have been investigating these issues through computer simulation by using realistic interatomic potentials that model Au (111) surfaces. Their results provide some evidence that interaction effects may be important in the annealing of the roughening resulting from dissolution. For example, they find that as a result of stress field interactions, vacancies are attracted to a down ledge and repelled from an up ledge.

REFERENCES AND NOTES

1. Q. Song, R. C. Newman, R. A. Cottis, K. Sieradzki, *J. Electrochem. Soc.* **137**, 435 (1990).
2. D. E. Williams, R. C. Newman, Q. Song, R. G. Kelly, *Nature* **350**, 216 (1991).
3. K. Sieradzki and R. C. Newman, *Philos. Mag. A* **51**, 95 (1985).
4. H. W. Pickering and C. Wagner, *J. Electrochem. Soc.* **114**, 698 (1967).
5. A. J. Forty and G. Rowlands, *Philos. Mag. A* **43**, 171 (1981).
6. K. Sieradzki, R. R. Corderman, K. Shukla, R. C. Newman, *ibid.* **59**, 713 (1989).
7. R. Sonnenfeld and P. K. Hansma, *Science* **232**, 211 (1986); H. Y. Liu, F. R. F. Fan, C. W. Lin, A. J. Bard, *J. Am. Chem. Soc.* **108**, 3838 (1986).
8. J. Wiechers, T. Twomey, D. M. Kolb, R. J. Behm, *J. Electroanal. Chem.* **248**, 451 (1988).
9. D. J. Trevor, C. E. D. Chidsey, D. N. Loiacono, *Phys. Rev. Lett.* **62**, 929 (1989).
10. D. J. Trevor and C. E. D. Chidsey, *J. Vac. Sci. Technol. B* **9**, 964 (1991).
11. M. P. Green *et al.*, *J. Phys. Chem.* **93**, 2181 (1989).
12. O. M. Magnussen, J. Hotlos, R. J. Nichols, D. M. Kolb, R. J. Behm, *Phys. Rev. Lett.* **64**, 2929 (1990).
13. S. L. Yau, C. M. Vitus, B. C. Schardt, *J. Am. Chem. Soc.* **112**, 3677 (1990).
14. S. Manne, P. K. Hansma, J. Massie, V. B. Elings, A. A. Gewirth, *Science* **251**, 183 (1991).
15. For reviews, see R. Sonnenfeld, J. Schneir, and P. K. Hansma [in *Modern Aspects of Electrochemistry*, R. E. White, J. O. M. Bockris, B. E. Conway, Eds. (Plenum, New York, 1990), vol. 21, pp. 1–28] and C. E. D. Chidsey [in *Applications of Surface Analysis Methods to Environmental/Material Interactions*, D. R. Barv, C. R. Clayton, G. D. Davis, Eds. (Electrochemical Society, Pennington, NJ, 1991), PV 91-7, p. 25].
16. Freshly cleaved mica substrates were thermally bonded with In to a heated Mo plate that was held at 300°C. Ag was evaporated from a resistively heated crucible, and Au was evaporated with an electron beam. The total deposition rates were typically a few angstroms per second. The system pressure was of the order of 5×10^{-7} torr during evaporation. For details of the deposition apparatus, see C. E. D. Chidsey, D. N. Loiacono, T. Sleator, and S. Nakahara [*Surf. Sci.* **200**, 45 (1988)].
17. We determined the Ag content by using elemental standards with the program Fundamental Parameters (Tracor X-ray, Princeton, NJ). This method was confirmed by Rutherford backscattering spectroscopy on the $Ag_{0.15}Au_{0.85}$ sample.
18. The steady-state electrochemical current at the tips was 100 pA or less at the potentials used during the experiments.
19. W. J. Kaiser and R. C. Jaklevic, *Surf. Sci.* **182**, L227 (1987).
20. G. Binnig, H. Rohrer, Ch. Gerber, E. Weibel, *ibid.* **131**, L379 (1983).
21. The small hillocks in Fig. 1A are occasionally observed on Au and Ag-Au alloy samples in air and electrolytes and are not understood.
22. In the experiments with the $Ag_{0.04}Au_{0.96}$ and $Ag_{0.15}Au_{0.85}$ alloys the electrolyte contained 1 mM $AgClO_4$, and the reference electrode was a Ag wire.
23. In the experiments with the $Ag_{0.15}Au_{0.85}$ alloy the electrochemical potential was raised to 0.70 V, at which time the counter electrode was opened and STM images were acquired. The potential of the sample slowly decreased.
24. Although monolayer de-alloying had not been examined before our investigation, polarization curve measurements reported by R. P. Tischer and H. Gerischer [*Z. Elektrochem.* **62**, 50 (1962)] on a series of Ag-Au alloys provide evidence of the compositional dependence of Ag dissolution. Their results indicate that for alloys with less than about 50% by atom Ag, dissolution occurs at potentials close to the Au oxidation potential, whereas for alloys with greater than 50% by atom Ag, dissolution occurs at potentials closer to the potential at which Ag dissolves from a pure Ag electrode.
25. K. Meinel, M. Klaua, H. Bethge, *Phys. Status Solidi A* **106**, 133 (1988); G. A. Somorjai, in *Chemistry and Physics of Solid Surfaces V*, vol. 35 in the *Springer Series in Chemical Physics*, R. Vanselow and R. Howe, Eds. (Springer-Verlag, Berlin, 1984), pp. 1–22.
26. The 2-D percolation threshold for the triangular lattice including first and second near neighbors is 0.295 [V. K. S. Shante and S. Kirpatrick, *Adv. Phys.* **20**, 325 (1971)].
27. Although there is no direct evidence for the formation of a Ag overlayer resulting from segregation in Ag-Au, low-energy ion scattering has shown that segregation of Au to Ni (111) surfaces results in the formation of a pure Au overlayer [T. M. Buck, in *Chemistry and Physics of Solid Surfaces IV*, vol. 20 of the *Springer Series in Chemical Physics*, R. Vanselow and R. Howe, Eds. (Springer-Verlag, Berlin, 1982), pp. 435–464].
28. Once a vacancy or a vacancy cluster is formed, its diffusion in the terrace could determine the rate at which other nearby Ag atoms dissolve, because a Ag atom adjacent to a vacancy probably dissolves more quickly than one isolated in a terrace.
29. K. Sieradzki, F. H. Strietz, I. C. Oppenheim, unpublished results.

30. The work of K.S. and I.C.O. was supported by the U.S. Department of Energy Office of Basic Energy Sciences (contract DE-FG02-90ER45421) and the NSF (contract DMR-9011047).

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Early Cambrian Foraminifera from West Africa

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Agglutinated foraminifera have been recovered from siltstones in the Walidiala Valley, Taoudeni Basin, West Africa. Associated faunas suggest an Early Cambrian age for these strata. These now earliest known unequivocal foraminifera help constrain hypotheses concerning the origin of skeletalization at the beginning of the Phanerozoic.

DISCUSSIONS CONCERNING THE APpearance of skeletonization near the base of the Cambrian [about 550 Ma (million years ago)] (*1*) are often restricted to metazoans and take little account of the acquisition of hard parts by protists at the same time. For example, hypotheses relating the evolution of skeletonization to increases in body size (*2*) and to detoxification of excess calcium (*3*) in metazoans do not apply to protists and hence are weakened by the appearance of testate protists in the Early Cambrian (*4*). However, this appearance is not inconsistent with the hypothesis, applicable to both metazoans and protists, that the initial function of skeletons was to protect the organism, primarily against predation (*5*). The presence of agglutinated foraminifera in the Lower Cambrian, probably Atdabanian Stage–equivalent strata, of the Taoudeni Basin, West Africa, is reported here. These specimens extend considerably the known geologic range of several genera, they represent the earliest known unequivocal foraminifera, and they further remind us that protists as well as metazoans should be considered in accounting for the origin of skeletalization.

The unmetamorphosed and generally undeformed Taoudeni Basin strata have been divided into three supergroups (*6*). Supergroup 1 is entirely Proterozoic in age, Supergroup 2 (about 1200 m thick) commences with an Upper Proterozoic tillite, and Supergroup 3 commences with an Upper Ordovician tillite (*6*). In the Walidiala valley at the Senegal-Guinea border, only the lower portion of Supergroup 2 is present and is represented by the Mali group (Fig. 1). This has been divided into the Hassanah Diallo Formation, composed of glacial diamictites and laminated siltstones with ice-rafted dropstones and representing the Late Proterozoic (Vendian) glaciation of West Africa (*6–11*), and the overlying Nandoumari Formation, commencing with intermittent quartz arenites (Tañague Member), and overlain by dolomites (Bowal Member) and green and red siltstones (Fougon Member) (*8*). The dolomites are of supratidal to shallow subtidal origin. Subtidal dolomites are interbedded with siltstones that pass conformably into the overlying Fougon Member siltstones. Hence, the Fougon Member is also of probable shallow marine origin (*8*).

A few specimens of small shelly fossils have been recovered from Bowal Member dolomites (*7*) and several hundred additional small shelly fossils and several agglutinated foraminifera have been recovered from two samples of the immediately overlying siltstones of the Fougon Member (Fig. 2).

Supergroup 2 strata in the Taoudeni Basin are poorly fossiliferous. The only recorded macrofossils from Supergroup 2 are inarticulate brachipods from near the top of the unit in the Mauritanian Adrar which indi-

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cate a Late Cambrian to Early Ordovician age (*10*). The age of the fossiliferous Mali group strata near the base of Supergroup 2 in the Walidiala valley is Early Cambrian based on micropaleontological evidence. The small shelly fossil fauna in the green and red siltstones of the Fougon Member is dominated by tubular and platy structures of probable echinodermal origin. Echinoderms are considered to have first appeared in the Atdabanian (*11*). *Lenastella* spicules, which were originally described from Atdabanian rocks (*12*), are also abundant. The underlying Bowal Member dolomite has yielded, through acid digestion, two specimens of *Aldanella attleborensis*, which occurs in the Tommotian but which does range into the Atdabanian (*7, 13*). Hence, the agglutinated foraminifera are probably Early Cambrian in age and can be assigned most readily to the Atdabanian.

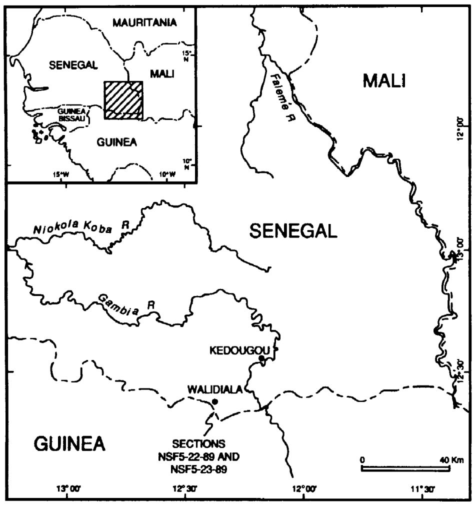

Fig. 1. Map locating sections NSF5-22-89 and NSF5-23-89 (indicated by arrow) that contain small shelly fossils and foraminifera. The base of NSF5-22-89 and NSF5-23-89 are located at 12°21'N and 12°23'W, 3 km south of Walidiala.

The few radiometric dates available from West Africa provide an additional but equivocal framework within which the fossiliferous Nandoumari Formation can be considered. Local folding of the Mali group in the Mauritanide orogen of southeast Senegal is suggested to be related to a Pan African II phase of tectono-thermal activity about 550 to 560 Ma (*14*). Upper Proterozoic tillites in the northern Taoudeni Basin were deposited during the isotopically constrained interval of 630 to 595 Ma (*15*). Hence, the Nandoumari Formation that directly overlies Upper Proterozoic tillites could be considered to be younger than 630 to 595 Ma and older than 550 to 560 Ma. However, the Nandoumari Formation may possibly represent a portion of the Mali group deposited after the Pan African II orogenic event at 550 to 560 Ma. The latter interpretation is supported by paleontological data given the mounting evidence that the age of the Precambrian-Cambrian boundary is about 540 to 550 Ma (*16*).

Thirteen specimens of agglutinated foraminifera have been recovered to date from the red and green siltstones of the Fougon Member. The siltstones were crushed and partially disaggregated in a heated solution of "Quaternary O," a strong detergent. The disaggregated siltstone was washed over a 63-μm sieve previously cleaned with an ultrasonic bath and a high-pressure water jet. The foraminifera are composed of silt-sized particles consistent with the siltstone source rock.

Six specimens can be assigned to the genus *Ammodiscus* (Fig. 3, A and B) and are probably conspecific. Single specimens can be assigned to the genera *Glomospira* and *Turritellella* (Fig. 3, C and D). One additional specimen is a flattened hemispherical test, one a flattened flask-shaped test, one a simple tube, and one a simple tube apparently attached to sediment particles (Fig. 3E). A single specimen has two chambers with a complete septum and may or may not be a foraminifer (Fig. 3F).

The *Ammodiscus* specimens fit within the size and morphological range of *Ammodiscus exsertus* Cushman, which is recorded widely in Silurian rocks (*17, 18*). It has not been recorded previously in Ordovician or Cambrian strata. However, probable *Ammodiscus* sp. has been recorded from the Middle Cambrian of Sardinia (*19*) and of Idaho (*4*). *Glomospira* has not been recorded previously in rocks older than Silurian, whereas *Turritellella* has been recorded from Upper Ordovician rocks (*18*).

The genera *Ammodiscus, Glomospira*, and *Turritellella* are morphologically simple: a proloculus followed by an undivided tube coiled in various ways. The specimens reported here cannot be distinguished from later Paleozoic representatives, but the latter specimens cannot easily be distinguished from modern specimens of these genera. Indeed, *A. exsertus* was originally described from modern sediments off the coast of Japan (*20*). Iterative evolution is common in benthic foraminifera and it is not surprising, therefore, that the specimens figured here closely resemble younger material. The overall morphology of the finely agglutinated two-chambered specimen (Fig. 3F) resembles that of the genus *Sorosphaera*, whose earliest record previously was from the Upper Ordovician (*18, 21*). Alternatively, but, given the agglutinated nature of the test, less likely, this specimen could be of algal origin.

The Walidiala valley fossils indicate that different life habits were present among

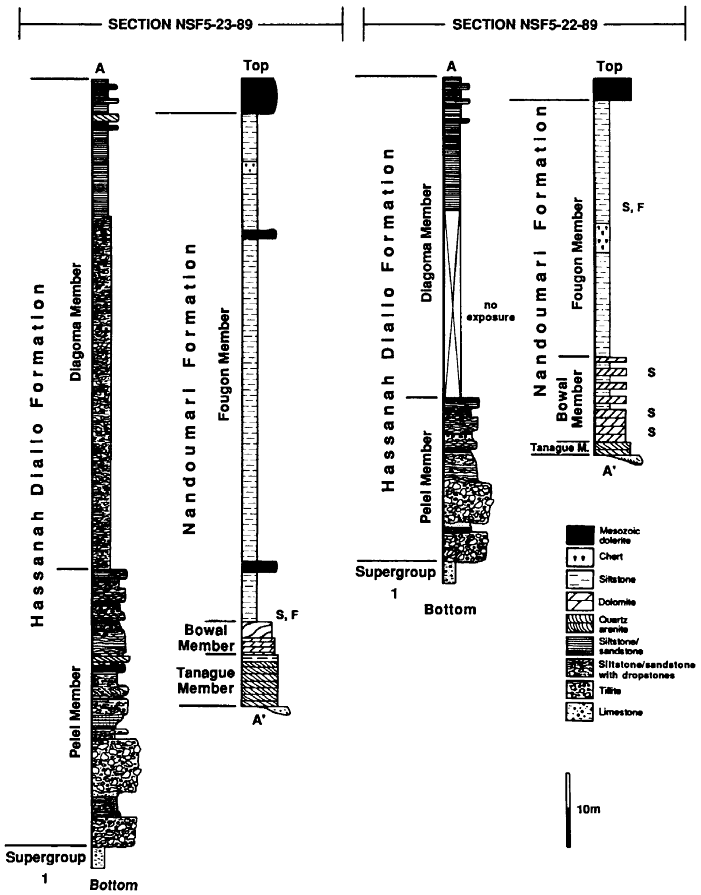

Fig. 2. Stratigraphic sections NSF5-22-89 and NSF5-23-89 located on either side of the Walidiala valley. S, samples containing small shelly fossils. F, samples NGS5-25-86F and NGS5-27-86E containing foraminifera.

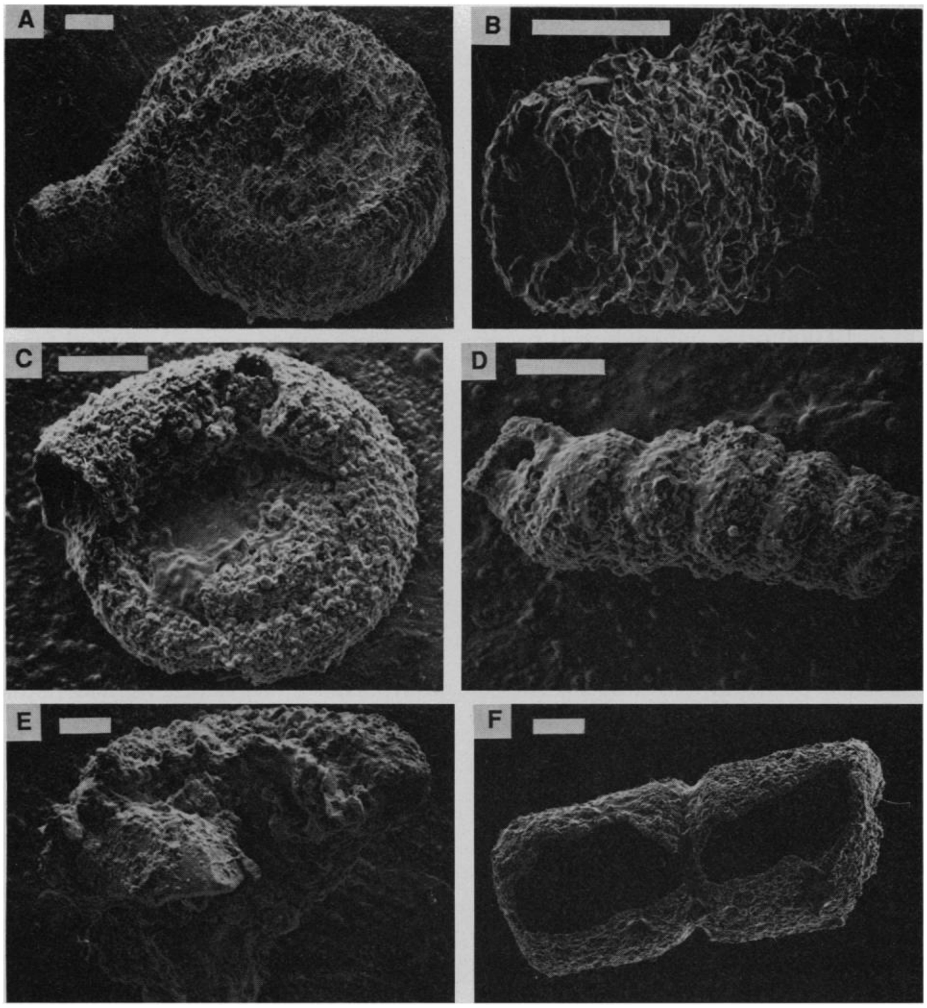

Fig. 3. (**A**) *Ammodiscus* sp., side view of planispirally coiled test. (**B**) *Ammodiscus* sp., circular aperture at end of uncoiled portion of tubular agglutinated chamber. (**C**) *Glomospira* sp., side view of streptospirally coiled test. (**D**) *Turritellella* sp., side view of high spired test, aperture to left. (**E**) Tubular foraminifer attached to sediment particles. (**F**) Side view of two-chambered agglutinated test. All specimens from sample NGS5-25-86F. Scale bars, 50 μm.

these early foraminifera. Observations of modern taxa suggest that *Ammodiscus* spp. were free-living taxa, and this mode of life can also be inferred for *Turritellella, Glomospira*, the flask-shaped forms, and perhaps the hemispherical forms. One tubular specimen is apparently attached to sediment particles (Fig. 3E); its form reflects the underlying grain morphology. Hence, an adherent life habit was also present in the Early Cambrian.

There are few other records of foraminifera from the Cambrian. The agglutinated genera *Thuramminoides, Psammosphaera, Hemisphaerammina, Ammodiscus*, and ammodiscids have been reported from Middle Cambrian strata (*19, 22*). Early Cambrian records are restricted to possible indeterminate agglutinated foraminifera from the Mackenzie Mountains in northwestern Canada (*23*). The straight agglutinated tube *Platysolenites*, and the related coiled tube *Spirosolenites*, from the East European Platform, the Baltic Shield, Newfoundland, California, Wales, and England (*24–28*), are considered by several investigators (*25, 29*) to be the earliest known foraminifera because they appear to be restricted to lowermost Cambrian, Tommotian-equivalent strata. But the placement of these genera in the Foraminiferida is not certain. Although *Platysolenites* is indistinguishable from the modern agglutinated foraminifer *Bathysiphon* (*25*), the relatively large size (several centimeters long) and the simple tubular morphology is such that non-foraminiferal affinities are possible and placement in the Foraminiferida may never be definite (*24, 26, 30*).

The discovery of several unequivocal foraminiferal genera in the Lower Cambrian of the Taoudeni Basin, West Africa, extends their known geologic range and extends the range of undoubted members of the order Foraminiferida back to Atdabanian-equivalent strata. Hypotheses concerning the widespread advent of skeletonization in the Early Cambrian faunas must, therefore, take into account the hard evidence from the protistan as well as the metazoan fossil record (*4*).

REFERENCES AND NOTES

1. J. W. Cowie and W. B. Harland, in *The Precambrian-Cambrian Boundary*, J. W. Cowie and M. D. Brasier, Eds. (Clarendon Press, Oxford, 1989), pp. 186–198.
2. D. Nicol, *J. Paleontol.* **40**, 1397 (1966).
3. K. Simkiss, *Calc. Tiss. Res.* **24**, 199 (1977).
4. J. H. Lipps, *Geol. Soc. Am. Abstr. Prog.* **17**, 644 (1985).
5. J. W. Evans, *C. R. 10th Sess. Congr. Géol. Int.* (Stockholm, 1910) **1**, 543 (1912); G. E. Hutchinson, *Am. Assoc. Adv. Sci. Publ.* **67**, 85 (1961); H. A. Lowenstam and L. Margulis, *BioSystems* **12**, 27 (1980); G. J. Vermeij, *Palaios* **4**, 585 (1989).
6. M. Deynoux, *Trav. Lab. Sci. Terre St. Jér. Marseille* **17**, 1 (1980).
7. S. J. Culver, J. Pojeta, Jr., J. E. Repetski, *Geology* **16**, 596 (1988).
8. S. J. Culver and D. Hunt, *J. Afr. Earth Sci.*, in press.
9. S. J. Culver and A. W. Magee, *Nat. Geogr. Res.* **3**, 69 (1987).
10. R. Trompette, *Trav. Lab. Sci. Terre St. Jér. Marseille* **7**, 1 (1973).
11. M. D. Brasier, in *The Origin of Major Invertebrate Groups*, M. R. House, Ed. (Academic Press, London, 1979), pp. 103–159.
12. V. V. Missarzhevsky and A. M. Mambetov, *Acad. Sci. U.S.S.R.* **326**, 1 (1981).
13. E. Landing, *J. Paleontol.* **62**, 661 (1988).
14. R. D. Dallmeyer and M. Villeneuve, *Geol. Soc. Am. Bull.* **98**, 602 (1987).
15. N. Clauer and M. Deynoux, *Precamb. Res.* **37**, 89 (1987).
16. A. P. Benus, *N.Y. State Mus. Bull.* **463**, (1988), pp. 8–9; S. Conway Morris, in *The Precambrian-Cambrian Boundary*, J. W. Cowie and M. D. Brasier, Eds. (Clarendon, Oxford, 1989), pp. 7–39.
17. W. L. Moreman, *J. Paleontol.* **4**, 42 (1930).
18. J. M. Kircher and M. D. Brasier, in *Stratigraphical Atlas of Fossil Foraminifera*, D. G. Jenkins and J. W. Murray, Eds. (Horwood, Chichester, 1989), pp. 20–31.
19. A. Cherchi and R. Schroeder, *Boll. Soc. Paleontol. Ital.* **23**, 149 (1985).
20. J. A. Cushman, *U. S. Nat. Mus. Bull.* **71**, 1 (1910).
21. J. E. Conkin and B. M. Conkin, *Univ. Louisville Stud. Paleo. Strat.* **11**, 1 (1979).
22. S. W. Alexandrowicz, *Rocz. Pol. Tow. Geol. Ann. Soc. Geol. Pol.* **39**, 27 (1969).
23. S. Conway Morris and W. H. Fritz, *Nature* **286**, 381 (1980).
24. A. Yu. Rozanov, in *Upper Precambrian Paleontology of the East European Platform*, B. M. Keller and A. Yu. Rozanov, Eds. (Akad. Nauk S.S.S.R., 1979), pp. 83—87.
25. M. R. Glaessner, *Bur. Min. Res. Bull. Aust.* **192**, 61 (1978).
26. M. D. Brasier, in *The Precambrian-Cambrian Boundary*, J. W. Cowie and M. D. Brasier, Eds. (Clarendon, Oxford, 1989), pp. 119–165.
27. S. Føyn and M. F. Glaessner, *Nor. Geol. Tidsskr.* **59**, 25 (1979).
28. E. Landing, P. Myrow, A. P. Benus, G. M. Narbonne, *J. Paleontol.* **63**, 739 (1989).
29. A. R. Loeblich, Jr., and H. Tappan, *Foraminiferal Genera and Their Classification* (Van Nostrand Reinhold, New York, 1987).
30. J. H. Lipps, *Benthos '90*, in press.
31. This work was supported by the National Geographic Society and NSF grant EAR 8816137. I thank O. Dia, B. Diene, B. Robineau, A. Harris, J. Repetski, J. Pojeta, Jr., D. Hunt, B. Loehrke, R. Orndorff, S. Hoebeke, and R. Ackerman, for logistical, field, and laboratory support, and J. H. Lipps, K. Towe, and M. D. Brasier for discussion on Cambrian foraminifera. Comments on this paper from J. H. Lipps, S. Conway Morris, A. Gooday, and M. D. Brasier are greatly appreciated.

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