exist at this time. During preglacial time, a much smaller Ohio River originated on the western limb of the Cincinnati Arch near present-day Madison, Indiana (Fig. 3), and flowed to the Mississippi Valley along a course essentially the same as that of the modern river (Wayne, 1952; Ray, 1974).

Pleistocene Geology

The upper Ohio River Valley east of Madison, Indiana, is a relatively recent feature that developed within the last million years. Detailed discussions and competing interpretations of the Ohio River Basin's complex evolution may be found in the literature (Leverett, 1902; Tight, 1903; Fenneman, 1916; Malott, 1922; Fowke, 1925; Wayne, 1952; Teller, 1973; Ray, 1974). At least three major advances and retreats of glacial ice, caused by global climate fluctuations during the Pleistocene Epoch, led to the formation of the modern Ohio River Valley and its sedimentary deposits. This report will use the chronology and provisional age assignments shown in Figure 4.

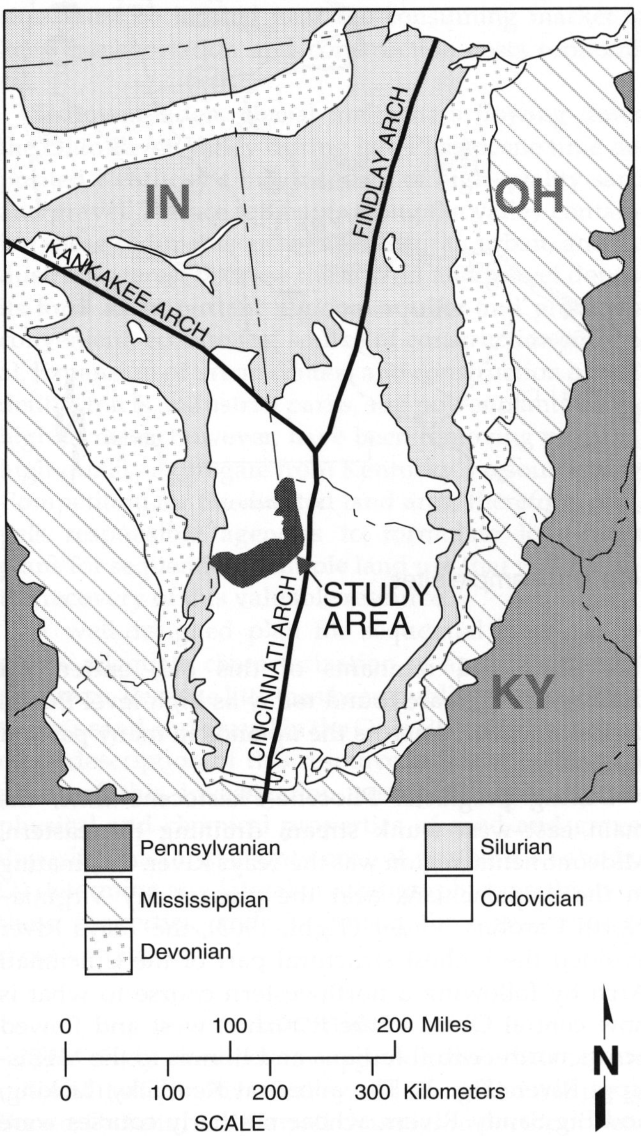

Figure 2. Geology of the North American Midcontinent. Bedrock and soils from north of Kentucky served as the source for the sand and gravel resources of the Ohio River Valley. (Modified from North American Geologic Map Committee, 1965).

Pre-Illinoian Stage

The earliest continental glacier approached and may have entered what is now northern Kentucky during early Pleistocene time (Fig. 4), radically modifying regional drainage by burying or damming portions of the preglacial Teays River and its tributaries (Teller, 1973; Ray, 1974; Swadley, 1979). Icebergs floating on lakes formed just beyond the frontal margin of the advancing glacier (termed *proglacial lakes*), in the blocked preglacial Licking and Kentucky River drainage basins, may have dropped glacial debris into present-day northeastern and central Kentucky, miles beyond the recognized drift boundary (Jillson, 1927; Leverett, 1929; Ray, 1969). Fine-grained outwash material in Kenton County has been attributed to this glacier (Schaber, 1962), but whether till deposits belong to this early glacier or to a later pre-Illinoian glacier is debatable (Leighton and Ray, 1965; Teller, 1970; Swadley, 1979).

Along the fluctuating margin of this early ice sheet, the Ohio River Valley gradually developed across the Cincinnati Arch as basin segments of the old Teays system were linked together by a series of spillover channels cut into drainage divides by the cresting floodwaters of proglacial lakes. For example, waters impounded in the preglacial Kentucky River and upper Teays River Basins spilled over and downcut drainage divides of resistant Silurian dolomite at present-day Madison, Indiana, and Manchester, Ohio, respectively (Fig. 3). These two major breaches resulted in capture of the preglacial Kentucky and Licking River Basins by the preglacial Ohio River west of present-day Madison, and diversion of the upper Teays system into the preglacial Manchester River east of present-day Cincinnati. The course of the early Pleistocene Ohio River, subsequent to deglaciation, followed a route similar to today's river except for a loop detouring north of present-day Cincinnati.

With flow rates greatly augmented by the discharge from pirated preglacial drainage basins, the early Pleistocene Ohio River began to vigorously incise its valley into the region's bedrock. The Ohio River Valley was essentially cut to its maximum depth during the early middle Pleistocene interglacial period, defined as "Deep Stage" (Fig. 4).

A second pre-Illinoian glacier definitely advanced into what is now northern Kentucky during middle

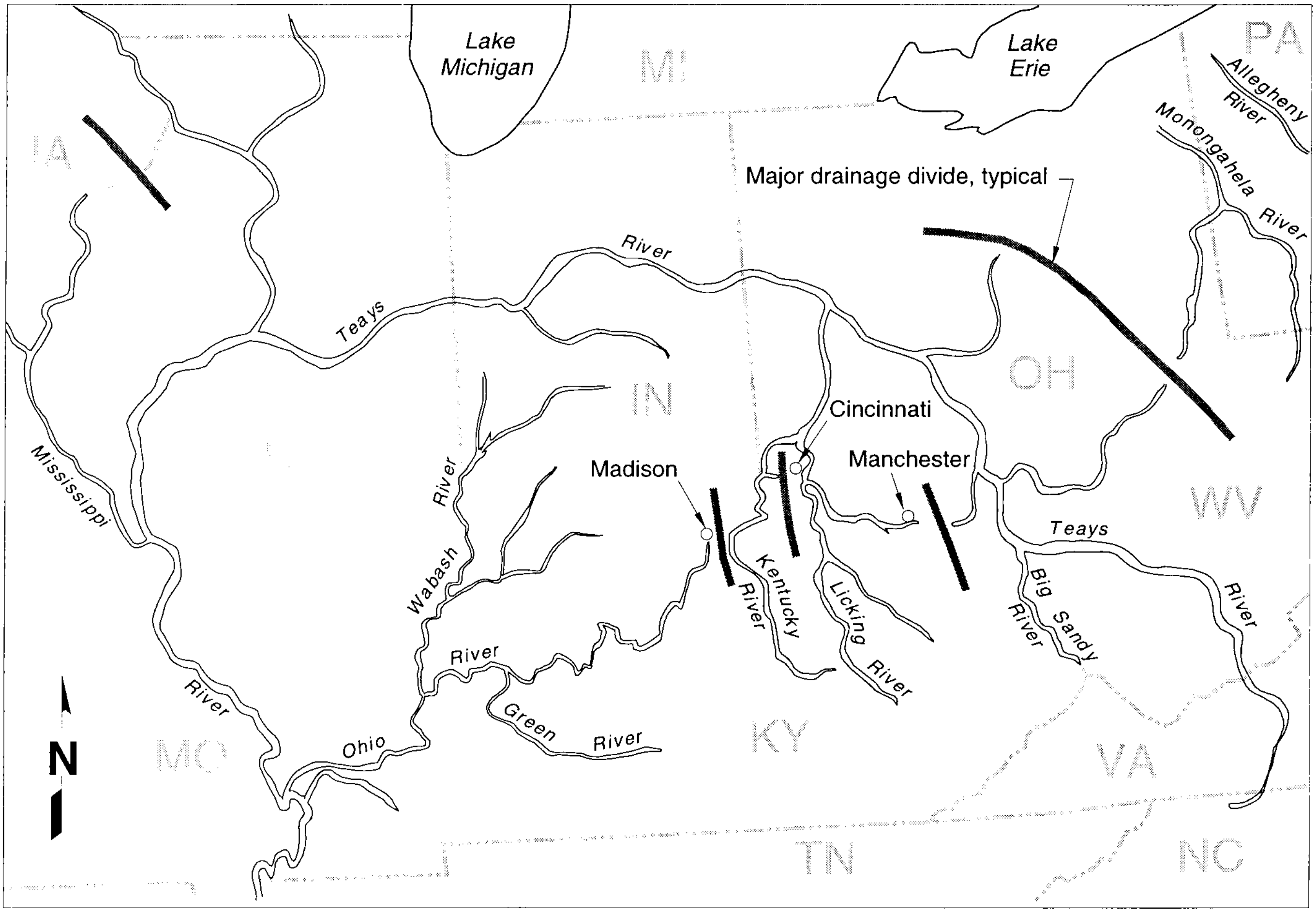

Figure 3. Preglacial drainage pattern of the Midcontinental United States.

Pleistocene time (Fig. 4), depositing drift across the uplands and within the abandoned channels of the preglacial Kentucky and Licking River drainage system. Drift remnants of this second pre-Illinoian glacier, preserved below the upland surface in small, high-level tributary valleys bordering the Ohio River (Ray, 1957; Swadley, 1979), imply that entrenchment of the Ohio River Valley during Deep Stage time was well advanced by the time the second glacier invaded Kentucky.

Illinoian Stage

The Illinoian glacier advanced to its maximum position during late middle Pleistocene time (Fig. 4), encroaching less than 3 miles into present-day northern Kentucky in several places (Fig. 5). A tongue of this glacier flowed down the Great Miami Valley and into the Ohio River Valley, terminating near present-day Carrollton, Kentucky (Fig. 1). Along its course, a significant thickness of drift was deposited (Swadley, 1976). The Illinoian glacier also buried the Deep Stage Ohio River loop north of present-day Cincinnati, thereby impounding the Ohio and Licking Rivers. Spillover waters from this impoundment rapidly downcut several local drainage divides south of present-day Cincinnati, creating the straight, shortened course of the Ohio River seen today between Newport, Kentucky, and Lawrenceburg, Indiana (Teller, 1973). Evolution of the upper Ohio River Valley was completed at this time.

With climate warming during the Sangamon interglacial period (Fig. 4) and a return to normal flow conditions, the Ohio River began dissecting its deposits of Illinoian drift. Downcutting by the river left paired terraces of glacial drift between the active river channel and bedrock valley walls. Only scattered remnants of these terraces remain today; their eroded top surfaces lie at elevations below 650 feet in the study area.

Wisconsinan Stage

The region's last continental glacier made its southernmost advance, to within 15 miles of what is now Kentucky near Cincinnati (Fig. 5), about 21,000 years ago during late Wisconsinan time (Fig. 4). For approximately the next 7,000 years the ice margin cyclically ad-

Formal Geochronologic Units		Informal Time Divisions			Age (years)
Period	Epoch	Stage			
QUATERNARY	Holocene				
					10,000
	Pleistocene	Late Pleistocene	Wisconsinan	Late Wisconsinan	
					35,000
				Middle Wisconsinan	
					65,000
				Early Wisconsinan	
					79,000
				"Eowisconsinan"	
					122,000
			Sangamon		
					132,000
		Late middle Pleistocene	Illinoian	Late Illinoian	
					198,000
				Early Illinoian	
					302,000
		Middle middle Pleistocene	Pre-Illinoian		
					610,000
		Early middle Pleistocene		"Deep Stage"	
					788,000
		Early Pleistocene			
					1,650,000
TERTIARY	Pliocene	Pre-Pleistocene			

Figure 4. Provisional ages for informal Pleistocene time division boundaries. (Adapted from Richmond and Fullerton, 1986.)

vanced and receded across much of what became Ohio, Indiana, and Illinois as the glacier made a gradual, staggered withdrawal from the region. Glacial drift accumulated as thin, overlapping till sheets during successive ice retreat cycles or as thick, hummocky terminal mounds called *moraines* along a stabilized ice margin in periods of ice growth–meltback equilibrium. The Ohio River Valley received outwash-laden meltwaters from the glacier via major sluiceways. They are, from east to west, the Scioto River at present-day Portsmouth, Ohio, the Little Miami River and Mill Creek at present-day Cincinnati, the Whitewater–Great Miami Rivers at present-day Petersburg, Kentucky, and the Wabash River at present-day Uniontown in Union County, Kentucky (Fig. 1). Based on the volume of sedimentary deposits, the most significant outwash distributor in the upper Ohio River Valley was the Great Miami–Whitewater sluiceway.

Alternating periods of outwash deposition (*aggradation*) and erosion (*degradation*) corresponded to the waxing and waning phases of glacial movement. Maximum outwash aggradation occurred generally at the onset of glacial retreat and during periods of ice stagnation. Sediment-rich meltwaters, flowing in a braided network of overloaded stream channels, rapidly laid down coarse- to fine-grained particles across entire valley floors. Confined within steep-walled, entrenched valleys and traceable back to till sheets or prominent terminal moraines, these outwash materials are commonly called *valley train deposits*. The valley train sediments were later eroded during periods of glacial advance or maximum ice recession, resulting in their partial removal and the formation of paired terraces.

Two late Wisconsinan terrace surfaces, representing separate periods of valley train development in the Ohio River Basin, have been recognized by Ray (1974) as equivalent in age to the Tazewell and Cary units of Illinois. Outwash materials composing the older and more prominent Tazewell valley train are associated with till and moraine deposits ranging in age, determined by carbon-14 dating, from 21,000 to 16,700 years before the present (Fullerton, 1986). Paired terraces of Tazewell outwash (Fig. 6), resulting from post-Tazewell erosion, have surface elevations of 500 to 535 feet above mean sea level in the study area. Commercial deposits of sand and gravel mined today in northern Kentucky come from pits on the Tazewell terrace surface.

Glacier readvancement into what is now north-central Ohio and Indiana about 15,500 years ago (Fig. 5) and subsequent melting led to the formation of the Cary valley train. Fine-grained Cary outwash, carried by meltwaters of the Scioto and Great Miami sluiceways, was deposited in the valley carved out of older Tazewell sediments (Ray, 1974). The Cary terrace, which lies about 15 feet below the Tazewell terrace sur-

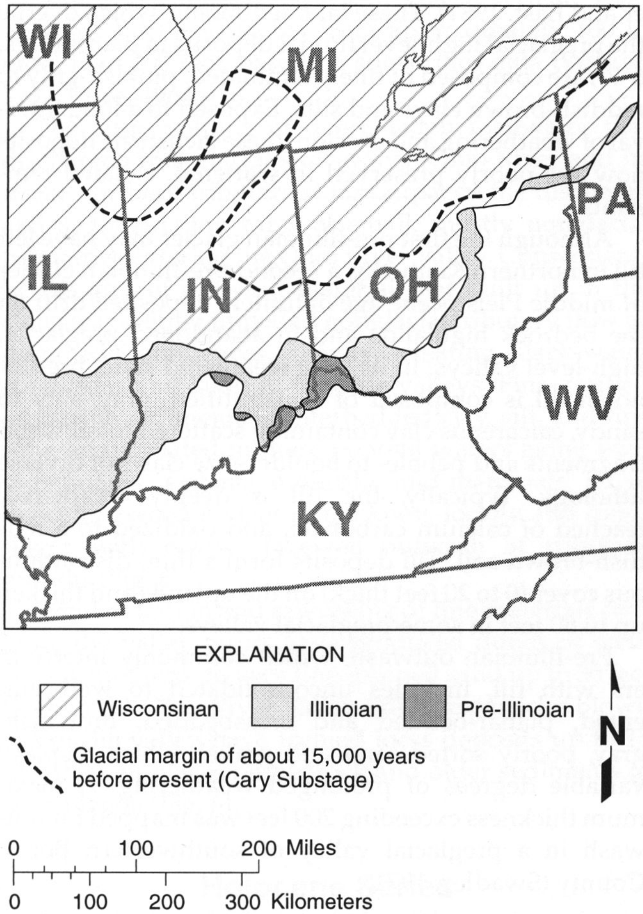

Figure 5. Glacial drift boundaries of the Midcontinental United States. (Compiled from Fullerton, 1986.)

face and 10 to 15 feet above the modern flood plain (Fig. 6), is difficult to recognize in many places because of subsequent erosion and deposition of alluvium by the Ohio River since the last deglaciation.

STRATIGRAPHY OF SAND, GRAVEL, AND RELATED DEPOSITS

The following summarizes northern Kentucky stratigraphic units mapped during the U.S. Geological Survey–Kentucky Geological Survey joint mapping program (Gibbons, 1972, 1976; Swadley, 1969, 1971, 1972, 1973, 1976). A typical stratigraphic column for the study area is shown in Figure 7. Spacial relationships between the various stratigraphic units, however, are best visualized in the schematic cross section of Figure 6.

Ordovician Period

The Upper Ordovician bedrock is composed of thin-bedded, gray, fossiliferous limestones interlayered with sparsely fossiliferous, calcareous shales, mudstones, and siltstones. Unconformably overlying the bedrock are mostly unconsolidated sediments, ranging in age from late Pliocene(?) to Holocene.

Pliocene(?)–Pleistocene Series

The late Pliocene(?)–early Pleistocene high-level fluvial deposits consist of deeply dissected, highly weathered, reddish-brown silt and clay containing scattered pebbles and cobbles of chert, quartz, and siliceous geodes. These sediments were derived from south-central Kentucky and deposited in abandoned, upland valleys and channels cut by the preglacial Kentucky River and its tributaries (Fig. 6).

Pleistocene Series

Pre-Illinoian Stage

The preglacial Kentucky and Licking Rivers and their tributaries were blocked by the first glacier, which created a series of proglacial lakes in which fine-grained sediments accumulated (Ettensohn, 1974; Tell-

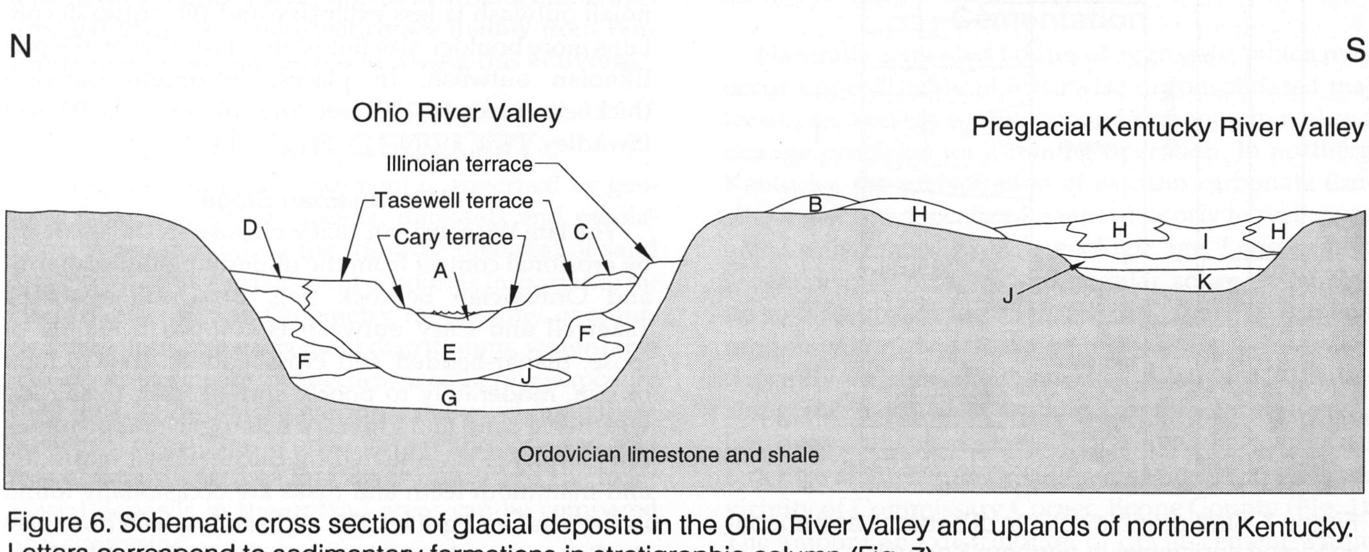

Figure 6. Schematic cross section of glacial deposits in the Ohio River Valley and uplands of northern Kentucky. Letters correspond to sedimentary formations in stratigraphic column (Fig. 7).

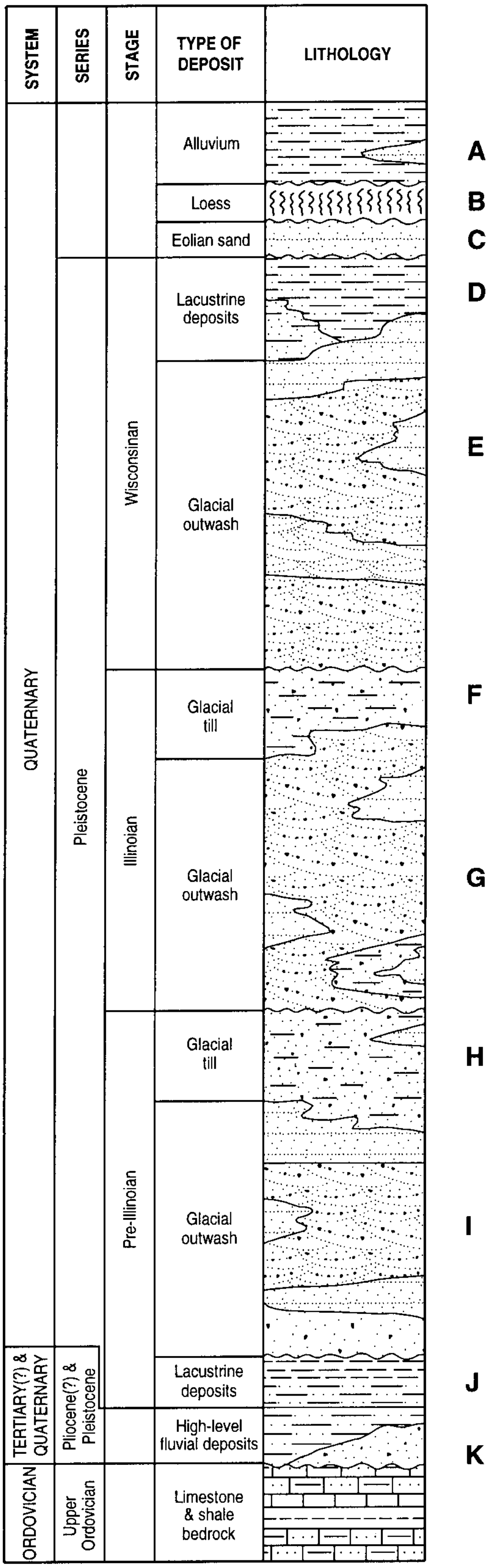

Figure 7. Stratigraphic column of bedrock and unconsolidated sediments in northern Kentucky.

er and Last, 1981). These lake sediments, which overlie the preglacial high-level fluvial deposits in places (Figs. 6–7), are composed of finely laminated, pinkish-gray to reddish-brown clays and silts. Exposed to a long interval of weathering and erosion, these lacustrine deposits now are poorly preserved in scattered, isolated remnants.

Although the first pre-Illinoian glacier may have left till in northern Kentucky, a second pre-Illinoian glacier of middle Pleistocene age definitely deposited drift on the bedrock highlands and in abandoned preglacial, high-level valleys. In its least weathered state, pre-Illinoian till is composed of nonstratified, gray, silty to sandy, calcareous clay containing scattered fossil wood fragments and pebble- to boulder-size clasts of diverse lithology. Typically, the till is deeply weathered, leached of calcium carbonate, and oxidized to a reddish-brown soil. Till deposits form a thin, discontinuous cover (0 to 20 feet thick) on the uplands and thicken up to 80 feet in some preglacial valleys.

Pre-Illinoian outwash, which commonly interfingers with till, includes unconsolidated to well-cemented, planar-bedded and crossbedded, brownish-gray, poorly sorted sand and gravel, which displays variable degrees of prolonged weathering. A maximum thickness exceeding 200 feet was mapped for outwash in a preglacial valley of southwestern Boone County (Swadley, 1971).

Illinoian Stage

Illinoian till, which interfingers with outwash, is confined to the Ohio River Valley (Fig. 6) and a few side tributaries. The yellowish- to grayish-brown Illinoian till differs from pre-Illinoian till in being less intensely weathered, sandier, and containing more dolomite pebbles (Teller, 1970). Calcite cementation in the Illinoian outwash is less extensive and the outwash contains more boulder-size limestone clasts than in the pre-Illinoian outwash. In places, maximum outwash thickness exceeds 150 feet and till exceeds 90 feet (Swadley, 1971, 1976).

Wisconsinan Stage

The late Wisconsinan Tazewell outwash is separated by erosional contact from the underlying Illinoian drift and Ordovician bedrock (Fig. 6). Undifferentiated Tazewell and Cary outwash is composed mainly of loose, planar-bedded and crossbedded, gray to light brown, moderately to poorly sorted, fresh to slightly weathered sand and gravel of heterogeneous composition; locally it is cemented by calcite. Fossil mastodon and mammoth teeth and tusks are occasionally found in the sand and gravel. Silt and sand, which dominate the Cary outwash and the upper 5 to 25 feet of the Tazewell outwash terrace, represent glacial retreat. Total outwash thickness varies from approximately 100 to more than 200 feet, based on subsurface data (Walker, 1957; Price, 1964a–b).

The large volume of debris-laden meltwater that discharged into glacial sluiceways (Ohio River and its major northern tributaries) far outpaced the discharge and sedimentation rates of small, mostly nonglacial tributaries entering the Ohio River Valley. Consequently, the glut of outwash material that built up in the sluiceways either impeded nonglacial tributary flow or dammed confluences, thereby creating slack-water conditions and lakes in the side valleys. Fine-grained lacustrine sediments of interbedded clay, silt, and fine sand accumulated in these ponded waters along with the remains of plants, mollusks, and mammals. These deposits exceed 60 feet in thickness locally and interfinger with coarse Tazewell outwash at tributary mouths (Fig. 6).

Wind deflation and reworking of fine materials covering the valley trains have produced dunes of well-sorted, medium- to very fine-grained sand up to 30 feet thick in the Ohio River Valley. Silt-size particles blown out of the valley have formed loess deposits up to 15 feet thick in places on bedrock and older sediments of the uplands (Fig. 6).

Holocene Series

Since the last deglaciation, late Wisconsinan deposits have been eroded and reworked as the Ohio River has downcut and shifted its course laterally. Holocene alluvium, as much as 80 feet thick in places, has been deposited on the eroded surfaces of the Tazewell and Cary outwash terraces (Fig. 6). The alluvial sediments consist of interbedded clay, silt, and sand with scattered lenses of gravel and plant debris. Sand and gravel dredged from the Ohio River comes mainly from Wisconsinan outwash material underlying this alluvium.

ECONOMIC GEOLOGY

Natural-resource development is governed by geologic factors as well as societal demands and regulations. When evaluating the resource potential of sand and gravel, geologic factors of economic importance include deposit size and geometry, topography, overburden thickness, natural cement distribution, water-table elevation, aggregate properties, weathering-exposure time, and depositional environment. By weighing these geologic factors, the economic potential of sand and gravel deposits in the Ohio River Valley and the older glacial deposits in the upland areas can be compared and contrasted.

Deposit Size and Geometry

Sand and gravel deposits of the Ohio River Valley in Boone, Gallatin, and Carroll Counties form a narrow, elongate, sinuous body averaging about 180 feet thick and covering an area of approximately 60 square miles. The total volume of this sedimentary body is roughly 11 billion cubic yards or 2 cubic miles. In contrast to this well-defined, continuous deposit, northern Kentucky's upland aggregate resources are distributed in disconnected patches totalling about 6 square miles (Fig. 1). Thickness ranges from zero to at least 200 feet (Swadley, 1971), but the average thickness has not been established. Assuming an average thickness of 75 feet, the upland resource volume would total about a half billion cubic yards or 0.1 cubic mile.

Topography

Local topography, because of its influence on surface drainage and the placement and maintenance of roads, either enhances or interferes with mining operations. Erosional processes have slightly modified the flat, gently sloping (6 inches per mile) terrace surfaces that lie 60 to 80 feet above the Ohio River. The upland deposits, on the other hand, have undergone varying degrees of erosional dissection, resulting in a gently rolling to moderately rugged topography.

Overburden Thickness

The less overburden material there is to remove and store, the more economical a deposit is to mine. Soil, loess, fine sand, and silt comprise the 5- to 20-foot-thick overburden on Ohio River Valley aggregate resources. Overburden thickness on the upland deposits, however, is more variable. Dense, clayey till, at least 15 to 30 feet thick in places, overlies a potential aggregate resource near Commissary Corner (Fig. 1).

Cementation

Naturally cemented bodies of aggregate, which may occur unpredictably in otherwise unconsolidated material, can damage equipment and present removal and storage problems for a mining operation. In northern Kentucky, the precipitation of calcium carbonate (calcite) has formed localized zones of poorly to well-cemented outwash, of varying geologic age. Lenses up to several feet in diameter or irregular zones measuring up to 5 feet by 25 feet (Swadley, 1973) are sparse and randomly scattered in the Ohio River Valley outwash deposits. Calcite cementation is relatively common along the margins of upland pre-Illinoian outwash, however, and is prominently displayed in steep-faced outcrops along tributary valleys of Middle Creek in the vicinity of Commissary Corner, Boone County (Fig. 1). The amount and distribution of calcite cement within the body of upland outwash deposits is not well known and would require core drilling to determine.

Water Table

Information on water-table elevation helps determine the thickness of mineable aggregate resources in the unsaturated zone above the water table. When the unsaturated zone has been mined out, the water table then limits the depth to which underwater parts of the deposit can be mined with a dredge or dragline. In the Ohio River Valley, water-table levels have been known and relatively stable since establishment of navigational and flood-control structures along the river. The upland water-table configuration is less predictable because of greater complexity in surface drainage patterns, relatively rugged local topographic relief, and unknown subsurface stratigraphy.

Aggregate Properties

An aggregate's physical and chemical properties determine its use and commercial application, as specified by engineering and government regulations. Size grading or grain-size distribution is perhaps the most important physical requirement an aggregate must meet. A deposit's ultimate value will depend on how much of the most desirable size grades are in demand by the aggregate marketplace. Grain-size distribution comparisons between the Ohio River Valley and upland deposits show no significant differences, although more silt and clay was found in the only upland locality examined.

Aggregate particle shape, a physical attribute perhaps less significant than size, becomes an important factor when too many undesirable shapes in the aggregate cause a poor quality or defective product. Wisconsinan outwash has under 10 percent undesirable flat and elongated pebble shapes. A higher potential for undesirable shapes, contributed primarily by limestone and sandstone clasts, is found in early Pleistocene upland deposits, where significantly greater concentrations of these lithologies occur.

Aggregate quality is a function of chemical composition, which is determined by the proportion of rocks and minerals composing the sand and gravel. Lithic and mineralogic composition affects particle soundness, absorption, chemical reactivity, and resistance to weathering and abrasion. There are strong compositional similarities between upland pre-Illinoian sediments and Ohio River Valley deposits of Illinoian outwash, but both are notably different than Wisconsinan outwash with respect to total carbonate-quartz-igneous/metamorphic (CQIM) clasts versus total chert-sandstone-shale (CSS) constituents. Wisconsinan-age gravel is characterized by 65 to 90 percent CQIM in fine to coarse sizes, respectively, and 10 to 35 percent CSS in coarse to fine gravels, respectively. The two older outwash units range from 40 to 70 percent CQIM for fine to coarse gravel, and 30 to 60 percent CSS for coarse to fine gravel. The high concentrations of potentially deleterious chert and unsound sandstone are serious disadvantages affecting the economic potential for both older outwash units.

Interdependent physical and chemical aggregate properties such as lithology versus size or shape have practical advantages. The size dependence of chert and sandstone in coarse aggregate can be used to reduce these potentially deleterious substances through a process called *beneficiation*, in which horizons or areas of a pit dominated by the size classes containing the greatest abundance of these materials can be set aside or these size classes can be separated through screening. Where the amount of these undesirable lithologies is high, as is generally the case for pre-Wisconsinan outwash, beneficiation would be of little use.

Weathering

Weathering of the various constituents in outwash deposits of northern Kentucky is a cumulative process. Because the upland deposits have been exposed to a much longer period of weathering than the Ohio River Valley outwash, the upland deposits contain mostly badly weathered, unsound particles. Carbonate-rock fragments in places have been essentially eliminated through leaching. In contrast, the upper few feet of Wisconsinan outwash have undergone only slight to moderate leaching.

Depositional Environment

Pleistocene history and depositional environments explain the complex stratigraphic and regional variations observed in northern Kentucky's aggregate resources. Knowing the depositional environment can help predict lateral and vertical changes in grain size and composition during exploratory and developmental phases of a mining operation.

Major meltwater sluiceways entering the Ohio River were sources for the coarsest Wisconsinan outwash aggregate, which accumulated in wedge-shaped deposits that thin downstream. Both grain size and percent gravel decrease downstream from these input sites in accordance with principles of fluvial hydraulics. For these reasons, locating a mine at the confluence or directly downstream from a major glacial sluiceway would be ideal. Unfortunately, only four of these points exist along the Ohio River in Kentucky. Upland deposits of thick, pre-Illinoian outwash would most likely occur along the abandoned preglacial channels of the ancestral Kentucky River drainage system.

Within the fluvial depositional environment, downstream and cross-channel variations in flow conditions control grain-size distribution and sediment sorting in a predictable, systematic fashion. Thus, the upstream ends and cores of meanders and lateral bars will have the coarsest particles in the greatest abundance, whereas areas bordering bedrock valley walls and downstream ends of bars and meanders will be finer grained and tend to have more deleterious materials.

Glacier terminus position with respect to an aggregate deposit explains the occurrence of glacial till and characteristic textural features associated with ice-contact sediments. Deposits containing excessive amounts of very fine or extremely coarse material, which often form near glaciers, would be unfavorable aggregate prospects. On the other hand, irregular ridges of stratified sand and gravel, called *kame deposits*, which also form close to the ice margin, are usually favorable sites for mining high-quality aggregate. Parts of the upland deposits of northern Kentucky formed near pre-Illinoian ice sheets; Illinoian till in the Ohio River Valley was also an ice-contact deposit. A kame origin has been suggested for the upland sand and gravel deposits near Commissary Corner in Boone County (Durrell, 1956).

Prospects for developing high-quality aggregate sources in upland areas bordering the Ohio River Valley appear unpromising because of severe particle weathering, large quantities of potentially deleterious material, considerable mud content, thick overburden, and extensive calcite cementation. This does not rule out the chance of finding upland areas where the aggregate is suitable for some uses, but with the availability of high-quality Wisconsinan aggregate nearby, exploiting the early Pleistocene outwash makes little economic sense.

DESCRIPTION OF DEPOSITS

Detailed descriptions of the lateral and vertical changes in grain-size texture, sediment composition, and particle morphology of Pleistocene outwash deposits are found in Appendix A. This information will be useful to mine operators evaluating aggregate resource potential, and assists in correlating stratigraphy and interpreting Pleistocene depositional environments.

Size

Pleistocene outwash sediments in northern Kentucky range in size from very large boulders to very fine clays. Deposits composed entirely of these extreme sizes are volumetrically small and of little or no economic importance. Boulder-size fragments typically were deposited near glacial ice margins within the Ohio River Valley during Illinoian time and on upland surfaces during pre-Illinoian time. Very fine-grained sediments accumulated where energy conditions were low: in lakes behind dammed tributaries, along valley wall margins, and in major channels where flow was severely restricted by the rapid buildup of outwash debris.

Bedding

Fine sand to coarse gravel, which constitute the majority of outwash sediments, were deposited in planar-bedded to crossbedded units. Crude planar bedding typifies most sandy gravels, but rare crossbedded horizons also occur. Well-developed horizontal and cross-stratified units are more commonly developed in sand and pebbly sand deposits. Textural variation within crudely bedded sandy gravels is not evident; in contrast, small-scale fining-upward sequences may develop in sandy units. Planar laminations and ripple and climbing-ripple laminations characterize the structures in fine-sand- to silt-size materials.

Grain Size

Average grain size among samples and from one location to another is highly variable. Grain-size sorting is uniformly poor to very poor for sandy gravel and pebbly sand; the sorting in fine aggregates is generally better, ranging from moderate to well sorted. Except for the better sorted sands, grain size in most outwash sediments does not follow a normal distribution. A typical sample is composed generally of two grain-size modes, constituting one population of gravel-size particles and one of sand sizes. These two populations are considered to represent the traction and temporary suspended (saltation) loads, respectively, carried during fluvial transport. Sediment textures range from gravels with sand-clogged pore spaces to sands with suspended pebbles. These sorting characteristics and bimodal size distributions are characteristic of modern glacial valley trains deposited by overloaded meltwater streams flowing in a system of braided channels.

Differences in grain size and degree of sorting of outwash between Wisconsinan and Illinoian deposits are insignificant, but the one area of pre-Illinoian drift studied is coarser grained and has a larger population of silt- and clay-size material compared to the younger strata. Vertical changes in size and sorting characteristics occur locally and include both upward-coarsening and upward-fining sequences. Larger scale vertical trends were not detected because of limited access to drilling and borehole sampling.

Lateral grain size variations in outwash deposits of the Ohio River Valley occur at two orders of magnitude. The first order is a large-scale, downstream decrease in average particle size, caused by diminishing amounts of gravel and corresponding increases in sand. This broad regional trend repeats itself along the course of the river; each downstream cycle begins at the confluence of a major meltwater sluiceway that fed the Ohio River Valley during late Wisconsinan time. The coarsest particle sizes and greatest abundance of gravel occur at these sediment-supply entry points and gradually diminish downstream. Accumulations of sand and gravel are also thickest at these sites and thin downstream, forming a wedge-shaped package of sediment. The fine-grained, attenuated, downstream end of the Little Miami River clastic wedge and the coarse-grained, upstream portions of the Great Miami River wedge intersect at Petersburg, Boone County.

The downstream decrease in average grain size, modal gravel size, and percent gravel is not uniform over the length of these large-scale cycles, partly because of a second-order textural variation superimposed on them. This smaller scale variation occurs in response to hydraulic energy gradients within the local depositional environment: around meander bends, across channel profiles, and over gravel bars. Where stream-current energy decreases near valley walls and on insides and downstream portions of meanders, the average grain size and gravel content drop. Thus, the best locations for coarse sand and gravel are on the upstream ends of meanders. The upstream ends of lateral bars along straight reaches are also sites for the coarsest grain size, lowest mud content, and greatest percentage of gravel locally available.

Composition

Aggregate composition systematically varies with grain size for both sand and gravel. Percentage of limestone and dolomite particles is highest in the coarsest grades of both sand and gravel, then decreases to its lowest levels in the finest size grades. Chert and sandstone clasts are least abundant in the coarsest gravels and most abundant in the finest gravels; percentages of both lithologies then rapidly decline over the sand-size grades. Quartzite and igneous and metamorphic rocks make up 10 to 20 percent of all coarse aggregate and vary little with changing gravel size; in the sand size range they form only a small percentage. Shale and clay clasts are found only in trace amounts in coarse aggregate, generally in the finest grades; shale constitutes a small percentage of the sand sizes. Monomineralic quartz, feldspar, and a variety of heavy minerals occur only in the sand grades and all increase in abundance with decreasing grain size. The increases in monomineralic grains are caused by the breakdown of rock fragments into their constituent parts by weathering and transportation. The variations shown in coarse aggregate composition with grain size have a more complex explanation. The relative abundance of the rock type, its characteristic size range, and its chemical and physical properties all combine in roles of varying importance to contribute to the observed changes. These lithic-particle variables have interacted with the contrasting mechanisms in which ice and water move and sort sediments to produce the observed composition versus size relationships.

Regional downstream variations in composition along the Ohio River Valley can be attributed in part to selective sorting by grain size during transport, to differential resistance to abrasion by the various lithologies, and to increasing distance from the glacial source area. Because the downstream composition changes coincide with the variations observed in composition versus grain size, an indeterminant component of regional composition variation may reflect a decrease in grain size caused by waning downstream current energy. The toughness and impact resistance of chert, quartz, and some igneous and metamorphic rocks in contrast to soft shale, sandstone, and carbonate rocks is perhaps the most important factor explaining downstream changes in composition. A doubling of sandstone pebbles and the sudden appearance of shale and preglacial chert pebbles 150 to 200 miles below the confluence of the Great Miami–Whitewater sluiceway indicates a downstream attenuation of the Wisconsinan outwash wedge and an increasing influence of nonglacial elements introduced from local bedrock and regolith sources.

Extreme lateral changes in composition may occur locally where fine-grained sediments accumulate. Along valley margin walls and on downstream portions of meanders, high concentrations of deleterious coal, clay pebbles, and chert are commonly found. The relationship between composition and grain size is clearly demonstrated in these areas.

Gravel composition can be used to distinguish Wisconsinan outwash from the two older Pleistocene stratigraphic intervals. Limestone to dolomite ratios are less than 1:1 in Wisconsinan outwash and usually greater than 5:1 in the pre-Wisconsinan. The amount of chert and sandstone particles is two to three times greater in pre-Wisconsinan outwash than in Wisconsinan sand and gravel. These compositional differences reflect Pleistocene depositional events and correspond to contrasts in ice-sheet composition. Illinoian and pre-Illinoian glacial advances overrode Upper Ordovician strata in what is now northern Kentucky and adjacent states and thus picked up great quantities of thin-bedded limestone fragments. The late Wisconsinan glacier stopped north of the Ohio River Valley and derived much of its debris from dolomite-rich strata of the Silurian bedrock. Chert-rich residual soils were eroded and incorporated into the drift deposits of the earliest glacier to invade the region. Subsequent glacial invasions have reworked the underlying, next-older drift unit so that chert content has become progressively diluted over time. Chert content in Ohio River outwash gravels thus tends to increase with depth, reflecting these stratigraphic changes. Reworking of Illinoian drift terraces by late Wisconsinan meltwater streams has probably also contributed to localized chert increases in Wisconsinan sand and gravel.

Pebble Morphology

Pebble shape (measured in terms of sphericity and form) variation with respect to grrain size and stratigraphic variation in pebble shape were found to be insignificant. Slight differences in average sphericity indicate the most resistant lithologies such as quartzite and igneous and metamorphic rocks tend to have the most spherical particles. Nearly half of all pebble shapes, when delineated by axial ratios and plotted on sphericity-form diagrams (Sneed and Folk, 1958; Dobkins and Folk, 1970), are classified as blades and compact blades. Although shape fails to distinguish among most pebble lithologies, it clearly differentiates limestone pebbles from all others. Limestone pebbles are the least spherical and platiest of all gravel types, a reflection of their thin-bedded nature. Extremely platy and elongate pebbles, whose axial ratios exceed the 3:1 axial cutoff ratio used by Federal testing laboratories, are generally found in concentrations less than 10 percent in most Ohio River Valley gravels. The greatest percentage of these undesirable shapes are found among limestone and sandstone pebbles. Because limestone and sandstone clasts are more abundant in pre-Wisconsinan outwash, these older outwash deposits have correspondingly higher percentages of undesirable shapes.

The majority of all Pleistocene outwash pebbles are rounded to well rounded. A close examination of pebble roundness variation, however, reveals significant sedimentological information. Plots of average roundness versus size for each pebble lithology show subtle roundness variations that reflect differences in rock hardness (resistance to abrasion) and transport history. In Wisconsinan outwash, roundness increases with decreasing pebble size for all rock types. Each rock type is clearly differentiated from the others according to relative hardness. For pre-Wisconsinan outwash, the relationship between roundness and grain size is poorly developed and the various pebble lithologies are poorly differentiated from one another based on their average roundness. Except for chert pebbles, all Wisconsinan pebble lithologies are better rounded than their pre-Wisconsinan counterparts. These contrasts in roundness between the youngest outwash and two older deposits is because of differences in sediment transport history. For Illinoian and pre-Illinoian outwash, the glacial source was proximal to the deposit and the clasts were transported a relatively short distance. The glacial source of Wisconsinan outwash was as much as 80 miles north of the Ohio River, so these pebbles traveled a much greater distance before being deposited.

Soundness

Gravel soundness varies with particle composition and age. Because of the increasing interval of time for exposure to weathering, successively older outwash units have progressively greater quantities of unsound, severely leached, poor quality aggregate. Upland deposits of pre-Illinoian outwash have the most unsound aggregate. Wisconsinan outwash has the least poor aggregate and this poor material tends to form in the upper few feet of the deposit, where leaching is most intense. Quartz pebbles are the most durable lithologies, resisting the effects of weathering best; lithologies most severely affected by weathering are carbonates and calcareous sandstones. Igneous and metamorphic rocks, a very diverse group of lithologies, range from strongly resistant to poorly resistant and therefore lie between the extremes.

Resource Potential

An evaluation of aggregate resource potential based on a number of geologic factors shows the upland deposits of pre-Illinoian outwash to be unfavorable sources of high-quality aggregate because of the high percentage of unsound, deleterious materials. These aggregates may be suitable for some purposes, but most of the deposit consists of material that would probably fail most tests of aggregate used for concrete. In contrast, the Wisconsinan outwash within the Ohio River Valley contains the greatest concentrations of readily available, high-quality aggregate with respect to particle size range, desirable composition, shape, and soundness.

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APPENDIX A:

CHARACTERIZATION OF SAND AND GRAVEL RESOURCES

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CHARACTERIZATION OF SAND AND GRAVEL RESOURCES

PROCEDURES

Sand and gravel characterization in this report is based on field and laboratory investigations supplemented by literature searches. Unpublished data from student theses and reports of private firms and government agencies were also incorporated into the study. Field studies consisted of measuring stratigraphic sections and making geologic descriptions of aggregate from outcrops, active and abandoned pits, trenches, and boreholes. Representative vertical channel and spot samples were collected from surface deposits; split-spoon cores and bailer samples were retrieved from subsurface boreholes. Petrographic examination of these samples in the laboratory made possible quantitative descriptions of particle size, composition, morphology, and surface alteration. Used primarily as a supplement to the engineer's empirical acceptance tests of natural aggregate for concrete, petrographic examinations establish the relative abundance of specific rock and mineral types and describe physical and chemical properties that have a bearing on the performance of the aggregate in its intended use (Mielenz, 1946). Researchers have demonstrated that petrographic composition actually is a better predictor of an aggregate's field performance than standard engineering tests (Rogers, 1990).

Size Analysis

Seventy-two samples of coarse to fine aggregate from 17 locations (Fig. 1) were mechanically classified by sieving to determine particle size distribution. Bulk, air-dried samples of sand and gravel were passed through the series of coarse and fine sieves listed in Table 1. The total sample was initially passed through a stack of 15 X 23 inch screens with mesh openings greater than 0.16 inch (No. 5 mesh) using a commercial, automated sieve shaker. The large amount of fine-grained material that passed through the No. 5 mesh screen was reduced by splitting to a sample weight of approximately 100 grams; this quantity was then passed through a nested set of 8-inch-diameter round sieves shaken on a Rotap machine. Sieve runs in both shakers were automatically timed for 15 minutes. Aggregate material from each screen was weighed electronically to the nearest gram for gravel and to the nearest 0.01 gram for sand and finer sizes. Raw sieve data, compiled in a spreadsheet format, were manipulated to obtain statistical analyses, summary tabulations, and graphs. Four grain-size parameters per sample were calculated by the method of moment statistics described for sediment analysis by Griffiths (1967).

Quantitative assessment of grain-size distribution aids both industry and science in the classification, correlation, quality control, and interpretation of samples. Raw grain-size data, generally expressed as a weight percent per size class, may be graphed, tabulated, summarized by statistical parameters, or reduced to a

Table 1. Sieve grades used in mechanical analyses. Asterisk indicates test sieves used by Kentucky Transportation Cabinet, Department of Highways.

Sieve Screen Opening			*KDOH Specified*
Inch/Mesh No.	*mm*	ϕ	
3.0 "	76	-6.25	*
2.5"	64	-6.00	*
2.0"	51	-5.65	*
1.5"	38	-5.25	*
1.0"	25	-4.65	*
0.75"	19	-4.25	*
0.62"	16	-4.00	
0.50"	13	-3.65	*
0.38"	10	-3.25	*
0.31"	8	-3.00	
0.25"	6.4	-2.65	
#4	4.8	-2.25	*
#5	4.0	-2.00	
#6	3.36	-1.75	
#8	2.38	-1.25	*
#12	1.68	-0.75	
#16	1.19	-0.25	*
#20	0.84	0.25	
#30	0.59	0.75	
#40	0.42	1.25	*
#50	0.30	1.75	
#70	0.21	2.25	
#100	0.149	2.75	*
#140	0.105	3.25	
#200	0.074	3.75	*
#270	0.053	4.25	

single value like the fineness modulus (Kentucky Transportation Cabinet, 1991). Each of these summary techniques were utilized in this report and the results, except for the graphs, can be found in Appendix B.

Particle-size nomenclature used in this report follows the limits outlined in Table 2. Grain diameters may be expressed in various units of measure (Table 1), but inch and phi (Φ) values will be used throughout. Phi size is a logarithmic transformation of the grain diameter measured in millimeters and conforms to the geometric grade scale of standard testing sieves in the United States: $\sqrt[4]{2}$ from a base of 1 mm (Krumbein, 1934). A particle diameter of 1 mm equals 0Φ; coarser sizes have increasingly negative phi values and finer sizes have increasingly positive values (Table 1). Advantages of the phi scale include the elimination of unwieldy decimal or fractional sizes and the equalization of the sieve grades, thereby allowing size data to be plotted on an arithmetic scale. Because phi size distributions approach normality, common statistical procedures can be used with the data.

Table 2. Grain-size class nomenclature.

Class Boundary		*Particle Class Name*	*Aggregate Class Name*
Inch	*φ*		
		Boulder	Boulder gravel
10	–8.0		
		Cobble	Cobble gravel
2.50	–6.0		
		Pebble	Pebble gravel
0.16	–2.0		
		Granule	Granule
0.08	–1.0		
		Sand	Sand
0.0025	4.0		
		Silt	Silt
0.00012	8.0		
		Clay	Clay

The size distribution of each sample was statistically described using the first four moment measures, briefly defined in basic statistics textbooks as follows: (1) mean, a measure of the distribution's central tendency, (2) standard deviation, an indicator of scatter about the mean, (3) skewness, a positive or negative number expressing the direction and degree to which the distribution curve departs from symmetry, and (4) kurtosis, a relative measure describing the distribution curve shape as flattened (negative) or arched (positive). Nonskewed, moderately arched (mesokurtic), normal distributions have skewness and kurtosis values of zero. The size parameters of prime interest in this study were the mean and standard deviation. Standard deviation is considered to have environmental significance, indicating how well a sediment has been winnowed or sorted (Folk and Ward, 1957). The sorting terminology used in this study to describe Pleistocene outwash is based on the phi standard deviation (Table 3).

Table 3. Grain-size sorting scale (from Folk and Ward, 1957).

φ Standard Deviation	*Sorting Class*
under 0.35	Very well sorted
0.35 to 0.50	Well sorted
0.50 to 1.00	Moderately sorted
1.00 to 2.00	Poorly sorted
2.00 to 4.00	Very poorly sorted
over 4.00	Extremely poorly sorted

Composition Analysis

Thirteen size-graded gravel samples from nine locations (Fig. 1) were selected for pebble counting. A pebble count is the tallying of the composition of a representative number of gravel particles that have been identified by eye or with a binocular microscope and are coarser than No. 5 mesh. The number of pebbles counted per sieve screen varied. On screens with fewer than 100 pebbles, all were identified and counted; a random grab sample averaging 175 pebbles was taken from screens with large populations. Over 8,100 pebbles from the 13 samples were identified and tallied.

Seven thin-section samples of partially cemented sand from six localities (Fig. 1) were examined microscopically for composition. Thin sections were prepared by impregnating the calcite-cemented sands with a colored epoxy resin, mounting them on glass slides, then slicing and grinding them to a thickness of 0.001 inch. The thin sections were optically analyzed in plain and polarized, transmitted light with a petrographic microscope. Average composition was determined by modal analysis in which 400 grains per thin section were systematically identified and counted. An estimate of average grain size was obtained by measuring approximately 200 grain diameters per thin section with a calibrated eyepiece.

Two samples of silt-size material and four samples of clay-size material were analyzed for mineralogic composition using a computerized X-ray diffractometer. The silt samples were ground to a powder, randomly oriented in a sample holder, and X-rayed. Clay samples received special preparation prior to X-raying. Particles less than 2 microns in diameter were concentrated and smeared onto glass slides to produce preferentially oriented clay mounts. Replicate samples of the oriented clay were X-rayed under three different conditions: untreated, solvated with ethylene glycol, and heated at 350 and 550°C. The diffraction data were stored and analyzed in the X-ray unit's computer.

Morphology Analysis

Particle shape and roundness were quantitatively determined exclusively on gravel from the size-graded pebbles used in the analyses for composition. Three mutually perpendicular axes were measured directly with an electronic digital caliper on pebbles in their most stable, flat-lying position—intermediate and long axes in the horizontal plane and the short axis in the perpendicular plane. These axial dimensions were then used to calculate sphericity and form, two aspects of particle shape. Pebble roundness was estimated semiquantitatively by visual comparison. Nearly 1,600 pebbles from nine locations (Fig. 1), representing all sizes greater than No. 4 mesh (0.19 inch), were measured. Shape and roundness data along with composition and size information were compiled in a spreadsheet to facilitate calculations and graphs.

Sphericity and Form

Shape is simply the spatial geometry of an object and can be approximated for sedimentary particles by utilizing measures of sphericity and form. Sphericity indicates how nearly equal the three dimensions of an object are and was originally defined in terms of a particle's surface area compared to that of a sphere of equal volume (Wadell, 1932). Because of difficulties in measuring pebble surface area and volume, more practical methods employing axial intercept ratios were devised for determining sphericity (Krumbein, 1941; Sneed and Folk, 1958). Pebble sphericity was calculated in this study by substituting axial dimensions into Sneed and Folk's (1958) maximum projection sphericity formula:

$$\sqrt[3]{\frac{S^2}{LI}}$$

where L, I, and S are the long, intermediate, and short axes, respectively. Maximum projection sphericity values are dimensionless numbers that correlate well with hydraulic particle settling velocity; a perfect sphere is represented as 1.00. Although a useful concept, sphericity does not uniquely define particle shape: a rod and a disk, for example, may have the same sphericity value. Such disparate shapes as rods and disks, however, can be differentiated by measuring particle form.

Form distinguishes three-dimensional geometric differences by measuring the relationship between a particle's three principal axial dimensions. Sneed and Folk (1958) considered particle form in terms of a continuum of axial ratio variables with three limiting endpoints—prolate spheroid, oblate spheroid, and sphere—which could be represented graphically on a trivariate diagram. Axial ratios of S/L and L–I/L–S are plotted along two sides of the triangle, and maximum projection sphericity values are represented along the third limb, thus showing the relationship between sphericity and form (Fig. 8). When plotted on this diagram, an object falls into one of 10 form classes. These classes include compact (equidimensional), elongated (rodlike), platy (disklike), and bladed; there are six additional intermediate and extreme categories (Sneed and Folk, 1958; Dobkins and Folk, 1970).

Statistical analysis of particle form is difficult because each sample must be represented by a pair of numbers. To overcome this problem, Dobkins and Folk (1970) devised the oblate–prolate index to quantify particle form with a single number, rather than a pair of ratios. The O–P index, 10L(L–I/L–S–0.50)/S, yields a negative or positive dimensionless number indicating how disklike (oblate) or rodlike (prolate) a particle is, respectively. Contoured O–P index values, superimposed over the form triangle, show their relationship to the 10 form classes (Fig. 8). Pebble form was classified and measured in this study with the form triangle of Sneed and Folk (1958) and the oblate–prolate index (Dobkins and Folk, 1970).

Roundness

Roundness was first distinguished from shape by Wadell (1932), who defined it as the average radius of curvature of all the corners of a particle divided by the radius of the largest inscribed circle. Roundness values are dimensionless numbers; a perfectly rounded object, like a ball, is equal to 1.0. The laborious nature of measuring particle roundness as thus defined has led to the development of more practical visual comparison methods (Krumbein, 1941; Powers, 1953) based on Wadell's theory. Krumbein's (1941) chart for visually estimating roundness, based on silhouettes of directly measured pebbles, was used in this study for semiquantitatively determining roundness for approximately 1,400 pebbles. Because neither verbal class designations nor class boundaries were assigned to Krumbein's (1941) chart, Powers' (1953) roundness class intervals and grade names are used to describe pebble roundness.

Pebble roundness variation. Pebble roundness values were grouped according to lithology, grain size, and stratigraphy, and averaged. The mean and standard deviation values of pebble roundness, summarized by lithology and age in Table 4, were used in statistical tests of significance. Statistical testing established significant differences in average roundness with respect to stratigraphy, grain size, and lithol-

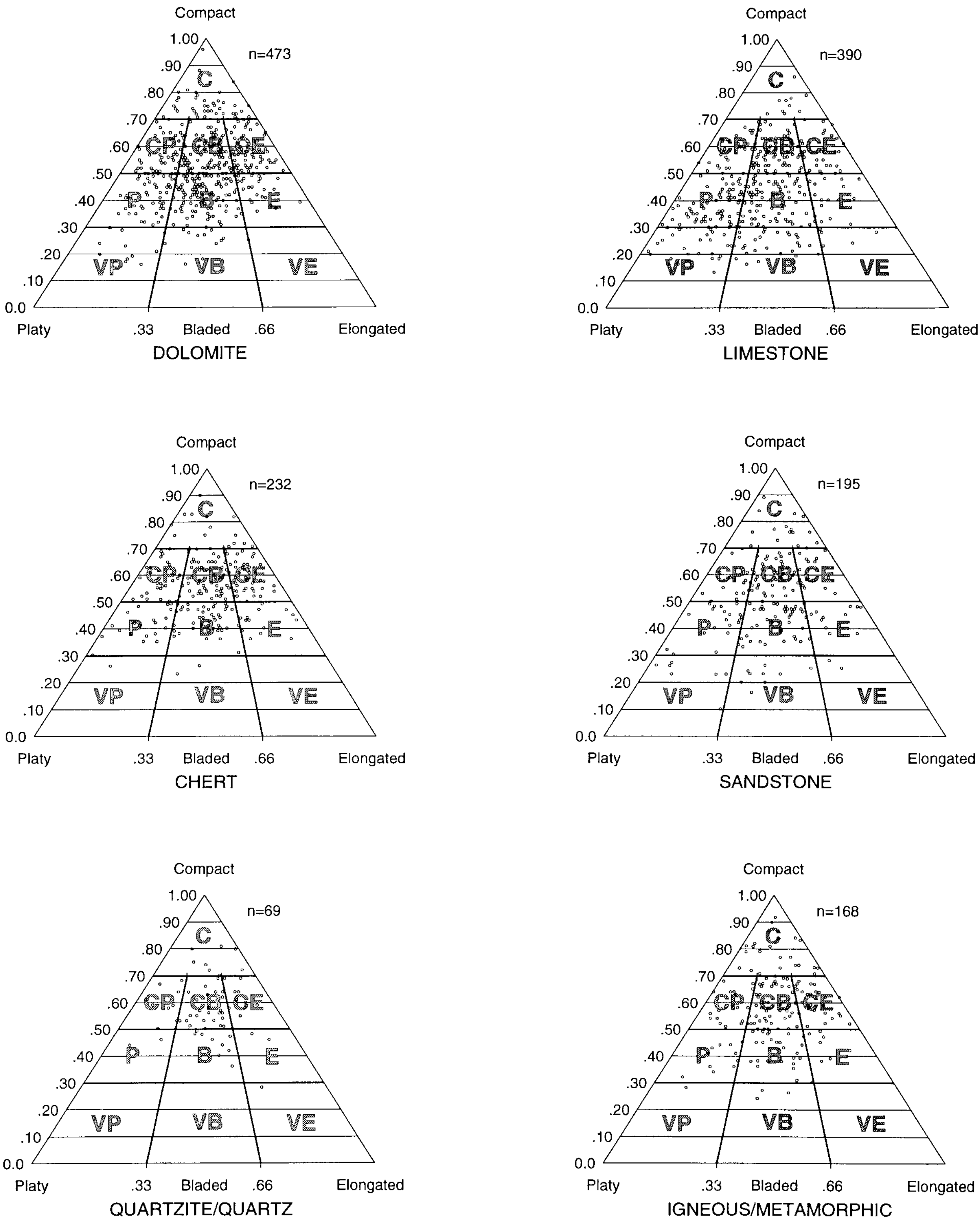

Figure 8. Pebble shape plots by rock type for Wisconsinan gravels.

ogy. Pebble roundness in Wisconsinan outwash, which averages 0.70, is significantly better than the average pebble roundness of 0.53 in the older outwash deposits. Plots of pebble roundness versus grain size for Wisconsinan and the two pre-Wisconsinan outwash deposits depict these differences for various pebble lithologies (Fig. 9). Except for quartz and chert, pebble rounding in the various lithologies of Wisconsinan outwash is significantly better than the rounding in older outwash units.

For Wisconsinan gravels, roundness increases linearly with decreasing pebble size. The roundness to size relationship in older outwash pebbles is generally ill defined (Fig. 9). Moreover, the various lithologies of Wisconsinan gravel are well differentiated with respect to roundness in comparison to the older outwash. Significant differences in mean pebble roundness occur between most Wisconsinan outwash lithologies, with the exception of sandstone and limestone pebbles and quartz and igneous/metamorphic pebbles (Table 4, Fig. 9). These differences and similarities are ranked, from most to least rounded, as follows:

most rounded ◄————► least rounded

dolomite	sandstone	igneous/metamorphic	chert
	limestone	quartz	

For the poorly differentiated Illinoian and pre-Illinoian gravels, the average limestone roundness is remarkably similar to chert.

The variability and distribution of pebble roundness in different compositions of Wisconsinan and Illinoian outwash gravels is indicated by standard deviation values (Table 4) and frequency histograms of roundness grades (Fig. 10). In Wisconsinan outwash, rounded and well-rounded pebbles predominate in all lithologies but chert, which consists mostly of rounded and subrounded pebbles (Fig. 10). Most Illinoian gravels are composed predominantly of rounded particles, but substantial amounts of subrounded and subangular pebbles occur in both limestone and chert (Fig. 10).

Because it is a sensitive indicator of abrasion resistance in rocks and minerals, particle roundness can be used to interpret the transport history of a sedimentary body. The variations in pebble roundness with respect to lithology, grain size, and stratigraphy can all be related to sediment transport history. Roundness differences among the various lithologies reflect differential hardness. For example, because soft sandstone and carbonate rocks abrade rapidly (Sneed and Folk, 1958), they are generally the most rounded. Because of their extreme hardness, durable particles of quartz and chert are the least rounded. Metamorphic and igneous rocks are also quite hard, but because they represent a more diverse group with varying degrees of hardness, they are slightly better rounded than chert and quartz.

Table 4. Means and standard deviations from measurements of pebble shape and roundness of Pleistocene gravel lithologies.

Morphology Measure	*Age*	*Mean/ Std. Dev.*	*Dolomite*	*Limestone*	*Chert*	*Sandstone*	*Quartz*	*Igneous/ Metamorphic*
Sphericity	Wisconsinan	Mean	0.70	0.62	0.73	0.69	0.75	0.74
		Std. Dev.	0.111	0.140	0.10	0.124	0.085	0.101
	Illinoian	Mean	*	0.61	0.71	0.68	0.76	0.72
		Std. Dev.	*	0.143	0.099	0.135	0.050	0.113
	Pre-Illinoian	Mean	*	0.65	0.73	0.72	*	*
		Std. Dev.	*	0.112	0.067	0.148	*	*
Form (Oblate-Prolate Index	Wisconsinan	Mean	-0.39	-3.17	0.14	-0.84	0.42	0.19
		Std. Dev.	4.65	6.20	4.62	5.22	3.78	4.25
	Illinoian	Mean	*	-2.02	-0.19	-1.14	1.48	-1.19
		Std. Dev.	*	6.33	5.12	5.06	2.88	4.07
	Pre-Illinoian	Mean	*	-0.52	-0.51	-1.70	*	*
		Std. Dev.	*	5.88	4.70	6.37	*	*
Roundness	Wisconsinan	Mean	0.72	0.67	0.49	0.69	0.57	0.60
		Std. Dev.	0.102	0.143	0.089	0.121	0.099	0.104
	Illinoian	Mean	*	0.48	0.47	0.58	0.59	0.56
		Std. Dev.	*	0.092	0.097	0.124	0.076	0.085
	Pre-Illinoian	Mean	*	0.55	0.43	0.58	*	*
		Std. Dev.	*	0.093	0.111	0.096	*	*

*Insufficient data

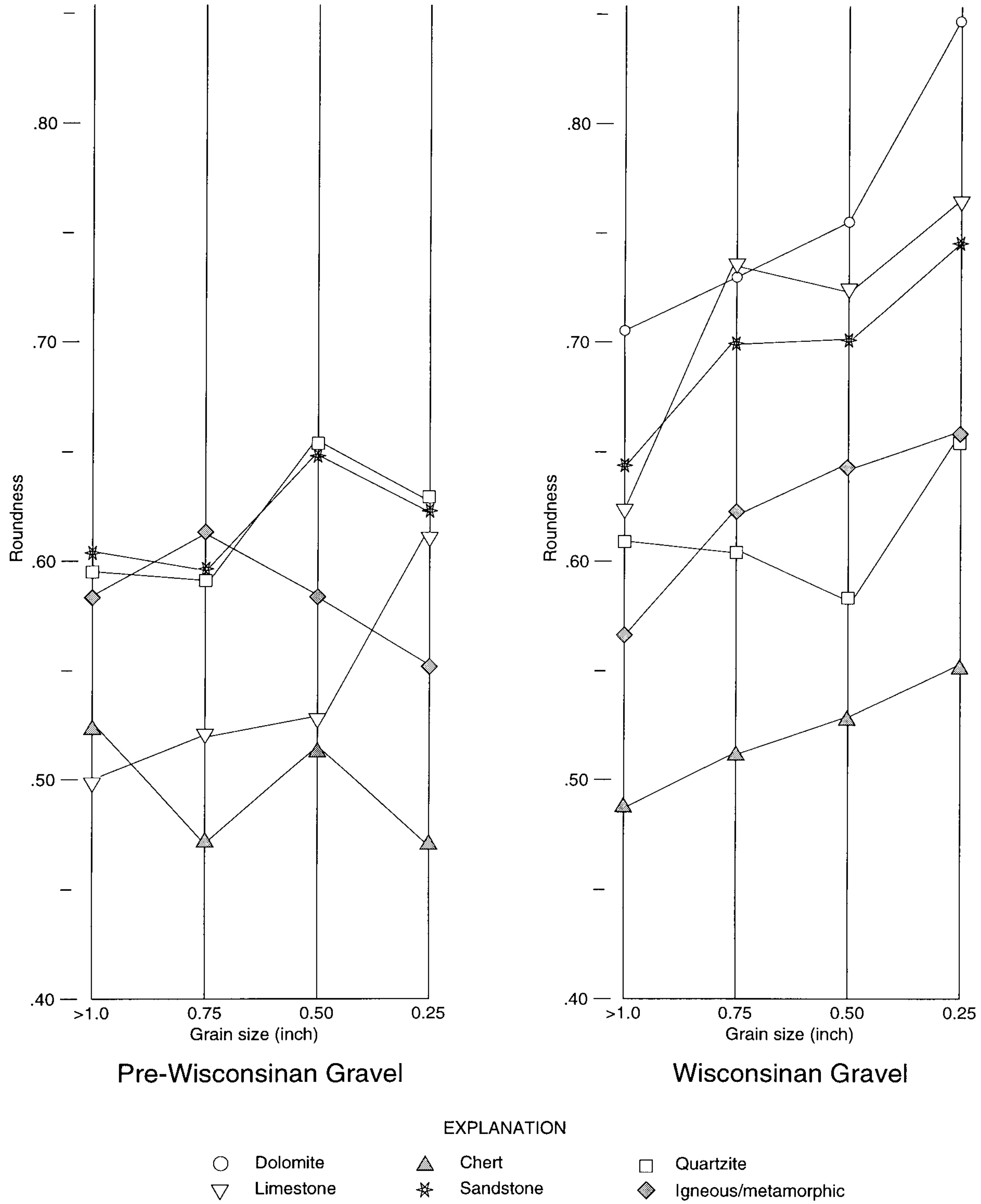

Figure 9. Pebble roundness as a function of grain size for various Pleistocene gravel lithologies.

Pronounced stratigraphic differences in roundness and roundness variations with respect to grain size (Fig. 9) indicate different transport histories for the Wisconsinan and pre-Wisconsinan outwash sediments. The pronounced roundness recorded in the finer pebble sizes of Wisconsinan gravel means they have undergone more abrasion than the coarser particles due to their greater mobility in transporting currents. The ill-defined roundness versus size trend for pre-Wisconsinan outwash indicates these sediments have

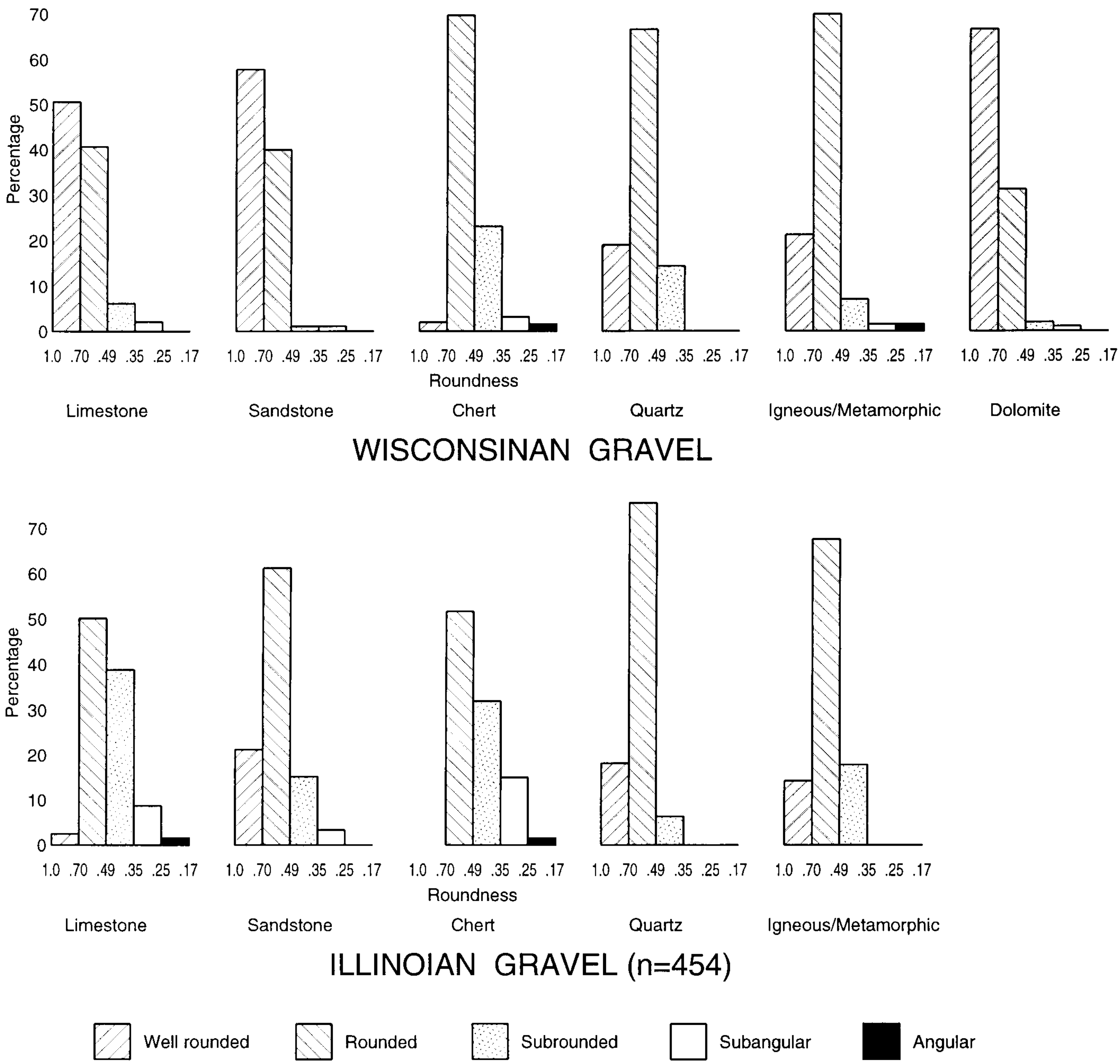

Figure 10. Percent variation by roundness class for lithologies of Illinoian and Wisconsinan gravel.

had less time to develop the trend shown by Wisconsinan outwash. These contrasting transport histories reflect differences in the fluvial-glacial depositional environment. Because the glacier terminus was near the depositional site of Illinoian and pre-Illinoian outwash, these gravels traveled a relatively short distance and consequently underwent less extensive abrasion. The glacier terminus supplying late Wisconsinan outwash gravels, on the other hand, lay 15 to 80 miles north of the Ohio River Valley in what is now southern Indiana and Ohio, a sufficient distance for distinctive roundness variations to develop.

Pebble Surface Analysis

The degree to which pebble surfaces have been altered or weathered was noted during the pebble count. Pebble surfaces were qualitatively described and classified based on observations made with a binocular microscope. Supplemental data from unpublished U.S.

Army Corps of Engineers reports were included in these analyses.

RESULTS

Size Analysis

Grain-Size Distribution

Particle size for most Pleistocene outwash samples from northern Kentucky does not follow a normal distribution. Departure from normality is indicated by distribution curve shape itself and by diagnostic grain-size parameters. Representative distribution curves of both cumulative grain size and grain-size frequency are shown in Figure 11. Normally distributed sediments are typically described by smooth, uniformly sloping, S-shaped cumulative curves and bell-shaped frequency plots. For most outwash samples, however, the cumulative distribution curves have distinctive slope breaks, signifying the presence of discrete grain-size populations within the sample. These separate populations are better visualized when the grain-size data are plotted as frequency curves (Fig. 11). The pebbly sand and sandy gravel observed in pit exposures (Fig. 12) produce a range of bimodal size distributions, similar to the distribution curves for samples 141005 and 141006 in Figure 11. Unimodal size distributions are found in relatively common, gravel-free to sparsely pebbly sands (Fig. 11, sample 141004) and in uncommon, sand-free, gravels with unfilled voids (Fig. 13). The bimodal grain-size distribution curves of Kentucky's Pleistocene deposits resemble those of modern proglacial valley train sediments in the Canadian Arctic (Church, 1972, Fig. 83).

The grain-size parameters of standard deviation, skewness, and kurtosis have been used as indicators of bimodality in fluvial sediments (Folk and Ward, 1957). In this study, kurtosis values greater than 2.0 generally signify a unimodal distribution (Fig. 11, sample 141004), exclusively in either sand or gravel fractions, whereas kurtosis values less than –1.0 indicate two subequal populations of sand and gravel (Fig. 11, sample 141006). A near-normal kurtosis value (–0.14) is indicated for the grain-size distribution of sample 141005 in Figure 11. The highest standard deviations (indicating the poorest sorting) are usually found in bimodal mixtures with equal amounts in the two modes (Fig. 11, sample 141006). The best sorting is associated with unimodal distributions (Fig. 11, sample 141004). Sorting can be qualitatively estimated from slope steepness of the cumulative curve or breadth of the frequency curve. On visual inspection of distribution curves, the sand mode was usually found to be better sorted than the gravel mode (Fig. 11). Every sample analyzed in this study was poorly sorted to very poorly sorted, averaging 2.56Φ.

Particle size in northern Kentucky glacial deposits ranges from boulders with diameters greater than 6 feet (–11Φ) to micron-size (11Φ) clays. The extreme grain-

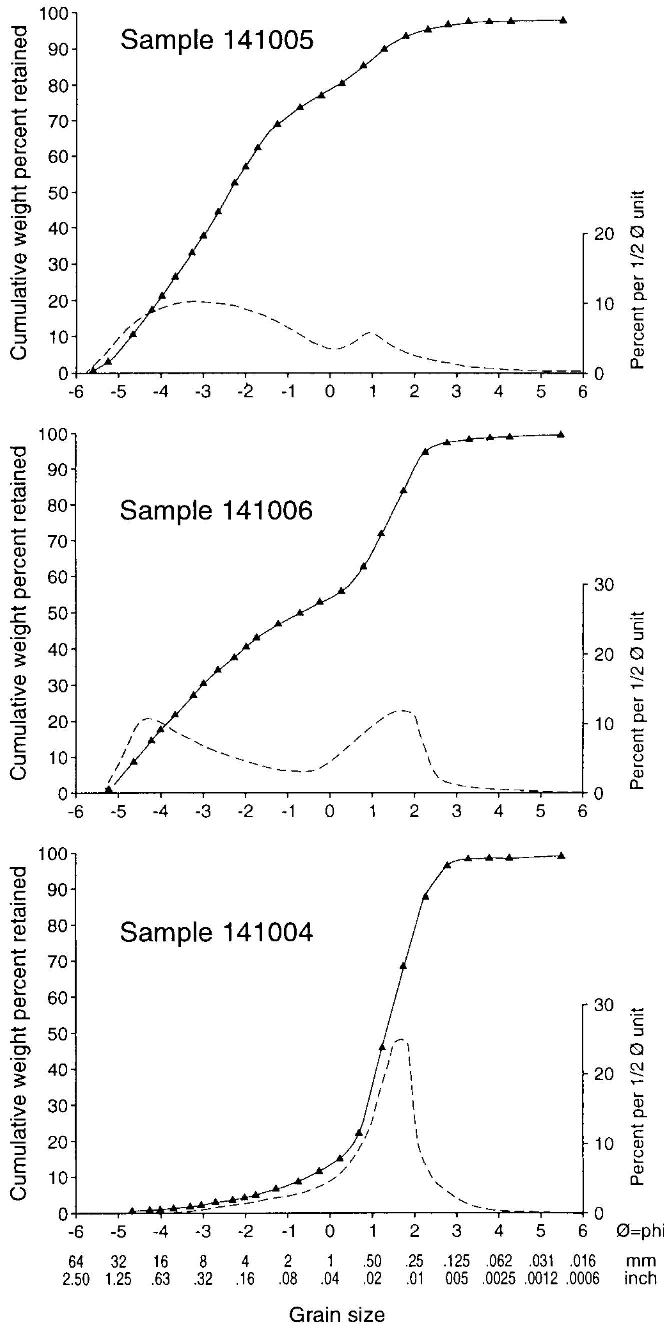

Figure 11. Representative grain-size distribution curves for sand and gravel deposits in northern Kentucky. Cumulative distribution curves (at top) indicate the sieve grades (represented by triangle symbols) used in analysis. Frequency distribution curves (at bottom) are read using scale to the right.

Figure 12. Interbedded pebbly sands and sandy gravels from a large commercial pit in northwestern Carroll County. Hammer for scale in upper right is 10 inches long. These rapidly deposited, bimodal sediments contain variable proportions of sand and gravel within the alternating layers.

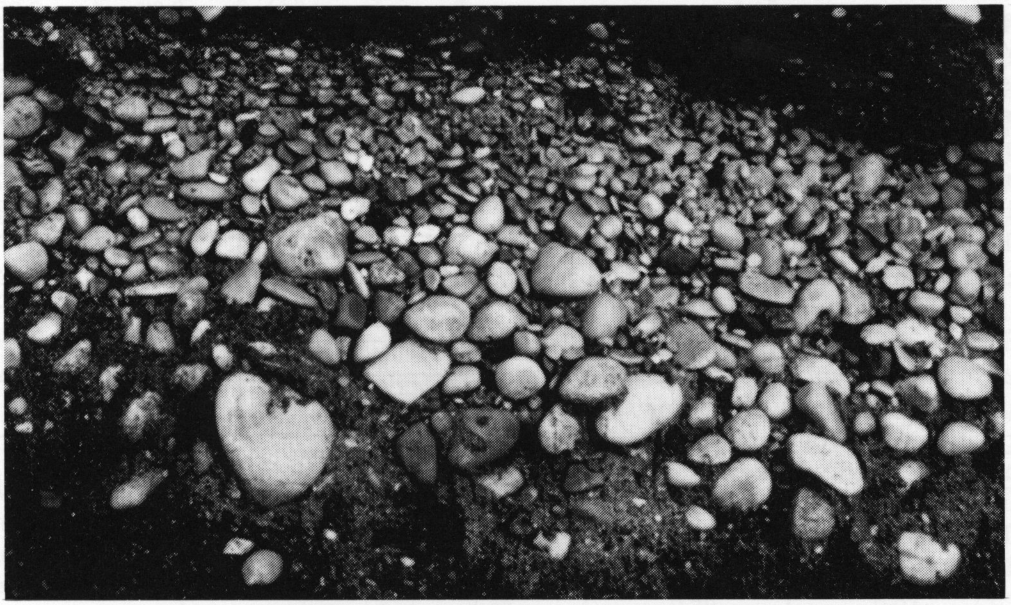

Figure 13. Size-graded, moderately sorted gravel pod preserved in poorly sorted pebbly sand. This upward-fining deposit of relatively sand-free gravel is characterized by a unimodal size distribution curve. Cobble at lower left is approximately 2 inches in diameter.

size variabilty in outwash sediments, within even relatively small areas, makes representative sampling difficult, and strongly influences quantitative measurements. Based on the sand and gravel sampled in this study, the average outwash particle is granule size (Table 2), with a mean diameter of 0.09 inch (–1.12Φ). Mean grain size yields a whole sample average, but says nothing about particle size within the various subpopulations of gravel, sand, and silt/clay. Modal grain size gives the diameter of the most frequently occurring particle in these populations. The modal diameter of gravel ranges from 2 inches to 0.16 inch (–5.65Φ to –2.0Φ) and averages 0.76 inch (–4.27). Modal sand size ranges from 0.02 to 0.007 inch (1.0Φ to 2.5Φ) and averages 0.0125 inch (1.64Φ), a medium-grained sand. The average separation between sand and gravel modes is 4.98Φ. Variations in the average modal diameter of sand and gravel were found to correlate slightly with the amount of gravel per sample; coefficents of correlation (r) were 0.38 for sand and 0.67 for gravel. If a sample's gravel total is under 10 percent, its sand is usually fine grained, averaging 0.008 inch (2.39Φ) in diameter. Samples with more than 10 percent gravel are generally composed of medium sand averaging 0.013 inch (1.63Φ) in diameter. The modal gravel size tends to be coarser in samples with large amounts of gravel than in those with sparse gravel populations.

An absence of correlation between modal size and the amount of gravel per sample has been interpreted to mean that particle size distribution is chiefly a function of the source area and has been little affected by hydraulic factors of the depositing currents (Folk and Ward, 1957). Conversely, a partial correlation between these variables might indicate some degree of current action or sorting within the depositional environment. The correlation found in this study between modal diameters and varying percentage of gravel suggests that an unsorted, Wisconsinan glacial source material had been partially sorted by current action before final deposition in the study area. Of the sediment subpopulations, each responded differently to hydraulic conditions during transport and deposition. In general, the gravel population represents the traction load dragged along fluvial channel bottoms and the sand population constitutes the temporary suspended load that became trapped in the interstices of the gravel as energy conditions waned. Silt and clay, forming the long-term suspended load, were either swept downstream out of the system or accumulated in slack water along the margins of the depositional environment. Such conditions explain the bimodal sand-gravel size distributions, the better sorting in sand versus gravel sizes, and the small amounts of silt and clay found in most samples of the Ohio River Valley outwash deposits.

Grain-Size Variation with Stratigraphy

Averages of mean and modal grain size, sorting, and percentages of maximum size, gravel, sand, and silt/clay are summarized in Table 5 for Wisconsinan, Illinoian, and pre-Illinoian outwash. To determine whether differences between grain-size averages among the different-age rocks are too great to be due to chance, a standard test of significance ("Student's" t-test) was used. No significant differences in grain-size characteristics were found between Wisconsinan and Illinoian outwash deposits in the Ohio River Valley. Although the single upland area investigated may not be representative of all pre-Illinoian outwash deposits, comparisons with the two younger units are useful. The percentage of sand in pre-Illinoian outwash is significantly lower than that in the Illinoian. In addition to the sand and gravel modes common to all three outwash deposits, the pre-Illinoian has a substantial third mode consisting of silt and clay. This additional mode indicates that sediment sorting in the pre-Illinoian outwash is significantly worse than in the Illinoian and Wisconsinan outwashes. It also affects mean grain size by counterbalancing the coarse size fractions, so that pre-Illinoian outwash is equal in mean grain size to the two younger deposits. The pre-Illinoian is actually composed of significantly coarser sand and gravel sizes, as shown by modal size (Table 5). Thus, modal diameter gives a more accurate description than mean diameter for this polymodal sedimentary deposit.

Table 5. Grain-size parameter averages according to age.

Size Parameter		*Wisconsinan*	*Illinoian*	*Pre-Illinoian*
Mean size	(in.)	0.09	0.05	0.07
	(Φ)	-1.21	-0.27	-0.81
Modal gravel size	(in.)	0.39	0.42	0.96
	(Φ)	-3.30	-3.40	-4.61
Modal sand size	(in.)	0.013	0.011	0.025
	(Φ)	1.60	1.79	0.67
Φ sorting		2.35	2.39	3.47
% >1"/Total gravel		21	23	28
% gravel		37	25	42
% sand		58	73	47
% silt/clay		5	2	11
Number of samples		46	6	14

Lateral Grain-Size Variation

Regional. Regional trends in grain-size variation were not investigated in pre-Illinoian and Illinoian deposits because of their limited outcrops. For Wisconsinan outwash sediments along the Ohio River Valley, local sample data from successive downstream segments were combined and averaged to determine regional changes in grain-size parameters and the percentages of gravel, sand, and silt/clay. The results of this averaging are summarized in Table 6. From Taylorsport to North Bend Bottom in Boone County (Fig. 1), particle size and percentage of gravel decrease rapidly downstream as silt and clay content increases, and sediment sorting improves, mainly due to the falloff in gravel (Table 6). A stratigraphic cross section based on subsurface borehole data (Fig. 14) shows that the downstream decrease in grain size and gravel content has persisted through geologic time along this reach of the Ohio River. Because this is the youngest portion of the upper Ohio River Valley, having been cut during Illinoian glaciation, the deposits along this reach consist of late Wisconsinan outwash and younger alluvium.

Below North Bend Bottom and Petersburg in Boone County, another large-scale trend extends to Milton in Carroll County (Fig. 1). Modal gravel size, percentage of coarsest gravel, and the total amount of gravel abruptly increase at Petersburg and then decrease nonuniformly downstream (Table 6). The greatest concentration of large-pebble gravels occur in Boone County; abundance of maximum gravel size (greater than 1 inch) drops from about 40 percent to roughly 20 percent in Gallatin and Carroll Counties. Webb (1970) has also shown a downstream decrease in maximum pebble size between Lawrenceburg, Indiana, and Jeffersonville, Indiana. The decline in the amount of gravel downstream is accompanied by proportionally increasing quantities of sand and little change in the low silt/clay content. Modal sand size abruptly changes from fine to medium at Petersburg and changes insignificantly downstream from there. Mean grain size follows the same pattern as modal sand size. Particle sorting for sand and gravel mixtures is generally poor to very poor throughout the study area, showing no systematic downstream variations (Table 6).

These lateral changes in average grain size and gravel content reflect hydrodynamic conditions within the fluvial meltwater regime of late Wisconsinan time. The sudden increase in grain size near Petersburg coincides with the confluence of the Great Miami River (Fig. 1), a major meltwater sluiceway entering the Ohio River Valley. Coarse-grained outwash accumulated rapidly at the confluence, forming a thick wedge of sediment that gradually thinned downstream. This wedge of outwash partially restricted the Ohio River's flow above the confluence. Slackened energy conditions above the confluence, therefore, explain the rapid decrease in grain size between Taylorsport and Petersburg (Fig. 14). Below the Great Miami–Ohio River confluence, decreases in grain size and gravel abundance conform to normal downslope declines in stream competence and volume, as distance from the glacial source lengthens (Fig. 5).

Local. Examination of pre-Illinoian and Wisconsinan outwash deposits showed that grain-size variations also occur on a local scale. Near Commissary Corner in Boone County (Fig. 1), calcite-cemented, bouldery sand and gravel of pre-Illinoian age form steep, rugged cliffs along Middle Creek and its tributaries. Muddy, fine to medium sand grading upward into planar and cross-stratified sandy gravel, pebbly sand, and cobbly gravel was studied in outcrop, prospect trenches, and boreholes adjacent to a small tributary valley north of Middle Creek (Fig. 15). Grain-size characteristics for this area are summarized in Table 5 for the pre-Illinoian outwash. These deposits are a mixture of large pebble gravel, coarse-grained sand, and 6 to 22 percent silt and clay, making them the worst sorted, coarsest outwash in the study area.

Table 6. Regional variation in grain-size parameters.

Location:		*Taylorsport*	*North Bend Bottom*	*Petersburg to Belleview*	*Steele Bottom to Ghent*	*Carrollton to Milton*
Size Parameter						
Mean Size	(inch)	0.04	0.006	0.14	0.11	0.11
	(Φ)	0.03	2.73	-1.86	-1.42	-1.47
Modal Gravel Size	(inch)	0.21	—	1.07	0.44	0.62
	(Φ)	-2.44	—	-4.76	-3.49	-3.97
Modal Sand Size	(inch)	0.015	0.01	0.013	0.012	0.015
	(Φ)	1.44	2.0	1.65	1.67	1.42
Phi Sorting		2.02	1.41	2.78	2.24	2.33
% >1"/Total Gravel		8	0	41	16	25
% Gravel		20	0	51	47	44
% Sand		76	74	46	49	54
% Silt/Clay		4	26	3	4	2
Number of Samples		4	1	10	16	10

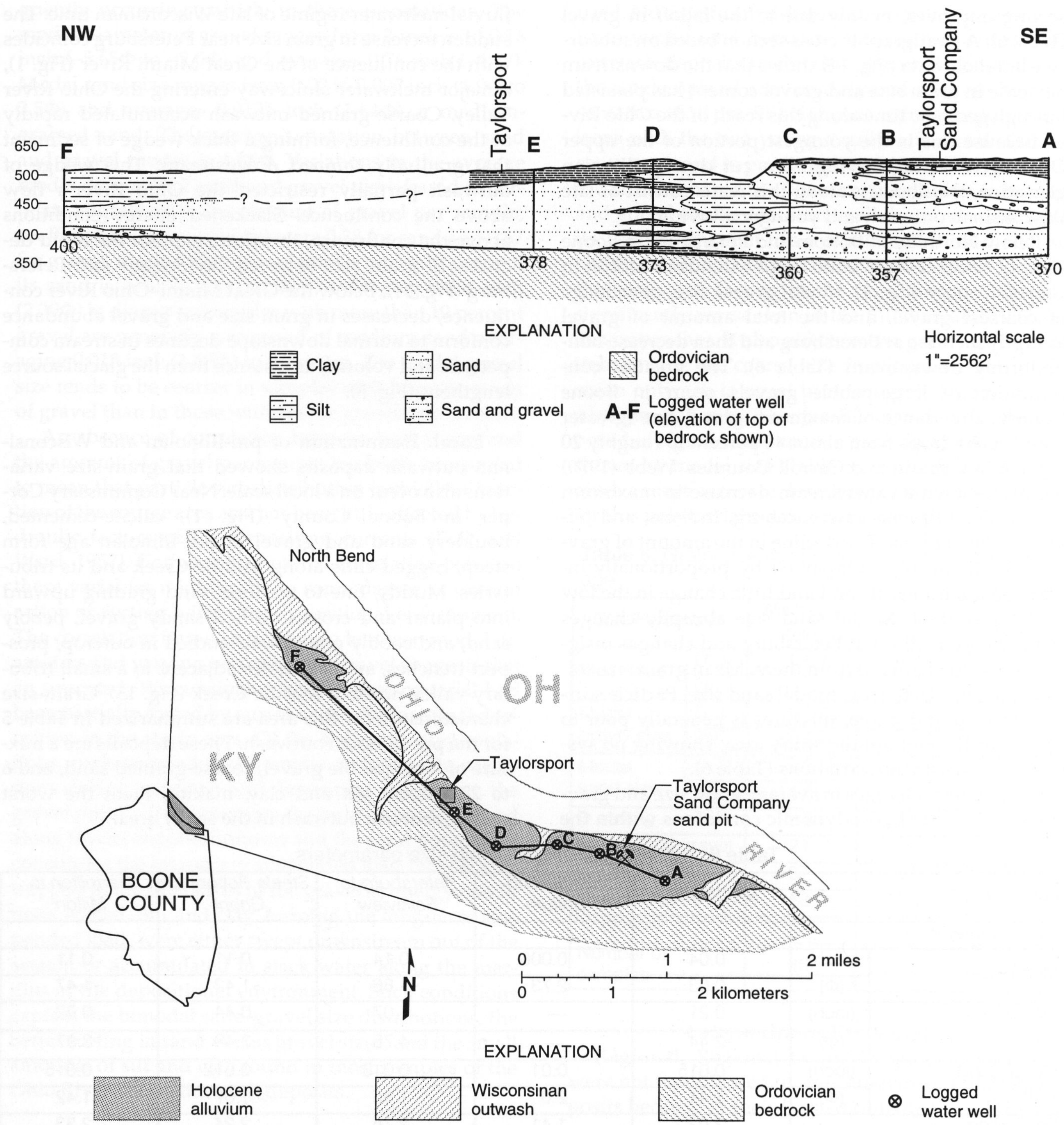

Figure 14. Stratigraphic cross section showing downstream decrease in grain size between the Boone County line and North Bend Bottom. Subsurface data from Price (1964a-b).

Figure 15 shows vertical and lateral grain-size variations in interbedded sand, gravel, and silty to pebbly clay that thicken eastward into an abandoned preglacial tributary valley of the ancestral Kentucky River. Variations in the thickest part of the subsurface resemble the outcrop: laminated, silty, fine to medium sands in the lower half grading upward into silty, pebbly sand and sandy gravel (Fig. 15, borehole 1). Stratigraphic variation in mean grain size indicates a coarsening-upward trend in boreholes 1 and 2 (Fig. 15). Sorting varies slightly from very poor near the base to extremely poor higher in the section (Fig. 15, borehole

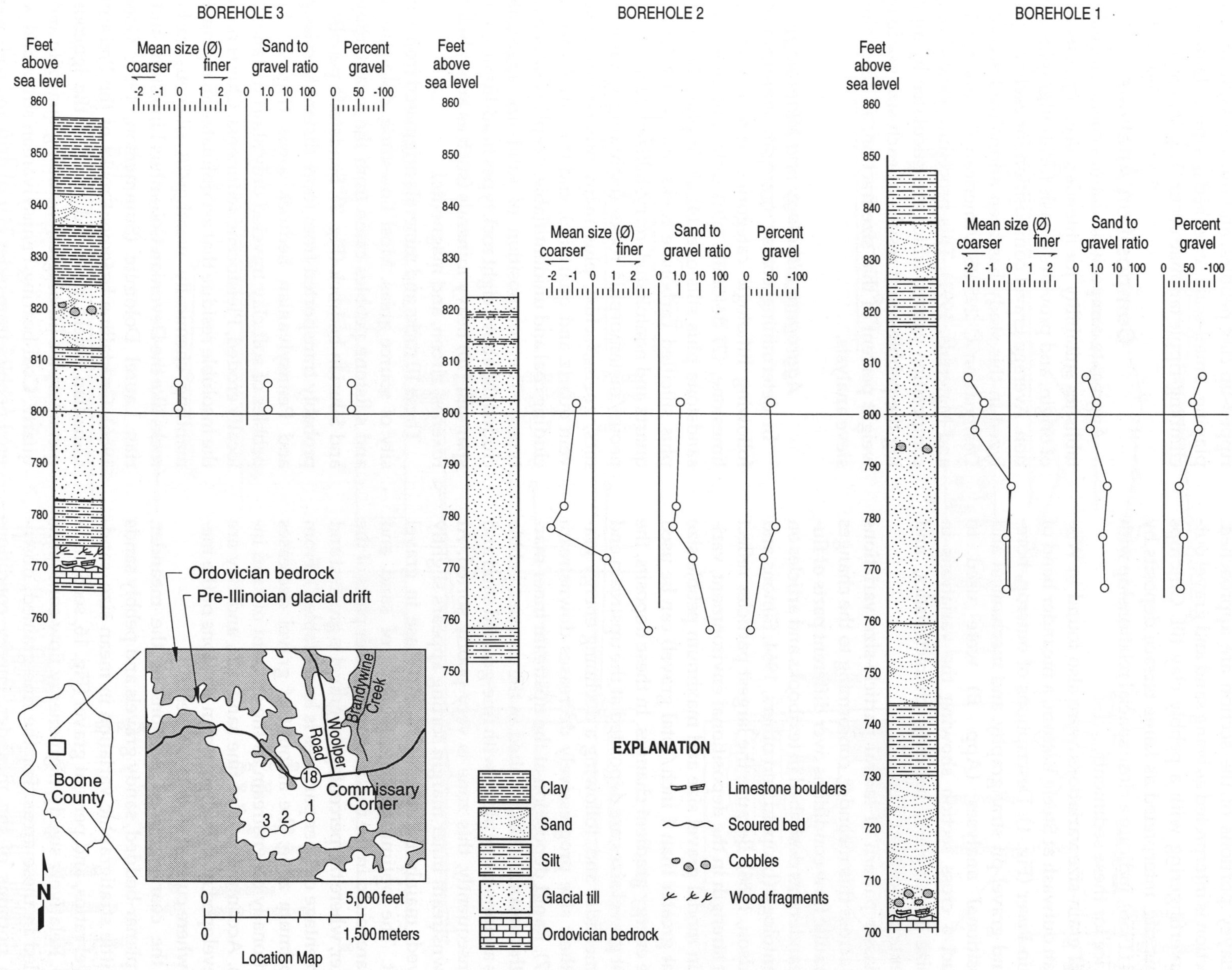

Figure 15. Stratigraphic sections showing grain-size textural variations in pre-Illinoian drift at Commissary Corner, Boone County.

2). Lateral variations in texture are also evident. Gravel content and average grain size decrease, mud content increases, and sorting worsens from east to west as the more clayey portions of the section are approached. This section is interpreted as being sand and gravel outwash interfingering with a pebbly clay till. Outcrops near this site, interpreted as kame terrace deposits by Durrell (1956), indicate a close spacial relationship with glacial ice for these sediments.

Local grain-size variations were also found in Wisconsinan outwash at Steele Bottom, a meander bend of the Ohio River (Fig. 1). Descriptions of outcrop, borehole, and gravel pit stratigraphy, and mechanical and compositional analyses (App. B) were used to construct a cross section showing the variations in grain-size parameters, bedding characteristics, and sediment composition (Fig. 16).

A classic pattern of lateral particle-size variations occurs across this meander, conforming to the changes in hydraulic flow conditions over different parts of fluvial meanders, as described in textbooks and articles on sedimentology (Leopold and others, 1964; Simons and Richardson, 1966). Because the largest particles reflect current strength in the depositional environment, variations in modal gravel size and maximum pebble size (percent greater than 1 inch/total gravel) can be used to trace energy gradient changes. In these deposits, the coarsest gravel sizes are deposited at the upstream end of the meander and, following a declining energy gradient, their size progressively decreases downstream (Table 7). Rapid deposition at the upstream inner margin of the meander has resulted in the coarsest pebble gravels accumulating along with fine-grained sand and silt; consequently, this zone is very poorly sorted. At the downstream inner margin sorting appears slightly improved, mainly because of the decrease in gravel content. The optimum accumulations of sand and gravel are found in the central core or outer parts of the meander, where the percentage of gravel is greatest and the percentage of finer particles is least (Table 7). From this optimum zone, the amount of gravel decreases proportionally downstream as the amount of sand increases. Accumulations of fine sand, silt, and clay are best developed in the downstream portions of the meander, where current flow is weakest.

On the coarse-grained portions of the meander, crude, planar-bedded, sandy gravels and pebbly sands show little stratigraphic variation in mean size, sand-to-gravel ratios, and percent gravel (Fig. 16, sections A and C). Relatively steady, high-energy flow conditions prevailed in these areas. For the fine-grained, downstream portions of the meander, energy conditions were weaker and highly variable. These conditions are reflected in cycles in which particle size fines upward, size variations are both abrupt and gradational, and lenses and thin beds of clay, scour-and-fill structures, ripped-up clay pebbles, and units of sand and silt displaying small-scale crossbeds, ripple laminae, and climbing-ripple laminae occur (Fig. 16, section D).

Composition Analysis

Aggregate composition defines chemical quality, establishes suitability for intended use, suggests sources of origin, and provides a basis for stratigraphic correlation. Average gravel composition for each sample analyzed in this study has been normalized according to Designation C 295-85 (American Society for Testing and Materials, 1991). This procedure yields weighted composition values, which are calculated by multiplying the pebble-count results of each size grade by the weight percent of that size fraction, as determined by sieve analysis.

Aggregate Lithology and Mineralogy

In determining coarse aggregate composition, the following lithologic categories were recognized: (1) limestone, (2) dolomite plus dolomitic limestone, (3) sandstone plus siltstone, (4) shale plus clay, (5) chert plus silicified carbonate rocks, (6) quartz (both vein quartz and nonfoliated, recrystallized quartzite), (7) igneous/metamorphic rocks (including granite, volcanics, gneiss, schist, plus many others, but excluding vein quartz and quartzite), and (8) miscellaneous (including coal and unidentifiable, deeply weathered rock types). The composition of sand-size aggregate included the above eight rock types in addition to (9) feldspar and (10) heavy minerals (such as amphiboles, pyroxenes, zircon, and magnetite).

These 10 rocks and minerals originated from a diversity of source areas. Most limestone, dolomite, shale, and siltstone pebbles came from the local Ordovician and Silurian bedrock (Fig. 2). Sandstone pebbles were probably transported from more distant Mississippian and Pennsylvanian bedrock areas (Fig. 2). Fragile pebbles of soft clay traveled only short distances from locally eroded, Pleistocene sediments. Cherts represent the insoluble residue that accumulated in regional soils mantling chemically weathered, siliceous carbonate rocks like the Devonian Columbus Limestone and Silurian Laurel Dolomite (Summerson, 1959; Gooding, 1966). Crystalline basement rocks of the Precambrian Canadian Shield provided most of the igneous and metamorphic lithologies, including quartzite and vein quartz. Coal-bearing Pennsylvanian strata and weathered pebbles from older glacial drift and soils were the sources of miscellaneous pebble types. Sand-size rock

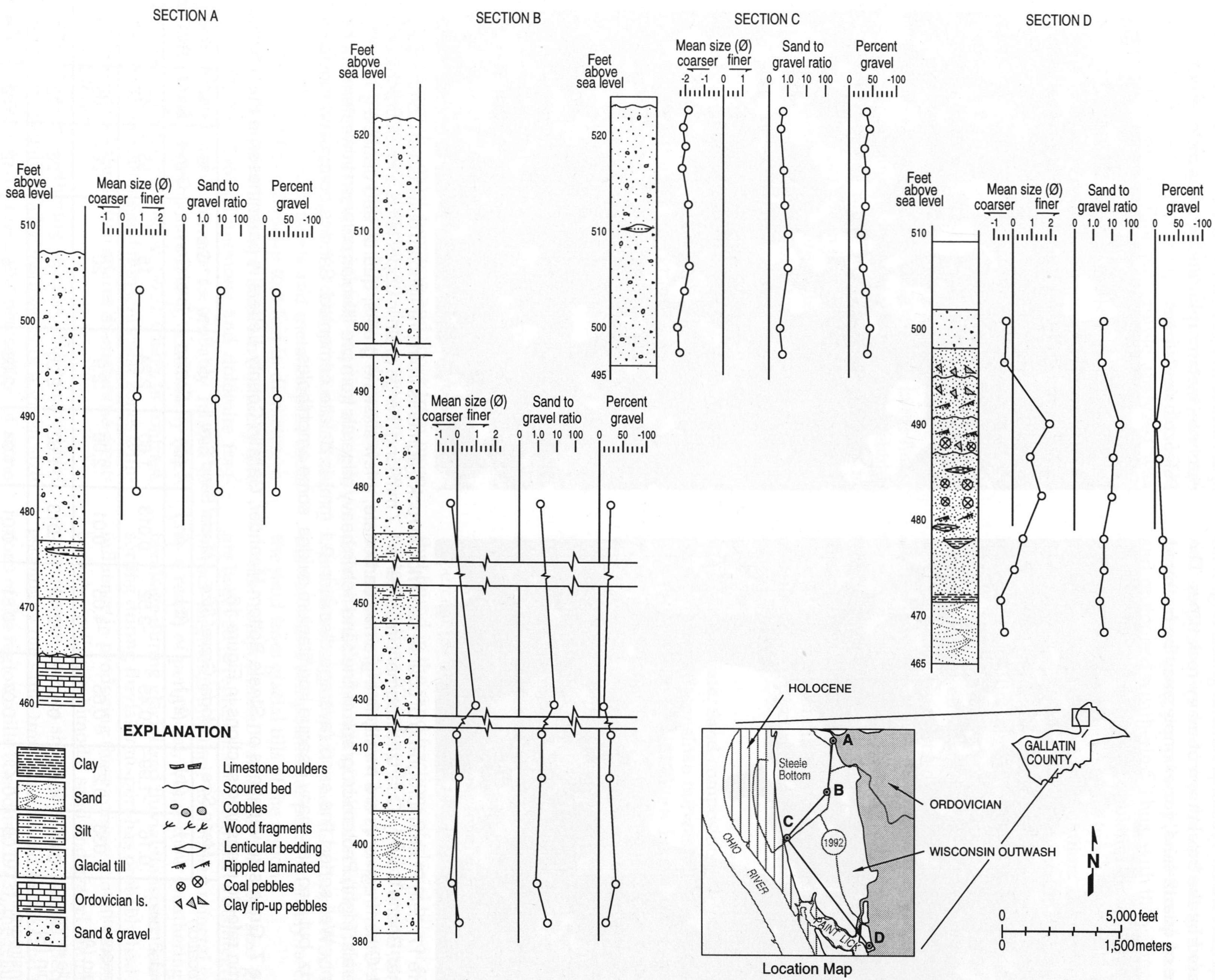

Figure 16. Stratigraphic sections showing bedding and grain-size textural variations at Steele Bottom meander bend, Gallatin County

fragments seen in thin sections (Fig. 17a) originate from the same sources as the coarse aggregate. Most sands, however, are monocrystalline mineral grains (Fig. 17b), produced by the breakdown of many rock types. The source of quartz sand, for example, may be fractured vein quartz or disaggregated sandstone, quartzite, granite, and arenaceous limestone. The source of feldspars and heavy minerals was either disintegrated Precambrian metamorphic and igneous rocks or immature Paleozoic sandstones.


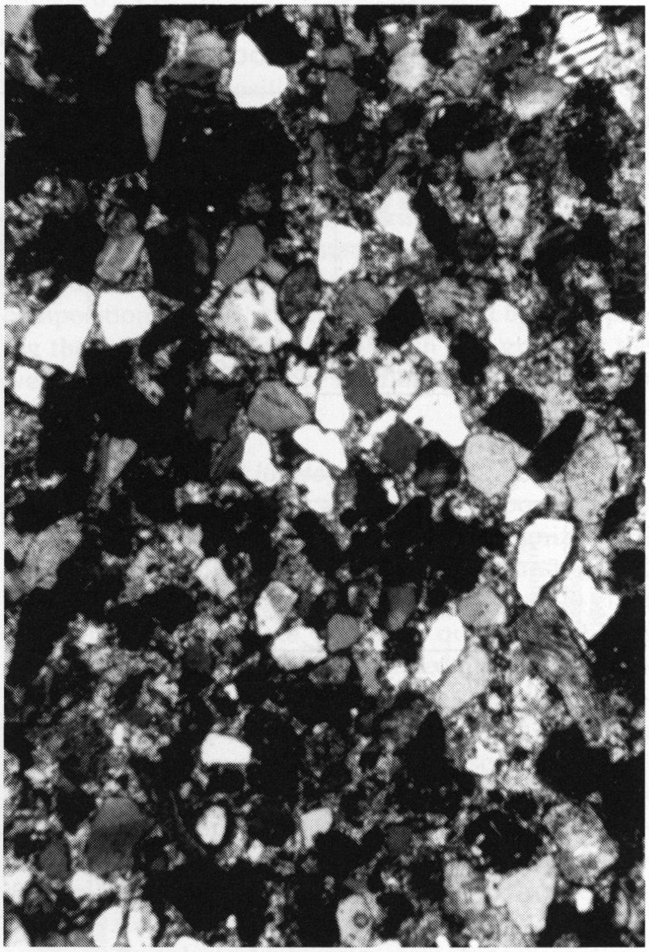

Figure 17. (left) Photomicrograph of coarse sand rich in rock fragments from pre-Illinoian outwash at Commissary Corner, Boone County. Quartzite fragment in center is 1.7 mm long. Large grain in upper left is a fossil brachiopod shell. Other fragments are mostly fine-grained carbonate, a few siltstone grains, quartz, and opaque iron oxide minerals. (right) Photomicrograph of fine sand rich in heavy minerals from pre-Illinoian outwash in western Boone County. Well-sorted fine sand (average diameter=0.1 mm) is calcite cemented. Sand is composed mostly of quartz, but also has many opaque iron/titanium oxides, some amphiboles.

Table 7. Grain-size variations on Steele Bottom Meander, Gallatin County. Letters in parentheses in the "Location" column refer to measured sections in Figure 16.

Location	*Mean Size*		*Modal Gravel Size*		*Modal Sand Size*		*Φ Sorting*	*% > 1" Gravel/ Total Gravel*	*% Gravel*	*% Sand*	*% Silt/Clay*
	(in.)	*(Φ)*	*(in.)*	*(Φ)*	*(in.)*	*(Φ)*					
Meander core (C)	0.16	-1.99	0.45	-3.52	0.013	1.60	2.24	15	55	43	2
Upstream inner margin (A)	0.033	0.27	0.65	-4.05	0.01	2.00	2.9	20	26	65	9
Middle inner margin (B)	0.05	-0.34	0.17	-2.12	0.013	1.62	2.26	6	26	72	2
Downstream inner margin (D)	0.03	0.41	0.07	-0.81	0.01	1.94	2.08	5	12	80	8

Compositional Variation with Grain Size

Coarse aggregate. Compositional variation between five size grades of Wisconsinan gravel was determined from nearly 6,000 pebbles; the four size classes analyzed in Illinoian gravel comprised just under 1,200 pebbles. The one pre-Illinoian sample analyzed was similar compositionally to the Illinoian. Both Wisconsinan and Illinoian outwash gravels show well-defined changes in composition with respect to grain size (Fig. 18). The content of limestone and dolomite decreases proportionally as the content of chert and sandstone increases with diminishing particle size. For Wisconsinan gravels, the total carbonate content ranges from nearly 80 percent in the coarsest sizes to about 50 percent in the finest sizes; in Illinoian gravels, carbonates range from 50 percent in the coarsest sizes to 20 percent in the finest sizes (Fig. 18). Combined chert and sandstone pebbles of Wisconsinan age range from about 10 percent in coarse sizes to 35 percent in fine sizes. In Illinoian gravels, chert and sandstone constitute about 30 percent of the coarsest sizes and about 60 percent of the finest sizes. Thus, in all Pleistocene stratigraphic units, the chert and sandstone content is relatively low in large-pebble gravels and high in small-pebble gravels. Quartz, igneous, and metamorphic pebble contents are about 15 percent in all size grades. Shale, clay clasts, and miscellaneous materials are generally insignificant and tend to occur mainly in the finest gravel sizes.

The apparently simple composition-size relationship involves a complex interplay between the lithic variables of relative abundance, size range, and physical-chemical properties and the processes of weathering and fluvial-glacial sedimentology. The relative abundance of a given pebble composition depends on the proximity of its source area: local bedrock lithologies are generally most common and those from more distant sources are successively less common. The grain-size range for a given lithology is dependent on such rock properties as intergranular bonding strength, joint or fracture spacing, and bedding thickness. Thus, massive, nonfoliated igneous and metamorphic rocks sometimes yield boulders up to 8 feet in diameter, reported as glacial erratics in northeastern Kentucky (Jillson, 1927; Ray, 1969). Limestone and dolomite fragments, whose maximum size is probably related to bedding thickness and joint spacing, occasionally reach diameters of 5 feet (Swadley, 1972). Chert, in contrast, is derived from nodules and thin lenticular zones within carbonate rocks and often attains diameters no greater than 1 foot.

The effects of weathering, erosion, and transport history on the available rock constituents of a given size grade will tend to increase the percentage of some lithologies relative to that of others. Resistance to mechanical wear and chemical attack, for example, favors the preservation of lithologies like chert, vein quartz, and quartzite over less resistant carbonate rocks and sandstones during periods of glacial-fluvial transport and prolonged weathering. Thus, with increasing time or transport distance, the population of more resistant rocks grows as the less resistant types decrease in number through attrition and dissolution. Because glacial ice and meltwater have contrasting sediment transport capabilities, the size range of available particles carried by each is significantly different. Glacial ice is able to pick up and move a broad spectrum of available sizes but is unable to effectively winnow or sort these particles. Glacial meltwaters, on the other hand, have lower carrying capacity but are better able to sort their particle load according to size, shape, and specific gravity (composition). The relative importance of each variable in explaining composition variation with pebble size is beyond the scope of this report, but some of these variables have been discussed in the literature (Sneed and Folk, 1958).

Fine aggregate. Sand composition for pre-Illinoian, Illinoian, and Wisconsinan outwash from six locations (Fig. 1) is summarized in Table 8. In coarse to fine sands of pre-Illinoian age, rock-fragment abundance is inversely proportional to monomineralic grains (Table 8). The ratio of rock fragments to mineral grains is about 5:1 for coarse sand, and about 1:5 for fine sand. Rock fragments and mineral grains are roughly equal in the medium size grades for all Pleistocene sands examined in this study. Abundance of carbonate rock fragments ranges from about 65 percent for coarse sand to about 30 percent for medium sand (Table 8), a trend similar to that found in the sand fractions of glacial tills of southeastern Indiana (Gooding, 1973). With decreasing grain size, quartz, feldspar, and heavy-mineral content increases and the amount of chert decreases (Table 8), a trend also observed in till sands (Gooding, 1973). Thus, outwash sand composition appears to closely resemble the sand from glacial tills of the region.

The compositional variations for sand-size grains are believed to represent the progressive disintegration of rock fragments into their component mineral grains as a result of periglacial, freeze-thaw weathering and breakage during glacial and fluvial transport. Selective sorting during fluvial transport has probably had little influence in producing these compositional variations, because sorting in bimodal sand and gravel samples is poor to very poor, as shown by size analysis. Because essentially the same trends are found in the sand fractions of the region's tills (Gooding, 1973), the relation-

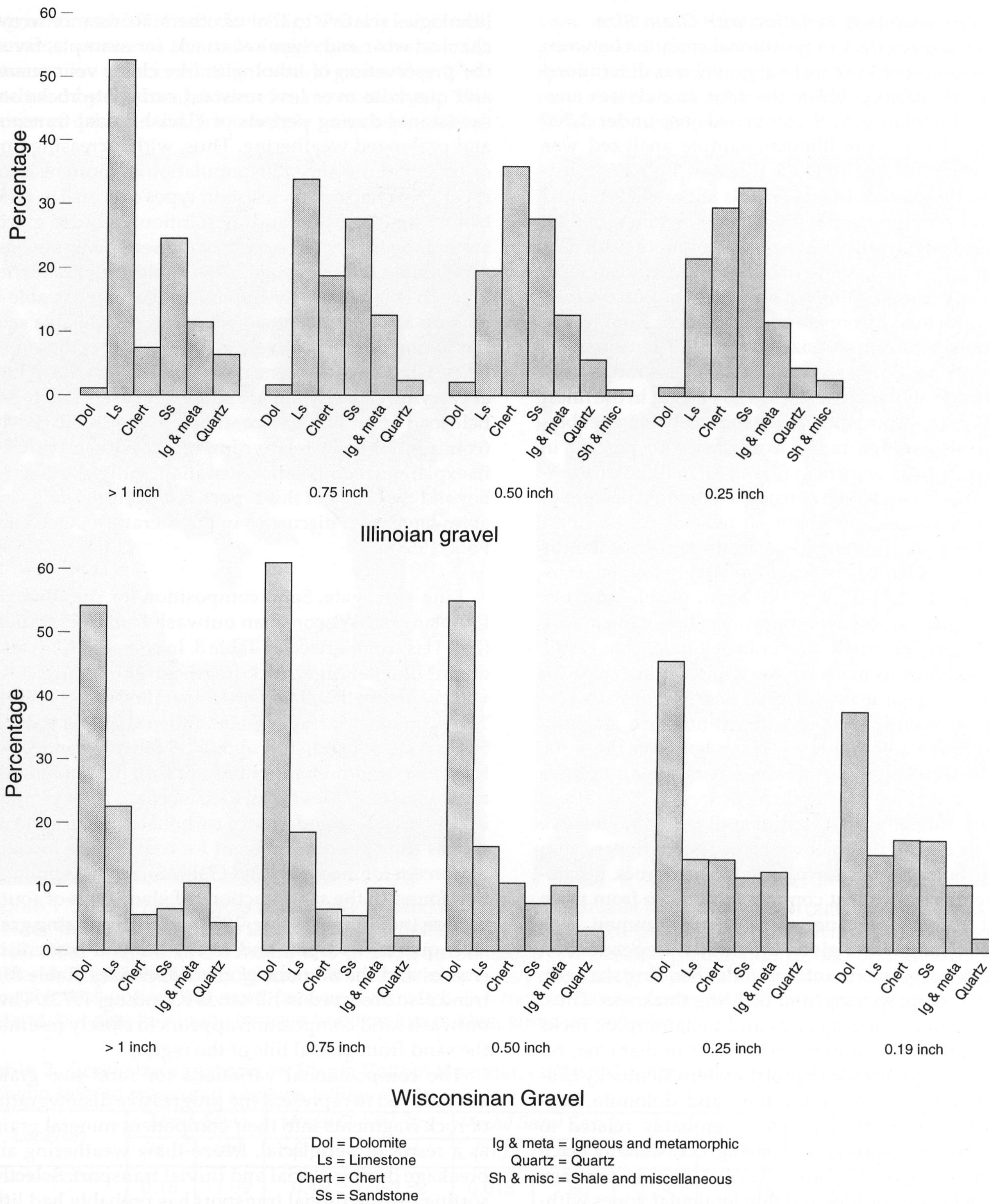

Figure 18. Percent variations in pebble lithology with respect to size and age.

ship between composition and grain size for most outwash sands, therefore, is considered to be inherited from the glacial source. Selective sorting, however, does commonly influence composition in well-sorted, unimodal sands. The relatively high content of heavy minerals found in the fine sand described in Figure 17b and Table 8 is primarily due to hydraulic sorting factors in a fluvial environment, which concentrated these minerals, like placer gold deposits, according to their size, shape, and high specific gravity.

Silt-size material constitutes a small percentage in all samples of Wisconsinan outwash. Several clayey silts from fine-grained facies at the outwash margins were sampled and X-rayed, and proved to be composed primarily of dolomite and quartz.

Compositional Variation with Stratigraphy

Because composition varies with particle size, intersample comparisons should be made using particles of equal size to avoid misleading results. Significant compositional differences were found between Pleistocene stratigraphic units of equal size grades in this study. Pre-Illinoian gravel composition closely resembles the Illinoian and, therefore, is not detailed here. In both older outwash units, limestone predominates over dolomite for both sand (Table 8) and gravel (Fig. 18), while the opposite holds for Wisconsinan outwash. The limestone/dolomite ratio ranges from 5:1 to 50:1 in older outwash, and less than 1:1 for Wisconsinan outwash. Teller (1970) found that the limestone/dolomite ratio for pre-Illinoian till pebbles exceeded 15:1, and that for Illinoian tills the ratio fell to between 1:1 and 6:1. Chert and sandstone pebbles in the two older gravels are generally two to three times more abundant than in Wisconsinan gravel. Higher chert contents, found in the sand sizes of older glacial tills (Gooding, 1973), are also found in medium-grained Illinoian outwash sand (Table 8). The frequency of quartz and igneous and metamorphic rock fragments shows only slight differences in either sand or gravel sizes for all three stratigraphic units.

Stratigraphic differences in composition were determined for subsurface samples collected above and below a 37-foot-thick clay horizon at Steele Bottom (Fig. 16, section B). For the sample above this clay bed, typical Wisconsinan compositional characteristics were found: total carbonate=60 percent, limestone/dolomite ratio=0.43:1, and chert plus sandstone=23 percent. The two samples below the clay had pre-Wisconsinan compositional characteristics: total carbonate=35 percent, limestone/dolomite ratio=50:1, and chert plus sandstone=58 percent. All three samples had modal gravel diameters of 0.16 inch (-2.0Φ). The two lower gravels must be Illinoian in age, based on geomorphic and glacial history: a tongue of Illinoian ice deposited glacial drift along this portion of the Ohio River Valley. The 37-foot-thick, sandy to pebbly clay zone between these contrasting gravel units (Fig. 16, section B) is considered to be a remnant of Illinoian till, based on X-ray analysis of the less-than-2-micron clay fraction. Results showing 25 percent expandable clay, 22 percent chlorite plus kaolinite, and 53 percent illite for this clay bed are close to the region's average Illinoian till composition found by Teller (1970). Because X-ray diffraction patterns of local bedrock shale and Wisconsinan outwash clays do not match the pattern for this subsurface clay bed, the alternative interpretations of colluvial shale and Wisconsinan outwash or lacustrine clays were ruled out.

Table 8. Constituent rock and mineral percentages for Pleistocene outwash sands. Sample locations are shown in Figure 1.

Age:	Pre-Illinoian	Pre-Illinoian	Pre-Illinoian	Pre-Illinoian	Illinoian	Wisconsinan	Pre-Illinoian
Location:	Commissary Corners	Highway 18	Commissary Corners	Middle Creek	Steep Creek	Ghent	Riddles Run
Mean Size:	Sand	Sand	Med. Sand	Med. Sand	Med. Sand	Med. Sand	Fine Sand
Component:							
Limestone	61	70	33	27	27	16	16
Dolomite	3	0	2	tr	4	21	0
Chert	5	4	2	2	6	3	0
Sandstone	9	9	5	5	10	7	0
Shale	2	2	4	7	2	4	0
Igneous/ Metamorphic	3	2	2	1	1	1	0
Quartz	11	10	45	48	43	41	63
Feldspar	3	2	5	6	6	6	7
Heavy Minerals	3	1	2	4	1	1	12

Stratigraphic differences in outwash composition reflect Pleistocene glacial history and compositional differences among the major ice sheets that invaded the region. The predominance of limestone over dolomite in Illinoian and pre-Illinoian deposits reflects the two older glaciers terminating within or along what is now the border of northern Kentucky, where bedrock is composed of thin-bedded Upper Ordovician limestone. The high proportion of dolomite to limestone for the Tazewell valley train, on the other hand, is explained by the position of the Wisconsinan glacial margin about 17,000 years ago: stagnated mainly over Silurian dolomite terrain in what is now southern Indiana and Ohio (Gooding, 1973). Large amounts of chert in pre-Illinoian and Illinoian outwash correspond to the high chert values found in tills of the same age, a consequence of entrainment of the region's chert-rich residual soils by these early glaciers (Gooding, 1966; Teller, 1972). Late Wisconsinan drift, though containing some chert, has less chert than pre-Illinoian and Illinoian drift because the chert content became more dilute as each successively younger ice sheet reworked the previous till (Gooding, 1966). With increasing stratigraphic age, therefore, Pleistocene glacial sediments—both till and outwash—tend to become more cherty.

The increase in chert content with depth, familiar to most local gravel pit operators, may be primarily due to the stratigraphic composition differences noted above. However, another factor is required to explain locally abundant chert in late Wisconsinan outwash deposits. At the close of Illinoian glaciation, cherty till and outwash filled much of the Ohio River Valley in the study area. Prior to Wisconsinan outwash deposition, the Illinoian drift was downcut and partially removed by the interglacial Sangamon-age Ohio River, forming paired terraces (Fig. 6). The noncohesive sediments of these Illinoian terraces, which formed the channel margins of subsequent Wisconsinan meltwater streams, were likely reworked into the younger Wisconsinan outwash as lateral fluvial cutting, and bank collapse took place. Such a phenomenon is commonplace in the formation of valley train deposits today in the Canadian Arctic (Church, 1972).

Lateral Variation in Composition

Extreme deviation from normal Wisconsinan gravel composition may occur locally in downstream portions of meander bends and along outwash margins at bedrock valley walls. Pebbles of coal, clay, and chert were found at these sites of fine-grained sedimentation (Fig. 16, section D). Otherwise, no systematic lateral variations in composition were observed in the study area. Because an absence of compositional variation may actually be a reflection of the limited size of the study area, an expanded reach of the Ohio River Valley was examined. In addition to data from the 10 sample sites in the study area (Fig. 1), pebble counts of Wisconsinan gravel from both published and unpublished sources were examined for four sites each in the Whitewater and Little Miami River basins and for six sites on the Ohio River as much as 150 miles downstream (Fig. 1, Table 9). Pebble-count data for all samples are listed in Appendix C.

Systematic variations in gravel composition are evident at this broader regional scale. Downstream, dolomite and limestone content drops by approximately one-third, while most other pebble lithologies increase (Table 9). The dramatic increase in chert below Louisville does not accurately depict outwash composition, because an undetermined portion of this chert represents an influx of preglacial, upland gravels washed into the Ohio River Valley from small side tributaries (Leverett, 1929; Straw, 1968). A smaller increase in outwash chert would otherwise be expected along this reach of the river. The compositional changes in outwash gravels along the Ohio River Valley resemble other Wisconsinan valley trains of the region (McCammon, 1961; Carr and Webb, 1970; Masters, 1983).

Table 9. Regional percentage variations in Wisconsinan gravel constituents. Sample locations are shown in Figure 1.

Constituent:	*Dol:Ls*	*Dol+ Ls*	*Sand-stone*	*Chert*	*Qz:Ign/Met*	*Qz+Ign/Met*	*Clay/ Shale*	*No. Sites*	*Data Sources*
Location									
Little Miami River	53:32	85	3	2		9	1	4	Doroshenko (1948)
Whitewater River	63:20	83	3	3	2:9	11	trace	4	McGregor (1960)
Ohio River									
Boone—Carroll Co.	49:23	72	4	7	5:12	17	trace	10	This study
Oldham—Jeff. Co.	54:12	66	4	10	6:16	22	trace	2	McGregor (1960)
Meade/Breck. Co.		48	8	26		15	3	4	Straw (1968)

Key variables in the process that control these downstream composition changes include (1) source-area composition, (2) proximity to the source area, (3) downriver decrease in meltwater volume and energy, and (4) differential transport survivability among pebble lithologies. Source-area composition largely reflects the regional geologic bedrock differences beneath the Wisconsinan ice sheet and varies from one meltwater basin to the next. How closely Wisconsinan outwash composition resembles its source material depends, in part, upon its proximity to the source area. Along meltwater tributaries and for some distance below their confluences with the Ohio River Valley, the large volumes of glacial outwash would tend to mask any nonglacial contributions from eroded bedrock valley walls and small side tributaries. With increasing distance from the melting ice front, however, the volume of outwash diminishes downstream, and contributions from nonglacial sediments or even different glacial basins become increasingly important. The introduction of preglacial chert gravels into outwash sediments below Louisville illustrates this point.

As outwash is transported from the ice margin, composition becomes slowly modified by fluvial meltwater processes that both sort and abrade constituent particles. Whether sorting or abrasion dominate in creating these compositional changes is difficult to determine. With diminishing flow volume and energy, gravel size tends to decrease downstream as smaller particles outrun larger ones. Because there is more chert and sandstone in the finer gravel sizes (Fig. 18), their increasing abundance downstream may correlate with the downstream decrease in grain size. However, according to differential hardness or abrasion resistance principles, sandstone pebble abundance should decrease rather than increase downstream (Sneed and Folk, 1958).

Increases in durable chert, quartz, and igneous and metamorphic pebbles along with decreases in soft limestone and dolomite pebbles are readily explained by the differential resistance to abrasion for these lithologies (Woolf, 1955). The weakly to moderately cemented sandstone and siltstone pebbles in this study have an abrasion resistance resembling that of carbonate pebbles (see **Roundness** below). Therefore, most sandstone pebbles issuing from the Whitewater–Great Miami drainageway would not likely have survived the long journey to Cloverport in Breckinridge County (Fig. 1). The unexpected doubling of sandstone and the abrupt appearance of shale pebbles in the region of Breckinridge County, therefore, must be attributed to local Upper Mississippian bedrock sources. These nonglacial shale and sandstone pebbles have been transported by small side tributaries to the Ohio River and mixed with the outwash.

Morphology Analysis

Shape and roundness, though commonly confused, are independent concepts used to characterize particle morphology. The principal methods for quantifying morphology include direct measurement of individual grains, indirect estimations by bulk sample analysis, mathematical modeling, and visual comparison with a reference standard. Analyses of particle morphology serve descriptive and predictive functions of significance to both industry and science. Particle shape in concretes, for example, controls aggregate packing and orientation, which, in turn, influence the pouring, workability, strength, and finishing characteristics of the product (Mather, 1955). Particle shape and roundness also help the sedimentologist predict hydrodynamic behavior of sediments and interpret environments of deposition. In this study, the axial dimensions of directly measured pebbles were utilized to determine sphericity and form, two aspects of shape. Roundness was semiquantitatively estimated with a visual comparator. Approximately 1,600 pebbles from Wisconsinan, Illinoian, and pre-Illinoian outwash were analyzed for shape and roundness.

Shape

Pebble shape variation. Sphericity and form values for about 1,600 pebbles were grouped according to stratigraphic age, particle size, and lithology and averaged. The pebble-shape means and standard deviations thus obtained were used in statistical t-tests at the 5 percent level of significance. Stratigraphic differences in average pebble shape for all lithologies are generally insignificant (Table 4). Differences in shape with respect to grain size are also statistically insignificant. Both sphericity and form, shown graphically in Figure 19, follow roughly parallel trends with respect to grain size, though sphericity appears to be slightly less variable. Sneed and Folk (1958) proposed that the relationship of grain size to sphericity may indicate distance traveled from a sediment's source area. Undifferentiated pebble sphericity with respect to grain size signifies a proximal source, whereas a highly differentiated size-sphericity relationship indicates a distal source. This relationship develops during downstream transport as pebbles are selectively sorted according to their shape. The lack of shape differentiation with respect to grain size for the Wisconsinan outwash of northern Kentucky confirms a nearby glacial source area.

Differences in pebble shape with respect to some rock types are significant (Fig. 19, Table 4). The differ-

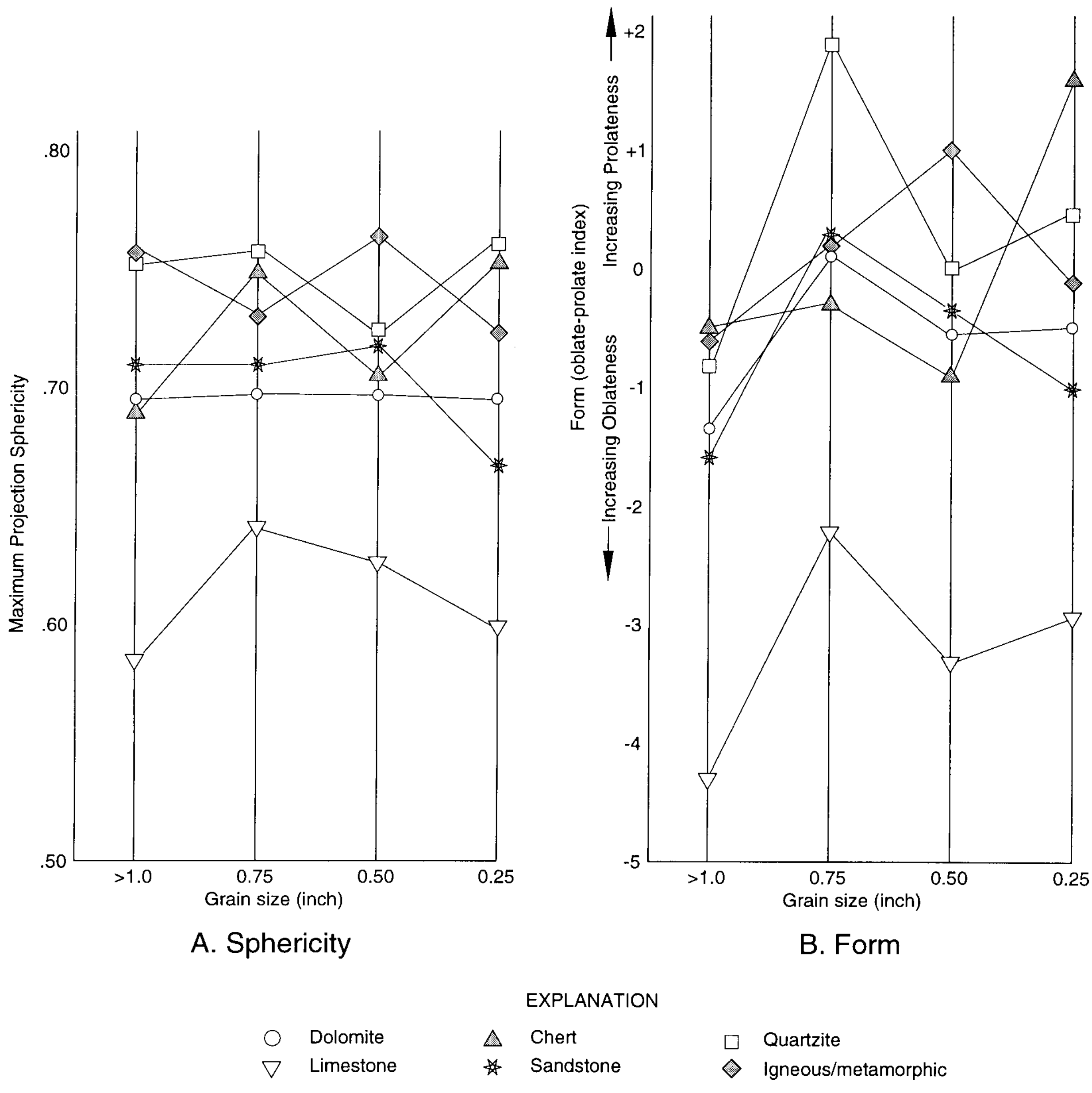

Figure 19. Pebble shape as a function of grain size for various Wisconsinan gravel lithologies.

ence between limestone and each of the other lithologies is distinct. Limestone pebbles are, on average, the least spherical and most platy of all lithologies. Quartz, chert, igneous, and metamorphic pebbles are the most spherical. Dolomite and sandstone sphericity is intermediate. Pebble lithology can thus be differentiated and ranked on the basis of average sphericity, from highest to lowest, as follows: quartz + chert + igneous/ metamorphic; dolomite + sandstone; and limestone. Pebble form, except for limestone versus each of the other lithologies, could not be used to discriminate between the various lithologies.

This ranking in pebble lithology with respect to sphericity appears to correlate with source-rock homogeneity differences and degree of durability. High-sphericity igneous and metamorphic rocks, quartz, and chert tend to be texturally homogeneous rock types composed of tightly interlocking, uniformly sized mineral grains. These rock types are also the toughest and most resistant to impact and abrasion (Woolf, 1955). Pebbles of intermediate and low average sphericity, on the other hand, correspond to bedded sedimentary rocks whose internal fabric decreases in uniformity from blocky-bedded dolomite to thin, flaggy-bedded limestone. These rocks are much less durable than the high-sphericity types.

Wisconsinan pebble shapes were classified by plotting their axial ratios on sphericity-form diagrams (Fig. 8). A percentage breakdown by form class for each pebble lithology is summarized in Table 10. About 45 percent of all pebbles fall into the compact bladed and bladed class. Subequal amounts of compact platy plus platy and compact elongated plus elongated each constitute about 20 percent. Pebble shapes in the compact, very platy, very bladed, and very elongated classes total about 15 percent. The average Wisconsinan outwash pebble, after adjusting for composition and grain-size distribution, is classified as compact bladed to bladed, with a sphericity of 0.69 and an O–P index of –1.0. The tendency for pebble shapes to concentrate in the bladed class appears to be a phenomenon of geologic processes (Sneed and Folk, 1958).

Particle shape tests have been used for years by the U.S. Army Corps of Engineers to evaluate aggregates for concrete in Federal construction projects. Excessive amounts of undesirable flat and elongated shapes, which exceed a specified 3:1 axial ratio, are cause for rejecting an aggregate (Mather, 1955). Unpublished petrographic tests, conducted on 22 northern Kentucky outwash gravels by the U.S. Army Corps of Engineers, show that undesirable elongates plus flats range from 3 to 10 percent and average about 6 percent in the study area. This average corresponds to the value found in this study for the combined totals of very platy, very bladed, and very elongated classes (Fig. 8, Table 10). Because the Corps' 3:1 undesirable cutoff ratio matches the horizontal 0.3 line of the shape triangles (Fig. 8), any particle that plots in the very platy, very bladed, and very elongated categories is classified as undesirable. Utilization of sphericity-form diagrams, therefore, has practical value.

Limestone and sandstone pebbles are the two largest contributors to the undesirable shape classes (Table 10). The low content (6 percent) of undesirable particles in Wisconsinan outwash reflects the relatively low proportions of limestone and sandstone in these sediments. However, for Illinoian and pre-Illinoian outwash, where limestone and sandstone concentrations are much greater, the percentage of undesirables is two to three times greater than for Wisconsinan outwash.

Roundness

Roundness is a measure of the sharpness or angularity of corners and edges relative to the average curvature of the particle as a whole. For practical applications, particle roundness has been shown to affect the workabilty and material requirements of concrete (Mather, 1955). A decrease in average roundness (or increased angularity) affects the percentage of voids in the aggregate which, in turn, influences concrete workability. The greater the overall particle roundness, for a given concrete, the less water and fewer sacks of cement per cubic yard of concrete are needed, thereby enhancing concrete strength and economizing simultaneously. Roundness also provides information on abrasion resistance for aggregate materials in a pavement and particles undergoing sedimentary transport.

Pebble Surface Analysis and Soundness

Particle surface characteristics and soundness are important factors that affect the suitability of aggregate. A large number of unsound particles in a concrete mixture, for instance, causes poor bonding when cement will not adhere to particles (called "pop-outs"), and excessive water requirements, thereby seriously impairing the concrete's stability (Mather, 1955). The weathering and soundness of gravel-size aggregate particles in this study was assessed by microscopic examination of pebble surfaces.

Table 10. Percentage of Wisconsinan gravel lithologies in each of the 10 form classes.

Lithology:	*Dolomite*	*Limestone*	*Chert*	*Sandstone*	*Quartz*	*Igneous/ Metamorphic*
Form Class:						
Compact	9	3	6	8	10	13
Compact platy	11	7	13	10	12	11
Compact bladed	19	18	23	24	39	27
Compact elongated	14	8	21	9	15	17
Platy	11	19	9	11	4	6
Bladed	25	22	19	23	16	18
Elongated	6	5	7	6	3	5
Very platy	2	8	1	4	0	1
Very bladed	3	8	1	4	0	2
Very elongated	< 0.5	2	0	1	1	0

Pebble surface weathering and soundness were divided into three arbitrary grades of good, fair, and poor, following qualitative descriptive criteria used by petrographers of the U.S. Army Corps of Engineers. Precise distinctions between these grades are subjective and, thus, may vary somewhat from one petrographer to the next. The good grade includes unweathered to slightly weathered particles with tough, dense, nonfriable surfaces. Pebbles judged as fair are moderately weathered with slightly porous, pitted, or friable surfaces. Badly weathered pebbles with soft, highly absorbent, porous, pitted, friable, or chalky surfaces are considered poor. Deleterious lithologies such as coal, shale, clay, and chert are also classified as poor. Visual appearance, feel, and resistance to scratching with a steel probe or fingernail were simple tests used in this study to judge soundness and degree of weathering.

Soundness grade distribution in Wisconsinan gravels averages 81 percent good, 6 percent fair, and 13 percent poor, according to unpublished analyses conducted in the study area by U.S. Army Corps of Engineers petrographers. This study found that for the Illinoian and pre-Illinoian samples examined for surface alteration, using the Wisconsinan averages as the basis for comparison, the percentage of good particles decreased by half and the percentage of fair particles incrased by two and a half times for each successively older stratigraphic unit. The percentage of poor particles in both older outwash units more than tripled the value for Wisconsinan outwash. The degree of gravel soundness clearly deteriorates with geologic time.

The effects of weathering and degree of soundness vary with pebble composition. Lithologies most susceptible to weathering are carbonate rocks and sandstone (Table 11). The carbonate cements and constituents in these rocks slowly react with weakly acidic atmospheric precipitation and dissolve, leaving only insoluble residues, which become part of the soil. Quartz, the most weather-resistant mineral, shows virtually no change with age. Igneous and metamorphic rocks, though generally quite resistant in Wisconsinan outwash, undergo progressive breakdown over an extended period and often crumble easily in samples of pre-Illinoian outwash. The decreasing percentages of high-quality outwash gravels parallel the weathering effects observed in glacial tills of the region (Gooding, 1963, 1966, 1973; Leighton and Ray, 1965; Teller, 1970, 1972). These studies demonstrate progressive leaching and destruction of carbonate fragments and gradual breakdown of igneous and metamorphic rocks with time. Extreme degrees of leaching, in which the carbonate rocks have been completely eliminated, are often described for pre-Illinoian drift in northern Kentucky (Ray, 1957; Schaber, 1962; Swadley, 1979).

Table 11. Percentages of good, fair, and poor grades of soundness in gravel rocks of Wisconsinan, Illinoian, and pre-Illinoian age.

Rock Type	*Grade*	*Stratigraphic Age*		
		Wisconsinan	*Illinoian*	*Pre-Illinoian*
Limestone + dolomite	Good	84	37	0
	Fair	7	52	66
	Poor	9	11	34
Sandstone	Good	67	39	29
	Fair	33	31	40
	Poor	0	30	31
Quartz	Good	100	95	100
	Fair	0	0	0
	Poor	0	5	0
Igneous + Metamorphic	Good	91	76	53
	Fair	9	17	41
	Poor	trace	7	6

The greatest weathering effects in Wisconsinan outwash were observed in the upper few feet of deposits. There, percolating meteoric waters are slowly leaching carbonate ions from particles of limestone, dolomite, calcareous sandstone, and siltstone. This leaching causes a gritty to powdery insoluble residue of variable thickness to form on the surfaces of these aggregates. Because these leached fragments generate excessive amounts of fine material and have poor bonding surfaces, their use in concrete is considered deterimental and therefore is prohibited by State and Federal regulations.

Rocks composed of microcrystalline silica (SiO_2) include chert, flint, chalcedony, and silicified limestone and dolomite. Surfaces of these siliceous rocks (referred to as chert throughout this report) vary from dense, hard, and tough to pitted, highly fractured, and broken. The most extremely weathered chert particles have porous to chalky surfaces. Although tough, dense, hard particles are normally classified as good aggregate, the most durable, unweathered chert is often condemned as poor because of its potential for reaction with cement alkalis and its high thermal expansion coefficient, which causes the formation of popouts in concrete. In some areas, however, chert may be permitted for use in concrete if its specific gravity exceeds a stipulated value.

APPENDIX B:

SUMMARY OF MECHANICAL ANALYSES OF SAMPLES FROM BOONE, GALLATIN, AND CARROLL COUNTIES, KENTUCKY

Appendix B. Summary of mechanical analyses of samples from Boone, Gallatin, and Carroll Counties, Kentucky. Samples are Wisconsinan in age unless indicated by I (Illinoian) or PI (Pre-Illinoian).

U.S. Standard Sieve Mesh Opening (in weight percent)			*Sample Numbers*							
mm	*Φ*	*inch/mesh #*	*141140*	*141075*	*141096*	*141097*	*141095*	*141081*	*141011*	*141013*
76	-6.25	3.0	0	0	0	0	0	0	7.1	0
64	-6.00	2.5	0	0	0	0	0	0	7.1	1.3
51	-5.65	2.0	0	0	0	0	0	1.9	12.6	5.6
38	-5.25	1.5	0	0	0	0.6	0	1.3	7.8	8.2
25	-4.65	1.0	0	3.1	0.8	3.4	0	3.5	11.7	11.2
19	-4.25	0.75	0	2.8	1.8	4.4	0	2.1	8.4	8.5
13	-3.65	0.50	0.6	6.1	3.2	6	0	2.9	7.6	13.5
10	-3.25	0.38	0.6	5.4	2.6	4.7	0	1.4	3.3	7
4.8	-2.25	#4	1.8	15.6	8.5	9.9	0	6	6.2	11.1
2.38	-1.25	#8	2.9	17.7	7	4.8	0.4	8.3	5.5	7.8
1.68	-0.75	#12	1.5	8.4	5.2	1.7	0.1	5	2	2.9
1.19	-0.25	#16	2.7	8.2	7.9	2	0.2	5.3	2.1	2.8
0.59	0.75	#30	14.4	15.1	19.7	6.5	2.2	12.7	4.9	8.2
0.42	1.25	#40	17.5	6.6	12	8.2	9.3	9.5	2.8	6.1
0.3	1.75	#50	35.4	5.3	14.4	18.6	15.5	14.4	4.3	2.8
0.149	2.75	#100	16.9	4	10.6	19.6	29.6	15.6	5.3	1.6
0.074	3.75	#200	2.4	0.9	1.7	4.7	16.9	3.8	0.6	0.5
		Pan	3.2	0.8	4.5	4.9	25.8	6.2	0.7	0.8
		Total Wt. %	99.9	100	99.9	100	100	99.9	100	99.9
Location or Company			Taylorsport Sand Co.				North Bend Bottom	Petersburg Abn. Pit	Northern Kentucky Aggregates	

Appendix B. Summary of mechanical analyses of samples from Boone, Gallatin, and Carroll Counties, Kentucky. Samples are Wisconsinan in age unless indicated by I (Illinoian) or PI (Pre-Illinoian).

U.S. Standard Sieve Mesh Opening (in weight percent)			*Sample Numbers*							
mm	*Φ*	*inch/mesh #*	*141015*	*141016*	*141017*	*141083*	*141084*	*141076*	*141077*	*141130*
76	-6.25	3.0	0	7	4.3	0	0	0	0	0
64	-6.00	2.5	0	3.9	3.7	0	1.8	0	0	0
51	-5.65	2.0	0	3.5	4.5	0.8	2.5	6	5.5	4.1
38	-5.25	1.5	6.6	3.8	6.4	2.4	5.5	9.2	9.2	5.4
25	-4.65	1.0	6.3	6.9	6.8	4.8	5.3	18.2	7.3	6.7
19	-4.25	0.75	6.6	4.7	4.8	4.7	2.8	8.6	5.4	6.1
13	-3.65	0.50	9.7	7.6	6.8	7.9	3.8	10	8.3	8.6
10	-3.25	0.38	7.5	4.6	4.5	5.1	3.2	6.1	6.7	7.9
4.8	-2.25	#4	18.1	10.7	9.9	13	8.3	7.9	16.7	19.2
2.38	-1.25	#8	13.2	8.6	8.1	10.7	6.1	6.4	10.2	13
1.68	-0.75	#12	4.2	2.7	3	4.4	2.5	2.4	3.3	4.9
1.19	-0.25	#16	3.5	2.6	2.9	4.4	2.6	2.3	2.9	4.6
0.59	0.75	#30	4.6	7.4	8.2	11.7	7.5	5.5	5.9	7.6
0.42	1.25	#40	2.4	6.7	7.2	12.2	6.9	5.2	4.1	4.8
0.3	1.75	#50	2.5	7.8	8.6	12.3	7.1	5.7	5.7	3.1
0.149	2.75	#100	2.5	8.1	7.7	5.3	17.3	3.6	5.4	2.4
0.074	3.75	#200	1.6	2.2	1.5	0.3	13.2	0.8	1.7	0.6
		Pan	10.7	1.3	1.2	0.1	3.8	2	1.8	1.3
		Total Wt. %	100	100.1	100.1	100.1	100.2	99.9	100.1	100.3
Location or Company			Northern Kentucky Aggregates			Belleview Sand and Gravel Co.		Boone County Sand & Gravel Co.		Steele Bottom, Gallatin Co., Barrow Pit

Appendix B. Summary of mechanical analyses of samples from Boone, Gallatin, and Carroll Counties, Kentucky. Samples are Wisconsinan in age unless indicated by I (Illinoian) or PI (Pre-Illinoian).

U.S. Standard Sieve Mesh Opening (in weight percent)			*Sample Numbers*							
mm	Φ	*inch/mesh #*	*141131*	*141132*	*141133*	*141134*	*141135*	*141136*	*141137*	*141138*
76	-6.25	3.0	0	0	0	0	0	0	0	0
64	-6.00	2.5	0	0	0	0	0	0	0	0
51	-5.65	2.0	0	0	0	0	0	4	0	0
38	-5.25	1.5	6.2	1.5	0.7	0	0	0	0	0
25	-4.65	1.0	14.5	14.6	2.3	5.6	3.8	2.3	3.3	9.5
19	-4.25	0.75	10.3	8.8	4.9	5.8	8	3.3	3.4	7.7
13	-3.65	0.50	13.1	11.6	11.4	10.2	11.1	6.8	8.5	14.7
10	-3.25	0.38	6.8	5.5	8.6	7.9	7.9	7.9	9.7	9.7
4.8	-2.25	#4	11	13.4	22.5	17.7	23.5	30.8	27.3	21.5
2.38	-1.25	#8	7.6	10.4	19	14.6	17.3	26.3	25.4	14.2
1.68	-0.75	#12	3.9	4.3	5.3	5.5	4.5	6.1	7.1	4.2
1.19	-0.25	#16	3.6	4.2	3	3.5	3.2	2.8	3.5	1.9
0.59	0.75	#30	6.3	6	4	3.7	4.2	2.5	2.1	1.3
0.42	1.25	#40	5.6	6.8	6.2	3.7	3.9	1.8	1.5	1.1
0.3	1.75	#50	5.1	7.6	8.3	5.6	4.1	1.4	1.6	2.3
0.149	2.75	#100	3.9	3.7	2.6	6.3	4.4	1.7	3.5	6.7
0.074	3.75	#200	0.9	0.8	0.5	3.1	1.5	0.7	1.4	2.4
		Pan	1.2	0.8	0.7	6.8	2.5	1.6	1.8	3
		Total Wt. %	100	100	100	100	99.9	100	100.1	100.2
Location or Company			Steele Bottom, Gallatin County, Barrow Pit							

U.S. Standard Sieve Mesh Opening (in weight percent)			Sample Numbers							
mm	Φ	*inch/mesh #*	*141139*	*141098*	*141099*	*141100*	*141046*	*I 141050*	*I 141052*	*I 141053*
76	-6.25	3.0	0	0	0	0	0	0	0	0
64	-6.00	2.5	0	0	0	0	0	0	0	0
51	-5.65	2.0	0	0	3.7	0	0	0	0	0
38	-5.25	1.5	0	0	4.4	2.8	0	0	0	1.7
25	-4.65	1.0	2.9	0.7	3.3	0.7	0.7	0	1.6	1.8
19	-4.25	0.75	4.1	4	2	2.8	1.5	0	2.9	3.2
13	-3.65	0.50	11.3	5.3	3.5	4.7	4.7	2.2	5.5	5.4
10	-3.25	0.38	11	4.5	3	3.8	4	1.4	3.4	3.2
4.8	-2.25	#4	28.2	11.3	7.3	9	12.1	4.2	8.5	5.3
2.38	-1.25	#8	17.6	10.9	5.7	7.7	14.3	5.9	8.7	4.4
1.68	-0.75	#12	5	4.3	3.6	4.7	9	2.2	3.8	2.1
1.19	-0.25	#16	2.9	3.1	3	3.4	7.8	2.5	4.4	2.9
0.59	0.75	#30	2.6	3.5	4.1	3.2	9.9	11.6	11.4	17.9
0.42	1.25	#40	2.2	4.6	3.9	4.8	10.2	20.5	13.7	19.7
0.3	1.75	#50	2.8	10.7	10.4	14.8	11	22.5	18.7	18.4
0.149	2.75	#100	4.7	19.3	20.1	23.4	9.8	19.4	13.9	9.1
0.074	3.75	#200	1.9	8.4	11	5.5	2.6	4.5	2.6	2.8
		Pan	2.9	9.4	11.1	8.7	2.6	2.8	0.8	2
		Total Wt. %	100.1	100	100.1	100	100.2	99.7	99.9	99.9
Location or Company			Steele Bottom, Gallatin County, Barrow Pit	Steele Bottom, Gallatin County, Steen Farm			Steele Bottom, Dravo #28 Borehole			
							42-50'	100-104'	107-115'	116-120'

U.S. Standard Sieve Mesh Opening (in weight percent)			*Sample Numbers*							
mm	Φ	*inch/mesh #*	*/ 141055*	*/ 141056*	*141042*	*141085*	*141086*	*141087*	*141088*	*141089*
76	-6.25	3.0	0	0	0	0	0	0	0	0
64	-6.00	2.5	0	0	0	0	0	0	0	0
51	-5.65	2.0	0	0.8	0	0	0.7	0	2.4	0
38	-5.25	1.5	6.2	0.5	0.9	0	0	0	0	0
25	-4.65	1.0	6.7	0.6	1.5	0	1.3	0	0	0.7
19	-4.25	0.75	4.3	0.6	1.2	0.2	0.2	0.9	0.6	0.2
13	-3.65	0.50	6.2	1.5	5.1	1.3	2.4	1.5	1.4	1
10	-3.25	0.38	4.3	1.4	5	1.5	3.1	1.8	1.7	1.2
4.8	-2.25	#4	7.7	7	14.9	9.6	12.1	8.6	6.8	4.2
2.38	-1.25	#8	4.8	10.1	12.7	15.2	16.2	12.5	11.3	5.8
1.68	-0.75	#12	1	5.5	4.8	14	10.6	8.6	7.7	5
1.19	-0.25	#16	0.8	6.8	4.3	14.8	9.6	8.1	5.6	3.9
0.59	0.75	#30	2.4	20.2	7.8	13.9	9.8	7.7	4.8	3.6
0.42	1.25	#40	3.1	17.4	8.6	7	7.8	6.9	4.8	3.9
0.3	1.75	#50	9.5	16.9	13.9	8.2	11	15.3	12.7	11.6
0.149	2.75	#100	34	7.7	13.9	7.7	9.3	16.5	18	23.1
0.074	3.75	#200	7.7	2	3.5	4.9	4.3	8	10.6	16.1
		Pan	1.2	1	2.1	1.8	1.7	3.6	11.6	19.6
		Total Wt. %	99.9	100	100.2	100.1	100.1	100	100	99.9
Location or Company			Steele Bottom, Dravo #28 Borehole		Dravo #29 Borehole	Steele Bottom, Gallatin County Paint Lick Creek				
			129-130'	132-143'	0-55'					

U.S. Standard Sieve Mesh Opening (in weight percent)			*Sample Numbers*							
mm	Φ	*inch/mesh #*	*141090*	*141091*	*141093*	*141094*	*141078*	*141079*	*141080*	*141027*
76	-6.25	3.0	0	0	0	0	0	0	0	1
64	-6.00	2.5	0	0	0	0	2.1	0	0	0
51	-5.65	2.0	0	0	0	0	0	0	0	3.6
38	-5.25	1.5	0	0	0	0	8.4	3.3	4.3	1.6
25	-4.65	1.0	0.7	0	0	0	12.2	3.1	13.6	6.1
19	-4.25	0.75	0.3	0	0.7	0.2	8.6	2.1	6.9	3.7
13	-3.65	0.50	0.9	0	1.7	0.8	10.6	5.8	8.8	4.8
10	-3.25	0.38	0.6	0.2	3.7	1.9	8.5	5.4	7.3	3.2
4.8	-2.25	#4	4.7	1.7	10.3	10.8	20.4	12	12.2	8
2.38	-1.25	#8	9	5.3	17.9	22.4	10.9	8	11.4	7.4
1.68	-0.75	#12	5.9	3.3	13.8	10.5	2.9	3.1	3.1	3
1.19	-0.25	#16	4.9	2.8	8.8	6.5	1.7	2.4	2.6	2.8
0.59	0.75	#30	5.1	3	7.1	5.8	2.8	6.7	5.9	9.2
0.42	1.25	#40	5.9	2.8	6.5	6.7	2.5	9.3	7.8	14.4
0.3	1.75	#50	15.7	9.6	10.6	13.2	2.5	12.3	7.8	19.1
0.149	2.75	#100	26.1	35.9	12.5	16.2	2.3	11	4.5	10.8
0.074	3.75	#200	8.7	16	4.1	3.6	1.2	5.4	1.3	1.1
		Pan	11.5	19.5	2.4	1.3	2.5	10.2	2.7	0.4
		Total Wt. %	100	100.1	100.1	99.9	100.1	100.1	100.2	100.2
Location or Company			Steele Bottom, Gallatin County Paint Lick Creek				Ghent Abn. Pit	Carrollton Abn. Pit		Martin-Marietta Basic Materials (Milton) Abn. West Pit

U.S. Standard Sieve Mesh Opening (in weight percent)			*Sample Numbers*							
mm	*Φ*	*inch/mesh #*	*141029*	*141034*	*141035*	*141002*	*141003*	*141004*	*141005*	*141006*
76	-6.25	3.0	0	0	0	0	0	0	0	0
64	-6.00	2.5	0	0	0	0	0	0	0	0
51	-5.65	2.0	0	0	3.8	1.2	2.5	0	1.0	0
38	-5.25	1.5	0	1.4	2.6	2.5	2	0	1.9	0.9
25	-4.65	1.0	0	5.4	8.3	4	4.1	0.4	7.8	7.7
19	-4.25	0.75	0	6.6	6.4	3.8	4.9	0	6.7	5.6
13	-3.65	0.50	0	13.6	11.7	6.7	8.9	0.7	9.4	7.8
10	-3.25	0.38	0.1	7.1	8.3	5.3	7.4	0.6	6.3	5.2
4.8	-2.25	#4	1.2	14	17.3	16.1	18.1	1.9	19.5	10.9
2.38	-1.25	#8	1.3	11	13.8	15.5	16.3	3.4	17	8.8
1.68	-0.75	#12	0.4	3.4	4.6	4.8	5.4	2.1	4.8	3.1
1.19	-0.25	#16	0.4	3.5	4.1	5.4	5.4	3	3.8	3.2
0.59	0.75	#30	1.2	10.1	6.9	15.7	12.9	10	7.6	9.6
0.42	1.25	#40	2.4	9.3	4.2	9.3	6.1	24	5	9.6
0.3	1.75	#50	3.6	8.9	3.6	5.9	3.1	22.4	3.6	11.7
0.149	2.75	#100	22.3	4.9	3.1	3.2	2.5	29.1	3.6	14.2
0.074	3.75	#200	30.1	0.5	0.4	0.4	0.4	1.5	1.1	1.2
		Pan	37.2	0.3	0.9	0.2	0.2	1.1	1	0.6
		Total Wt. %	100.2	100	100	100	100.2	100.2	100.1	100.1
Location or Company			Martin-Marietta Basic Materials (Milton) Abandoned West Pit			Milton Sand and Gravel Co.				

U.S. Standard Sieve Mesh Opening (in weight percent)			Sample Numbers							
mm	Φ	*inch/mesh #*	*141008*	*I 141127*	*PI 141141*	*PI AK1-9*	*PI AK1-10*	*PI AK1-11*	*PI AK1-13*	*PI AK1-15*
76	-6.25	3.0	0	0	0	0	0	0	0	0
64	-6.00	2.5	0	2.7	0	0	0	0	0	0
51	-5.65	2.0	3.3	11.7	4.8	0	0	0	0	0
38	-5.25	1.5	4	10.3	0	0	0	0	0	0
25	-4.65	1.0	8.1	10.6	1.9	2.2	21.2	3.6	8	9.7
19	-4.25	0.75	5	3.2	2.3	15.8	2.9	9.6	0.9	3.7
13	-3.65	0.50	5.9	6.5	1.4	16	8.8	14.1	3.1	1.6
10	-3.25	0.38	3.6	3.6	2.5	12.3	4.1	10.4	3	4.1
4.8	-2.25	#4	9.2	7	9.2	24.3	12.5	24.2	7.6	12.9
2.38	-1.25	#8	11.1	5.4	9.4	10.4	10.1	9.5	12.9	12.2
1.68	-0.75	#12	4	2.4	5.4	3	4.7	4.1	7.6	5.4
1.19	-0.25	#16	4.5	2.6	6.2	2.3	5.3	4.5	10.4	7.1
0.59	0.75	#30	11.6	6	12.3	3.7	9.2	7.3	18.3	14.1
0.42	1.25	#40	11.1	5.3	5.2	1.4	4.3	4.1	6.9	6.8
0.3	1.75	#50	11.3	8.6	6.1	0.6	3.2	0.9	3.1	4
0.149	2.75	#100	6.4	9.8	22	0.7	2.3	1.1	4.3	4.6
0.074	3.75	#200	0.6	1.4	5.7	0.7	2.6	1.1	2.2	2.5
		Pan	0.2	2.8	5.7	6.6	8.8	5.5	11.8	11.3
		Total Wt. %	99.9	99.9	100.1	100	100	100	100.1	100
Location or Company			Milton Sand and Gravel Co.	Steep Creek Boone Co.	Commissary Corner, Boone County Berry Farm					

U.S. Standard Sieve Mesh Opening (in weight percent)			Sample Numbers							
mm	Φ	*inch/mesh #*	*PI AK1-17*	*PI AK2-4*	*PI AK2-8*	*PI AK2-9*	*PI AK2-10*	*PI AK2-13*	*PI AK3-10*	*PI AK3-11*
76	-6.25	3.0	0	0	0	0	0	0	0	0
64	-6.00	2.5	0	0	0	0	0	0	0	0
51	-5.65	2.0	0	0	0	0	0	0	0	0
38	-5.25	1.5	0	0	14.5	15	0	0	0	0
25	-4.65	1.0	7.1	11.9	15.1	2.9	10	0	16.7	0
19	-4.25	0.75	2.9	13.5	2.7	4.6	3.1	0	3.3	7.9
13	-3.65	0.50	5	7.7	2.9	15.9	6.7	0	7.1	6.3
10	-3.25	0.38	2.4	3.6	3.1	4.6	2.9	0	1.7	7
4.8	-2.25	#4	10.3	7.9	12.9	13.4	6.8	2	8.9	15.5
2.38	-1.25	#8	13.2	5.8	8.8	9.7	7.3	3.4	8.6	14.8
1.68	-0.75	#12	6.3	4	4.3	3.9	4	1.3	4.7	5.8
1.19	-0.25	#16	9.3	4.8	4.7	4.3	4.6	0.8	5	4.6
0.59	0.75	#30	14.4	12	8.1	7.3	10.5	1.9	9.4	7.7
0.42	1.25	#40	7	6.9	4.2	2.9	6.1	1.6	4.4	3.7
0.3	1.75	#50	5.8	4.2	2.9	2.5	5.7	11.7	3.3	2.9
0.149	2.75	#100	4.1	4.4	3.7	4.3	8.4	40	4	5.5
0.074	3.75	#200	3.4	1.6	2.1	1.6	2.3	19.8	4.4	1.4
		Pan	8.8	11.7	10	7.1	21.6	17.5	18.5	16.9
		Total Wt. %	100	100	100	100	100	100	100	100
Location or Company			Commissary Corner, Boone County, Berry Farm							

Sample No.:		141140	141075	141096	141097	141095	141081	141011	141013	141015
% Gravel	(> 4 mesh)	3	33	17	29	0	19	72	66	55
% Sand	(4-200 mesh)	94	66	78	66	74	75	27	33	34
% Silt/Clay	(< 200 mesh)	3	1	5	5	26	6	1	1	11
% > 1" Gravel/Total Gravel		0	9	5	14	0	35	65	39	23
Mean Grain Size	(Φ)	1.18	-1.22	0.13	0.02	2.73	0.12	-3.44	-2.83	-1.67
	(inch)	0.017	0.092	0.036	0.039	0.006	0.036	0.429	0.281	0.125
Modal Gravel Size	(Φ)	-2	-2.25	-2.25	-3.25		-4.65	-5.25	-4.65	-3.65
	(inch)	0.157	0.187	0.187	0.375		0.988	1.498	0.988	0.494
Modal Sand Size	(Φ)	1.50	1.00	1.50	1.75	2.00	1.75	1.75	1.25	1.50
	(inch)	0.014	0.02	0.014	0.012	0.01	0.012	0.012	0.017	0.014
Stnadard Deviation	(Φ)	1.33	1.98	2.10	2.69	1.41	2.57	2.78	2.41	3.08
Skewness		-0.33	0.10	-0.09	-0.19	0.12	-0.23	0.48	0.38	0.54
Kurtosis		3.46	-0.39	0.04	-0.98	-0.62	-0.23	-0.30	-0.32	0.46
Fineness Modulus						0.89				
Location or Company		Taylorsport Sand Co.				North Bend Bottom	Petersburg Abn. Pit	Northern Kentucky Aggregates		

Sample No.:		141016	141017	141083	141084	141076	141077	141130	141131	141132
% Gravel	(> 4 mesh)	53	52	39	33	66	59	58	62	55
% Sand	(4-200 mesh)	46	47	61	63	32	39	41	37	44
% Silt/Clay	(< 200 mesh)	1	1	1	0	4	2	2	1	1
% > 1" Gravel/Total Gravel		47	49	20	46	51	37	28	33	29
Mean Grain Size	(Φ)	-2.08	-2.05	-1.23	-0.38	-2.75	-2.24	-2.29	-2.41	-2.08
	(inch)	0.166	0.163	0.092	0.051	0.265	0.186	0.192	0.209	0.167
Modal Gravel Size	(Φ)	-5.65	-5	-3.65	-5.25	-4.65	-5.25	-3.65	-4.65	-4.65
	(inch)	1.977	1.26	0.494	1.498	0.988	1.498	0.494	0.988	0.375
Modal Sand Size	(Φ)	1.50	1.50	1.50	2.50	1.50	1.75	1.00	1.50	1.50
	(inch)	0.014	0.014	0.014	0.007	0.014	0.012	0.02	0.014	0.014
Stnadard Deviation	(Φ)	2.99	2.96	2.31	3.15	2.70	2.65	2.28	2.48	2.40
Skewness		0.11	0.10	-0.09	-0.17	0.44	0.30	0.29	0.37	0.26
Kurtosis		-1.15	-1.20	-1.24	-1.21	-0.33	-0.51	-0.01	0.46	-0.79
Fineness Modulus										
Location or Company		Northern Kentucky Aggregates		Belleview Sand and Gravel Co.		Boone County Sand & Gravel Co.		Steele Bottom, Gallatin County Barrow Pit		

Sample No.:		141133	141134	141135	141136	141137	141138	141139	141098	141099
% Gravel	(> 4 mesh)	50	47	54	55	52	63	57	26	27
% Sand	(4-200 mesh)	49	46	43	43	46	34	40	65	62
% Silt/Clay	(< 200 mesh)	1	7	3	2	2	3	3	9	11
% > 1" Gravel/Total Gravel		5	12	7	11	6	15	5	3	42
Mean Grain Size	(Φ)	-1.79	-1.30	-1.85	-2.19	-1.97	-2.16	-1.89	0.24	0.25
	(inch)	0.136	0.097	0.142	0.18	0.155	0.176	0.146	0.033	0.033
Modal Gravel Size	(Φ)	-3.25	-3.25	-3.65	-2.65	-3	-3.25	-3.25	-3.25	-5.25
	(inch)	0.375	0.375	0.494	0.247	0.315	0.375	0.375	0.375	1.498
Modal Sand Size	(Φ)	1.50	1.75	1.50	1.25	2.25	2.00	1.75	1.75	2.25
	(inch)	0.014	0.012	0.014	0.017	0.008	0.01	0.012	0.012	0.008
Stnadard Deviation	(Φ)	2.02	2.72	2.24	1.83	1.88	2.41	2.17	2.76	3.20
Skewness		0.34	0.38	0.51	0.55	0.68	0.61	0.66	-0.04	-0.22
Kurtosis		-0.17	-0.36	0.62	3.01	2.42	0.83	1.37	-1.15	-0.98
Fineness Modulus										
Location or Company		Steele Bottom, Gallatin County Barrow Pit							Steele Bottom, Gallatin County, Steen Farm	

Sample No.:		141100	141046	/ 141050	/ 141052	/ 141053	/ 141055	/ 141056	141042	141085
% Gravel	(> 4 mesh)	24	23	8	22	21	35	12	29	13
% Sand	(4-200 mesh)	67	75	89	77	77	64	87	69	85
% Silt/Clay	(< 200 mesh)	9	2	3	1	2	1	1	2	2
% > 1" Gravel/Total Gravel		15	3	0	7	17	36	15	8	0
Mean Grain Size	(Φ)	0.32	-0.41	0.88	-0.11	0.02	-0.32	0.09	-0.42	-0.20
	(inch)	0.031	0.052	0.021	0.043	0.039	0.049	0.037	0.053	0.045
Modal Gravel Size	(Φ)	-3.65	-2	-2	-3.25	-3.25	-4.65	-2	-2.25	-0.5
	(inch)	0.494	0.157	0.157	0.375	0.375	0.988	0.157	0.187	0.056
Modal Sand Size	(Φ)	2.00	1.50	1.50	2.25	1.50	2.50	1.25	1.75	1.75
	(inch)	0.01	0.014	0.014	0.008	0.014	0.007	0.017	0.012	0.012
Stnadard Deviation	(Φ)	2.75	2.16	1.76	2.20	2.28	3.09	1.83	2.36	1.77
Skewness		-0.17	0.06	-0.44	-0.29	-0.39	-0.21	-0.37	-0.03	0.20
Kurtosis		-0.82	-0.56	1.14	-0.74	-0.14	-1.45	0.69	-0.98	-0.13
Fineness Modulus										
Location or Company		Steele Bottom, Gallatin County, Steen Farm	Steele Bottom, Dravo #28 Borehole						Dravo #29 Borehole	Steele Bottom, Gallatin County, Paint Lick Creek
			42-50'	100-104'	107-115'	116-120'	129-130'	132-143'	0-55'	

Sample No.:		141086	141087	141088	141089	141090	141091	141093	141094	141078
% Gravel	(> 4 mesh)	20	13	13	7	7	2	17	14	71
% Sand	(4-200 mesh)	78	83	75	73	81	79	81	85	27
% Silt/Clay	(< 200 mesh)	2	4	12	20	12	19	2	1	2
% > 1" Gravel/Total Gravel		11	0	18	10	10	0	0	0	32
Mean Grain Size	(Φ)	-0.38	0.37	0.77	1.78	1.23	2.21	-0.21	-0.11	-2.76
	(inch)	0.051	0.03	0.023	0.011	0.017	0.008	0.046	0.043	0.267
Modal Gravel Size	(Φ)	-0.75	-1	-1.25	-0.75	-0.75	-0.75	-0.75	-0.75	-4.25
	(inch)	0.066	0.079	0.094	0.066	0.066	0.066	0.066	0.066	0.749
Modal Sand Size	(Φ)	1.75	1.75	1.75	2.25	2.25	2.50	1.75	1.75	1.50
	(inch)	0.012	0.012	0.012	0.008	0.008	0.007	0.012	0.012	0.014
Stnadard Deviation	(Φ)	2.05	2.07	2.54	2.31	2.16	1.86	1.99	1.94	2.37
Skewness		0.02	-0.06	-0.18	-0.31	-0.19	-0.30	0.13	0.07	0.62
Kurtosis		-0.36	-0.68	-0.37	-0.17	-0.21	-0.21	-0.59	-0.96	1.37
Fineness Modulus							1.32			
Location or Company		Steele Bottom, Gallatin County Paint Lick Creek								Ghent Abn. Pit

Sample No.:		141079	141080	141027	141029	141034	141035	141002	141003	141004
% Gravel	(> 4 mesh)	32	53	32	1	48	58	40	48	4
% Sand	(4-200 mesh)	58	44	68	62	52	41	60	52	95
% Silt/Clay	(< 200 mesh)	10	3	0	37	0	1	0	0	1
% > 1" Gravel/Total Gravel		20	34	38	0	14	25	19	18	11
Mean Grain Size	(Φ)	-0.14	-1.91	-0.77	3.29	-1.66	-2.36	-1.49	-1.92	1.13
	(inch)	0.043	0.148	0.067	0.004	0.124	0.202	0.11	0.149	0.018
Modal Gravel Size	(Φ)	-3.65	-4.65	-4.65		-3.65	-3.65	-2.25	-3.25	-1.25
	(inch)	0.494	0.988	0.988		0.494	0.494	0.187	0.375	0.094
Modal Sand Size	(Φ)	1.75	1.50	1.50	3.50	1.50	1.25	1.25	1.00	2.00
	(inch)	0.012	0.014	0.014	0.003	0.014	0.017	0.017	0.02	0.01
Stnadard Deviation	(Φ)	2.92	2.65	2.64	1.70	2.33	2.23	2.14	2.07	1.35
Skewness		-0.02	0.27	-0.27	-0.06	0.12	0.33	-0.02	0.10	-0.73
Kurtosis		-1.01	-0.73	-1.06	4.43	-1.22	-0.08	-0.94	-0.70	3.99
Fineness Modulus					0.56					
Location or Company		Carrollton Abn. Pit		Martin-Marietta Basic Materials (Milton) Abandoned West Pit				Milton Sand and Gravel Co.		

Sample No.:		141005	141006	141008	I 141127	PI 141141	PI AK1-9	PI AK1-10	PI AK1-11	PI AK1-13
% Gravel	(> 4 mesh)	53	38	39	55	22	71	50	62	23
% Sand	(4-200 mesh)	46	61	61	42	72	22	41	32	65
% Silt/Clay	(< 200 mesh)	1	1	0	3	6	7	9	6	12
% > 1" Gravel/Total Gravel		20	22	39	63	31	3	43	6	35
Mean Grain Size	(Φ)	-2.06	-1.00	-1.41	-2.19	0.01	-2.22	-1.41	-1.88	-0.06
	(inch)	0.165	0.079	0.105	0.18	0.039	0.183	0.105	0.145	0.041
Modal Gravel Size	(Φ)	-4.65	-4.65	-4.65	-5.25	-5.65	-4.25	-4.65	-3.65	-4.65
	(inch)	0.988	0.988	0.988	1.498	1.977	0.749	0.988	0.494	0.988
Modal Sand Size	(Φ)	1.25	1.75	1.50	1.75	2.50		-0.25	0.75	-0.25
	(inch)	0.017	0.012	0.014	0.012	0.007		0.047	0.023	0.047
Stnadard Deviation	(Φ)	2.21	2.55	2.55	3.20	2.71	2.95	3.46	2.88	3.31
Skewness		0.31	-0.07	-0.09	0.21	-0.18	1.2	0.62	1.02	0.52
Kurtosis		-0.14	-1.36	-1.29	-1.19	-0.52	5.94	1.26	4.74	1.23
Fineness Modulus										
Location or Company		Milton Sand and Gravel Co.			Steep Creek, Boone Co.	Commissary Corner, Boone County Berry Farm				

Sample No.:		PI AK1-15	PI AK1-17	PI AK2-4	PI AK2-8	PI AK2-9	PI AK2-10	PI AK2-13	PI AK3-10	PI AK3-11
% Gravel	(> 4 mesh)	32	27	45	51	56	30	2	38	37
% Sand	(4-200 mesh)	57	64	43	39	37	48	80	44	46
% Silt/Clay	(< 200 mesh)	11	9	12	10	7	22	18	18	17
% > 1" Gravel/Total Gravel		30	26	27	57	32	34	0	44	0
Mean Grain Size	(Φ)	-0.36	-0.38	-0.86	-1.48	-2.17	0.57	2.7	-0.15	-0.14
	(inch)	0.051	0.051	0.071	0.11	0.177	0.027	0.006	0.044	0.043
Modal Gravel Size	(Φ)	-4.65	-4.65	-4.25	-5	-5.25	-4.65		-4.65	-4
	(inch)	0.988	0.988	0.749	1.26	1.498	0.988		0.988	0.63
Modal Sand Size	(Φ)	1	1	1.25	0.25	0.25	1.25	3.5	1	-0.75
	(inch)	0.02	0.02	0.017	0.033	0.033	0.017	0.003	0.02	0.066
Stnadard Deviation	(Φ)	3.44	3.13	3.76	3.81	3.46	4.15	2.19	4.19	3.85
Skewness		0.52	0.5	0.51	0.58	0.7	0.29	0.37	0.38	0.56
Kurtosis		1.01	1.4	0.53	0.92	1.82	-0.5	2.76	-0.34	0.32
Fineness Modulus								1.1		
Location or Company		Commissary Corner, Boone County Berry Farm								

APPENDIX C:

PERCENTAGES OF ROCK TYPES IN WISCONSINAN OUTWASH GRAVELS OF THE OHIO RIVER AND TWO OF ITS PRINCIPAL MELTWATER TRIBUTARIES

Appendix C. Percentages of rock types in Wisconsinan outwash gravels of the Ohio River and two of its principal meltwater tributaries.

County, State	*Location*	*Dolomite*	*Limestone*	*Dol. + Ls.*	*Sandstone*	*Chert*	*Quartz*	*Ign/Met*	*Quartz + Ign/ Met*	*Clay/ Shale*	*No. of Samples*	*Source of Data*
Clermont, Oh.	Little Miami River, Miamiville	46	38	84	4	4			7	1	1	Doroshenko (1948)
Clermont, Oh.	Little Miami River, Terrace Park	64	24	88	3	1			7	1	1	Doroshenko (1948)
Hamilton, Oh.	Little Miami River, Newtown	58	26	84	2	2			11	1	1	Doroshenko (1948)
Hamilton, Oh.	Little Miami River, Cincinnati	45	41	86	2	1			10	1	1	Doroshenko (1948)
Randolph, Ind.	Whitewater River, 3 mi. south-southeast of Modoc	65	20	85	1	4	2	6	8	2	1	McGregor (1960)
Wayne, Ind.	Whitewater River, 1 mi. south of Hagerstown	74	11	85	2	1	2	10	12	trace	1	McGregor (1960)
Union, Ind.	East Fork, Whitewater River, Dunlapsville	62	23	85	2	1	2	9	11	1	1	McGregor (1960)
Franklin, Ind.	Whitewater River, 2 mi. north-west of Cedar Grove	49	26	75	7	7	2	9	11	trace	1	McGregor (1960)
Boone, Ky.	Taylorsport Sand Co.	43	32	75	4	11	2	8	10	0	1	This study
Boone, Ky.	Ohio River, mile 497-498			52	2	4	20	22	42	0	2	U.S. Army Corps of Engineers
Boone, Ky.	Northern Kentucky Aggregate Co.	57	20	77	7	2	5	9	14	0	1	This study
Boone, Ky.	Eaton Sand & Gravel, Belleview			80	6	1	1	11	12	1	1	U.S. Army Corps of Engineers
Boone, Ky.	Boone County Sand & Gravel Co.	53	28	81	4	6	2	7	9	0	1	This study
Gallatin, Ky.	Barrow Pit, Steele Bottom	42	17	59	11	15	5	10	15	trace	2	This study
Gallatin, Ky.	Pits (now abandoned) at War-saw			71	5	11	2	10	12	1	7	U.S. Army Corps of Engineers
Carroll, Ky.	Carrollton Sand & Gravel (aban-doned)			73	4	7	2	13	15	1	1	U.S. Army Corps of Engineers
Carroll, Ky.	Martiin-Marietta (now Nugent)			80	2	5	2	10	12	1	4	U.S. Army Corps of Engineers
Carroll, Ky.	Milton Sand & Gravel Co.	50	15	65	9	10	4	12	16	0	2	This study
Clark, Ind.	Grant 18, Clark Military Grant	42	14	56	6	14	10	14	24	trace	1	McGregor (1960)
Clark, Ind.	Grant 7, Clark Military Grant	65	9	74	1	5	2	18	20	trace	1	McGregor (1960)
Harrison, Ind.	Mauckport			48	4	28			18	2	1	Straw (1968)
Crawford, Ind.	Oxbow Bend			58	3	20			18	1	1	Straw (1968)
Breckinridge, Ky.	Yellowbank Creek			42	13	29			10	6	1	Straw (1968)
Breckinridge, Ky.	Cloverport			45	10	29			14	2	1	Straw (1968)