A FIELD METHOD FOR DETERMINING THE FIRMNESS OF COLONIZED SEDIMENT SUBSTRATES

MURRAY K. GINGRAS[1] AND S. GEORGE PEMBERTON[2]
[1] *Department of Geology, University of New Brunswick, Fredericton, New Brunswick, Canada E3B 5A3*
e-mail: *mgingras@unb.ca*
[2] *Deptartment of Earth and Atmospheric Sciences, 1–26 Earth Sciences Building, University of Alberta, Edmonton, Alberta, Canada T6G 2E3*

ABSTRACT: **Substrate firmness influences the erodibility, remobilization, and topographic expression of that substrate. Sediment distribution patterns, remobilization of sediment, and the architecture of biogenic sedimentary structures are strongly affected by the firmness and cohesiveness of the sediment. Given the potentially important role sediment firmness plays in different depositional settings it is important to have a consistent means of evaluating it.**

This paper demonstrates that a modified metallurgical technique, the Brinell hardness test, can be used to produce accurate and consistent firmness data in modern depositional settings. In this method a glass or metal sphere (the indentor) is dropped from a fixed height into a cohesive medium; the size of the indent produced is inversely proportional to the firmness of the media. Firmness values can be reported as a pressure exerted by the substrate (kPa). This method has some advantages over standard penetrometers, such as: ease of use, portability and simplicity of equipment, testing a large area, and flexibility of calculation. Field tests show that this method is accurate if the indentation diameter is between 10% and 80% of the indentor diameter. The method is inappropriate for dry, unconsolidated sand and thixotropic mud. It is, however, extremely useful for assessing the firmness of a wide range of soft to firmground sediments that are composed of clay through coarse sand.

INTRODUCTION

The Sedimentological Significance of Firm Substrates

Substrate cohesiveness, or firmness, is difficult to assess from the rock record. Several studies have shown, however, that trace fossil assemblages in softgrounds, firmgrounds, woodgrounds and hardgrounds are distinctly different from each other. This distinctiveness has permitted ichnologists to characterize these substrate-sensitive trace associations as ichnofacies. These include several softground ichnofacies (Seilacher 1964), and the *Glossifungites, Teredolites,* and *Gastrochaenolites* ichnofacies respectively, all of which reflect the different boring or burrowing strategies that are utilized to colonize a substrate. Burrows in soft sediment, for example, result from the activities of infauna moving on and through the sediment for diverse purposes. At the other end of the spectrum, hardground fauna live in hollowed-out living spaces that are similar to their body shape. Firmgrounds encompass a range of sediment cohesiveness and generally consist of advected and excavated burrows that include open tubes, tunnels, and living chambers. It is somewhat intuitive that the degree of firmground induration affects the burrow architecture used to colonize a substrate (Frey and Seilacher 1980; Pemberton and Frey 1985). This has been illustrated in the modern (Pemberton and Frey 1985; Gingras et al. 2000) but has not been related to the rock record; a situation attributable to the small database of modern studies and an absence of reported (comparable) firmness measurements.

The firmness of a substrate in modern depositional settings is related to many factors. These include grain size, pore-water content, drainage, compaction, and (in carbonates) the potential for early cementation of grains. Notably, physical and biogenic processes are influenced by the overall cohesiveness of the substrate. For example, cohesive substrates resist the erosion and resuspension of grains (Knighton 1984; DeVries 1992; Dade et al. 1992). Also, antecedent topography due to the erosion of surfaces characterized by the patchy distribution of firmgrounds (Huang 1993) affects sediment distribution patterns on many scales (Sanford and Halka 1993). Finally, bioturbation itself alters the overall cohesiveness of the substrate (Cadée 1998; Gingras et al. 2000).

The dependence of the aforementioned processes on substrate firmness suggests that researchers of modern depositional environments would benefit from making detailed observations on the distribution of firmness profiles. Thomas Ronan, a benthic ecologist/paleontologist, repeatedly demonstrated the control substrate stability exerts on burrowing animals. He developed a method for evaluating substrate consistency using a large, weighted rod penetrometer (Ronan 1975). Although his work has not been publicized widely, it provides a framework for comparative, analytical studies (Ronan et al. 1981).

Most commonly, however, compaction tests are of greater interest to geotechnical researchers. Their studies range from calculating the mechanical resistance of soils (Ohnuki et al. 1997) to subsurface (borehole) environmental interpretation using penetrometer soundings (Nelson et al. 1997). Most previous studies have utilized conical and plate penetrometers. The simplest of these is the drop penetrometer (Levacher 1985), which consists of a dropped conical apparatus that invades the substrate to a certain depth. With the exception of the drop penetrometer, the aforementioned devices do not provide the simplest and most portable equipment for use in field applications. Also, measurements derived from such an apparatus are specific, and can be indicative of the sediment firmness over areas less than 1 or 2 mm diameter. This is not necessarily true of measurements taken in relatively soft sediments.

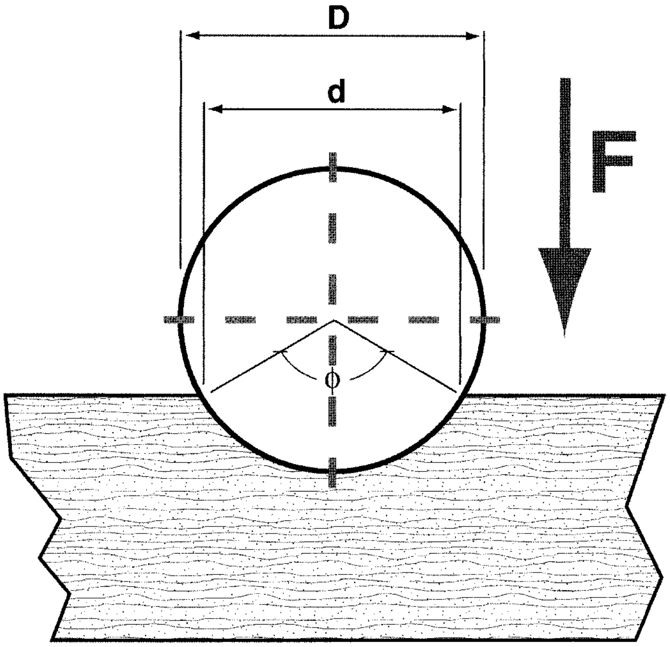

FIG. 1.—Test configuration of the modified Brinell firmness test. The parameters used to calculate the force exerted by the substrate are the diameter of the indentor (D), and the diameter of the impression (d).

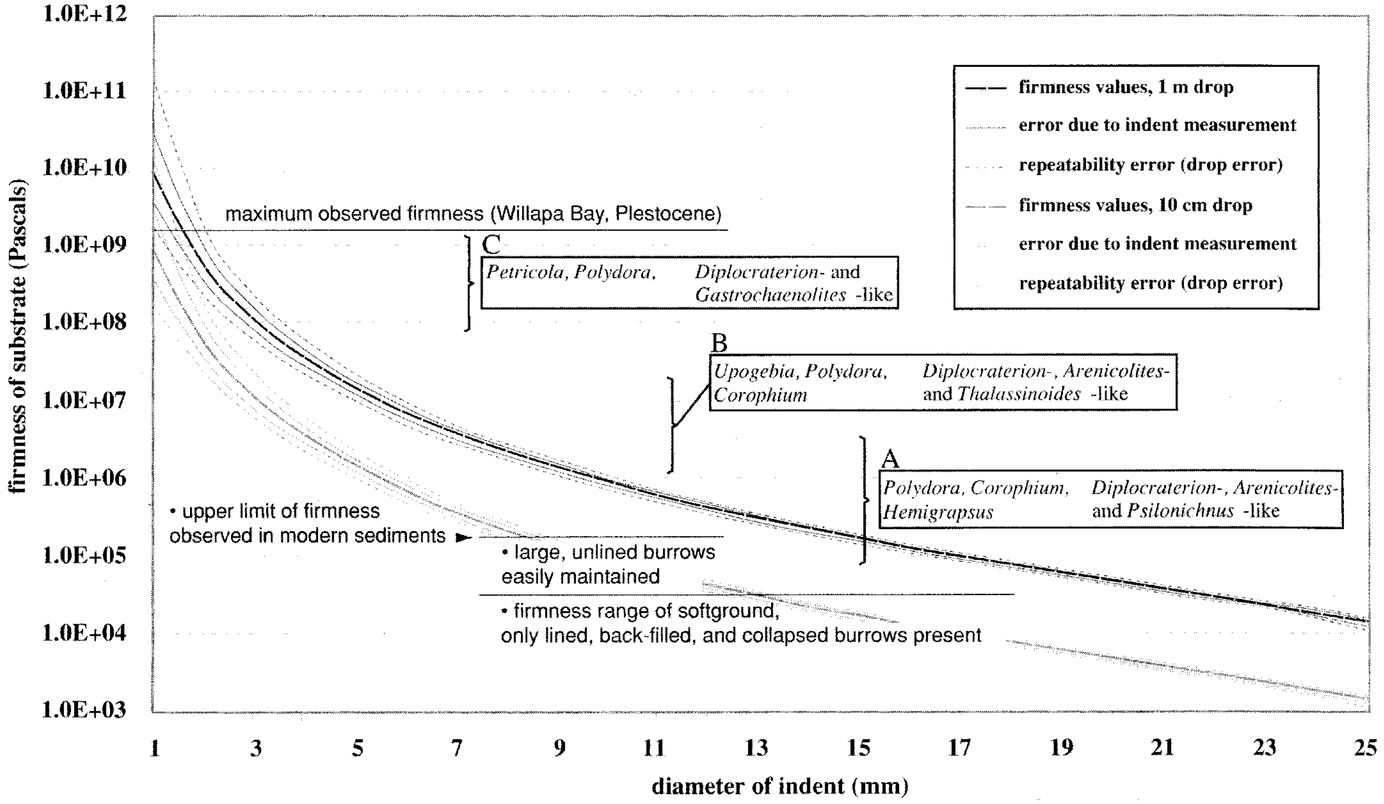

FIG. 2.—Graph of the pressure exerted by the substrate vs. the diameter of the indentation made during the firmness test. The upper (black) curves estimate the pressure produced by an indentor based on a 1 m free fall, and the lower (gray) curves indicate pressure values produced from a 10 cm drop. Thin, solid lines indicate the error due to measurement. Thin dashed lines indicate the error due to the release of the ball; this *includes* the measurement error. Also shown on this graph are the firmness ranges exploited by different assemblages of bioturbators at Willapa Bay, Washington (Gingras et al. 2000). The primary trace makers and their associated traces are indicated.

Polydora = small spionid worm; *Corophium* = small amphipod; *Hemigrapsus* = shore crab; *Upogebia* = mud shrimp; *Petricola* = boring bivalve. The ability of the various sediments to maintain open burrow systems is also noted. These data are reported in Gingras et al. (2000).

In these regards, sedimentologists might adapt methods from the metallurgical sciences, where the hardness testing of alloyed, heat-treated, and annealed metals has been practiced since the early 1900s. A general overview of these practices can be found in O'Neill (1967). The metallurgical equivalent of the conical penetrometer is the Rockwell hardness tester, a mechanical device that applies a fixed force against a small pyramid that is driven into the metal being tested. The hardness of the metal is inversely proportional to the area of the indentation imposed by the pyramid. Because the application of a fixed force requires a somewhat sophisticated mechanical apparatus, this method is seldom used in field applications. Field measurements are preferentially derived from the Brinell hardness test (Brinell 1900). In the field, this method depends on driving a steel ball into the metal with a dynamic force, usually a three-pound hammer accelerating at the end of a person's arm. In this case, the hardness of the metal is inversely proportional to the area of the indentation created by the ball. The advantages of this method are clear. The equipment is unsophisticated and portable, and the procedure is simple and can be repeated many times. Also, the measurements produced by this seemingly crude method accurately assess the hardness of the metal within half an order of magnitude (hardness in metals varies over several orders of magnitude). Indentations due to Brinell hardness tests are notably larger than those caused by the Rockwell pyramid. The Brinell test therefore takes more general measurements of metal hardness.

This paper suggests that a modified version of the Brinell hardness test is equally appropriate for assessing the firmness of substrates in modern depositional environments. Portable, simple equipment that is capable of providing reproducible results that accurately average the firmness of the sediment provides the opportunity to take a greater quantity of firmness measurements. A somewhat larger area of measurement allows for assessments of the sediment firmness that average small-scale heterogeneities, such as minute burrows or variations in pore-water content. Finally, this paper demonstrates that the calculations utilized to approximate sediment firmness are simple and can be easily modified to accommodate variations in the method applied. This is a decided advantage over penetrometer tests in which the drop-cone is typically of fixed weight and dimension.

THE METHOD

A glass or metal indentor, 25 mm in diameter, is dropped from a fixed height of 10 or 100 cm. Calculation of the pressure exerted by the substrate requires equating the potential energy at the top of the indentor's free fall to the energy (or impulse) absorbed by the substrate. This can be calculated as a proxy by calculating potential energy (into the substrate) as a function of mass, acceleration, and depth of penetration into the substrate.

$$PE_1 = PE_2 \qquad m \times g \times h_1 = m \times a \times h_2$$

$$(m \times g \times h_1)/h_2 = m \times a = F_2 \tag{1}$$

Where:

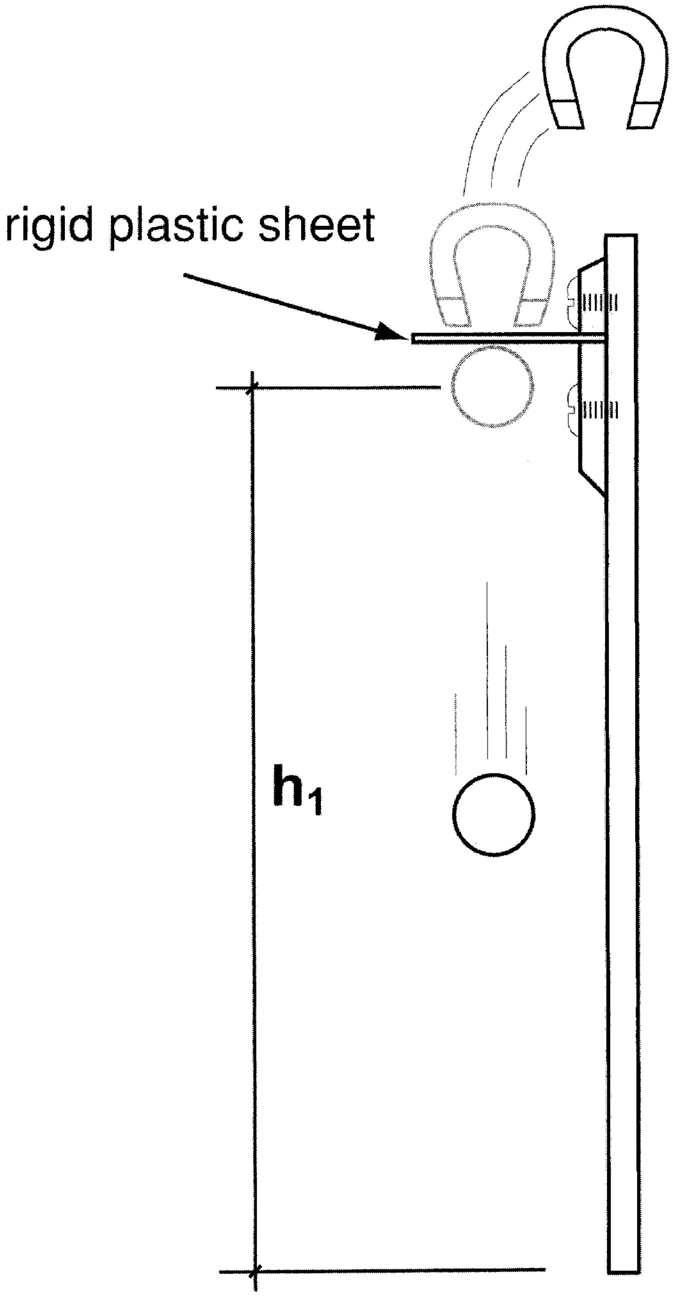

FIG. 3.—Modified Brinell test with magnetic release apparatus.

PE = potential energy m = mass g = acceleration (gravity)

h_1 = height of drop h_2 = depth of indent

a = deceleration of indentor

F_2 = force exerted by substrate

The force exerted by the substrate (F_2) can be converted to mean pressure by dividing F_2 by the projected area of the indent (Fig. 1), a method recommended to metallurgists by O'Neill (1967), in that it represents the area of substrate resisting indentation. The relationship between the depth of the indent and the pressure exerted by the substrate during impact is nonlinear, and the practical measurable range using a 25.4 mm glass ball is between 5.0 kpa and 1.0×10^8 kpa (Fig. 2).

TABLE 1.—*All the uncompacted samples are derived from tidal flat sediments. Compacted muds were derived from Pleistocene intertidal deposits that were in various states of (modern) firmground colonization.*

Substrate Type	Indent Measurement (mm) 1	2	3	4	5	avg.	mode
uncompacted mud a	16	17.5	16	16	17	16.5	16
uncompacted mud b	9	8	10	8	9	8.8	9
uncompacted mud c	18	18	19	19.5	18	18.5	18
uncemented sand a	8	8	8	9	8	8.2	8
uncemented sand b	11	11.8	12	12.5	12	11.86	12
compacted mud a	6	6	6	6	6	6	6
compacted mud b	3.5	3	3	3	3	3.1	3
compacted mud c	2	3	2	2	2	2.2	2

The simplest means of releasing the indentor is by hand release. A more consistent release is provided by the magnetic release mechanism, in which case a steel ball bearing must replace the glass indentor (Fig. 3). In both cases, the indentor's height is calibrated to a decimeter or meter scale. Because this procedure is so simple, firmness tests can be made on *in situ* substrates or box-core samples.

DISCUSSION

Sources of Error and Limitations

Many sources of error are evident in the previously outlined method. The most significant are related to the measurement of the indentation and the variability due to the initial release of the indentor. Normally, the diameter of the indentation can be measured to within ± 0.25 mm. On firm substrates, where the indent diameter is less than 2 mm, the log error produced in measurement approaches 10%. This value represents a range of one order of magnitude about the actual firmness of the medium (Fig. 2). If the indent diameter exceeds 9 mm, the log error falls below 4% (Fig. 2).

Multiple trials show that the error due to manual release of the indentor is small. Several repeat runs ($n = 5$) showed that the maximum error about the modal measurement was 0.5 mm (Table 1). Given that the error attributed to measuring the diameter of the indent is ± 0.25 mm, we have assumed that the error due to the release of the indentor is ± 0.25 mm as well. Therefore, indent diameters approaching 1 mm are inherently inaccurate because the log error approaches 20% (Table 1). Where the indent diameter is 2.5 mm, or 10% of the indentor diameter, the log error is an acceptable 8%. Although measurement and release errors are notably small for indent diameters exceeding 20 mm (80% of the indentor diameter), we have found that deformation of the substrate upon removal of the indentor makes these measurements exceedingly inaccurate. We therefore suggest that this method be used where the indent diameter is greater than 10% and less than 80% of the indentor diameter. In the field, drop heights might be adjusted to find an ideal middle range. The adjusted height (h_1) can then be substituted into equasion 1 and the sediment firmness assessed.

All of the above assumes the indentor strikes a horizontal surface from the vertical axis. Indents that are visually out of round are disregarded. Also, the modified Brinell method is inappropriate for dry, unconsolidated sand and extremely thixotropic mud, where indents collapse and cannot be measured. Although these limitations may be significant, the Brinell method is extremely useful for quickly assessing the firmness of most softground and firmground substrates.

Burrow Assemblages and Sediment Cohesiveness

Figure 3 also details the dominant burrowing assemblages present in substrates of differing firmness as observed at Willapa Bay, Washington (from Gingras et al. 2000). The least indurated of firmground sediments (10^5 to 10^7 Pa) are colonized by infauna associated with Assemblage A

(Fig. 3). This assemblage is dominated by small U-shaped tubes (*Arenicolites*-like and *Diplocraterion*-like traces) and the cavernous excavations of shore crabs. In intermediate substrates (10^6 to 10^8 Pa) Assemblage B is present. These sediments also contain *Arenicolites*-like and *Diplocraterion*-like traces, but large, branching *Thalassinoides* supplant the crab burrows. In the firmest sediments observed (10^8 to 10^9 Pa), Assemblage C is common. This trace suite consists primarily of the living chambers of bivalves (*Gastrochaenolites*) and various *Diplocraterion*-like traces.

It is fair to question how permeability measurements relate to burrowing and boring animals. Does a weighted rod driven into the sediment have any relationship to the activity of burrowing (cf. Ronan et al. 1981)? Does an indentor mimic the actions of a sand shrimp? No, they do not. But *they all respond to a physical property that must be overcome by the rod, ball, and shrimp to invade the sediment.* In this case that property is shear strength. Other strength parameters, such as yield strength and ductile strength, can be measured in materials; these generally increase disproportionately with shear strength (Avner 1974). Several other factors influence the ability of the aforementioned organisms to colonize substrates that are variably indurated. These include functional morphology, behavioral adaptation, and larval recruitment. For the case of Willapa Bay, these are discussed in greater detail in Gingras et al. (2000). The burrow associations (and their relationship to substrates of different firmness) outlined above suggest that shear strength is an extremely important factor for burrowing animals and that they respond to it by modifying their burrow architecture (Gingras et al. 2000).

SUMMARY

Substrate firmness is a physical characteristic that strongly affects the erodibility and remobilization of sediment. It also creates antecedant topography that may influence sedimentation patterns on different scales. Furthermore, organism trace assemblages are profoundly influenced by the overall cohesiveness of the sediment. Considering these observations, a portable, simple, and expedient means of measuring sediment firmness would help establish a more comprehensive database relating to firmness variations in different depositional environments. A modified version of the Brinell hardness test fulfills these requirements.

The modified Brinell firmness test assesses the impulse imparted to the sediment by a sphere dropped from a fixed height. The impulse is converted to pressure and is regarded to be representative of the sediment's firmness.

Primarily because of measurement errors, the method is inaccurate where the diameter of the indent imparted to the substrate is less than 10% and greater than 80% of the indentor diameter. If the indent diameter does not fall between these two values, the drop height can be adjusted. In such cases, the simple formula provided herein can be used to correctly assess the firmness of the substrate. The modified Brinell test is inappropriate for measuring the firmness of dry, unconsolidated sands and thixotropic muds. It is, however, useful for the assessment of the firmness of most softground and firmground substrates that are composed of clay through coarse sand.

In short, the advantages of this testing procedure are simplicity, portability, flexibility of method, ease of calculation, and relative accuracy. The primary disadvantages include substrate limitations, and constraints regarding indent-to-indentor ratios.

ACKNOWLEDGMENTS

Funding of this research was generously provided by the Natural Sciences and Research Council (NSERC) Operating Grant (No. A0816) to S.G. Pemberton, John Van Wagoner at Exxon Production Research, Lee F. Krystinik at Union Pacific Resources, and Grant Wach at Texaco Inc. This paper benefited from comments by Greg Nadon and Molly Miller, and was inspired by Al Curran.

REFERENCES

AVNER, S.H., 1974, Introduction to Physical Metallurgy, Second Edition: New York, McGraw Hill, 696 p.

BRINELL, J.A., 1900, II Congress Internationál de Methodes d'Essai: Iron and Steel Institute Journal, v. 59, p. 243.

CADÉE, G.C., 1998, Influence of benthic fauna and microflora, *in* Eisma, D., ed., Intertidal Deposits; River Mouths, Tidal Flats, and Lagoons: Boca Raton, Florida, CRC Press, p. 383–402.

DADE, W.B., NOWELL, A.R.M., AND JUMARS, P.A., 1992, Predicting erosion resistance of muds: Marine Geology, v. 105, p. 285–297.

DEVRIES, J.W., 1992, Field measurements of the erosion of cohesive sediments: Journal of Coastal Research, v. 8, p. 312–318.

FREY, R.W., AND SEILACHER, A., 1980, Uniformity in marine invertebrate ichnology: Lethaia, v. 13, p. 183–207.

GINGRAS, M.K., PEMBERTON, S.G., AND SAUNDERS, T.D.A., 2000, Firmness profiles associated with tidal-creek deposits; the temporal significance of *Glossifungites* assemblages: Journal of Sedimentary Research, v. 70, p. 1017–1025.

HUANG, J., 1993, Experimental study on the scouring of cohesive deposits in salt water: International Journal of Sediment Research, v. 8, p. 67–83.

KNIGHTON, D., 1984, Fluvial Forms and Processes: New York, Halstead Press, 218 p.

LEVACHER, D., 1985, Penetrometre a chute libre; impact et penetration dans des argiles reconstituees: Canadian Geotechnical Journal, v. 22, p. 129–135.

NELSON, C.V., BRINK, J.D., HEPPLER, L., BISHOFF, J., BRACEROS, C., AND BROWN, K., 1997, Interpretation of late Pleistocene and Holocene stratigraphy and depositional environments in the Salt Lake Valley, Utah, using borehole logs and cone penetrometer soundings (abstract): Geological Society of America, Abstracts with Programs, v. 29, p. 149.

OHNUKI, Y., TERAZONO, R., IKUZAWA, H., HIRATA, I., KANNA, K., AND UTAGAWA, H., 1997, Distribution of colluvia and saprolites and their physical properties in a zero-order basin in Okinawa, southwestern Japan: Geoderma, v. 80, p. 75–93.

O'NEILL, H., 1967, Hardness Measurement of Metals and Alloys, Second Edition: London, Chapman & Hall, 238 p.

PEMBERTON, S.G. AND FREY, R.W., 1985, The Glossifungites Ichnofacies: Modern examples from the Georgia Coast, U.S.A., *in* Curran, H.A., ed., Biogenic Structures: Their Use in Interpreting Depositional Environments: SEPM, Special Publication 35, p. 237–259.

RONAN, T.E., JR., 1975, Structural and paleoecological aspects of a modern marine soft-sediment community; an experimental field study [unpublished Ph.D. Thesis]: University of California, Davis, 220 p.

RONAN, T.E., JR., MILLER, M.F., AND FARMER, J.D., 1981, Organism–sediment relationships on a modern tidal flat, Bodega Harbor, California, *in* Frizzel, V., ed., Modern and Ancient Biogenic Structures, Bodega Bay, California, SEPM, Pacific Section, p. 15–31.

SANFORD, L.P., AND HALKA, J.P., 1993, Assessing the paradigm of mutually exclusive erosion and deposition of mud, with examples from upper Chesapeake Bay: Marine Geology, v. 114, p. 37–57.

SEILACHER, A., 1964, Sedimentological classification and nomenclature of trace fossils: Sedimentology, v. 3, p. 253–256.

Received 29 October 1999; accepted 15 April 2000.