# GRAIN-SIZE AND TEXTURAL CLASSIFICATION OF COARSE SEDIMENTARY PARTICLES

TERENCE C. BLAIR[1] AND JOHN G. McPHERSON[2]
[1]*Blair & Associates, 1949 Hardscrabble Place, Boulder, Colorado 80303, U.S.A.*
[2]*Mobil Exploration and Producing Australia Pty Ltd., GPO Box L902, Perth 6001, Australia*

ABSTRACT: **The Udden–Wentworth grain-size scale is widely used as the standard for objective description of sediment, but it inadequately covers gravel, the dominant fraction in many environments such as alluvial fans. The scale is most detailed in the sand and mud fractions, where grades such as ''fine sand'' are defined by particle intermediate axial length ($d_I$). We propose similar detailed grades for gravel with $d_I$ boundaries consistently determined by extending the Udden–Wentworth scheme of multiples of 2 (whole $\phi$ increments). The 2 to 4 mm granule class ($-1$ to $-2$ $\phi$) in this system consists of just one grade, but the pebble class comprises four: *fine pebbles* with $d_I$ from 4 to 8 mm ($-2$ to $-3$ $\phi$), *medium pebbles* from 8 to 16 mm ($-3$ to $-4$ $\phi$), *coarse pebbles* from 16 to 32 mm ($-4$ to $-5$ $\phi$), and *very coarse pebbles* from 32 to 64 mm ($-5$ to $-6$ $\phi$). Coarser grades are *fine cobbles* with $d_I$ from 6.4 to 12.8 cm ($-6$ to $-7$ $\phi$), *coarse cobbles* from 12.8 to 25.6 cm ($-7$ to $-8$ $\phi$), *fine boulders* from 25.6 to 51.2 cm ($-8$ to $-9$ $\phi$), *medium boulders* from 51.2 to 102.4 cm ($-9$ to $-10$ $\phi$), *coarse boulders* from 102.4 to 204.8 cm ($-10$ to $-11$ $\phi$), and *very coarse boulders* from 204.8 to 409.6 cm ($-11$ to $-12$ $\phi$). These terms can be used in Folk's texture classification to derive detailed descriptions such as ''angular, poorly sorted, fine to coarse boulder conglomerate''.**

**This grain-size scheme is further extended to account for particles coarser than boulders ($d_I > 4.1$ m), which we collectively call *megaclasts*, and the sediment they comprise *megagravel* or, if lithified, *megaconglomerate.* Megagravel is divided into four classes based on $d_I$, including *blocks* from 4.1 to 65.5 m ($-12$ to $-16$ $\phi$), *slabs* from 65.5 to 1049 m ($-16$ to $-20$ $\phi$), *monoliths* from 1 to 33.6 km ($-20$ to $-25$ $\phi$), and *megaliths* from 33.6 to 1075 km ($-25$ to $-30$ $\phi$). The first three classes cover the coarsest sediment currently known. Their grades are *fine blocks,* with $d_I$ from 4.1 to 8.2 m ($-12$ to $-13$ $\phi$), *medium blocks* from 8.2 to 16.4 m ($-13$ to $-14$ $\phi$), *coarse blocks* from 16.4 to 32.8 m ($-14$ to $-15$ $\phi$), *very coarse blocks* from 32.8 to 65.5 m ($-15$ to $-16$ $\phi$), *fine slabs* from 65.5 to 131 m ($-16$ to $-17$ $\phi$), *medium slabs* from 131 to 262 m ($-17$ to $-18$ $\phi$), *coarse slabs* from 262 to 524 m ($-18$ to $-19$ $\phi$), *very coarse slabs* from 524 to 1049 m ($-19$ to $-20$ $\phi$), *very fine monoliths* from 1.0 to 2.1 km ($-20$ to $-21$ $\phi$), *fine monoliths* from 2.1 to 4.2 km ($-21$ to $-22$ $\phi$), *medium monoliths* from 4.2 to 8.4 km ($-22$ to $-23$ $\phi$), *coarse monoliths* from 8.4 to 16.8 km ($-23$ to $-24$ $\phi$), and *very coarse monoliths* from 16.8 to 33.6 km ($-24$ to $-25$ $\phi$). These grades also can be used in Folk's texture classification for objective sediment description. We reserve the *megalith* class and five attendant grades for even coarser megaclasts, with $d_I$ spanning from 33.6 to 1075.2 km ($-25$ to $-30$ $\phi$).**

## INTRODUCTION

The ''Udden–Wentworth'' size scale for detrital particles (Udden 1914; Wentworth 1922, 1935; Tanner 1969; Folk et al. 1970) is widely accepted and used as the practical standard for objective and detailed description of grain size needed for communicating observations and deductions about sediment and sedimentary rocks. This scale recognizes three fractions, gravel (2 to 4096 mm), sand (1/16 to 2 mm), and mud ($<$ 1/16 mm). The mud fraction has been divided into silt and clay classes, and the gravel fraction into granule, pebble, cobble, and boulder classes (Fig. 1). Udden (1914) devised more detailed subclasses called ''grades'', with boundaries defined by a logarithmic scale using 1 mm as the starting point. Coarser grade boundaries were established by progressive multiples of 2, and finer ones by progressive multiples of 1/2 (Fig. 1). Wentworth (1922) assigned the now widely used names for the sand grades, including very coarse sand (1 to 2 mm), coarse sand (1/2 to 1 mm), medium sand (1/4 to 1/2 mm), fine sand (1/8 to 1/4 mm), and very fine sand (1/16 to 1/8 mm; Fig. 1). Udden's (1914) silt grades are still used, including coarse silt (1/16 to 1/32 mm), medium silt (1/32 to 1/64 mm), fine silt (1/64 to 1/128 mm), and very fine silt (1/128 to 1/256 mm). The use of sieves for size analysis dictates that the intermediate axial length ($d_I$) of a grain is the one that determines classification (e.g., Folk 1974).

Krumbein (1934, 1938) devised the phi scale ($\phi$), based on the equation $\phi = -\log_2$ of the grain $d_I$ in mm, to convert the sediment grade boundary values from fractional numbers to more simple whole numbers. The negative sign in this equation causes an unnecessarily complicated inverse relationship between $\phi$ and $d_I$, rather than a direct one. This sign was added so that phi values in most of the sand fraction are positive (Fig. 1), exemplifying the historical emphasis on sand and the limited consideration of gravel. This emphasis also has resulted in more formal divisions (five) for the small size range covered by sand, than the four that have been established for the gravel fraction.

A better focus on gravelly sediment has developed during the last three decades because of an expanded interest in the deposits of rivers, piedmonts, glacial settings, volcanic slopes, and marine slopes, as well as in the rubbly deposits on the surface of other planets (e.g., Birkeland 1968; Boulton 1978; Lucchitta 1978; Siebert 1984; Blair 1987; Moore et al. 1989). This multidisciplinary attention has generated a need for both the systematic subdivision and the objective and detailed description of gravel deposits akin to what has been achieved for finer sediment. Four approaches have emerged to deal with this need. The first is to use a direct or comparative description, such as ''boulders 4 m across'', or ''boulders the size of Volkswagens''. A second approach is to propose more general terms not consistent with the Udden–Wentworth system, such as ''megaboulder'' (Sundell and Fisher 1985), or terms based only partly on size used primarily by those studying glacial deposits, such as ''diamicton'', ''tilloid'', ''mixtite'', ''symmictite'', ''psephites'', ''aquatillite'', ''megamictite'', ''teramictite'', and ''oromictite'' (e.g., Flint et al. 1960a, 1960b; Schermerhorn 1966). These terms are problematic because they are not self-explanatory, precise, or nongenetic—attributes critical to the objective description of sediment (e.g., Rodgers 1950; Crowell 1957). Fortunately, such terms have not taken hold, although ''diamicton'' is used especially by glaciologists for a poorly sorted, gravelly sediment texture.

A third approach to gravel characterization now widely used in place of objective description entails classifying a deposit into a choice of ''lithofacies'' from the Miall (1985) ''facies and architectural element code''. This code is based on the studies of river deposits, but is promoted and used by many as a comprehensive scheme applicable to other environments such as alluvial fans. One of the problems of this approach is that it deals with grain size only in the broadest sense, whether it is mud, sand, or gravel. Planar-cross-bedded gravel, for example, is classified in this code as ''Gp'' regardless of if it consists of granules or boulders (e.g., Cole and Stanley 1995). As applied by most users, this code also has a problematic genetic connotation. The ''Gp'' facies, for example, is interpreted by this system as a ''transverse bar'' of a river whether a river deposit or not, whether a ''bar'' or not, and regardless of flow regime (also see Bridge 1993 for discussion). This problem is compounded by the fact that pub-

JOURNAL OF SEDIMENTARY RESEARCH, VOL. 69, NO. 1, JANUARY, 1999, P. 6–19
 1073-130X/99/069-6/$03.00

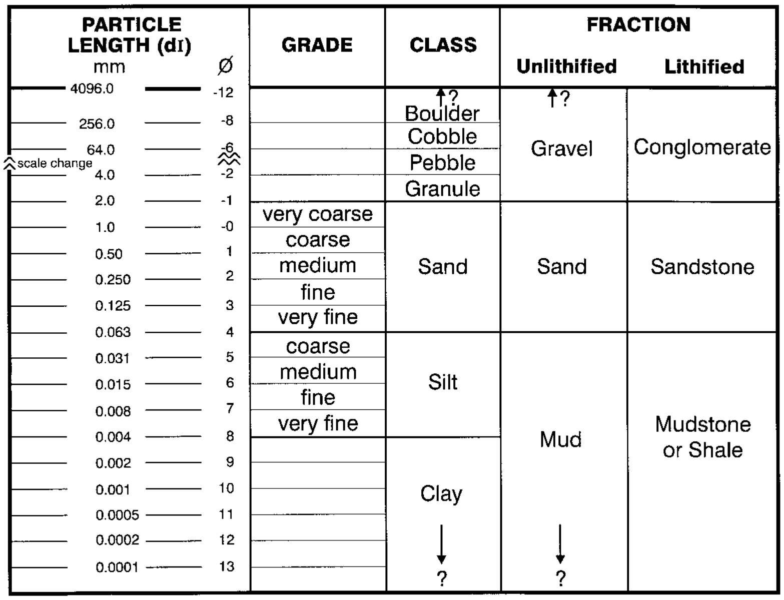



FIG. 1.—Widely used Udden–Wentworth sedimentary grain-size scale (after Udden 1914; Folk 1954, 1974; and Folk et al. 1970).

lished articles using the ''code'' commonly lack sufficient basic description, beginning with grain size and texture, for readers to otherwise determine the character or origin of the deposit.

The fourth approach, and the one promoted in this paper, is the logical extension of the Udden–Wentworth grade system into the gravel fraction, resulting in terms such as ''fine to medium boulder gravel'' (Blair 1987; Blair and McPherson 1994). The key purpose of this paper is to present and exemplify this fundamental scale for coarse sediment. A second objective is to demonstrate how these grades can be incorporated, with some modifications, into Folk's (1954, 1968; Folk et al. 1970) textural classification to produce descriptions of gravelly sediment rivaling in objectivity and detail those of finer sediment. The final goal is to summarize the terrestrial occurrence of coarse sedimentary particles by surveying their generative mechanisms, and the surficial processes capable of transporting this material.

## GRAVEL SIZE GRADES AND THEIR USE IN TEXTURAL CLASSIFICATION

### *Pebble, Cobble, and Boulder Size Grades*

With the exception of granules ($d_I$ between 0.2 and 0.4 cm or $-1$ and $-2$ $\phi$), all of the gravel classes in the Udden–Wentworth scheme span multiple whole-phi intervals, including pebbles with four ($d_I$ from 0.4 to 6.4 cm or $-2$ to $-6$ $\phi$), cobbles with two ($d_I$ from 6.4 to 25.6 cm or $-6$ to $-8$ $\phi$), and boulders with four ($d_I$ from 25.6 to 409.6 cm or $-8$ to $-12$ $\phi$; Fig. 1). We propose formal grades for these classes based on the particle intermediate axial length ($d_I$). These grades, consistent with Udden–Wentworth, are bounded by multiples of 2 (whole-phi numbers), and designated by the modifiers ''very fine'', ''fine'', ''medium'', ''coarse'', or ''very coarse''. Thus, the four phi units spanned by the pebble class define four grades: *fine pebbles,* with $d_I$ from 0.4 to 0.8 cm ($-2$ to $-3$ $\phi$); *medium pebbles,* with $d_I$ from 0.8 to 1.6 cm ($-3$ to $-4$ $\phi$); *coarse pebbles,* with $d_I$ from 1.6 to 3.2 cm ($-4$ to $-5$ $\phi$); and *very coarse pebbles,* with $d_I$ from 3.2 to 6.4 cm ($-5$ to $-6$ $\phi$; Fig. 2). These grades generally correlate to informal classes such as ''fine gravel'' or ''very coarse gravel'' denoted by Udden (1914) and Lane et al. (1947), or to the ''small pebble'' or ''large pebble'' classes listed, but not discussed, by Folk (1974, p. 26) in his phi-to-millimeter conversion graph. The finer of the pebble divisions, like sand, can be analyzed by mechanical sieving, and the coarser divisions by direct $d_I$ measurement (e.g., Folk 1974).

The proposed cobble and boulder grades are *fine cobbles* for clasts with $d_I$ from 6.4 to 12.8 cm ($-6$ to $-7$ $\phi$), *coarse cobbles* with $d_I$ from 12.8 to 25.6 cm ($-7$ to $-8$ $\phi$), *fine boulders* with $d_I$ from 25.6 to 51.2 cm ($-8$ to $-9$ $\phi$), *medium boulders* with $d_I$ from 51.2 to 102.4 cm ($-9$ to $-10$ $\phi$), *coarse boulders* with $d_I$ from 102.4 to 204.8 cm ($-10$ to $-11$ $\phi$), and *very coarse boulders* with $d_I$ from 204.8 to 409.6 cm ($-11$ to $-12$ $\phi$; Fig. 2). These grades are similar to the ''small cobble'', ''large boulder'', and other grades proposed by Lane et al. (1947), but employ terminology more consistent with the Udden–Wentworth scheme. For easier commitment to memory, the $d_I$ value bounding the cobble and boulder grades can be rounded off to a simple fraction or whole multiple of 1 m (Blair 1987). For example, fine boulders can be rounded off to the 1/4 to 1/2 m span; medium boulders to 1/2 to 1 m; coarse boulders to 1 to 2 m; and very coarse boulders to 2 to 4 m. This rounding probably is sufficiently accurate for field description given that the introduced error likely is less than operator or true sampling error. Though this rounding and division of 1 m mimics the fractionation of sand based on 1 mm, Udden's precise numerical definition of grade boundaries is maintained for consistency (Fig. 2).

### *Use of Gravel Size Grades in Textural Description*

Folk's (1954, 1968, 1974; Folk et al. 1970) textural classification for sediment and sedimentary rocks is widely used because of its objectivity and practicality. This classification is a flexible polynomial scheme in which various sediment attributes are systematically listed. The roots of this scheme are the textural classes (e.g., silty sand), which are qualified by other attributes in an adjective string. The long version of this scheme we find useful for describing clastic sediment is: color, fabric, dominant sedimentary structure, rounding, sorting, textural class. Other parameters that can be listed include clast shape and biological modifications. The pebble, cobble, and boulder grades proposed herein can be incorporated into Folk's textural classification in the same manner as the sand and silt grades with some slight modifications to better differentiate various gravel mixtures.

**Gravel Textural Classes.**—Our modified scheme for textural classes is summarized herein, with the proposed changes evident by comparing it to the original (Fig. 3A, B). In keeping with Folk's system, textural classes are differentiated first by the key (usually modal) component, and secondly by the lesser components, which are listed as descriptors of the key com-

| PARTICLE LENGTH (dI) km | m | mm | φ | GRADE | CLASS | FRACTION Unlithified | FRACTION Lithified |
|---|---|---|---|---|---|---|---|
| 1075 | | | -30 | very coarse | Megalith | Megagravel | Mega-conglomerate |
| 538 | | | -29 | coarse | | | |
| 269 | | | -28 | medium | | | |
| 134 | | | -27 | fine | | | |
| 67.2 | | | -26 | very fine | | | |
| 33.6 | | | -25 | very coarse | Monolith | | |
| 16.8 | | | -24 | coarse | | | |
| 8.4 | | | -23 | medium | | | |
| 4.2 | | | -22 | fine | | | |
| 2.1 | | | -21 | very fine | | | |
| 1.0 | 1048.6 | | -20 | very coarse | Slab | | |
| 0.5 | 524.3 | | -19 | coarse | | | |
| 0.26 | 262.1 | | -18 | medium | | | |
| | 131.1 | | -17 | fine | | | |
| | 65.5 | | -16 | very coarse | Block | | |
| | 32.8 | | -15 | coarse | | | |
| | 16.4 | | -14 | medium | | | |
| | 8.2 | | -13 | fine | | | |
| | 4.1 | 4096 | -12 | very coarse | Boulder | Gravel | Conglomerate |
| | 2.0 | 2048 | -11 | coarse | | | |
| | 1.0 | 1024 | -10 | medium | | | |
| | 0.5 | 512 | -9 | fine | | | |
| | 0.25 | 256 | -8 | coarse | Cobble | | |
| | | 128 | -7 | fine | | | |
| | | 64 | -6 | very coarse | Pebble | | |
| | | 32 | -5 | coarse | | | |
| | | 16 | -4 | medium | | | |
| | | 8 | -3 | fine | | | |
| | | 4 | -2 | | Granule | | |
| | | 2 | -1 | very coarse | Sand | Sand | Sandstone |
| | | 1 | 0 | coarse | | | |
| | | 0.50 | 1 | medium | | | |
| | | 0.25 | 2 | fine | | | |
| | | 0.125 | 3 | very fine | | | |
| | | 0.063 | 4 | coarse | Silt | Mud | Mudstone or Shale |
| | | 0.031 | 5 | medium | | | |
| | | 0.015 | 6 | fine | | | |
| | | 0.008 | 7 | very fine | | | |
| | | 0.004 | 8 | | Clay ↓ ? | | |
| | | 0.002 | 9 | | | | |
| | | 0.001 | 10 | | | | |
| | | 0.0005 | 11 | | | | |
| | | 0.0002 | 12 | | | | |
| | | 0.0001 | 13 | | | | |

FIG. 2.—Modified Udden–Wentworth grain-size scale proposed to better differentiate coarse sediment.

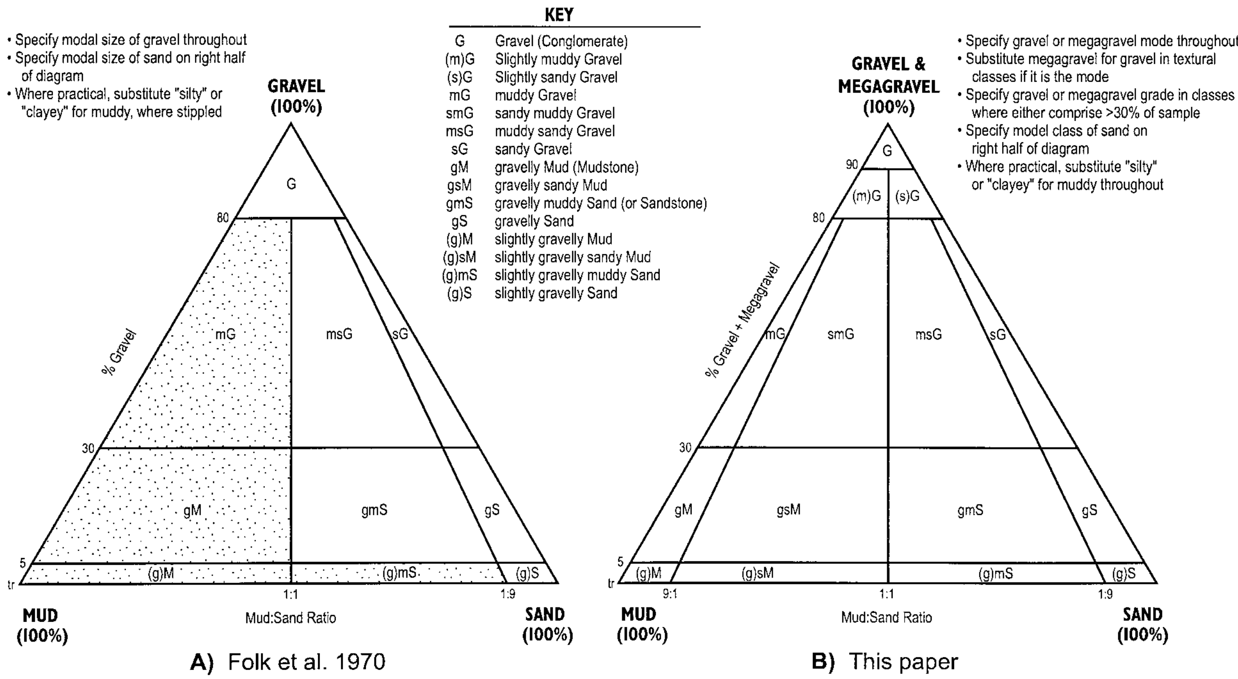


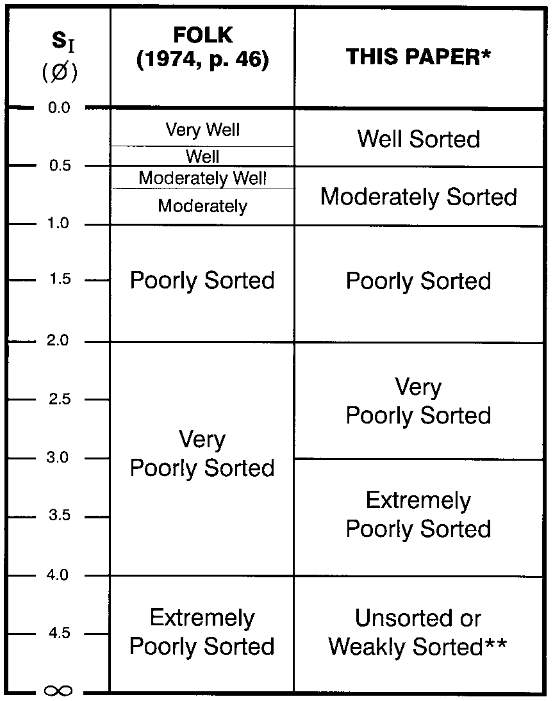

FIG. 3.—**A)** Commonly used sediment textural classification scheme (after Folk et al. 1970). **B)** Proposed adjustments to the Folk textural classification for better coverage of gravelly sediment.

ponent. Gravelly sediment in this new scheme, like the original, is categorized as one of 15 textural classes based first on the amount (weight percent) of gravel, and secondly on whether the mud-to-sand ratio of the rest of the sample is $>$ 9:1, between 9:1 and 1:1, between 1:1 and 1:9, or $<$ 1:9 (Fig. 3B). These texture types are illustrated as partitions of a triangle with poles representing 100% gravel, 100% sand, and 100% mud. Five texture families are differentiated on the basis of ranges of gravel volume, each comprising a tier on the triangle, and containing a similar style of modifying terms. Sediment composed of $>$ 90% gravel (tier 1) is simply classified as *gravel,* or where lithified, conglomerate. If the gravel content of a deposit is 80–90% (tier 2), then the textural term includes a modifier denoting whether sand or mud makes up the majority of the remaining sediment, giving rise to *slightly muddy gravel* or *slightly sandy gravel* divisions (Fig. 3B). For sediment with gravel content between 30 and 80% (tier 3), four textures are differentiated on the basis of the $>$ 9:1, 9:1 to 1:1, 1:1 to 1:9, or $<$ 1:9 mud-to-sand ratios. These are, respectively, *muddy gravel, sandy muddy gravel, muddy sandy gravel,* and *sandy gravel* (Fig. 3B). In sediment where the gravel volume is 5–30% (tier 4), four textures are designated using the same mud-to-sand ratios: *gravelly mud, gravelly sandy mud, gravelly muddy sand,* and *gravelly sand.* The adjective *slightly* precedes each of these tier 4 textural classes in the case where gravel constitutes a trace to 5% of the sediment (tier 5, Fig. 3B).

Like the original scheme (Fig. 3A), the modal gravel class is specified in all fields (e.g., ''cobbly sandy mud''), the modal sand grades are specified where the sand-to-mud ratio is $>$ 1:1 (e.g., ''slightly pebbly, muddy, fine to medium sand''), and the term *silt* or *clay* is substituted for *mud* where determined (e.g., ''slightly pebbly, silty, fine to medium sand''). We propose, in addition, that the modal and common gravel grade(s) be provided where the gravel content of the sediment mixture is $=$ 30% (e.g., ''muddy, fine cobbly, coarse to very coarse pebble gravel'', or ''slightly sandy, medium to coarse boulder gravel''). Optionally, the gravel grades can also be provided for more accurate description of sediment mixtures with trace to 30% gravel (e.g., ''medium to fine pebbly, granular, coarse to very coarse sand''). In all cases, the various modifier grades are listed in order of increasing abundance, consistent with Folk's system.

**Sorting Terms.**—The descriptive textural classes are further characterized by a sorting term using the system of Folk (1968, 1974) and Folk et al. (1970), modified particularly within the more poorly sorted realm to better differentiate degrees of sorting encountered in gravelly sediment (Fig. 4). Folk's sorting categories are bounded by whole-phi numbers of calculated standard deviation ($S_I$, the Inclusive Graphic Standard Deviation parameter), using percentiles (in phi) from a cumulative curve of an analyzed sample (Folk 1974, p. 46), where $S_I = (\phi_{84} - \phi_{16})/4 + (\phi_{95} - \phi_5)/6.6$. Folk's categories of sorting are assigned the descriptive terms ''very well sorted'' for $S_I$ values between 0.00 and 0.35 $\phi$, ''well sorted'' for $S_I$ between 0.35 and 0.50 $\phi$, ''moderately well sorted'' for $S_I$ between 0.5 and 0.7 $\phi$, ''moderately sorted'' for $S_I$ between 0.7 and 1.0 $\phi$, and ''poorly sorted'' for $S_I$ between 1.0 and 2.0 $\phi$. In contrast to the five detailed sorting categories in this scheme into which muddy and sandy sediment commonly plot, the more poorly sorted sediment domain typical of gravelly sediment are provided just two categories, ''very poorly sorted'' for $S_I$ values between 2.0 and 4.0 $\phi$, and ''extremely poorly sorted'' for $S_I > 4.0\ \phi$. We propose adjusting this more poorly sorted domain to contain three categories. These are *very poorly sorted* for $S_I$ between 2.0 and 3.0 $\phi$, *extremely poorly sorted* for $S_I$ between 3.0 and 4.0 $\phi$, and *weakly sorted* or *unsorted* for $S_I > 4.0\ \phi$ (Fig. 4). *Unsorted* is used in the latter case unless some indication of grain segregation, such as grading, is apparent in the deposit despite its $S_I > 4.0\ \phi$ value, in which case the term *weakly sorted* instead is used. To simplify and balance Folk's sorting scheme, we further propose to reduce the number of categories in the better sorted realm to two, *well sorted* and *moderately sorted* (Fig. 4). As with the original Folk scheme, the proposed sorting categories are used as adjectives of the textural class (e.g., poorly sorted, slightly granular, fine to coarse pebble gravel). Also, as proposed by Folk, the sorting terminology for a bimodal mix is characterized independently for each mode (e.g., ''well-sorted, bimodal, fine and coarse boulder gravel'').

Both the original and modified versions of these sorting categories require quantitative grain-size analysis, data relatively easy to generate using standard laboratory sieve, pipette, and laser-particle methods for sediment finer than about coarse pebbles ($d_I < 1.6$ cm or $-4\ \phi$), though some error




* Follow Folk's exception for bimodality

** Use "Weakly Sorted" for $S_I > 4.0$ where some grain segregation such as grading is apparent, otherwise classify as "Unsorted."

FIG. 4.—Sorting classification of Folk (1974; middle column) based on the Inclusive Graphic Standard Deviation values ($S_I$), and the proposed adjustments to the Folk sorting scheme (right column).

is introduced by combining these methods (e.g., Folk 1974; Konert and Vandenberge 1997). Quantitative grade abundances are more difficult to obtain for coarser-grained sediment mixtures, especially those with cobbles and boulders, because their size precludes standard sieve analysis. One approach to this problem is to compare size distributions and parameters such as $S_I$ only for the sediment sizes that can be handled in the laboratory. We have found in our studies that focusing laboratory analyses on sediment of medium pebble grade and finer ($d_I < 1.6$ cm or $-4\ \phi$) is a useful though arbitrary cutoff that allows standardized comparison and important discrimination of sediment consistently based on weight percent. Another method for determining size distributions of coarse gravel is to combine the results of standard laboratory size analysis of the fraction that can be processed in the laboratory with data from coarser constituents obtained from scaled photographs of the sediment in a planar (usually vertical) exposure. In this case, the amount of each of the various coarse ($\geq 1.6$ cm or $-4\ \phi$) grades present in the sample is determined by point-counting the area of the photograph they comprise (Blair 1987). These area-percent data are used as a proxy for, and prorated and combined with, the weight-percent data obtained from the finer fraction, the latter also prorated on the basis of its area of the scaled photograph. This method is similar to determining the size distribution of a sandstone by thin-section point counting, and it probably also contains the same inaccuracies such as overestimation of elongated grains (e.g., Krumbein 1935; Greenman 1951; Friedman 1958). This area-percent method of size analysis of coarse sediment more recently has been achieved digitally by computer imaging of sediment photographs collected with a video camera, a method called photo-sieving (Ibbeken and Schleyer 1988).

Folk et al. (1970, p. 947) also offered a field method for estimating the sorting class of sediment without the benefit of quantitative size analysis. We find this method valuable, and also simple to use given our modified sorting classification and proposed gravel grades (Fig. 4). Sorting is estimated in this procedure by examining the central two-thirds of the range of grain sizes (i.e., disregard the coarsest one-sixth and finest one-sixth of the sedimentary particles). If the central two-thirds of the size population is of just one size grade, the sediment is classified as well sorted. A range of two grades denotes moderate sorting, a three-grade range denotes poor sorting, a four-grade range is very poorly sorted, a five-grade range is extremely poorly sorted, and a six-grade range is either weakly sorted or unsorted.

**Rounding.**—Another gravel attribute that can be objectively described is roundness. This attribute is typified with terms such as ''well rounded'' or ''subangular'' using a standard index (Krumbein 1941; Powers 1953). The rounding descriptor is placed before sorting in the Folk scheme (e.g., ''subangular, moderately sorted, fine to medium pebble gravel''). A range in degrees of rounding is listed where such variation is common (e.g., ''subrounded to rounded, well-sorted, coarse cobble gravel''). In the case of a gravel deposit with two prominent and nongradational rounding attributes, both are listed and combined by the conjunction ''and'' (e.g., ''well-rounded and angular, poorly sorted, fine to very coarse pebble gravel''). Some gravel mixtures may have more than one typical roundness attribute that is size specific. In this case, the rounding terms are intermixed with the textural class, with each rounding term placed immediately before the respective grain size (e.g., ''weakly sorted, angular very coarse sandy, well-rounded fine to coarse pebble gravel'').

**Fabric.**—Three objective aspects of fabric useful to gravel description are: (1) whether the gravel is *clast-supported, matrix-supported,* or *variably clast- to matrix-supported;* (2) whether the deposit is *graded* or *ungraded,* and if so, whether it is *normally graded* or *inversely graded;* and (3) whether or not the various clast axes have a preferred *(organized)* or random *(disorganized)* orientation (e.g., Krumbein 1939; Walker 1975). A simple shorthand procedure to characterize axis fabric is to first identify whether this fabric is disorganized or organized and, if the latter, to identify the orientation of both the long *(a)* axis and the intermediate *(b)* axes. Following Walker (1975), these orientations are abbreviated as: p = horizontal and parallel to slope, t = horizontal and transverse to slope, v = vertical, and i = imbricate. The shorthand scheme for river-bed gravel, for example, with *a* axes preferentially oriented transverse to flow, and with *b* axes preferentially dipping upslope, is a/t, b/i (Walker 1975). The terms ''matrix-supported'' or ''variably clast- to matrix-supported'' typically are listed in the description if this fabric attribute is common. In contrast, ''clast support'' tends to not be mentioned, although this characteristic can be listed for clarity (e.g., ''clast-supported, inversely graded, organized (a/p b/v), subangular to angular, weakly sorted, clayey, pebbly, cobbly, fine to medium boulder gravel'').

**Other Descriptive Parameters.**—The descriptive string of fabric, rounding, sorting, and textural class may be further characterized by listing other objective parameters such as color, biological modifications, shape, and sedimentary structures. Color may be general or detailed, the latter option listing a Munsell system number. Biological modifications of the sediment include rooting, burrowing, boring, and bioturbation. These attributes provide important and objective environmental information, and can be added to the description by listing both the modification type and its intensity (e.g., ''extensively rooted. . .'' or ''commonly burrowed. . .''). In the latter case, the qualifiers ''abundantly, commonly, slightly, rarely, or unburrowed'' are useful. Shape may include terms, per Wadell (1935) and Krumbein (1941), such as spherical, discoidal, platy, bladed, or tabular. Sedimentary structure names should follow the established terminology (e.g., McKee and Weir 1953; Ingram 1954; Reineck and Singh 1980; Allen 1982) for clarity, and be limited to objective, nongenetic terms (e.g., ''brown, thick and horizontally bedded, sparsely rooted, variably clast- to matrix-supported, normally graded, organized (a/p, b/i), discoidal, angular, very poorly sorted, slightly sandy, fine to coarse pebble gravel'').

Examples of this proposed gravel description system are provided in Figures 5 and 6.

## BEYOND BOULDERS: CLASSIFYING THE COARSEST SEDIMENTARY PARTICLES

### *Megaclasts, Megagravel, and Megaconglomerate*

The upper size limit of boulders is placed at $d_I$ = 4.1 m (−12 **ϕ**; e.g., Wentworth 1922; Tanner 1969; Folk 1974), yet coarser particles have been documented in a variety of depositional environments. Research on the deposits of these environments requires a clear and consistent classification for this coarsest end of the grain-size spectrum. We herein propose a new fraction of sediment size to account for these *megaclasts* called *megagravel* or, if lithified, *megaconglomerate* (Fig. 2). We further propose four new size classes for the megagravel fraction, *block, slab, monolith,* and *megalith,* based on particle $d_I$, and by consistently extending the Udden–Wentworth system beyond the boulder realm. The term ''block'' has long been used to designate clasts coarser than boulders (e.g., Saussure 1796; Playfair 1802; Trowbridge 1911; Simons et al. 1966; Sundell and Fisher 1985). We herein formally define the *block* class to account for particles with a $d_I$ from 4.1 to 65.5 m (−12 and −16 **ϕ**). Four grades bounded by whole-phi units are present in this class: *fine blocks* with $d_I$ from 4.1 to 8.2 m (−12 to −13 **ϕ**), *medium blocks* from 8.2 to 16.4 m (−13 to −14 **ϕ**), *coarse blocks* from 16.4 to 32.8 m (−14 to −15 **ϕ**), and *very coarse blocks* from 32.8 to 65.5 m (−15 to −16 **ϕ**; Fig. 2). Blocks and blocky sedimentary facies are exemplified in Figure 7.

The term ''slab'' is commonly used for geological entities of significant size, especially those related to slope failures (e.g., Masson et al. 1998). We formally designate the *slab* class to cover particles with a $d_I$ between 65.5 and 1049 m (Fig. 2). Grades within this class, bounded by whole-phi units, are *fine slabs* with $d_I$ from 65.5 to 131 m (−16 to −17 **ϕ**), *medium slabs* from 131 to 262 m (−17 to −18 **ϕ**), *coarse slabs* from 262 to 524 m (−18 to −19 **ϕ**), and *very coarse slabs* from 524 to 1049 m (−19 to −20 **ϕ**). The coarsest sedimentary particles documented on Earth are monolithic in stature, having $d_I$ as large as 1 to 20 km (e.g., Siebert 1984; Brocher and ten Brink 1987; Moore et al. 1989). We propose the *monolith* class to account for these megaclasts (Fig. 2). This class is divided into five grades bounded by whole-phi units: *very fine monoliths* with a $d_I$ from 1.0 to 2.1 km (−20 to −21 **ϕ**), *fine monoliths* from 2.1 to 4.2 km (−21 to −22 **ϕ**), *medium monoliths* from 4.2 to 8.4 km (−22 to −23 **ϕ**), *coarse monoliths* from 8.4 to 16.8 km (−23 to −24 *ϕ*), and *very coarse monoliths* from 16.8 to 33.6 km (−24 to −25 *ϕ*; Fig. 2). Sedimentary deposits bearing slabs and monoliths are exemplified in Figure 8.

We reserve the *megalith* class for heretofore undocumented coarser sedimentary particles. Whole-phi-bounded *very fine, fine, medium, coarse,* and *very coarse megalith* grades are established to cover such megaclasts, with $d_I$ spanning from 33.6 to 1075 km (−25 to −30 *ϕ*; Fig. 2). The rock slides that spawned the submarine rock avalanches illustrated in Figure 8E, for example, were of megalith size prior to their break up into monolith-rich deposits.

Megaclasts can be incorporated into the modified Folk textural classification scheme by adding them to the gravel fraction in the gravel–sand–mud triangular diagram, to form a megagravel+gravel–sand–mud plot (Fig. 3B). Thus, to determine textural classes, the pigeonhole spot is first located by plotting the estimated or calculated volume percentages, and then the mode is used to determine whether this class is identified as gravel or megagravel. The definitions of sorting, rounding, fabric, and other descriptive parameters remain the same except that they are expanded to incorporate the megaclasts. Thus, the proximal part of the submarine rock-avalanche deposits illustrated in Figure 8E may be described as ''angular, unsorted, blocky, slabby, very coarse to very fine monolith megagravel''.

## TERRESTRIAL OCCURRENCE OF COARSE PARTICLES

Gravel and megagravel are found in a variety of terrestrial sedimentary environments where such clasts are generated, and where processes capable of coarse-particle transport are operative. Our final section surveys these generative and transport mechanisms from the perspective of grain size.

### *Generation of Gravel and Megagravel*

Gravel and megagravel originate at or near the Earth's surface by a variety of physical weathering mechanisms that disintegrate bedrock, especially tectonic fracturing, jointing, shearing, and faulting. Breakdown of bedrock by these mechanisms is accentuated by other weathering processes such as ice wedging, salt crystallization, exfoliation, and mineral oxidation, hydrolysis, and dissolution (Ritter 1975; Church et al. 1979). The formation of gravel and megagravel is strongly promoted by the existence of relief, especially tectonic topography where relief is coincident with fracturing, jointing, shearing, and faulting. The specific gravel grades yielded by physical weathering are dependent upon factors such as spacing or density of the tectonic discontinuities, and the splitting properties of the bedrock (Blair and McPherson 1994). Bedrock splitting is controlled by the presence or absence of internal planes of weakness or geologic discontinuities such as bedding planes, foliation planes, lithologic contacts, and inherited joints or faults. Isotropic bedrock such as granite commonly react to tectonic stress by jointing and fracturing at an equidimensional spacing that yields abundant boulders and blocks, whereas the same stress in layered volcanic rocks yields abundant pebbles and cobbles. Rocks with ''coarse'' splitting planes, such as thick-bedded sedimentary rocks or coarsely foliated metamorphic rocks, weather along these zones to yield abundant boulders and cobbles. Gravel and megagravel also are liberated by cataclastic shearing between rock (Higgens 1971), and can be formed rapidly through disintegration of destabilized bedrock slopes that transform into rock avalanches. Coarse sediment may also form by destabilization of rock slopes induced by external affects such as earthquakes or extraterrestrial impacts. Gravel may also be of multicycle origin, yielded through erosion of older gravelly deposits.

### *Gravel and Megagravel Transport*

Gravel and megagravel are transported at the Earth's surface by a variety of sedimentary processes, which decrease in number as grain size increases because of mechanical limitations and megaclast availability. We provide an overview of these key coarse-particle transport processes, based on our experience and a literature survey, as a way to summarize the terrestrial distribution of the gravel and megagravel grades. These processes are organized into mechanical classes identified by the main agent of transport, and with a focus on the size–process relationship, expanding on the ''fluid gravity flow'' versus ''sediment gravity flow'' scheme of Middleton and Hampton (1976). This scheme is expanded to better differentiate and categorize the types of fluids (air or water), slope materials (rock or preexisting sediment), and forces that are directly involved in the physical transport of coarse sediment (Fig. 9).

*Air-pressure-gradient flows* are flows that transport sediment as a byproduct of wind, a force created as the atmosphere responds to differential pressure. Two types of such flows are distinguished on the basis of whether the fluid medium of transport is air (eolian) or water (wind waves). Air is a poor medium for gravel transport because of its low density and viscosity. Wind carries sediment as dust load, suspended load, and bed load, with the last state the only one capable of moving gravel. Granules are a common eolian bed-load size, whereas fine to coarse pebbles probably are the coarsest sediment moved by terrestrial wind (Fig. 9; Kocurek 1996). Wind-generated waves on a lake or ocean are a more competent gravel transport agent. Gravelly shorezones are common in settings where standing water abuts gravelly sediment, such as where lakes impinge upon piedmonts

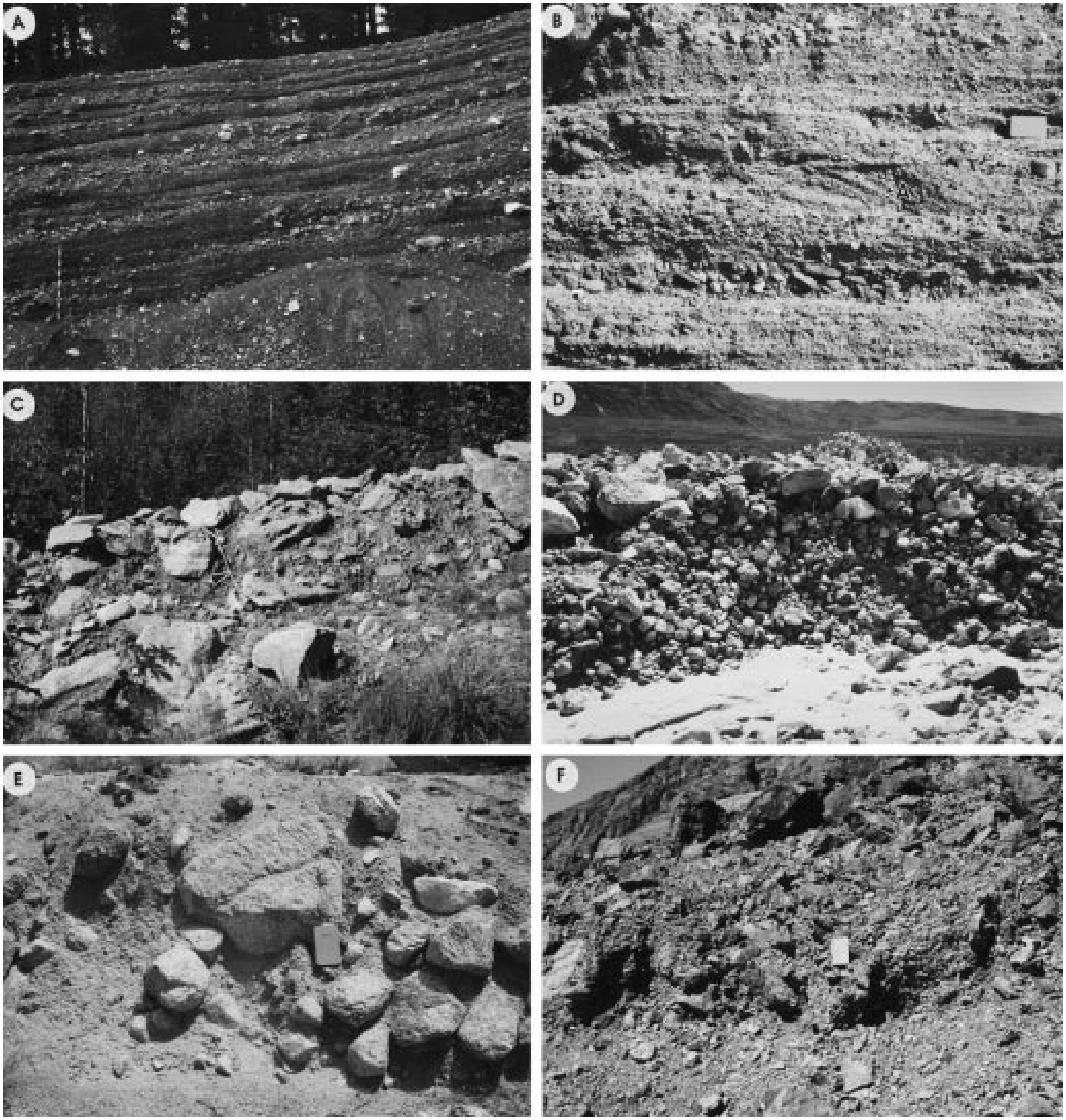



FIG. 5.—Examples of alluvial-fan deposits described using the modified grain-size and texture classification. **A)** Planar-bedded, clast-supported, angular, poorly sorted, fine cobbly, coarse to very coarse pebble gravel rhythmically interstratified with sandy, fine to medium pebbly granule gravel. Jacob's staff (left) is 150 cm long. Little River fan sheetflood strata, New Zealand. **B)** Planar-bedded, organized (a/t, b/i), angular, poorly sorted, fine to coarse pebble gravel interstratified with sandy, granular, fine pebble gravel. These deposits contain a set of high-angle backset-bedded, angular, extremely poorly sorted, sandy, granular, medium to fine pebble gravel (A). Antidune set (A) encased by sheetflood couplets, Anvil Spring fan, Death Valley, California (fan slope is to left). **C)** Matrix-supported, clast-rich, slightly organized (a/p, b/v), subangular to angular, unsorted, muddy, pebbly, cobbly, medium to fine boulder gravel (scale bar is 1 m long). Debris-flow levee, Ravin des Vouillordes fan, Chamonix, France. **D)** Clast-supported, clast-rich, weakly inverse-graded, angular to subangular, extremely poorly sorted, muddy, fine cobbly, coarse to very coarse pebble gravel. Cut 1 m high through a debris-flow lobe on the Panamint Canyon fan, California. **E)** Variably clast- to matrix-supported, slightly organized (a/t, b/v), subangular to subrounded, unsorted, sandy, granular, pebbly, cobbly, medium to fine boulder gravel. Noncohesive sediment gravity flow of the Tuttle Creek fan, Owens Valley, California. Fieldbook is 20 cm long. **F)** Clast-rich, clast-supported, weakly inverse-graded, very angular, weakly sorted, silty, pebbly, coarse to fine bouldery, fine to coarse cobble gravel. Rock avalanche on the EC-38 fan, Death Valley. Fieldbook (arrow) for scale.

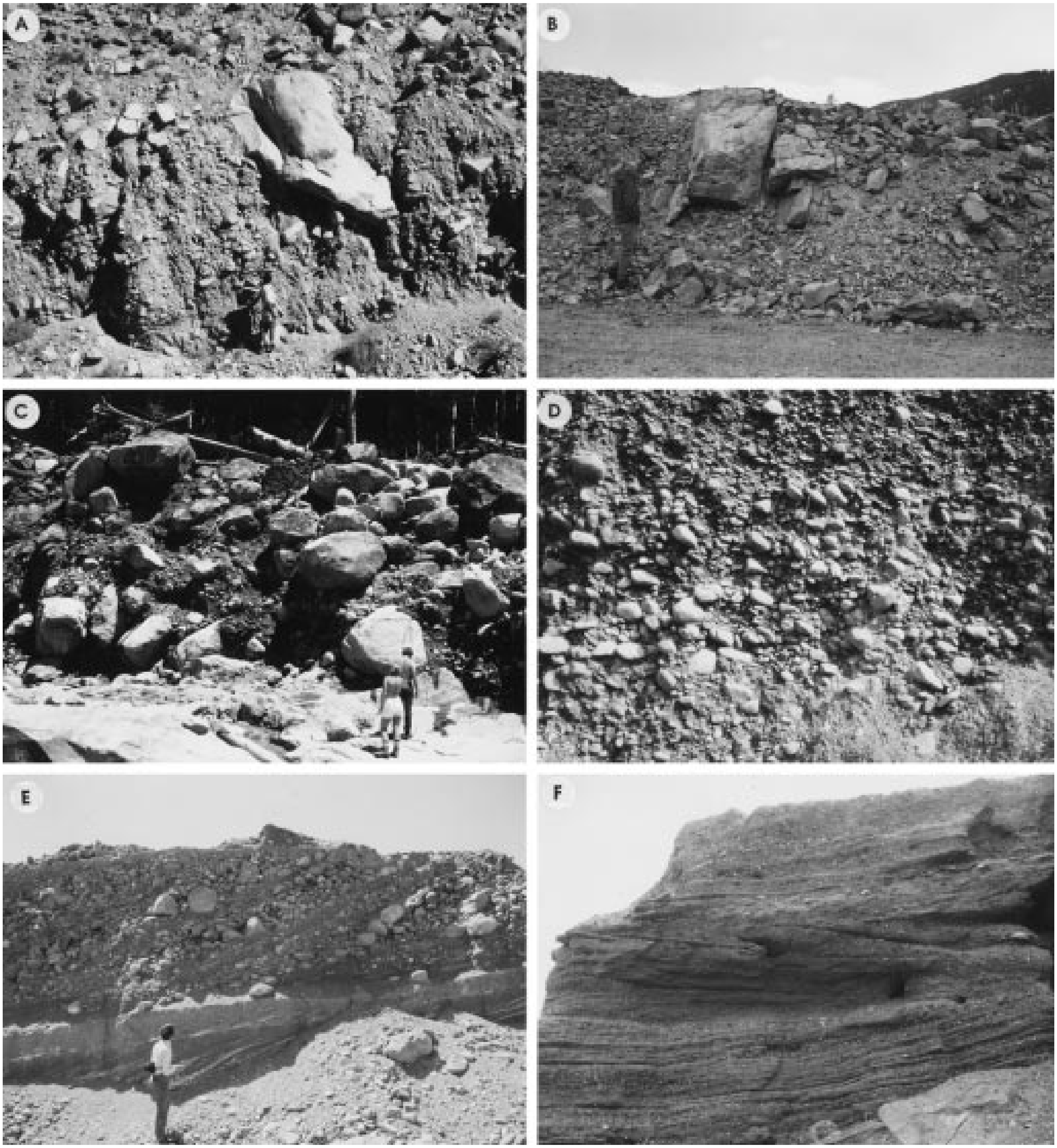



FIG. 6.—Gravelly non-fan examples described using the modified grain-size and texture classification. **A)** Variably clast- to matrix-supported, disorganized, subangular to very angular, unsorted, clayey, sandy, pebbly, cobbly, very coarse to fine boulder gravel. Colluvium cut near Schurz, Nevada (person for scale). **B)** Variably clast- to matrix-supported, disorganized, very angular, unsorted, sandy, pebbly, bouldery, fine to coarse cobble gravel. Rock avalanche triggered by a 1959 earthquake, southwest Montana. **C)** Variably clast- to matrix-supported, slightly organized (a/t, b/v), angular to subrounded, unsorted, sandy, granular, pebbly, cobbly, fine to coarse boulder gravel. Glacial moraine exposed in Rocky Mountain National Park, Colorado. **D)** Horizontally and thickly bedded, clast-supported, well-imbricated (a/t, b/i), subangular to rounded, moderately sorted, slightly sandy, coarse to very coarse pebble gravel. Exposure is 2 m tall. Waiau River terrace, New Zealand. **E)** Upper set consists of large-scale cross-bedded, clast-supported, poorly organized (a/t, b/p), subangular to rounded, poorly to very poorly sorted, bimodal, slightly pebbly, cobbly, medium to fine boulder gravel interstratified with slightly sandy, cobbly, fine to very coarse pebble gravel. This upper set overlies low-angle bedded, angular to subrounded, very poorly sorted, sandy, granular, coarse to fine pebble gravel. Truckee River lacustrine braid-delta front, Nevada. **F)** Bidirectionally dipping, low-angle bedded, clast-supported, well-organized (a/p, b/t), subrounded, moderately sorted, bimodal, fine cobbly, very coarse pebble gravel and coarse to medium pebble gravel. Lake Lahontan foreshore (left-dipping) and backshore (right-dipping) barrier-spit deposits, Churchill Butte, Nevada. Exposure is 3 m tall and 6 m wide.

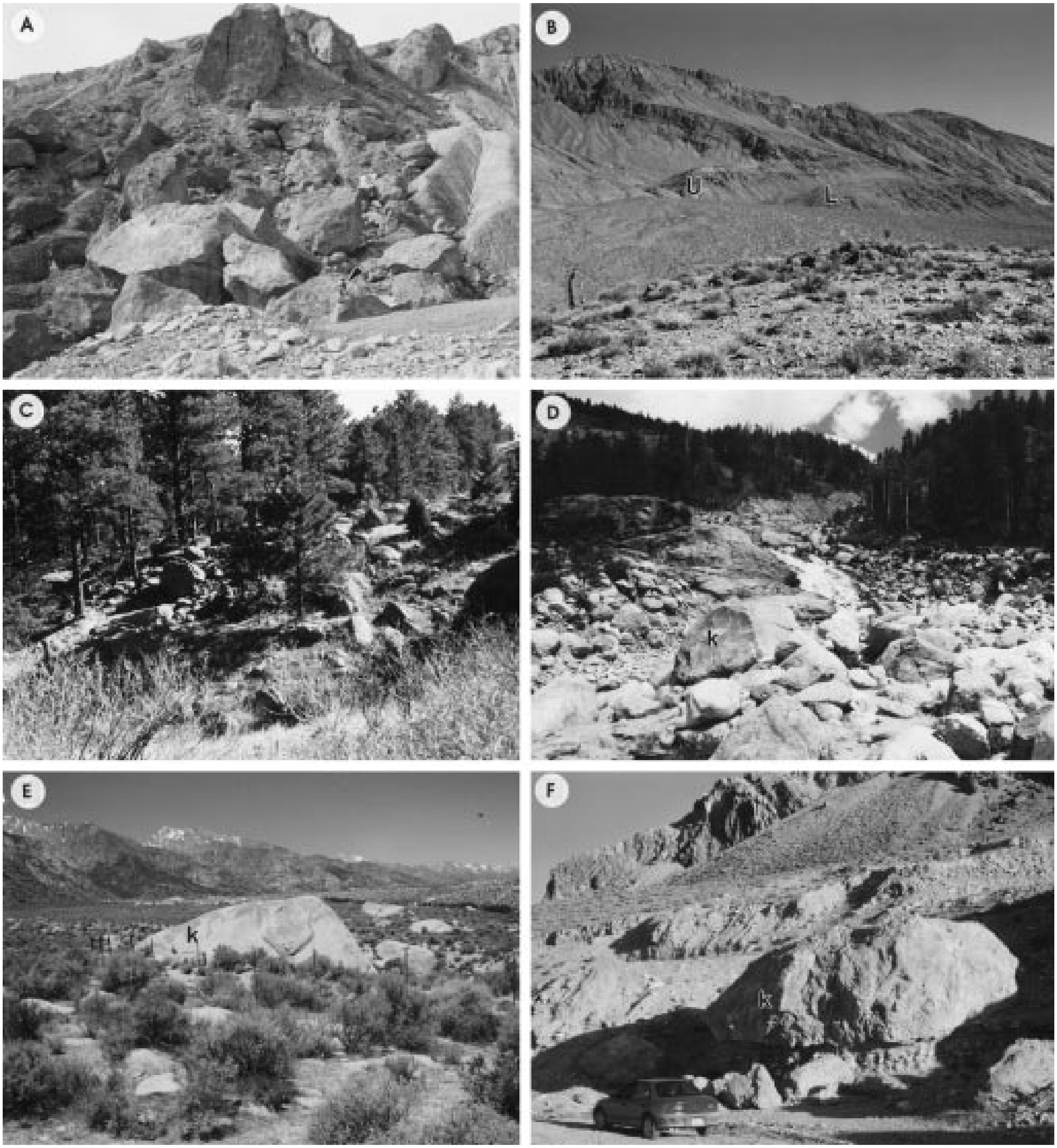



FIG. 7.—Examples of blocks and blocky sedimentary facies. **A)** Mantle of very angular, medium to fine blocks deposited as rock fall, Death Valley (person for scale, arrow). **B)** View of two rockslide megaclasts, the upper one (U) a very coarse block ($d_I = 55$ m), and the lower one (L) a fine slab ($d_I = 128$ m). Cottonwood piedmont, Racetrack Valley, California. **C)** Weakly sorted, fine blocky, medium to very coarse boulder gravel of the South Shanahan rock avalanche, Boulder, Colorado. **D)** Fine blocky, fine to very coarse boulder gravel of the Roaring River fan, Colorado. The larger megaclasts ( ''k'') have $d_I$ of 4.5 to 5.5 m. **E)** Medium block (k) 8.4×12.9×16.8 m in size located 4 km from the Sierra Nevada range front, Owens Valley. Noncohesive sediment gravity flow deposit, Lone Pine Creek fan. **F)** Fine block (k) 2.6×7.3×8.5 m in size moved by rock fall from the Desert Mountains (background), and incorporated into a nearshore lake deposit; pit near Fallon, Nevada.

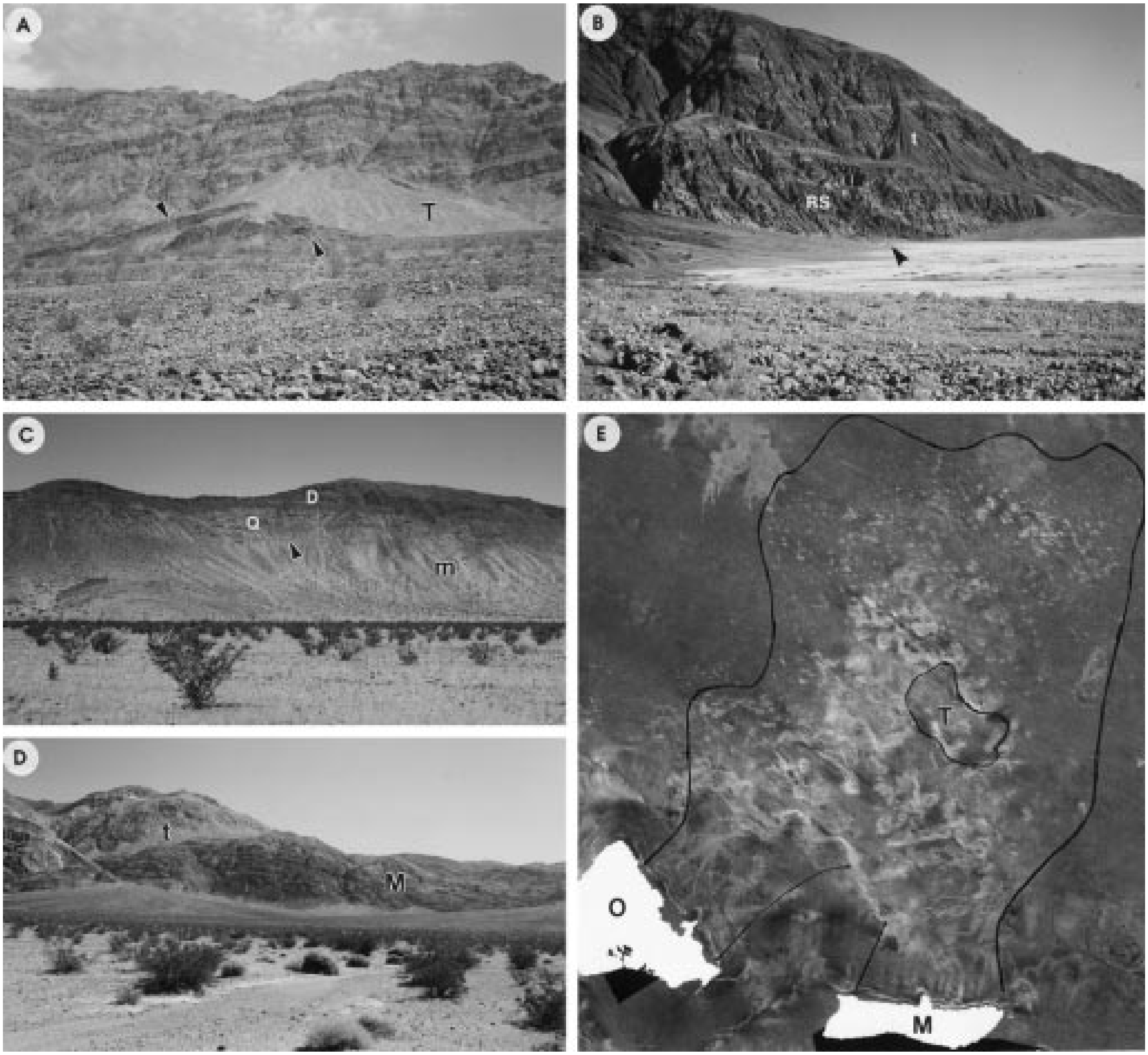



FIG. 8.—Examples of sedimentary slabs and monoliths. **A)** Two medium to coarse slabs of carbonate rock (arrows) with $d_I$ of 255 and 380 m transported to the piedmont as rock slides from the Grapevine Mountains (background); South Titanothere Canyon fan (T), Death Valley. **B)** Very coarse slab 320×540×1020 m in size deposited as a rock slide (RS) along the Black Mountains front, Death Valley. Cobbly pebble gravel derived from the detachment have accumulated as talus (t); vehicle (arrow) for scale. **C)** Lake Hills rock avalanche consisting of an 87 m thick, massive basal bed of unsorted, very angular, pebbly fine to coarse cobble gravel (m), Panamint Valley. This bed is overlain (at arrow), by a coarse slab of intact and stratified bedrock 55 m thick and 370×1770 m in area that rafted 5 km from the range front on the avalanche. It consists of stratified quartzite (Q) and dolomite (D). **D)** Very fine monolith (M) 590+ m high and 1070×2160 m in area deposited as a rock slide from the Cottonwood range front in Panamint Valley. Talus (t) delineates the slide detachment. **E)** GLORIA sonar image of the 2500–5000 m deep seafloor north of the Hawaiian Islands of Oahu (O) and Molokai (M). Two rock-avalanche deposits as much as 2500 m thick blanket 40,000 km² of the seafloor (outlined). These avalanches were derived and extend as far as 180 km from the islands (e.g., Moore et al. 1989). Irregular avalanche forms are imaged megaclasts, many with $d_I > 1$ km. The largest megaclast, a very coarse monolith called the Tuscaloosa Seamount (T), spans an area of 17 km×30 km, rises 1.8 km above the avalanche top, and was transported 100 km north of its Molokai source. Overall, the deposits have an angular, unsorted, blocky, slabby, very coarse to very fine monolith megagravel texture in the proximal zone, and a monolithic, blocky, very coarse to fine slab megagravel texture distally. View is orthogonally oriented with north upward; true width is 175 km and height is 200 km. Photograph provided courtesy of J.G. Moore and C. Gutmacher.

(Figs. 6F, 7F). Clasts as coarse as granules may be transported as intermittent suspended load in the shorezone, whereas pebbles, cobbles, and fine boulders commonly are moved as bed load (Fig. 9; e.g., Russell 1885; Emery 1955). Coarser boulders and fine to medium blocks are transported by waves generated by especially strong storms (e.g., Hearty 1997).

Water waves capable of transporting boulders and fine to medium blocks also are generated by several catastrophic mechanisms. One type are waves instigated by earthquakes, called *seismic-wave flows* or tsunamis (e.g., Hearty 1997). Rare, highly competent waves also can be instigated by water displacement through rapid submersion of a solid mass such as a landslide,

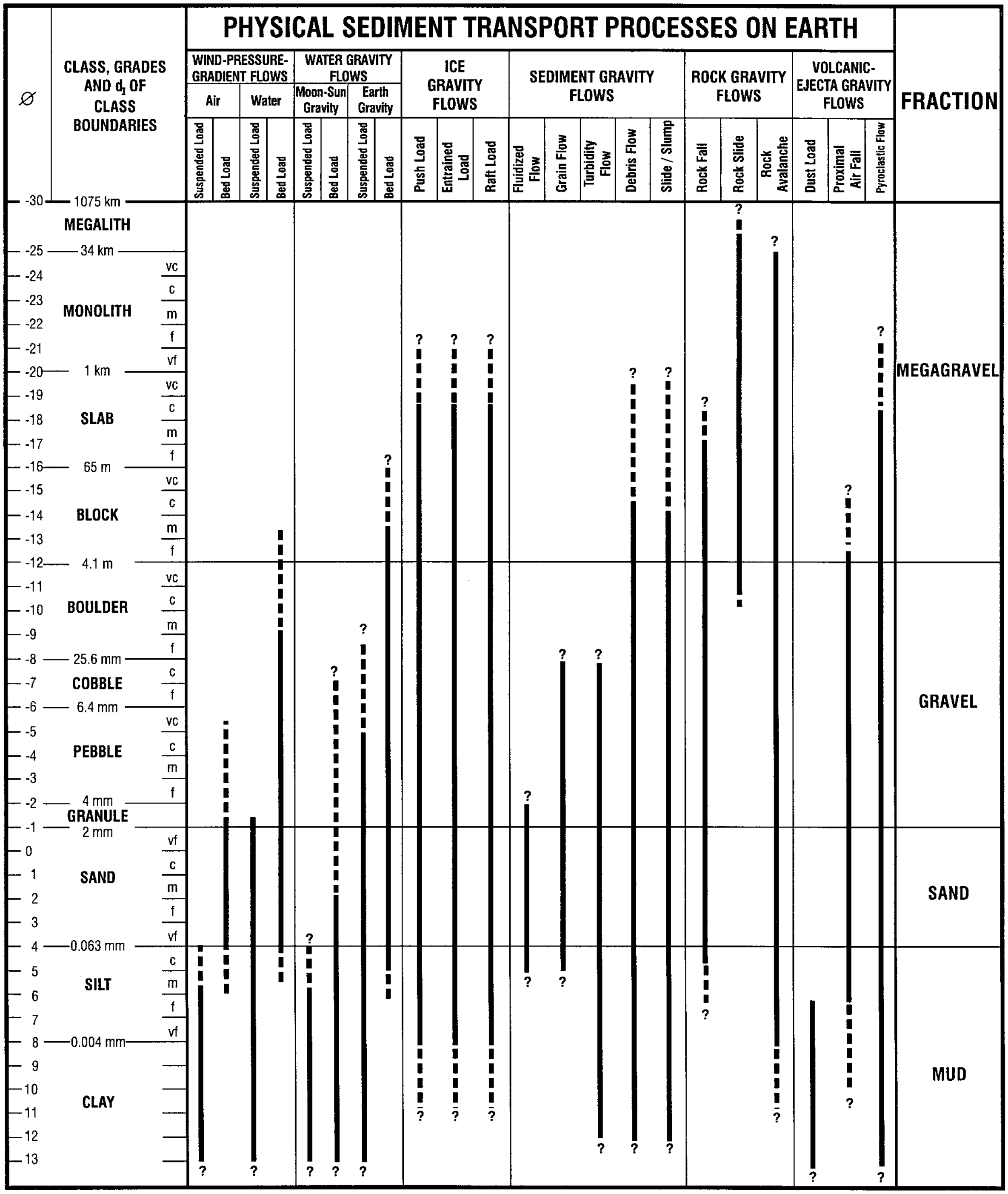



FIG. 9.—Particle sizes transported by physical processes active under the Earth's surface conditions.

producing *displacement-wave flows* (e.g., Miller 1960; McCulloch 1966; Slingerland and Voight 1979; Evans 1989).

*Water gravity flows* are events in which sediment is transported by the force of gravity acting directly on the water. Two types of water gravity flows are differentiated, extraterrestrial and terrestrial, depending upon the gravity source. *Extraterrestrial water gravity flows* encompass tidal currents, which result from the gravitational forces of the Moon and Sun. Tidal currents most typically transport sediment finer than gravel (Reineck and Singh 1980) but locally move granules and pebbles (Fig. 9; Thompson 1968; Larsonneur 1975). *Terrestrial water gravity flows* are incited by water moving downslope, such as in rivers. They are significantly more competent because of the stronger force of Earth's gravity. Terrestrial water gravity flows in mountainous terrane commonly transport the full spectrum of granules, pebbles, cobbles, and fine to coarse boulders (Fig. 9; e.g., Baker and Ritter 1975; Costa 1983). More rarely, particles the size of very coarse boulders and fine to medium blocks have been transported by catastrophic terrestrial water gravity flows (Krumbein 1940; Birkeland 1968; Malde 1968; Baker 1973; Lliboutry et al. 1977; Elfström 1987). Megaclast transport in such flows results from the attainment of extraordinary depth and velocity achieved by the rapid release of stored water during failures of natural dams. Examples include the Ely, Minnesota flood resulting from failure of the glacial moraine dam containing Bass Lake (Theil 1932), failure of the Red Rock Pass area of Idaho containing Lake Bonneville (Malde 1968; O'Conner 1993), the Washington Channeled Scabland floods produced by rapid drainage of glacial Lake Missoula (Baker 1973), and the Swedish Lapland floods resulting from rapid drainage of breached moraine-dammed lakes along the Pite River (Elfström 1987).

Coarse sediment also is transported on the Earth's surface by unique processes related to glaciation. These processes are grouped as *ice gravity flows* because sediment transport results from the force of gravity acting on ice. The full spectrum gravel grades, as well as block and fine to coarse slab megagravel, can be transported as ice gravity flows. Such flows include movement by ice pushing, glacial entrainment, or rafting on top of or within the glacier (Fig. 9). Gravel and megagravel are commonly transported in alpine glacial settings because of the availability of coarse sediment and the presence of relief (e.g., Fig. 6C). Ice-gravity-flow transport of coarse particles also occurs in continental glacial settings where clasts are derived from reworking of river sediment or plucking of bedrock (Flint 1947; Boulton 1978; Elfström 1987). Flint (1947) noted that the coarsest glacial erratics in North America transported by continental ice sheets have $d_I$ values of 12 to 30 m (medium to coarse blocks).

*Sediment gravity flows* are those in which sediment transport is achieved by the force of the Earth's gravity acting directly on the sediment (Middleton and Hampton 1976), and which thus require the existence of topography for activation. They are instigated by the failure of colluvium or previously deposited sediment comprising a slope, and can occur in either subaerial or subaqueous settings. Colluvial slope failures result in a variety of sediment transport mechanisms, such as fluidized flow, grain flow, turbidity flow, debris flow, and sliding and slumping (Middleton and Hampton 1976). All of these flow types can account for the transport of granules and finer-grained sediment. Additionally, resedimented turbidity flows are capable of transporting the spectrum of pebble grades (Walker 1979), and grain flows can transport pebbles, cobbles, and various grades of boulders (Fig. 9). Debris flows are competent to transport the spectrum of boulders and fine blocks (Rodine and Johnson 1976; Johnson 1984). Noncohesive sediment gravity flows, a clay-deficient debris-flow type, are competent to move all grades of gravel as well as fine to coarse blocks (Blair 1987). Slippage of colluvium on steep mountain slopes also facilitates the transport of blocks and slabs (e.g., Campbell 1975).

*Rock gravity flows,* comprising rock falls, rock slides, and rock avalanches, are sedimentary flows instigated by the failure of a rock slope under the force of gravity (Fig. 9; Blair and McPherson 1994). They are responsible for transport of the coarsest sediment documented on Earth. Like sediment gravity flows, they require the presence of topography for activation. Rock fall is the least competent of these flow types, moving granules through boulders, and fine to medium blocks (Fig. 7A; Simons et al. 1966; Beaty and dePolo 1989; Turner 1996). In contrast, the full range of blocks, slabs, monoliths, and probably megaliths are common sizes transported as rock slides in either subaerial or subaqueous, high-relief settings (Figs. 8A–B; e.g., Schultz and Southworth 1989). Rock slides in many cases disintegrate and transform during motion into rock avalanches, a flow type capable of transporting the newly formed particles ranging from clay to very coarse monoliths (Fig. 9; Mudge 1965; Shreve 1968; Moore et al. 1989; Masson et al. 1998). The coarsest megaclasts documented in subaerial rock avalanches vary from fine blocks to very coarse slabs (Crandell and Fahnestock 1965; McSaveney 1978; Pflaker and Ericksen 1978; Porter and Orombelli 1980; Siebert 1984; Fauque and Strecker 1988; Evans et al. 1989). Even coarser megaclasts have been transported by subaqueous rock avalanches, such as the monolith-rich deposits flanking the Hawaiian Islands (Figs. 8E, 9; Moore et al. 1989, Moore et al. 1995).

Another form of sediment transport is achieved by volcanism, where hot material is ejected explosively from the release of confining pressure or by gravitational collapse of actively growing lava bodies, forming *volcanic-ejecta gravity flows.* The resulting pyroclastic sediment travels as dust load, air fall, and bed load (Fig. 9). The latter two transport gravel, including as pyroclastic flows and as air fall, where lapilli and bombs as coarse as blocks are known (e.g., Wentworth and Williams 1933; Fisher 1966; Sparks 1976). Boulders, blocks, slabs, and monoliths also are transported as hot debris avalanches or hot debris flows associated with eruptions (Kesel 1973; Voight et al. 1983; Stoopes and Sheridan 1992).

The range of clast sizes and competency limits of the transport mechanisms plotted in Figure 9 reflect conditions at the Earth's surface. Key factors promoting or limiting the range of sediment grades moved by these mechanisms are the magnitude of Earth's gravity, tidal forces, and topography; as well as the existence of standing and frozen water, an atmosphere, precipitation, volcanism, and tectonism. The latter attribute is especially important for the production of gravel and megagravel, and the creation of topography instrumental to the initiation of the transport mechanisms. Variations in any of these factors on the surface of other planets will change the range of sedimentary particles that are produced, and the competency limits of the various transport processes.

## CONCLUSIONS

The detrital particle classes and subclasses of the Udden–Wentworth grain-size scale, as modified by Folk (1954, 1974) and Folk et al. (1970), are widely used for sand and mud, and are essential for the objective description of clastic sediment. This scheme can be extended to also cover the coarser realm of sedimentary particles found on Earth, including various grades of pebbles, cobbles, and boulders in the gravel fraction, and various grades of blocks, slabs, monoliths, and megaliths in the megagravel fraction (Fig. 2). Such grades can be used in Folk's texture classification to provide an objective description of coarse sediment akin in detail to that achieved for finer-grained sediment.

## ACKNOWLEDGMENTS

We thank reviewers P. Carling and E. Wohl, Associate Editor P. Wiberg, Corresponding Editor J. Southard, and Editor G. Ashley for their evaluations of this manuscript on behalf of JSR. Blair & Associates and Mobil Oil Corporation kindly provided research support.

## REFERENCES

ALLEN, J.R.L., 1982, Sedimentary Structures: Their Character and Physical Basis, Vol. 2: Amsterdam, Elsevier, 663 p.
BAKER, V.R., 1973, Paleohydrology and Sedimentology of Lake Missoula Flooding in Eastern Washington: Geological Society of America, Special Paper 144, 79 p.
BAKER, V.R., AND RITTER, D.F., 1975, Competence of rivers to transport coarse bedload material: Geological Society of America, Bulletin, v. 86, p. 975–978.
BEATY, C.B., AND DEPOLO, C.M., 1989, Energetic earthquakes and boulders on alluvial fans: Is there a connection?: Seismological Society of America, Bulletin, v. 79, p. 219–224.
BIRKELAND, P.W., 1968, Mean velocities and boulder transport during Tahoe-age floods of the Truckee River, California–Nevada: Geological Society of America, Bulletin, v. 79, p. 137–142.
BLAIR, T.C., 1987, Sedimentary processes, vertical stratification sequences, and geomorphology of the Roaring River alluvial fan, Rocky Mountain National Park, Colorado: Journal of Sedimentary Petrology, v. 57, p. 1–18.
BLAIR, T.C., AND MCPHERSON, J.G., 1994, Alluvial fans and their natural distinction from rivers based on morphology, hydraulic processes, sedimentary processes, and facies: Journal of Sedimentary Research, v. A64, p. 451–490.
BOULTON, G.S., 1978, Boulder shapes and grain-size distributions of debris as indicators of transport paths through a glacier and till genesis: Sedimentology, v. 25, p. 773–799.
BRIDGE, J.S., 1993, Description and interpretation of fluvial deposits: A critical perspective: Sedimentology, v. 40, p. 801–810.
BROCHER, T.M., AND TEN BRINK, U.S., 1987, Variations in oceanic layer 2 elastic velocities near Hawaii and their correlation to lithospheric flexure: Journal of Geophysical Research, v. 92, p. 2647–2661.
CAMPBELL, R.H., 1975, Soil slips, debris flows, and rainstorms in the Santa Monica Mountains and vicinity, southern California: U.S. Geological Survey, Professional Paper 851, 51 p.
CHURCH, M., STOCK, R.F., AND RYDER, J.M., 1979, Contemporary sedimentary environments on

Baffin Island, N.W.T., Canada: Debris slope accumulations: Arctic and Alpine Research, v. 11, p. 371–402.
COLE, R.B., AND STANLEY, R.G., 1995, Middle Tertiary extension recorded by lacustrine fan-delta deposits, Plush Ranch basin, western Transverse Ranges, California: Journal of Sedimentary Research, v. B65, p. 455–468.
COSTA, J.E., 1983, Paleohydraulic reconstruction of flash-flood peaks from boulder deposits in the Colorado Front Range: Geological Society of America, Bulletin, v. 94, p. 986–1004.
CRANDELL, D.R., AND FAHNESTOCK, R.K., 1965, Rockfalls and avalanches from Little Tahoma Peak on Mount Rainier, Washington: U.S. Geological Survey, Bulletin 1221-A, 30 p.
CROWELL, J.C., 1957, Origin of pebbly mudstones: Geological Society of America, Bulletin, v. 68, p. 993–1010.
ELFSTRÖM, A., 1987, Large boulder deposits and catastrophic floods: Geografiska Annaler, v. A69, p. 101–121.
EMERY, K.O., 1955, Grain size of marine beach gravels: Journal of Geology, v. 63, p. 39–49.
EVANS, S.G., 1989, The 1946 Mount Colonel Foster rock avalanche and associated displacement wave, Vancouver Island, British Columbia: Canadian Geotechnical Journal, v. 26, p. 447–452.
EVANS, S.G., CLAGUE, J.J., WOODSWORTH, G.J., AND HUNGR, O., 1989, The Pandemoniun Creek rock avalanche, British Columbia: Canadian Geotechnical Journal, v. 26, p. 427–446.
FAUQUE, L., AND STRECKER, M.R., 1988, Large rock avalanche deposits (Sturzströme, sturzstroms) at Sierra Aconquija, northern Sierras Pampeanas, Argentina: Eclogae Geologicae Helvetiae, v. 81, p. 579–592.
FISHER, R.V., 1966, Rocks composed of volcanic fragments and their classification: Earth-Science Reviews, v. 1, p. 287–298.
FLINT, R.F., 1947, Glacial Geology and the Pleistocene Epoch: New York, Wiley, 589 p.
FLINT, R.F., SANDERS, J.E., AND RODGERS, J., 1960a, Symmictite: A name for nonsorted terrigenous sedimentary rocks that contain a wide range of particle sizes: Geological Society of America, Bulletin, v. 71, p. 507–510.
FLINT, R.F., SANDERS, J.E., AND RODGERS, J., 1960b, Diamictite: A substitute term for symmictite: Geological Society of America, Bulletin, v. 71, p. 1809.
FOLK, R.L., 1954, The distinction between grain size and mineral composition in sedimentary-rock nomenclature: Journal of Geology, v. 62, p. 344–359.
FOLK, R.L., 1968, Petrology of Sedimentary Rocks: Austin, Hemphill Publishing Company, 170 p.
FOLK, R.L., 1974, Petrology of Sedimentary Rocks: Austin, Hemphill Publishing Company, 182 p.
FOLK, R.L., ANDREWS, P.B., AND LEWIS, D.W., 1970, Detrital sedimentary rock classification and nomenclature for use in New Zealand: New Zealand Journal of Geology and Geophysics, v. 13, p. 937–968.
FRIEDMAN, G.M., 1958, Determination of sieve-size distribution from thin-section data for sedimentary petrological studies: Journal of Geology, v. 66, p. 394–416.
GREENMAN, N.M., 1951, The mechanical analysis of sediments from thin-section data: Journal of Geology, v. 59, p. 447–462.
HEARTY, P.J., 1997, Boulder deposits from large waves during the last interglaciation on North Eleuthera Island, Bahamas: Quaternary Research, v. 48, p. 326–338.
HIGGENS, M.W., 1971, Cataclastic rocks: U.S. Geological Survey, Professional Paper 687, 97 p.
IBBEKEN, H., AND SCHLEYER, R., 1988, Photo-sieving: A method for grain-size analysis of coarse-grained, unconsolidated bedding surfaces: Earth Surface Processes and Landforms, v. 11, p. 59–77.
INGRAM, R.L., 1954, Terminology for thickness of stratification and parting units in sedimentary rocks: Geological Society of America, Bulletin, v. 65, p. 937–938.
JOHNSON, A.M., 1984, Debris flow, *in* Brunsden, D., and Prior, D.B., eds., Slope Instability: New York, Wiley, p. 257–361.
KESEL, R.H., 1973, Notes on the lahar landforms of Costa Rica: Zeitschrift für Geomorphologie, Supplementband 18, p. 78–91.
KOCUREK, G.A., 1996, Desert aeolian systems, *in* Reading, H.G., ed., Sedimentary Environments: Processes, Facies and Stratigraphy, 3rd Edition: Oxford, U.K., Blackwell Science, p. 125–153.
KONERT, M., AND VANDENBERGE, J., 1997, Comparison of laser grain size analysis with pipette and sieve analysis: A solution for the underestimation of the clay fraction: Sedimentology, v. 44, p. 523–536.
KRUMBEIN, W.C., 1934, Size frequency distributions of sediments: Journal of Sedimentary Petrology, v. 4, p. 65–77.
KRUMBEIN, W.C., 1935, Thin section mechanical analysis of indurated sediments: Journal of Geology, v. 43, p. 482–496.
KRUMBEIN, W.C., 1938, Size frequency distributions of sediments and the normal phi curve: Journal of Sedimentary Petrology, v. 8, p. 84–90.
KRUMBEIN, W.C., 1939, Preferred orientation of pebbles in sedimentary rocks: Journal of Geology, v. 47, p. 673–706.
KRUMBEIN, W.C., 1940, Flood gravel of San Gabriel Canyon, California: Geological Society of America, Bulletin, v. 51, p. 639–676.
KRUMBEIN, W.C., 1941, Measurement and geological significance of shape and roundness of sedimentary particles: Journal of Sedimentary Petrology, v. 11, p. 64–72.
LANE, E.W., BROWN, K., GIBSON, G.C., HOWARD, C.S., KRUMBEIN, W.C., MATTHES, G.H., RUBEY, W.W., TROWBRIDGE, A.C., AND STRAUB, L.G., 1947, Report of the subcommittee on sediment terminology: American Geophysical Union, Transactions, v. 28, p. 936–938.
LARSONNEUR, C., 1975, Tidal deposits, Mont Saint-Michel Bay, France, *in* Ginsburg, R.N., ed., Tidal Deposits: New York, Springer-Verlag, p. 21–30.
LLIBOUTRY, L., MORALES ARNAO, B., PAUTRE, A., AND SCHNEIDER, B., 1977, Glaciological problems set by the control of dangerous lakes in Cordilleran Blanca, Peru, I. Historical failures of morainic dams, their causes and preventions: Journal of Glaciology, v. 18, p. 239–290.
LUCCHITTA, B.K., 1978, A large landslide on Mars: Geological Society of America, Bulletin, v. 89, p. 1601–1609.
MALDE, H.E., 1968, The catastrophic late Pleistocene Bonneville flood in the Snake River plain, Idaho: U.S. Geological Survey, Professional Paper 596, 52 p.
MASSON, D.G., CANALS, M., ALONSO, B., URGELES, R., AND HUHNERBACH, V., 1998, The Canary Debris Flow: source area morphology and failure mechanisms: Sedimentology, v. 45, p. 411–432.
MCCULLOCH, D.S., 1966, Slide-induced waves, seiching, and ground fracturing caused by the earthquake of March 27, 1967, at Kenai Lake, Alaska: U.S. Geological Survey, Professional Paper 543-A, 41 p.
MCKEE, E.D., AND WEIR, G.W., 1953, Terminology for stratification and cross-stratification in sedimentary rocks: Geological Society of America, Bulletin, v. 64, p. 381–390.
MCSAVENEY, M.J., 1978, Sherman Glacier rock avalanche, U.S.A., *in* Voight, B., ed., Rockslides and Avalanches, 1: Amsterdam, Elsevier, p. 197–258.
MIALL, A.D., 1985, Architectural-element analysis: a new method of facies analysis applied to fluvial deposits: Earth-Science Reviews, v. 22, p. 261–308.
MIDDLETON, G.V., AND HAMPTON, M.A., 1976, Subaqueous sediment transport and deposition by sediment gravity flows, *in* Stanley, D.J., and Swift, D.J.P., eds., Marine Sediment Transport and Environmental Management: New York, Wiley, p. 197–218.
MILLER, D.J., 1960, Giant waves in Lituya Bay, Alaska: U.S. Geological Survey, Professional Paper 354-C, p. 51–83.
MOORE, J.G., BRYAN, W.B., BEESON, M.H., AND NORMARK, W.R., 1995, Giant blocks in the south Kona Island landslide, Hawaii: Geology, v. 23, p. 125–128.
MOORE, J.G., CLAGUE, D.A, HOLCOMB, R.T., LIPMAN, P.W., NORMARK, W.R., AND TORRESAN, M.E., 1989, Prodigious submarine landslides on the Hawaiian Ridge: Journal of Geophysical Research, v. 94, p. 17,465–17,484.
MUDGE, M.R., 1965, Rockfall-avalanche and rockslide-avalanche deposits at Sawtooth Ridge, Montana: Geological Society of America, Bulletin, v. 76, p. 1003–1014.
O'CONNER, J.E., 1993, Hydrology, Hydraulics, and Geomorphology of the Bonneville Flood: Geological Society of America, Special Paper 274, 83 p.
PLAFKER, G., AND ERICKSEN, G.E., 1978, Nevados Huascaran avalanches, Peru, *in* Voight, B., ed., Rockslides and Avalanches, Vol. 1: Amsterdam, Elsevier, p. 277–314
PLAYFAIR, J., 1802, Illustrations of the Huttonian Theory of the Earth: London, Cadell and Davis, 524 p. (reprinted by Dover Publications, New York, 1964).
PORTER, S.C., AND OROMBELLI, G., 1980, Catastrophic rockfall of September 12, 1717 on the Italian flank of the Mont Blanc massif: Zeitschrift für Geomorphologie, v. 24, p. 200–218.
POWERS, M.C., 1953, A new roundness scale for sedimentary particles: Journal of Sedimentary Petrology, v. 41, p. 1069–1072.
REINECK, H.-E., AND SINGH, I.B., 1980, Depositional Sedimentary Environments: Berlin, Springer-Verlag, 549 p.
RITTER, D.F., 1975, Process Geomorphology: Dubuque, Iowa, W.C. Brown, 603 p.
RODGERS, J., 1950, The nomenclature and classification of sedimentary rocks: American Journal of Science, v. 248, p. 297–311.
RODINE, J.D., AND JOHNSON, A.M., 1976, The ability of debris heavily freighted with coarse clastic materials to flow on gentle slopes: Sedimentology, v. 23, p. 213–234.
RUSSELL, I.C., 1885, Geological history of Lake Lahontan, a Quaternary lake of northwest Nevada: U.S. Geological Survey, Monograph 11, 288 p.
SAUSSURE, H.B. DE, 1796, Voyages dans les Alpes; Précédes d'un Essai sur l'Historie Naturelle des Environs de Genève: Neuchatel, Lous Fauche-Borel, part 4, 594 p.
SCHERMERHORN, L.J.G., 1966, Terminology of mixed coarse-fine sediments: Journal of Sedimentary Petrology, v. 36, p. 831–835.
SHREVE, R.L., 1968, The Blackhawk landslide: Geological Society of America, Special Paper 108, 47 p.
SCHULTZ, A.P., AND SOUTHWORTH, C.S., 1989, Large bedrock landslides of the Appalachian Valley and Ridge province of eastern North America, *in* Schultz, A.P., and Jibson, R.W., eds., Landslide Processes of the Eastern United States and Puerto Rico: Geological Society of America, Special Paper 236, p. 57–74.
SIEBERT, L., 1984, Large volcanic debris avalanches: Characteristics of source areas, deposits, and associated eruptions: Journal of Volcanology and Geothermal Research, v. 22, p. 163–197.
SIMONS, F.S., RAUP, R.B., HAYES, P.T., AND DREWES, H., 1966, Exotic blocks and coarse breccias in Mesozoic volcanic rocks of southeastern California: U.S. Geological Survey, Professional Paper 550-D, p. 12–22.
SLINGERLAND, R.L., AND VOIGHT, B., 1979, Occurrences, properties, and predictive models of landslide-generated water waves, *in* Voight, B., ed., Rockslides and Avalanches, Vol. 2: Amsterdam, Elsevier, p. 317–397.
SPARKS, R.S., 1976, Grain size variations in ignimbrites and implications for the transport of volcanic flows: Sedimentology, v. 3, p. 147–188.
STOOPES, G.R., AND SHERIDAN, M.F., 1992, Giant debris avalanches from the Colima volcanic complex, Mexico: Implications for long-runout landslides ($>$ 100 km) and hazard assessment: Geology, v. 20, p. 299–302.
SUNDELL, K.A., AND FISHER, R.V., 1985, Very coarse grained fragmental rocks: A proposed size classification: Geology, v. 13, p. 692–695.
TANNER, W.F., 1969, The particle size scale: Journal of Sedimentary Petrology, v. 39, p. 809–812.
THIEL, G.A., 1932, Giant current ripples in coarse fluvial gravel: Journal of Geology, v. 40, p. 452–458.
THOMPSON, R.W., 1968, Tidal Flat Sedimentation on the Colorado River Delta, Northwestern Gulf of California: Geological Society of America, Memoir 107, 133 p.
TROWBRIDGE, A.C., 1911, The terrestrial deposits of Owens Valley, California: Journal of Geology, v. 19, p. 736–740.
TURNER, A.K., 1996, Colluvium and talus, *in* Turner, A.K., and Schuster, R.L., eds., Landslides:

Investigation and Mitigation: Washington D.C., National Research Council, Transportation Research Board, Special Report 247, p. 525–554.
UDDEN, J.A., 1914, Mechanical composition of clastic sediments: Geological Society of America, Bulletin, v. 25, p. 655–744.
VOIGHT, B., JANDA, R.J., GLICKEN, H., AND DOUGLASS, P.M., 1983, Nature and mechanics of the Mount St. Helens rockslide–avalanche of 18 May 1980: Geotechnique, v. 33, p. 243–273.
WADELL, H., 1935, Volume, shape, and roundness of rock particles: Journal of Geology, v. 40, p. 443–451.
WALKER, R.G., 1975, Conglomerate: Sedimentary structures and facies models, *in* Depositional Environments as Interpreted from Primary Sedimentary Structures and Stratification Sequences: SEPM, Short Course Notes 2, p. 133–161.
WALKER, R.G., 1979, Turbidites and associated coarse clastic deposits, *in* Walker, R.G., ed., Facies Models: Geoscience Canada Reprint Series 1, p. 91–102.
WENTWORTH, C.K., 1922, A scale of grade and class terms for clastic sediments: Journal of Geology, v. 30, p. 377–392.
WENTWORTH, C.K., 1935, The terminology of coarse sediments: National Research Council, Bulletin 98, p. 225–246.
WENTWORTH, C.K., AND WILLIAMS, H., 1933, The classification and terminology of the pyroclastic rocks: National Research Council, Bulletin 89, p. 19–53.

Received 6 March 1998; accepted 3 August 1998.