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RECONNAISSANCE OF ALLUVIAL FANS AS POTENTIAL SOURCES OF GRAVEL AGGREGATE, SANTA CRUZ RIVER VALLEY, SOUTHEAST ARIZONA

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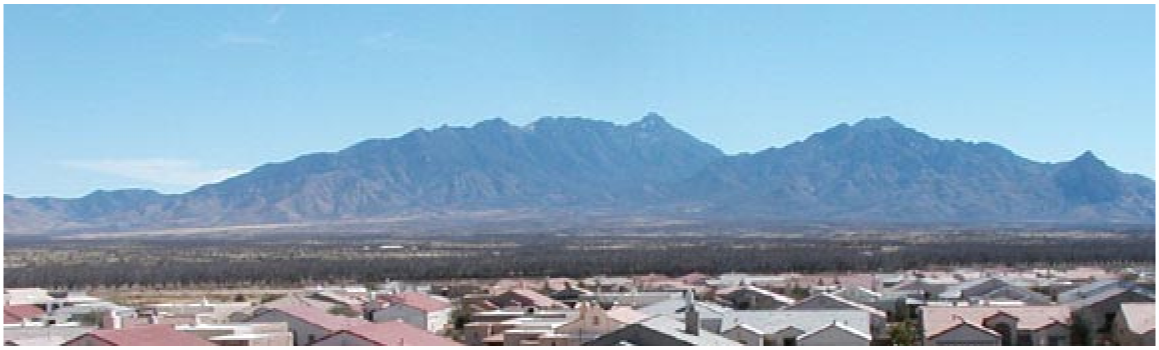

Madera Canyon fan and Santa Rita Mountains east of Green Valley

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Abstract

This investigation was conducted to provide information on the aggregate potential of alluvial fan sediments in the Santa Cruz River valley. Pebble lithology, roundness, and particle size were determined in the field, and structures and textures of alluvial fan sediments were photographed and described. Additional measurements of particle size on digital photographs were made on a computer screen. Digital elevation models were acquired and compiled for viewing the areal extent of selected fans.

Alluvial fan gravel in the Santa Cruz River valley reflects the lithology of its source. Gravel derived from granitic and gneissic terrane of the Tortolita, Santa Catalina, and Rincon Mountains weathers to grus and is generally inferior for use as aggregate. Gravel derived from the Tucson, Sierrita, and Tumacacori Mountains is composed mostly of angular particles of volcanic rock, much of it felsic in composition. This angular volcanic gravel should be suitable for use in asphalt but may require treatment for alkali-silica reaction prior to use in concrete. Gravel derived from the Santa Rita Mountains is of mixed plutonic (mostly granitic rocks), volcanic (mostly felsic rocks), and sedimentary (sandstone and carbonate rock) composition. The sedimentary component tends to make gravel derived from the Santa Rita Mountains slightly more rounded than other fan gravel.

The coarsest (pebble, cobble, and boulder) gravel is found near the heads (proximal part) of alluvial fans. At the foot (distal part) of alluvial fans, most gravel is pebble-sized and interbedded with sand and silt. Some of the coarsest gravel was observed near the head of the Madera Canyon, Montosa Canyon, and Esperanza Wash fans. The large Cienega Creek fan, located immediately south and southeast of Tucson, consists entirely of distal-fan pebble gravel, sand, and silt.

Introduction

Most aggregate in the Tucson area is produced from bedrock quarries and from large gravel pits on the floodplain of the Santa Cruz River. Because gravel mining on the river floodplain may affect water flow and quality as well as riparian habitat, applications for mining permits require environmental studies and may be denied if the risk of adverse impact on the environment is great. Although mining on alluvial fans may carry environmental risks also, fan surfaces present large areas for mining gravel away from stream channels. However, little is known about the aggregate potential of alluvial fans in southeast Arizona. This reconnaissance investigation of alluvial fan sediments in the Santa Cruz River valley (Fig. 1) was conducted to provide a first look at fans as a source of gravel for aggregate in southeast Arizona.

Some gravel has been mined for aggregate from alluvial fans in the Santa Cruz River valley. Most aggregate production from fan sediments has been from borrow pits along highways. The Arizona Department of Transportation (ADOT) maintains extensive files on production, particle size, and other characteristics of gravel from borrow pits (Langland, 1987). ADOT records indicate that most pits in alluvial fans are small. Most pits no longer in use have been reclaimed. Although we examined some pits for this study, most of our field study was conducted on road cuts and the banks of incised streams on fans.

Alluvial fans

Alluvial fans form where streams leave the mountains. At that point, stream slope and sediment carrying power decrease abruptly, forcing streams to deposit sediment close to the mountain front. As sediment accumulates at the mountain front, stream channels are diverted repeatedly to one side or the other of the accumulating sediment to form a fan-shaped deposit. Particle size of fan sediment decreases downstream (Blissenbach, 1954). Commonly, fans from small streams leaving the mountains coalesce to form an apron of alluvial sediment called a bajada.

Both gravity and flowing water deposit sediment on alluvial fans (Bull, 1972; Blair and McPherson, 1994). Depositional processes near the fan head may include rock avalanches, gravity slides, and debris flows. Flowing water, either confined to channels or unconfined on the fan surface, may carry sediment to any part of the fan. Most deposition by flowing water occurs at the end of catastrophic flow, either in incised channels (streamflood deposits) or on the unconfined fan surface (sheetflood deposits). Commonly, the proximal region of the fan has been incised by channels that carry sediment to an active depositional lobe on the middle or lower part of the fan. On the depositional lobe, shallow braided channel deposits pass into sheetflood deposits. The alluvial fans of the Santa Cruz River valley were deposited mostly by streamflood and sheetflood.

Interpretation of gravel as streamflood or sheetflood was made with reference to descriptions and photographs by Bull (1972) and Blair and McPherson (1994). In general, streamflood gravel is densely packed, imbricated, and weakly stratified; evidence of channels confirms streamflood interpretation. Sheetflood gravel is well-stratified, with pronounced differences in grain size between adjacent beds; beds are thin and continuous or only slightly lenticular, as would be expected if deposited on an unconfined surface.

Fan formation is promoted by down-faulting along basin margins. Basin-range faulting in southeast Arizona is considered to have ended 3-6 Ma ago, in latest Miocene to Pliocene time (Menges and McFadden, 1981). However, topographic relief was sufficient to permit alluvial fans to form well into Pleistocene time. In addition to structurally-caused relief, climatic change may also have initiated fan deposition (Menges and McFadden, 1981). Some of the highest, most extensive ranges surrounding the Santa Cruz River valley are on the north and east sides. Extensive alluvial fans, 4-6 miles from head to toe, formed at the foot of the Tortolita, Santa Catalina, and Santa Rita Mountains.

Although many adjacent fans tend to coalesce, some fans, such as the Madera Canyon and Montosa Canyon fans, maintain their distinct form. The very old (Early Pleistocene and late Pliocene) Cienega Creek fan, which extends about 15 miles west from the gap between the Rincon and Empire Mountains, is clearly visible on satellite images (Houser and others, in press).

The size and shape of fans in the Santa Cruz River valley have been influenced by rates of deposition and by local structural features. In response to extensive fan deposition on the eastern side of the Santa Cruz River valley, the Santa Cruz River near Tucson was forced toward the west side of the valley (e.g., Demsey and others, 1993). The west side of the river is flanked by short fans 2-3 miles long that have coalesced to form bajadas at the foot of the Tucson Mountains. In contrast, the Sierrita Mountains, located farther south and west of Tucson, are surrounded by coalesced fans that extend 6-8 miles east to the Santa Cruz River. South toward Tubac, the river is confined to narrow fault-bounded basins between the Tumacacori and Santa Rita Mountains (Gettings and Houser, 1997). Short coalesced fans flank the east side of the Tumacacori Mountains but fans on the west side of the Santa Rita Mountains are as much as 6 miles long and maintain their distinct shape.

Most alluvial fans of the Santa Cruz River valley were probably formed in latest Pliocene and Early Pleistocene time (Menges and McFadden, 1981; Houser and others, in press). Since then, the fans have been reworked to form surfaces of Middle to Late Pleistocene age that are inset below the original fan surfaces (e.g., Pearthree and Youberg, 2000). Tributary streams of the Santa Cruz River have cut into the fans and the river has eroded the toes of the fans. The Santa Cruz River defines the base level for streams draining the fans and, when base level dropped during periods of downcutting by the river, its tributary streams cut into the fans. Along its course in the valley, the river formed terraces that represent successive base levels during Holocene time (Haynes and Huckell, 1986). Fan incision was probably intermittent.

Scope and Purpose of Investigation

Alluvial-fan sediments in the Santa Cruz River valley were examined in reconnaissance for aggregate resource potential. Most localities examined are located between Tucson and Tubac (Fig. 1, Table 1), within a few miles of Interstate Highway 19, where good exposures of fan gravel can be found. At one locality (14), the lithology of gravel from the modern channel of the Santa Cruz River was examined for comparison with fan gravel.

Three areas north and west of Tucson were also examined briefly (Fig. 1, Table 1). Small coalesced fans of Middle Pleistocene age, located between the Tucson Mountains and the Santa Cruz River contain volcanic gravel that has been mined for highway construction. The gravel east of the Tucson Mountains is mostly covered by residential development. An area of active fan deposition (locality 1, the Cottonwood fan; described by Field, 1994) on the south side of the Tortolita Mountains was examined, mostly to gain better understanding of fan processes, but data were collected on gravel composition. Finally, the lithology of gravel in waste piles from the Cemex pit (locality 2), representing gravel from beneath the modern Santa Cruz River, was examined for comparison with fan gravel.

Methods

Data on gravel lithology and roundness were collected at 17 localities and particle size was estimated at 14 localities (Table 1). All localities were located with a global positioning system. Exposures at each locality were photographed and sedimentary features noted. Although the exposed thickness of gravel was noted, the total thickness of gravel was seldom evident from exposures. U.S. Geological Survey digital elevation models (DEMs) were acquired from the EROS data center, Sioux Falls, South Dakota, to provide information on the areal extent of selected fans. Field locations, data on gravel lithology and particle size, field photographs, and selected DEMs were compiled.

Gravel lithology and roundness (Table 2) were estimated by classification of approximately 100 pebbles (approximately 1-3 inches in long dimension) at each locality. At most localities, a subset of 50 pebbles was placed into rows by lithology and columns by roundness on a board and photographed. Sampling consisted of selecting approximately the first 100 pebbles encountered from a defined area or traverse across an outcrop. The pebbles were washed in water and examined with a hand lens for rock identification. Lithologic names were adapted to local circumstances and, as the investigation proceeded, systematized by combining closely related lithologies. For example, the many variations of volcanic rocks were classified as crystal-poor ignimbrite (ash-flow tuff), rhyolite crystal tuff, volcanic porphyry with quartz, volcanic porphyry without quartz, diorite, and basalt. Except for diorite and basalt, the other volcanic rocks consist of at least several variants according to color and phenocryst content. Pebble roundness (the degree to which pebbles lack angular corners) was estimated visually using the method of Pettijohn (1975, fig. 3-24). In this method, pebbles are assigned letters A-E for angular to well-rounded. Both pebble lithology and roundness may affect aggregate quality (Langer and Knepper, 1998).

Particle size (Table 3) was estimated at outcrops by recording sizes of particles measuring approximately > 0.75 inch along an outstretched tape. A length of 50-90 inches of tape was placed vertically across the outcrop and secured at each end. The maximum exposed size of each particle encountered was measured. Particles were not extracted from the outcrop. The measured sizes were binned into geometric classes 0.75-1.5, 1.5-3, 3-6, 6-12, and >12 inches and counted. The tape was moved vertically or laterally and the procedure was repeated 3-5 times at each locality, so that much of the accessible outcrop was represented by measurements. The class frequencies were then multiplied by the midpoints (e.g., 1.125 inches for the 0.75-1.5 inch class) and 18 inches for the >12-inch class, totaled, and subtracted from the total tape length to find the frequency of < 0.75-inch particles. This procedure is herein called the "binning method." In coarse (cobble) gravel, the binning method overestimates the frequency of large (> 3 inch) particles and seriously underestimates the amount of < 0.75-inch material. Most fan sediment examined consists of pebble gravel and finer sediment; however, fan sediment at localities 11, 17, 19, and 20 contains cobbles and boulders. At localities 11 and 12, particle size was re-measured by recording exact tape intercepts of particles > 0.75 inch, herein called the "intercept method." Using the intercept method, the total of all intercepts was subtracted from the tape length to obtain the percent of particles < 0.75 inch. At locality 11, which consists of coarse gravel, particles of < 0.75 inch were re-estimated at 31 pct. At locality 12, which consists of pebble gravel, results using tape intercepts of particles were indistinguishable from the binning method. Measurements of coarse gravel by the binning method at localities 17, 19, and 20 were corrected by assuming a value of 30 percent (pct) for < 0.75-inch particles, based on comparison with locality 11 and measurements of coarse gravel elsewhere.

Additional measurements of particle size were made from digital photos at selected localities using NIH Image (Table 4), a public domain computer program distributed by the National Institutes of Health (Rosband, 1999). On traverses placed on digital photographs, the lengths of clast intercepts > 0.75 or > 1.5 inches (depending upon photo scale and resolution) were estimated on a computer screen. This procedure is the equivalent of the field intercept method, but done on a computer screen. The program enables collection of data in tabular form; the data are copied to a spreadsheet for calculations. Both the field and photo data on particle size data were then compared on cumulative frequency plots.

Digital elevation models were acquired from the EROS Data Center, Sioux Falls, South Dakota, to determine the extent of individual fans sampled. After merging models, the area of selected fans and their source drainage was outlined on the computer screen and the surrounding area removed. The resulting image is a three-dimensional model of the fan and its source area.

Locality descriptions

Alluvial fan gravel

Fans derived from the Tortolita and Santa Catalina Mountains contain dominantly gneissic and granitic detritus (locality 1, Table 2; Fig. 2) (Dickinson, 1999). Brief field examination of the Cottonwood fan and adjacent fan surfaces of Pleistocene age (described by Field, 1994, and Demsey and others, 1993, respectively) revealed that the Tortolita fans contain only poor quality gravel. Examination of pebbles revealed a tendency to weather and break into angular to subround shapes (Fig. 3). The granitic and gneissic detritus that compose the fans disintegrate to grus when weathered.

The bajada (coalesced fan) sediments east of the Tucson Mountains (localities 5, 9, 21, and 22) consist mostly of angular pebble gravel of felsic volcanic composition (Table 2). In all outcrops observed, the gravel beds are well-stratified sheetflood deposits (Figs. 4 and 5). Borrow pits along Silverbell Road reveal that the bajada gravel has been used locally. Both the composition and angularity of the gravel particles (Fig. 6) reflect derivation nearby from the Tucson Mountains. More than 85 pct (percent) of pebbles are volcanic rocks, with rhyolite crystal tuff and crystal-poor ignimbrite being the most abundant. The felsic volcanic composition of the Tucson Mountains gravel would indicate likely presence of abundant unstable silica minerals, which could cause alkali-silica reaction if it were used untreated in Portland cement concrete.

The very old (latest Pliocene to Early Pleistocene) Cienega Creek fan south and southeast of Tucson drained a region of uncertain location between the Rincon and Empire Mountains (Houser and others, in press). The fan contains much silt, sand, and pebble gravel. Large pits south of Tucson (locality 23 and farther east) and smaller ones to the southeast (localities 24 and 25) suggest commercial production as well as local use of gravel from the Cienega Creek fan. Pit walls reveal that much of the gravel was deposited as thin beds (Figs. 7, 8, and 9), probably by sheetfloods on the distal part of the Cienega fan. Thicker intervals of mostly fine gravel, sand, and silt are intercalated with gravel. Pebbles range from subangular to rounded, probably reflecting relatively long transport compared to gravel of the Tucson Mountains bajada (Figs. 10 and 11). In addition to abundant (30-54 pct) volcanic rocks, the pebble fraction contains 41-62 pct sandstone and carbonate rock. The lithology of the Cienega Creek gravel makes it attractive for use in concrete because it contains the least volcanic material of any gravel samples, except the grus-rich gravel shed from the Tortolita Mountains. The presence of abundant rhyolite crystal tuff, however, could still present problems with alkali-silica reaction if used untreated in concrete.

The Box Canyon fan is a somewhat poorly defined fan that heads where Box Canyon emerges from the Santa Rita Mountains; the fan coalesced with adjacent fans (not examined) to the north and south. The distal end of the Box Canyon fan (locality 10) was sampled in a road cut near Centennial, but no examination of proximal fan sediments was made. Gravel pits nearby have commercial production. The fan sediments consist of interbedded fine and coarse gravel, including beds of coarse gravel as much as 8 ft in thickness. Among pebble-sized particles, subangular to rounded shapes and volcanics predominate, with about 13 pct granitic rocks also present. Among volcanic rocks, crystal-poor ignimbrite (33 pct) is most abundant, with lesser amounts of rhyolite crystal tuff and porphyry (Table 2). The presence of abundant foliated ignimbrite may pose problems if crushing is required; possibly, the ignimbrite may split into weak plate-shaped particles.

The Madera Canyon fan drains a region of granitic and volcanic rocks northwest of Mt. Wrightson in the Santa Rita Mountains (Drewes, 1980). The Madera Canyon fan (Fig. 12) was sampled at three places. Locality 11, in the banks of Florida Canyon Wash, represents coarse proximal fan gravel deposited mostly by streamflood (Fig. 13). A bed of debris-flow cobble and boulder gravel about 10 ft in thickness is also present at locality 11 (Fig. 14). Localities 12, in a roadcut north of Florida Canyon Wash, and 13, in the bank of Madera Canyon Wash, represent the most distal parts of the fan. A small pit northeast of locality 13 produces gravel for local use. Distal fan sediments in the Madera Canyon fan are mostly well-stratified sheetflood pebble gravels interbedded with finer sediment (Figs. 15 and 16). Pebble counts indicate that some parts of the Madera Canyon fan contain abundant (41-79 pct) clasts of granitic rocks (Table 2). In fresh outcrop as much as 10 ft beneath the surface, these granitic clasts disintegrate to grus. Among other rock types, gray crystal-poor ignimbrite is abundant (38-66 pct) at two of three localities (Figs. 17 and 18). As speculated for gravel of the Box Canyon fan, the ignimbrite may crush to platy fragments.

Located west of the Santa Cruz River, the Esperanza Wash fan has its source in the Sierrita Mountains. The Sierrita Mountains consist largely of volcanic and plutonic (granitic and related compositions) rocks, but also contain some conglomerate of Tertiary age (Drewes, 1980). The Esperanza Wash fan was sampled in distal and proximal locations. Large road cuts approximately 50 ft high at the Canoa interchange on I-19 (locality 15) expose distal fan sediments of gravel, sand, and silt (Fig. 19). Thin beds of pebble gravel were probably deposited by sheetflood (Fig. 20). The fan gravel has been exploited in numerous borrow pits along I-19. Pebbles are mostly subangular to rounded volcanic rocks (77 pct), with lesser (18 pct) granitic rocks (Fig. 21). Volcanic rocks include 45 pct rhyolite crystal tuff and subordinate (20 pct) crystal-poor ignimbrite. Quality for use in concrete may be poor without treatment for alkali-silica reaction. At the head of the Esperanza Wash fan (locality 20), young gravel beneath an incised stream terrace consists of stratified pebble and cobble gravel deposited by streamfloods (Fig.

22). The gravel contains abundant crystal-poor ignimbrite (38 pct) and basalt (15 pct, mapped as "andesite" by Drewes, 1980) (Table 2).

The Diablo Wash fan is one of a series of coalesced fans that have their source in the Tumacacori Mountains west of the Santa Cruz River. The Tumacacori Mountains consist of mostly volcanic rocks, but also contain a granitic pluton at the north end. The fan was sampled at its distal end southwest of the Agua Linda interchange on I-19 (locality 16). Approximately 30 ft of sand, silt, and thin beds of gravel are exposed (Fig. 23). Pebble gravel occurs in thin sheetflood beds and small channels (Fig. 24). Imbrication in one channel showed eastward flow, toward the Santa Cruz River. Pebbles have mostly subangular to rounded shapes and are composed mostly of volcanic rocks (82 pct) with subordinate granitic rocks (16 pct) (Table 2). Among volcanic rocks, rhyolite crystal tuff (47 pct) and crystal-poor ignimbrite (19 pct) are abundant. Southward, the mostly volcanic terrane of the Tumacacori Mountains does not offer promise of gravel lithologies free from unstable silica minerals.

The Montosa Canyon fan (Fig. 25) heads southwest of Mt. Wrightson in a structurally complex region in the Santa Rita Mountains composed of diverse volcanic, plutonic, and sedimentary rocks (Drewes, 1980). The fan, located east of the Santa Cruz River, was sampled at both distal and proximal positions (localities 17 and 19, respectively). Gravel for road construction has been produced from a wash downstream from locality 17. At locality 17, about 20 ft of pebble and cobble gravel overlying a 10-foot interval of silt is exposed in a stream bank (Fig. 26). At locality 19, about 30 feet of weakly stratified pebble and cobble gravel is exposed in the north bank of the wash (Fig. 27). Large boulders are present, especially near the surface. The top 4 feet of gravel is strongly weathered. At both localities, coarse gravel was probably deposited by streamfloods. Pebbles at both localities tend to be subangular to subround, with abundant volcanic (37-62 pct) and plutonic (mostly granitic) rocks (31-44 pct) (Table 2) (Figs. 28 and 29). At locality 17, gabbroic rocks (8 pct) and carbonate rocks (16 pct) are common. Both rhyolite crystal tuff and porphyry with quartz are abundant at locality 19. The diverse assemblage of lithologies in the Montosa Canyon fan might make it more attractive as a multi-use source of aggregate than the volcanic-dominated fans west of the Santa Cruz River.

Stream channel gravel

Gravel in the present channel of the Santa Cruz River was sampled at locality 14 north of Tubac. Pebbles from the channel gravel are mostly subangular to subround and appear to have been derived locally; however, a few rounded and well-rounded pebbles appear to have undergone lengthy or repeated transport (Table 2) (Fig. 30). Common pebble lithologies include granitic rocks, crystal-poor ignimbrite, rhyolite crystal tuff, volcanic porphyry without quartz, and brown sandstone; this diverse assemblage is consistent with derivation from local sources to the south.

Gravel below the modern floodplain of the Santa Cruz River was sampled at locality 2 northwest of Tucson. The exact level of the source beneath the modern floodplain is not known because the sample was taken from a waste pile. Pebbles in this pre-modern gravel are much more rounded than the modern channel gravel at locality 14 (Table 2, Fig. 31), suggesting prolonged or repeated transport by the river. The pebble fraction is dominated by crystal-poor ignimbrite, rhyolite crystal tuff, and volcanic porphyry without quartz, all consistent with derivation from the nearby Tucson Mountains as well as other volcanic sources farther south. Granitic rocks and gneiss are also common in the sample; these might have come from the Santa Catalina or Rincon Mountains to the east via Rillito Creek. Upstream, in the Tucson Ready Mix pit at the junction of the Santa Cruz River with Rillito Creek, Priznar (1999) noted gravel with abundant volcanic clasts underlying gravel composed of granitic and gneissic clasts. Possibly, the sample at locality 2 could represent a mixture of gravel beds from different sources, or gravel derived from beds of different composition like those at the Tucson Ready Mix pit.

Particle size

Particle size is generally coarsest (pebble to cobble gravel) in the upper reaches of the Madera Canyon, Montosa Canyon, and Esperanza Wash fans. As mentioned in the description of localities, particle size in the lower parts of these fans is limited to pebble gravel and thick intervals of sand and silt. The bajada on the east side of the Tucson Mountains consists mainly of pebble gravel. The Cienega Creek fan is perhaps the finest-grained of all fan sediments examined; beds of pebble gravel are generally thin and accompanied by much sand and silt.

Particle size as determined in the field by the binning method (Table 3) and on the computer screen by the intercept method (Table 4) was compiled into cumulative frequency curves for comparison (Fig. 32). In general, the field binning method yields higher estimates of coarse particle size than does the computer screen method. This disparity probably results both from classifying particles by their apparent long dimension and from binning particle sizes into classes in the field rather than measuring the actual intersects of particles on transects, as was done on the computer screen. The apparent long dimension of particles probably influences estimates of particle size in the field; if so, estimates by the field binning method probably come closer to representing long dimensions instead of intermediate dimensions of particles. Estimates produced by the computer screen method are more likely to represent intermediate particle dimensions analogous to sieve analysis. Intercepts can also be measured in the field, but this was done at only two localities (11 and 12).

At localities where pebble gravel and finer material is dominant, field measurements indicate that 47-79 pct of particles are less than 0.75 inch in long dimension; 72-89 pct are less than 1.5 inches; and 82-93 pct are less than 3 inches (Fig. 32A). At localities where coarse gravel was encountered (11, 17, 19, and 20), roughly 30 pct of all particles are estimated at less than 0.75 inch in long dimension; 43-50 pct are less than 1.5 inches; 52-64 pct are less than 3 inches; and 68-90 pct are less than 6 inches. Cobbles larger than 6 inches and boulders larger than 12 inches are common.

Where pebble gravel and finer material is dominant (localities 13, 15, and 16), measurements by the computer screen method indicate that 72-86 pct of particles are less than 0.75 inch in intermediate dimension: 80-97 pct are less than 1.5 inches; and 91-100 pct are less than 3 inches (Fig. 32B). For localities where coarse gravel was encountered (11, 17, 19, and 20), corresponding values are 59 pct less than 0.75 inch (locality 11 only), 64-69 pct less than 1.5 inches; 79-88 pct less than 3 inches; and 90-96 pct less than 6 inches.

Relationship between pebble lithology and rounding

The relationship between pebble lithology and rounding is discussed briefly mainly because the data available from this investigation permit quantification and interpretation. The data may be useful in assessing aggregate suitability for certain applications. Data on pebble lithology and rounding are important for interpretation of the source and depositional history of gravel and may also be helpful in understanding processes that affect aggregate quality.

Data on pebble roundness and lithology from all localities sampled in the Santa Cruz River valley were compiled into a contingency table (Table 5; for a discussion of contingency tables, see Siegel, 1956). Calculation of the chi-square value confirms significant departure from expected frequencies of individual roundness-lithology cells (Tables 6A,B). Inspection of Table 5 reveals that some lithologies tend to form angular pebbles and others tend to form rounded pebbles. Pebbles of gneiss, granitic rocks, and volcanic rocks tend to be subangular or subround (classes B and C); for these lithologies, angular (A) and rounded (D) tend to be subequal in abundance. In contrast, angular pebbles of sedimentary rocks (sandstone and carbonate rock) are very scarce, and rounded pebbles are about as abundant as subangular pebbles. A few well-rounded (E) pebbles of most lithologies were also noted, but these are not numerous. Not surprisingly, we infer that igneous (plutonic and volcanic) rocks tend to remain angular, whereas fluvial processes more easily round the softer sedimentary rocks (sandstone and limestone).

The results of the contingency table have some implications for aggregate use. Gravel composed mostly of volcanic rock particles should, when sieved, produce an angular product suitable for use in asphalt without crushing. Gravel composed mostly of rounded sedimentary particles should not pose a potential for alkali-silica reaction in Portland cement, but crushing may be required to produce the desired particle shape as well as size.

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Figures 1-32

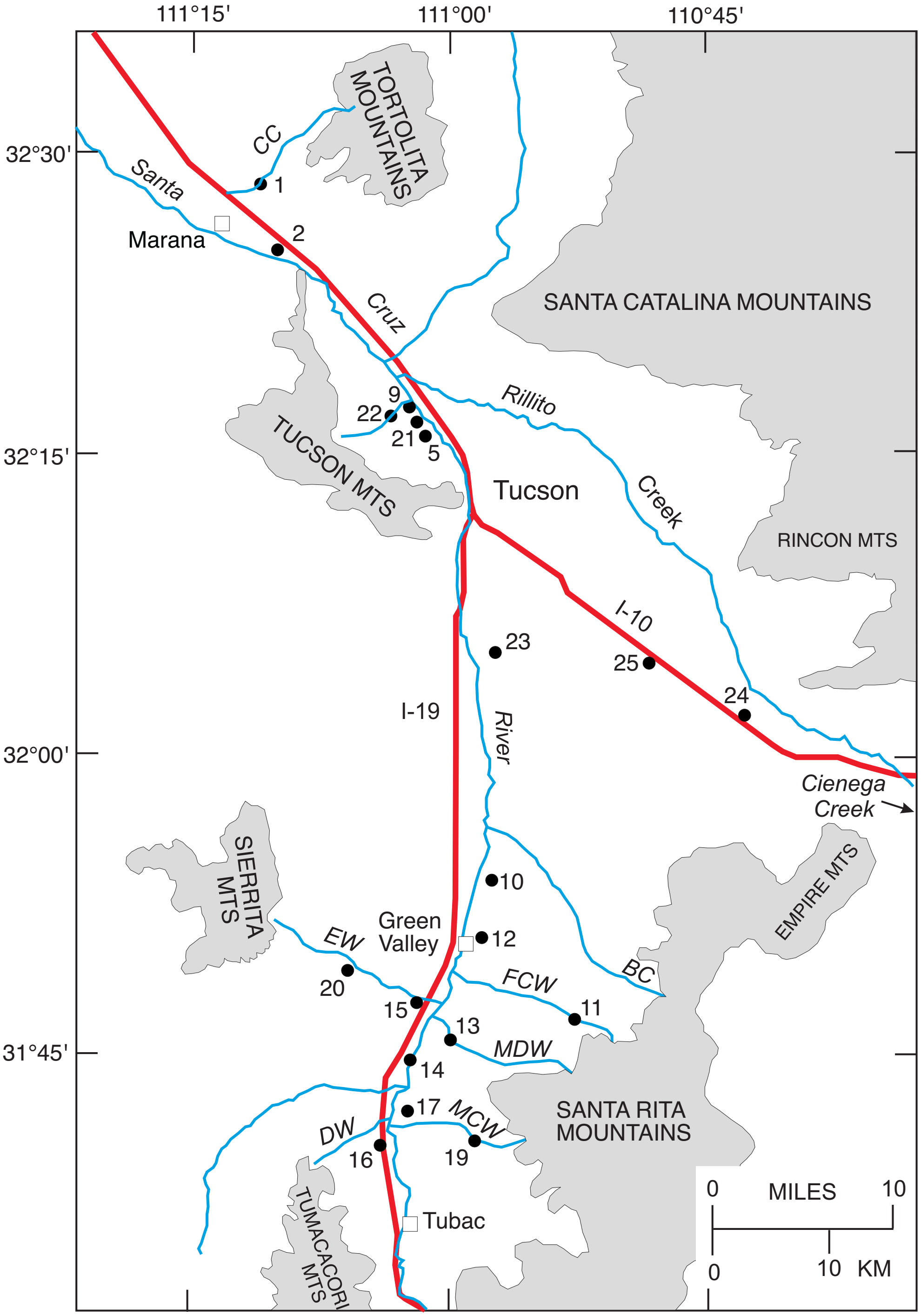


Figure 1.—Location of sampling stations for gravel in the Santa Cruz River valley, southeast Arizona. BC, Box Canyon; CC, Cottonwood Canyon; DW, Diablo Wash; EW, Esperanza Wash; FCW, Florida Canyon Wash; MCW, Montosa Canyon Wash; MDW, Madera Canyon Wash.

Figure 2.—Photograph showing recent fan deposits of granitic and gneissic rocks weathered to grus, locality 1, Cottonwood Canyon fan, south of Tortolita Mountains. View upstream of braided main channel and bank (right side) about 5 feet (ft) high; partly vegetated gravel bars lie in channel. Sheetflood deposition occurs on 500-1,000-ft-wide fan to left and downstream from this point (Field, 1994).

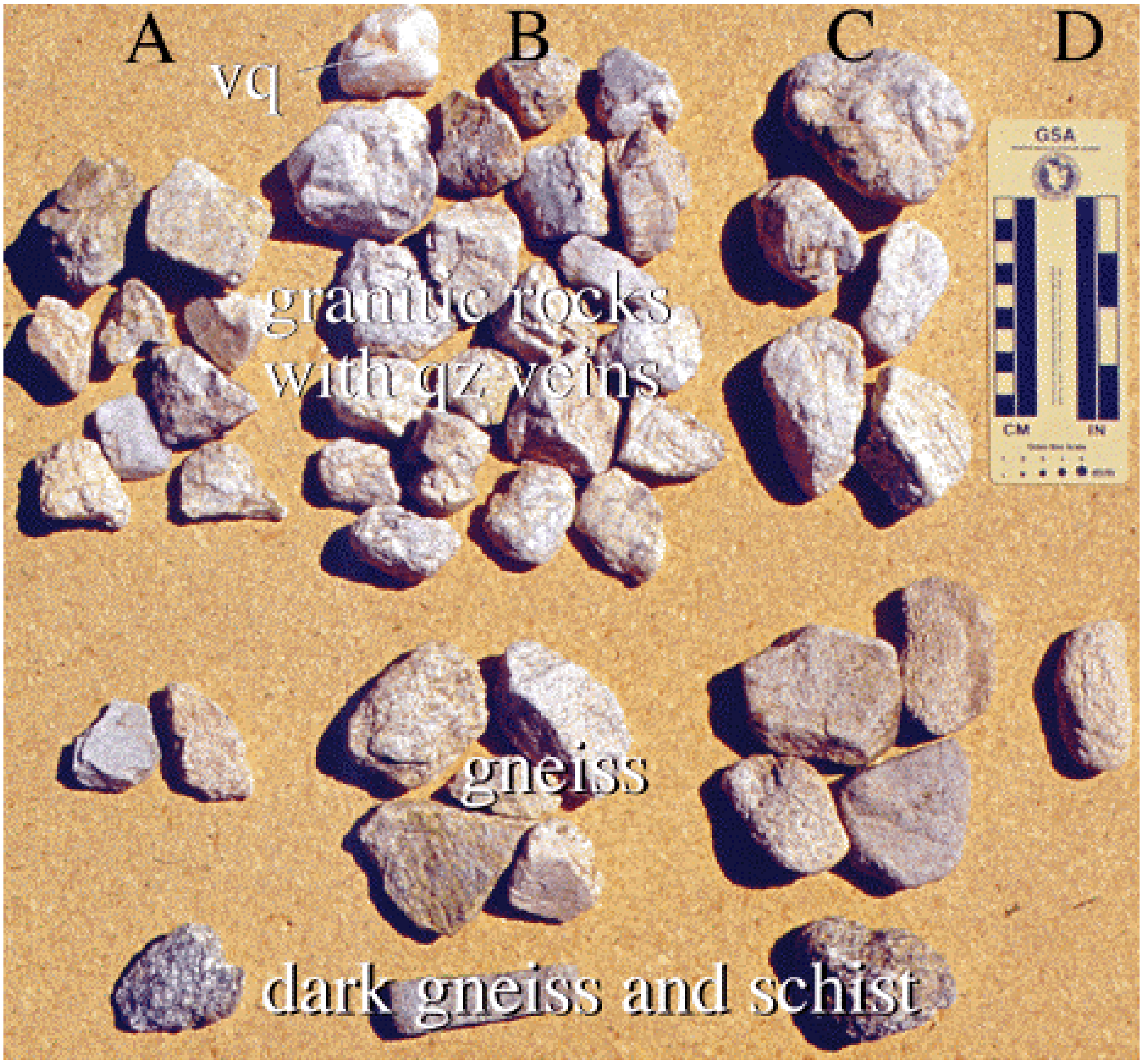


Figure 3.—Photograph showing pebble lithology (rows) and roundness (columns) of granitic-gneissic gravel, locality 1, Cottonwood fan, south of Tortolita Mountains. Abbreviations: A, angular; B, subangular; C, subrounded; D, rounded; vq, vein quartz; qz, quartz.

Figure 4.—Photograph showing stratified pebble gravel deposited by sheetflood, locality 22, bajada east of Tucson Mountains. Tape about 90 inches in length.

Figure 5.—Photograph showing detail of stratified pebble gravel deposited by sheetflood, locality 5, bajada east of Tucson Mountains. Scale shows centimeter (left side) and inches (right side).

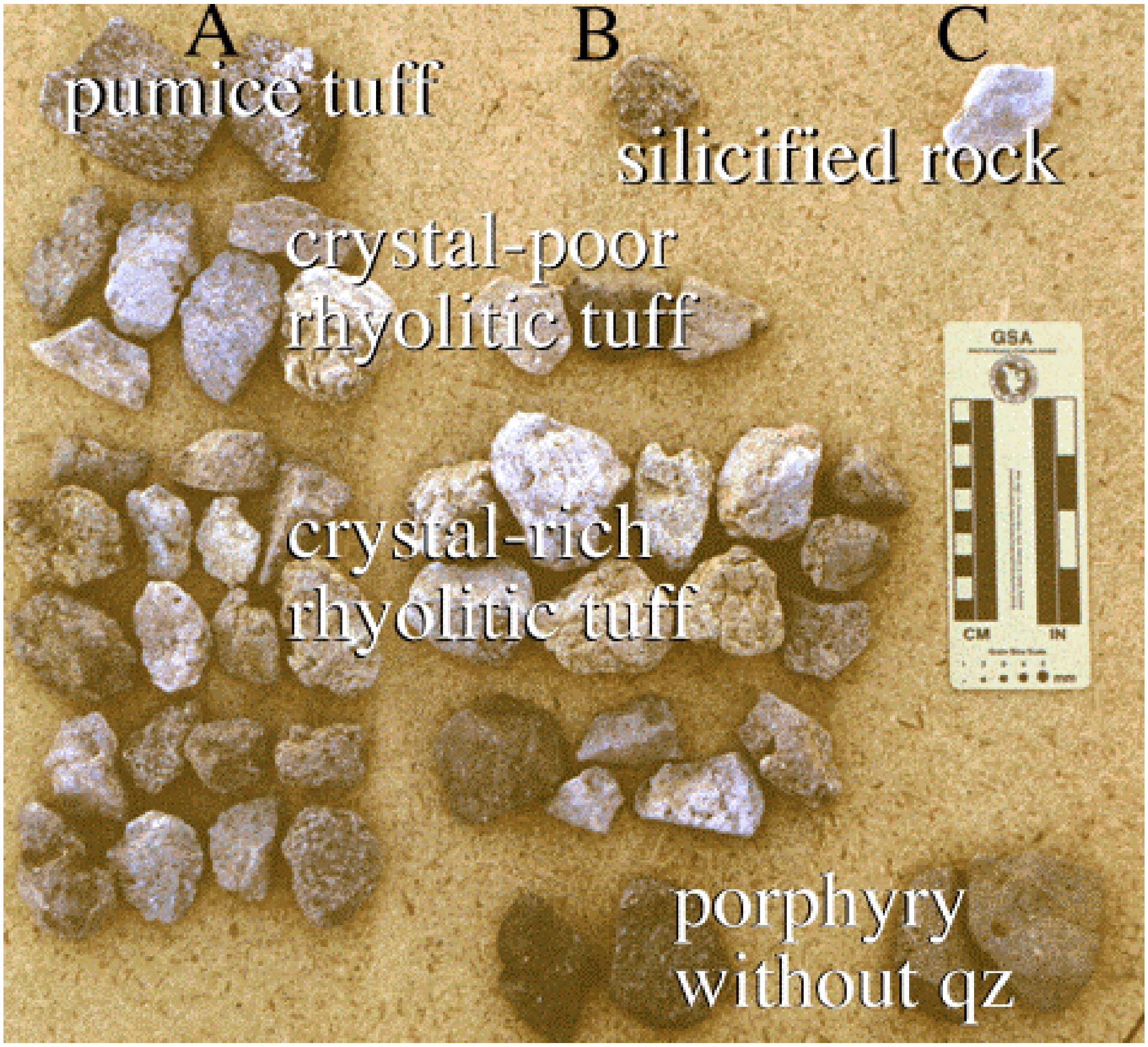


Figure 6.—Photograph showing pebble lithology (rows) and roundness (columns) of volcanic gravel, locality 9, bajada east of Tucson Mountains. Abbreviations: A, angular; B, subangular; C, subrounded; qz, quartz.

Figure 7.—Photograph showing stratified pebble gravel, sand, and silt deposited by sheetflood, locality 23, Cienega Creek fan, south of Tucson.

Figure 8.—Photograph showing stratified pebble gravel deposited by sheetflood, locality 24, Cienega Creek fan, south of Tucson. Scale in center about 6 inches long.

Figure 9.—Photograph showing stratified pebble gravel deposited by sheetflood?, locality 25, Cienega Creek fan, south of Tucson. Tape about 70 inches in length.

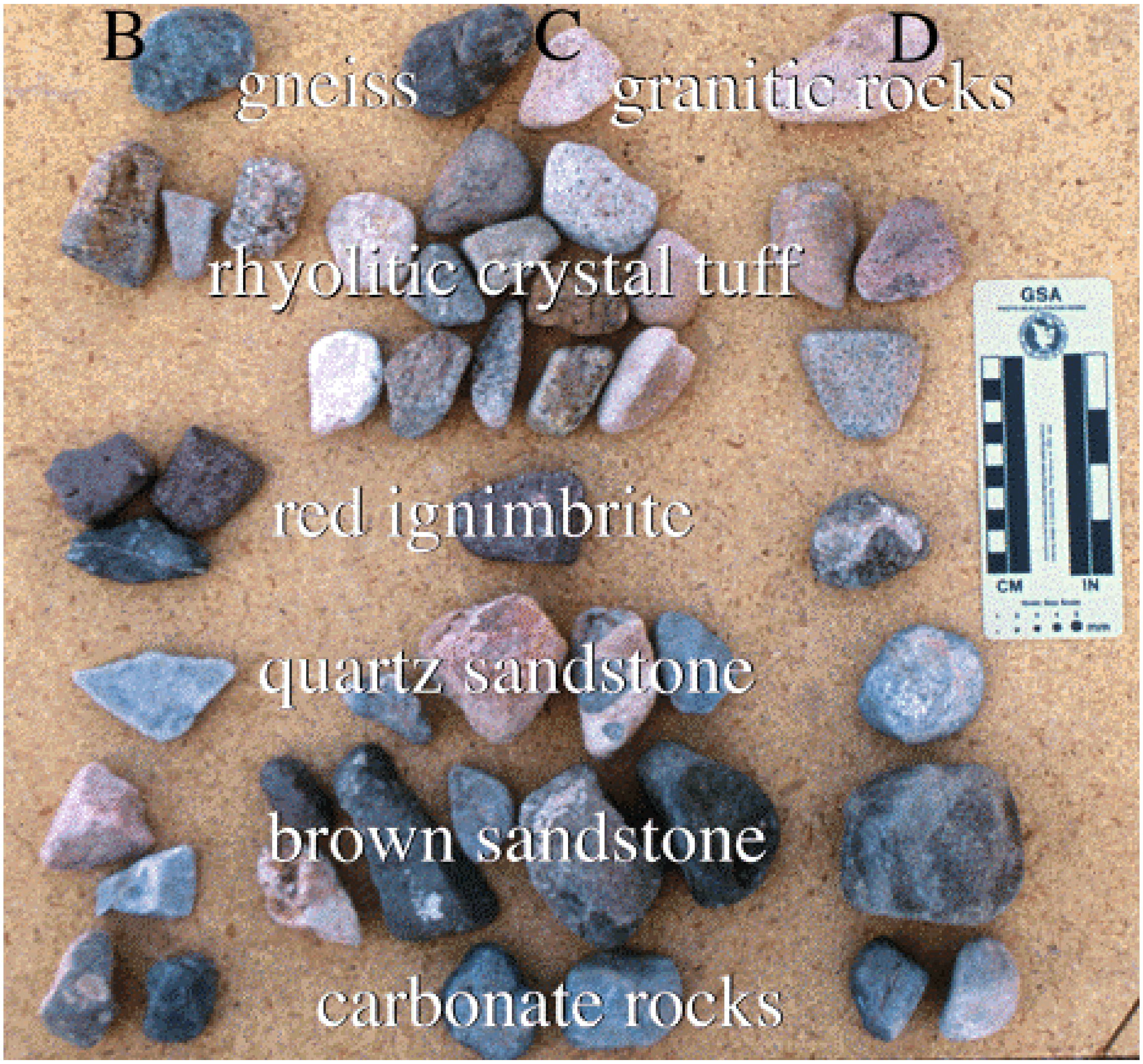


Figure 10.—Photograph showing pebble lithology (rows) and roundness (columns) of gravel, locality 23, Cienega Creek fan, south of Tucson. Abbreviations: B, subangular; C, subrounded; D, rounded.

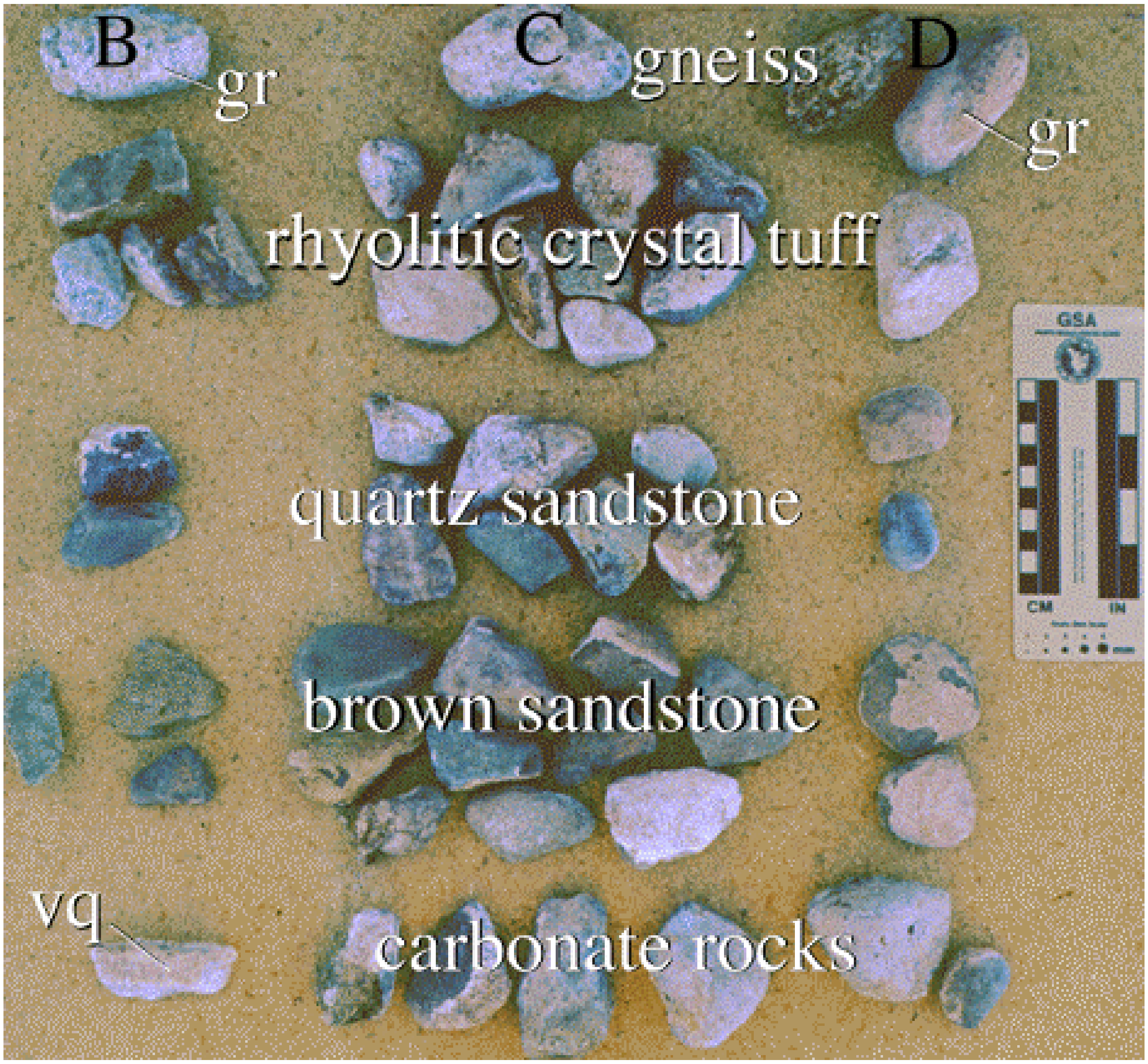


Figure 11.—Photograph showing pebble lithology (rows) and roundness (columns) of gravel, locality 25, Cienega Creek fan, south of Tucson. Abbreviations: B, subangular; C, subrounded; D, rounded; gr, granite; vq, vein quartz.

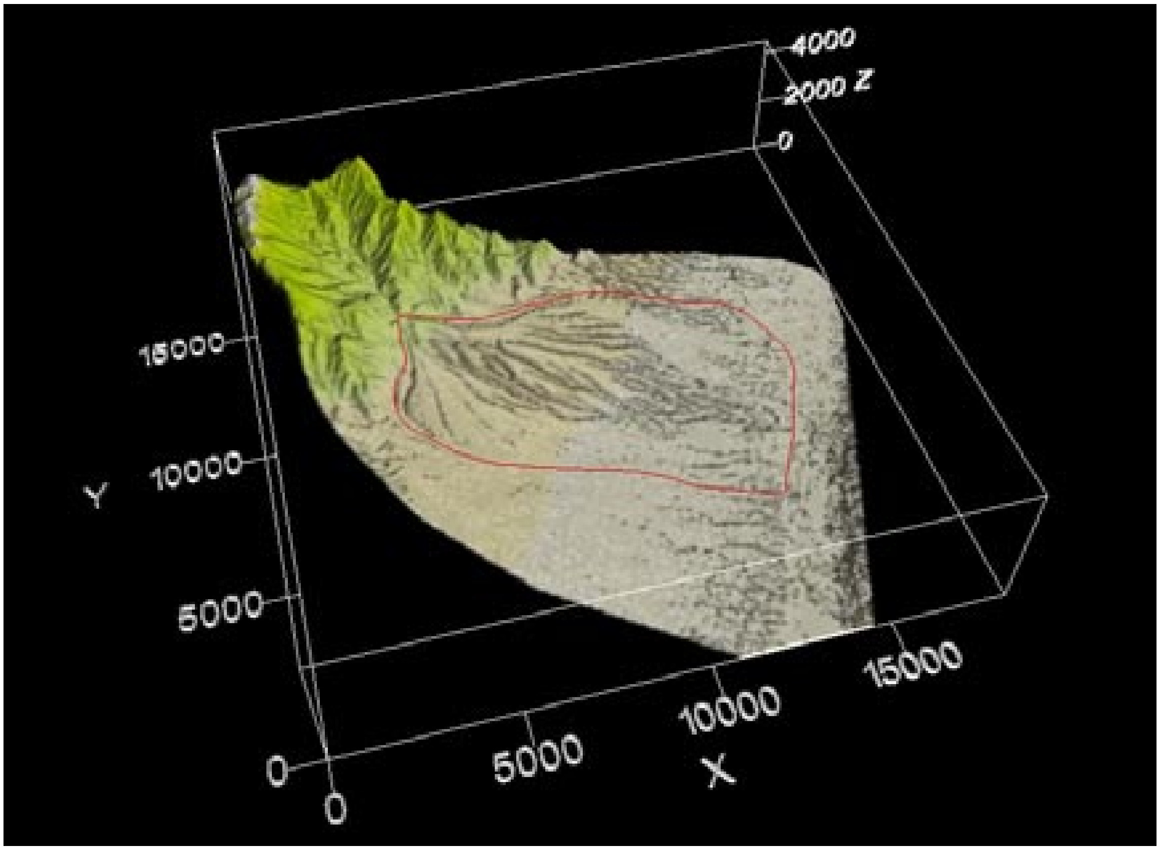


Figure 12.—Digital Elevation Model (DEM) of Madera Canyon fan (outlined) and its source basin, west of Santa Rita Mountains. Grid is arbitrary; outlined fan is about 6 miles (10 km) from head to toe.

Figure 13.—Photograph showing coarse pebble, cobble, and boulder gravel deposited by streamflood, locality 11, Madera Canyon fan, west of Santa Rita Mountains.

Figure 14.—Photograph showing coarse cobble and boulder gravel deposited by debris flow, locality 11, Madera Canyon fan, west of Santa Rita Mountains.

Figure 15.—Photograph showing pebble gravel deposited by sheetflood, locality 12, Madera Canyon fan, west of Santa Rita Mountains. Scale is yardstick.

Figure 16.—Photograph showing pebble gravel, sand, and silt deposited by sheetflood, locality 13, Madera Canyon fan, west of Santa Rita Mountains.

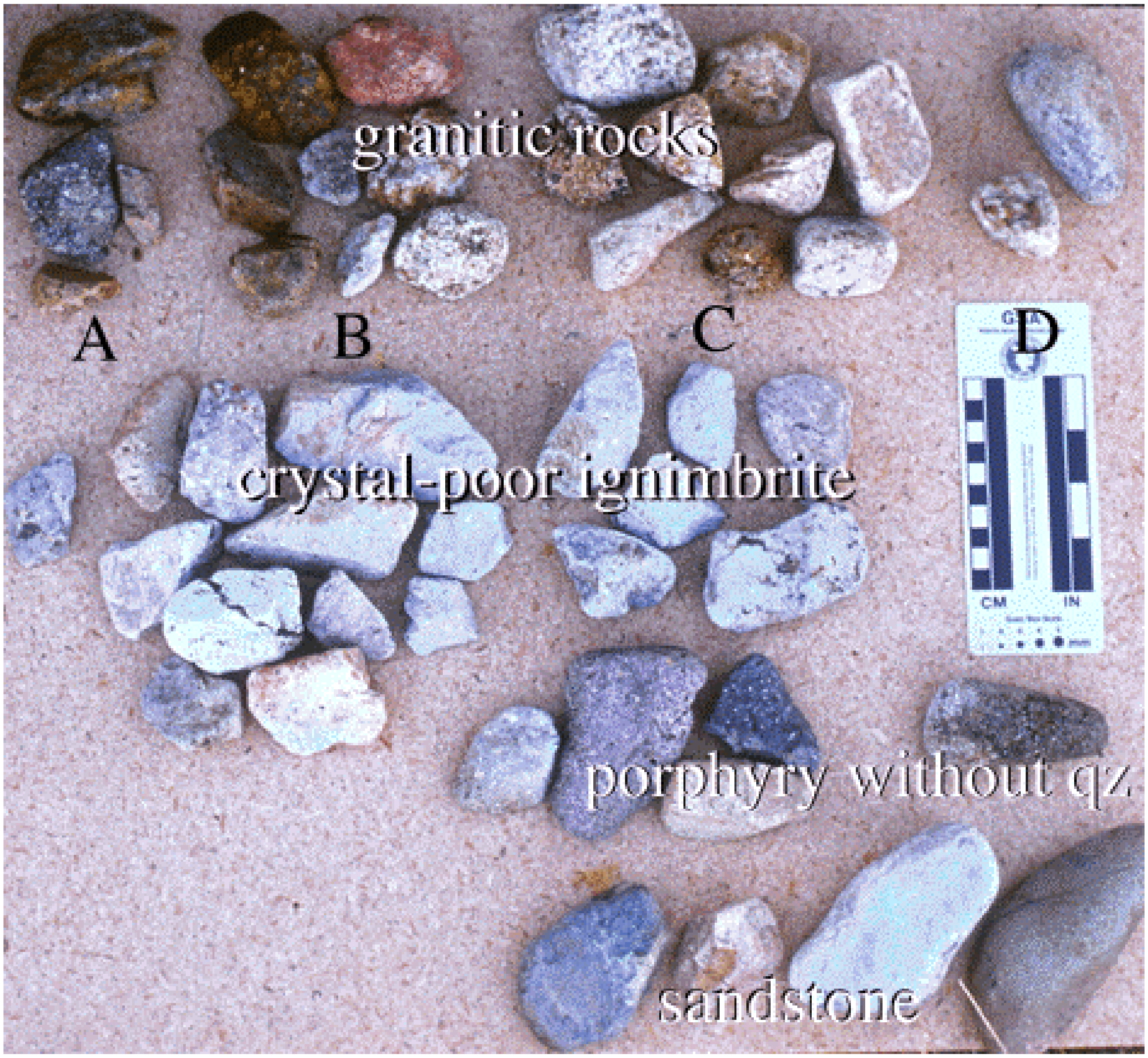


Figure 17.—Photograph showing pebble lithology (rows) and roundness (columns) of gravel, locality 11, Madera Canyon fan, west of Santa Rita Mountains. Abbreviations: A, angular; B, subangular; C, subrounded; D, rounded; qz, quartz.

Figure 18.—Photograph showing detail of crystal-poor ignimbrite boulder and cobbles at locality 11, Madera Canyon fan, west of Santa Rita Mountains.

Figure 19.—Photograph showing gravel interbedded with finer sediment in 50-foot roadcut, locality 15, Esperanza Wash fan at Canoa interchange, east of Sierrita Mountains.

Figure 20.—Photograph showing pebble gravel, sand, and silt deposited by sheetflood, locality 15, Esperanza Wash fan at Canoa interchange, east of Sierrita Mountains. Scale in upper center is about 6 inches long.

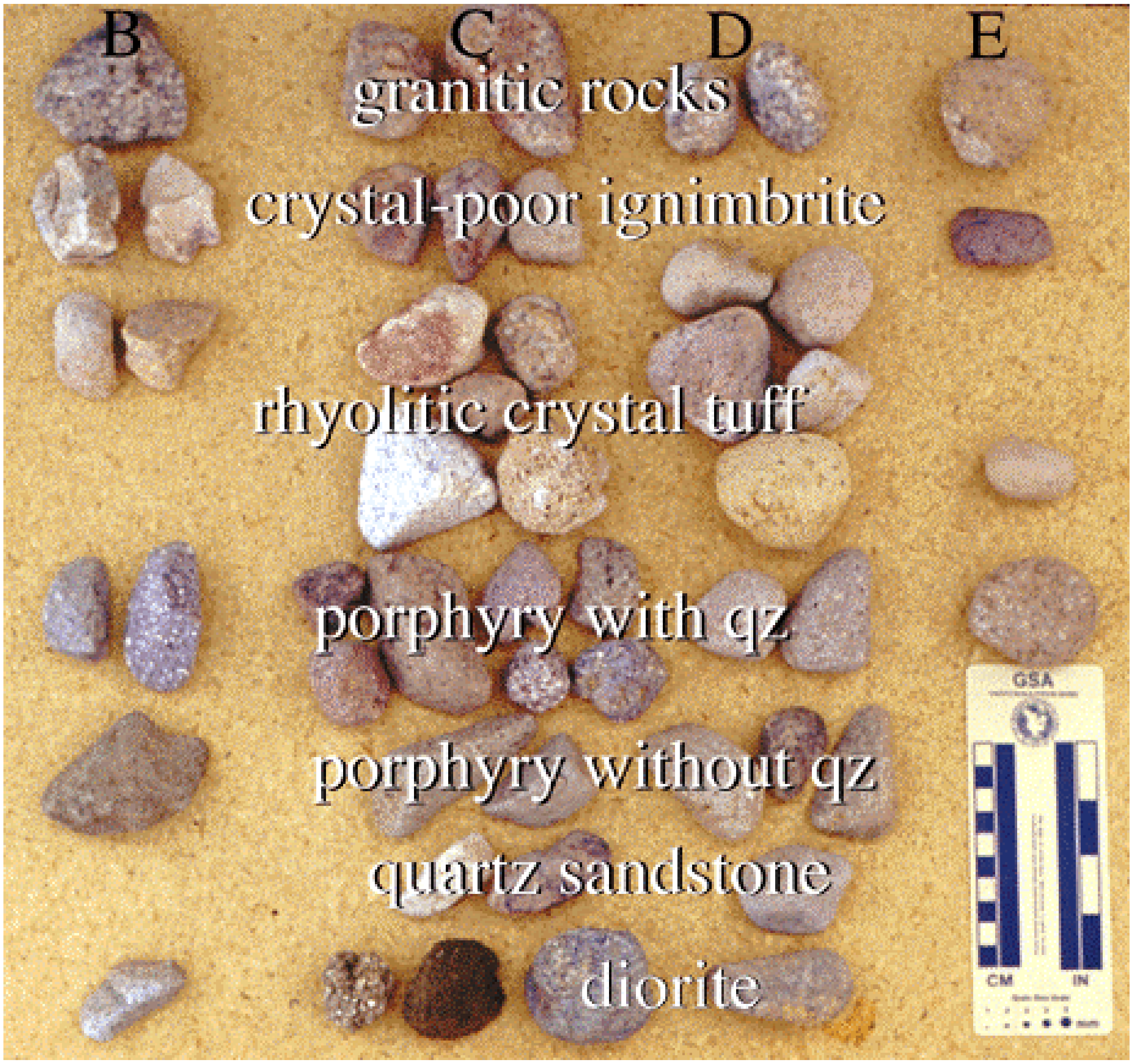


Figure 21.—Photograph showing pebble lithology (rows) and roundness (columns) of volcanic gravel, locality 15, Esperanza Wash fan at Canoa interchange, east of Sierrita Mountains. Abbreviations: B, subangular; C, subrounded; D, rounded; E, well rounded; qz, quartz.

Figure 22.—Photograph showing coarse pebble and cobble gravel deposited by streamflood, locality 20, head of Esperanza Wash, east of Sierrita Mountains.

Figure 23.—Photograph showing gravel interbedded with finer sediment in 30-foot roadcut, locality 16, Diablo Wash fan at Agua Linda interchange, east of Tumacacori Mountains. Yellow tape is about 90 inches long.

Figure 24.—Photograph showing streamflood gravel filling channel, locality 16, Diablo Wash fan at Agua Linda interchange, east of Tumacacori Mountains.

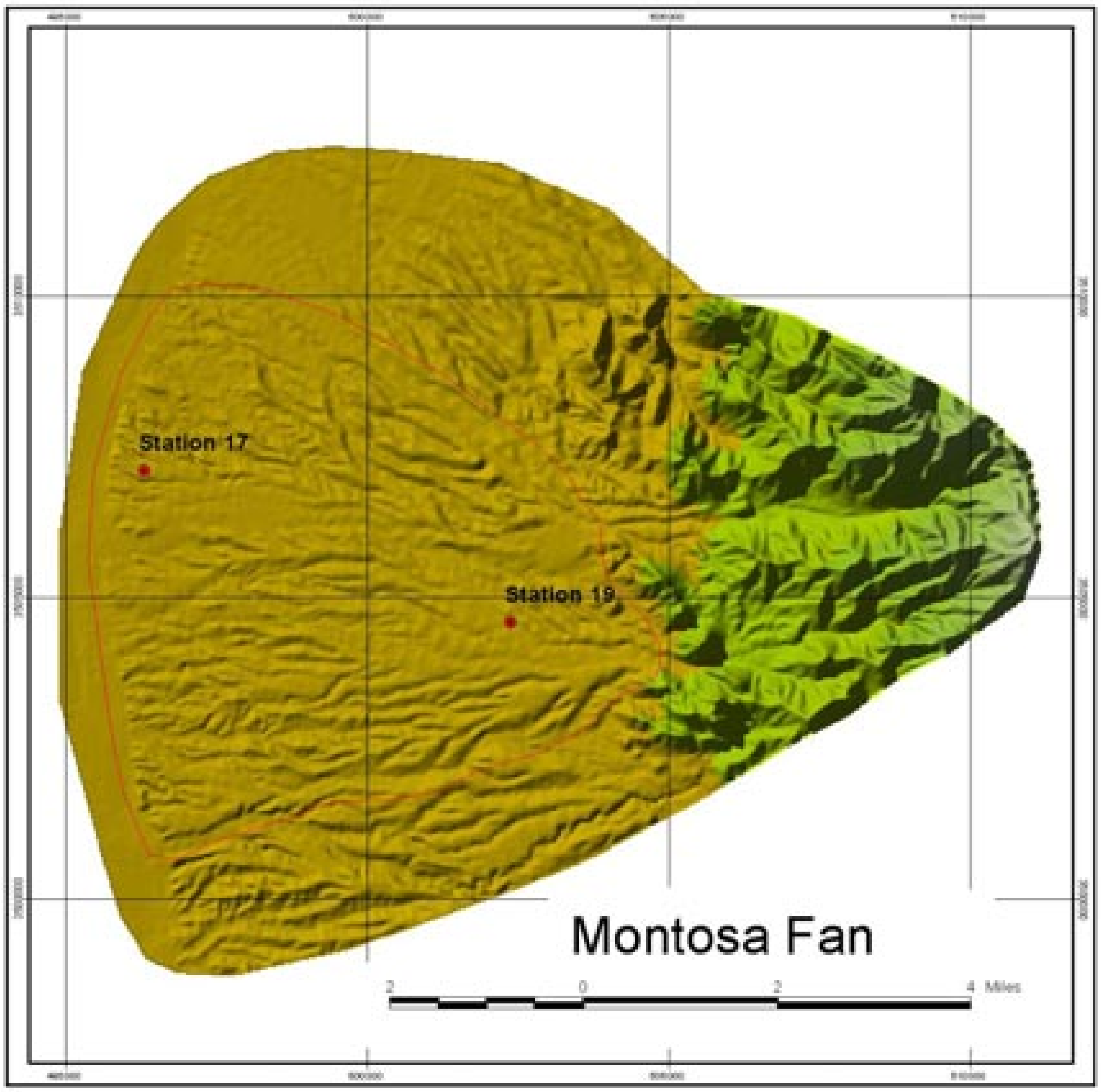


Figure 25.—Digital Elevation Model (DEM) of Montosa Canyon fan (outlined) and its source basin, west of Santa Rita Mountains.

Figure 26.—Photograph showing coarse pebble and cobble gravel over silt, locality 17, Montosa Canyon fan, east of Santa Rita Mountains. Tape about 70 inches in length.

Figure 27.—Photograph showing coarse pebble and cobble gravel, locality 19, near head of Montosa Canyon fan, east of Santa Rita Mountains.

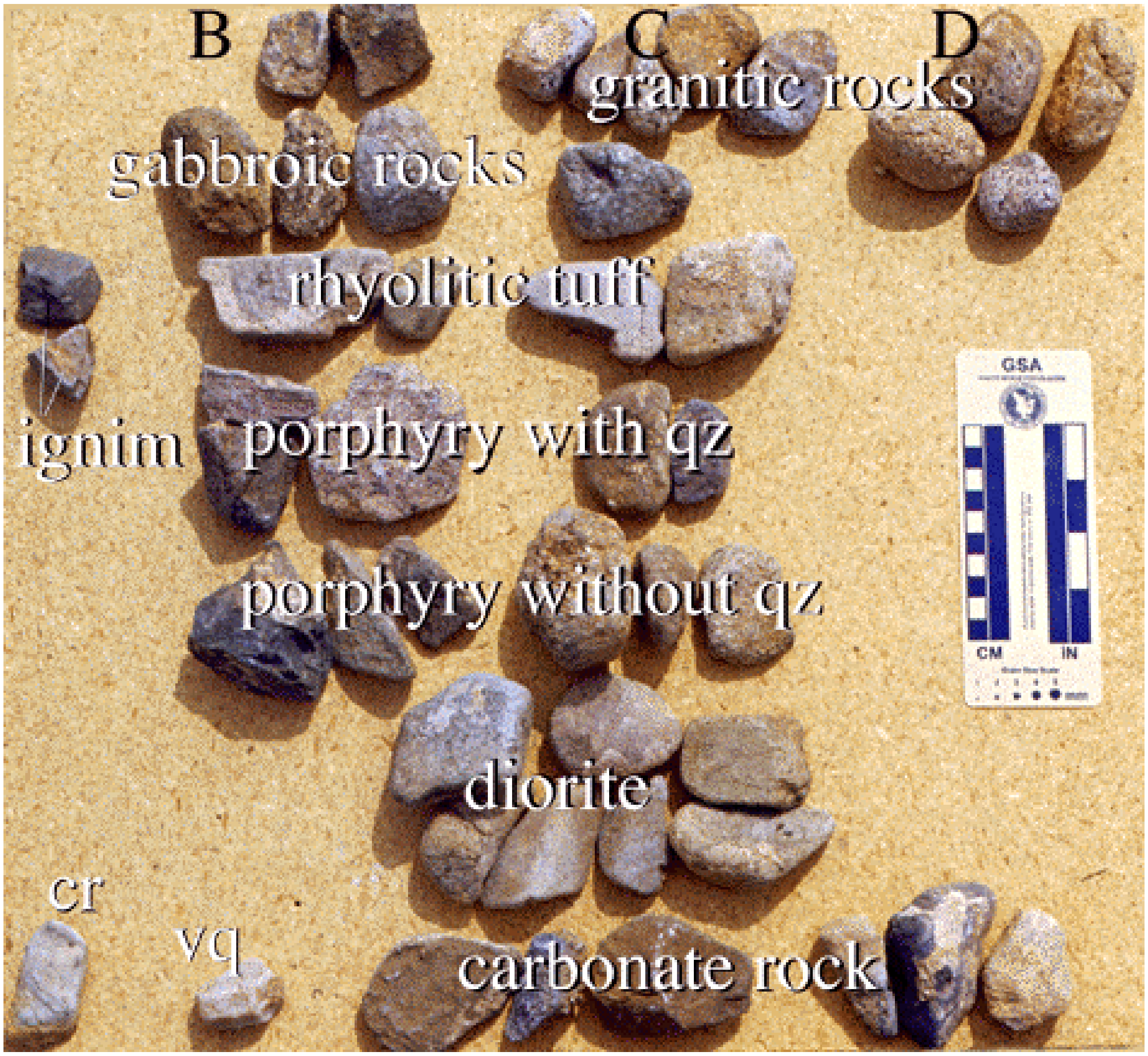


Figure 28.—Photograph showing pebble lithology (rows) and roundness (columns) of gravel, locality 17, Montosa Canyon fan, east of Santa Rita Mountains. Abbreviations: B, subangular; C, subrounded; D, rounded; ignim, ignimbrite; qz, quartz; cr, carbonate rock; vq, vein quartz.

Figure 29.—Photograph showing pebble lithology (rows) and roundness (columns) of gravel, locality 19, Montosa Canyon fan, east of Santa Rita Mountains. Abbreviations: B, subangular; C, subrounded; D, rounded; E, well rounded; ignim, ignimbrite; qz, quartz; ls, limestone; ss, sandstone.

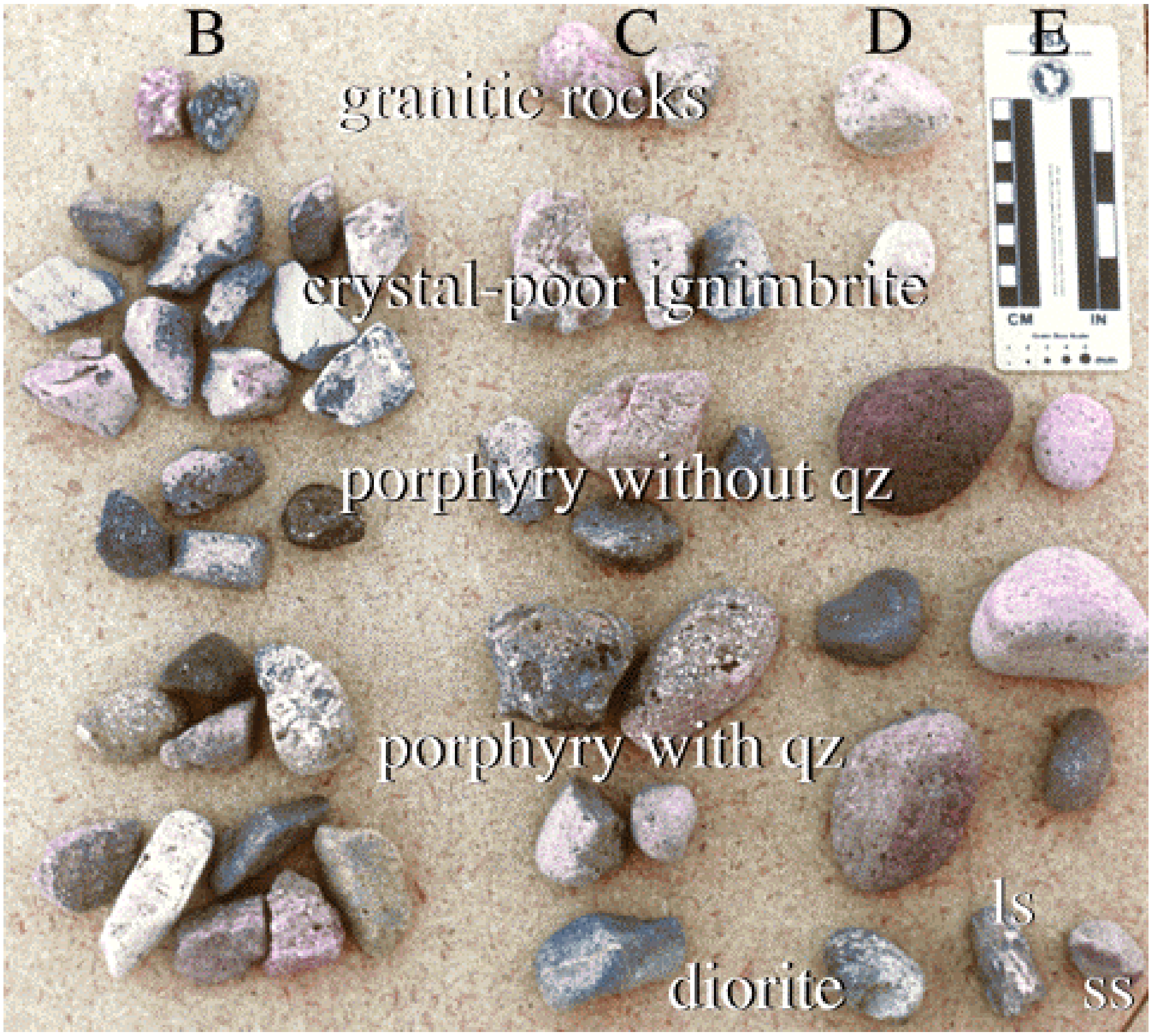


Figure 30.—Photograph showing pebble lithology (rows) and roundness (columns) of gravel, locality 14, modern channel of Santa Cruz River. Abbreviations: B, subangular; C, subrounded; D, rounded; E, well rounded; qz, quartz; ls, limestone; ss, sandstone.

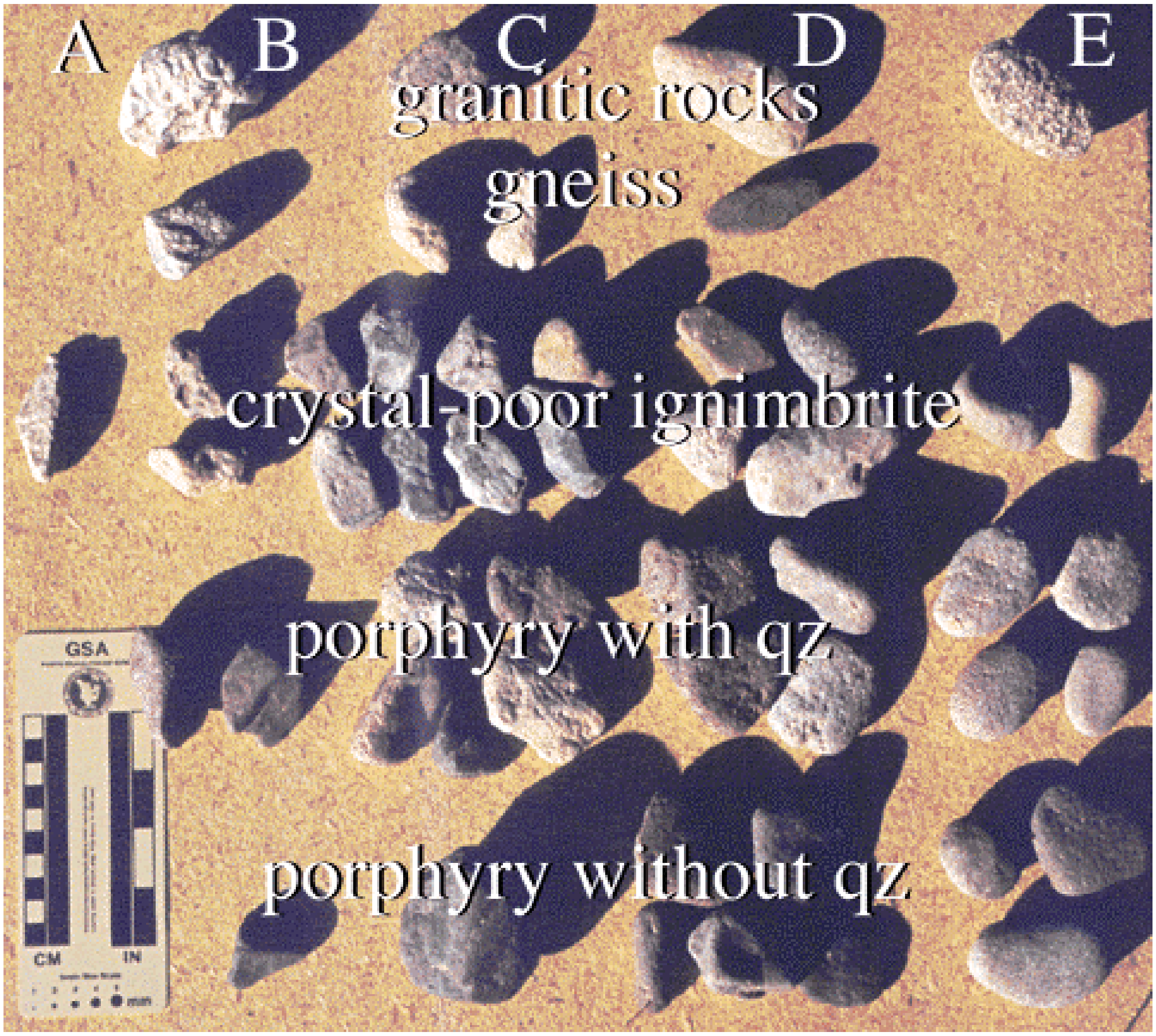
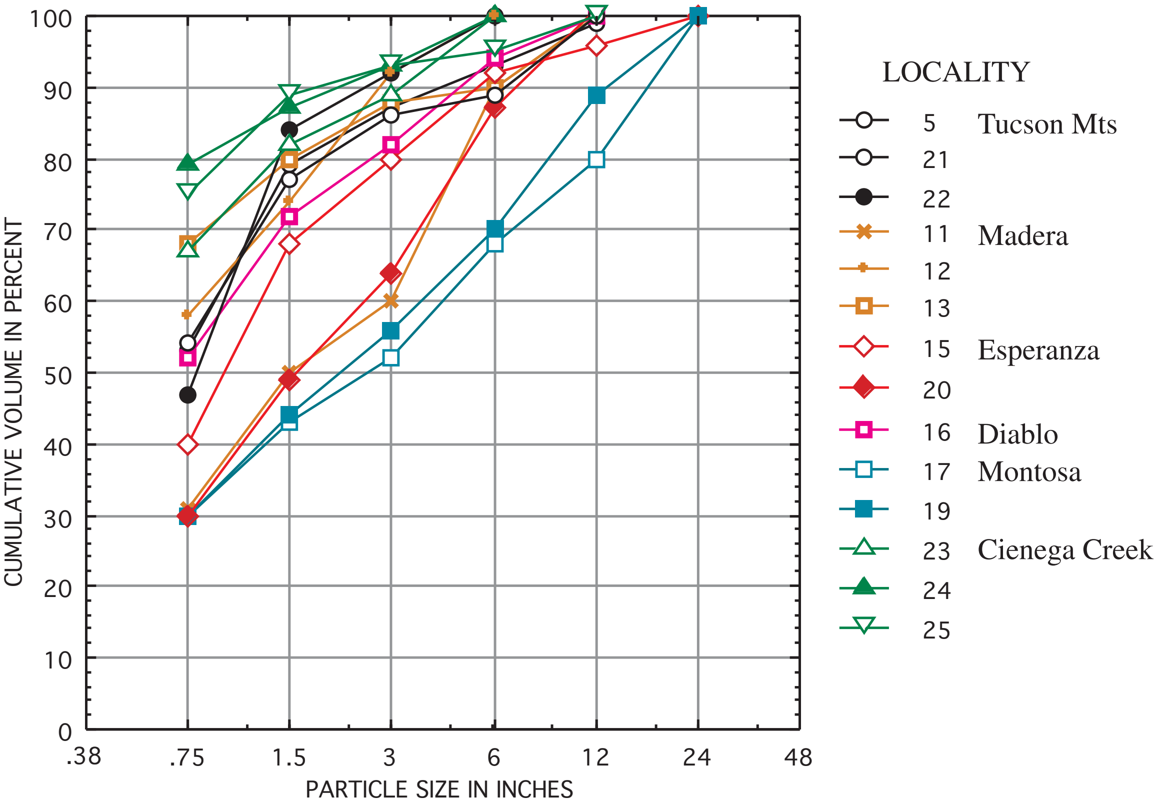
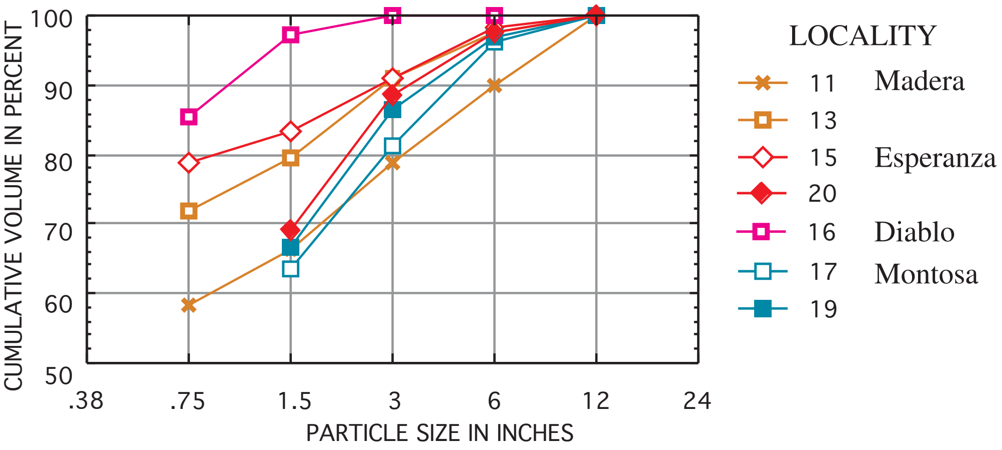


Figure 31.—Photograph showing pebble lithology (rows) and roundness (columns) of gravel, locality 2, beneath modern floodplain of Santa Cruz River north of Tucson Mountains. Abbreviations: A, angular; B, subangular; C, subrounded; D, rounded; E, well rounded; qz, quartz.



A--FIELD MEASUREMENT, BINNING METHOD
(ESTIMATES LONG DIMENSION OF PARTICLES)



B--PHOTO MEASUREMENT, COMPUTER SCREEN METHOD
(ESTIMATES INTERMEDIATE DIMENSION OF PARTICLES)

Figure 32.—Cumulative frequency curves showing (A) particle size determined by field measurement, binning method (estimates long dimension of particles) and (B) photo measurement, computer screen method (estimates intermediate dimension of particles).

Tables 1-6

Table 1.—Description of sample localities, Santa Cruz River valley, southeast Arizona. UTM, location specified by Universal Transverse Mercator Grid, zone 12, 1983 datum. Sample type: L, lithology; PS, particle size. Age of deposit: Ql, Late Pleistocene; Qm, Middle Pleistocene; Qe, latest Pliocene to Early Pleistocene; queried (?) where uncertain. Ages based on maps of Jackson, 1989 (localities 5, 9, 21, 22, 23, 24); Pearthree and Youberg, 2000 (localities 10 and 12); and estimates by the authors.

LOCALITY NUMBER	UTM NORTH	UTM EAST	SAMPLE TYPE	TYPE OF EXPOSURE	DEPOSITIONAL SETTING	AGE OF DEPOSIT
1	3592780	482629	L	SURFACE	COTTONWOOD FAN	MODERN
2	3587044	484600	L	WASTE PILE	SANTA CRUZ RIVER VALLEY FILL	-?-
5	3568122	498687	PS	ROAD CUT	TUCSON MOUNTAINS BAJADA	Qm
9	3572270	496375	L	STREAM BANK	TUCSON MOUNTAINS BAJADA	Qm?
10	3528739	503954	L	ROAD CUT	BOX CANYON FAN	Qm
11	3516275	510980	L,PS	STREAM BANK	MADERA CANYON FAN	Qm
12	3523839	502715	L,PS	ROAD CUT	MADERA CANYON FAN	Qm
13	3514113	500300	L,PS	STREAM BANK	MADERA CANYON FAN	Qm
14	3512034	496679	L	STREAM BED	SANTA CRUZ RIVER CHANNEL	MODERN
15	3517358	497941	L,PS	ROAD CUT	ESPERANZA WASH FAN	Qm?
16	3504260	493901	L,PS	ROAD CUT	DIABLO WASH FAN	Qm?
17	3507178	496295	L,PS	STREAM BANK	MONTOSA CANYON FAN	Qm?
19	3504568	502544	L,PS	STREAM BANK	MONTOSA CANYON FAN	Qm?
20	3520164	490832	L,PS	STREAM BANK	ESPERANZA WASH FAN	Ql?
21	3570196	497531	PS	GRAVEL PIT	TUCSON MOUNTAINS BAJADA	Qm
22	3571865	494526	L,PS	STREAM BANK	TUCSON MOUNTAINS BAJADA	Qm
23	3549634	504176	L,PS	GRAVEL PIT	CIENEGA CREEK FAN	Qe
24	3543934	526877	L,PS	GRAVEL PIT	CIENEGA CREEK FAN	Qe
25	3548592	518171	L,PS	PROSPECT PIT	CIENEGA CREEK FAN	Qe

Table 2.—Roundness and lithology of pebbles (approximately 1-3 inches in size), alluvial fan and other alluvial deposits, Santa Cruz River valley, southeast Arizona. LOC. NO., locality number. UTM, location specified by Universal Transverse Mercator Grid, zone 12, 1983 datum. Roundness classes A (angular), B (subangular), C (subrounded), D (rounded) and E (well rounded) are those of Pettijohn (1975, fig. 3-24). PCT, percent.

LOC. NO.	**UTM NORTH**	**UTM EAST**	**NUMBER COUNTED**	**ROUNDNESS CLASS IN PERCENT (PCT)**				
				PCT A	**PCT B**	**PCT C**	**PCT D**	**PCT E**
1	3592780	482629	100	25.0	53.0	21.0	1.0	0.0
2	3587044	484600	99	3.0	11.1	34.3	31.3	20.2
9	3572270	496375	107	51.4	42.1	6.5	0.0	0.0
10	3528739	503954	100	0.0	21.0	56.0	19.0	4.0
11	3516275	510980	99	9.1	39.4	43.4	8.1	0.0
12	3523839	502715	100	0.0	27.0	58.0	15.0	0.0
13	3514113	500300	100	0.0	32.0	61.0	7.0	0.0
14	3512034	496679	99	1.0	56.6	31.3	7.1	4.0
15	3517358	497941	100	0.0	16.0	50.0	30.0	4.0
16	3504260	493901	103	7.8	19.4	39.8	28.2	4.9
17	3507178	496295	99	2.0	40.4	48.5	9.1	0.0
19	3504568	502544	95	1.1	40.0	48.4	9.5	1.1
20	3520164	490832	103	5.8	24.3	63.1	6.8	0.0
22	3571865	494526	102	10.8	52.0	37.3	0.0	0.0
23	3549634	504176	101	0.0	25.7	56.4	15.8	2.0
24	3543934	526877	103	0.0	14.6	81.6	1.9	1.9
25	3548592	518171	103	1.9	16.5	65.0	15.5	1.0

Table 2. ——Continued.

LOC NO.	LITHOLOGY IN PERCENT							
	GNEISS	GRANITIC ROCKS	GABBROIC ROCKS	CRYSTAL -POOR IGNIM- BRITE	RHYOLITE CRYSTAL TUFF	VOLCANIC PORPHYRY WITH QUARTZ	VOLCANIC PORPHYRY WITHOUT QUARTZ	DIORITE
1	30.0	69.0	0.0	0.0	0.0	0.0	0.0	0.0
2	7.1	7.1	0.0	35.4	31.3	0.0	19.2	0.0
9	0.0	0.0	0.0	23.4	65.4	0.0	8.4	0.0
10	0.0	13.0	0.0	33.0	16.0	18.0	14.0	0.0
11	0.0	41.4	0.0	38.4	0.0	0.0	11.1	1.0
12	0.0	13.0	0.0	66.0	0.0	0.0	13.0	0.0
13	0.0	79.0	0.0	7.0	0.0	6.0	3.0	5.0
14	1.0	10.1	0.0	30.3	20.2	0.0	17.2	3.0
15	0.0	11.0	3.0	20.0	45.0	0.0	12.0	4.0
16	0.0	14.6	1.0	19.4	46.6	0.0	12.6	0.0
17	0.0	22.2	8.1	4.0	11.1	9.1	13.1	14.1
19	0.0	24.2	0.0	5.3	33.7	15.8	7.4	6.3
20	0.0	4.9	0.0	37.9	13.6	0.0	29.1	0.0
22	0.0	0.0	0.0	25.5	49.0	0.0	10.8	0.0
23	3.0	4.0	0.0	12.9	34.7	0.0	1.0	0.0
24	0.0	4.9	0.0	8.7	42.7	0.0	2.9	0.0
25	3.9	2.9	0.0	5.8	22.3	0.0	1.9	0.0

LOC. NO.	LITHOLOGY IN PERCENT					THREE MAJOR ROCK GROUPS IN PERCENT		
	BASALT	QUARTZ SAND- STONE	BROWN SAND- STONE	VEIN QUARTZ	CARBONATE ROCKS	PLUTONIC AND GNEISSIC ROCKS	VOLCANIC ROCKS	SEDIMENTARY ROCKS
1	0.0	0.0	0.0	1.0	0.0	99.0	0.0	0.0
2	0.0	0.0	0.0	0.0	0.0	14.1	85.9	0.0
9	0.0	0.0	0.0	2.8	0.0	0.0	97.2	0.0
10	2.0	1.0	2.0	0.0	1.0	13.0	83.0	4.0
11	0.0	4.0	4.0	0.0	0.0	42.4	49.5	8.1
12	0.0	4.0	4.0	0.0	0.0	13.0	79.0	8.0
13	0.0	0.0	0.0	0.0	0.0	84.0	16.0	0.0
14	0.0	2.0	15.2	0.0	1.0	14.1	67.7	18.2
15	0.0	5.0	0.0	0.0	0.0	18.0	77.0	5.0
16	2.9	2.9	0.0	0.0	0.0	15.5	81.6	2.9
17	0.0	0.0	0.0	2.0	16.2	44.4	37.4	16.2
19	0.0	0.0	3.2	0.0	4.2	30.5	62.1	7.4
20	14.6	0.0	0.0	0.0	0.0	4.9	95.1	0.0
22	0.0	0.0	14.7	0.0	0.0	0.0	85.3	14.7
23	0.0	12.9	14.9	3.0	13.9	6.9	48.5	41.6

24	0.0	18.4	16.5	0.0	5.8	4.9	54.4	40.8
25	0.0	22.3	27.2	1.0	12.6	6.8	30.1	62.1

Table 3.—Particle size measured in the field, alluvial fan gravel, Santa Cruz River valley, southeast Arizona. Binning method used (see discussion of methods). LOC. NO., Locality number; *, recalculated assuming 30 pct < 0.75-inch particles; UTM, location specified by Universal Transverse Mercator Grid, zone 12, 1983 datum.

LOC. NO.	**UTM NORTH**	**UTM EAST**	**SIZE CLASS IN INCHES DATA IN PERCENT**						**TOTAL**
			<0.75	**0.75-1.5**	**1.5-3**	**3-6**	**6-12**	**>12**	
5	3568122	498687	53	26	8	6	6	0	99
11	3516275	510980	31	19	10	30	10	0	100
12	3523839	502715	58	16	18	8	0	0	100
13	3514113	500300	68	12	8	2	10	0	100
15	3517358	497941	40	28	12	12	4	4	100
16	3504260	493901	52	20	10	12	6	0	100
17*	3507178	496295	30	13	9	16	12	20	99
19*	3504568	502544	30	14	12	14	19	11	100
20*	3520164	490832	30	19	15	23	14	0	99
21	3570196	497531	54	23	9	3	11	0	100
22	3571865	494526	47	37	8	8	0	0	100
23	3549634	504176	67	15	7	11	0	0	100
24	3543934	526877	79	8	6	7	0	0	100
25	3548592	518171	75	14	4	2	5	0	100

Table 4.—Particle size measured from selected digital photographs on computer screen using NIH Image, Santa Cruz River valley, southeast Arizona. --, insufficient resolution for measurement.

LOCALITY NUMBER	**LENGTH MEASURED (INCHES)**	**SIZE CLASS IN PERCENT**			
		0.75-1.5 INCHES	**1.5-3 INCHES**	**3-6 INCHES**	**6-12 INCHES**
11	360	8	13	11	10
13	350	7	12	6	3
15	500	5	8	7	2
16	240	12	3	0	0
17	240	--	18	15	4
19	420	--	20	10	3
20	350	--	19	9	3

Table 5.—Contingency table showing observed frequencies for roundness and lithology, pebble counts at all sample localities, Santa Cruz River valley, southeast Arizona.

LITHOLOGY	**ROUNDNESS CLASS**					**LITHOLOGY TOTAL**
	A	**B**	**C**	**D**	**E**	
Gneiss	7	16	18	4	0	45
Granitic rocks	29	103	142	42	4	320
Gabbroic rocks	0	6	3	3	0	12
Crystal-poor ignimbrite	33	151	156	31	5	376
Rhyolite crystal tuff	47	120	185	54	13	419
Volcanic porphyry with quartz	0	34	27	4	3	68
Volcanic porphyry without quartz	3	46	90	28	11	178
Diorite	0	5	25	3	0	33
Basalt	0	14	4	1	1	20
Quartz sandstone	0	10	48	12	4	74
Brown sandstone	2	21	66	12	2	103
Vein quartz	0	8	2	0	0	10
Carbonate rock	2	13	30	10	0	55
Roundness Total	123	547	796	204	43	1713*

*Total pebbles counted

Table 6A.—Contingency table modified for chi-square analysis of pebble roundness and lithology so that no more than 20 pct of cell values are less than 5 and no values are zero (criteria of Siegel, 1956). Rows for gabbroic rocks and vein quartz deleted; roundness classes A and B combined; and classes D and E combined.

LITHOLOGY	**ROUNDNESS CLASS**			**LITHOLOGY TOTAL**
	A+B	**C**	**D+E**	
Gneiss	23	18	4	45
Granitic rocks	132	142	46	320
Crystal-poor ignimbrite	184	156	36	376
Rhyolite crystal tuff	167	185	67	419
Volcanic porphyry with quartz	34	27	7	68
Volcanic porphyry without quartz	49	90	39	178
Diorite	5	25	3	33
Basalt	14	4	2	20
Quartz sandstone	10	48	16	74
Brown sandstone	23	66	14	103
Carbonate rock	15	30	10	55
Roundness Total	656	791	244	1691*

*Total pebbles counted

Table 6B.—Chi-square and other statistics, calculated from Table 6A.

STATISTIC	**VALUE**
Degrees of freedom	20
Chi Square	97.6
Chi Square P-Value	<.0001
Contingency Coefficient	.234