
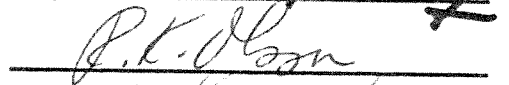
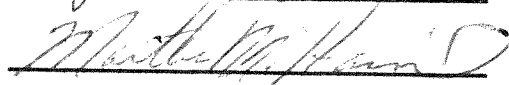



CEMENTED PLEISTOCENE GRAVELS
OF NORTHERN NEW JERSEY

By MARTHA WARREN PENDLETON

A thesis submitted to
The Graduate School
of
Rutgers University
in partial fulfillment of the requirements
for the degree of
Master of Science

Written under the direction of
Professor Raymond C. Murray
of the Department of Geology
and approved by

New Brunswick, New Jersey

January, 1973

ABSTRACT OF THE THESIS

CEMENTED PLEISTOCENE GRAVELS
OF NORTHERN NEW JERSEY
by MARTHA WARREN PENDLETON
THESIS DIRECTOR: PROFESSOR RAYMOND C. MURRAY

Within the glaciated area of northern New Jersey, there are fluvio-glacial gravels and till that are locally coated and/or cemented with calcium carbonate. X-ray analysis demonstrates that this cement is, for the most part, low-magnesium calcite with lesser amounts of aragonite.

This study was undertaken in an attempt to determine: 1) the ground water environment in which the cement was precipitated, 2) the age of the cement, and 3) the process (es) by which the cement was precipitated.

The low-magnesium cement has a drusy mosaic fabric, i. e. it is pore filling, and the size of the crystals increases away from grain boundaries. Because of capillary action and gravity, water has been differentially retained at grain boundaries and on the underside of individual cobbles. Differential water retention has produced an uneven cement that is thicker at grain boundaries and on the underside of the gravels.

Two carbon-14 dates were made on the low magnesium calcite cement and corrected for error induced by isotopic fractionation during sample formation and sample preparation.

It is proposed that the carbonate cement was formed in the vadose environment. On the basis of corrected carbon-14 dates, it is also proposed that cementation occurred during the Hypsithermal Interval either

by evaporation or exchange of carbon dioxide between water and pore atmosphere.

ACKNOWLEDGEMENTS

The assistance of Professor Raymond C. Murray, Department of Geology, Rutgers: The State University, was invaluable to the completion of this study, and is gratefully acknowledged.

INTRODUCTION

Throughout the northern United States, in areas that were covered by drift of the Pleistocene glaciation, there are outwash gravels and till that are locally coated and/or cemented with calcium carbonate (see figure 1 and table 1). In some areas, these carbonate accumulations are termed caliche. In other areas, however, the present climate is such that caliche should not be forming. The calcium carbonate cement found in areas where caliche should not be forming today can be explained by 1) precipitation at some time in the past when the climate may have been more typical of a caliche forming environment or 2) precipitation today by some other process.

Caliche is a general term given to carbonate crusts such as those that are found in the semi-arid southwestern United States. The formation of caliche appears to be determined by climate. According to Arellano (1953), the basic requirement is an area of true chernozem. This type of soil is found in dry-cold climates, in cool or temperate semi-arid climates where a soil that is black and rich in humas and carbonates develops. There is a close relationship between the distribution of chernozem and the distribution of loess and glacial drift in North America. Arellano's observations of caliche in North America and the western Mediterranean lead to some conclusions concerning climatic limitations on the development of caliche. Caliche does not form in areas of high precipitation. An annual rainfall in excess of 650 mm. (24.6 in.) inhibits its growth. In addition, temperature is a limiting factor. The zone of

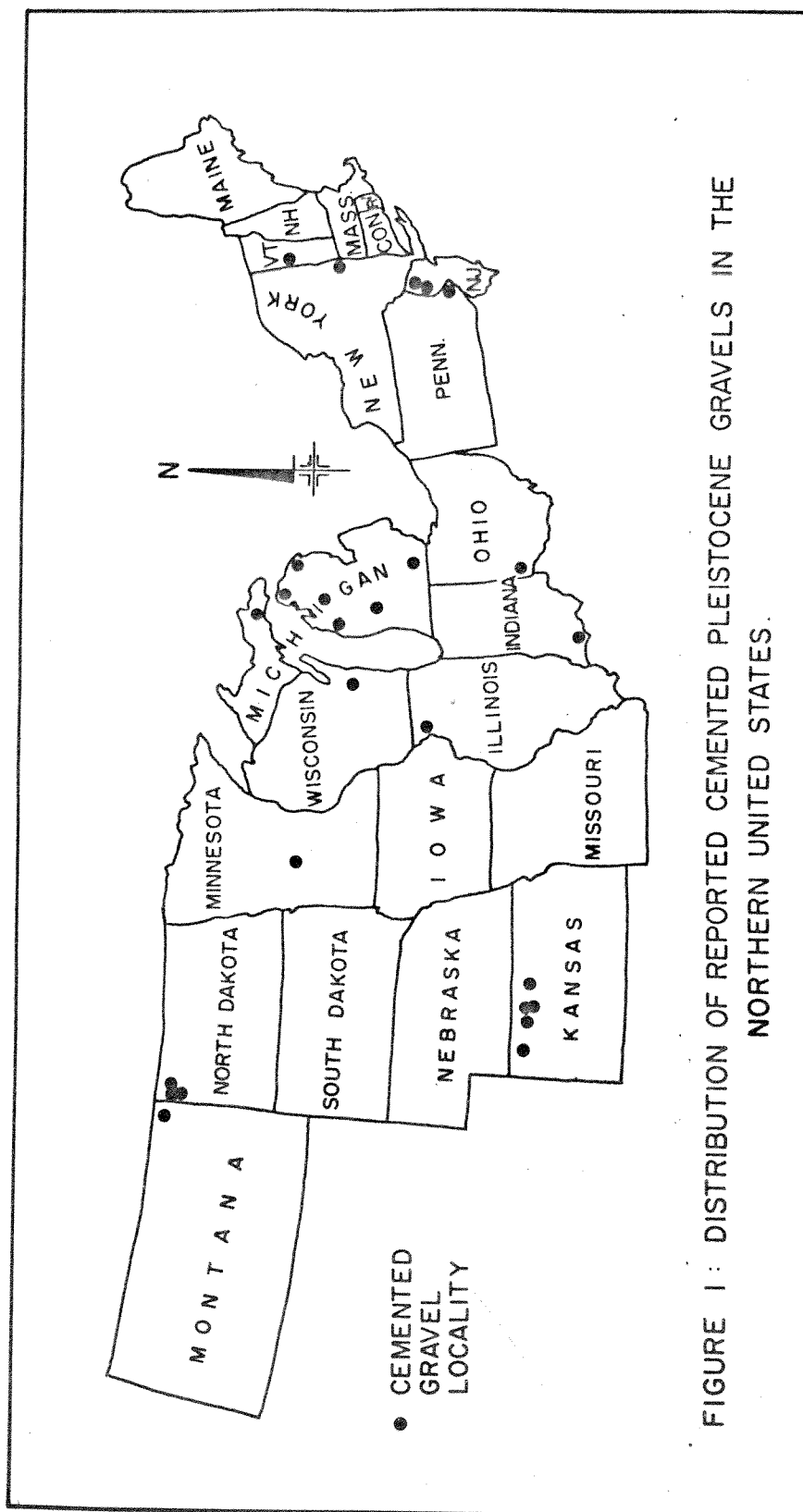
caliche formation today extends from 39° to 50° latitude in North America.

Table 1: Localities of calcium carbonate cemented Pleistocene gravels in the Northern United States.

State	Locality Description	Previous Work
Illinois	West of Rock River. Cementation in lower levels of gravels (till). Lime carbonate carried down from above. Sterling area, Seward.	Alden, W. C. (1918)
Indiana	Rockport; section of Ohio River Bluff. Partly cemented gravel - typical of Illinoian drift, rare in Wisconsin.	Leverett, F. and Taylor, F. B. (1915)
Kansas	Northcentral. Sanborn formation is spotted with caliche crusts and in places cemented into a firm conglomerate.	Frye, J. C. (1945)
Michigan	Distribution not limited to any 1 part of the state. Cementation is patchy and shows no noticeable relationship to changes in porosity or permeability. Massive sections of cemented gravels within uncemented gravels. In some places, gravels too well cemented to be workable.	Segall, R. T., personal communication.
Minnesota	Central. Stratified drift of the Wadena Lobe, a portion of the Keewalin drift, is characterised by calcium carbonate coatings. In general, the gravels of the stratified Keewalin drift contain a high percentage of limestone cobbles, and the individual cobbles are commonly coated with secondary calcite. Annual precipitation ranges from 23-26 ins; mean annual temperature varies from 37°-42° F.	Schneider, A. F. (1961)

Table 1, cont'd.

Montana - N. Dakota	Caliche crusts on the undersides of many of the pebbles in early and later Wisconsin tills. The Cartwright gravel is in some localities cemented by calcium carbonate. The late Wisconsin Mankato drift contains pebbles coated with calcium carbonate on their undersides. This is part of a regional caliche horizon. The climate is semi-arid with an average rainfall of 12-16 ins. per year.	Howard, A.D., 1946 _____, 1947
New York	Central. Fluvio-glacial gravel with pebbles of sandstones, limestone, gneiss, quartzites, and granite. Cemented by calcium carbonate.	Friedman, G.M., and Kolesar, P.T., 1969 Schmidt, V.E., 1947
Ohio	Mill Creek Valley. Fluvio-glacial gravels consisting almost entirely of limestone. Cementation with calcium carbonate by evaporation. Deposits of Illinoian Age.	Fenneman, N.M., 1916
Penn.	Eastern. Two miles south of Morrisville, pleistocene gravels are exposed in Warner Brother's gravel pit. At the north end of the pit, the well-sorted gravels are calcareous (cherty limestone and grey dolomite) and are cemented with calcium carbonate.	Pellier, L.C., 1959
Vermont	Proctor. A glacial gravel containing quartz, mica, and rock fragments, including dolostone. The cement is low-magnesian calcite with a fabric of drusy calcite mosaic. A metamorphic dolostone surrounding three sides of this gravel is thought to be the source of carbonate for the cement.	Friedman, G.M. and Kolesar, P.T., 1969



Cemented Pleistocene gravels occur throughout northern New Jersey. The present climate of northern New Jersey should inhibit the growth of caliche because New Jersey is an area of high precipitation. The average annual rainfall in New Jersey from 1890 through 1904 was 46.79 inches. This figure is almost double Arellano's figure of 24.6 inches which is the maximum amount of rainfall possible for the precipitation of caliche.

Table 2: Mean annual rainfall in New Jersey 1890-1904. (From the Report of the New Jersey Weather Service, 1890-1904.)

1890	49.34 inches	
1891	47.98	"
1892	42.51	"
1893	37.29	"
1894	51.72	"
1895	52.35	"
1896	47.37	"
1897	47.90	"
1898	42.02	"
1899	45.84	"
1900	42.71	"
1901	51.80	"
1902	59.44	"
1903	56.25	"
1904	37.41	"

Assuming that caliche should not be forming today in northern New Jersey, and that there is no evidence to suggest that the cementation is taking place today, one must consider 1) the time of cementation and 2) how and under what ground water conditions the cement formed. In addition, the cementation of these pleistocene gravels provides an example of Recent diagenesis. Examination of Recent cements may prove helpful in the interpretation of the diagenetic environment of ancient sedimentary

rocks.

Table 3: Sample localities of cemented Pleistocene gravels of northern New Jersey.

Locality	Description
1. Sand and gravel pit one mile south of Bevans, New Jersey.	The pit exposes stratified Wisconsin outwash gravels. Locally, layers are cemented or coated with calcium carbonate. To the northeast of the pit, there is a ridge of Silurian limestone.
2. Till, north of the Montague Hotel (Bevans area).	This outcrop is exposed in a well (Salisbury, 1902). Underneath twenty feet of clay-sized calcareous till, there are 12 feet of gravel, cemented by calcium carbonate into a conglomerate.
3. Terrace material, Belvidere area.	The terrace material is exposed along the L and HR railroad and in gravel pits. Most of the cobbles are limestone and shale. In places, the terrace material is firmly cemented. Also, the cobbles are coated with calcium carbonate.
4. The Ogdensburg embankment.	The best exposure is on the western side of the embankment near Walkill. The cobbles are 40% limestone, 40% gneiss, and 20% slate and sandstone. The cobbles are partially cemented with calcium carbonate.
5. North Church Gravel Pit.	Located 4 miles west of Ogdensburg, this pit contains cobbles of shale, quartzite, limestone, and gneiss. Here, cementation occurs locally, and individual cobbles are coated, especially on the underside.
6. Hardyston Sand and Gravel Co., Inc.	Located 1.4 miles north of Hamburg on route 94, this pit exposes gravels in a kame terrace. The cobbles consist of limestone, gneiss, granite, shale, slate, and sandstone. Calcium carbonate coats the underside of many cobbles and locally cements them together.

Table 3, cont'd.

7. Between the recessional moraine and Monroe, New Jersey.	Kame terraces are found at the northern end of Lake Grinnel towards Monroe. 50% of the cobbles are limestone. This material is locally well cemented with calcium carbonate.
8. Terminal moraine at Great Meadows.	This exposure is located off of route 46 in Great Meadows. Rock fragments are limestone, shale, gneiss, sandstone, and quartzite. The fragments are coated and locally cemented with calcium carbonate.
9. Houdaille Construction Co.	This company is working gravels in southern Warren County along the Delaware River north of Carpentersville. Calcium carbonate coats and cements cobbles in this outwash deposit. Cobble types include sandstone, limestone, quartzite, gneiss, and chert.
10. Montville.	The outcrop is 13 miles northeast of Morristown just southeast of Montville. The cobbles of this kame include limestone, gneiss, Green Pond conglomerate, shale, amphibolite, and greenstone. Calcium carbonate coats and cements the cobbles.

A large part of northern New Jersey is covered by Pleistocene deposits of Wisconsin age. A well defined terminal moraine extends across the state from Belvedere on the western border of New Jersey in a northeasterly direction to Dover and then southeast to Perth Amboy on the eastern seaboard. In addition, there are a few recessional moraines and numerous deposits of stratified drift in the form of kames, kame terraces, eskers, and deltas. In places, the stratified drift and till of northern New Jersey are locally coated and cemented with calcium

carbonate. Figure 2 shows the relationship between limestone bedrock and localities of cemented gravels and till in the area studied. A description of localities where cemented gravels were collected is summarized in Table 3.

DESCRIPTION OF THE CEMENT

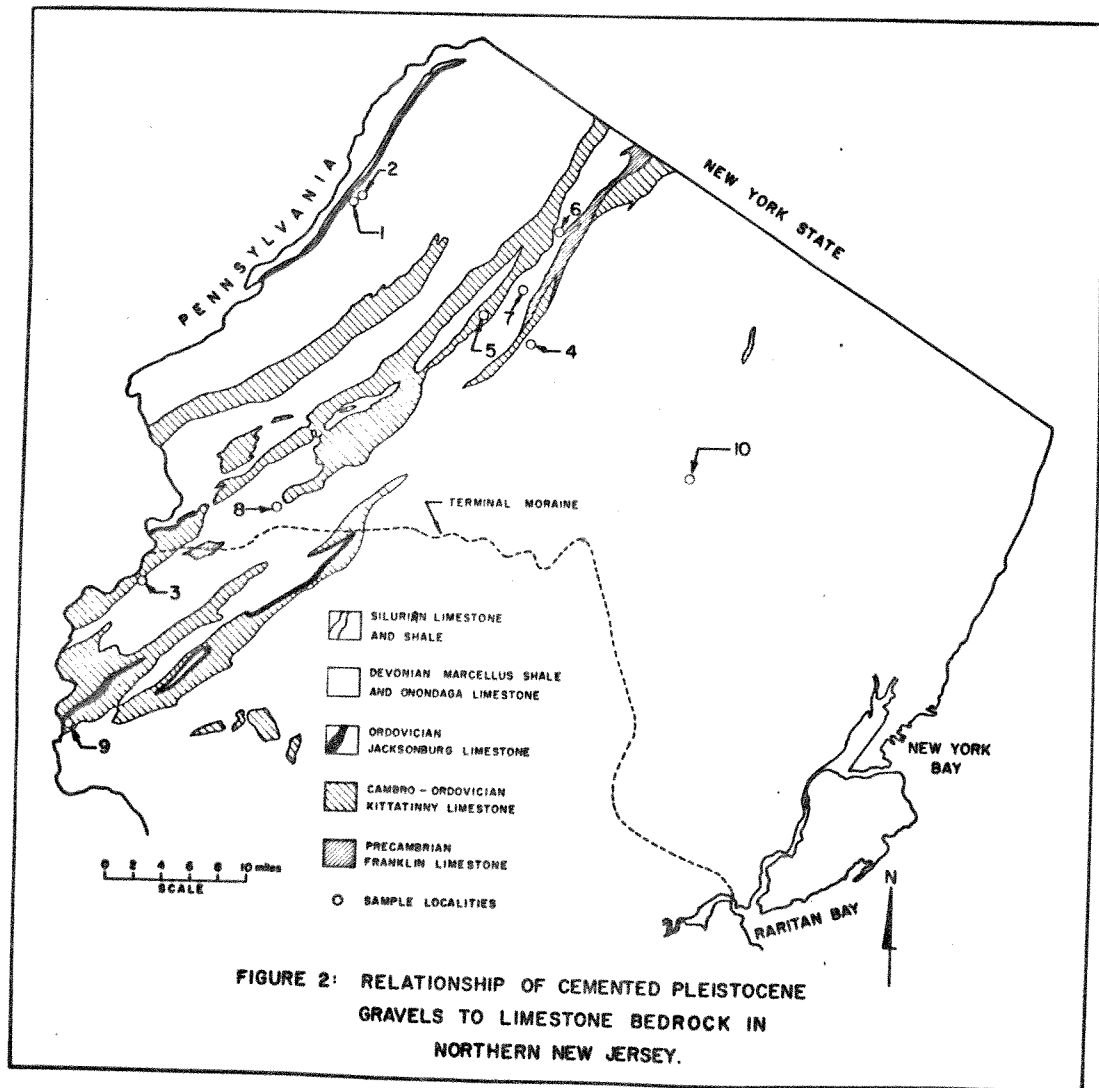
X-ray analysis demonstrates that the Wisconsin gravels of northern New Jersey are locally coated and cemented with calcium carbonate. The majority of the cement is low-magnesium calcite. However, in one locality, aragonite crystals were found in addition to the calcite cement.

The low magnesium calcite forms a drusy cement (Bathurst, 1959). That is to say, the cement is pore filling and the size of the crystals increases away from the grain boundary. The calcite is a gravitational cement as defined by Muller (1971). In hand specimen one can see that the cement has been preferentially precipitated on the underside of cobbles. There is also a preferential precipitation of cement at grain contacts. Both in hand specimen and in thin section, one notices that the cement has grown unevenly on grain surfaces.

The aragonite cement is rare and has only been found growing as a secondary cement on a crust of low magnesium calcite. It occurs as radiating clusters and single crystals of acicular aragonite.

DISCUSSION

The cemented gravels are found well above the present water table.



Depending on the age of the gravels, cementation could have taken place under either vadose or phreatic conditions. Various characteristics of the cement help to determine in which of the two realms of meteoric diagenesis cementation has taken place.

Muller (1971) considers gravitational cement to be indicative of the vadose environment for subaerially cemented material. He argues that in the phreatic environment, since the pore spaces are filled with water, one would expect cement to be precipitated evenly along grain boundaries. On the other hand, in the vadose environment, the pore spaces are filled with air and water. Consequently, the water would tend to coat grains. If you consider an individual grain, the film of water, coating the grain, would be thicker on the underside of the grain. The thicker accumulation of water on the underside of the grain would allow a thicker cement to be precipitated in that area. Thus, cementation would occur preferentially on the underside of a grain in the vadose environment.

Gravitational cement is a common feature in the gravels studied. Examining the outcrops after a rain, one can see that water is preferentially retained on the underside of the cobbles. Furthermore, where the gravels are coated, the cement is not only thicker on the bottom of a cobble but also coats only the underside of many cobbles. At the Hardy-ston Sand and Gravel Co. (outcrop number 6), the gravels of a kame terrace are being worked. Close examination of these gravels shows that the cement has developed almost entirely as a coating on the underside of

individual cobbles.

In the vadose environment, water should be preferentially retained at grain boundaries by capillary action. Thus, according to Dunham (1971), vadose cementation can produce a meniscus cement, i. e. a cement that is more extensive at grain contacts than along grain surfaces. Samples of the cemented gravels, in thin section and in hand specimen, indicate that the cement is thicker at grain boundaries than along an individual grain surface.

The concepts of gravitational and meniscus cement both lead to the same conclusion. In the vadose environment, pore spaces are only partially filled with water. As the water enters a pore space, it tends to coat grains. In places, either by capillary action or by gravity, the film of water will be thicker. Where there is a greater accumulation of water, there is a greater opportunity for cement to develop. In the vadose zone, an uneven cement will develop. The cement will be uneven, i. e. of varying thickness, because of differential water retention. In the phreatic environment, where pore spaces are filled with water, water is not a limiting factor in the process of cementation. The cement should develop evenly along grain surfaces. Cementation of the Pleistocene gravels of northern New Jersey is uneven; the calcite cement has developed differentially. Where there is a greater probability of water retention, on the underside of cobbles and at grain contacts, the cement is thicker. Thus, at the time of cementation, the gravels were in the vadose environment, and the ground water table was no higher than it is today.

Another feature, related to the cement, is an accumulation of clay sized particles. It is important to consider whether this material is residual or infiltrated. X-ray analysis shows that this material consists of quartz, calcite, and lesser amounts of dolomite and chlorite. This mineralogy would lead you to believe that the material is or was derived from rock flour. The material is not residual. Frei, E. and Cline, M.G. (1949) discuss the difference in appearance between residual and infiltrated clay. If the clay has been infiltrated, you would expect to find an uneven distribution, layering, strongly oriented grain coatings, and perhaps ripple-like structures (Stephen, A.F., 1967). The brown material associated with the cement has an irregular distribution and coats grains. It has been infiltrated or translocated before and during cementation. In thin section, one can see the relationship grain, clay layer, cement. Also, one can see another relationship: grain, clay coating, cement, clay, cement. This material was not weathered in place, but was added to the system before and during cementation in the vadose zone.

The aragonite cement appears to be a problem. It is found at only one locality (3). In hand specimen the aragonite crystals appear to be growing on a crust of calcite near the top of the cemented section some twelve feet below the surface. It is a secondary stage of cementation and younger than the calcite cement.

Despite the rarity of the aragonite cement, one must consider the problem of its formation. J.W. Murray (1954) discusses the conditions

that favor the precipitation of aragonite in cave deposits. He lists high temperature, low concentrations of calcium bicarbonate, and a high concentration of other elements, such as magnesium, strontium, and lead, as factors influencing the precipitation of aragonite. In most caves, where precipitates are derived from fresh as opposed to saline water, calcite is the predominant mineral found. As the calcite is precipitated, the remaining solution will become more concentrated in other solutes. If the concentration of other solutes is an important factor in controlling the precipitation of aragonite versus calcite, then as the concentration of other solutes increases, the chances of precipitating aragonite may increase.

One must also consider the nature of the initial solution from which the precipitates are derived. Here, again, it is important to take into account the role of the other elements in solution. According to Murray, magnesium and strontium content of the solution are important in determining whether calcite or aragonite is precipitated. Holland et al (1964) find three controls on the evolution of cave waters: carbonation in the soil zone, solution of calcite and/or dolomite, and equilibration with the cave air. Solution of dolomite instead of calcite will provide higher concentrations of magnesium to the initial solution. Also, according to Holland, the strontium content will depend partly on the mineralogy of the precipitate and partly on the ratio of the concentration of strontium to calcium in the parent water. In his studies of the cave deposits of the Luray Caverns, the concentration of strontium in solution was determined

by the amount of dolomite that was dissolved by rain water. If the parent solution is dissolving dolomite, it will become enriched in both magnesium and strontium. With an increased concentration of magnesium and strontium in solution, aragonite may be the more likely mineral phase to precipitate. Many of the glacial gravels studied contain dolomite or dolomitic limestone cobbles so there is a source of both strontium and magnesium to go into solution in the ground water.

Holland notes that aragonite is only precipitated when the product, $a_{\text{Ca}^{+2}} \cdot a_{\text{CO}_3^{-}}$ exceeds the solubility product of aragonite. At 15°C, the solubility product of aragonite is approximately ten percent greater than the solubility product of calcite (Holland et al, p.65). Thus there is a range for the product $a_{\text{Ca}^{+2}} \cdot a_{\text{CO}_3^{-}}$ during which calcite will precipitate instead of aragonite. Analysis of cave waters show that during the loss of CO_2 to the cave atmosphere, cave waters can become more than ten percent supersaturated with respect to calcite. At this time calcite or aragonite may precipitate from the solution. Perhaps as the ground water reaches a pore space in the gravels, there is a loss of CO_2 to the pore atmosphere. This reequilibration of CO_2 to the pore atmosphere could also cause the ground water to become increasingly supersaturated with respect to calcite. The precipitate from this ground water during loss of CO_2 could then be either calcite or aragonite. This explanation of the presence of aragonite depends on the hypothesis that the environment of cementation in the gravels is analagous to the environment of precipitation in a limestone cave.

Age of the Cement

There is no direct evidence that the cement is forming today. It is younger than the gravels which it cements. Wisconsin age fluvio-glacial gravels are exposed in a gravel pit on Hutcheson Road in Harmony Township, New Jersey (locality 3). Excavation in the gravel pit has exposed thirty-five feet of terrace material (interbedded sand and gravel) that is locally cemented and coated with calcium carbonate. The section is cemented and/or coated below the soil zone down to fifteen feet above the present ground water table. At the time of deposition, the gravels were at or below the ground water table, and therefore, in the phreatic zone. Consequently, cementation must have occurred some time after deposition when the ground water table had fallen (or almost to) its present level. The drop in ground water table brought the gravels from the phreatic zone to the vadose zone, where the cement was precipitated. Thus, cementation began some time after the Wisconsin ice sheet receded from its southernmost extent in New Jersey.

Carbon-14 dates were made on two samples of low magnesian calcite cement from this gravel pit (see Table 4). The samples were taken from the same horizon ten feet apart near the top of the cemented zone. These dates indicate that cementation took place during the Hypisthermal interval. According to Deevey, E.S. and Flint, R.F. (1957), this interval when the mean annual temperatures exceeded those of the present extends from about 7000 B.P. to 600 B.P. The pollen record in the temperate zones implies that the Hypisthermal Interval shows several oscillations

in climate occurred, i. e. parts of the Hypisthermal were warmer than others. Because some of the warmest episodes are demonstrated by hot, dry summers preceeding 600 B.P. in northwestern Europe, and because repeated glacial advances appear to be restricted to alpine areas, Flint and Deevey extend the Hypisthermal to 600 B.P.

Sample	HR-1	HR-2
✓ Carbon-14	548 ± 7	528 ± 7
Apparent Age	6380 ± 125	6030 ± 120
✓ Carbon-13	-8.6	-10.6
Δ Carbon-14 ₁	574.2	559.5
Corrected Age ₁	6855 ± 125	6585 ± 126
Δ	496.8	483.1
Corrected Age ₂	5515 ± 125	5300 ± 126

Table 4: Comparison of measurements on two samples of calcite cement.

In order to correct the apparent age of the cement for error induced by isotopic fractionation during sample formation and sample preparation, ✓ C¹⁴ IS corrected to C¹⁴.

$$(1) \quad \delta C^{14} = \left[\frac{A_* - A_o}{A_o} \right] \times 1000$$

where A_* = C¹⁴ activity and A_o = standard activity C¹⁴
 C¹⁴ is corrected by normalization to the C¹³/C¹² ratio by the following equation: (Broecker, W.S. and Walton, A., 1959).

$$(2) \quad \Delta C^{14} = \delta C^{14} - 2 \delta C^{13} \left[1 + \frac{\delta C^{14}}{1000} \right]$$

The term ΔC^{14} is independent of fractionation. In equation two, a factor of -50.0 per mil is added:

$$(3) \quad \Delta C^{14} = \delta C^{14} - 2 \delta C^{13} \left[1 + \frac{\delta C^{14}}{1000} \right] - 50.0$$

The addition of the -50.0 per mil factor was revised (Broecker, W.S. and Edwin, A.O., 1961), and $\left[1 + \frac{\delta C^{14}}{1000} \right]$ replaces unity as a multiplier of the constant term, 50.0. This revision should reflect Δ values which show exact per-millage change in the fractionation-normalized C^{14} concentrations. With the final revision Δ replaces the term C^{14} to avoid confusion as to which constant has been used.

$$(4) \quad \Delta = \delta C^{14} - 2 \delta C^{13} \left[1 + \frac{\delta C^{14}}{1000} \right] - 50.0 \left[1 + \frac{\delta C^{14}}{1000} \right]$$

The term, -50.0 per mil was originally added to make the 1890 wood zero on the normalized scale (Broecker, W.S. and Walton, A., 1959). For means of comparison, two age corrections were calculated. The first, corrected age 1, was based on equation (2); the second, corrected age 2, was based on equation (4). Whether or not the scale is normalized to zero, the corrected age will fall within the Hypisthermal Interval. The added constant is not essential, but does provide a convenient ΔC^{14} scale which gives the corrected dates more immediate significance.

The corrected carbon-14 dates limit the errors produced by dating a calcite cement. According to C.H. Hendy (1970), in a discussion of the use of carbon-14 dating on cave processes,

"The most serious difficulty with this method has been the estimation of the initial carbon 14/carbon 12 ratio, which may

vary from 100% to 50% of the atmospheric level and may thus introduce an uncertainty of more than 5000 years in the age determination. "

On the other hand, Broecker, W.S. and Walton, A. (1959) feel that although quite low carbon-14/carbon-12 ratios might be expected, some factors will tend to make the ratio higher. Considering cave deposits in a high carbonate area, at least two factors will raise the carbon 14/carbon 12 ratio. The first factor would be the exchange of atmospheric carbon dioxide at the surface. Secondly, one must consider the exchange with carbon dioxide in the air during transportation of carbonate in solution and during precipitation. These factors lead Broecker to believe that there is sufficient incorporation of carbon-14 in solution to provide a reasonable carbon-14 date on cave deposits. In this case, the estimated error would be limited to 800-1800 years. The technique of carbon-14 dating on cave deposits has been used by Broecker, W.S., Olson, E.A., and Orr, P.C. to define annual rings in cave formations. This study supports the validity of carbon-14 dates on cave formations.

Once the apparent carbon-14 ages have been corrected for errors in fractionation that occur during formation and during sample preparation, then it is reasonable to say that cementation of the fluvio-glacial gravels from locality (3) took place during the Hypisthermal Interval.

Summary and Conclusions

In northern New Jersey, Pleistocene gravels have been cemented and/or coated with calcium carbonate. Salisbury (1902) refers to this cement as caliche and states that it precipitated from solution by evaporation. This study was undertaken to determine 1) the ground water environment in which the cement was precipitated, 2) the age of the cement, and 3) the process(es) by which the cement was precipitated.

In the phreatic environment, pore spaces are filled with water, and cement should be precipitated evenly along grain boundaries and grain surfaces. In the vadose environment, pore spaces are filled with water and air. Where there is greater water retention, a thicker accumulation of cement is possible. Precipitation of cement in the vadose environment is, therefore, limited by the amount of water available. The Pleistocene gravels of northern New Jersey are unevenly cemented. This cement can be characterized as gravitational, i. e. there is a preferential precipitation of cement on the underside of cobbles. Also, the cement is thicker at grain boundaries where there is greater water retention by capillary action. Because the cement is uneven and because of infiltrated clay associated with the cement, it is proposed that the cement was formed in the vadose environment.

Two samples of cement were dated by carbon-14. The apparent carbon-14 ages of these samples are: HR-1: 6380 ± 125 years B. P. and HR-2: 6030 ± 120 years B. P. These dates fall within the Hypisthermal Interval (7000-600 B. P.). The carbon-14 dates show that the cement is a

relic cement and is not forming today. The apparent carbon-14 ages were corrected for errors in fractionation that may have occurred during formation and during sample preparation.

The role of evaporation in the formation of this cement would be minor if the cement were forming today. Since the cement is a relic and was formed during the Hypisthermal Interval, evaporation may have been an important mechanism for precipitation. Presently, it is impossible to determine the exact processes by which the cement was precipitated. Supplementary pollen data is necessary to determine the climatic environment of New Jersey during the Hypisthermal Interval.

REFERENCES

- Alden, W.C., 1918, Quarternary Geology of Southwestern Wisconsin: U.S. Geol. Survey Prof. Paper 106.
- Arellano, A.E., 1953, Barrilaco Pedocal, A Stratigraphic Marker Ca 5,000 B.C. and its climatic significance: ed. *Déserts actual et anciens*, 19th International Geol. Cong., Algiers, Compton Rendus, sec. 7, Fasc 7, p. 53-76.
- Bathurst, R.G.C., 1958, Diagenetic fabrics in some British Dinantian Limestones: *Liverpool and Manchester Jour. Geol.*, v.2, p. 11-36.
- Bretz, J.H., 1958, Vadose and phreatic features of limestone caverns: *Jour. Geol.*, v. 50, part 2, p. 675-811.
- Broecker, W.S., Olson, E.A., and Orr, P.C., 1960, Carbon 14 measurements and annual rings in cave formations: *Nature*, v. 185, p. 93-94.
- _____, Ewing, M., and Heezen, B.C., 1960, Evidence for an abrupt change in climate close to 11,000 years ago: *AM. Jour. Sci.*, v. 258, p. 429-448.
- _____, and Walton, A., 1959, The geochemistry of C^{14} in the fresh water systems: *Geochim et Cosmochim. Acta*, v. 16, p. 15-34.
- _____, and Olson, E.A., 1961, Lamont Radiocarbon Measurements VIII: *Radiocarbon*, v. 3, p. 176-204.
- Cole, H.S., 1965, The redistribution of calcium and magnesium carbonates in a fluvio-glacial terrace of Wisconsin Age: unpublished Henry Rutgers Thesis.
- Deevey, E.S., and Flint, E.F., 1957, Post Glacial Hypisthermal Interval: *Science*, v. 125, p. 182-184.
- Dunham, R.T., 1971, Meniscus Cement, p. 299-300, in *Carbonate Cements*: Johns Hopkins Univ. Studies in Geology, no. 19, 376 p.
- Fenneman, N.M., 1916, Geology of Cincinnati and Vicinity: *Geol. Survey of Ohio, Fourth Series, bulletin 19*, p. 127-130.
- Frei, E., and Cline, M.G., 1949, Profile Studies of Normal Soils of New York: II. Micromorphological Studies of the grey-brown Podzolic-brown Podzolic Soil Sequence, *Soil Science*, v. 68, pp. 333-344.

- Friedman, G.M., and Kolesar, P.T. Jr., 1971, Fresh-water Carbonate Cements, p.122-126, in Carbonate Cements: Johns Hopkins Univ. Studies in Geology, No.19, 376 p.
- Frye, J.C., 1945, Problems of Pleistocene stratigraphy of Thomas County, Kansas: Kansas Univ. State Geol. Survey Bull. 59, p.110.
- Fyfe, W.S., and Bischoff, J.L., 1965, The calcite-aragonite problem: S.E.P.M. Spec. Pub. No. 13, p.3-13.
- Hendy, C.H., 1970, The use of C^{14} in the study of cave processes, p.419-443 in Radiocarbon Variations and Absolute Chronology, Nobel Symposium No. 12, 652 p.
- Holland, M., Kirsipu, T.V., Huebner, J.S., and Oxburgh, N.M., 1964, On some aspects of the chemical evolution of cave waters: Jour. Geol., v.72, p.36-67.
- Howard, A., 1946, Caliche in glacial chronology: Geol. Soc. America Bull., v.57, No.12, p.1204.
- _____, 1947, Evaluation of caliche coated pebbles in glacial chronology, Geol. Soc. America Bull., v.58, No.12, p.1194-1195.
- Leverett, F., and Taylor, F.B., 1915, The Pleistocene of Indiana and Michigan: U.S. Geol. Survey Monograph, v. VIII.
- Lonsdale, J.T., 1926, The occurrence of caliche in Oklahoma: Oklahoma Acad. Sci. Proc., v.5, p.132-136.
- Miller, J.P., 1952, A portion of the system calcium-carbonate-carbon-dioxide-water with geologic implications: Am. Jour. Sci., v.250, No.3, p.161-203.
- Mibard, J.P., 1961, End moraines on Kittatiny Mountain, Sussex County, New Jersey: U.S. Geol. Survey Prof. Paper 424-C, p. C61-C64.
- Müller, G., 1971, Gravitational cement: An indicator for the vadose zone of the subaerial diagenetic environment, p.301-302 in Carbonate Cements: Johns Hopkins Univ. Studies in Geology, No.19, 376p.
- Murray, J.W., 1954, Deposition of Calcite and aragonite in caves: Jour. of Geol., v.62, p.481-492.
- Pellier, L.C., 1959, Late Pleistocene Deposits, ch. 5 in Penn. Topographic, Geologic Survey Bull, Fourth Series, C9, p.163-183.

- Price, W.A., 1940, Origin of caliche: Geol. Soc. America Bull., v. 51, no. 12, part 2, p. 1939.
- Salisbury, R.D., 1902, The glacial geology of New Jersey: Geol. Survey of New Jersey, v. 5, Annual Report of the State Geologist.
- Schmidt, V.E., 1947, Boulders of interglacial conglomerate in central New York: Am. Jour. of Sci., v. 245, p. 123-127.
- Schneider, A.F., 1961, Pleistocene of the Randall Region, central Minnesota: Minnesota Geol. Survey Bull. 40, 151 p.
- Stephen, I., and Osmond, D.A., 1967, Clay Orientation in Soils: S. S. S. A. Special Publication Series No. 1.
- White, G.W., and Shepps, V.C., 1952, Characteristics of Wisconsin tills in northeastern Ohio: Geol. Soc. America Bull., v. 63, no. 12, part 2, p. 1388.
- Williston, S.W., 1897, The Pleistocene of Kansas, Kansas Univ. Geol. Survey, v. 2, p. 299-308.