Field Description of Coarse Bioclastic Fabrics

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Shell- and bone-bearing rocks can be readily categorized into 9 macroscopic fabric types using semi-quantitative scales for close-packing and size-sorting of bioclasts greater than 2 mm in diameter. Although designed to describe fossiliferous siliciclastics and volcaniclastics, this system of field description can also be used to enlarge upon standard petrographic descriptions of fossiliferous carbonates. In cross-sectional bed views, coarse bioclasts may be densely packed *(bioclast-supported deposit, bioclast/bioclast contacts common; analogous to grainstones and packstones of Dunham, 1962),* loosely packed *(matrix-supported but with most bioclasts within one bioclast-length of each other, or possibly in a loose house-of-cards arrangement; comparable to some wackestones of Dunham, 1962), or* dispersed *(matrix-supported, most bioclasts more than one bioclast-length apart from each other, direct contacts rare; wackestones to mudstones of Dunham, 1962). These coarse bioclasts (>2 mm) may be* well sorted *(central 80% of bioclasts lie within 1 or 2 adjacent phi size-classes),* bimodal *(well sorted but with a distinct second mode), or* poorly sorted *(central 80% of bioclasts distributed over 3 or more adjacent size-classes). Despite the complicating effects of bioclast shape, novices show 90% accuracy in estimating close-packing from photographs. They have only 60% accuracy in estimating size-sorting (the most common error is underestimating goodness of sorting), underscoring the importance of size-tallies to cross-check visual estimates when first using this scheme.*

This packing/sorting approach provides a good visual image of the fabric, and narrows the range of possible modes of origin more than alternative criteria such as volumetric percent-abundance (which shows no one-to-one equivalence with close-packing), orientation, and fragmentation. However, detailed interpretations of fabrics usually require information on these and other features of the deposit, including bioclast condition, associated sedimentary structures, life-habits of bioclast-producers, and stratigraphic context.

INTRODUCTION

Shells and bones can occur in any sedimentary rock type, but only for carbonate rocks are the abundance and disposition of skeletal hardparts described as a routine procedure. This owes largely to the wide acceptance of Dunham's (1962) fabric categories of grainstone, packstone, wackestone, and mudstone among carbonate petrographers. These terms could be stretched to describe bioclast-rich deposits having siliciclastic rather than micrite or spar matrix, but the potential confusion would be great. Consequently, bioclastic sediments with non-carbonate matrix are usually described by various non-standard terms such as coquina, bone bed, shell gravel, and lumachelle (in Europe), or by the ambiguous adjective "fossiliferous."

Because coarse bioclastic deposits are fairly common in the sedimentary record, and have important applications to stratigraphic analysis as well as being sources of paleontologic information (see Kidwell, in press, for review), some standardization in descriptive terminology is desirable. Ideally, a macroscopic classification for bioclastic rocks should: 1) convey an immediate visual image of rock fabric; 2) permit description of lithified as well as unlithified deposits with matrix of any grain size or mineralogic composition; 3) accommodate deposits in which fossils are preserved as molds (voids); 4) be reasonably objective and quantifiable; and 5) be easy to use in the field by non-specialists. Descriptive categories should have genetic value.

This is a great deal to ask of any single classification, and so compromises between simplicity, generality, accuracy, and precision are unavoidable. For practical reasons, we favor: A) a *semi-quantitative scale* of bioclastic fabric types, analogous to Power's (1953) Roundness Scale, whereby fabric types are estimated visually rather than by direct measurement; B) categories based on *cross-sectional views* of bioclastic beds, since these are more common than bedding-plane views; and C) a *limited number of fabric categories,* based on a minimum number of outcrop features.

Our solution, after experimenting with a number of different methods over the past decade, is to use only 2 features of bioclastic fabrics—close-packing and size-sorting—to subdivide the spectrum of types. These two aspects convey an immediate mental picture of a bioclastic fabric, and also are complementary to successful schemes for carbonate rocks.

DEFINITIONS

A coarse *bioclast* is defined here as any body fossil or fossil fragment larger than 2 mm; particles smaller than 2 mm are difficult to identify as to skeletal type in the field (although

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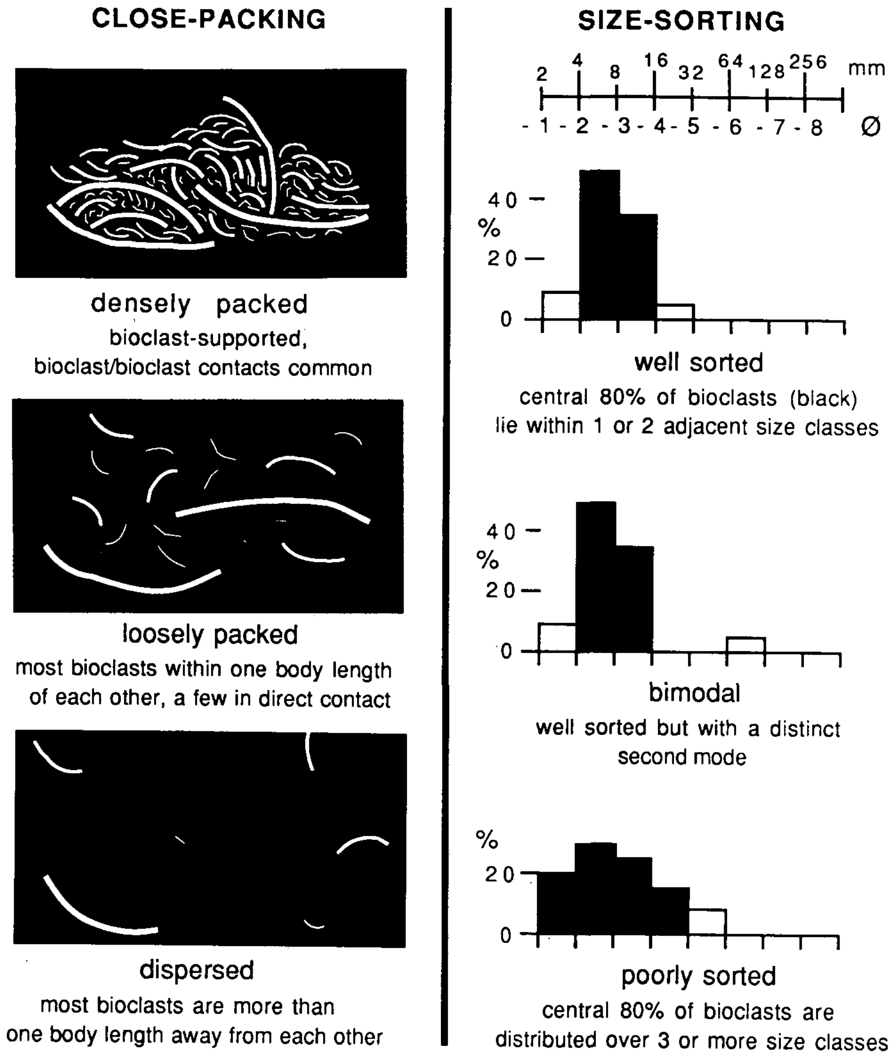


FIGURE 1—Schematic illustrations of close-packing and size-sorting categories for coarse bioclastic fabrics, with coarse bioclasts defined as body fossils or fossil fragments larger than 2 mm. Note: histograms on right are not meant to describe close-packing diagrams on left.

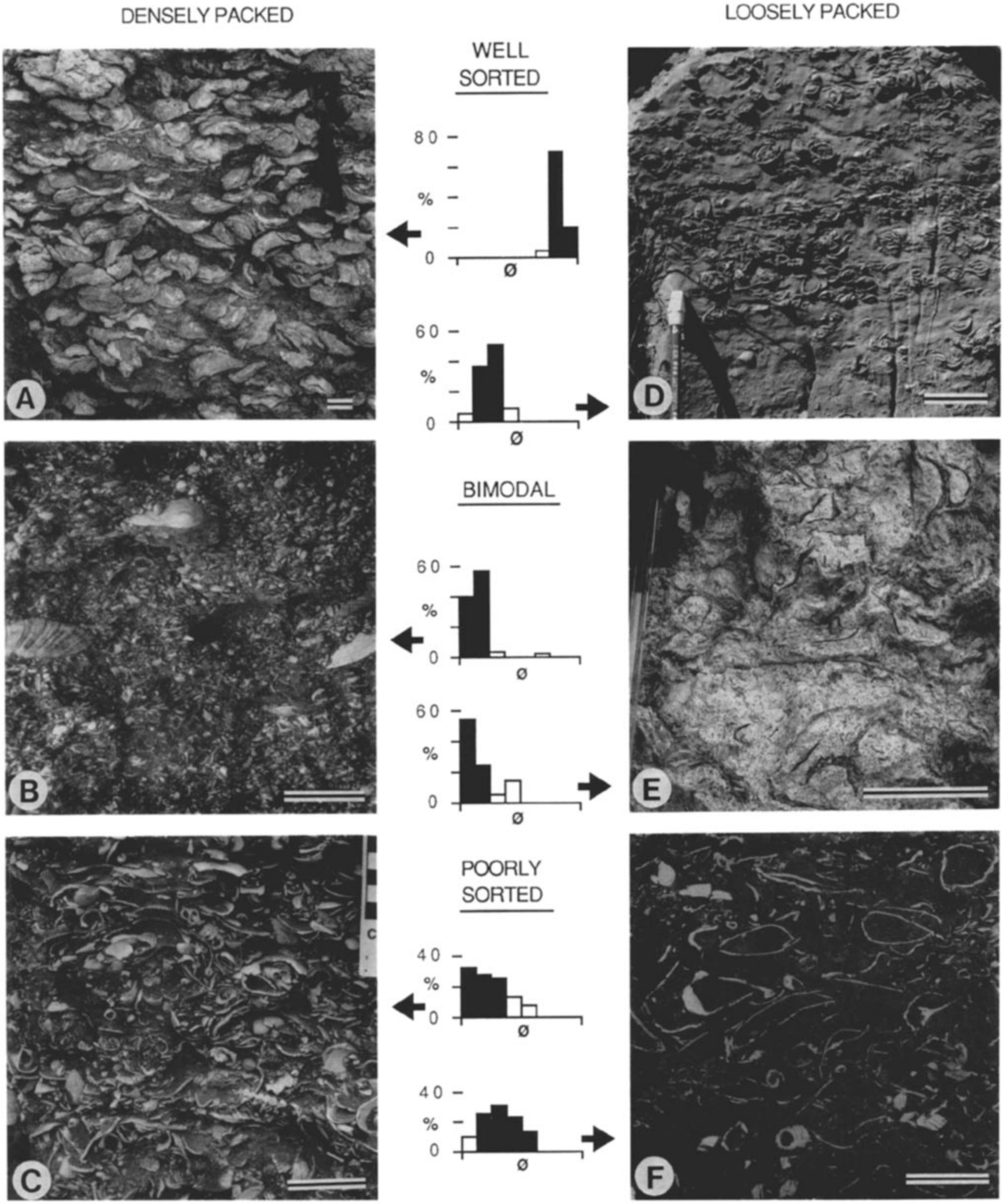
they can usually be identified as skeletal, hence bioclastic). This cut-off follows Embry and Klovan (1972), who differentiated coarse-grained carbonates containing >10% grains larger than 2 mm (e.g., grain-supported rudstones and matrix-supported floatstones) from all other limestone types.

By *bioclastic deposit* we mean any sedimentary deposit containing such coarse bioclasts, which may be very sparse or constitute virtually the entire deposit. The scheme proposed here is intended solely for description of non-reefal deposits, in which coarse bioclasts are primarily in mechanical contact only. Some proportion of these bioclasts may be organically bound, either by encrusting organisms (e.g., coralline algae, some bryozoans and corals) or by mutually attaching behavior (e.g., cementing or byssate bivalves such as oysters, rudists, and mussels; branching corals and bryozoans). However, when a significant proportion of the bioclasts are organically bound, the fabric is better described as some form of boundstone or framestone (Embry and Klovan, 1972; Cuffey, 1985). Many such constructions have bioclastic interbeds or grade laterally or vertically into fully bioclastic deposits, and so both fabric schemes may be needed to describe some stratigraphic intervals.

Close-Packing

Three semi-quantitative degrees of close-packing are recognized (Fig. 1).

Densely packed describes deposits that are bioclast-supported; that is, coarse bioclasts clearly provide mechanical support for the bed, with finer particles or cement filling the interstices. Bioclast/bioclast contacts are common, but some bioclasts may appear to "float" in the matrix because of their irregular shapes (a


DENSELY PACKED
LOOSELY PACKED
WELL SORTED
80
%
0
Ø
60
%
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BIMODAL
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POORLY SORTED
40
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A
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stereologic problem discussed by Dunham (1962) and by Folk (1980)) (Fig. 2A–C; densest fabrics Fig. 3A–C). Skeletal grainstones, packstones, and rudstones are carbonate examples of dense fabrics.

Loosely packed describes deposits that are matrix-supported, but with coarse bioclasts that are closely associated. Most of these are within one diameter or body length of each other, or show sufficient numbers of direct contacts to suggest a "house-of-cards" arrangement: were intervening sediment to be removed, these bioclasts would shift or collapse into closer proximity (Fig. 2D–F; Fig. 3D, E). Skeletal wackestones and floatstones with a high proportion of coarse bioclasts are carbonate examples.

Dispersed describes deposits that are matrix-supported, with sparsely distributed bioclasts. Most bioclasts are separated from each other by more than one diameter or body length; direct contact of bioclasts is rare (e.g., most sparsely fossiliferous areas in Fig. 3D, E). Skeletal wackestones and floatstones with a low proportion of bioclasts, and bioclast-bearing mudstones (<10% bioclasts by volume following Dunham's (1962) definition) are carbonate examples.

Sedimentary deposits that lack coarse bioclasts are described as barren.

Size-Sorting

Three semi-quantitative degrees of size-sorting of the coarse bioclasts are recognized (Fig. 1).

Well sorted describes deposits that exhibit very little variation in the sizes of bioclasts larger than 2 mm. In qualitative terms, the fabric gives a strong visual impression of having a single, well-defined mode. This mode may be relatively fine (Fig. 2D) or coarse (Fig. 2A; Fig. 3B, C). Quantitatively, the central 80% of individuals lie within two adjacent phi (ϕ) size-classes (Fig. 1). For complete statistical description of sorting in sedimentary rocks, Folk (1980) recommended using the average of two calculated values: sorting based on only the central 66% of the size-distribution, and sorting based on the central 90% (his Inclusive Graphic Standard Deviation method). Our simplified method of using the central 80% appears to be a reasonable alternative to use in the field: test fabrics that are well sorted by our system are either well sorted or very well sorted by Folk's system.

Bimodal describes deposits that are well sorted with respect to the primary mode, but also have a distinct second mode. Qualitatively, the fabric gives a strong visual impression of having two discrete modes. The most obvious bimodal fabrics have a few large bioclasts loosely packed or dispersed among a multitude of significantly finer bioclasts (Fig. 2B, E); it is possible for the primary size mode to be the coarser of the two, but we have not observed this in the field. Most fabrics that appear to be bimodal upon qualitative examination have a well-sorted primary mode (i.e., central 80% in 1 or 2 adjacent size-classes) and a highly subordinate second mode. Hypothetically at least it is possible to have two distinct but subequal modes (i.e., each with about 40% of bioclasts).

Poorly sorted describes deposits with great variation in bioclast size. Qualitatively, they may look mixed in sizes or simply lack an obvious, strong primary mode (Fig. 2C, F; Fig. 3D). Quantitatively, the central 80% of the distribution spans three or more size-classes. This sorting category includes the moderately sorted, poorly sorted, and very poorly sorted categories of Folk (1980).

APPLICATION

Because close-packing and size-sorting of coarse bioclasts vary continuously rather than in discrete steps, there will always be some fabrics that fall—or appear to fall—between categories on one axis or the other.

Ambiguity and Variability in Close-Packing

Close-packing can be ambiguous for several reasons. For example, deposits that are truly bioclast-supported may appear to be only loosely packed because of the irregular shapes of bioclasts, as emphasized and illustrated by Dunham (1962). This can be particularly pronounced in some cross-sectional views, as for example in end-on views of elongate bioclasts (such as the branching bryozoans in Figure 3C, where bioclasts appear to float in the matrix), and so more than one cross-sectional view should be examined if possible. Weathered outcrop surfaces can be useful in this regard because of the slightly 3-dimensional views they provide of bioclast shape and arrangement, in contrast to smooth or polished surfaces.

In general, the more irregular and less spheroidal the bioclast, the more "open" a bioclast-supported fabric may appear in a cross-sectional plane of view. One useful approach to distinguishing between densely packed and loosely packed fabrics in cross-section is to visualize whether the bed would collapse were non-bioclastic material to be removed: if the answer is unequivocally yes, then the bed is loosely packed rather than densely packed.

Dunham's (1962) photographs of natural and synthetic bioclast-supported sediments provide a valuable exercise on the shape/fabric relation-

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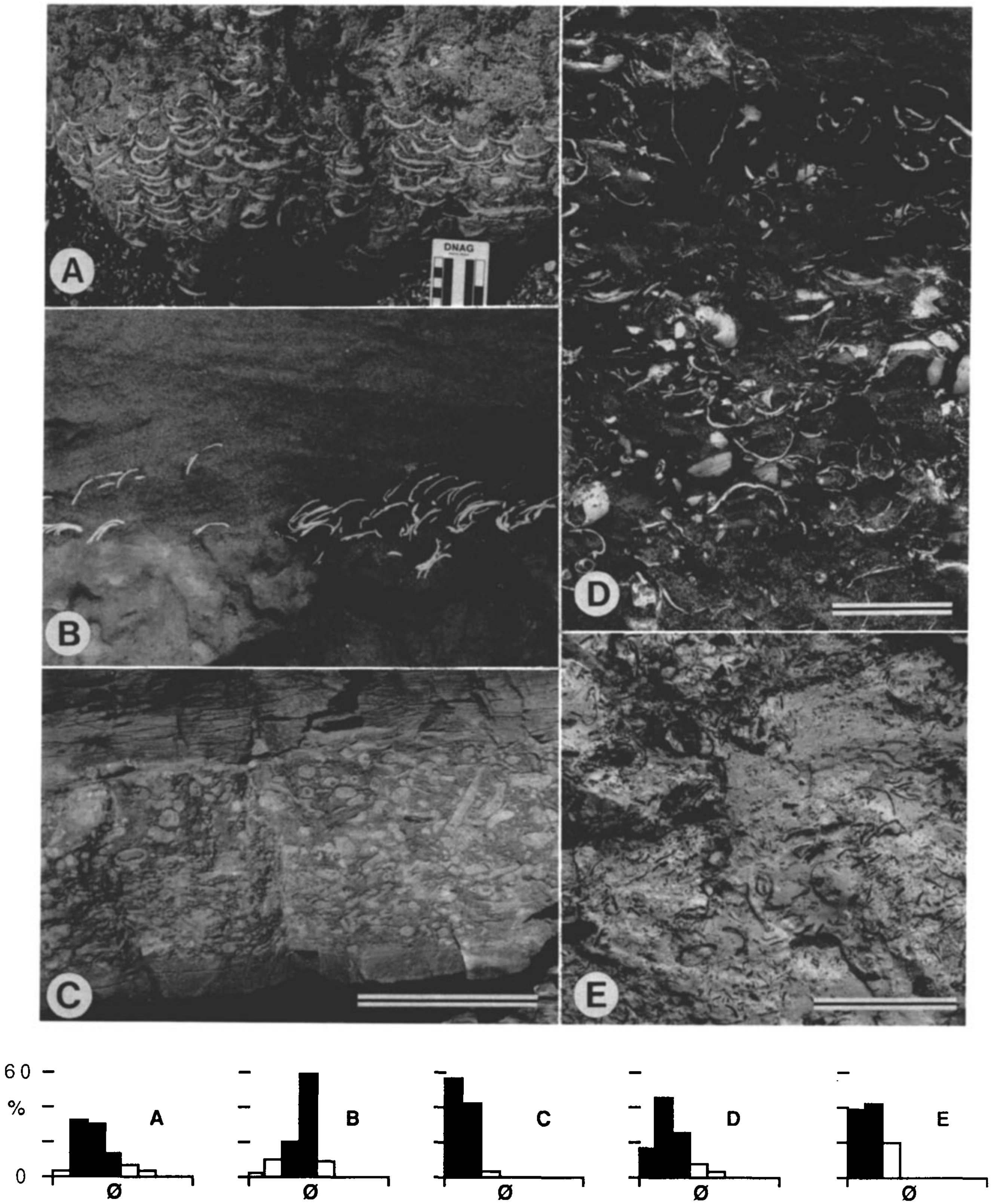
FIGURE 2—Field examples of densely packed and loosely packed fabrics of mollusks and (D) brachiopods. Bioclast sorting is based on the size-frequency distribution of ≥50 nearest-neighbors counted within a sub-quadrant of the photograph. Scale bars = 5 cm. **A)** Pliocene Imperial Formation, Coyote Mountains, California. **B)** Miocene St. Marys Formation, Calvert County, Maryland. **C** and **F)** Miocene Choptank Formation, Calvert County and St. Marys County (respectively), Maryland. **D)** Devonian Martin Formation, Dry Canyon, Arizona. **E)** Early Kimmeridgian lumachelle, Wierzbica, Poland.


A
B
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ship in polished sections. He suggested that shelter features (voids under large bioclasts), sediment-floored interstices, embayed contacts (sutured carbonate grains), and overly close packing could be used to identify bioclast-supported fabrics in carbonates. Shelter features and floored interstices would be especially useful in distinguishing between real and apparent loose-packing, but we have not observed these in ancient bioclast-rich siliciclastics.

If one is unsure whether a fabric should be described as densely packed, even after examining several different cross-sectional views and considering the morphology of the bioclasts, then there are two options. One is that the fabric should be assigned to the less restrictive loosely-packed category. In this way, the dense-packed category is reserved for fabrics that are definitely bioclast-supported, and the descriptive classification is also saved from becoming too inferential. Keeping the densely packed category restrictive should also keep its genetic implications more specific. This same approach can be used for borderline cases between loosely packed and dispersed, that is, assign the fabric to the dispersed category.

A second (and we believe preferable) solution would be to simply describe borderline fabrics as "dense/loose" or as "loose/dispersed." We use a similar approach in describing deposits that vary in close-packing over short distances (e.g., the variably loose to dispersed packing in the field of view in Fig. 2D, and in Fig. 3D).

To determine error in estimating close-packing, as well as any systematic trends in errors, we had 10 novices try our scheme on 22 photographed fabrics (220 datapoints). Despite the photographs being at different scales and quality, test-operators described close-packing correctly 89% of the time. Errors were evenly distributed among over- and under-estimates. We believe that accuracy in the field would be greater, given the advantages of close inspection and several cross-sectional views.

Ambiguity in Size-Sorting

Based on our tests, novices and experienced persons alike will err in one-third to one-half of samples when size-sorting is estimated visually. We warned our novices about our own tendency to over-estimate the goodness of sorting, and so this may have led to their consistent under-estimations.

Error in estimating size-sorting might be caused by several phenomena. One is that, when confronted with a mixture of sizes, the eye tends to be drawn to the larger bioclasts, which are then weighted more heavily than they deserve; essentially, the brain ranks bioclasts according to their volume or cross-sectional area in the field of view, rather than by their numerical abundance. This can cause one to under-estimate the sorting of predominantly fine-grained fabrics (e.g., Fig. 3E, which looks poorly sorted to us, but is actually well sorted), and can cause one to over-estimate the sorting of coarse bioclastic fabrics (e.g., Fig. 3A, which looks well sorted because of the large shells, but is actually poorly sorted owing to many particles in the 4–16 mm range).

A second difficulty lies in the log nature of the phi size-scale. To visually estimate sorting using this scale, the eye must become accustomed to discriminating doublings in sizes, rather than arithmetic increments. Moreover, because the scale is logarithmic, the absolute sizes of bioclasts are important: in terms of centimeters, a wider range of sizes of bioclasts fall into the -5, -6, -7, and -8 phi classes than in the -1, -2, and -3 intervals (Fig. 1). For example, a well-sorted fabric in which the primary mode is relatively coarse might qualitatively appear to be less well-sorted than a fabric in which the primary mode is fine, because the range in cm-scale sizes is greater in the first than in the second. It is thus possible to mistake well sorted coarse fabrics for poorly sorted ones, and poorly sorted fine fabrics for well sorted ones. Interestingly, this does not seem to counter-balance the opposite effect of the "large bioclast phenomenon" described above. Instead, test-operators simply show great variance in their estimates of size-sorting.

An obvious and easy solution is to tally the sizes of a subsample of individual bioclasts. A tally of 50 individuals (nearest neighbors) within a quadrant marked on the rock face is fast and worthwhile: if 40 of the 50 bioclasts lie within 2 adjacent size-classes, then the fabric may be described as well sorted. We would otherwise recommend trying to err conservatively: if the fabric is not obviously well-sorted or bimodal, then call it poorly sorted in order to keep the other qualitative categories as clear-cut as possible. A quick tally is, however, vastly superior.

Heterogeneity in Fabric

In many instances, a single bioclastic deposit exhibits a range of fabric types. This variation should be a part of the fabric's description, as it may provide important clues to genesis. For example, distinctive parts of the deposit may reflect separate events or simply different phases of

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FIGURE 3—Field examples of small-scale heterogeneity in fabric, and of the complicating effects of bioclast shape and absolute size on visual estimates of size-sorting; see text for discussion. Scale bars = 5 cm. **A**) Jurassic Trigonia clavellata Formation, Dorset, England; densely packed, poorly sorted. **B**) Pliocene Quinault Formation, Olympic Peninsula, Washington; densely to loosely packed, well sorted. **C**) Ordovician Martinsburg Formation, Narrows, Virginia; densely to loosely packed, well sorted. **D**) Miocene Choptank Formation, Calvert County, Maryland; loosely packed with pockets of dispersed fabric, poorly sorted. **E**) Early Kimmeridgian lumachelle, Wierzbica, Poland; predominantly loosely packed with small densely packed areas, well sorted.

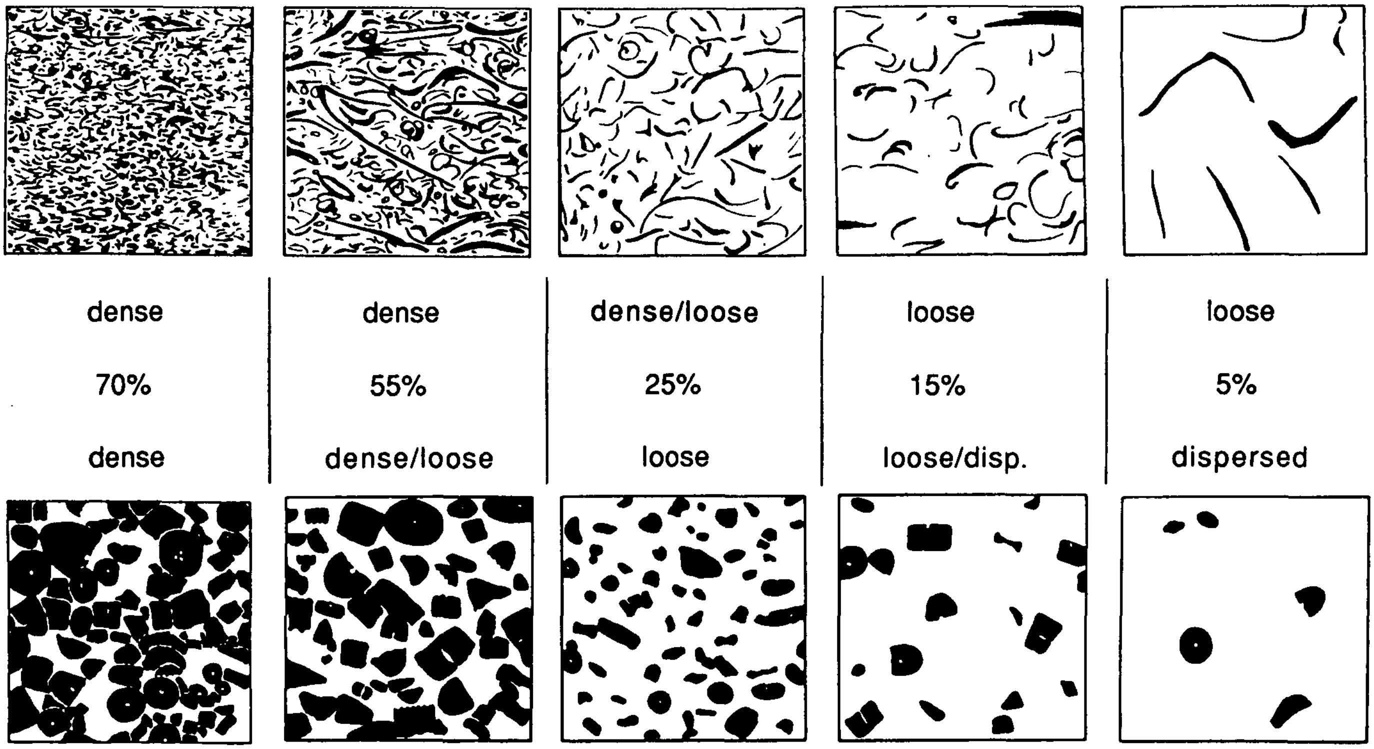

FIGURE 4—Bioclasts of different shapes may constitute the same percent-volume of a rock (line-drawings of Schäfer, 1969), but exhibit significantly different degrees of close-packing (our terms).

bioclast deposition during a single sedimentary event (e.g., microstratigraphic juxtaposition of less dense upon more dense fabric in Fig. 3C), or partial reworking (e.g., probably bioturbational origin of loose to dispersed packing in Fig. 3D). Heterogeneous fabrics thus should not be described by their "average" state, but by their variance at a given scale or field of view.

RELATION TO OTHER MEASURES

Close-packing is generally, but not precisely, related to the absolute abundance of bioclasts in a deposit, as discussed by Dunham (1962) for carbonates. For example, a densely packed fabric made of hollow spheres (e.g., biconvex bivalves or brachiopods) will have a lower bioclast content than a densely packed fabric composed of well-aligned sticks (e.g., fragments of branching skeletons) or of flat-lying plates (e.g., bivalve fragments, echinoid plates).

Schäfer's (1969) visual estimation charts for percent-volume bioclasts provide good examples of this shape and orientation effect (Fig. 4). Deposits with $\geq$55% bioclasts, for example, create densely packed fabrics regardless of bioclast shape and orientation. In contrast, deposits with 25% bioclasts may be densely packed if the bioclasts are bowls (e.g., bivalves, brachiopods) but only loosely packed if they are spheroidal (e.g., crinoid ossicles); 5% bioclasts can yield loosely packed fabrics of randomly oriented bowls, but only dispersed packing of spheroids. No simple equivalence between our close-packing categories and percent-volume measures of bioclast abundance is apparent (also see plates of Dunham, 1962). For related reasons, we would also not expect a simple correlation of close-packing with weight-percent measures of bioclast abundance.

Like Dunham (1962), we believe that close-packing has greater hydraulic and depositional significance than estimates of bioclast abundance. Each method, however, has its advantages and disadvantages, and each describes a different aspect of the rock. Therefore, we tend to describe both in the field. For example, although it is only semi-quantitative, close-packing can be estimated very quickly and consistently, and its accuracy in fact benefits from the irregularities of weathered outcrops. Percent-abundance charts, on the other hand, are slightly more quantitative and comparably consistent when used on polished or thin-sections (see tests by Flügel, 1982, p. 246), but are difficult to use in many outcrops where matrix has "retreated" back from the exposed edges of the bioclasts. In such instances, more bioclasts will be visible than would be in a single plane, leading to overestimation relative to values from polished sections. Because the methods describe different aspects of the rock record, we usually use both whenever possible, generating two

TABLE 1—Macroscopic features useful in genetic interpretation of bioclastic deposits. Adapted from Kidwell (in press).

Sedimentologic features of the deposit	Stratigraphic features of the deposit
Close-packing of bioclasts	Thickness of deposit
%-volume bioclasts in deposit	Lateral extent
Size-sorting of bioclasts	Scale relative to facies
Type of matrix	Geometry of deposit
Relative sizes and hydraulic equivalence of bioclasts and matrix	Stratigraphic contacts, especially any close association with erosion/omission surfaces
Associated physical and biogenic sedimentary structures	Internal complexity or microstratigraphy
Taphonomic features of the bioclasts	Position within depositional sequence
Orientation	Paleoecologic features of the bioclasts
in plan view	Number of species
in cross-section	Relative abundances of species
Degree of articulation of carcasses	Taxonomic composition
Fragmentation	Life habits
Rounding	Ontogenetic age spectrum
Surface abrasion, corrosion, bioerosion or encrustation	Original mineralogy and microarchitecture
Preserved mineralogy and microarchitecture	

different, independent descriptions of each bioclastic fabric.

In contrast to the biofabric scheme presented by Kidwell et al. (1986), our scheme focusses on *coarse* bioclasts, identifies size-sorting rather than orientation as a major variant, and divides the spectrum of close-packing more finely. Specifically, fabrics that they would categorize as "bioclast-supported" are here termed densely packed; this is a semantic difference only. Their "matrix-supported" fabrics we subdivide into loosely packed, dispersed, and barren (the latter if composed of fine bioclasts only).

GENETIC IMPLICATIONS

Close-packing and size-sorting are only two features used in interpreting the origin of bioclastic sediments; many others (e.g., Table 1) are required to reconstruct the oftentimes complex histories of these deposits with confidence. Although it provides an incomplete description, categorization by close-packing and size-sorting does limit the number of possible origins, leading to some basic hypotheses that can be tested using other taphonomic, paleoecologic, sedimentologic, and stratigraphic (bedding) features.

High degrees of close-packing, for example, may reflect winnowing of matrix (hydraulic or biogenic), failure of sediment supply (low dilution of "normal" or background bioclast input), or some event or episode of high bioclast input (ecological aggregation, mass mortality, hydraulic or biogenic delivery or concentration of exotic material). High degrees of size-sorting may reflect sorting associated with winnowing (either hydraulic or biogenic), ecological conditions (gregarious settlements of single cohorts, highly size/age dependent death), or taphonomic or diagenetic culling (leaving a residuum that is relatively homogeneous with respect to size, shape, or mineralogy). Distinguishing among these alternative hypotheses requires information on shell condition (e.g., abrasion, rounding, bioerosion, diagenesis), associated sedimentary structures, life-habits of the shell-producers, and stratigraphic context, at the very least.

For example:

Fig. 2A: the high frequency of articulated, life-positioned oysters in this dense-packed well sorted fabric, together with the large scale of the deposit, its low-relief lenticular shape, and its occurrence within a fine-grained stratigraphic interval, all indicate an accretionary buildup formed by ecological aggregation and little hydraulic or other reworking (Kidwell, 1988).

Fig. 2B: the densely packed bimodal fabric is characterized by highly *dis*articulated infaunal bivalves and shell fragments, occurs in a cross-bedded unit with a well-sorted fine sand matrix, and is almost certainly hydraulic in origin.

Fig. 2C: the poorly sorted, densely packed shells are in various states of preservation and are associated with anastomosing discontinuity surfaces within a stratigraphically condensed transgressive shelly sand: the fabric reflects hydraulic and biogenic amalgamation of many different generations of local benthos, with repeated burial/exhumation cycles (Kidwell, 1989).

Fig. 3A, B: concave-up stacking of disarticulated bivalves (A) is diagnostic of settling out of high-density turbulent flows (cf. Middleton, 1967) such as generated by high-energy storm events, whereas the concave-down imbrication of disarticulated bivalves (B) indicates tractive reworking of bivalves on a firm, high-friction substratum. Note concentration of shells along the contact of the lower silty unit and the cross-bedded sand in B; the clumping of bioclasts is probably the result of shell/shell interference (cf. Futterer, 1978).

One reviewer suggested that degree of abrasion was a common variant among calcarenitic bioclastic textures (i.e., bioclasts <2 mm) and that, because of its depositional significance, plays an important role in classification (at least informally). Abraded bioclasts have not been common components in coarse bioclastic fabrics that we have examined, although it must be admitted that this may be an artifact of our experience. Certainly abrasion can be important in crinoidal shoals, molluscan beach coquinas, etc. We thus have ranked bioclast abrasion high in the list of secondary features to include in field descriptions, because these do seem to be strong indicators of bioclast residence in beach or shoal environments, regardless of the bioclast's ultimate depositional environment.

CONCLUSIONS

This fairly simple, semi-quantitative system satisfies most of the demands for a field classification of coarse bioclastic fabrics. The packing and sorting descriptors (1) convey an immediate visual image of the deposit, (2) can be applied to terrigenous as well as carbonate rock types, (3) can be applied to void-fabrics as well as those characterized by recrystallized and unaltered bioclasts, and (4) are easy to use in the field by non-specialists. The semi-quantitative method for estimating close-packing is highly consistent among operators and among diverse fabrics, and complements existing methods for carbonate rocks. Quantitative size-frequency data are essential if fabrics are to be categorized correctly with respect to size-sorting of coarse bioclasts. However, given a tally of only 50 bioclasts, the central 80% of the distribution can be estimated quickly and accurately. Used alone or in combination, these packing and sorting scales should improve the objectivity and thus eventually the interpretive value of field descriptions.

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