the interval were identified by G. A. Cooper (*6*), who concluded that the large productoids and spirifers suggest an Early to Middle Pennsylvanian age. The brachiopods include: *Anthracospirifer occiduus* (Sadlick), *Crurithyris* sp., *Inflatia*-like productoids, *Neochonetes* sp., *Reticulatia* sp., and *Rynchopora* sp.

Approximately 325 m of unfossiliferous shale, siltstone, and fine-grained sandstone occur between the highest Paleozoic limestone and an unconformity that is overlain by Lower Cretaceous conglomerate. Shale in the lower 80 m of the interval is variegated, whereas rocks in the upper 245 m commonly are light to medium greenish brown. Because of lack of evidence to indicate a significant interruption of depositional processes, and because of the thickness of strata, it seems likely that at least the upper part of the sequence may be Late Pennsylvanian or Permian in age. At this time, lack of paleontological control prevents the precise location of the Mississippian-Pennsylvanian and possible Pennsylvanian-Permian boundaries in the upper Paleozoic sequence.

Structural relationships between rock units in the Nochixtlán region indicate that block faulting, intrusion, and erosion occurred between the end of the final cycle of Paleozoic sedimentation and the resumption of marine sedimentation in the Early Cretaceous. Remnants of Paleozoic rocks are preserved in greatly displaced fault blocks formed during that interval. Several dikes and sills intrude Paleozoic rocks in the Barranca de Santiago Ixtaltepec and indicate intrusive activity that probably was concomitant with the block faulting.

In conclusion, the Paleozoic and related rock record now known in the Nochixtlán region of Oaxaca indicates the following sequence of historical events:

1) Metamorphism and intrusion of sedimentary rocks of Precambrian age approximately 1 billion years ago.

2) Uplift and deep erosion of Precambrian rocks.

3) Subsidence and accumulation of at least 200 m of marine sediment during the Late Cambrian and Early Ordovician (Tremadocian).

4) Uplift, tilting, and erosion between Early Ordovician and Early Mississippian time. Erosion, at least locally, appears to have removed as much as 180 m of Tremadocian strata.

5) Subsidence and accumulation of at least 625 m of mostly, if not all, marine sediment during the Mississippian, Pennsylvanian, and possibly Permian.

6) Block faulting, intrusion, and erosion between the Pennsylvanian and Early Cretaceous.

7) Subsidence and accumulations of marine sediment commencing at least by Early Cretaceous time.

JERJES PANTOJA-ALOR
Instituto de Geología, Ciudad Universitaria, México 20, D.F. México

RICHARD A. ROBISON
Department of Paleobiology, Smithsonian Institution, Washington, D.C. 20560

References and Notes

1. J. C. Aquilera and Ezequiel Ordoñez, *Imprenta y Fotocolografia del Cosmos* (Tacubaya, D.F., 1893); Tomás Barrera, *Inst. Geol. Mem.* (1946); J. L. Martínez-Bermudez and López-Avila, *Inst. Nac. Invest. Recursos Minerals*, unpublished report (1955); Zoltan De Cserna, *Tectonic Map of Mexico* (Geol. Soc. Amer., New York, 1961).
2. F. K. G. Mullerried, A. K. Miller, W. M. Furnish, *Amer. J. Sci.* **239**, 397 (1941).
3. Carl Fries, Jr., E. Schmitten, P. E. Damon, D. E. Livingstone, R. Erickson, *Univ. Nacl. Autonoma Méx. Inst. Geol. Bol.* **64**, 45 (1962).
4. D. L. Clark, personal communication, May 1967.
5. R. H. Flower, personal communication, April 1967.
6. G. A. Cooper, personal communication, September 1966.
7. We thank R. E. Grant for critical review of the manuscript of this paper. Field work was supported by the Instituto Geología, Cuidad Universitaria, and the Walcott Fund administered by the Smithsonian Institution.

29 June 1967

Fossiliferous Bauxite in Glacial Drift, Martha's Vineyard, Massachusetts

Abstract. *Pebbles of pisolitic bauxite occur in Pleistocene drift on Martha's Vineyard. The bauxite contains plant remains and relict quartz and was derived from plant-bearing sediments, probably from the preglacial coastal plain of New England. The preservation of plant tissue suggests that bauxitization took place beneath, rather than above, the water table, as generally believed. This occurrence of bauxite is the northernmost known in eastern North America and suggests the possible existence of undiscovered deposits in the northern coastal plain.*

Four pebbles of pisolitic bauxite have been found in Pleistocene drift on Martha's Vineyard, an island 6.4 km south of Woods Hole, at the southwestern tip of Cape Cod (Fig. 1). The pebbles undoubtedly came from a bauxite deposit that was part of the preglacial regolith of southern New England and were transported by glacial ice from their place of origin to their present position. All four specimens came from the same drift, tentatively considered to be Kansan in age (*1*). Three of the specimens were found in Gay Head, the sea cliff at the western tip of the island. A fourth pebble was discovered in till in the interior of the island.

The pebbles vary from one that is hard, with a light-gray matrix (Fig. 2), to one that is somewhat friable and iron-stained. Megascopically they closely resemble "birdseye" ore from Arkansas (*2*). The pisolites are ellipsoidal to spherical, attaining a maximum diameter of 20 mm. They are of a wide variety of colors within the range black, brown, red, and white. Most have a laminated outer shell that may be darker or lighter than the core. Some pisolites are compounded of several cores wrapped together into ellipsoidal, or bean-shaped, masses by the outer shell. In thin-section, some of the black to deep-red pisolites are opaque and consist dominantly of iron oxide, presumably hematite. Others consist of aggregates of minute gibbsite spherulites or large book-shaped crystals of gibbsite in a fine-grained iron oxide matrix. All pisolites are broken by radial shrinkage cracks that are filled with a clear slightly yellowish amorphous material, possibly allophane.

The matrix of the bauxite is mainly cryptocrystalline gibbsite organized into oölitic shapes and peppered with mi-

Table 1. Chemical analysis of ferruginous bauxite cobble, Gay Head, Massachusetts.

Oxide	Weight (%)	Oxide	Weight (%)
SiO_2	21.0	H_2O^-	2.9
Al_2O_3	41.2	H_2O^+	12.9
Fe_2O_3	13.7	TiO_2	1.5
FeO	1.9	P_2O_5	0.83
MgO	0.03	MnO	.01
CaO	.02	CO_2	$<.05$
Na_2O	.07	Total S *	.15
K_2O	.05	Organic matter †	1.5

*As SO_3. † By ignition loss.

nute colored crystallites. Scattered throughout the matrix and making up about 13 percent by volume are quartz grains. Quartz grains also occur in some pisolites. The quartz is generally angular, 0.1 to 2.0 mm in maximum dimension, and has pronounced undulatory extinction between crossed nicol prisms. Adjacent grains are generally not in optical continuity, but some grains do extinguish between crossed nicols with one or more of their neighbors, an indication that they are pieces of larger grains that had been fragmented by solution during the process of bauxitization. Solution of quartz is shown further by embayments and fissures filled with gibbsite and, in places, siderite. Fairly coarse-grained siderite also occurs in patches throughout the bauxite, and in one pebble it makes up about 4 percent of the matrix.

A chemical analysis (Table 1) of the iron-stained bauxite from Gay Head shows that it is fairly high in SiO_2 and Fe_2O_3. This undoubtedly reflects the high contents of quartz, hematite (?), and siderite just described. The presence of organic matter is confirmed by the finding of plant tissue in thin sections of the gray pebble, described below.

Small elongated dark shapes, independent of pisolites, were noticed in the gray pebble (Fig. 2) that in thin-section were seen to be pyrite crystals, unevenly dispersed in and about material with a well-organized cellular structure which, in all probability, was plant tissue (*3*). The cell walls were an isotropic deep reddish brown—probably the carbon compound detected in the chemical analysis—and the cell cavities were filled with colorless siderite (Fig. 3). The shredlike plant fragments were embedded in cryptocrystalline gibbsite with oölitic fabric.

Plant material closely associated with, or embedded in, bauxite has been reported by Gordon *et al.* (*2*, pp. 133–36, Fig. 55-D). This bauxite, referred to by those authors as Type 4, is thought to be of detrital origin rather than primary. Therefore, the Arkansas plant remains are later than the formation of the primary bauxite. The Martha's Vineyard bauxite, on the other hand, gives no evidence of a secondary origin. The gibbsitic matrix that surrounds the plant material is not fragmented, nor is there any textural evidence that it was ever a bauxite sediment rather than a normal pisolitic bauxite of primary origin. The oölitic structure is a fabric that is produced by movement and organization of aluminum oxide colloids rather than by granular sedimentation. The Martha's Vineyard bauxite, therefore, gives evidence of having formed in the presence of plant tissue.

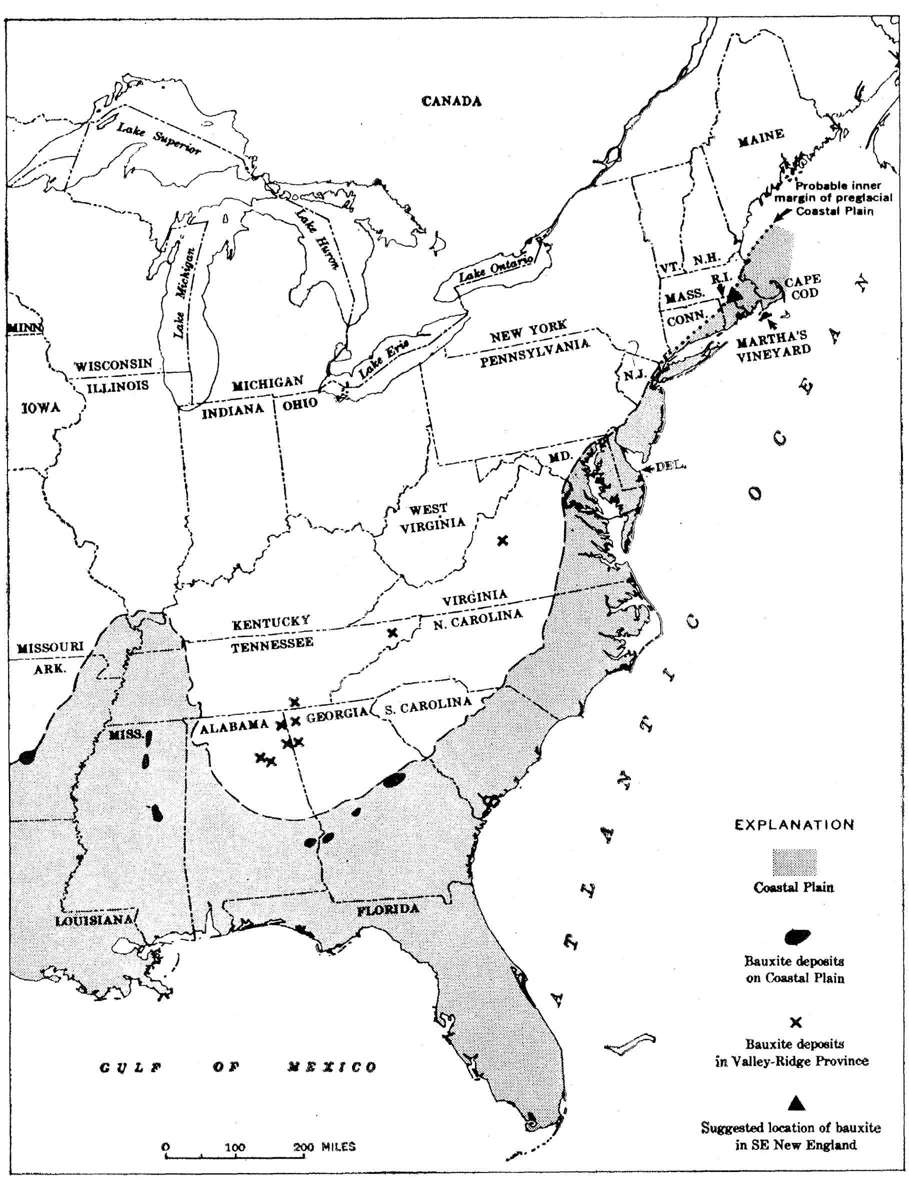

Fig. 1. Eastern United States showing coastal plain (gray area), location of known bauxite deposits (dark spots), and suggested location of source of Martha's Vineyard bauxite (solid triangle). Crosses indicate location of bauxite in the valley-ridge province.

Stanley, Duncan, and Montgomery (*4*) have described bauxite from Adairsville, Georgia, which contains lenses of organic clays rich in megascopic plant remains, pollen, and spores. In Surinam and Guyana (*5*), important bauxite deposits are closely associated with peat and swamp deposits. In this locality peat generally overlies bauxite, but in a few places masses of peat are embedded in bauxite.

Behre (*6*) and Bramlette (*7*) have speculated on the importance of swamp deposits and humus in the origin of certain bauxites. Other writers (*5*, *8*) have continued this line of thought and have suggested that in places bauxitization is in some way closely related to podsolization, or gleying (to use the long-established pedologic term). This idea, in conjunction with the implication of the plant fossils in the Martha's Vineyard bauxite, is of especial interest, for it brings into question the widely held theory (*2*, p. 137; *9*) that bauxite invariably forms above the water table, in contrast to kaolinite which is thought to form at the same time but beneath the water table. The importance of plant remains to this question is that plant tissue is highly perishable in an

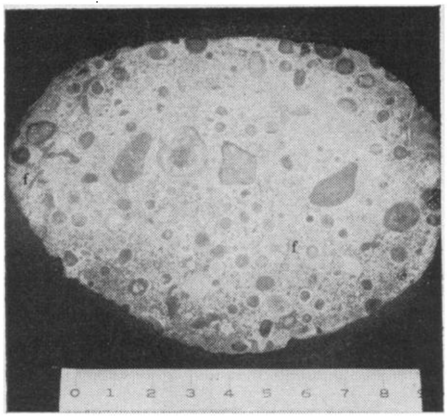

Fig. 2. Sawed face of gray pisolitic bauxite showing shredlike plant fossils (*f*).

oxidizing environment (such as that which exists above the zone of saturation), and particularly in a warm humid climate where biochemical decay is active. Yet there is widespread agreement that bauxite forms slowly and in tropical humid climates. The presence of plant remains embedded within primary bauxite therefore substantiates the idea that some bauxitization takes place in a zone that is saturated with acid groundwater derived from peaty deposits.

The location of the original bauxite deposit from which the pebbles came can be roughly determined. Some of the rock types found in the Kansan(?) drift indicate that that ice came from the northwest. It is very likely, therefore, that the bauxite deposit also lay in this direction from Martha's Vineyard. Because both the quartz and the plant remains in the bauxite are relicts of this material, it must have been a plant-bearing sandy sediment. If the parent material was a sandstone, fossiliferous sandy beds in the Rhode Island Formation of Pennyslvanian age would be a likely source. These crop out in the Narragansett Basin in Rhode Island and adjacent Massachusetts (*10*). The maximum distance of outcrops of these sandstones northwest of Martha's Vineyard is about 96 km.

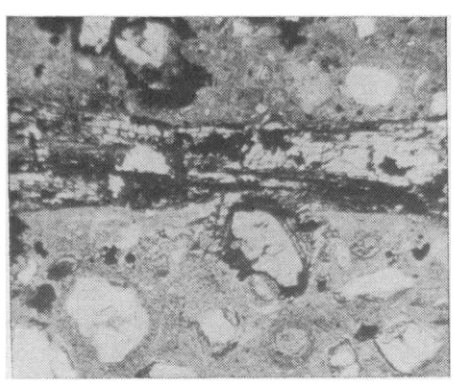

Fig. 3. Plant remains in bauxite. Clear grains are quartz showing solution embayments. Large, dark-rimmed polyhedral grain just below plant fragment is siderite. Scattered black grains are pyrite. Matrix is gibbsite which appears granular because of crystallites; oölite is at bottom center. Plane polarized light.

If, on the other hand, the parent material was unconsolidated, there is a good possibility that it formed part of the coastal plain of southern New England. A belt of Cretaceous and Tertiary sediments, similar to that at present rimming the eastern seaboard of the United States south of New York, blanketed coastal New England in preglacial time. It is estimated that in early Pleistocene time the inner margin of the coastal plain was about 48 to 64 km inland from the present Rhode Island and adjoining Massachusetts coast. Although this belt of sediments has been almost entirely removed by glacial erosion, they are exposed in Martha's Vineyard, most notably in Gay Head cliff. Here the sediments are predominantly of Late Cretaceous age, but a thin unit of fossiliferous greensand of Miocene age is also present (*11*). The Upper Cretaceous sediment consists in large part of clayey (kaolinitic) quartz sand with scattered plant fossils and lignite beds. The Miocene greensand also contains some quartz sand and wood fragments. In addition, sand and clay with plant fossils of Eocene age formed part of the coastal plain, but our knowledge of these is limited to one exposure in Scituate Third Cliff, about 35 km southeast of Boston (*12*). Conceivably one of these stratigraphic units could have been the parent material of the bauxite.

The age of the New England bauxite—that is, the bauxitization as distinct from the age of the parent material—is conjectural, but in all likelihood it is the same as that of the deposits in Arkansas and in southeastern United States. Stratigraphic evidence points to these having formed in the early Eocene and possibly in the late Paleocene (*2, 13*). Lately an Eocene flora has been found (*4*) in organic-rich clays embedded in bauxite from near Adairsville, Georgia.

The Martha's Vineyard find considerably extends the known geographical range of bauxite. The nearest known deposit of bauxite in the coastal plain is in central Georgia (*13*). The northernmost deposit of bauxite in eastern North America is in the valley and ridge province of western Virginia (*14*), although small quantities of gibbsite (associated with limonite deposits) have been found in Richmond, Berkshire County, Massachusetts, and Unionvale, Dutchess County, New York (*15*), and gibbsite occurs in the Pensauken Formation of New Jersey (*16*). Climatic and other conditions favorable for bauxitization in the early Tertiary could not have been as localized as today's known deposits. Indeed, numerous bauxite deposits probably occurred formerly along the coastal plain from the Gulf of Mexico to New England, and also inland on the deeply weathered uplands. Most of these undoubtedly were destroyed by Tertiary and Quaternary erosion. However, undiscovered deposits probably remain, particularly on the coastal plain between Georgia and New York, where bauxite may lie buried beneath the blanket of younger sediments.

CLIFFORD A. KAYE

U.S. Geological Survey,
270 Dartmouth Street,
Boston, Massachusetts 02116

References and Notes

1. C. A. Kaye, *U.S. Geol. Surv. Prof. Paper* **501-C**, 134–139 (1964).
2. M. Gordon, Jr., J. I. Tracey, Jr., M. W. Ellis, *U.S. Geol. Surv. Prof. Paper* **299**, 1–268 (1958).
3. E. S. Barghoorn (personal communication), is in agreement with this conclusion.
4. E. A. Stanley, W. H. Duncan, F. Montgomery, *Georgia Acad. Sci. Bull.* **24**, 25 (1966).
5. J. F. Van Kersen, *Leidse Geol. Mededel.* **21**, 250–375 (1956–1958).
6. C. H. Behre, Jr., *Econ. Geol.* **27**, 678–680 (1932).
7. M. N. Bramlette, *Arkansas Geol. Surv. Inform. Circ.* **8**, 1–68 (1936).
8. J. H. Bateson and G. Harden, *Econ. Geol.* **58**, 1301–08 (1963); S. H. Patterson, in *Clays and Clay Minerals, Proceedings 12th National Conference* (Pergamon Press, Oxford, 1964), p. 153.
9. P. L. C. Grubb, *Econ. Geol.* **58**, 1267 (1963).
10. A. W. Quinn and W. A. Oliver, Jr., *Pennsylvanian System in the United States* (American Association of Petroleum Geologists, Tulsa, 1962), p. 60; N. S. Shaler, J. B. Woodworth, A. F. Foerste, *U.S. Geol. Surv. Monograph* **33**, 1–394 (1899).
11. J. B. Woodworth and E. Wigglesworth, *Harvard Mus. Comp. Zool. Mem.* **52**, 1–322 (1934).
12. C. A. Kaye and E. Leopold, in preparation.
13. E. F. Overstreet, *U.S. Geol. Surv. Bull.* **1199-A** (1964).
14. W. C. Warren, J. Bridge, E. F. Overstreet, *U.S. Geol. Surv. Bull.* **1199-K** (1965).
15. C. Palache, H. Berman, C. Frondel, *The System of Mineralogy of James Dwight Dana and Edward Salisbury Dana, 1837–1892* (Wiley, New York, 1944), vol. 1.
16. W. Lodding, *Amer. Mineral.* **45**, 228 (1960).
17. I thank Mary Mrose for x-ray analyses of bauxite material; C. Milton for examination of thin sections of some of the bauxite; S. H. Patterson for ideas on bauxite genesis; P. Elmore, S. Botts, G. Chloe, L. Artis, and N. Smith for analyses; J. B. Cathcart, F. Osterwald, and S. H. Patterson, for review of the manuscript. Publication authorized by the Director, U.S. Geological Survey.

26 May 1967; revised 17 July 1967