3, and the lowest values, 11.4°C and 1740 mm, with zone FL-2. For comparison, present-day averages over the 10-year interval at nearby Battleground are 17.4°C and 1436 mm (*18*). This sequence covers the interval before the Fraser Glaciation (FL-3) and the succeeding Evans Creek and Vashon stades of the Fraser Glaciation (FL-2), when glaciers advanced into the lowland at different times (*19*).

The frequency of pumiceous fallout from Mount St. Helens and other Cascade Range volcanoes along a 100-km stretch to the west of the mountain front can be approximated from available lake records for the past 35,000 years. Between 35,000 and 17,000 years ago at Fargher Lake (Table 1), fallout occurred at intervals of 1000 years (TA-5 and TA-6) to 5000 years (TA-2 and TA-3), or an average of 2800 years. Tephra layers TA-1 and TA-2 were deposited at roughly the same time as a pair of layers in the lower part of a core from Davis Lake (*15*), about 40 km north of Mount St. Helens. Deposition of six younger layers at Davis Lake occurred every 1100 to 1400 years. At Mineral Lake (*20*), 20 km north of Davis Lake, four tephra layers were dated between 17,500 and less than 3700 radiocarbon years. On the basis of their ages and stratigraphic positions, they appear to correspond to certain tephra layers at the other lake sites. In all, the combined records for some 13 tephra layers at Fargher, Davis, and Mineral lakes indicate an average deposition interval of 2700 years over the 35,000-year time span. The data suggest that future ashfalls in western Washington are not likely to take place for at least a millennium.

The sources of the ejecta are, in the main, uncertain. Ash from Mount Mazama (Crater Lake) in Oregon, which erupted about 6700 years ago (*21*), is found at both Davis and Mineral lakes. It is widely distributed in the northwestern United States and in southwestern Canada (*6*). A layer of Mazama ash was not found at Fargher Lake, evidently because of deflation and disturbance caused by cultivation of the lake bed. Pyroclastic deposits on Mount Rainier and Mount St. Helens (*4, 5*) are only partly represented in the sediments of all three lakes. The ash from most of the eruptions, which was distributed eastward, would not likely have settled in the western lowland. At Mount St. Helens (*5*), the volcano nearest to Fargher Lake, pumice layer Cy, dated at about 36,000 ± 2000 radiocarbon years, may correspond with tephra layer TA-7 (Table 1), while any layer of set M, dated at between 18,560 ± 550 and 20,350 ± 500 years, may correlate with TA-1 and TA-2. Until the tephra layers can be shown to be related through more precise dating or by petrographic and chemical analyses, their sources of origin can only be suggested.

CALVIN J. HEUSSER
LINDA E. HEUSSER

Department of Biology, New York University, Tuxedo 10987

References and Notes

1. G. B. Rigg, *Wash. Div. Mines Geol. Bull. 44* (1958).
2. R. W. Mathewes, *Can. J. Bot.* **51**, 2085 (1973); P. J. Mehringer, Jr., S. F. Arno, K. L. Petersen, *Arct. Alp. Res.* **9**, 345 (1977); R. N. Mack, N. W. Rutter, S. Valastro, *Ecology* **59**, 956 (1978).
3. S. C. Porter, *Quat. Res. (N.Y.)* **10**, 30 (1978).
4. D. R. Mullineaux, *U.S. Geol. Surv. Bull. 1326* (1974).
5. D. R. Crandell, D. R. Mullineaux, M. Rubin, *Science*, **187**, 438 (1975); D. R. Mullineaux, J. H. Hyde, M. Rubin, *J. Res. U.S. Geol. Surv.* **3**, 329 (1975); D. R. Mullineaux, R. E. Wilcox, W. F. Ebaugh, R. Fryxell, M. Rubin, *Quat. Res. (N.Y.)* **10**, 171 (1978).
6. H. A. Powers and R. E. Wilcox, *Science* **144**, 1334 (1964).
7. J. F. Franklin and C. T. Dyrness, *U.S. Dep. Agric. For. Serv. Gen. Rep. PNW-8* (1973), p. 45.
8. R. B. Waitt, Jr., personal communication.
9. The lake bed was cored in 1977 and again at the same site in 1979 to obtain samples for radiocarbon dating and for the analysis of phenocrysts in the tephra layers. A hand-operated Hiller sampler effectively penetrated the consolidated 45-cm-thick tephra layer at 4.2 m, but failed to pick up some of the soupy clay near the base of the deposit.
10. W. King, *New York Times*, 14 June 1980, p. 6.
11. In the cases of TA-1, TA-2, TA-3, TA-5, and TA-7, samples for dating are from 2.5 cm above to 2.5 cm below each layer; samples from above and below TA-4 and at the top of TA-6 are each 5 cm thick. Pooling of samples from multiple corings provided the material for dating and for petrographic and chemical study.
12. J. E. Armstrong, D. R. Crandell, D. J. Easterbrook, J. B. Noble, *Geol. Soc. Am. Bull.* **76**, 321 (1965).
13. Prominences of grasses, composites, and mountain hemlock (10,000 to 28,000 years, zone FL-2) (Fig. 2) and of western hemlock (28,000 to 34,000 years, zone FL-3) are well documented, and their radiocarbon ages have been established [L. E. Florer, *Quat. Res. (N.Y.)* **2**, 202 (1972); C. J. Heusser, *ibid.*, p. 189; *Geol. Soc. Am. Bull.* **85**, 1547 (1974); *Quat. Res. (N.Y.)* **8**, 282 (1977); *Can. J. Earth Sci.* **15**, 1568 (1978); B. S. Hansen and D. J. Easterbrook, *Geol. Soc. Am. Bull.* **85**, 587 (1974); R. W. Mathewes, *Can. J. Earth Sci.* **16**, 847 (1979)]. These bracket the layers of tephra; additional dating from within each of the zones enables age adjustments to be made for each layer.
14. Samples at 10-cm intervals in the core were deflocculated by boiling in 5 percent potassium hydroxide followed by treatment with 49 percent hydrofluoric acid and acetolysis [K. Faegri and J. Iversen, *Textbook of Pollen Analysis* (Hafner, New York, 1975)]. They were then sieved through 150- and 7-μm nylon screens and mounted. Pollen percentages are from counts of at least 300 grains in each sample.
15. C. L. Barnosky, thesis, University of Washington, Seattle (1979). The oldest sediments in Davis Lake, dated at 26,100 ± 1200 radiocarbon years (QL-1308), do not show prominences of western hemlock and fir pollen and thus appear to be younger than zone FL-3 at Fargher Lake.
16. C. J. Heusser, *Can. J. Bot.* **56**, 1510 (1978).
17. ——, L. E. Heusser, S. S. Streeter, *Nature (London)* **286**, 702 (1980).
18. *U.S. Dep. Commer. Climatol. Data Annu. Summ. Wash. 72–81* (1968–1977).
19. D. R. Crandell and R. D. Miller, *U.S. Geol. Surv. Prof. Pap. 847* (1974); S. C. Porter, *Geol. Soc. Am. Bull.* **87**, 61 (1979).
20. D. M. Hibbert, thesis, University of Washington, Seattle (1979).
21. P. J. Mehringer, Jr., E. Blinman, K. L. Petersen, *Science* **198**, 257 (1977).
22. We thank R. B. Waitt, Jr., and F. McCoy, Jr., for their comments on the manuscript. Supported by NSF grants DEB 76-12561 and DEB 79-10505.

7 July 1980; revised 28 August 1980

Calcite-Impregnated Defluidization Structures in Littoral Sands of Mono Lake, California

Abstract. *Associated locally with well-known tufa mounds and towers of Mono Lake, California, are subvertical, concretionary sand structures through which fresh calcium-containing artesian waters moved up to sites of calcium carbonate precipitation beneath and adjacent to the lake. The structures include closely spaced calcite-impregnated columns, tubes, and other configurations with subcylindrical to bizarre cross sections and predominantly vertical orientation in coarse, barely coherent pumice sands along the south shore of the lake. Many structures terminate upward in extensive calcareous layers of caliche and tufa. Locally they enter the bases of tufa mounds and towers. A common form superficially resembles root casts and animal burrows except that branching is mostly up instead of down. Similar defluidization structures in ancient sedimentary rocks have been mistakenly interpreted as fossil burrows.*

Sublacustrine deposits of calcareous tufa (sinter), which form pavements, mounds, and towers in alkaline lakes throughout the world, become exposed as evaporation reduces lake levels. Three modes of origin have been proposed for such tufa deposits: (i) physicochemical precipitation, (ii) biological precipitation by algae, and (iii) combined physicochemical and biological precipitation. Presently there is general agreement that the basic mechanism is physicochemical, with local algal activity influencing only form and surface texture. This view is supported by observations of tufa and closely related defluidization structures exposed on the south shore of Mono Lake.

Mono Lake is a shallow saline-alkaline remnant of much larger and deeper freshwater glacial lakes. It lies in Mono Basin, a closed structural depression at

0036-8075/80/1128-1009$00.50/0

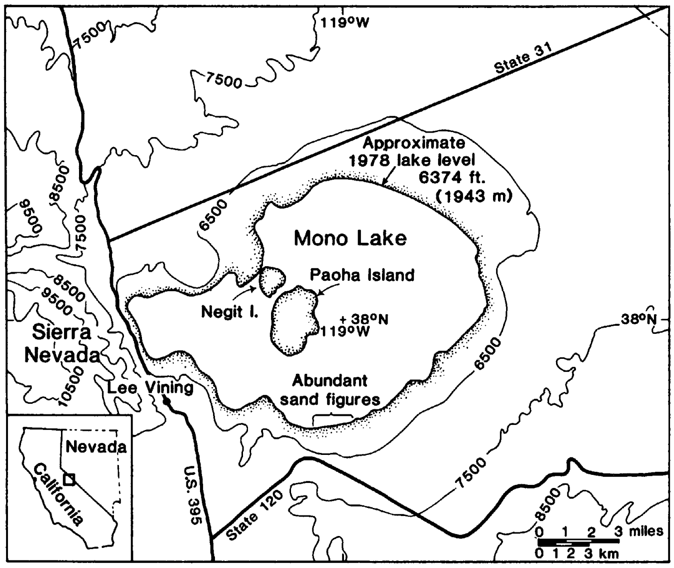

Fig. 1. Index map of Mono Lake area. Contour elevations are in feet (after USGS (topographic map).

the foot of the Sierra Nevada near the eastern boundary of central California (Fig. 1). Between 1941 and 1978 the lake level fell from 1956 m (6417 feet) to 1943 m (6374 feet) due primarily to diversion of water in Sierran feeder streams from Mono Basin to Los Angeles. At present rates of diversion the lake will probably stabilize at about 1927 m (6323 feet), roughly 27 m below the predicted nondiversion level, by the year 2070 (*1*). Under these conditions the lake will have roughly 40 percent and 20 percent of its estimated nondiversion surface area and volume, respectively, and Negit and Paoha islands will be part of a large peninsula attached to the north shore of the lake. The connection of Negit Island with the north shore in 1978 opened the large California gull (*Larus californicus*) rookery on the island to mainland predators, resulting in almost complete nesting failure in 1979 (*2*).

The high concentration of dissolved solids in the present lake water results primarily from the evaporative reduction in lake volume at the end of the Pleistocene about 10,000 years ago. Under present climatic conditions the annual rate of evaporation in the vicinity averages six times that of precipitation (*3*). The sources of the dissolved solids are the freshwater streams and springs that enter the lake mainly from the Sierra Nevada; these are supplemented by hot springs in and around the lake. As the lake level falls, salinity of the lake water increases. The salinity was 5.2 percent in 1889 (*4*), 5.4 percent in 1953 (*5*), 6 percent in 1961 (*6*), and 8.9 percent in 1974 (*7*). Sodium cations [1.9 percent in 1889 (*4*), 2.2 percent in 1961 (*6*), and almost 3 percent in 1974 (*7*)] and chloride, carbonate, and sulfate anions account for most of the dissolved components. The pH of the lake water was 10.3 in 1953 (*5*). It was 9.7 in 1961 (*6*), 1977 (*1*), and June 1978 when measured by Cloud. The pH varies slightly but is always high and currently seems to be buffered at 9.7 (*1*).

Calcium carbonate is the only chemical precipitate (mainly as tufa mounds) in Pleistocene and Holocene lacustrine deposits in the basin and is the principal precipitate under present conditions. If the lake level continues to fall, sodium sulfates and chlorides will probably become the dominant chemical precipitates.

The close association of tufa mounds and towers with freshwater springs in or near the lake is the strongest argument for the predominantly inorganic origin of the tufa as outlined by Russell (*4*) and Dunn (*5*). Several tufa masses display open, subvertical axial channels that locally still carry water to their summits (*4*, *8*). Lateral flow from the flanks or bases of emerged towers is common. Where fresh, calcium-bearing spring waters enter and mingle with the alkaline, carbonate-bearing lake water $CaCO_3$ is immediately precipitated as calcite or aragonite (aragonite is favored over calcite in the open lake waters of high ionic strength, and calcite, at other sites of precipitation). Where spring flow is concentrated beneath the lake, prominent tufa towers and pinnacles build up above the lake floor in an open fabric of mainly aragonite rhombs. Such structures grow until they reach or emerge above lake level. Flat-bottomed horizontal flanges on some towers mark old lake levels where light spring water from emergent summit orifices flowed out over the heavier saline lake waters and precipitated carbonate. Although algae may be a subordinate factor locally (*8*, *9*), especially near or above lake levels where they may influence the texture and surface morphology of tufa buildups, it is clear that they control neither the place nor the mode of tufa formation.

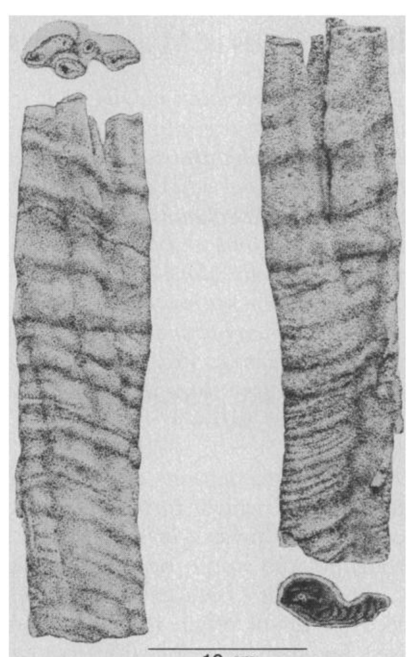

Fig. 2. Sketches of a portion of a flattened compound tube showing simple upward branching and preservation of bedding structures.

The sand figures discussed in this report (Figs. 2 to 4) are associated with buildups of tufa along the south shore of Mono Lake (Fig. 1). These figures consist of tubes, columns, and associated structures of calcite-impregnated pumice sand and were formed within fairly young beach and lake-bottom sediments near the shore of the lake. They were exposed by the recent drop in lake level and subsequent wind erosion of the loose sand in which they were formed.

The well-stratified beds of well-sorted, medium- to course-grained sand in which the best figures are developed dip a few degrees to 28° northward toward the lake. Primary sedimentary structures of the host sand, such as cross-bedding and other fine laminations, continue through and are preserved by the indurated sand figures (Figs. 2 and 3). In some instances bedding features are not preserved in the loose sand within the axial conduits of tubes. This loose sand can be poured out or blown out by the wind, giving the false impression that broken and fallen tubes are hollow (Figs. 2 and 3D). Similar but generally more irregular structures that are indurated throughout (Figs. 3C, middle ground, and 4), are referred to as columns.

Both tubes and columns are approximately vertical regardless of the dip of the stratified sand in which they are formed (Fig. 3, A and C). Locally, however, they curve into or terminate in indurated sets of laminae and structures that flare away from the vertical in areas of distinct cross-bedding as inclined sheets, flat or intricately fluted columns, broad cones, and bowl-like structures (Fig. 3B).

The tubes are irregular and commonly compound in horizontal cross section (Figs. 2 and 3D). They converge, branch, expand, taper, pinch out, or send off small subsidiary conduits. They range in diameter from a few millimeters to, more commonly, several centimeters or larger. They rise up to a meter or more between intervening and cemented cross laminae or beds, and they tend to be irregular in branching pattern and degree of induration.

In one area that is gradational from tubes to columns, both terminate upward in a well-preserved zone of hard, ropy, almost pure caliche that is about 15 to 30 cm thick and essentially coincident with the present upslope ground surface (Fig. 3, A and B). This layer probably formed after recent emergence but before erosional breaching and ablation. Higher and lower layers are superficially similar but are punky calcareous matter and carbonate-coated or indurated sand formed by other processes.

Some well-defined layers preserved in the sand tubes and columns may mark former sediment-water interfaces associated with brief pauses in clastic sedimentation. Others are only indurated, coarse-grained and cross-bedded layers or surficial coatings on sand tubes that may result from a former resubmergence and precipitation at the sediment-water interface or from evaporation at the most recently emerged level. In some areas small conical structures or mounds of similar calcitic matter, incipient tufa towers, rise up fractions of a meter above the main calcified surface. At one place the main calcareous surface grades laterally into thin porous crusts and tufa towers that rise up to 1 or 2 m above a zone of calcite-cemented sand columns that appear to feed into the bases of the towers (Fig. 3C). At another place, well-bedded slabby beach rock occurs in a narrow zone, several hundred meters long and a few meters wide, which is parallel to and inland from the south shore of the lake.

These observations bear on the question of origin of the sand figures. When first observed, the tubes and columns were thought to be root casts. However, their gross variation and complexity in morphology and branching (upward branching is usual) rule out this mode of origin as well as the possibility that they are animal burrows. Instead, the described characteristics of the sand-impregnated tubes and columns are best explained by physicochemical processes within the littoral sediments. Their formation is related to, and controlled by, the chemical and physical contrasts between the saline lake waters and the

Fig. 3. Sand tubes and related structures. (A) General view showing sand tubes and columns with a subhorizontal caliche cap. Note tube morphology and vertical orientation with reference to cross-bedding. (B) Variation in tube morphology and selective induration of cross-bedded layers. (C) Sand columns in middle-ground grading up into tufa towers. (D) Ablated tubes showing morphological variation, subsidiary columns, and internal complexity. Scale is given by the hammer (31.5 cm long) in (A) to (C) and by the pocket knife (8.3 cm long) in (D).

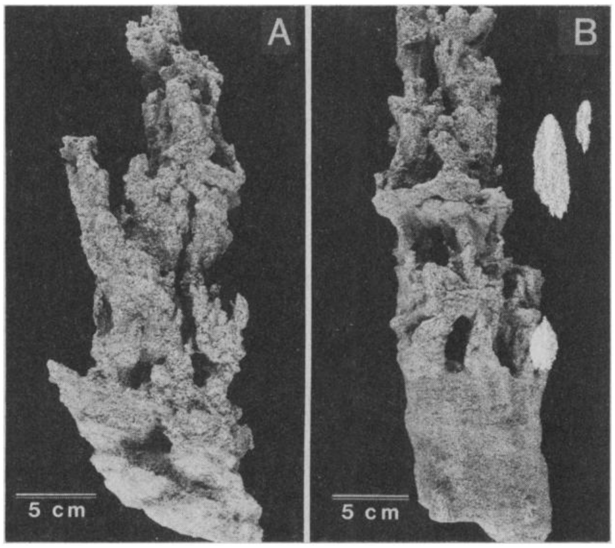

Fig. 4. Arborescent sand columns.

freshwaters from tributary seepage, springs, and streams (as is the case with the calcareous tufa), and by local, high rates of evaporation. None of the sand tubes or columns display algal structures like those found in the surface layers of some tufa towers formed near or above lake levels (*8*, *9*). Indeed, algal activity can have nothing to do with the deposition of the calcitic matter that forms the sand tubes and columns under aphotic conditions below the sediment-water interface.

As fresh, calcium-bearing ground water from upslope impinges on or flows through porous sediments saturated with heavier saline water near the shore of the lake, the difference in density, reinforced by hydraulic head, causes the freshwater to rise. Because of the high energy required for mixing, upward flow of freshwater tends to be confined to subcylindrical, vertical pathways, except where it locally fans out sideways through more permeable beds or cross-bedded layers. Sufficiently vigorous upward circulation of the freshwater locally displaces saline lake water and limits calcite precipitation to the fairly sharp interface between calcium-bearing freshwater and carbonate-rich lake water, creating solidly indurated, subcylindrical walls, 2 to 5 mm thick, around a core of loose sand. The resulting elongate concretions are the sand-filled tubes. Once the two water masses are physically separated by a solid barrier of calcite cement, chemical precipitation ceases; therefore, the tube walls remain relatively thin (1 to 5 mm) (Figs. 2 and 3D). Vigorous, physically confined, upward flow of water destroys horizontal bedding features in the loose sands within some of the tubes.

Where upward movement of freshwater through a sand bed is less vigorous, vertical passages become solidly indurated columns, at places displaying complexly anastomosing or arborescent patterns (Fig. 4). Sand columns, but not tubes, have been observed to grade into the base of tufa towers and pinnacles of sublacustrine origin. This relation and the areal distribution of the sand columns suggest that columns and associated tufa masses originated mainly beneath the lake, whereas the sand tubes, although formed in sands saturated by lake water, may have originated farther upslope and landward from the lakeshore. The fact that many tubes and some columns terminate upward in extensive layers of surface caliche, up to 30 cm thick, suggests that they continued to convey water to emergent surfaces where evaporation and algal activity controlled carbonate deposition.

The emerged calcite-impregnated defluidization tubes and columns reported occur at elevations between about 1943 and 1948 m (6374 and 6391 feet) and at very shallow burial depths of 0 to 3 m. The rapid fall of the lake since 1965 exposed the beds of pumiceous sand in which these figures were formed. Thus, it seems likely that all the tubes, columns, and associated structures were formed very recently, perhaps within the past century or so. Similar structures are probably forming today where freshwater rises through coarse- to medium-grained sand saturated with saline-alkaline water near the lakeshore.

Although these structures have not been described before, they have been observed in older deposits in Mono Basin (*10*) and Searles Valley (*11*). In both places, they were interpreted as older shoreline indicators. Similar tubes were also observed within a few meters of the lake surface [elevation, 1952 m (6403 feet)] near the boat ramp at Lee Vining at the west end of Mono lake in 1955 (*11*).

It is not surprising that similar structures in older rocks, especially tubes with no bedding in the sand of the axial conduit, have been described as fossil worm burrows or root casts. At one time almost any tube-like structure perpendicular to bedding in sedimentary rocks was likely to be called a worm burrow. Although the expression "metazoan burrow" is now more usual, the problem of certain identification remains vexing where evidence other than gross morphology is lacking. Thus, the vertical defluidization tubes of the late Proterozoic Noonday Dolomite, described by Cloud *et al.* in 1974 (*12*), as well as similar tubes in the later Proterozoic Areyonga sandstone of central Australia and other pre-Phanerozoic defluidization structures resembling the Noonday tubes, were long supposed to be "worm burrows" and were even referred to the genus *Scolithus* by competent, if biologically unsophisticated, geologists. The defluidization structures at Mono Lake are an important type of nonbiological structure to keep in mind when weighing the need for informed advice on whether some new structure of unclear origin may or may not be an authentic part of the geological record of life.

PRESTON CLOUD
Department of Geological Sciences, University of California, Santa Barbara 93106

KENNETH R. LAJOIE
U.S. Geological Survey, Menlo Park, California 94025

References and Notes

1. D. W. Winkler, Ed., *Univ. Calif. Davis Inst. Ecol. Publ. 12* (1977), p. 184.
2. The ecology of Mono Lake and Basin and the environmental effects of water diversion from the basin are described in (*1*); D. T. Mason, *Univ. Calif. Berkeley Publ. Zool.* **83**, 110 (1967); D. Gaines, Ed., *Mono Lake, Its Uncertain Future* (Mono Lake Committee, P.O. Box 29, Lee Vining, Calif. 93541).
3. Data from Los Angeles Department of Water and Power, reported in D. W. Scholl, R. von Huene, P. St.-Amand, J. B. Ridlon, *Geol. Soc. Am. Bull.* **78**, 583 (1967).
4. I. C. Russell, *U.S. Geol. Surv. Annu. Rep.* **8**, 261 (1889).
5. J. R. Dunn, *J. Sediment. Petrol.* **23**, 18 (1953).
6. H. C. Whitehead and J. H. Feth, *Geol. Soc. Am. Bull.* **72**, 1421 (1961).
7. Los Angeles Department of Water and Power data from 1974, reported in (*1*).
8. W. W. Scholl and W. H. Taft, *J. Sediment Petrol.* **34**, 309 (1964).
9. I. C. Russell, *U.S. Geol. Surv. Bull.* **108**, 108 (1893).
10. K. R. Lajoie, thesis, University of California, Berkeley (1968).
11. G. I. Smith, letter to P. Cloud (1979).
12. P. Cloud, L. A. Wright, E. G. Williams, P. Diehl, M. R. Walter, *Geol. Soc. Am. Bull.* **85**, 1869 (1974).
13. The authors thank G. I. Smith and I. Barnes of the U.S. Geological Survey for review and constructive criticism of the manuscript, David Crouch for drafting, and A. Carter and A. Olsen for typing.

22 April 1980; revised 10 August 1980