INDIANA OOLITIC LIMESTONE: RELATION OF ITS NATURAL FEATURES TO ITS COMMERCIAL GRADING

By G. F. Loughlin

ABSTRACT

This report was prepared under a cooperative agreement among the Supervising Architect's Office, the United States Geological Survey, the Bureau of Standards, and the former Indiana Limestone Quarrymen's Association. As the criteria for grading are necessarily based on a number of geologic and related factors, of which those quarrying and using the stone had only an imperfect understanding, the first part of the report presents a very elementary account of the origin, structure, and chemical and physical properties of the stone and their relations to durability and utilization and serves as a foundation for the second part, which discusses grading and proposes limits for grade established by the quarrymen.

Salient features set forth in part 1 are the variations in uniformity of stone due to cross-bedding and local unconformities; the relative prominence of weathering effects on the coarser, uneven-grained surfaces and their apparent absence on fine, uniform-grained surfaces, although the amount of weathering is the same on each; the formation of "crowfeet" (stylolites) by solution under pressure, and the fact that, whereas the thinnest "crowfeet" have no noteworthy effect on weathering quality or strength, the thicker ones are likely to weather out rapidly and to promote splitting; the influence of fracturing on the oxidation of the original gray or "blue" to buff color above the ground-water level; the interpretation of chemical analyses and the evidence that both gray and buff colors are due mainly to organic matter supplemented by small to moderate amounts of pyrite or its oxidation product, limonite; the formation of stains and efflorescences mainly by the seepage of water from the floors, roofs, and inner walls of buildings through the stone facing, as shown by recent work at the Bureau of Standards and Purdue University; and the corrosive power of river waters not already saturated with calcium bicarbonate.

Part 1 also contains the results of several quantitative experiments by George Steiger of the United States Geological Survey, showing that carbon dioxide gas, even in very humid atmospheres, has no corrosive effect on limestone but that carbon dioxide in water exerts a slow solvent action and that rain water containing carbon dioxide but no other acid radicle and falling at the rate of 40 inches a year (the rate for the District of Columbia) would require 450 years to corrode the surface of the stone to an average depth of 1 centimeter or two-fifths of an inch. Preliminary experiments with sulphuric acid show a much greater rate of corrosion, but corresponding quantitative data have not yet been obtained.

Physical tests made at the Bureau of Standards are interpreted, and it is shown that as strength of the stone increases and its porosity decreases with

increase in the degree of cementation, the specific gravity or the weight per cubic foot may serve as a convenient index of the stone's other physical properties. The average specific gravity is 2.3, and the average weight per cubic foot is 144 pounds. The drying or seasoning of newly quarried stone is recommended as an aid in the prevention of staining and of freezing in places of severe exposure but is not believed necessary to prevent freezing under most conditions of use. Where the stone has been frozen, either in abandoned quarries or in the laboratory, spherical or concentric cracks imply stone of good quality, but parallel cracks or spalls either along or across the bedding imply stone of inferior quality, in which there is considerable marly or chalky material instead of a well-crystallized calcite matrix.

Part 2 points out that too rigid a system of grading based on fineness of grain would cause the wasting of much stone of good quality and that there is little or no difference in physical properties, other than appearance, in the different recognized grades of the trade, with the exception of grade H, the extra hard, impervious, and strong stone. After a study of samples submitted by most of the quarry companies of the region, reasonable limits in the fineness of grain, the blending of different shades of buff or gray, the number of shell holes and "glass" (calcite) spots are recommended for each grade, with a certain tolerance for a few blocks of stone that may not quite conform to the limits of a specified grade. These limits are set forth in a diagram, and each grade is discussed in some detail with special reference to the sample studied. The grades are listed below:

Buff: AA, statuary; unusually fine, uniform grained. A, select; fine, uniform grained. B, standard; prevailingly medium grained with rather distinct bedding. C, rustic; prevailingly coarse grained. Gray: D, E, EE, correspond to grades A, B, and C of buff stone. Variegated (buff and gray in a single block): F, variegated statuary, corresponding to AA; G, variegated, corresponding to B and C. Special grades: Hard, "Indiana travertine," very coarse grained with many large shell holes; "old Gothic," or stone of any color or grade, with or without "crowfeet" or other features that would exclude it from regular grades; "short length" stone equal in quality to the regular grades but in blocks smaller than those usually sent to stone mills.

INTRODUCTION

This report is the result of a cooperative agreement by the Supervising Architect's Office of the Treasury Department, the United States Geological Survey of the Department of the Interior, the Bureau of Standards of the Department of Commerce, and the former Indiana Limestone Quarrymen's Association for a study intended to lead to a uniform system of grading of the Indiana oolitic limestone to be used particularly in Federal Government buildings. In 1926 most of the companies in the Indiana Limestone Quarrymen's Association were taken over by the newly organized Indiana Limestone Co., and shortly afterward the technical investigations begun by the association were continued by the architects' service bureau of the new company.

As the criteria for grading are based on a number of geologic factors, supported by results of physical and chemical tests that have not always received due consideration, and as informal discussions of grading and related subjects with quarrymen, salesmen, cut-stone contractors, architects, and builders have revealed so general an interest in the fundamental causes of the characteristic features and variations in the Indiana oolitic limestone, this report is presented in two parts. The first part, entitled " Geology," treats of the origin of the stone and its characteristic features and their influence on its chemical and physical properties; the second part, which is based on the first, discusses the subject of grading and proposes limits for the different grades that were established by the Indiana Limestone Quarrymen's Association.

The writer began his study of the quarries in the Bedford-Bloomington district, Ind., in 1917. At that time plans were made for a comprehensive series of tests. Samples from most of the active quarries were assembled at Bedford, Ind., in August, 1917, and the writer, accompanied by Messrs. Packard and Roberts, of the Supervising Architect's Office, and D. W. Kessler, of the Bureau of Standards, examined them before shipment to the Bureau of Standards in Washington for testing.

Already, however, the entrance of the United States into the World War had placed so many demands for special information upon the United States Geological Survey that the writer was drafted for administrative work and for a long time had no opportunity to give this report any attention. Curtailment of building both by the Government and by private parties during the war rendered this delay of less consequence than it would otherwise have been, but the delay is none the less regretted.

PART 1. GEOLOGY

BIBLIOGRAPHY

Influences affecting the economic value of the Indiana oolitic limestone began with the deposition of the limestone and have continued in greater or less degree ever since. The geologic history of the stone will therefore be outlined with special reference to economic features. As the writer's field work was directed mainly to the study of quarries, he had depended a great deal upon the published reports of others for general regional information. The following reports are of particular interest:

Hopkins, T. C., and Siebenthal, C. E., The Bedford oolitic limestone: Indiana Dept. Geology and Nat. Res. Twenty-first Ann. Rept., pp. 291–427, 1897. (See also U. S. Geol. Survey Eighteenth Ann. Rept., pt. 5, pp. 1050–1057, 1897.)

Newsom, J. F., A geologic and topographic section across southern Indiana: Indiana Dept. Geology and Nat. Res. Twenty-sixth Ann. Rept., p. 281, 1903.

Ashley, G. H., The geology of the Lower Carboniferous area of southern Indiana: Indiana Dept. Geology and Nat. Res. Twenty-seventh Ann. Rept., pp. 83–84, 1903.

Cumings, E. R., and Beede, J. W., Fauna of the Salem limestone of Indiana: Indiana Dept. Geology and Nat. Res. Thirtieth Ann. Rept., pp. 1187–1486, 1906.

Blatchley, R. S., The Indiana oolitic limestone industry in 1907: Indiana Dept. Geology and Nat. Res. Thirty-second Ann. Rept., pp. 299–460, 1908.

Beede, J. W., and others, Geology of the Bloomington quadrangle: Indiana Dept. Geology and Nat. Res. Thirty-ninth Ann. Rept., pp. 190–314, 1915.

Logan, W. N., Handbook of Indiana geology: Indiana Dept. Conservation Pub. 21, pp. 475–507, 1922. (Contains a complete bibliography of the Indiana oolitic limestone.)

FACTORS GOVERNING DEPOSITION OF LIMESTONE

SOURCES OF MATERIAL

Limestones are so many and various that a thorough discussion of the conditions governing or influencing their deposition would occupy a volume of considerable size. Therefore, only those conditions that have developed conspicuous features in the Indiana oolitic limestone are considered in this paper. Limestone may be formed by the deposition of calcium carbonate from three sources—from shells and other hard parts of animals or plants (organic origin); from direct chemical precipitation, with or without the aid of living matter; or from débris accumulated by erosion of older limestones. Most limestones, including the oolitic stone of Indiana, are derived from more than one of these sources. For example, coral reefs are primarily the result of organic deposition and may be regarded as accumulations of the skeletons of many generations of corals; but the cavities in these skeletons that were originally occupied by soft parts of the animal may sooner or later become filled with additional calcium carbonate deposited from sea water in the same manner that salt is deposited from brine. Besides the corals themselves, shells of mollusks, large or small, and of small organisms, such as Foraminifera, may also accumulate. From this complex mass, which is repeatedly attacked by the waves, fragments may be broken and washed back and forth for a time but eventually become cemented together by additional calcium carbonate from the sea water and remain close by or even upon the original coral mass. The entire formation is therefore due in part to all three modes of origin.

The foregoing illustration is perhaps the easiest to understand because of the relatively great size and stationary character of coral reefs and because of the excellent illustrations of them in literature and in museum collections. Readers who have seen oyster beds or colonies of mussels or other mollusks along the seashore and who have also seen broken shells from these colonies strewn thickly along the beach and in places cemented together can readily understand that many varieties of limestone may be formed, according to the kinds of life supplying the material, the force of waves and currents eroding and moving it, and the rapidity and extent to which the eroded fragments become cemented.

In the vicinity of Florida and the Bahamas limestone is being formed at the present time under conditions similar in many ways to those that controlled the deposition of the Indiana oolitic limestone. There the climatic conditions and the extensive areas of shoal waters favor the abundant growth of Foraminifera, minute animals which consist of a single cell of living matter incased in a minutely perforated shell somewhat resembling a snail shell and whose name implies "hole-bearing."

Another condition that favors the abundant growth of Foraminifera is the local supersaturation of sea water with calcium carbonate. Sea water everywhere appears to be nearly saturated with calcium carbonate, but its capacity to contain this compound decreases with rise in temperature. The shallow depths and the climate of the region around Florida and the Bahamas have an unusual tendency to warm the sea water and therefore to promote supersaturation locally, so that not only is material furnished for the shells of Foraminifera and mollusks and the skeletons of corals but also some calcium carbonate is directly precipitated.

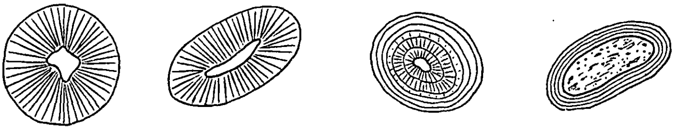

FIGURE 17.—Oolites

These conditions also promote an abundant growth of denitrifying bacteria, which by the generation of ammonia can cause precipitation of calcium carbonate from sea water. The calcium carbonate thus precipitated is likely to form minute spherical grains, called oolites[1] from their resemblance to the roe of a fish. (See fig. 17.) Experiments by Vaughan have shown that oolitic growth may also take place without the aid of bacteria if the water or solution is saturated with calcium carbonate and is continuously agitated, especially if small grains of some material are present to serve as nuclei.[2] The nuclei may be small grains of quartz, small shell fragments, or unbroken minute shells.

One of the most instructive discussions of oolitic growth is that by Bucher.[3] He first cites the important work of Heinrich Schade,

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[1] From the Greek ὠόν, egg, and λίθος, stone. The name oolite has been applied both to the single grains and to extensive rock formations composed mainly of them.

[2] Vaughan, T. W., and others, Some shoal-water bottom samples from Murray Island, Australia, and comparisons of them with samples from Florida and the Bahamas: Carnegie Inst. Washington Pub. 213, pp. 235–317, 1918.

[3] Bucher, W. H., On oolites and spherulites: Jour. Geology, vol. 26, pp. 593–609, 1918.

which shows experimentally that concretionary bodies such as oolites form when a substance passes from the state of a colloid emulsion to that of a solid. When this change leads to a crystalline state the resulting structure is radial if the substance is pure but is concentric if other substances are deposited at the same time. Bucher reviews the occurrences of different kinds of oolitic materials and concludes that the shapes of the particles are due to growth in suspension. For example, the oolitic grains along the shore of Great Salt Lake grew suspended in jellylike masses of algae, and those along the shores of the Bahama Islands grew in soft limy mud. After oolites have been formed, the deposit containing them may be elevated and subjected to erosion by waves and currents. The grains then become separated from the matrix and moved about and sorted like ordinary grains of sand, finally to be redeposited and cemented by additional calcium carbonate precipitated from the sea water.[4]

CROSS LAMINATION OR CROSS-BEDDING

The agitation of sea water produced by waves, tides, and shifting currents has a still more pronounced effect upon the texture of limestone beds that are being formed. Where coral reefs and large mollusk shells are broken by the force of the waves, the larger fragments remain close to their points of origin, small fragments of coral and shell sand are carried or rolled along for considerable distances, and the smallest fragments, or "calcium carbonate mud," are carried still farther, finally settling in deep and relatively quiet water.

As these sandy fragments are moved into slight depressions they produce a local progressive filling, similar to the fillings produced by rills washing sand into puddles of water or by streams emptying into ponds or lakes. These fillings are built up of successive sloping layers, each layer representing a slight change in velocity of the current (fig. 18, A), and the process continues as long as the direction of the current continues to be essentially uniform. As the sloping laminae are oblique or crosswise to the prevailing nearly horizontal position of the beds their attitude is referred to as cross lamination or cross-bedding. A considerable increase in velocity, such as might be caused by a storm, would not only interrupt deposition but by increasing the carrying capacity of the water would cause partial removal of the newly formed layers. Resumption of deposition

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[4] For further discussion of oolites see Brown, T. C., Origin of oolites and the oolitic texture in rocks: Geol. Soc. America Bull., vol. 25, pp. 745–780, 1914. Vaughan, T. W., Corals and the formation of coral reef: Smithsonian Rept. for 1917, pp. 217–219. Twenhofel, W. H., and others, Treatise on sedimentation, pp. 236–242, 533–543, 1926. (These authors cite numerous other references.)

would be marked by a discordance between the remnants of these eroded layers and the layers deposited upon them. (See fig. 18, B.)

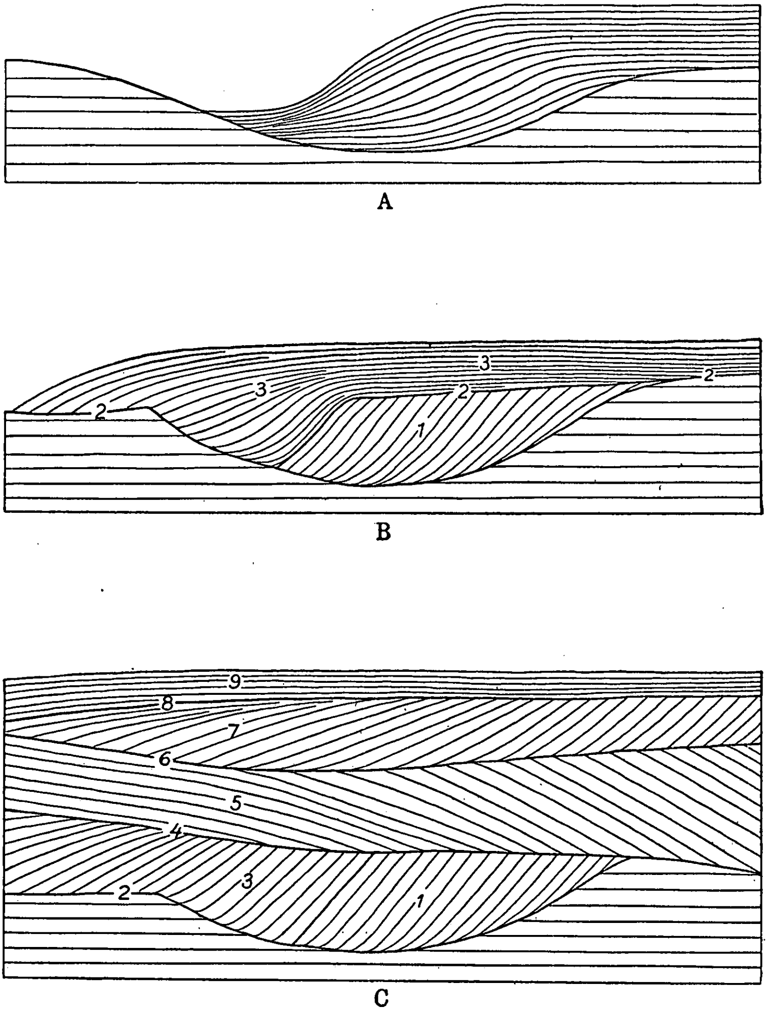

Figure 18.—Cross lamination. A, Cross lamination produced by deposition of sand in a depression from an essentially continuous current, each layer indicating slight changes in velocity. B, Cross lamination produced in two stages interrupted by a stage of erosion: 1, First stage of deposition, corresponding to A; 2, erosion surface; 3, second stage of deposition. C, Cross lamination produced in several stages by shifting currents: 1–3, Stages shown in B; 4, erosion surface beveling the laminae of both 1 and 3 and removing much of erosion surface 2; 5, cross laminae deposited in opposite direction from 1 and 3; 6, erosion surface beveling 5; 7, cross laminae parallel to 1 and 3; 8, erosion surface beveling 7; 9, horizontal laminae

A change in direction of prevailing winds with a corresponding change in direction of waves and currents may cause similar discordance in bedding. (See fig. 18, C.)

UNCONFORMITIES

Slight elevations or depressions of the land may have a similar effect by lessening or increasing the depth of shoal water with resulting increase or decrease in velocity of the waves and currents. More pronounced elevation may raise a considerable part of the newly deposited calcium carbonate sand above sea level and subject it to erosion by the pounding of surf and to erosion or solution by rain water. The surface of the formation thus becomes irregular, and single grains from it as well as fragments composed of several grains cemented together are washed into the new area of shoal water, to become incorporated in new strata. (See fig. 19.)

If subsidence again submerges the formation its eroded top marks a more or less definite boundary between layers deposited before elevation and those formed after subsidence. Such boundaries are more extensive and more conspicuous than the discordances of cross-bedding and are called unconformities. They are likely to be characterized by an abundance of fragments in the bottom layers of the new part derived from the topmost layers of the old part. Unconformities differ greatly in magnitude; several very minor ones may be present in a single formation, whereas greater ones may be accompanied by changes in deposition so marked that the older and the newer strata are recognized as distinctly different formations. This partial description of unconformities is presented to serve as a basis for explaining certain features of the Indiana oolitic limestone. For a more complete description the reader is referred to standard textbooks of geology.

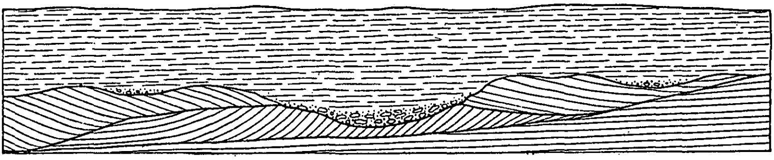

FIGURE 19.—Local unconformity. Fragments (pebbles and sand grains) eroded from the older formation accumulate in depressions and become incorporated in the lower beds of the younger, overlying formation

THE INDIANA OOLITIC LIMESTONE

NAMES OF THE FORMATION

The reports cited in the bibliography (p. 115) and others of less immediate interest disclose a number of different names for the same formation. This diversity in names is the natural outcome of progressive studies in different localities and from different points of view. The two principal points of view are (1) that of the geologist or stratigrapher, who desires an appropriate name applicable to formations of the same geologic age and characterized by certain index fossils, and (2) that of anyone interested in the commercial use of the stone.

Fossils collected from the oolitic limestone at Spergen Hill, Washington County, Ind., were described by James Hall[5] in a paper published in 1858, and since that time the beds that contain these fossils have been frequently called Spergen Hill beds and Spergen beds. As early as 1862 the oolitic limestone quarried at Bedford, Ind., became known to the building and quarry trade as the "Bedford rock" or "Bedford stone," and although the quarry rock has since that time frequently been called by other local names, such as "White River stone," "Ellettsville stone," and "Salem stone," the formation as a whole has become generally known to the trade as Bedford limestone, Bedford oolitic limestone, and Indiana oolitic limestone. In 1897, owing to the general usage of the term Bedford in a trade sense, the name Bedford oolitic limestone was proposed in a geologic time or stratigraphic sense by Siebenthal,[6] but the name Bedford had been firmly established since 1870 to designate a shale formation in Ohio, much older geologically than the oolitic limestone in Indiana. It was therefore proposed by Cumings,[7] in 1901, that the term Bedford limestone be replaced by "Salem limestone," but the United States Geological Survey, after considering all these facts, decided in 1904 to adopt the name Spergen limestone, because of its priority and significance, as the name of the formation containing the Spergen Hill fossils, which is underlain by the Warsaw limestone and overlain by the St. Louis limestone and which is widely distributed in Indiana, Illinois, Missouri, and western Kentucky and Tennessee.

Logan[8] took strong exception to this decision, as he in 1901 had proposed the name "Salem limestone," derived from that of Salem, the nearest town to the Spergen Hill bed and once famous for its quarries. He had considered and dismissed the name Spergen because of the small thickness and nontypical lithologic character of the outcrop at Spergen Hill, and because the geographic name Spergen Hill is entirely forgotten, even by the people of that locality. "Salem limestone" is the name officially adopted by the Indiana Department of Geology and Natural Resources and is synonymous with the name Spergen limestone of the United States Geological Survey.

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[5] Hall, James, Description of new species of fossils from the Carboniferous limestones of Indiana and Illinois: Albany Inst. Trans., vol. 4, pp. 1–36, 1858.

[6] Hopkins, T. C., and Siebenthal, C. E., op. cit., p. 298.

[7] Cumings, E. R., The use of Bedford as a formational name: Jour. Geology, vol. 9, pp. 232–233, 1901.

[8] Logan, W. N., op. cit., pp. 499–502.

So far as the stone industry is concerned, the name Salem is not favored, as no quarries of building stone have been operated near Salem for several years, although some development work was begun there in 1926. It is also maintained that the term Bedford is too local to include the active quarry districts of Clear Creek, Bloomington, Ellettsville, and Stinesville. The name "Indiana oolitic limestone" has therefore been adopted as most truly representative of the industry. As this report is mainly economic that name is herein used.

TIME OF DEPOSITION

The Indiana oolitic limestone was formed in the Meramec epoch of the Mississippian or lower Carboniferous division of geologic time, which was one of the later divisions of the Paleozoic era. During the Paleozoic era the area of the present continent was largely covered by extensive shallow seas, comparable to Hudson Bay. The major divisions of the Paleozoic era indicate changes in the distribution of these seas, due to elevation or depression of the land, each change marked by the prevalence of certain kinds of animal and plant life. Mollusks and brachiopods were by far the most characteristic animals of the different divisions and subdivisions of Paleozoic time.

The distribution of land and sea in North America during that part of Mississippian time when the Indiana oolitic limestone was deposited is approximately shown in Plate 28. The Mississippian epoch, according to Schuchert,[9] began with an extensive spreading of the sea, and the first half of it ended with an emergence of the land of wide extent. The next spreading of the sea was relatively small but is of economic interest because it brought about the deposition of the Indiana oolitic limestone. Other formations were deposited over this one, and the total thickness of strata ranged from 1,100 to 1,500 feet. These strata were repeatedly marked by oolitic texture, formed by the coating of Foraminifera and small shell fragments with thin layers of chemically deposited calcium carbonate, and were characterized by mollusks and brachiopods of unusually small size, known as the Spergen fauna because of their prominent development at Spergen Hill. During invasion by the sea the beds deposited were mainly limestones, some of them oolitic; during subsequent emergence beds of oolitic limestone were deposited between beds of sandstone; and the last stage of the Mississippian was marked by the deposition of shale and limestone, some of it oolitic.

These beds remained above the sea for a short interval before they sank beneath it and were covered by a great thickness of sandstone, shale, and coal during the Pennsylvanian epoch, when the principal

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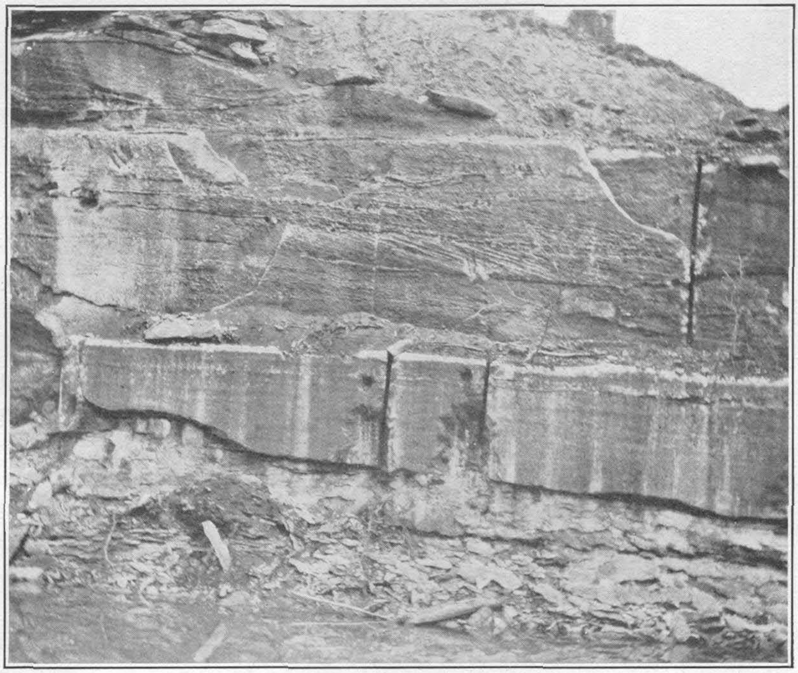
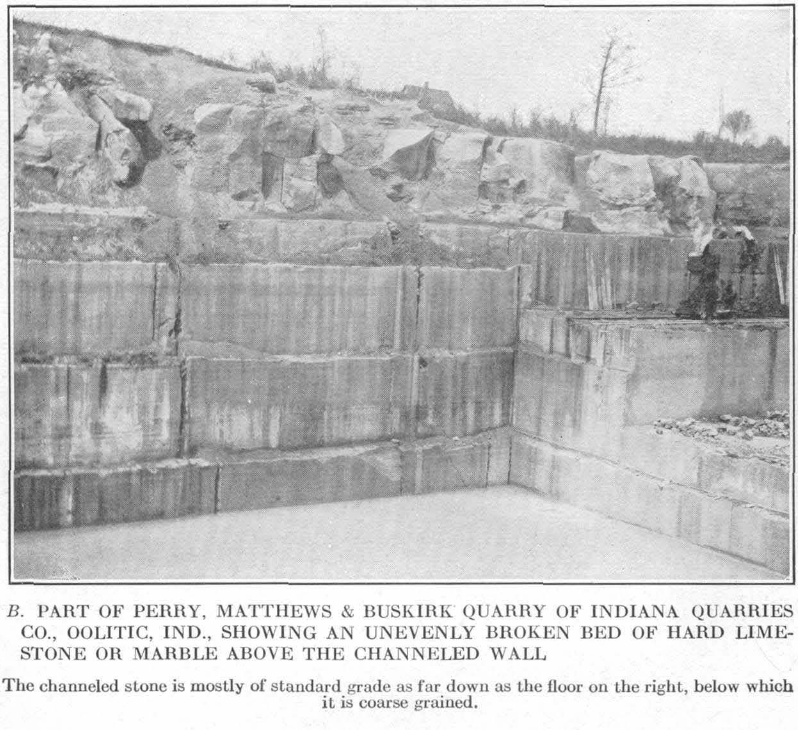
[9] Schuchert, Charles, Paleogeography of North America: Geol. Soc. America Bull., vol. 20, pp. 552-555, pl. 81, 1910; vol. 34, p. 221, 1923.

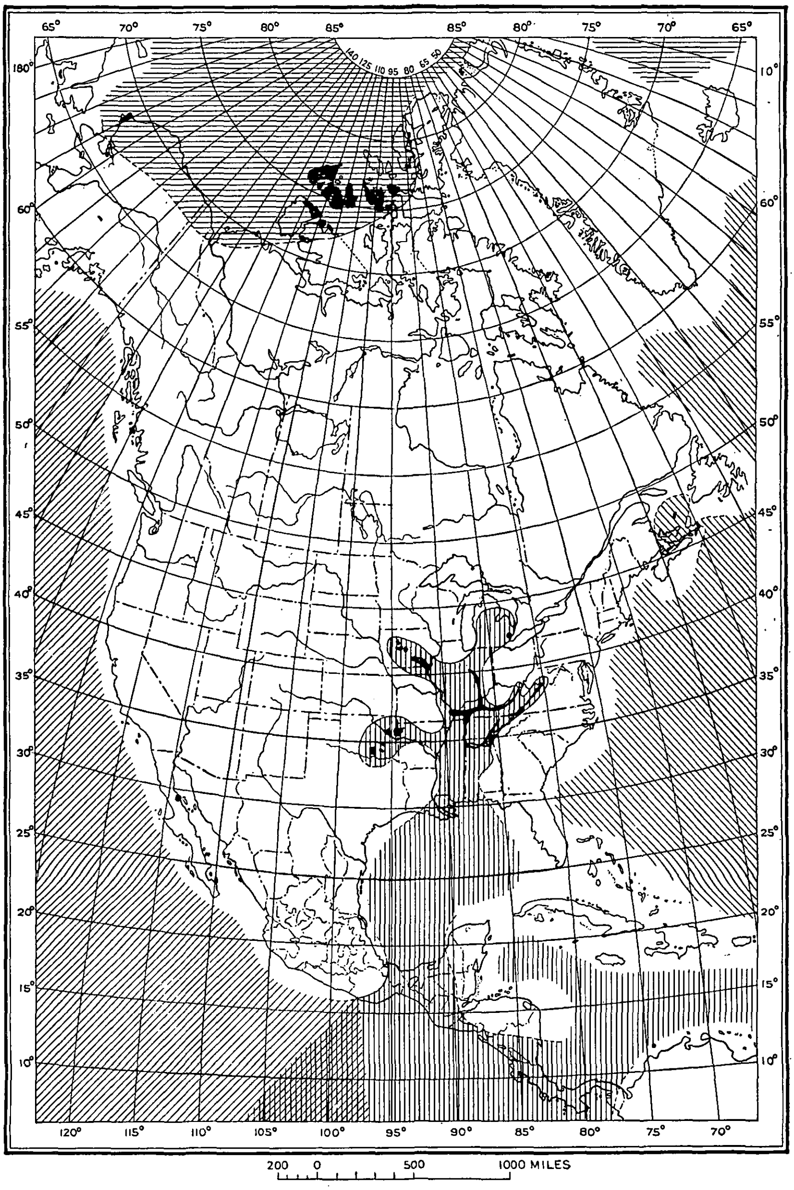


A. FACE OF ABANDONED QUARRY SHOWING CROSS LAMINATION ALONG A WEATHERED FRACTURE, ALSO SPALLING DUE TO FROST ACTION



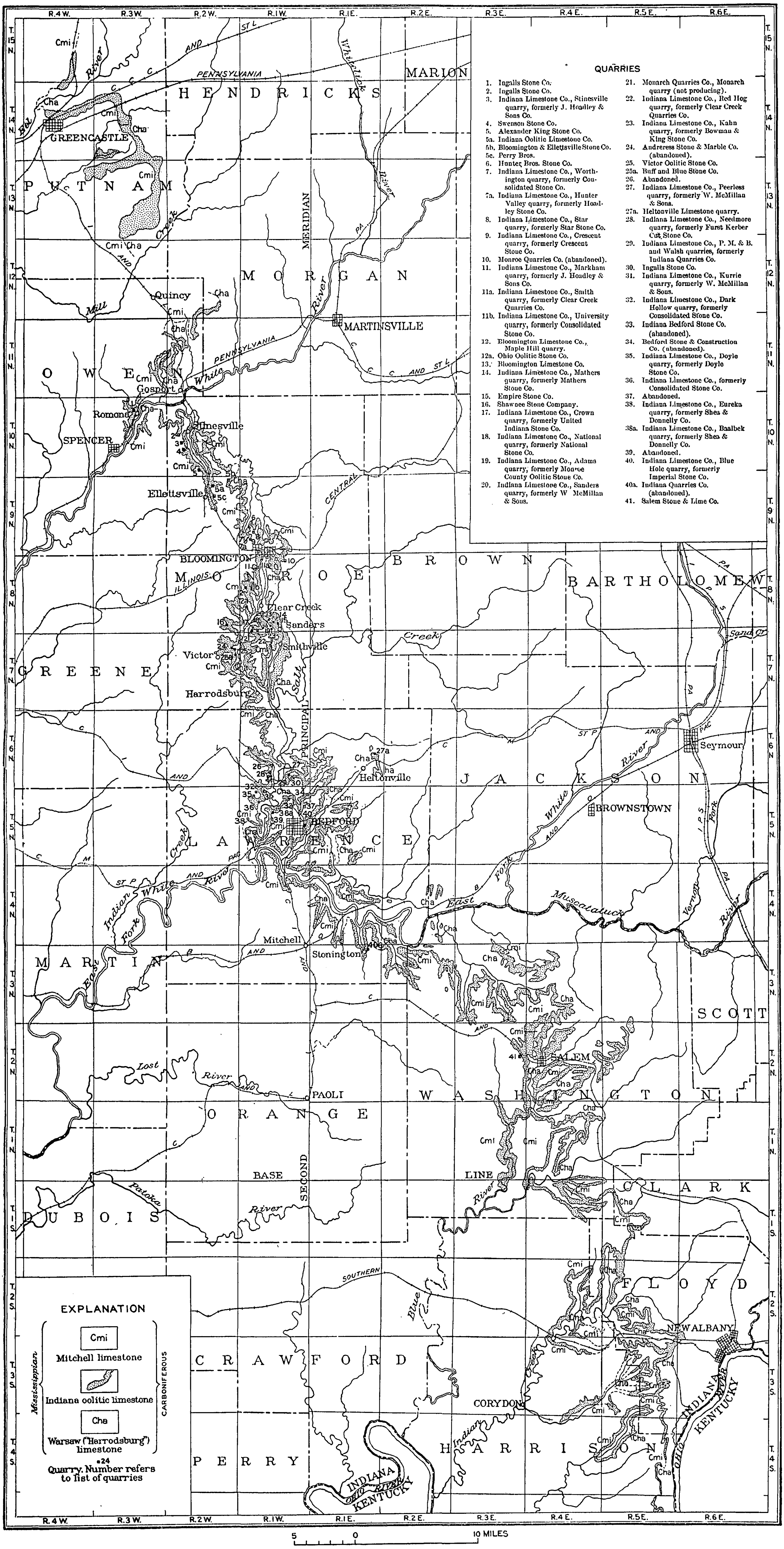
B. PART OF PERRY, MATTHEWS & BUSKIRK QUARRY OF INDIANA QUARRIES CO., OOLITIC, IND., SHOWING AN UNEVENLY BROKEN BED OF HARD LIMESTONE OR MARBLE ABOVE THE CHANNELED WALL

The channeled stone is mostly of standard grade as far down as the floor on the right, below which it is coarse grained.



MAP SHOWING THE PORTION OF EAST-CENTRAL NORTH AMERICA COVERED BY A SHALLOW SEA DURING THE PART OF THE MISSISSIPPIAN EPOCH WHEN THE INDIANA OOLITIC LIMESTONE AND CLOSELY RELATED FORMATIONS WERE DEPOSITED

After Schuchert. Solid black represents present exposed areas of these formations; vertical ruling represents approximate extent of the shallow sea; other ruling represents approximate marginal extent of Atlantic, Pacific, and Arctic Oceans at that time.



QUARRIES

1. Ingalls Stone Co.
2. Ingalls Stone Co.
3. Indiana Limestone Co., Stinesville quarry, formerly J. Hoadley & Sons Co.
4. Swenson Stone Co.
5. Alexander King Stone Co.
5a. Indiana Oolitic Limestone Co.
5b. Bloomington & Ellettsville Stone Co.
5c. Perry Bros.
6. Hunter Bros. Stone Co.
7. Indiana Limestone Co., Worthington quarry, formerly Consolidated Stone Co.
7a. Indiana Limestone Co., Hunter Valley quarry, formerly Hoadley Stone Co.
8. Indiana Limestone Co., Star quarry, formerly Star Stone Co.
9. Indiana Limestone Co., Crescent quarry, formerly Crescent Stone Co.
10. Monroe Quarries Co. (abandoned).
11. Indiana Limestone Co., Markham quarry, formerly J. Hoadley & Sons Co.
11a. Indiana Limestone Co., Smith quarry, formerly Clear Creek Quarries Co.
11b. Indiana Limestone Co., University quarry, formerly Consolidated Stone Co.
12. Bloomington Limestone Co., Maple Hill quarry.
12a. Ohio Oolitic Stone Co.
13. Bloomington Limestone Co.
14. Indiana Limestone Co., Mathers quarry, formerly Mathers Stone Co.
15. Empire Stone Co.
16. Shawnee Stone Company.
17. Indiana Limestone Co., Crown quarry, formerly United Indiana Stone Co.
18. Indiana Limestone Co., National quarry, formerly National Stone Co.
19. Indiana Limestone Co., Adams quarry, formerly Monroe County Oolitic Stone Co.
20. Indiana Limestone Co., Sanders quarry, formerly W McMillan & Sons.
21. Monarch Quarries Co., Monarch quarry (not producing).
22. Indiana Limestone Co., Red Hog quarry, formerly Clear Creek Quarries Co.
23. Indiana Limestone Co., Kahn quarry, formerly Bowman & King Stone Co.
24. Andreress Stone & Marble Co. (abandoned).
25. Victor Oolitic Stone Co.
25a. Buff and Blue Stone Co.
26. Abandoned.
27. Indiana Limestone Co., Peerless quarry, formerly W. McMillan & Sons.
27a. Heltonville Limestone quarry.
28. Indiana Limestone Co., Needmore quarry, formerly Furst Kerber Cut Stone Co.
29. Indiana Limestone Co., P. M. & B. and Walsh quarries, formerly Indiana Quarries Co.
30. Ingalls Stone Co.
31. Indiana Limestone Co., Kurrie quarry, formerly W. McMillan & Sons.
32. Indiana Limestone Co., Dark Hollow quarry, formerly Consolidated Stone Co.
33. Indiana Bedford Stone Co. (abandoned).
34. Bedford Stone & Construction Co. (abandoned).
35. Indiana Limestone Co., Doyle quarry, formerly Doyle Stone Co.
36. Indiana Limestone Co., formerly Consolidated Stone Co.
37. Abandoned.
38. Indiana Limestone Co., Eureka quarry, formerly Shea & Donnelly Co.
38a. Indiana Limestone Co., Baalbek quarry, formerly Shea & Donnelly Co.
39. Abandoned.
40. Indiana Limestone Co., Blue Hole quarry, formerly Imperial Stone Co.
40a. Indiana Quarries Co. (abandoned).
41. Salem Stone & Lime Co.

MAP SHOWING EXTENT OF THE INDIANA OOLITIC LIMESTONE IN INDIANA

Prepared from a geologic map published by the Indiana Department of Geology and Natural Resources in 1901.

coal deposits of the country were formed. At the end of the Pennsylvanian, when the great upheaval that developed the Appalachian Mountains with their folded or upturned strata took place in the region of the Eastern States, the region including the Central States was also elevated, but with only a slight tilting or warping of the strata, which preserve to-day the attitude they then received. Ever since that time the region has been above sea level and subjected to continuous erosion by frost action, chemical weathering, and stream cutting, until the overlying rocks have been removed from extensive areas and the Indiana oolitic limestone has been exposed and partly worn through, so that to-day it is at the surface, mainly along the slopes of hills, from Greencastle, Ind., southward into Kentucky.

EXTENT OF PRESENT EXPOSURES

The exposures of the oolitic limestone have been mapped by Hopkins and Siebenthal [10] over a considerable part of south-central Indiana and more recently on a larger scale by Beede [11] in the Bloomington quadrangle, which extends from Ellettsville on the north to Harrodsburg on the south.

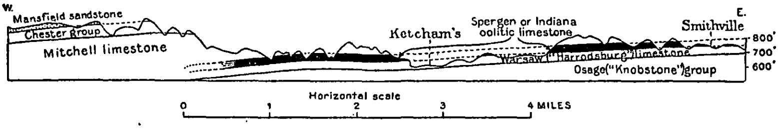


FIGURE 20.—East-west section through Smithville, Ind., showing westward dip of the Indiana oolitic limestone and its relations to overlying and underlying strata

The same formation has been studied and mapped in southern Indiana by Ashley [12] and Newsom,[13] and the results of all this work have been compiled on the geologic map of Indiana,[14] a part of which is reproduced on a small scale in Plate 29.

This mapping has shown that the Indiana oolitic limestone lies horizontal or slopes westward at very low angles, not more than 70 feet to the mile and averaging 50 to 60 feet to the mile, according to Hopkins and Siebenthal, and 34 feet to the mile, according to Beede.[15] The position of the oolitic limestone and its relations to the overlying and underlying strata in the southern part of the Bloomington quadrangle are shown in Figure 20, which is compiled from Beede's geologic map.

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[10] Hopkins, T. C., and Siebenthal, C. E., op. cit., pp. 350, 376. (The map is reprinted in Indiana Dept. Geology and Nat. Res. Thirty-second Ann. Rept., 1908.)

[11] Beede, J. W., and others, op. cit., p. 190.

[12] Ashley, G. H., op. cit., p. 83.

[13] Newsom, J. F., op. cit., p. 281.

[14] Geological map of Indiana, W. S. Blatchley, State geologist · compiled by T. C. Hopkins, 1901–1903; scale, 4 miles=1 inch.

[15] Beede, J. W., and others, op. cit., p. 190.

The map and section apparently indicate a practically unlimited quantity of stone in the formation. Even the small fraction of it accessible under present methods of quarrying would last for centuries, were it all readily salable; but the stone differs from place to place in texture and to a certain extent in degree of soundness as well as thickness; and a considerable portion of it is too thin for economical quarrying or has not met the requirements of architects and builders where great uniformity in appearance is desired. Extensive prospecting with the drill has been conducted by a few companies, and it has been stated informally on the basis of this prospecting that really large supplies of the uniformly very fine grained stone, which has been popularly regarded as the most desirable, constitute only a fraction of the total quantity readily available for quarrying; but no data have been compiled to show even approximately the ratio of this stone to the whole in undeveloped areas. Factors determining the commercial quality of the stone are discussed on pages 181–186.

The formations above and below the Indiana oolitic limestone and their thicknesses are set forth below, the oldest formation at the bottom of the list.

Carboniferous formations of southern Indiana

		Feet
Pennsylvanian ("Coal Measures"):		
Sandstone, shale, and limestone (thickness from Hanover across to Vincennes)		800
Mansfield sandstone		0–280
Unconformity.		
Mississippian:		
Chester group—		
Limestone, sandstone, and shale; thickest in southern Indiana		43–600±
Limestone at base	Mitchell limestone	150–400
Chester or Meramec group—		
Ste. Genevieve limestone.		
Meramec group—		
St. Louis limestone		
Spergen limestone (Salem limestone of Indiana Department of Geology and Natural Resources; Indiana oolitic limestone of the trade)		20–100
Warsaw ("Harrodsburg") limestone		60–140
Osage ("Knobstone") group		40–650
Rockford ("Goniatite") limestone		1–3

GENERAL FEATURES OF THE INDIANA OOLITIC (SPERGEN) AND ADJACENT LIMESTONES

For the benefit of those interested in the quarries the following brief descriptions of formations immediately below and above the Indiana oolitic limestone are given.[16]

WARSAW ("HARRODSBURG") LIMESTONE

The Warsaw or "Harrodsburg" limestone in its lower part is a very coarse-grained rock characterized by remnants of crinoids ("sea lilies"). Its middle portion is finer grained, and near the top it has much the same character as the Indiana oolitic limestone, so that inspection with a lens may be necessary to distinguish the two by means of the small fossil fragments contained. The upper 10 to 15 feet of the formation is composed largely of comminuted bryozoan remains with some indeterminate elongate particles. At the bridge over the Monon Route between Smithville and Sanders the Warsaw and Indiana oolitic limestones are separated by a stylolite or "crowfoot" seam. In many places they are separated by a brownish bituminous marl (very fine-grained argillaceous limestone), which locally replaces the base of the oolitic limestone. At other places it is difficult to locate the boundary within 2 to 6 feet. The bituminous marl is found below the oolitic limestone in some places, above it in others, and both above and below it in still others. Locally the oolitic limestone pinches out, leaving only the bituminous marl.

MITCHELL LIMESTONE

The Mitchell limestone, which overlies the oolitic limestone, is sharply distinguished from it where the two are exposed in quarries. It is bluish gray, except where it is oxidized to light brown along fractures and open bedding planes, and is very fine grained, in part resembling lithographic stone, in part containing oolites, and in part brecciated (composed of angular fragments cemented by a matrix). It also contains beds of sandstone and shale, and many stylolites, or "crowfeet." Its lower 40 feet contains considerable shale and marl, above which lies stone of lithographic appearance overlain by shale. Above this shale is cherty and fossiliferous rock, and above that, in ascending order, oolitic rock with quartz grains, hard oolitic rock, and finally in places sandstone and shale.

SPERGEN LIMESTONE (INDIANA OOLITIC LIMESTONE)

GENERAL CHARACTER

The Indiana oolitic limestone is characterized by its pale to medium buff color above ground-water level and its gray or bluish-

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[16] Abstracted from Beede, J. W., and others, op. cit., pp. 195, 204.

gray color below. It has a granular texture and commonly a cross-bedded structure. The grain of the usual salable stone ranges from fine (less than 1 millimeter in diameter) through medium (1 to 3 millimeters) to coarse (greater than 3 millimeters). Some stone contains considerable very fine grained or dense material, either as a matrix for the visible grains or in layers or streaks between granular layers. The constituent grains include an abundance of Foraminifera and small fragments of crinoid stems with poorly defined oölitic coatings, which are characteristic throughout its thickness. The coarser-grained varieties include distinct fragments of brachiopod, pelecypod, and gastropod shells, Bryozoa, and corals. Ostracodes are said to be characteristic of the stone as a whole, but few if any have been noted in specimens examined microscopically by the writer. Layers or small lenses of unusually well-developed oolitic grains are present in the coarser-grained stone, and layers of minute well-formed oolitic grains are also present in the very fine grained and dense stone.

CONDITIONS OF DEPOSITION

Fossils.—Comparison of the contained fossils, the oolitic character, and the cross-bedded structure with the similar features of the recently formed oolitic limestones throws considerable light upon the conditions existing when the Indiana oolitic limestone was deposited. The land at that time was low and flat and consisted mainly of newly formed limestone. Drainage from the land was sluggish and contributed little coarse sediment; neither did it contribute appreciable quantities of siliceous sand or clay. The sea was shallow and saturated with calcium carbonate, but, except at the beginning and end of the period, it was deficient in food supply and in other conditions that would have favored the normal growth of mollusks. Because of these conditions fossil mollusk shells of normal size occur only in the top and bottom beds of the limestone. Throughout the rest of the formation the mollusk shells, though similar in other respects to those in the Warsaw ("Harrodsburg") and Mitchell limestones, are dwarfed and scarce, whereas Foraminifera are very abundant. As generation after generation of these small animals died, their shells settled to the shallow bottom, where calcium carbonate precipitated from the sea water, with or without the aid of bacteria, formed oolitic skins around them. The coated shells in part remained where they settled, but a great proportion of them were rolled back and forth by waves or swept along by currents. The small shells and sections of crinoid stems, protected by films of water, largely escaped being broken by grinding together in the moving water and owing to their flat surfaces and thin dimensions were floated along and deposited among the Foraminifera. Larger shells were more liable to break, and fragments from them were also deposited among the unbroken finer material.

Effects of cross-bedding.—Where periods of agitation alternated with periods of quiet, the granular or cross-bedded stone formed alternating layers with chalky, calcareous "mudstone" or marl. This alternation is conspicuous in the topmost part of the formation in several quarries, and the stone that contains it is discarded by the quarrymen. Where increasing distance from shore was accompanied by deepening water, the granular cross-bedded stone graded into the marl, and beyond this zone of gradation only marl was deposited. Where deposition took place in landlocked bays or lagoons comparatively small bodies of the marl accumulated, practically surrounded by cross-bedded granular material. Owing to changing conditions at any one place, first one kind of material and then the other may have been deposited, and the marl is therefore found above the cross-bedded stone in some places, below it in others, and both above and below in still others.

Beede concluded, from his studies in the Bloomington quadrangle[17] and elsewhere, that the stone of commercial quality forms a series of great lenses embedded in the marl, which commonly contains considerable bituminous matter derived from decaying organisms. Surface exposures are insufficient for separate mapping of the typical commercial limestone and the marly material, and Plate 29 shows the extent of the formation as a whole. Prospecting with the diamond drill is necessary to determine undeveloped areas of commercial stone. A great amount of drilling has already been done, but few if any adequate records have been kept, and therefore no estimate of the reserves of commercial stone can be given.

So long as the particles were moved about by currents and waves they remained loose calcareous sand, but when they became sufficiently covered by further accumulations of the sand to rest undisturbed, a matrix or filler of calcium carbonate precipitated from the sea water gradually grew in the crystalline form of calcite, binding the grains together and filling a considerable part of the interstices within and among them. It is a common law of chemistry that precipitation from a saturated solution is hastened by insertion of a crystal or fragment of the material to be crystallized. Slowly precipitated material, if not agitated, tends to grow as an enlargement of this nucleus, the two forming a single crystal, and the compound origin is not recognizable unless the presence of some impurity in the nucleus serves to distinguish it. If deposition is very rapid or accompanied by agitation of the solution, several small crystals will develop instead of one large one, but these may, if left immersed for

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[17] Beede, J. W., and others, op. cit., pp. 204–205.

a sufficient time, recrystallize into one large crystal, yielding the same result that would come from slow undisturbed growth.

In the typical varieties of Indiana oolitic limestone the shell fragments and oolitic skins are largely converted into crystalline grains of calcite, which preserve the original markings but not the original structure. The matrix, in growing as enlargements of these crystalline grains, has formed interlocking contacts characteristic of the grains of marble. Where the matrix has completely filled the pores the stone has the properties of marble, but for the most part a considerable degree of porosity remains. In the more marly varieties of the stone, which are avoided by quarrymen, this process of crystallization took place only to a minor degree, and the soft, chalky character of the matrix remains. In the examination of stone from undeveloped ledges the character of the matrix, whether recrystallized and sound or still chalky and subject to rapid disintegration, is of critical importance.

The process of deposition produced some interesting changes in the character of stone found within a single quarry. For example, at one of the former Indiana Quarries Co.'s large openings coarse-grained cross-bedded stone is present in the lower part of the formation at one end of the quarry and grades into medium and fine grained stone toward the middle; at the other end coarse-grained stone, with cross-bedding dipping in an opposite direction, is found in the upper part and grades into finer material toward the middle. Such variations in texture both horizontally and vertically are duplicated to a greater or less extent in many places.

The effect of cross-bedding generally is to add a certain degree of variation and distinctive character to an otherwise uniform and monotonous appearance. The strength and durability may or may not be affected, the determining factors being the composition of the stone, the thoroughness of its cementation, and other details of deposition. Where cross-bedding is produced by continuous deposition, by which the inclined layers or " foresets " become gradually covered with horizontal layers or "topsets," as shown in Figure 18, A, there is a perfect bond to the layers; where the inclined layers were beveled by erosion before being covered by horizontal or differently inclined layers, as shown in Figures 18, B and C, the boundary is firmly bonded if the grains and cement in both parts are of uniform composition and texture; if the boundary is marked by a film of fine shaly or marly material, as in a few rather remote openings in the Indiana oolitic limestone, the bond is weak, the stone will readily split along it, and if exposed to the weather the fine material will weather rapidly.

So far as noted in buildings and in quarry blocks ready for shipment, cross-bedding in the Indiana oolitic limestone is practically without exception free from partings or marly films. One quarry block was noted where the contact between two sets of layers was incompletely cemented for a few inches, and this exception may serve as a warning for quarrymen and inspectors to look out for weakness along cross-bedding contacts; but as a few cracks have been seen in inferior blocks without cross-bedding, experience has proved that Indiana oolitic limestone with cross-bedding is quite as durable as that without it.

On a few old buildings—for example, in the steps of the State capitol at Indianapolis—partings or cracks have opened between inclined layers in several stones, indicating that at some places fluctuation in currents was so extreme that after deposition of a layer of ordinary coarseness the water remained still long enough for a film of "limestone mud" or "marl" to be deposited before the next normal layer. These cracks also suggest that the stone was used without proper seasoning. The quarry or district from which this stone was taken is not known, but the defect shown by it is a rare exception. The detection of mere films of marl or of imperfectly cemented layers in newly quarried blocks is not easy, but if the blocks are thoroughly seasoned—that is, if their original quarry water or "sap" has been entirely dried out of them—before use, such undesirable features may become apparent or may be detected by the resonance test. A well-consolidated stone free from such imperfections will ring when struck by the hammer, whereas one whose resonance is decreased or destroyed by such imperfections gives a dull or "dead" sound. This test, however, is not infallible, as it is conceivable that a stone containing much of the finest-grained material may be sufficiently consolidated to ring when struck by a hammer, though it may still retain moisture sufficiently to be injured by frost.

Effects of local unconformities.—At intervals during the deposition of the Indiana oolitic limestone slight elevation brought recently consolidated deposits up to a level where they could be eroded by waves or currents. Fragments were broken from these beds, moved short distances, and incorporated in a new layer of sediment. The distance of movement of some fragments was so slight that a single quarry block may show both the fragment and the scar where it was removed from the eroded surface. It is not known at how many places such old erosion surfaces or unconformities occur, but blocks that contain these features have been seen in several buildings, most of them in positions where they are not conspicuous but some of them in very conspicuous places. An old erosion surface is said to occur at the bottom of the Doyle quarry, in the Dark Hollow district, and blocks showing an unconformity were also seen in a stock pile of coarse-grained stone at a quarry in the Sanders section of the district. (See fig. 21.) Another local unconformity was noted in the Peerless quarry. (See fig. 22.) The conspicuousness of such unconformities argues against their indiscriminate inclusion in quarry-run material of any regular grade, but they may be properly included in an off-grade or special stock, such as that called "old Gothic," a name recently adopted by the Indiana Limestone Quarrymen's Association to designate stock that includes all sound varieties of stone in the Indiana oolitic limestone. Exceptional examples have been seen of their effective use as matched blocks for certain purposes.

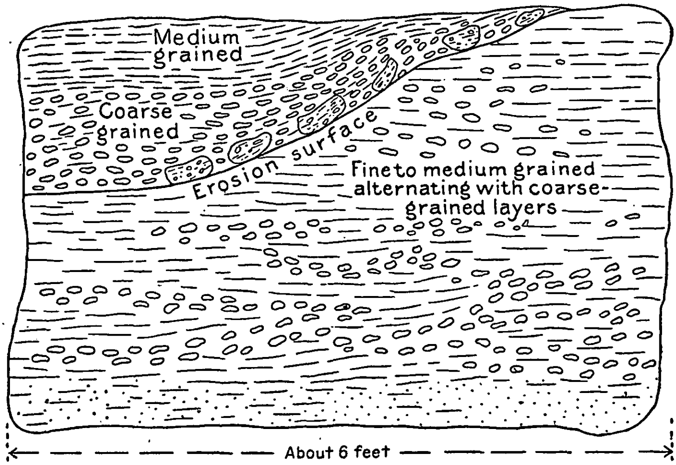

FIGURE 21.—An unusual quarry block from the Empire quarry, Sanders district, Indiana, showing a local erosion surface or unconformity. Scattered fragments from the stone below are incorporated in the lowest layers of the stone above

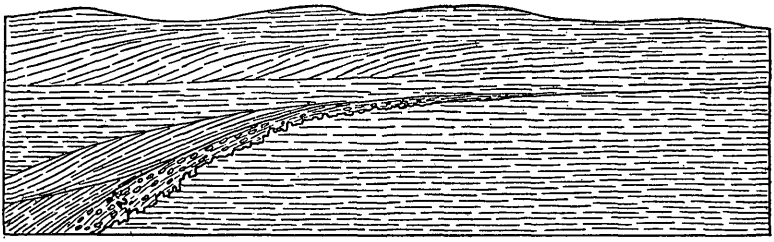

FIGURE 22.—Upper channeled walls in part of Peerless quarry (1917), 4 miles north of Bedford, Ind., showing a local unconformity along which there is a prominent "crowfoot" seam. It marks the margin of a channel eroded in stone of standard to select grade, which is abruptly cut off by a coarse-grained bed that contains many large shells and is of no value, unless for "old Gothic" stock. The coarse-grained bed is overlain by stone of commercial quality but more conspicuously cross-bedded than the stone below the unconformity

The presence of such an unconformity is no indication of the durability of the stone. Some of these blocks that have been seen are weathering very well; on the other hand, others that contain poorly cemented or marly material along the unconformity show cracks or crumbling of the surface. A few of the blocks used in the coping on the parapet wall around the roof of the Industrial Building of the Bureau of Standards, at Washington, erected in 1919, are of this inferior kind, whereas similar stone on the roof of the Interior Department Building, erected in 1917, has, on the whole, weathered satisfactorily. The use of stone of inferior weathering quality in positions where it is protected and does not mar the appearance or affect the permanence of the structure is not to be condemned, as its quarrying along with the regular quarry run of the ledges is necessary, and therefore the proper utilization of this stone materially lowers the cost of the stone to the builder.

Microscopic features of typical varieties.—Microscopic features of the different varieties of the stone are illustrated in Plates 30–33, which represent thin sections prepared for study with the petrographic microscope. As a thin section is only 0.03 millimeter or 0.0012 inch thick, allowance must be made in nearly every one for the tearing out of a considerable part of the grains and matrix during cutting and grinding.

Plate 30, *A*, represents a very fine-grained buff stone submitted by one company as extra fine and uniform grained stone of statuary or AA grade. The white areas are holes where grains and matrix have been torn out by grinding. The dark particles, so far as they can be identified, are shells of Foraminifera smaller than the average. Their actual average diameter is less than half a millimeter. Their dark color is due to brown bituminous matter derived from the soft parts of the organisms. The oolitic coatings or " skins " are inconspicuous, although such coatings may have formed and later been destroyed by recrystallization into the calcite matrix. The calcite matrix is represented by the light-gray material, which binds the dark grains together and even incloses some of them. Examination of this stone by the petrographic microscope with crossed nicol prisms shows that recrystallization has converted the different areas of matrix and the inclosed or adjacent dark grains into single crystals of calcite. The large oval area is a section of a complete brachiopod shell, which owing to its hollowness was moved by waves and currents as easily as the fine grains. The light-gray lining of its interior is calcite. Had the deposition of calcite continued until the shell was filled, a " glass spot " would have been developed; as it is, a small shell hole or pit about 2 millimeters (one-twelfth inch) in diameter is present. Such holes and " glass spots " are very few in so fine grained a stone, but they can be expected to occur here and there, from the very nature of the stone. The fact that this shell has remained intact, even in a section so thinly ground, is proof that it is no source of weakness, and the fact that it has not been filled with calcite indicates that it is thoroughly sealed by the calcite matrix and does not increase the percentage of absorption of water, even though it does increase the amount of porosity.

Plate 30, *B*, represents a light-gray stone from the former Shea & Donnelly quarry. It is a coarser-grained stone than that represented by Plate 30, *A*, and most of its grains are from 1 to 2 millimeters in diameter. Its gray color is due to finely divided black bituminous matter within the grains. It shows near the top a broken brachiopod, whose interior contains five oolite grains. The oolites show clearly their nuclei (small fossil fragments) and thick skins composed of several layers. They are exceptionally well developed and preserved compared with the average oolite in Indiana oolitic limestone. These oolites are cemented by well-crystallized calcite. The outside of the brachiopod also has an oolitic coating, which has recrystallized. Coatings around most of the other grains are not evident. The shell with concentric black lines in the center of the plate is a foraminifer (*Endothyra*), and the round snail-like shell at the left is a dwarf gastropod. The triangular white-spotted grain in the lower right corner and a similarly marked one near the upper left corner are fragments of crinoid stems. The finely speckled round, rectangular, and angular grains are fossil fragments whose identifying marks have been removed during grinding of the section. The long, narrow, somewhat curved grains are fragments of brachiopod or pelecypod shells. The interstitial calcite (light grayish white) is typically developed where not destroyed during grinding of the section.

Plate 31, *A*, represents a dark-gray stone, also from the Shea & Donnelly quarry, whose color is due to the greater number of grains that contain or are bordered by jet-black bituminous matter. The conspicuous grains average about 1 millimeter in diameter. The solid black elongate grain in the upper right part and the small black grains in the lower left part represent the mineral pyrite, a yellow disulphide of iron. Pyrite is unusually prominent in this plate, and special attention is drawn to it because some have supposed that the color of the gray or "blue" stone has been derived from it, and that the brown coloring matter of the buff stone has been derived from the iron oxide limonite, which has formed through oxidation of pyrite; but the scarcity and irregular distribution of pyrite, even in this specimen, as compared with the uniform abundance of black bituminous matter, show clearly that the color of the stone is due mainly to the bituminous matter. The black bituminous borders around some of the grains, when more strongly magnified, have the structure of miniature stylolites or "crowfeet." (See p. 135.)

Plate 31, *B*, represents a gray stone in which the oolitic texture is unusually well developed, but even here the oolitic growth forms only a thin skin around the original shells. The firm bond between the skins and the calcite matrix is demonstrated where they have remained intact, but the original shells, especially in the lower part of the plate, have dropped out during grinding of the section. The holes in this plate appear black because the photograph was taken between crossed nicols. The inferior cohesive strength of the original shells is attributed to the bituminous matter contained in them. It is a characteristic of several if not most oolitic limestones. A curious feature about this unusually well developed oolitic growth is that it is found mainly in stone that contains so many large shell fragments and hard streaks of calcite or films of marly material that it is discarded from the regular grades of building stone. Even in the absence of the large shells and of unsound marly films, this stone contrasts so strongly with the average stone that it is either classified as cull stock or is discarded. In other words, the ordinary commercial building grades of Indiana oolitic limestone are those in which the oolitic texture is not really conspicuous.

Plate 32, *A*, represents coarse uneven-grained buff stone in which large elongate fragments of shells have been further enlarged by the growth of interstitial calcite. The large speckled fragment of shell and the nearly white interstitial calcite are now parts of one crystal, whose growth has inclosed a few fragments of a bryozoan (*Fenestella*), which have some resemblance to the oolitic grains in this plate. Long sections of this bryozoan, resembling rows of oolite grains, constitute a large part of this thin section. The contrast in appearance between this stone and those shown in preceding plates is directly due to the difference in weathering effects. Whereas the finer uniform-grained stones show very little roughening of the surface after many years of exposure, coarse uneven-grained stone, like that shown in Plate 32, *A*, is conspicuously roughened. The reason is that the finer, more porous grains are more readily corroded by weathering, as they are more easily penetrated by water and therefore present more surface to attack, whereas the large, impervious, well-crystallized grains present only their outer surface to attack. Corrosion is progressing on small and large grains alike, but by the time the small grains are completely corroded the effect on the surface of the large grains is inconspicuous, and they are left in relief; in fact, it requires this unevenness of grain to emphasize the effects of weathering. The finer uniform-grained stone weathers as a whole as rapidly as the finer layers of the uneven-grained stone but so uniformly that the effects of weathering are not so noticeable. Study of a great number of buildings shows that under the severe attack by the atmosphere of smoky cities, weathering effects on uneven-grained stones are noticeable on close inspection after 15 to 20 years; but even after 40 years the extreme depth of corrosion of the fine-grained layers is not more than 1.5 millimeters, or one-sixteenth inch. In finer even-grained stone the weathering has been so uniform that details of tool work are about as conspicuous as when the stone was placed in the building.

Plate 32, *B*, represents a medium-grained buff stone of standard grade, more thoroughly cemented and therefore somewhat harder than the average. This section was purposely cut somewhat thicker than the others to help preserve the matrix. The original grains range from less than half a millimeter to more than 2 millimeters in length, and their enlargement by interstitial growth of calcite gives a somewhat coarser-grained effect to the unaided eye. The interlocking character of the enlarged grains is shown by their thin dark boundary lines.

Plate 33, *A*, represents a very hard stone from the top bed of an abandoned quarry northeast of Bedford, formerly operated by the Bedford Stone & Construction Co. The superior hardness is due to complete filling of interstices and of pores within the original shells by the crystallization of calcite. The enlarged and interlocking crystal grains are especially well shown in the central part of the plate. Crystallization is so complete that this stone has the properties of marble. It takes a good polish, although its appearance when polished is monotonous and not distinctive, and it is particularly suited for steps, tiles, and other forms that must withstand abrasion. The finely speckled grains of various shapes are fragments of crinoid stems. The elongate dark grains with oblique white lines in the upper right quarter are probably dwarf gastropods. The long curved grain in the lower right quarter is a fragment of a bryozoan. Other fragments of fossils are too poorly preserved to be identified. The small, unevenly scattered jet-black grains are pyrite.

The illustrations that form Plates 30–33 show certain typical details. The actual area of the material that they represent, less than 1 square inch, is far too small to illustrate any of the grades of stone as a whole, although the difference in uniformity and average size of grain in the statuary (AA), select (A), standard (B), and rustic (C) grades can be appreciated. The extra-coarse grained stone with many large cavities, called "Indiana travertine," has no special microscopic features that have not already been illustrated. Although called travertine because of its cellular character, which has some resemblance to that of the Tivoli or Roman travertine, this stone is not a true travertine in origin. True travertine is of strictly chemical origin, with or without the aid of bacteria, and is formed by the deposition of calcium carbonate from saturated spring water, either

travertine

in the conduits of the spring or on the ground over which the run-off from the spring flows. The "Indiana travertine" has the same origin as the typical Indiana oolitic limestone and differs only in the possession of comparatively large shells with unfilled interiors or of conspicuous cavities that have been dissolved out by circulating water close to fissures or mud seams above the level of ground water. The beds that contain considerable quantities of such large shells are confined to the uppermost and lowest parts of the formation. The characteristic cavities, however, may not be present in all such beds. For example, the bed just below the lowest quarried floor of the Peerless quarry contains large shells, but its openings are completely filled and it is so thoroughly crystallized that it is practically a marble. So far as seen in the quarries the "Indiana travertine" is found only at intervals in the upper part of the formation. Conditions at the quarry of the Bedford Stone & Construction Co., and to a less extent in certain quarries in other parts of the district, favored the development of hard stone at the top of the formation. The development of a hard top bed is probably due to the presence of an impervious bed at the base of the overlying Mitchell limestone, whereas the "travertine" character was preserved or developed where such impervious beds were absent and circulation of ground water was free.

FEATURES DEVELOPED SHORTLY AFTER DEPOSITION

Styolites or "crowfeet."—Styolites or "crowfeet" are peculiar dark-gray to black zigzag markings in certain limestones and marbles. They differ somewhat in composition. Some consist mainly of shale or consolidated clay with more or less organic matter; some contain finely divided dark-green grains of chlorite or related iron silicates; others consist mainly of black bituminous matter. Small quantities of pyrite may also be present and through oxidation impart a rusty color to the stylolites in outcrops or close to the surface.

The stylolites in the Indiana oolitic limestone consist mainly of black bituminous shaly matter and irregularly distributed pyrite. They occur mostly at the top and bottom of the formation but also locally within it and lie along boundaries between certain beds. At a few places, notably the abandoned quarry at Stonington, which was formerly owned by the Indiana Quarries Co., they are unusually abundant and follow undulating courses, as shown in Plate 34. Plate 34, *A*, is a general view of the quarry wall. The thin-bedded cap rock is the basal part of the Mitchell limestone. The undulating dark lines along the smooth, channeled walls are "crowfeet," whose abundance was a principal cause of this quarry's abandonment, for it was impracticable, if not impossible, to obtain blocks of commercial size that were not disfigured by one or more "crowfeet." Plate 34, *B*, is a close view of a few prominent "crowfeet" which have weathered out and left grooves in the channeled wall. Cross-bedding is also shown, and it may be noted that no set of beds crosses a "crowfoot."

Plate 33, *B*, is a microscopic view of a "crowfoot" in gray fine-grained, well-cemented stone taken from the Blue Hole quarry, at Bedford. The zigzag and interlacing character is well shown here and also the tendency for the black material to be comparatively thick at the apex of each "finger" and thin along its sides. The rapid weathering out of the thick portions intensifies the original disfigured appearance and has barred stone with prominent "crowfoot" markings from stock for the ordinary run of cut stone; but such stone has been used extensively of late years for the rougher kinds of work, such as sawed masonry facings.

In some building stones, notably the pink and gray marbles of the Knoxville district, Tennessee, "crowfeet" are numerous and follow undulating courses, as in the stone at the Stonington quarry, which is illustrated in Plate 34, but they are as a rule so thin and the stone containing them is so thoroughly crystallized that they have become a specially attractive feature in the appearance of the stone. Where they are locally thick and retain their shaly character, however, they fail to take a polish and weather rapidly in marble used out of doors.

Further reference to Plate 33, *B*, will show that both shells and matrix are sharply cut off along the boundaries of the "fingers" and that no corresponding parts of them are found across the boundary. Opposite-pointing "fingers" are parts of distinct layers that have been dovetailed into each other but in such a way that neither shows any deformation due to compression.

The origin of stylolites or "crowfeet" has interested and puzzled geologists for many years, and different interpretations have been offered, but the most satisfactory one is that the stylolites were formed by the differential solution of limestone by ground water along certain bedding planes and fractures while the pressure of the superincumbent beds closed the spaces produced by solution as fast as they were formed. The differential character of the solution process was due to the greater resistance to solvents by the larger and more crystalline grains and the more thoroughly cemented portions of the adjacent beds. Solution was most successfully resisted at certain points along one bed and at other points along the adjacent bed, so that, as the process went on these resisting points were gradually pushed into the cavities opposite them by the weight of the overlying rock. The most recent and thorough discussion of the origin of stylolites is given by Stockdale,[18] who made a thorough study of stylolites in the Indiana oolitic limestone as well as in the Mitchell and Warsaw or "Harrodsburg" limestones. He also gives a historical review and a complete bibliography on the subject. In other recent papers on the subject Gordon[19] and Dale[20] also conclude that stylolites are due to solution.

The dark shaly material that generally accompanies stylolites has been regarded by some as the deformed remnants of thin layers or films of shale that originally separated the limestone or marble beds and by others as the accumulated insoluble residue of the dissolved portions of the stone. Stockdale regards those in the Indiana oolitic limestone as insoluble residue and presents chemical analyses and calculations to support his conclusion.[21]

The period in which the stylolites were formed is not clear. The stone had become consolidated and could be reached by percolating waters unsaturated in calcium carbonate. Such waters in limestone regions are ordinarily found above ground-water level, a fact that would imply that the stone after consolidation had been elevated and lay close to the surface of the land before it became deeply buried beneath the overlying strata. Some deeply circulating artesian waters, however, could accomplish the same result and would be active at depths where pressure would be more likely to produce the stylolites. The presence of long-pointed crystals (scalenohedrons) of calcite as well as crystals of pyrite along the stylolites implies that after solution had taken place the limestone, if once elevated, had again subsided below the ground-water level, which marks the general lower limit of oxidation. Pyrite, a disulphide of iron, would not form in the presence of free oxygen, and the long-pointed crystals of calcite, according to the writer's experience, are also characteristic of deposits that contain or are associated with pyrite and certain other metallic sulphides. The deep-seated waters that deposited the pyrite and calcite were presumably similar to the deep-seated sulphurous spring waters of French Lick and West Baden, Ind.

Fine-grained veins or streaks.—At some time subsequent to consolidation but evidently prior to covering by later sediment, short cracks, many of them irregular, were formed apparently by contraction. These cracks then became filled by finely divided calcium carbonate, which thoroughly cemented the cracks and developed

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[18] Stockdale, P. B., Stylolites: their nature and origin: Indiana Univ. Studies, vol. 9, No. 55, 96 pp., 1922.

[19] Gordon, C. H., On the nature and origin of the stylolitic structure in the Tennessee marble: Jour. Geology, vol. 26, pp. 561–569, 1918.

[20] Dale, T. N., Constitution and adaptation of the Holston marble of East Tennessee: Tennessee Dept. Education, Div. Geology, Bull. 28, pp. 98–113, 1924.

[21] Stockdale, P. B., op. cit., pp. 67–85.

light-colored streaks a quarter of an inch or less in thickness. These streaks may be seen occasionally in the finished stone. They interrupt the original structure of the stone but, so far as seen, do not impair its strength or weathering qualities. The writer is informed that these light-colored streaks are also present in some of the more porous stone. The colorless calcite veins or "glass seams" are explained below (pp. 139–140).

Seams or joints[22] *and faults.*—After deposition of the Pennsylvanian rocks ("Coal Measures"), the whole region was uplifted with little tilting or warping. The stress causing this movement was sufficient to develop fractures of greater or less extent. Some of these are inconspicuous or even invisible "strain-line" cracks ("dries" or "dry seams") that extend a few feet or yards, for no apparent reason unless correlated with the larger fissures, when they may prove to be due to shearing or torsional movement.

Of the larger fissures, many are simple cracks, but a few are accompanied by a small amount of displacement or faulting of their walls. The only one of these faults noted is in the Blue Hole quarry, just east of Bedford. It has a steep dip and a normal displacement of 6 inches along the dip. Vertical cracks or seams branch from it. A few weakly cemented bedding planes are opened near these cracks, and it is impossible to obtain mill blocks of ordinary size (8 by 4 by 4 feet) for milling for several feet on either side of the fault. Owing to the sudden jar that accompanied the formation of the fault and associated seams, the rock for a few inches on either side of them may contain microscopic cracks and for this reason should be avoided, even if no discoloration or indication of shattering is visible.

Ground water.—These fractures served as channels for water that percolated from the surface downward to the level of permanent ground water. Below this level all rocks are saturated with water. The upper boundary of this saturated zone in regions of humid climate slopes in the same general directions as the surface of the ground but less steeply. Where it reaches the surface it gives rise to springs and streams. For a long time the ground-water level was in the "Coal Measures," but after a prolonged period of erosion it became lowered into the Mitchell limestone and later into the Indiana oolitic limestone.

Above ground-water level rain water containing oxygen and carbon dioxide obtained from the air and from decaying vegetation percolated along fractures and open bedding planes and through the body of the stone, especially the more porous strata. After every

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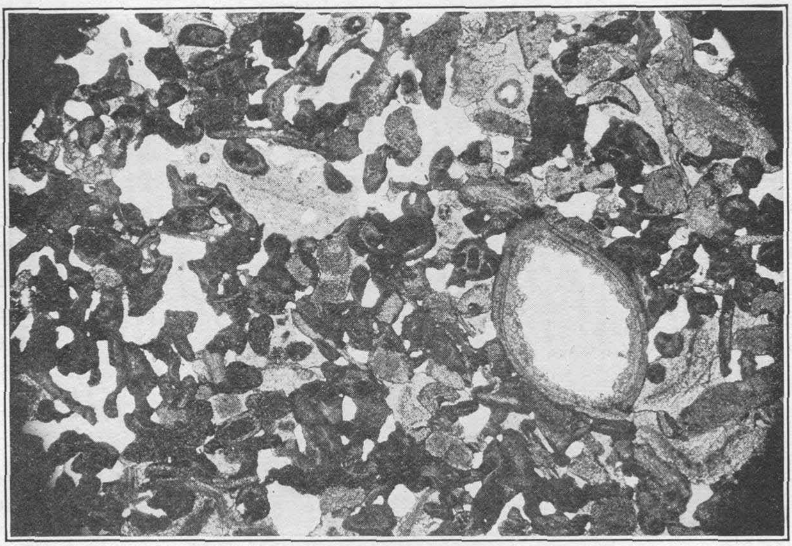
[22] Joint is the usual geologic term to denote simple cracks in rocks, but to avoid possible confusion to readers unaccustomed to this use of the word, the quarryman's term "seam" is given preference here.

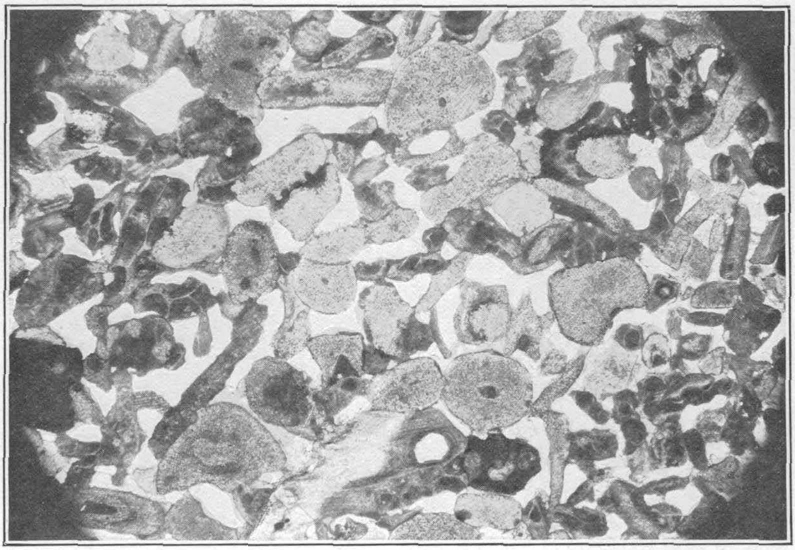


A. PHOTOMICROGRAPH OF VERY FINE GRAINED BUFF LIMESTONE OF "STATUARY" OR AA GRADE

The oolitic coatings of grains are inconspicuous. Enlarged 18 diameters.

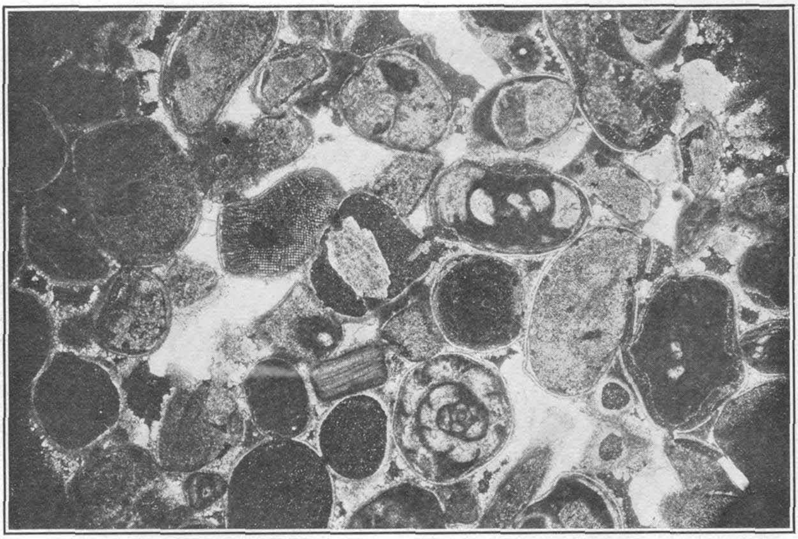
B. PHOTOMICROGRAPH OF MEDIUM GRAINED LIGHT-GRAY LIMESTONE FROM THE SHEA & DONNELLY QUARRY, NEAR BEDFORD, IND.

Enlarged 18 diameters.



A. PHOTOMICROGRAPH OF RATHER FINE GRAINED DARK-GRAY LIMESTONE FROM THE SHEA & DONNELLY QUARRY, NEAR BEDFORD, IND.

Enlarged 18 diameters.

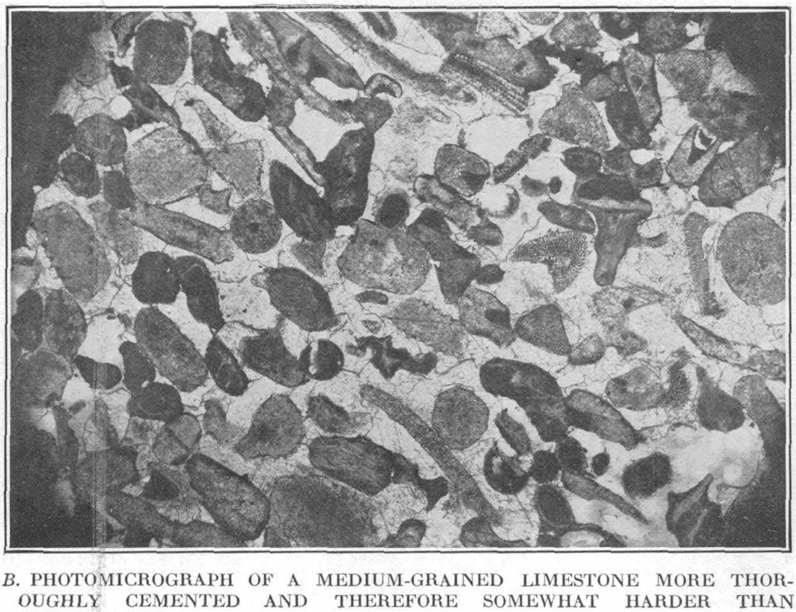


B. PHOTOMICROGRAPH OF LIMESTONE WITH OOLITIC COATINGS OF GRAINS UNUSUALLY WELL DEVELOPED

Enlarged 18 diameters.

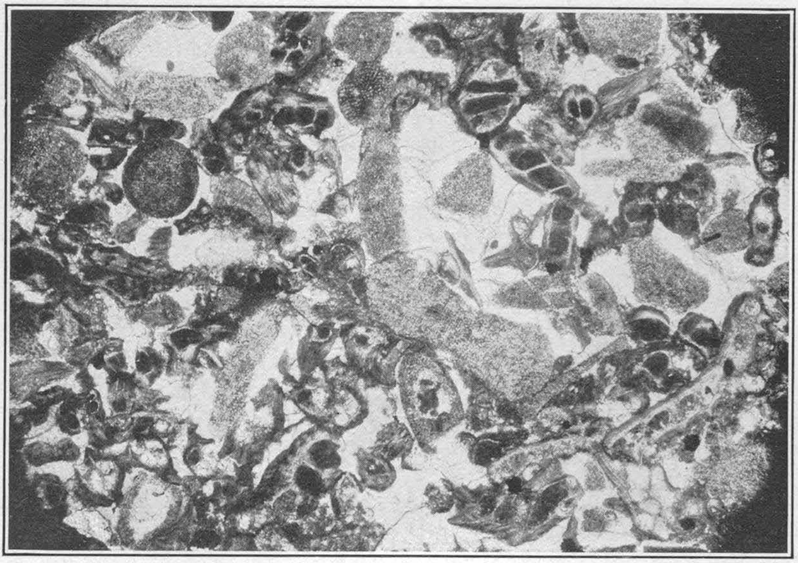
A. PHOTOMICROGRAPH OF A COARSE, UNEVEN-GRAINED BUFF LIMESTONE

Enlarged 18 diameters.



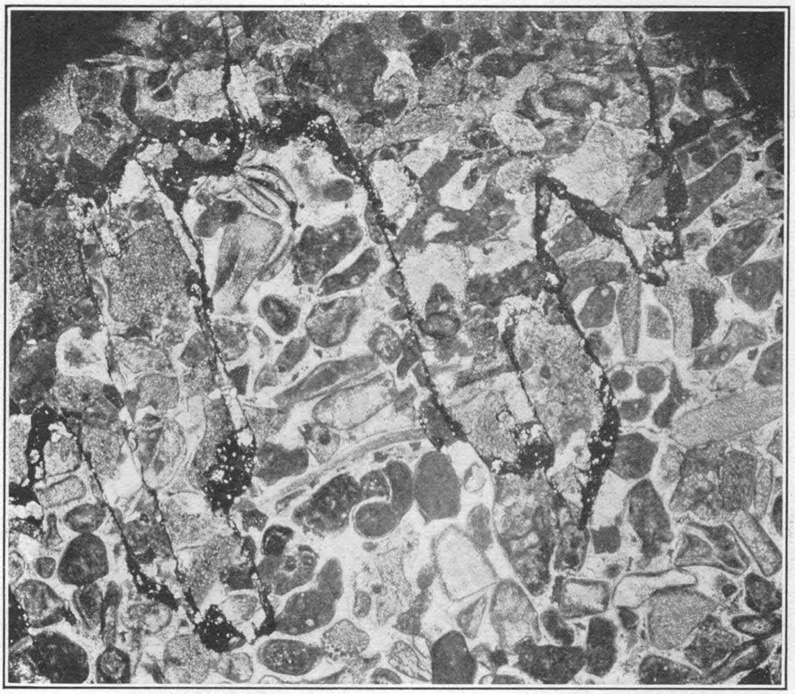
B. PHOTOMICROGRAPH OF A MEDIUM-GRAINED LIMESTONE MORE THOROUGHLY CEMENTED AND THEREFORE SOMEWHAT HARDER THAN THE AVERAGE

Enlarged 18 diameters.



A. PHOTOMICROGRAPH OF VERY HARD LIMESTONE FROM TOP BED IN QUARRY OF BEDFORD STONE & CONSTRUCTION CO., NORTHEAST OF BEDFORD, IND.

Enlarged 18 diameters.

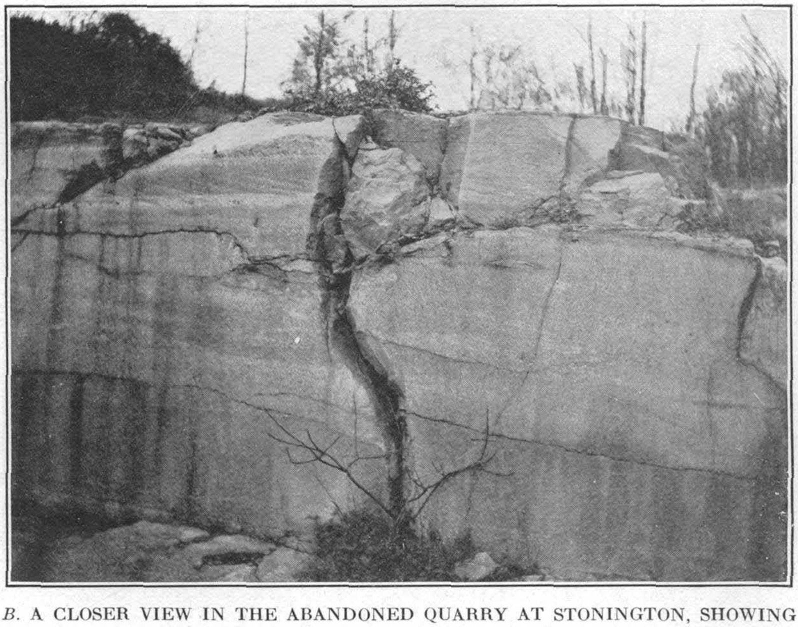


B. PHOTOMICROGRAPH OF A STYLOLITE OR "CROWFOOT" IN STONE FROM THE BLUE HOLE QUARRY, ON THE EAST SIDE OF BEDFORD, IND.

Enlarged 18 diameters.

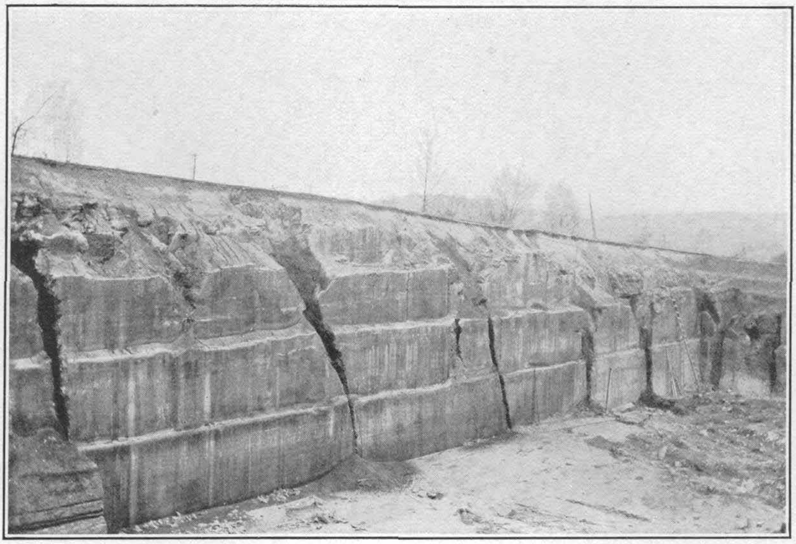
A. VIEW OF ABANDONED QUARRY AT STONINGTON, IND., SHOWING UNDULATING STYLOLITES OR "CROWFEET"

The abundance and prominence of the "crowfeet" constituted the principal reason for abandoning the quarry. The thin-bedded rock above the channeled wall is the Mitchell limestone.

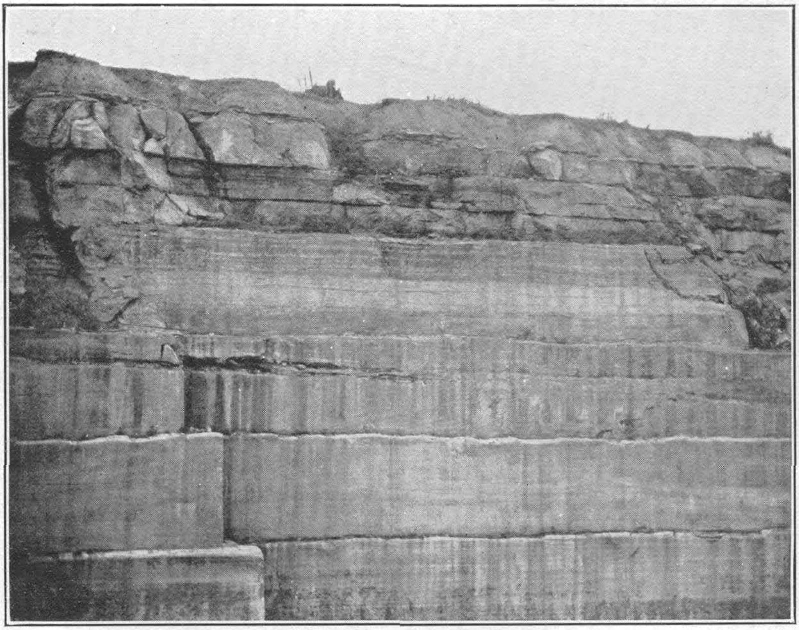


B. A CLOSER VIEW IN THE ABANDONED QUARRY AT STONINGTON, SHOWING STYLOLITES, CROSS FRACTURES OR "DRY SEAMS," AND THE VARIATION IN GRAIN OF THE CROSS-BEDDED STONE

The groovelike depressions along the stylolites, due to the weathering out of the bituminous clayey material, are clearly indicated. The marked variation in texture together with the stylolites detracts from the architectural value of the stone, and the close spacing of fractures prevents the production of blocks large enough to comply with the demands of stone-cutting mills.

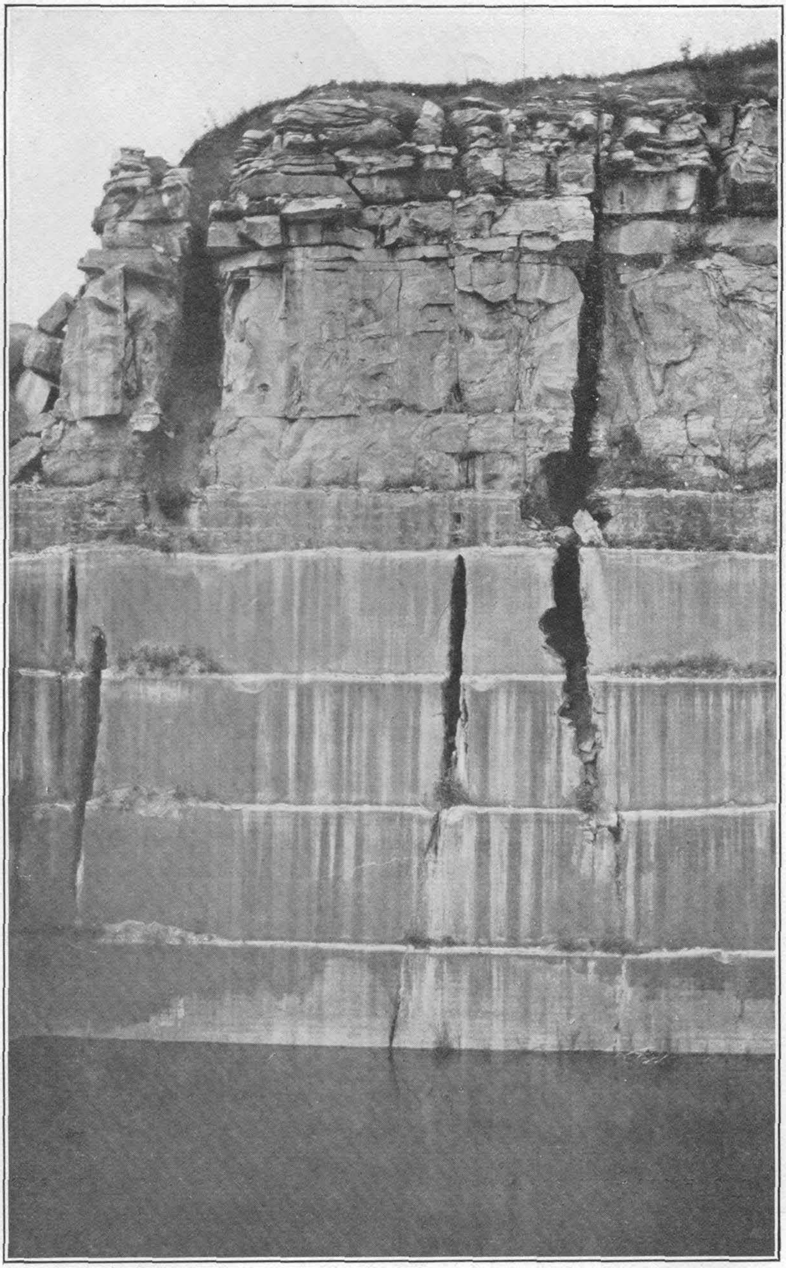


A. PART OF PERRY, MATTHEWS & BUSKIRK QUARRY OF INDIANA LIMESTONE QUARRIES CO., OOLITIC, IND., SHOWING TYPICAL MUD SEAMS DEVELOPED ALONG INCLINED FISSURES



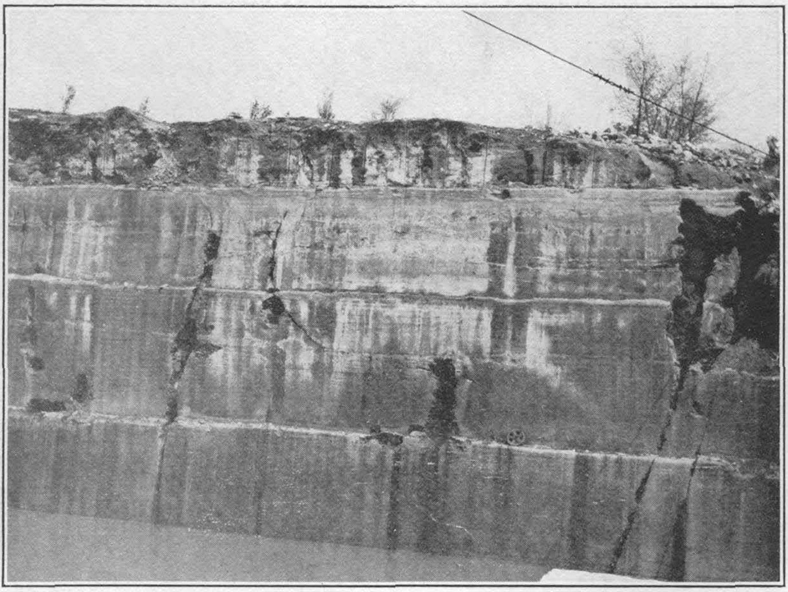
B. PART OF DARK HOLLOW QUARRY (1917) OF CONSOLIDATED STONE CO., SHOWING INCLINED MUD SEAM (UPPER LEFT) CONNECTING DOWNWARD WITH A HORIZONTAL MUD SEAM OR SMALL CAVE ALONG BEDDING

Mitchell limestone extends from the surface down to a bed of "Indiana travertine," which shows on the channeled wall as far down as the horizontal mud seam. The "travertine" is underlain by stone of select and standard grades.



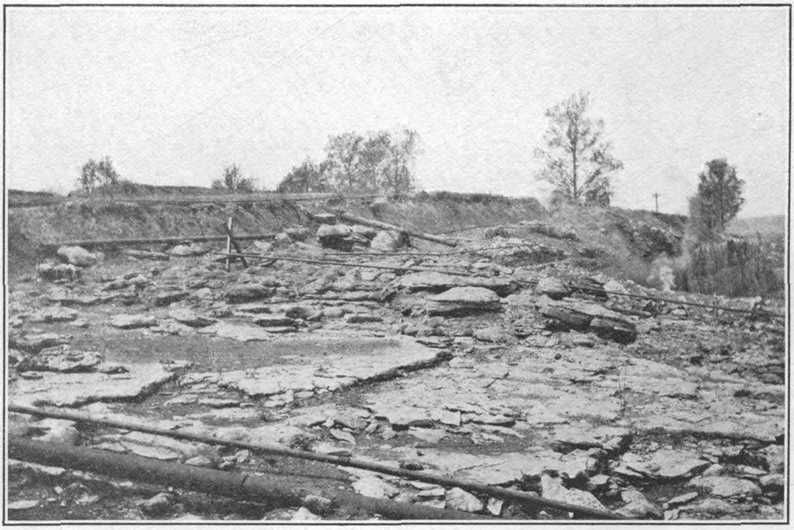
WEST END OF DOYLE QUARRY, DARK HOLLOW, IND. (1917), SHOWING MUD SEAMS IN THE MITCHELL AND INDIANA OOLITIC LIMESTONES

The overburden of Mitchell limestone is about 30 feet thick and is underlain by a thin bed of striped rock called "bastard."



A. PART OF SHEA & DONNELLY QUARRY, NEAR BEDFORD, IND. (1917), SHOWING MUD SEAMS OF VARIOUS DIMENSIONS

The top channeled bed is "Indiana travertine" and is underlain by stone of select or standard grade.



B. ERODED SURFACE OF INDIANA OOLITIC LIMESTONE AT PEERLESS QUARRY, 4 MILES NORTH OF BEDFORD, IND. (1917), EXPOSED AFTER REMOVAL OF RESIDUAL SOIL BY HYDRAULICKING abundant rainfall a new supply of water followed this complicated course, and after each supply had passed downward the moist openings were filled with air.

Examination of the Mitchell limestone where it is exposed along the tops of quarry walls shows that it consists largely of beds which are themselves impervious but which are separated from one another by many open or poorly cemented bedding planes. Along vertical or steeply inclined joints the carbon dioxide in the descending water dissolved the calcium carbonate or main constituent of the stone, and the oxygen oxidized the iron and the finely divided organic matter, converting the original bluish-gray color of the stone to a yellowish brown or buff. The same chemical reactions have taken place along the open bedding planes, but, owing to the prevailing impervious character of the Mitchell limestone, they were limited to these openings. The bluish-gray color of the Mitchell limestone therefore persists very close to these openings. In this respect the Mitchell limestone differs from the Indiana oolitic limestone, as shown on page 143.

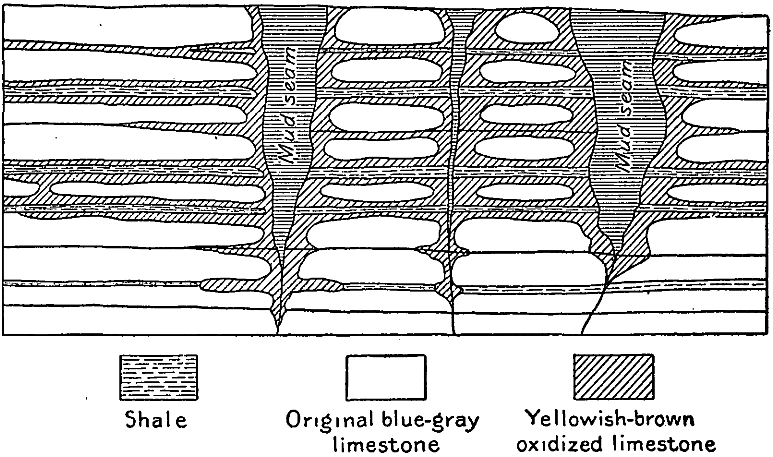


FIGURE 23.—Effects of oxidation on the color of the Mitchell limestone

"*Glass*" *seams and spots.*—The material thus dissolved was carried downward to the great body of ground water that still permeated the Indiana oolitic limestone and was moving very slowly through it. Continuous additions of calcium carbonate had saturated the ground water, and wherever local stagnation or some other cause permitted the loss of carbon dioxide supersaturation ensued and calcium carbonate, or calcite, was deposited in the pores, shell holes, and cracks of the stone. This calcite was colorless and glassy, in contrast to the calcite in the original grains and matrix of the rock, and thus formed the "glass" seams and spots that are occasionally found.

Other favorable places for deposition of glassy calcite were in the uppermost beds just beneath the contact with the Mitchell limestone and along "crowfoot" seams, where impervious barriers locally stagnated the ground water. There the additional calcite thus added made the rock harder and more flinty than normal. These local barriers thus exerted the same influence upon this later process as upon the cementation of the rock while it was still beneath the sea.

The spots and seams of glassy calcite, like those of the extremely fine grained calcite described on page 138, affect the appearance but do not decrease the durability of the stone; on the other hand, they may very locally increase the hardness and strength of the stone by additional cementation. In fact, where the stone has been subjected to prolonged weathering the better-developed crystalline grains of glassy calcite have proved more resistant than the main body of the stone. Many blocks on the waste dumps of quarries contain considerable glassy calcite and have been rejected by quarrymen because of their excessive hardness. The acceptance or rejection of finished stone containing "glass" spots or seams should, as a rule, be governed only by the desired appearance. "Glass" seams should be carefully examined, however, in stone that is to withstand a considerable shearing test, as some such seams only partly fill the fractures containing them. Crushing tests of samples submitted by the quarry companies showed that a few blocks with "glass" spots were among the strongest, whereas others did not differ appreciably from the average. The presence of "glass" spots is therefore not a certain indication that the blocks of stone containing them are on the whole superior in strength to other blocks.

Mud seams.—After erosion began to bring the Indiana oolitic limestone above ground-water level, the chemical action upon the limestone changed from one of cementation to corrosion and leaching. The descending water upon reaching the top beds was not saturated with calcium carbonate but contained an excess of carbon dioxide and oxygen. It dissolved the stone along the walls of cracks, gradually converting them into V-shaped chasms; it also percolated more abundantly along the more porous beds and dissolved them more rapidly than the others. Red mud or clay, which had accumulated as an insoluble residue while the overlying limestone was being worn away, was carried downward and filled these chasms as they grew, converting them into mud seams. There are various shapes and sizes of these mud seams, depending upon the tightness or insolubility of the overlying rock and the extent to which it has been removed. The variations are illustrated in Plates 34–37.

Plate 35, *A*, shows typical mud seams developed along continuous steeply inclined joints. The Mitchell limestone and the hard top rock of the oolitic limestone have been entirely eroded, and the oolitic limestone has been gradually worn to a gentle slope.

In Plate 36 the Mitchell limestone has roughly broken surfaces and the Indiana oolitic limestone channeled surfaces. The prominence of upper thin beds of Mitchell limestone is intensified by solution along the bedding planes. The vertical openings or mud seams are joints or fissures that have been widened by solution of the limestone and filled with mud. These fissures commonly occur in overlapping groups connected by minor fractures and are not simple continuous rifts. Solution has taken place along the more open parts of the fissures but does not extend appreciably below water level.

Plate 35, *B*, shows an inclined fissure enlarged into a mud seam extending through a few beds of Mitchell limestone and the hard (striped) top rock of the Indiana oolitic limestone, below which it pinches out. Water descending in this seam has worked its way into an especially permeable bed, where it has dissolved the stone and formed a small horizontal mud seam. The junction of the fissure and the permeable bed is concealed by an angle in the quarry wall.

Plate 37, *A*, shows different varieties of mud seams. At the extreme left is a common V-shaped seam opened along a pronounced fissure that is continuous through the Mitchell and oolitic limestones. At the extreme right is an unusually large irregular cavity that has been opened at an intersection of fissures, only two of which are included in the picture. The central openings are along minor joints or fractures, which either do not extend upward into the Mitchell limestone or are so tight above the openings that no appreciable circulation of water took place. The original joints were analogous to the " dries " before they were enlarged by solution.

Plate 37, *B*, shows a typical gently sloping hill from which the Mitchell limestone has been entirely eroded. The surface cap of residual soil has been removed by hydraulicking, exposing the remnants of upper oolitic beds, which have been largely removed by solution along beds. Typical mud seams extending downward from this erosion surface are exposed in the Peerless quarry in the extreme right background.

The removal of the oolitic limestone by solution, as shown in these plates, has extended to different degrees and in some places, as shown in Figure 20, has been complete.

Development of buff color.—Another notable effect of descending water was the conversion of gray to buff stone. So long as the oolitic limestone remained below ground-water level it was entirely of gray or "blue" color. As shown on page 132 the gray color is due to finely divided black bituminous matter, accompanied by a very small quantity of the yellow iron disulphide, pyrite. The composition of the bituminous matter has not been precisely determined, but field and microscopic study shows that above ground-water level it has been oxidized to a brown color which represents the coloring matter of the buff stone. During its oxidation the pyrite also was oxidized to the brown or rust-colored hydrous oxide, limonite, and where grains or clusters of grains were large enough to be seen, conspicuous rust specks or streaks were formed. An extreme example of stone with such rust streaks is the "goldenrod" or "antique buff" stone of the Peerless quarry. Oxidized portions of the "extra dark" stone of the Shea & Donnelly quarry would have similar coloring. The oxidation of pyrite generates sulphuric acid, which very quickly dissolves calcium carbonate, and for that reason the more conspicuous rust spots or streaks are found in unusually porous or leached rock.

During oxidation a little of the bituminous matter and of the calcium carbonate were removed in solution from the stone, but the quantity actually removed, as shown in the chemical analysis on page 146, is so small that the strength of the stone is not appreciably affected, as is shown by a comparison of crushing strengths of buff and gray stone of similar grades recorded in the table on pages 167–169. Theoretically the gray stone should be slightly stronger, slightly less porous, and slightly heavier than the buff stone.

Distribution of buff and gray stone.—The distribution of buff and gray stone is not monotonously uniform, as it would be if the oolitic limestone were equally permeable and equally subjected to oxidation. If that were the case, the boundary between the buff stone above and the gray stone below would be practically horizontal and at or slightly below ground-water level. The conditions causing divergence from this ideal relation are explained in the following paragraph.

Where the oolitic stone lies directly beneath soil or only a few feet of cap rock, its upper layers are all buff. Where creek beds, and therefore ground-water level, are well below the base of the oolitic stone and its top is covered by little or no cap rock, its entire thickness is buff. Where the lower part is well below ground-water level it is gray, except perhaps for a little development of buff stone along the walls of pronounced fissures. Where the cap rock (Mitchell limestone), is thick and its contact with the oolitic stone is tight and impervious, the buff stone is limited to the vicinity of fractures or mud seams, along which the descending water succeeded in penetrating the oolitic formation, and the presence of the buff stone indicates the extent to which oxidation has been able to spread laterally during the downward course of the water. (See fig. 24.) The buff portions, which are extremely narrow at the top, spread downward and may coalesce, leaving residual masses of gray stone at the top. This position of the gray stone may at first glance appear to have no relation to water level and to contradict the statement that the gray stone normally underlies the buff stone; but where this abnormal position exists oxidation has been slower than usual, and the gray masses represent the portions that have been the most protected from oxidation. Occurrences of this kind yield a relatively large quantity of variegated (buff and gray) stone.

As the quarry advances into the hill and the covering of Mitchell limestone becomes thicker, the proportion of gray rock will become greater, and by the time the mud seams fail to reach down to the top of the oolitic limestone the quarry will be almost entirely in gray stone. If underground quarrying or mining is to be adopted at some quarries in the future to avoid the handling of excessive waste, gray stone is to be expected in increasing quantity until it becomes the only quarry product.

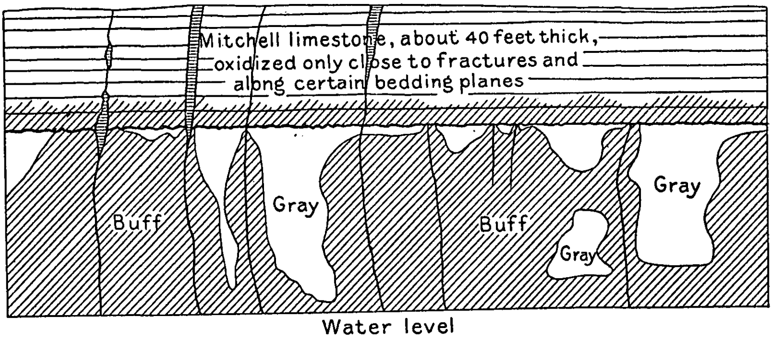


FIGURE 24.—Wall of Shea & Donnelly quarry west of Bedford, Ind. (1917), showing relation of buff color to fissures in the Indiana oolitic limestone. An impervious bed at the top of the formation has resisted oxidation and retained its original gray color. Water descending through this bed along fissures has spread into the underlying part of the formation, gradually oxidizing it to a buff color, but large masses with the original gray color still remain between fissures

This fact also emphasizes the growing importance of a detailed survey to determine the available supply of the different grades of stone. The district of course still has a long period of life, but the supply of certain grades of stone is far from inexhaustible, and some quarry companies will sooner or later be confronted with the problem of determining how long their present properties will last and where equally good undeveloped ground may be located. Geologic mapping and experience in utilization of the stone (pp. 127 and 135) have already proved that some areas of the oolitic limestone formation are inferior to others in the quantity or quality of stone yielded, but the information has not yet been put upon a quantitative basis.

Changes in demand, such as the present call for variegated and "rustic" or coarse-grained buff stone, as well as for "old Gothic," a mixture of off-grade, rather coarse-grained stone of either buff or gray color, increase the quantity of marketable material and correspondingly prolong the life of the district; but these grades constitute only a small proportion of the present output and do not materially lessen the need for a detailed survey. For such a survey detailed data on the kinds and variations of stone in every quarry and in every drill core will be necessary, and all drill records should be carefully preserved. Some companies have already done considerable prospecting with the drill, but no systematic correlation of their drill records has been made public. It will be to the mutual advantage of these companies eventually if they cooperate in contributing their records to a study of the entire district.

CHEMICAL PROPERTIES

The chemical and also the physical properties of the Indiana oolitic limestone are all dependent on its mode of origin and the features subsequently developed in it. In the following description frequent reference will therefore be made to the preceding pages.

SIGNIFICANCE OF DIFFERENT CONSTITUENTS

The chemical properties, which depend on chemical and mineral composition, are color and its permanence; resistance to weathering agencies, including rain water, sea water, ground water that has been drawn into the stone by capillary attraction, or water that has seeped through the stone from roofs, floors, or walls of buildings; and resistance to various chemicals that may be applied to the stone during cleaning or other operations.

The oolitic limestone consists essentially of grains and matrix of calcium carbonate, which is crystallized or recrystallized as the mineral calcite. Scattered through the stone is a small amount of bituminous coloring matter, a little pyrite, and minute quantities of a few other minerals whose presence may be overlooked during microscopic study but is indicated by the chemical analyses in Table 1. These analyses, however, are too incomplete to show clearly the mineral forms in which all these minor constituents are present.

Of the constituents other than calcium carbonate ($CaCO_3$) shown in these analyses, magnesium carbonate may have been originally present as a minor constituent of certain shells, its quantity varying with the proportions of the different kinds of shells. Clarke and

Wheeler[28] have shown that certain shells contain considerable quantities of magnesium carbonate and that the quantity contained by any one kind tends to vary with temperature, increasing in colder regions. Such shells on the whole were scarce in the Indiana oolitic limestone, although they may have been relatively numerous in the stone represented by analyses 5 and 6. Magnesium carbonate may also be introduced or augmented in limestone by the alteration of newly deposited sediment, magnesium carbonate being deposited at the expense of calcium carbonate, and the double carbonate dolomite being formed. The percentage by weight of dolomite in these stones is about 2.1 times that of the quantity of magnesium carbonate present but is too small to be of any practical significance, unless in the stone represented by analyses 5 and 6, where the dolomite, if segregated in streaks, might appear in slight relief after many years of weathering.

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[28] Clarke, F. W., and Wheeler, W. C., The inorganic constituents of marine invertebrates: U. S. Geol. Survey Prof. Paper 102, 56 pp., 1917.

TABLE 1.—*Chemical analyses of Indiana oolitic limestone*

No.	Locality	Quarry	Year	Calcium carbonate ($CaCO_3$)	Magnesium carbonate ($MgCO_3$)	Insoluble	Iron oxide (Fe_2O_3)	Alumina (Al_2O_3)	Alkalies (K_2O+Na_2O)	Water (H_2O)	Total	Authority
1	Bedford	Bedford Indiana Stone Co.	1896	98.27	0.84	0.64	0.15	------	------	------	99.90	W. A. Noyes, Rose Polytechnic Institute.
2	Hunter Valley	Hunter Bros.	1896	98.11	.92	.86	.16	------	------	------	100.05	Do.
3	Romona	Romona Oolitic Stone Co.	1896	97.90	.65	1.26	.18	------	------	------	99.99	Do.
4	Twin Creek	Twin Creek Stone & Land Co.	1896	98.16	.97	.76	.15	------	------	------	100.04	Do.
5	Big Creek	Indiana Steam Stone Works	------	93.80	4.01	.15	.64	------	------	1.09	100.00	L. H. Streaker, Indiana State University.
6	do	do	------	93.07	4.22	.50	.71	------	------	1.19	100.00	Do.
7	Bedford	Chicago & Bedford Stone Co.	1878	96.60	.27	.50	.98	------	0.40	.61	100.00	Indiana Geological Survey Eighth, Ninth, and Tenth Annual Reports, page 95, 1878.
8	do	Hoosier, buff	------	98.20	.39	.63	.39	------	------		99.61	Bedford Quarries Co. circular.
9	do	Hoosier, blue	------	97.26	.37	1.69	.49	------	------	------	99.81	Do.
10	Spencer, 4 miles east of.	Simpson & Archer	1878	96.79	.23	.70	.91	------	.32	.41	99.90	Indiana Geological Survey Eighth, Ninth, and Tenth Annual Reports, page 94, 1878.
11	Bloomington	Dunn & Dunn, white	1881	95.62	.89	1.74	.23	0.06	------	.59	99.45	Indiana Department of Geology and Natural History Eleventh Annual Report, page 32, 1881.
12	do	Dunn & Dunn, blue	1881	95.55	.93	1.60	.09	.09	------	.42	99.37	
13	do	Dunn & Co.	1878	95.54	.40	.65	1.00	------	.55	.25	98.39	Indiana Geological Survey Eighth, Ninth, and Tenth Annual Reports, page 95, 1878.
14	Stinesville	Monroe Marble Co.	1862	95.00	.22	.90	3.00	------	.83	.05	100.00	Owen, Richard, Report of a geological reconnaissance of Indiana, page 137, 1862.
15	Salem		1886	96.04	.72	1.13	1.06	------	.15	.10	99.20	Indiana Department of Geology and Natural History Fifteenth Annual Report, page 144, 1886.
16	Harrison County	Stockslager	1878	98.09	------	.31	.18	.14	.40	.12	99.24	Indiana Geological Survey Eighth, Ninth, and Tenth Annual Reports, page 96, 1878.
	Average		------	96.50	1.00	.88	.75	------	.17	.29	------	

The column headed "Insoluble" gives the amounts of organic (bituminous) matter, together with silica and perhaps other constituents of such insoluble minerals as clay, feldspar, and mica. The incompleteness of the analyses leaves the reader in doubt as to the exact amount of insoluble matter originally present, for a part of the organic matter may have been expelled along with water by heating and therefore recorded as water. The partial analyses quoted in Table 2, below, are more explicit, but the percentages of inorganic insoluble matter shown in them are higher than in most of the analyses quoted in Table 1. The different insoluble constituents will be considered separately.

Organic matter, as shown in the discussion of the color of the stone, includes two fractions, one of which is slowly removed by the oxidizing influence of ground water, although it may not be readily soluble in the acids used in the laboratory; the other is very stable. The analyses quoted below[24] were made to determine the coloring constituents of the stone. The figures do not appear very significant unless it is remembered that organic matter or amorphous carbon has a specific gravity only about one-sixth that of iron oxide; consequently to obtain an equal bulk per unit weight, or, in other words, an equal coloring effect, the percentages of organic matter should be multiplied by six, which would put them far in excess of the iron. Comparison of the analyses of buff and "blue" or gray stone shows that in each of the three quarries represented about half of the organic matter was removed when the stone was oxidized from "blue" or gray to buff.

TABLE 2.—*Partial analyses of gray ("blue") and buff oolitic limestone*

[Made for Indiana Department of Geology and Natural Resources by W. A. Noyes, Rose Polytechnic Institute, Terre Haute, Ind.]

Quarry	Color	Inorganic insoluble matter	Organic matter	Ferrous oxide (FeO)	Ferric oxide (Fe_2O_3)
Thornton	Gray	2.16	0.24	0.067	0.196
Do	Buff	.86	.12	.050	.126
Hunter	Gray	1.25	.22	.063	.044
Do	Buff	1.10	.11	.055	.150
Perry	Gray	1.14	.21	.055	.089
Do	Buff	1.24	.13	.050	.119

As might be expected, the organic matter that remains after having been subjected to oxidizing conditions is very stable, possibly approaching in its resisting properties bituminous coal or amorphous carbon. Generally, such organic compounds, if very finely divided, are of a brownish color, and this color is augmented by what little brown iron oxide is present. The buff coloring matter is very stable

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[24] Hopkins, T. C., and Siebenthal, C. E., op. cit., p. 309.

chemically, resisting both fairly high temperatures and chemical solvents.

The difference in stability of these two kinds of coloring matter raises the question whether the gray stone used in building is likely to turn to buff. The ordinary shade of gray in newly quarried stone becomes lighter after exposure, evidently because of the evaporation of moisture, or "sap," and of minor volatile constituents in the organic matter, but change of the color of the nonvolatile portion of the organic matter from gray to buff through oxidation does not take place. Exceptionally dark gray stone, like some of that from Dark Hollow in which microscopic pyrite is relatively abundant, is said to retain its darkness of tone after prolonged exposure. The change effected by ground water was the result of prolonged leaching for thousands of years, whereas few if any buildings containing the gray stone have been standing more than 50 years; furthermore, without the direct agency of percolating ground water a change from gray to buff is not to be expected.

The silica present is derived from the same shells that supplied the calcium and magnesium, also from the inorganic residues of sponges and perhaps diatoms, which were insignificant in quantity. This silica was in part concentrated within the sediment and crystallized as aggregates of minute grains. In the stone of select and standard grade such aggregates have been noted only under the microscope, but at some places, particularly in the coarse-grained stone, fragments of shells originally composed of calcium carbonate have been replaced by silica, all the markings of the shell being preserved. This feature explains in part the relatively great hardness of some coarse-grained stone, although the principal cause of hardness is the degree of cementation by calcium carbonate. Silicification also accounts for the prominence of the few scattered shell fragments, which stand in much greater relief than even the largest shells of calcium carbonate in stone that has been long exposed to weathering. A few striking examples have been seen in New York, where Indiana oolitic limestone of generally uniform fine-grained texture would appear to have resisted chemical erosion perfectly were it not for a silicified shell here and there, which protrudes for a sixteenth of an an inch or more and marks the original surface, after exposure for perhaps 40 years. One of the best places to see this feature is in the buildings on Fifty-ninth Street opposite the south end of Central Park, New York City. Attention is particularly directed to a small silicified coral on the front of 228–230 Fifty-ninth Street.

Alumina is present in such small quantity that the mineral containing it has not been recognized by the writer, but, like the silica, it was probably derived, in part at least, from the original shells.

It may be present in clay, feldspar, or mica, but even if all the alumina represented in the analyses on page 150 were contained in one or more of these minerals their combined weight would amount to less than 1 per cent, and they would be too thinly scattered throughout the stone to be of any significance.

Iron is present in part as pyrite (the sulphide) and in part as limonite (hydrated oxide) derived by the oxidation of pyrite, and a trace of it may be present as ferrous carbonate. In the analyses, however, it is recorded only as oxides. The ferrous oxide reported in the analyses on page 147 represents iron in pyrite, which is present in very small quantities, and perhaps also iron carbonate, which was deposited in certain of the shells, either as an original constituent or by impregnation while the stone was still below water level and not subject to oxidation.

The ferric oxide represents the iron in limonite, a part or all of which was derived from pyrite and siderite, through the action of oxygen in ground water. An insignificant amount is possibly present in minerals of the insoluble portion of the stone. Iron in the form of either sulphide or carbonate is more readily oxidized above the ground level than the bituminous matter; for this reason some stone with its iron largely oxidized still contains enough of the darker bituminous matter to retain its gray color. The oxidation of pyrite, as shown on page 142, generates sulphuric acid, 2 molecules of acid (196 parts by weight) coming from 1 molecule (120 parts) of pyrite, and where oxidation of the pyrite has been unusually intense the limestone is correspondingly leached.

The forms in which the alkalies (soda and potash) are present have not been determined. They may occur in minute grains of feldspar and mica, but the ratio of alkalies to alumina, especially in analysis 16, which is more complete than the others, is too high to account for more than a very small part of it in this way. They may therefore represent salts from the sea water in which the limestone was deposited. These salts are readily soluble in water and may account for any slight efflorescence that appears during the seasoning of the stone. They may also be present in efflorescences that are brought to the surface by excess water used in mortar, which escapes through the pores of the stone. Such white efflorescences are quickly washed away by rains or by cleaning the surface with water. Efflorescences caused by water that has leaked through roofs, leaching soluble salts from concrete or brick backing and concrete floors or from mortar and carrying them through to the surface of the stone, are similar but far more abundant and will continue to appear so long as the leakage is permitted or until all the soluble matter has been leached from the concrete and brick.

The water represented in the analyses on page 146 may be in part combined with organic matter, clay, brown iron oxide, amorphous silica, and alkali salts and in part absorbed moisture retained in capillary pores. Its varying though small quantity prevents an assignment of this water to definite compounds, but the quantities shown in analyses 5 and 6 are too great to be accounted for in any way except as absorbed moisture and presumably indicate that the samples had not been seasoned. These quantities are sufficient to cast some doubt upon the resistance of the two stones to frost action, but the general absence of injury from frost in the stone that has been used in buildings is adequate evidence as to the weathering quality of the stone as a whole. The water recorded in most of the analyses is obviously no indication of the quantity of quarry water, or "sap," in the stone before quarrying.

The impurities in oolitic limestone are thus of no material consequence in affecting its resistance to chemical weathering. This property is governed by the solubility of the calcium carbonate (calcite). The usual forms in which calcium carbonate occurs do not differ widely from those of the oolitic limestone in their solubility in acids and other solutions. In the following pages it is shown by quantitative experimentation that the solubility of this stone in carbonated water is of the same order of magnitude as the solubility of other forms of calcium carbonate, and data obtained from some simple qualitative experiments indicate that this is apparently true in regard to the action of hydrochloric and sulphuric acids.

After the foregoing discussion was written, the eight chemical analyses quoted below were published by the Bureau of Standards.[25]

TABLE 3.—*Chemical analyses of Indiana limestone*

[Alice W. Epperson, analyst]

	8	63	64	46	85	93	Composite A	Composite B
SiO_2	0.24	0.70	0.40	0.24	0.94	0.30	0.69	0.80
Fe_2O_3	.05	.08	.08	.05	.10	.05	.18	.12
Al_2O_3	.55	.68	.52	.75	.62	.61	.44	.68
CaO	54.80	54.54	54.70	54.60	54.50	54.80	54.58	54.40
MgO	.72	.59	.60	.68	.78	.38	.60	.56
K_2O	.00	.00	.00	.00	.00	.00	.00	.00
Na_2O	.005	.16	.16	.12	.21	.21	----------	----------
SO_3	.07	.06	.05	.05	.22	.05	----------	----------
Total S	.26	.25	.27	.85	.34	.63	Trace.	----------
Loss	43.53	43.31	43.00	43.57	42.56	43.60	43.58	43.45
CO_2	43.30	42.90	41.70	43.10	42.50	43.10	----------	43.24
Organic matter	Trace.	Trace.	Trace.	Trace.	Trace.	Trace.	Trace.	----------

Calculations from these analyses show calcite to range from 93.6 to 96.2 per cent, and dolomite from 1.7 to 3.31 per cent. There is a small but persistent excess of calcium oxide over the amount necessary for calcite and dolomite, and this excess may be present in or-

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[25] Bur. Standards Tech. Paper 349, p. 550, 1927.

ganic matter, as indicated by Anderegg's work cited on page 165. The amount of iron in most of these analyses, 0.05 to 0.10 per cent, is surprisingly small and implies a negligible amount of pyrite in both the buff and gray samples. In contrast the total sulphur present is appreciable and is therefore inferred to be largely present in organic matter. The recording of only "traces" of organic matter in these analyses is surprising in view of the appreciable residues of carbonaceous material left when small chips of the stone are dissolved and of the organic stains that are discussed elsewhere in this report. The other constituents are present in too small and too variable quantities to be calculated into definite minerals. The ratio of alumina to silica and soda is too great to represent feldspar and clay entirely, and some of the alumina is evidently present as hydrous oxide. The soda may be present as carbonate and sulphate and if so would be of some significance in the tendency of different samples to stain when treated with distilled water (see p. 165); but this suggestion can be proved only by a leaching test, and the fact that few samples showed staining unless treated with alkaline solutions implies that no appreciable amounts of sodium carbonate or sulphate are commonly present.

EXPERIMENTAL DATA ON WEATHERING EFFECT OF CARBON DIOXIDE

By George Steiger

GENERAL FEATURES

Pure water in equilibrium with air having a partial pressure of CO_2 of 2.19×10^{-7} at 16° will dissolve 0.016 gram of calcium carbonate per liter. However, limestone in ordinary use never comes into contact with water of this purity. The average CO_2 content of the air is a little less than 3×10^{-4} (3 parts in 10,000). Water in contact with air of this CO_2 concentration will dissolve 0.056 gram of $CaCO_3$ per liter.[26]

It is not uncommon for the air in the cities where oolitic limestone is largely used to carry as much as 5 or 6 parts of CO_2 per 10,000 and remain at this concentration for long periods of time. In certain specific localities the content of CO_2 may run very much higher, but usually in these places the high concentration is maintained for only brief periods.

The data presented in Table 4 for the solubility of calcite ($CaCO_3$) in water at 16° C. in equilibrium with air containing partial pressures of CO_2 were calculated by Johnson and Williamson from the results of work by Schlosing (1872), Engle (1888), and other experimenters.

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[26] Wells, R. C., Washington Acad. Sci. Jour., vol. 5, p. 617, 1915.

TABLE 4.—*Solubility of calcite (calcium carbonate) in water containing carbon dioxide.*

Partial pressure of carbon dioxide. (atmospheres)	Grams of calcium carbonate per liter
9.78×10^{-9}	0.026
6.14×10^{-8}	.018
2.19×10^{-7}	.016
3.73×10^{-7}	.0159
3.85×10^{-7}	.0159
6.07×10^{-7}	.016
7.62×10^{-6}	.022
7.63×10^{-5}	.040
2.15×10^{-4}	0.056
2.00×10^{-4}	.055
2.50×10^{-4}	.059
3.00×10^{-4}	.063
3.50×10^{-4}	.066
4.00×10^{-4}	.069
4.50×10^{-4}	.072
5.00×10^{-4}	.075

Water in contact with air containing a partial pressure of CO_2 of 5 parts in 10,000, as shown in the last line of the table, will dissolve 0.075 gram of $CaCO_3$ per liter, or about 50 per cent more than the average dissolved by water in contact with normal air. The corrosion which might be expected in cities is therefore much higher than in rural districts, although, as shown below, the corrosion of limestone by carbon dioxide alone is negligible.

EXPERIMENTS WITH CUBES OF INDIANA OOLITIC LIMESTONE

In an experiment by G. P. Merrill[27] nineteen 1-inch cubes cut from as many varieties of marble (calcite and dolomite) and oolitic limestone were, after weighing, suspended by means of small threads in water saturated with CO_2. At the end of the experiment, which lasted for three months, the cubes were withdrawn, dried at 100° C., cleaned from loose particles by brushing, and again weighed, after which they were carefully examined and notations made as to their color and the manner in which the solvents acted.

In the oolitic limestone the oolites were eaten out, leaving the more crystalline interstitial material and fossil fragments in relief. The outlines of some of the oolites were preserved by their insoluble impurities, a condition in accord with natural weathering. Three specimens of oolitic limestone were contained in the series, and the losses by weight ranged from 0.032 per cent in the sample from Bowling Green, Ky., through 0.049 in that from Bedford to 0.05 per cent in the stone from Salem, Ind. Calcite marble lost from 0.015 to 0.023 per cent, whereas dolomite lost only from 0.0009 to 0.015 per cent.

To obtain further data on the effect of carbon dioxide on the Indiana oolitic limestone certain experiments were conducted in the chemical laboratory of the United States Geological Survey.

In the course of these experiments water containing varying proportions of CO_2 was allowed to drip on a 5-centimeter cube. The re-

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[27] Merrill, G. P., Report on some carbonic acid tests on the weathering of marbles and limestones: U. S. Nat. Mus. Proc., vol. 49, p. 347, 1916.

sulting solubility is discussed further on. The surfaces of these cubes are similar in appearance to those of the cubes described by Merrill. Plate 38 illustrates the surfaces of cubes used in the Geological Survey's experiments. A peculiarity worthy of notation is the marked difference between the effect of carbonic acid and that of the stronger acids. Both sulphuric and hydrochloric acids allowed to act similarly on oolitic limestone will smooth rather than roughen the surface, as the harder and larger crystalline particles are acted upon quite as rapidly as the softer and smaller particles, and the surface assumes a polished or fused appearance.

The solubility of oolitic limestone in water saturated with CO_2 was determined by placing three 5-centimeter cubes of the stone in a large-mouthed jar, covering them with distilled water, and passing a slow current of CO_2 through the liquid. The water was then kept saturated with CO_2 at atmospheric pressure. At the end of 14 days 50 cubic centimeters of the water was withdrawn and found to contain an equivalent of 0.84 gram of $CaCO_3$ per liter.

The experiment was then continued for an additional 105 days, a total of 119 days, at the end of which the liquid contained calcium equivalent to 1.12 grams of $CaCO_3$ per liter. This experiment shows that although the action is rather slow the final solubility of this limestone is of the same order of magnitude as that of other forms of calcium carbonate. The experiment was conducted at laboratory temperature ranging from 70° to 80° F.

The next experiment called for 40 of the 5-centimeter cubes cut from different varieties of Indiana oolitic limestone with differently finished surfaces—planed, fluted, crandalled, and rock faced. The cubes were placed in a fairly tight box, and a slow current of CO_2 was introduced, after the gas had been washed by bubbling through water. The experiment was continued through the 5-year period from 1922 to 1927. During by far the greater part of this time the temperature of the laboratory was between 70° and 80° F., though at times during the summer it reached 95°, and during winter nights it occasionally fell as low as 40°, but such periods were of short duration. The humidity during most of the experiment also varied with that of the laboratory.

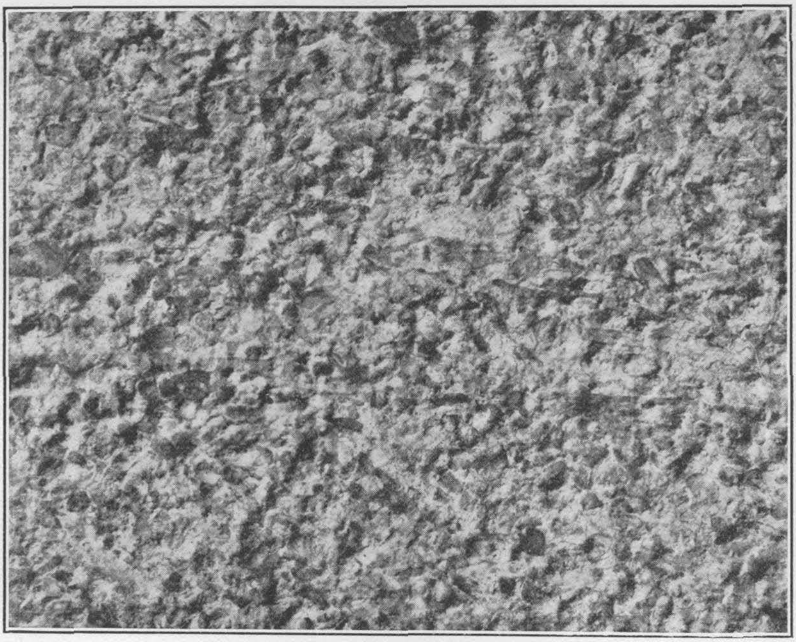
For several periods of three or four weeks each strips of cheesecloth hung inside the box were kept moist, and at these times the humidity was close to 100 per cent. The portion of the time during which this high humidity was maintained is estimated at 5 to 8 per cent, although no actual record was kept. Conditions during this experiment varied through wide limits, both as to temperature and humidity, but stone in its general use also is subjected to these wide variations, even greater in northern climates, where the temperature frequently falls much below that reached in this experiment. The concentration of CO_2, however, was 2 and 5 per cent—many times that which might be encountered in nature.

A portion of each block was protected with a coating of paraffin. At the end of the experiment the paraffin coatings were removed and the surfaces carefully examined. In no specimen could any effect of the exposure be detected. The color, texture, markings, and other characteristics of the exposed stone were identical with those of the surfaces that had been protected by the paraffin coating, and no efflorescence was noted on any of the specimens.

DRIP EXPERIMENTS

In the drip experiments a 5-centimeter cube of medium-grained or standard stone was used. The cube was supported on a glass funnel, and water saturated with CO_2 at atmospheric pressure allowed to drip on it at varying rates of speed. The $CaCO_3$ dissolved was estimated in two ways: in one the cube was dried at 120° C., weighed, subjected to the drip, dried again at 120° C., and reweighed, and the $CaCO_3$ was obtained by difference; in the other the water after passing over the cube was collected, and its calcium content was determined gravimetrically by the oxalate method and calculated as $CaCO_3$.

In this experiment water dropping on the middle of the top face and flowing to the edge, down the side, and into the middle of the bottom face would traverse a distance of 10 centimeters in its shortest course; that part of the water running to the corner of the top surface would go considerably farther; to compensate for this, however, much of the water would not reach the middle of the bottom face but would drip from points near the edge, so that 10 centimeters could be taken as a good average. By direct determination it was found that 2 cubic centimeters of water was constantly retained on the top surface, representing an average thickness of 0.8 millimeter, whereas the film running down the sides was much thinner, probably not more than a few hundredths of a millimeter, and the water in contact with the bottom face formed large drops several millimeters in thickness. It was assumed that there was constantly during these experiments 4 cubic centimeters of water in contact with the stone, that the top and bottom faces were wholly wet, and that only a portion of the sides was traversed by the water, which ran down the sides in selected channels, so that only about 75 square centimeters of the total 150 square centimeters of the surface of the cube was acted upon. Under these conditions the average depth of liquid would be 0.54 millimeter. This experiment might therefore be compared with one in which water would run over a surface 10 centimeters long and 7.5 centimeters wide to an average depth of 0.54 millimeter.



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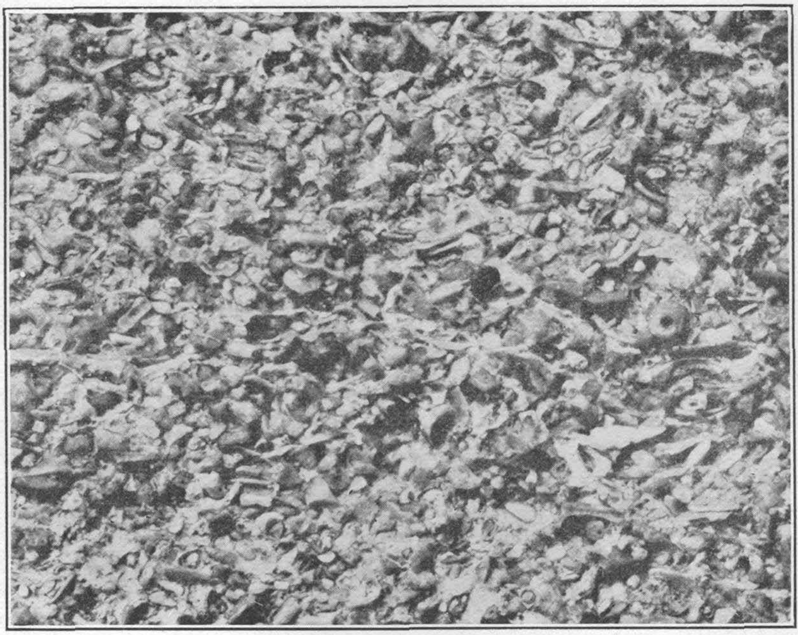

B

INDIANA OOLITIC LIMESTONE BEFORE (*A*) AND AFTER (*B*) TREATMENT WITH CARBONATED WATER

Enlarged 5 diameters.

The results of these experiments are given in Table 5.

TABLE 5.—*Results of experiments to show the effect of carbonated water on cubes of Indiana oolitic limestone*

Number of experiment	1 Total volume of liquid (cubic centimeters)	2 Total time (minutes)	3 Total $CaCO_3$ (grams)	4 $CaCO_3$ per 1,000 cubic centimeters of liquid (gram)	5 Time per 1,000 cubic centimeters per centimeter of width (minutes)	6 Actual time of contact (minutes)	7 Flow per minute per centimeter of width (cubic centimeters)	8 Rate of flow (centimeters per minute)
1	44, 500	4, 260	1. 2200	0. 0274	720	0. 38	1. 390	26. 3
2	460	54	. 0214	. 0465	877	. 47	1. 140	21. 3
3	255	53	. 0150	. 0588	1, 560	. 83	. 641	12. 00
4	64, 000	18, 360	3. 2000	. 0500	2, 160	1. 15	. 463	8. 70
5	16, 500	7, 200	. 9200	. 0557	3, 277	1. 75	. 305	5. 71
6	250	200	. 0193	. 0772	6, 000	3. 20	. 166	3. 13
7	140	112	. 0108	. 0771	6, 000	3. 20	. 166	3. 13

Quantity of water constantly in contact, 4 cubic centimeters.
Total area, 75 square centimeters.
Average depth of water, 0.54 millimeter.

TOWER EXPERIMENTS

Tower experiments were also conducted. The material used in these experiments was prepared from three grades of stone—select (grade A), standard (grade B), and rustic (grade C). Approximately equal weights of each were crushed, and the portion that passed through a sieve with 0.05-millimeter openings and the particles too large to go through the openings of a No. 8 sieve (2.362 millimeters) were discarded. The rest of the crushed limestone was washed in a strong stream of water until all dust had been washed away, all loose particles or sharp corners had been broken off, and the granules had become partly rounded. The cleaned material, after drying, was separated by suitable sieves into four fractions of different grain sizes. The object of this procedure was to find the total surface area of the grains, as recorded in Table 6.

TABLE 6.—*Total surface area of granulated stone*

Sieve No. (Bureau of Standards)	Diameter of sieve openings (millimeters)	Average diameter (millimeters)	Surface of average grain (square millimeters)	Total weight of material (grams)	Number of grains per gram	Total number of grains	Total surface of all grains (square millimeters)
8 10	2. 362 1. 651	2. 006	12. 64	57	160	9, 120	1, 150
10 14	1. 651 1. 168	1. 410	6. 25	134	300	40, 200	2, 500
14 20	1. 168 . 833	1. 000	3. 14	100	750	75, 000	2, 350
20 28	. 833 . 589	. 711	1. 59	106	2, 408	255, 248	4, 050
				397			10, 050

The surface areas as given were arrived at by considering the grains perfect spheres of equivalent diameter; no attempt was made to apply a correction for their irregular shapes, as the figures in the table give a close enough approximation to their true surface.

After the data given in Table 6 were obtained the four fractions were roughly mixed and put into tube A (fig. 25), being carefully guarded against loss. As the particles of this mixture were not the ultimate grains of the rock but simply fragments made by mechanically breaking or splitting, they still retained the smaller original pores of the rock.

The apparent specific gravity of the stone, including the original pores, was determined as 2.27, which gives a porosity of about 15 per cent. In this calculation the specific gravity of the ultimate material was taken as equivalent to that of calcite (2.7).

If 2.27 is taken as the specific gravity of the granules, the 397 grams of limestone in tube A have a volume of 174 cubic centimeters. The volume of tube A occupied by the granulated stone (*m* to *n*, fig. 25) is 297 cubic centimeters, and after deducting the 174 cubic centimeters occupied by the stone there remains 123 cubic centimeters, which represents spaces between the granules; or 58.7 per cent of this portion of the tube is occupied by the stone and 41.3 per cent by interstices. If the pores of the original rock are taken into consideration the interstitial space will be increased to 49.1 per cent, but these pores are so small that they do not become filled with water until after relatively prolonged immersion; furthermore, there is not a free circulation of the liquid in these minute pores, and as the experiments were of rather short duration these original pores had little or no effect. For the present experiments, therefore, they need not be considered, and the surface areas of the rock fragments alone should enter into the calculations.

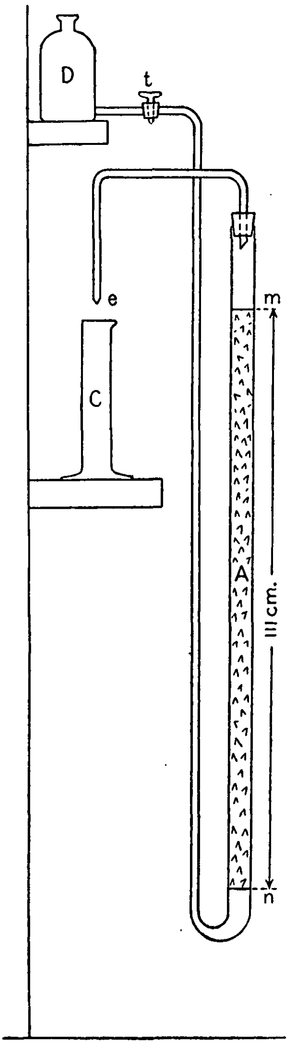

FIGURE 25.—Apparatus used in tower experiment to determine the amount of corrosion on Indiana oolitic limestone by carbonated water. See text for explanation

From Figure 25 it will be seen that the portion of tube A occupied by the granulated stone is 111 centimeters long, and from Table 6 that the combined area of the surface of the grains is 10,050 square centimeters. The thickness of the liquid between the grains ranged from 1 or 2 millimeters at the points of greatest separation down to zero at the point of contact. The interstitial space of 123 cubic centimeters distributed over the 10,050 square centimeters of surface of the grains plus 645 square centimeters in the walls of the tube would give an average depth of liquid of 0.11 millimeter. The inactive surface of the glass walls of the tube, however, has not been taken into consideration in the data given in Table 7. This experiment might be roughly compared with the quantity of water running over a surface 111 centimeters long and 90 centimeters wide and having an average depth of 0.11 millimeter.

After filling tube A the apparatus is connected up as shown in Figure 25. To start a test, bottle D is filled with the liquid to be used, stopcock *t* is opened, and when liquid appears at *e*, *t* is so adjusted as to regulate the flow to the desired rate. This rate of flow is maintained until the liquid delivered at *e* is somewhat greater than the interstitial space between the grains of stone (123 cubic centimeters) in tube A; then a graduated cylinder (C) is placed under *e* and the time noted. When the desired quantity of liquid has been collected in the cylinder the flow is stopped, the elapsed time recorded, and dissolved calcium determined by the standard oxalate method.

The results of the tower experiment are contained in Table 7. The rain water and the distilled water used were in equilibrium with the CO_2 of the laboratory air, which ranged between 5 and 10 parts per 10,000; the temperature ranged from 70° to 80° F.

TABLE 7.—*Results of tower experiments on crushed Indiana oolitic limestone*

Carbonated water

Number of experiment	1 Total volume of liquid (cubic centimeters)	2 Total time (minutes)	3 Total $CaCO_3$ (grams)	4 $CaCO_3$ per 1,000 cubic centimeters of liquid (gram)	5 Time per 1,000 cubic centimeters per centimeter of width (minutes)	6 Actual time of contact (minutes)	7 Flow per minute per centimeter of width (cubic centimeters)	8 Rate of flow (centimeters per minute)
8	320	3	0.1482	0.4631	850	1.15	1.176	96.5
9	300	7	.1986	.6620	2,100	2.87	.476	38.7
10	200	5	.1366	.6830	2,250	3.08	.444	36.0
11	300	22	.2198	.7327	6,600	9.02	.151	12.3

TABLE 7.—*Results of tower experiments on crushed Indiana oolitic limestone*—Continued

Distilled water

Number of experiment	1 Total volume of liquid (cubic centimeters)	2 Total time (minutes)	3 Total $CaCO_3$ (grams)	4 $CaCO_3$ per 1,000 cubic centimeters of liquid (gram)	5 Time per 1,000 cubic centimeters per centimeter of width (minutes)	6 Actual time of contact (minutes)	7 Flow per minute per centimeter of width (cubic centimeters)	8 Rate of flow (centimeters per minute)
16	1,000	9	0.0223	0.0223	810	1.11	1.235	100.2
17	1,000	11	.0280	.0280	990	1.35	1.010	82.0
18	1,250	15	.0271	.0217	1,080	1.48	.926	75.0
19	1,000	17	.0212	.0212	1,530	2.09	.654	53.1
20	1,000	23	.0296	.0296	2,070	2.83	.483	39.2
21	1,150	50	.0270	.0235	3,910	5.34	.255	20.8
Rain water								
12	7,065	70	0.3123	0.0442	900	1.23	1.111	90.2
13	6,670	84	.2730	.0410	1,130	1.55	.885	71.6
14	150	4	.0064	.0427	2,400	3.28	.417	33.8
15	1,160	34	.0354	.0305	2,700	3.70	.370	30.0
31	1,300	37	.0300	.0231	2,520	3.44	.396	32.3

Quantity of water constantly in contact, 123 cubic centimeters.
Area of surface of grains, 10,050 square centimeters.
Thickness of efficient layer of water, 0.11 millimeter.

COMPARISON OF TOWER WITH CUBE EXPERIMENTS

In experiments 10 and 6 the time of contact was about the same, 3.08 and 3.20 minutes, respectively, but in experiment 10 the rate of flow was about twelve times as fast as in experiment 6, and about nine times as much $CaCO_3$ was dissolved per liter of water.

In experiments 11 and 3 a rate of flow of 12 centimeters per minute was maintained. The time of contact, however, was 9.02 minutes in experiment 11 and only 0.83 minute in experiment 3, a ratio of about 11 to 1, resulting in $CaCO_3$ being dissolved in the ratio of about 12 to 1.

The actual time of contact in experiment 21 is about five times as long as in experiment 16, but the rate of flow is only one-fifth as fast. Here the greater time of contact is offset by a corresponding decrease in the rate of flow, and we find but little difference in the quantity of calcium carbonate dissolved. A comparison of experiments 8 and 11 leads to similar results.

These experiments suggest that the rate of solution may be roughly proportional both to the rate of flow and to the time of contact. However, it must be borne in mind that the conditions varied widely in the two sets of experiments; in the tower experiments only the CO_2 dissolved from air by the water before entering the tube was active, whereas in the cube experiments a thin film of water was constantly in contact with air and consequently was continuously provided with a fresh supply of CO_2.

Experiments with rain and snow water gave such variable results that no deductions could be drawn. These variations, which are in all probability due to impurities as well as to changing concentrations of CO_2, require further study based on a very large number of tests on samples taken under varying atmospheric conditions.

In one experiment tap water of the Washington water supply was used. A 5-centimeter cube was placed on a nichrome triangle so that there were only three small points of contact. Tap water was allowed to drip on the middle of the top face at the rate of 30 drops per minute for three days. The cube was then dried to constant weight at 130° C., and this weight was taken as the starting point of the experiment. Next the cube was again placed on the triangle, and the water was turned on as before and regulated to 4 cubic centimeters a minute, a rate maintained as closely as possible during the entire test. After three days the cube was removed again, dried at 130° C., and weighed. This treatment was twice repeated, first for an additional 24 days and then for 22 days, making in all 49 days.

In each of the three tests the time per 1,000 cubic centimeters per centimeter of width was 1,875 minutes, the actual time of contact one minute and the rate of flow over the surface 10 centimeters a minute. The loss in weight was 0.02 gram in the first three days, 0.15 gram in the following 24 days, and 0.10 gram in the final 22 days. This gave a rate of loss (solubility) of the limestone per 1,000 cubic centimeters of water of 0.00116, 0.00108, and 0.00096 gram, respectively.

In these solubility experiments an attempt has been made to bring the results to a common basis, but this was only partly possible. The present work is simply preliminary, more elaborate and careful work being now in progress, and the writer hopes in the not distant future to be able to publish more definite data based on conditions closer to those that surround the stone in actual use. Carbonic acid gas is the most common and widely distributed component of the atmosphere affecting limestone and for this reason has been used first. However, some of the transient constituents, such as sulphuric or hydrochloric acids and atomized salts, will doubtless prove to be more detrimental.

In considering the chemical disintegration of limestone it has been shown that the action of CO_2 is dependent on the presence of moisture in large percentage, and it is evidently necessary that the moisture be in the liquid state before any visible attack will be made.

Laboratory experiments by different investigators have shown that water in contact with atmosphere of normal CO_2 content, 3 parts in 10,000, is capable of dissolving 0.05 gram of calcium carbonate per liter. Different experimenters have differed slightly from this figure. Whether the variations are due to different forms of $CaCO_3$ employed or to experimental error is not determined; they could easily be explained in either way. The Indiana oolitic limestone is mainly calcite, and one experiment already noted in this paper showed that its solubility is at least of the same order of magnitude as that of other occurrences of $CaCO_3$. On the assumption that 0.05 gram of $CaCO_3$ per liter is the maximum amount removable by rain water containing CO_2 and that 2.27 is the specific gravity of the stone, 1 liter of rain water per square centimeter would wear the surface of the stone down 0.022 centimeter. With a rainfull of 100 centimeters (40 inches) a year it would require 10 years for 1 liter of rain water to fall on 1 square centimeter, so that the stone would wear down only 1 centimeter in 450 years—a negligible rate when figuring on the life of a building stone. Furthermore, not only is the rain water far from being saturated with CO_2, but only a small percentage of the stone in a building is subjected to the full effect of rain, most of the stone being protected by the eaves.

As regards the actual amount of chemical weathering, however, other gases encountered in cities doubtless have a greater effect than CO_2. Consideration must also be given here to the fact that although the quantity of calcium carbonate dissolved is small, solution may be concentrated largely on the finer interstitial particles, especially in the medium and coarse grained stone, until the larger grains which they surround become so loosened that they can drop out or are easily removed by wind or other mild abrasive agencies. The effects of chemical and mechanical weathering therefore can not be absolutely separated.

Experiments cited on page 153 indicate that so far as carbon dioxide is concerned water is necessary for chemical reaction, and that the vapor present in the atmosphere, even though the humidity is near saturation point, is not sufficient to promote any corrosion. The problem therefore resolves itself into the effect of rain water and water in the soil. Rain will easily dissolve the gaseous impurities of the atmosphere and carry them directly or indirectly to the stone under conditions ideal for chemical action, so that the end to be sought is the protection of the stone so far as practicable from the rain and also from ground water. The effects of ground water and water that has been in contact with cement used in setting the stone have been under thorough investigation at Purdue University. (See p. 165.)

Although the average CO_2 concentration which prevailed in the air of the laboratory while these tests were in progress was more than double that of normal atmospheric air, it was but little higher than the percentage found in the air of congested areas in large cities or near many industrial plants where Indiana oolitic limestone is used; in fact, protected courts or narrow streets are very liable to contain air of even higher CO_2 concentration.

EXPERIMENTS WITH SLABS OF INDIANA OOLITIC LIMESTONE

In a slab of the stone a groove 50 centimeters long, 1 centimeter wide, and 0.2 centimeter deep was accurately cut. It was found by direct examination that at a rate of 1,000 cubic centimeters in 50 minutes 3 cubic centimeters of water was in contact with the bottom of the groove at all times. This quantity of water spread over the 50 square centimeters of the bottom of the trough gives an average depth of 0.6 millimeter. After thoroughly washing away all loose powder, the sides were covered with paraffin so that water running down the groove came into contact with the limestone only on the bottom. In conducting these tests one end of the slab was elevated about 1 centimeter and the water was allowed to drip at the desired rate in the groove at the high end. This experiment approximates closely actual conditions found when the exposed surface of the stone is nearly horizontal, as in copings or tops of monuments.

TABLE 8.—*Results of experiments with slabs of Indiana oolitic limestone*

Number of experiment[a]	1 Total volume of liquid (cubic centimeters)	2 Total time (minutes)	3 Total $CaCO_3$ (grams)	4 $CaCO_3$ per 1,000 cubic centimeters of liquid (gram)	5 Time per 1,000 cubic centimeters per centimeter of width (minutes)	6 Actual time of contact (minutes)	7 Flow per minute per centimeter of width (cubic centimeters)	8 Rate of flow (centimeters per minute)
34 D	2,750	1,560	0.0123	0.0045	567	1.703	1.76	29.4
35 D	5,000	1,200	.0166	.0033	240	.720	4.16	69.4
38 R	1,000	60	.0178	.0178	60	.180	16.66	277.7
40 R	1,060	85	.0184	.0173	80	.240	12.50	208.3
41 S	1,050	70	.0062	.0060	67	.201	14.92	248.7
42 S	1,600	120	.0109	.0068	75	.225	13.33	222.2
44 S	1,350	94	.0088	.0065	70	.210	14.28	238.1
45 S	2,100	125	.0104	.0050	60	.180	16.66	277.7
47 S	1,420	159	.0055	.0039	112	.337	9.00	148.4
48 S	1,730	165	.0080	.0046	95	.285	10.52	175.4
50 S	1,150	42	.0083	.0072	37	.111	27.03	450.5
51 S	1,320	203	.0064	.0048	153	.460	6.53	108.8
52 S	1,140	57	.0027	.0024	50	.150	20.00	333.3
53 S	775	243	.0030	.0038	314	.932	3.18	53.0

[a] D, distilled water; R, rain water; S, snow water.

Quantity of water constantly in contact, 3 cubic centimeters.
Total area, 50 square centimeters.
Average depth of water, 0.6 millimeter.

In columns 1, 2, and 3 of Tables 5, 7, and 8 are recorded the data obtained by experimental work; figures in columns 5, 6, 7, and 8 were derived from them by calculation.

SOLVENT ACTION OF RIVER WATER

Limestone used for bridge piers and other structures in rivers is subject to abrasion by coarse sand and gravel moved by swift currents and to chemical attack by any water not already saturated with calcium bicarbonate. Natural waters have been classified by Palmer[28] into five groups based on the relative proportions of dissolved matter. One of these groups, represented by the Youghiogheny River at McKeesport, Pa.,[29] contains free acid, derived from industrial wastes, such as acid water from coal mines and manufacturing plants. Such river waters obviously exert a marked solvent action on limestone. Waters of the other four groups have their acid radicles balanced by bases, principally alkalies and alkaline earths, but may still have a solvent action on limestone until they become saturated with calcium bicarbonate. Soft waters especially may be expected to have an appreciable solvent action on limestone, and the continuous contact of the stone with moving water will produce corrosion much more rapidly than contact with city atmospheres; but only few data are available to indicate the rate. Berkey[30] cites an observation by T. C. Brown, who noted that blocks of limestone that had been subject to the action of flowing water for 35 to 40 years in locks of the Delaware & Hudson Canal had been corroded to a depth of one-eighth to one-half inch, as shown by the siliceous impurities left in relief. In some places solution pits were an inch deep. Blocks of the same stone used in houses for a much longer time were only slightly corroded. He also cites the Thirlmire Aqueduct in England,[31] where serious leakage resulted within a year owing to the dissolution of limestone aggregate from the concrete walls.

This evidence is sufficient to call for discretion in the use of limestone for parts of structures submerged below the water line. Even the most rapid corrosion progresses very slowly when measured by years, and for structures of definitely limited duration it may be perfectly safe as well as most economical to use limestone, whereas for others, of monumental character, the use of limestone below the water line will eventually cause undermining.

RESISTANCE TO SEA WATE.

Experiments tend to show that ordinary sea water is everywhere nearly or quite saturated with calcium carbonate near its surface,

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[28] Palmer, Chase, The geochemical interpretation of water analyses: U. S. Geol. Survey Bull. 479, 31 pp., 1911.

[29] Idem, table 1, p. 14.

[30] Berkey, C. P., Geology of the New York City (Catskill) Aqueduct: New York State Mus. Bull. 146, p. 140, 1911.

[31] Idem, pp. 138–139.

but the building of shells and skeletons by sea animals as well as direct precipitation in warm latitudes (p. 117) continually depletes the supply, and saturation of sea water, therefore, implies a balance between that removed and that brought in, chiefly by river water and to a minor degree by corrosion of limestone in natural exposures or artificial structures along the ocean shore, especially in the cooler latitudes. In city harbors this slight capacity to corrode may be increased by pollution with matter containing organic or other acids, but the writer has no definite data in regard to the resistance of limestone to sea water.

The use of salt water for mixing mortar may be mentioned here. Although the salt water itself will have no appreciable corrosive effect on the stone, the drawing of its salts to the surface through the pores of the stone will cause a temporary efflorescence, and the existence of the salts near or at the surface of the stone will attract and retain moisture which may promote frost action. Furthermore, if the salts accumulate in appreciable quantity the force exerted by their growing crystals will cause disintegration or exfoliation of the stone's surface. This action is also to be expected on sea walls a short distance above the water line, where salts are repeatedly deposited by the evaporation of water that has been drawn up by capillary action. Similar effects are produced by seepage through masonry, which is briefly considered in the next paragraphs.

STAINING AND EFFLORESCENCE

The staining and efflorescence on newly erected or even only partly erected structures has been a cause of considerable worry to both producers and users of Indiana oolitic limestone. Staining in the broadest sense includes (1) black, brown, and green films that clearly have been washed down from iron, copper, or bronze work, (2) white efflorescences, and (3) brown and blue-black stains that have no visible connection with ironwork or other external sources of staining. Avoidance of stains of the first kind may be attained by so designing structural details that drippings from metal work will be caught and drained through the interior of the building. Iron and copper sulphates, chlorides, and carbonates dissolved in water quickly react with limestone and marble, which go into solution, while the iron is deposited as hydrate and the copper as green carbonate, over the stone surface. Periodical removal of such coatings means the gradual wearing away of the stone surface, and it would be better if the drainage from metal work could be conducted away without touching the stone.

The white efflorescences are due to the deposition of salts on the surface and in the pores adjacent to the surface by the evaporation of water that has been drawn out of the stone. The water and salts may to a small extent represent quarry water or "sap" in the stone itself, or to a greater extent they may be derived from the mortar; but the most pronounced efflorescence is usually due to water that has worked its way repeatedly through a considerable quantity of concrete or brick backing and derived soluble salts from it as well as from the mortar. Soluble salts that originate in the stone itself are mostly calcium carbonate, together with locally appreciable quantities of calcium sulphate and alkali carbonates and sulphates. These substances will be drawn to the surface during the seasoning of the stone and can be washed off or, if the rough stone has been seasoned, they may be cut away during the finishing process. Soluble salts derived from concrete and brick backing and from cement mortar, or from the soil around the base of the building, include a larger proportion of alkalies and are necessarily drawn through the more porous parts of the stone to its outer surface. If they are drawn mainly along pervious mortar joints, they may be spread by capillary attraction over the adjacent surface of the stone for as much as several inches. Although these salts in small quantity exert no appreciable chemical action on the calcium carbonate of the limestone, the alkali salts in particular react with some of the organic matter and promote the third kind of staining, which is discussed below. The salts as a whole absorb moisture, thus tending to promote frost action; but the worst damage that results from their accumulation in considerable quantity is the disintegration of the stone's surface by the force of their growing crystals. The obvious precautions against efflorescence are to use only seasoned stone, to avoid the use of materials in the backing and joints that contain appreciable quantities of soluble salts, to guard against faulty construction that permits rain water to seep through the walls, and to prevent the capillary rise of ground water along the base course of the buildings; also to avoid excessive quantities of water, especially hard water, in the mixing of concrete and mortar and in the wetting of dry stone surfaces by sponging or drenching just prior to setting them in the mortar. If hard water is used, its reaction with lime sets free carbon dioxide, which may leach alkali carbonates from the backing and mortar. Water that contains large quantities of soluble sulphates and also sea water should obviously be avoided.

The brown and blue-black staining has been attributed to unclean sand in mortar, to iron from many sources, and to organic matter in the stone, but recent thorough investigations at the Bureau of Standards[32] and Purdue University[33] indicate conclusively that the staining is due mainly or entirely to reaction between a part of the organic matter in the stone and soluble alkali salts derived mainly from cement. Sodium carbonate is one of the most efficient salts in carrying or driving the organic matter to the surface. Kessler found that different samples did not react uniformly and concluded that the soluble constituent of the organic matter was relatively abundant in some and practically absent in others. He also found that a few samples, apparently exceptions, developed some stain and efflorescence when tap water was passed through them. He repeated the experiment with distilled water and obtained similar results.[34] Anderegg, on the other hand, obtained no stains with the use of distilled water alone and feels that a little alkali is essential to produce them. His interpretation of the staining process is that a part of the organic matter forms by oxidation (above ground-water level) an acidlike substance that reacts with the calcium carbonate of the stone to form an organic calcium compound which is insoluble in pure water; but if attacked by dissolved alkali salts the calcium is exchanged for alkali, which forms a soluble organic compound. This compound is drawn to the surface and forms a brown stain that closely resembles varnish in its physical and chemical properties. This brown stain, when newly formed, is rather easily removed by washing with a solution of sodium carbonate,[35] which should preferably be promptly neutralized with formic acid.[36] A poultice of unslaked lime and water is also recommended. A process of cleaning with live steam has also been recently developed with success.

The blue-black stains are characteristic on some of the gray stone. These stains have in part a glassy appearance, which is due to the deposition of a glaze of calcium carbonate from the "sap" of unseasoned stone and the inclusion of finely divided black organic matter in the glaze; but others are dull and appear to be due, like the brown stains, to the leaching action of alkaline solutions. The degree of staining by the organic matter is presumably governed by the quantity of alkali salts seeping through the stone. This staining is now under investigation at Purdue University under the general direction of Prof. H. C. Peffer.

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[32] Kessler, D. W., and Sligh, W. H., Physical properties of the principal commercial limestones for building construction in the United States: Bur. Standards Tech. Paper 349, pp. 526–534, 1927.

[33] Anderegg, F. O., Efflorescence on Indiana limestone: Purdue Eng. Rev., vol. 21, January, 1926, pp. 3–5; The staining of Indiana limestone: Idem, March, 1926, pp. 7–10. Huber, Lee, Staining and efflorescence on Indiana limestone caused by moisture seepage through backing masonry materials: Am. Soc. Testing Materials Proc. 31st annual meeting, 1928, 12 pp. The investigations at Purdue University have been conducted under the general direction of Prof. H. C. Peffer.

[34] Kessler, D. W., and Sligh, W. H., op. cit., pp. 528–529.

[35] Idem, p. 531.

[36] Anderegg, F. O., op. cit. (March, 1926), p. 9.

The prevention of brown and blue-black stains depends upon the same general precautions as those for preventing white efflorescence, and emphasis may once more be placed on protection from excessive use of water and from rains during construction and protection from leakage through the roof or elsewhere. If no moisture passes through the stone after it is in the building, no white efflorescence or brown or blue-black stains will appear. Seasoned stone is less readily attacked by water containing small quantities of alkaline salts, but the use of seasoned stone is not a guaranty against staining under severe conditions.

PHYSICAL PROPERTIES

GENERAL RELATIONS

The principal physical properties of stone that ordinarily interest builders are porosity, percentage of absorption, resistance to freezing, crushing strength, transverse strength, modulus of elasticity, specific gravity, and weight per cubic foot. Several of the physical properties are so closely related that one can not be adequately discussed without reference to others. Thus specific gravity and porosity together determine weight per cubic foot, and the amount and character of porosity determine the capacity for absorption and the liability to injury from freezing. Specific gravity, porosity, and weight per cubic foot indicate the degree of cementation of the constituent grains, which, in turn, largely determines the crushing and transverse breaking strengths, elasticity, and resistance to abrasion. In short, so closely are all these physical properties related in the Indiana oolitic limestone, as shown by a comparison of the test data in Table 9, that the specific gravity or the weight per cubic foot may serve as an index of the general physical character. The greater the specific gravity or the weight per cubic foot, the lower the degree of porosity and the greater the resistance to crushing and transverse stresses and abrasion. This index, however, must be used with judgment. The average stone shipped from the district weighs about 144 pounds per cubic foot (specific gravity 2.3) and has proved generally satisfactory. Heavier stone should be above the average in general quality up to a certain degree, but the strongest stone is relatively scarce and so much harder and more expensive to work that it is restricted to certain uses where maximum strength and hardness are essential.

TABLE 9.—*Tests on 72 samples of Indiana oolitic limestone*

[By D. W. Kessler, Bureau of Standards]

Laboratory No.	Producer's mark	Compressive strength (pounds per square inch)				Transverse strength (modulus of rupture in pounds per square inch)		Absorption tests					Apparent specific gravity		Porosity	Weight per cubic foot
		Specimens dry		Specimens wet				Number of tests	Percentage of absorption by weight			Average by volume				
		On bed (average of two tests)	On edge (average of two tests)	On bed (average of two tests)	On edge (average of two tests)	Right angles to bed (average of two tests)	Parallel to bed (average of two tests)		Maximum	Minimum	Average		Number of tests	Average		
19851	AA5	6,898	8,356	9,296	8,730	1,719	1,235	12	4.68	4.14	4.43	10.10	4	2.28	16.18	142
19852	AA9	5,442	4,574	4,084	3,454	1,105	957	4	6.90	6.53	6.68	14.50	4	2.17	20.22	136
19853	AA10	5,880	4,433	4,112	4,310	995	615	12	6.63	6.06	6.39	14.06	4	2.20	19.13	138
19854	AA16P	7,850	6,380	5,881	6,438	1,432	954	4	5.61	5.46	5.53	12.33	4	2.23	18.03	139
19855	AA16S	7,000	8,232	7,098	6,428	1,398	1,259	4	5.60	5.07	5.39	12.18	4	2.26	16.92	141
19856	AA23	6,118	5,944	6,424	6,224	1,492	1,104	12	4.94	4.52	4.70	10.76	4	2.29	15.82	143
19857	A2	8,356	8,985	8,926	9,176	1,810	1,504	11	4.35	4.02	4.17	9.88	3	2.37	12.88	148
19858	A5	6,393	5,702	5,732	5,308	1,269	995	10	4.87	4.48	4.72	10.81	3	2.29	15.07	144
19859	A7	7,496	7,678	6,874	6,208	1,394	963	7	4.63	3.82	4.40	10.08	4	2.29	15.82	143
19860	A8	5,698	4,617	6,083	5,439	1,116	936	4	7.33	6.82	6.98	15.15	3	2.17	20.22	136
19861	A9	5,360	4,306	4,509	3,790	841	439	4	5.09	4.90	5.01	11.32	4	2.26	16.92	141
19862	A10	7,208	6,092	6,584	5,548	1,290	1,030	12	5.76	5.38	5.51	12.34	4	2.24	17.65	140
19863	A11	6,226	5,293	5,350	4,467	950	580	12	6.17	5.41	5.75	13.00	4	2.26	20.37	141
19864	A13	7,685	6,362	6,514	6,662	1,370	966	12	6.17	4.89	5.04	11.34	4	2.25	17.28	141
19865	A13R	9,592	8,325	8,086	7,133	1,400	1,060	12	4.65	4.35	4.49	10.42	4	2.32	14.70	145
19866	A14x	6,892	7,066	6,132	6,720	973	1,101	4	5.37	5.02	5.18	11.91	4	2.30	15.44	144
19867	A14y	8,773	8,028	9,002	8,634	1,510	1,320	9	4.73	3.45	4.03	9.18	2	2.28	13.97	142
19868	A16P	6,391	5,522	6,650	5,674	1,400	1,060	4	5.82	5.16	5.52	12.48	4	2.26	16.92	141
19869	A16Rx	9,000	8,200	7,036	7,396	1,478	1,134	4	3.64	3.47	3.57	8.46	4	2.37	12.88	148
19870	A16Ry	8,214	7,688	7,788	6,688	1,561	1,228	12	5.09	4.36	4.64	10.62	4	2.29	15.82	143
19871	A16S	9,503	8,112	8,724	7,301	1,320	1,091	4	4.03	3.87	3.97	9.21	4	2.32	14.70	145
19872	A19	7,400	5,800	5,767	4,880	1,036	1,011	6	5.78	4.90	5.25	11.97	3	2.28	16.18	142
19873	A23	6,468	6,730	6,998	5,908	1,257	965	4	4.37	4.15	4.26	9.90	4	2.31	15.07	144
19874	B2	3,730	3,580	6,332	4,814	798	844	11	7.21	5.36	6.24	14.16	3	2.27	16.56	142
19875	B5	6,442	5,639	6,172	4,815	888	1,107	4	4.48	4.34	4.38	10.08	4	2.30	15.44	144
19876	B7	8,922	7,506	8,294	7,512	1,355	1,330	12	4.18	3.33	3.85	8.97	4	2.37	12.88	148
19877	B8	4,695	4,644	6,316	4,760	842	608	4	6.12	5.45	5.87	13.21	4	2.25	17.28	141
19878	B9	6,652	6,191	6,460	5,670	1,248	1,074	4	4.90	4.51	4.68	10.86	4	2.32	14.70	145
19879	B10	8,696	7,080	7,606	7,062	1,275	819	12	4.64	4.04	4.37	10.05	4	2.30	15.44	144

TABLE 9.—*Tests on 72 samples of Indiana oolitic limestone*—Continued

Laboratory No.	Producer's mark	Compressive strength (pounds per square inch)				Transverse strength (modulus of rupture in pounds per square inch)		Absorption tests					Apparent specific gravity		Porosity	Weight per cubic foot
		Specimens dry		Specimens wet					Percentage of absorption by weight							
		On bed (average of two tests)	On edge (average of two tests)	On bed (average of two tests)	On edge (average of two tests)	Right angles to bed (average of two tests)	Parallel to bed (average of two tests)	Number of tests	Maximum	Minimum	Average	Average by volume	Number of tests	Average		
19880	B11	7,446	5,522	7,146	5,585	1,023	614	4	3.94	3.78	3.84	8.98	4	2.34	13.97	146
19881	B16P	6,484	6,268	5,803	6,380	1,225	1,092	8	6.15	4.58	5.36	11.79	2	2.20	19.13	138
19882	B16R	5,127	4,386	5,347	5,457	1,009	948	12	5.98	4.97	5.23	11.71	4	2.24	17.65	140
19883	B16Sx	5,507	4,440	5,024	4,638	1,124	880	4	6.17	5.99	6.12	13.59	4	2.22	18.40	139
19884	B16Sy	4,635	5,311	5,732	4,037	985	1,284	11	5.56	5.18	5.35	12.25	3	2.29	15.82	143
19885	B19	3,916	3,206	3,275	3,044	707	535	10	6.90	3.03	5.61	12.17	3	2.17	20.22	136
19886	B23	9,016	7,152	7,875	7,188	1,196	1,168	4	3.92	3.45	3.64	8.44	4	2.32	14.70	145
19887	C2	7,906	6,465	8,300	8,210	1,121	995	6	5.07	3.33	4.19	9.93	4	2.37	12.88	148
19888	C5	5,364	4,465	5,002	4,684	1,032	858	12	5.81	5.54	5.70	12.88	4	2.26	16.92	141
19889	C8	4,559	5,332	3,535	3,500	795	595	7	6.92	6.07	6.43	14.47	4	2.25	17.28	141
19890	C9	5,472	4,660	5,978	4,658	1,078	901	4	4.81	4.23	4.60	10.67	4	2.32	14.70	145
19891	C10	6,078	5,749	6,442	6,364	1,301	1,196	4	4.91	4.37	4.63	10.70	4	2.31	15.07	144
19892	C14	4,024	4,012	3,986	3,562	928	667	4	6.12	5.63	5.82	12.94	4	2.23	18.02	139
19893	C16P	6,115	5,602	5,389	4,946	1,122	1,023	12	6.09	5.41	5.71	12.68	4	2.22	18.03	139
19894	C16S	5,524	4,847	5,260	5,015	904	942	4	5.13	5.00	5.07	11.60	4	2.29	15.82	143
19895	C19	6,748	5,708	6,140	5,115	1,050	911	12	6.05	5.64	5.81	12.78	4	2.20	19.13	138
19896	C23	7,751	6,488	6,037	5,165	1,570	1,258	12	5.98	5.36	5.64	12.58	4	2.23	18.03	139
19897	D2	10,184	9,635	9,058	7,768	1,678	1,111	4	4.01	3.88	3.94	9.43	4	2.38	12.50	149
19898	D5	7,324	6,146	6,930	6,150	1,396	1,028	8	4.02	3.62	3.80	9.08	4	2.39	12.13	149
19899	D7	9,080	6,690	7,428	6,620	1,600	1,100	4	4.62	4.15	4.36	10.07	4	2.31	15.07	144
19900	D8	11,051	6,911	8,339	8,164	1,044	966	12	6.86	3.96	5.26	12.31	4	2.34	13.97	146
19901	D14x	8,202	6,992	6,761	7,044	1,245	1,119	6	3.54	3.30	3.45	8.14	3	2.36	13.25	148
19902	D14y	7,496	7,291	7,276	7,334	1,628	1,220	12	4.47	4.00	4.18	9.70	4	2.32	14.70	145
19903	D16S	6,760	5,618	5,736	4,388	1,197	906	4	6.17	5.69	5.97	13.31	4	2.23	18.03	139
19904	D20	9,075	8,308	9,504	7,101	1,355	1,355	10	3.42	2.84	3.08	7.45	4	2.42	18.39	151
19905	D23	7,498	6,500	7,864	6,462	1,343	1,155	12	4.58	4.14	4.32	10.02	4	2.32	14.70	145
19906	E5	6,658	5,426	6,917	5,464	1,334	1,450	4	3.76	3.32	3.51	8.32	4	2.37	12.88	148
19907	E7	10,413	9,161	9,577	8,859	1,687	1,571	4	3.20	2.99	3.10	7.53	4	2.43	10.67	152
19908	E19	4,585	3,770	4,608	3,568	1,098	834	4	7.58	7.09	7.31	16.01	4	2.19	19.50	137
19909	E23	6,716	5,898	6,453	5,914	1,258	1,234	4	3.32	3.00	3.18	7.65	4	2.40	11.77	150
19910	F2	8,000	7,736	8,032	7,270	1,398	1,432	9	6.65	3.84	5.16	11.92	4	2.31	15.07	144

19911	F5	9,752	8,780	8,220	7,850	1,671	1,113	4	4.46	3.59	4.02	9.41	4	2.34	13.97	146
19912	F7	8,186	7,752	8,456	7,326	1,540	1,315	6	5.05	3.25	3.96	9.23	4	2.33	13.62	147
19913	F8	3,714	2,717	2,797	2,912	1,047	642	4	6.77	6.48	6.60	14.65	4	2.22	18.40	139
19914	F14x	6,874	5,340	5,306	4,854	1,332	1,554	4	5.73	4.93	5.38	12.09	4	2.25	17.28	140
19915	F14y	5,845	5,684	5,226	4,307	1,222	1,090	4	3.96	3.64	3.81	8.84	4	2.32	14.70	145
19916	F16P	8,282	6,447	7,412	6,454	1,365	1,204	4	4.39	4.22	4.32	10.10	4	2.34	13.97	146
19917	F23	7,898	6,168	7,798	5,322	1,152	983	4	4.14	3.95	4.06	9.43	4	2.32	14.70	145
19918	G5	8,594	6,693	7,869	6,358	1,122	1,355	4	3.68	3.32	3.48	8.24	4	2.37	12.88	148
19919	G7	9,690	7,990	8,819	7,537	1,510	1,456	6	3.90	3.65	3.76	8.84	4	2.35	13.62	147
19920	G23	5,602	5,425	6,238	5,975	1,148	922	4	4.77	4.64	4.71	10.74	4	2.28	16.18	143
19921	H2	15,700	17,426	12,730	12,976	2,016	1,985	10	2.53	2.27	2.41	6.02	4	2.50	8.09	156
19922	H10	9,838	8,735	8,104	7,097	1,212	1,252	4	5.01	4.58	4.79	11.02	4	2.30	15.44	144

SPECIFIC GRAVITY AND WEIGHT PER CUBIC FOOT

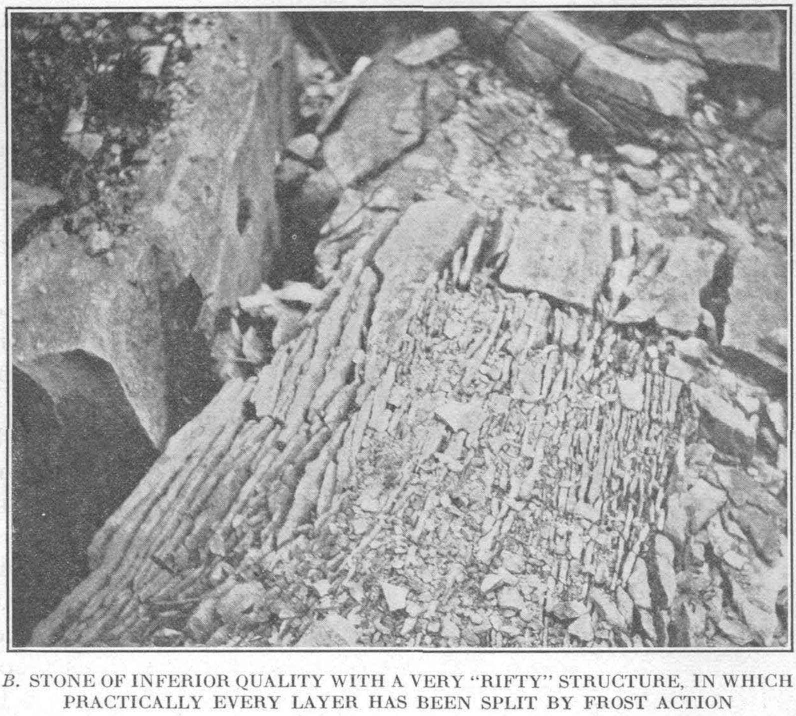
Pure calcite has a specific gravity of 2.7; in other words, it is 2.7 times as heavy as an equal volume of water. As water weighs 62.5 pounds per cubic foot, pure calcite weighs 168.8 pounds per cubic foot. The original calcareous grains of the Indiana oolitic limestone, as shown on page 128, have recrystallized into calcite, and the stone now differs chemically from pure calcite by its small content of carbonaceous matter, iron, silica, and alumina. The carbonaceous matter is considerably and the silica slightly lighter than calcite, whereas iron minerals are considerably heavier. They therefore tend to compensate each other, and the net weight of the stone (with due allowance for pore space in and among the grains) should not differ materially from the weight of an equal volume of pure calcite. In other words, the difference between the recorded (apparent) specific gravity and 2.7, or between the determined weight per cubic foot and 168.8 pounds, indicates the degree of porosity.

POROSITY AND ABSORPTION

The porosity of the Indiana oolitic limestone, as shown by the large number of tests made at the Bureau of Standards, is comparatively high. These tests (Table 9, p. 167) may show somewhat higher results than some of the tests made elsewhere but were made with such precautions that they should more correctly express the true porosity. Comparison of the results will show that the percentage of water absorbed does not vary exactly with the degree of porosity. This difference is due to the fact that some pores are so tightly sealed that moisture does not penetrate them, even if the test piece is immersed for a considerable time. A striking illustration of such a sealed pore is given in Plate 30, *A*. It should be remembered, however, that most of the large openings shown in the photomicrographs (pls. 30–33) are not natural pores but are formed by the tearing out of particles during the grinding of thin sections. In general the percentages of absorption by volume are from one-fourth to one-third lower than the percentage of porosity.

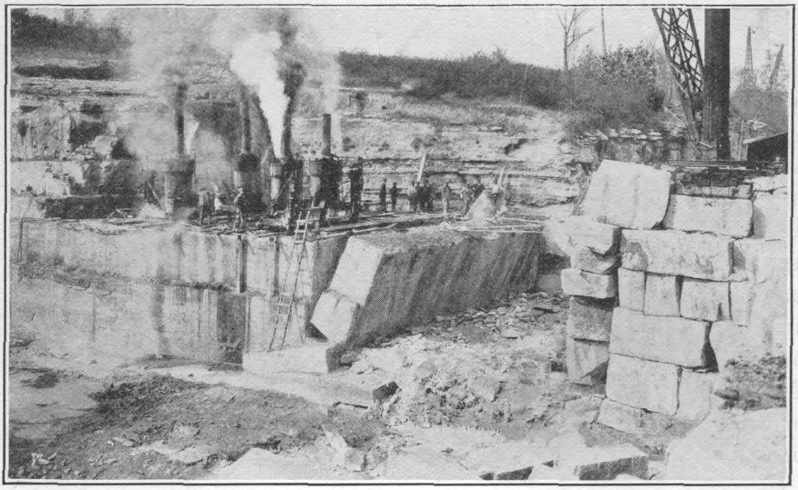
The curves for porosity and absorption in Plate 45, as is to be expected, have an opposite trend to that of specific gravity. Where this relation does not hold the samples may have contained an unusual number of air-tight pores, or there may have been an error in the performance or recording of the experimental work. Samples A5, A13, and A14y are noteworthy in this respect. The porosity and specific gravity curves from A14y to A5 both increase, but such a relation should be impossible, for porosity is calculated from specific gravity. The porosity of A14y should evidently be about 16, instead of 13.97.

A. STONE OF INFERIOR QUALITY WITH COMPARATIVELY FEW WEAK LAYERS OPENED BY FROST ACTION



B. STONE OF INFERIOR QUALITY WITH A VERY "RIFTY" STRUCTURE, IN WHICH PRACTICALLY EVERY LAYER HAS BEEN SPLIT BY FROST ACTION

BLOCKS CRACKED BY FROST ACTION ON SWAMPY FLOOR OF ABANDONED QUARRY JUST NORTH OF BEDFORD, IND.



A. VIEW SHOWING ONE STEP IN QUARRYING INDIANA OOLITIC LIMESTONE

The long tilted block or "cut" in the foreground is 60 feet long, 13 feet high, and 4 feet thick and weighs about 235 tons. It has been loosened from the ledge by cutting a vertical channel, drilling holes along its base, inserting wedges in the holes, and prying away from the floor. The *completely loosened block is being pulled over onto* its side by the derrick, and the force of its fall will be broken by the cushions of small stones on the quarry floor. The bedding, originally horizontal, will then lie vertical.

B. DARK HOLLOW QUARRY OF FORMER CONSOLIDATED STONE CO., NOW INDIANA LIMESTONE CO.

A loosened quarry block or "cut," tipped over, as in *A*, and partly cut into mill blocks by drilling rows of holes with a jack hammer drill and driving wedges into the holes until the block splits. The bedding as the loosened block lies is vertical. Most of the mill blocks will be so sawed and cut that the finished stone will be placed in the building with its bedding vertical. Each channeled layer or ledge of the stone is *10 feet thick*. *Beyond the ledge being worked is a hole that has been* worked to the bottom of the oolitic limestone and is now partly filled with quarry water and waste. Photograph furnished by former Indiana Limestone Quarrymen's Association, now research division of Indiana Limestone Co.

The percentage of porosity in all the samples is distinctly higher than the percentage of absorption by volume, and the failure of the two curves to remain parallel indicates variation in the quantity of air-tight pores. The most striking examples of this variation are samples A11, B16P, and C19. In grade AA, samples 5, 9, and 16P have relatively high percentages of air-tight pores. Sample 5 may represent the sample with the large " glass " spot, and therefore support the suggestion that deposition of secondary calcite, which accounts for the " glass " spot, has also produced an extra degree of cementation and strength, as well as air-tight pores. Sample 9, on the other hand, is comparatively weak and has a higher percentage of absorption. Sample 16P has only a moderate percentage of absorption and is moderately strong, in spite of the large number of conspicuous holes.

In grade A sample 8 is very porous and absorptive, as would be expected from its large number of minute and moderate-sized holes. Sample 2 also has a conspicuous number of minute and larger holes, but its " glass " spots and high specific gravity indicate that it is well cemented. Its ratio of absorption by volume to its porosity, however, is relatively high, indicating a relative scarcity of air-tight pores. Samples 7 and 23, on the other hand, have more conspicuous holes and correspondingly low specific gravity, but they also show low percentages of absorption and therefore must contain a large proportion of air-tight pores. Samples 13, 16P, and 9 are similar in porosity, and sample 16P, the most absorptive, has a large " glass " spot. Deposition of the secondary calcite that formed the " glass " spot was evidently too local to affect the absorptive quality and strength of the sample as a whole. The remaining samples, which were submitted as of grade A but which have conspicuous medium and large holes, show similar variations. Sample 14y is especially noteworthy as having the largest number of holes and the coarsest grain but among the lowest percentages of porosity and absorption and a medium specific gravity. The question arises as to whether the absorption tests could have been made on pieces relatively free from holes.

In grade B there are similar contrasts and abnormal relations among appearance, porosity, absorption, and specific gravity. The contrast between samples 2 and 16P is especially conspicuous. Sample 16P is the coarser grained and more porous but the less absorptive and must have a large proportion of air-tight holes. Sample 7 shows more holes than samples 2 and 16P but has a high specific gravity and low porosity and absorption. The holes evidently happened to appear on the surface but can not have been so numerous throughout the sample. The same abnormal difference appears between samples 19 and 23. Sample 23 has more conspicuous holes than sample 19 but a higher specific gravity and lower porosity and absorption. The same lack of consistent relationship between appearance and physical properties is shown in grade C.

The gray varieties, grades D and E, show the same general variations as the buff varieties (AA to C) but are on the whole less absorptive. Sample 20 in grade D, however, affords the most striking example of high porosity and low absorption. In grade H, sample 2 appears sufficiently dense and crystalline to be classed as a marble, but it has 6 per cent absorption by volume and 8 per cent porosity, whereas the well-known marbles of the Eastern States have considerably less than 1 per cent of either.

The degree of porosity shows that in wet or damp places moisture can readily penetrate the stone, which therefore must be coated or parged with some impervious material. Before quarrying the pores are filled with ground water, or "quarry sap," which has saturated the stone for so long a time that the water contains considerable calcium bicarbonate in solution, and the surfaces of each grain consist of a colloidal film of mutually absorbed calcite and water. These films permit an easy separation of the grains, and the freshly quarried or "green" stone is therefore softer and more easily cut or tooled than dried stone. When the quarried stone is thoroughly dried in the air, or "seasoned," this moisture is slowly removed, the surfaces of the grains become firmly cemented together, and the stone becomes appreciably harder. Were the stone to be immersed again for a long enough time, it would again tend to soften; in fact, Kessler[37] has found that softening due to soaking in water for 14 days causes an average reduction of 7 per cent in crushing strength. Under conditions of ordinary usage, however, rain water entering the pores of the stone is so quickly removed by wind and sun that no softening of the stone can take place.

RESISTANCE TO FREEZING

The differences between the seasoned and unseasoned stone account for the superior resistance of the seasoned stone to frost action. Examination of a great many buildings in different parts of the country has shown a very small percentage of weathering defects in stone of average quality or better that may be attributed solely to frost. Where defects were noted they occurred in inferior stone from quarries now abandoned or in places where frost had an unusual opportunity to act upon continually saturated stone.

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[37] Kessler, D. W., personal communication.

The unseasoned stone, on the other hand, which is thoroughly saturated and comparatively soft, has been much more seriously affected by frost; indeed, the exceptions noted in the preceding paragraph may have been due in part to the use of unseasoned stone as well as to its use in wet or damp places. Striking examples of fully saturated unseasoned inferior stone destroyed by frost on the swampy floor of an abandoned quarry are shown in Plate 39, and in scaling along channeled walls of a few abandoned quarries in Plate 27, *A*.

Inspection of the block shown in Plate 39, *A*, showed that splitting was favored where there were several relatively large, flat fragments of fossil shells parallel to the bedding in prevailingly fine-grained material. Comparison with more recently quarried blocks of similar irregular texture suggests that films of "limestone mud" may have coated these large fragments of shells, but the splitting took place long enough ago for all traces of the "mud" to have been removed in solution by rain water. Splitting had not taken place along the uniformly coarse-grained layers in this block but cut diagonally across them from one of the fine-grained layers to another. The block shown in Plate 39, *B*, had an unusually developed "rifty" structure with a sufficient quantity of "muddy" films along bedding and cross-bedding planes to retain moisture and permit splitting after repeated freezing. In contrast to this splitting along layers, fine-grained blocks without such highly developed rifty structure are inclined, if subjected to severe freezing before they become seasoned, to crack concentrically. Evidently the freezing of their surfaces produced no cracking, as the strength of the stone was at first sufficient to direct the growth of minute ice crystals inward along its pores; but as freezing progressed toward the center of the block this process reached its limit, and the remaining interstitial water, unable to move farther inward, had to make room for freezing by bursting the block. Concentric frost cracks may be an indication of good stone abused, whereas cracks along bedding planes indicate poor stone. Poor stone also tends to scale along channeled walls across the bedding, but most of the scaling along channeled walls noted by the writer occurred in shady places close to swampy ground, where even good stone is put to a severe test. Hopkins[38] stated that scaling took place only where the stone was coarse grained, and coarse-grained stone of poor quality may be seen at several abandoned quarries; but as seen by the present writer the texture of the stone had little influence compared with the character of its matrix and the position of the channeled wall in a place where continuous presence of shade and moisture gave frost an unusual opportunity.

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[38] Hopkins, T. C., and Siebenthal, C. E., op. cit., p. 321.

No scaling or other evidence of frost action on channeled walls was noted in any quarries that are allowed to fill with water during the winter or that have been recently abandoned. This fact indicates that considerable time for saturation with water and for repeated freezings without intervening opportunities for drying is necessary to produce scaling.

It is said that some quarry operators give little heed to seasoning, and that much stone has been cut and shipped without waiting to be seasoned and has not been later injured by frost. To account for this lack of injury it may be said that in some quarries the stone is so far above ground-water level that its moisture content is already comparatively small, and it undergoes considerable further seasoning from the time it is removed from the quarry until it is milled and finally placed in the building; and even after it is set in the building, most stone is placed well above ground, where it is exposed to much dry wind and sun and has far more opportunity to season than to be injured by frost. Experience has therefore shown that with much of the stone a special seasoning may not be necessary to prevent injury from freezing; but stone to be used in shady places, especially close to the ground, should certainly be thoroughly seasoned before being so placed.

It has sometimes been maintained that the ideal way for handling stone that requires seasoning is to mill it as soon as it is quarried and to allow the finished stone to season before use. This arrangement would require the obtaining of a contract before quarrying the stone and would require the builder to wait while the finished stone was seasoning. The principal argument in favor of such a plan is that the mineral matter dissolved in the "quarry sap" would be drawn to the surface of the finished stone and deposited, filling the pores and rendering the stone less subject to penetration by moisture; whereas if the stone is seasoned before milling this protective coating would at least in part be lost.

This method has seldom if ever been followed and probably can not be so long as modern methods and speed of erecting buildings are maintained. Furthermore, the protective coating, if it forms in considerable quantity, may disfigure the finished surface with white or colored stains and aid in injuring the surface of the stone, as shown on pages 164–165. On the whole, therefore, it is preferable to season the stone before it is milled into its finished form.

Freezing tests made on 35 samples at the Bureau of Standards gave generally satisfactory results.[39] The samples were first oven dried and then soaked for 14 days, and after each freezing they were

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[39] Kessler, D. W., and Sligh, W. H., op. cit., p. 551.

placed in water for 30 minutes. A few samples of different grades were practically destroyed in less than 200 freezings; 34 per cent of the samples were practically destroyed in less than 400 freezings, which are roughly equivalent to 100 years of exposure in a climate like that of Washington, D. C.; 38 per cent were not destroyed by 1,000 freezings, equivalent to 250 years of exposure, although many of them doubtless showed slight to considerable degrees of disintegration. The chief value of the tests is to express the degree of resistance in measurable terms and to afford comparisons of different stones. Those failing in less than 400 freezings have a relatively low resistance to frost and represent stone which should be used only in the less severely exposed parts of structures. The successful resistance of seasoned stone in ordinary correct usage has been amply demonstrated by actual experience, but these tests show that even seasoned stone will eventually be injured by frost if used where it will be frequently or continuously saturated with moisture.

Evidence as a whole, both from studies of buildings and from laboratory tests, is that stone of all the grades in actual use contains pores large enough to avoid long retention of water absorbed during rains and therefore to be practically immune to freezing. Exceptions are blocks with fine layers of calcareous " mudstone " or marl, inconspicuous cracks or dry seams along the bedding, or "crowfeet," containing a considerable quantity of bituminous shaly matter. Rarely the cohesion of the stone is deficient along a bedding plane, for no obvious reason but presumably because of a film of "mudstone." Such partings or planes of weakness are common in some sandstones and limestones but are very exceptional in the Indiana oolitic limestone. It is interesting to note that although the rustic stone (grade C) is comparatively coarse grained, some of it has been found to contain these defects. Although this grade of stone is prevailingly coarse grained, it is also uneven grained and may contain inconspicuous fine-grained streaks, partings, or " crowfeet " along the bedding. Stone of grade C and the still coarser-grained and more irregular " travertine " should be given more rigid inspection than the standard and select grades to avoid the placing of inferior blocks in very exposed positions. Such stone has adequate resistance for use in wall ashlar and other less exposed places above grade line.

CRUSHING STRENGTH

The crushing strength of the Indiana oolitic limestone, as shown by laboratory tests, has a considerable range and is dependent on the degree of seasoning and the degree of cementation or development of crystalline matrix. Data on crushing tests are also dependent on the testing machine used. The curves in Figure 26 represent crushing tests made with different machines and show a consistent variation. The tests made at the Bureau of Standards illustrate the range in crushing strength under uniform conditions of 72 samples of stone selected by a number of different companies to

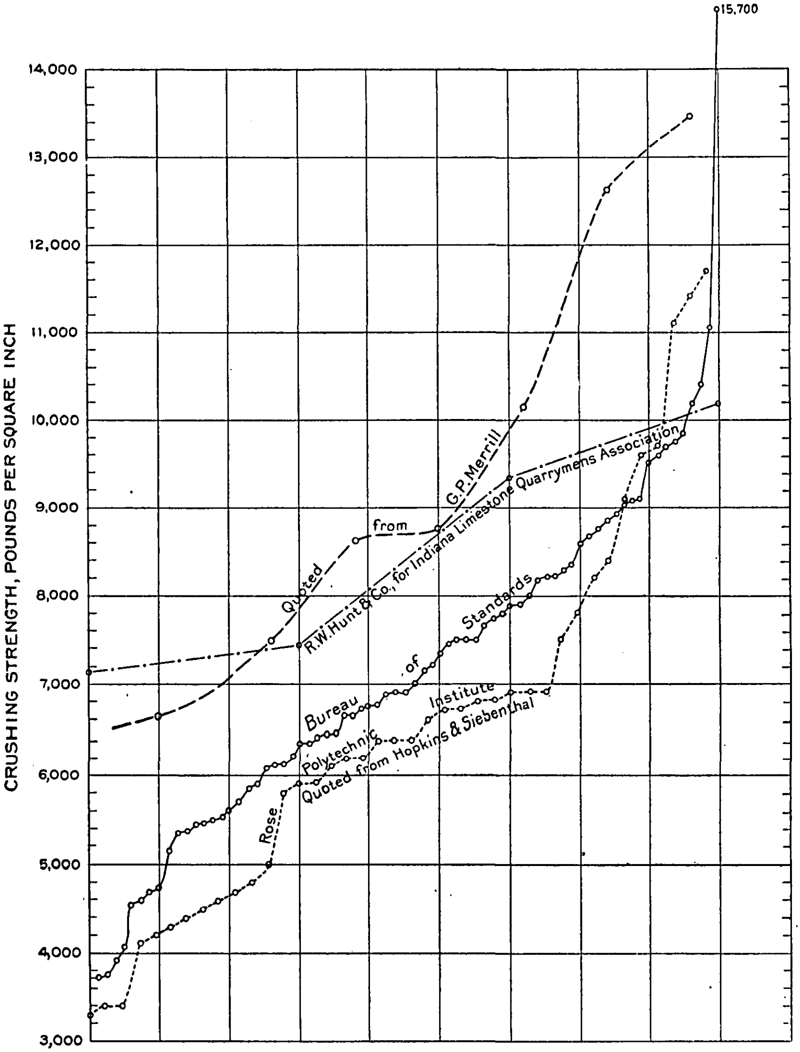

FIGURE 26.—Crushing strength of Indiana oolitic limestone determined at different laboratories, arranged in the order of increasing strength

illustrate the different grades quarried by them. These were dry samples crushed on bed. The ranges in strength of each grade of stone are shown in Plates 42 and 43. Specially hard, thoroughly crystalline stone is the strongest, but the other grades offer little choice, so far as crushing strength is concerned. Even the lowest strength recorded is well above the requirements of ordinary usage, but with so many quarries to choose from the weakest stone may well be avoided.

Differences in strength may be shown by cubes cut from the same sample block. A dry cube compressed "on bed," with the load applied perpendicular to its bedding, is supposed to offer the greatest resistance to crushing, and this relation is verified by a majority of the samples tested; but several wet cubes in similar position offered greater resistance than the corresponding dry cubes. A few cubes on edge, some of them even when wet, showed greater crushing strength than the corresponding dry cubes on bed. The results of the tests show considerable variation in crushing strength within a single block of stone, and it is a mere chance whether the stronger or weaker cubes have been tested on bed or on edge, dry or wet. This difference in strength of some sets of cubes more than offsets the weakening due to wetting. On the whole, however, the cubes on bed, whether wet or dry, show greater strength than those on edge.

Owing to the method of quarrying (pl. 40, *A*, *B*) many large blocks and practically all columns are likely to be placed in a building on edge, and for this reason the crushing strength of cubes on edge deserves particular attention. Very few of the tests, however, show less than 5,000 pounds per square inch, and unless the stone is intended to bear an unusually heavy load there is little or no reason for emphasizing crushing strength in its selection.

Occasionally stone of different kinds in old and even rather new buildings has spalled along the joints, and the spalling might, without due reflection, be attributed to incipient crushing; but in the great majority of such buildings the load on the stone is altogether too light to have had appreciable effect, and the true cause is likely to be faulty construction, whereby the load is concentrated upon a small part of a stone, or more likely whereby too little allowance is made for the expansion of stone exposed to much direct sunshine.

The effect of fatigue on the crushing strength of Indiana oolitic limestone is being tested at the Bureau of Standards, but no results are available yet.

TRANSVERSE BREAKING STRENGTH

The transverse breaking strength of a stone, like the crushing strength, should be well in excess of the load that is intended to be placed upon it. Transverse cracks in buildings, however, are seen altogether too frequently, not only in the Indiana oolitic limestone but in the strongest granite, and again the conclusion must be drawn that faulty construction or the uneven settling of buildings is usually to blame. Strong stone with no load on it has been cracked owing to the uneven settling of foundations or of soft ground. Stresses due to such causes evidently accumulate during some time and finally act so suddenly that the strain exceeds the resistance of the stone.

Tests made at the Bureau of Standards and quoted in Table 9 (p. 167) show that the transverse breaking strength of the Indiana oolitic limestone varies in general directly as the crushing strength. (See pls. 43 and 44, *B*.) On the whole, the strength of pieces tested at right angles to the bedding exceeds that of pieces tested parallel to the bedding. Exceptions to this general rule can not be explained without inspection of each piece before and after testing, but it is fair to assume that, as the stone differs in strength from place to place, the exceptional results are due to the chance selection of relatively weak pieces for testing at right angles to the bedding.

It is also noticeable that where the curves representing transverse strength at right angles to the bedding (pl. 44) differ from the corresponding curves for crushing strength (pls. 42 and 43) they conform to one or more of the other curves for crushing strength. This fact further emphasizes the original variations in strength in different parts of the same sample block, variations that more than offset the influence of soaking in water or, in some samples, variations in the direction of application of load.

Hopkins[40] quotes a series of tests by T. H. Johnson[41] intended to show the weakening effect of tool dressing on the stone. His results, which are interesting but of little value, showed that tool-dressed small samples had less than two-thirds the strength of sawed samples and that the sawed samples were resonant when struck by a hammer, whereas the tool-dressed samples gave a dull sound; but as the two sets of samples came from different quarries the differences may have been mainly inherent in the stone. It is very improbable that the effect of modern tool dressing penetrates more than a small fraction of an inch below the surface of the stone. This amount may be enough to weaken small test pieces but is of no consequence in even the smallest commercial blocks.

PART 2. THE GRADING OF INDIANA OOLITIC LIMESTONE

From what has been said in the preceding pages, it is obvious that hard and fast rules can not be too rigidly applied in the acceptance or rejection of any particular grade of stone without causing needless waste of good material and unnecessary increase in the time required for quarrying the stone and completing a building. On the other hand, some limit to the variations in color, composition, texture, and structure of a stone must be established if the appearance of the

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[40] Hopkins, T. C., and Siebenthal, C. E., op. cit., p. 318.

[41] Johnson, T. H., Experiments upon the strength and elasticity of building stones: Indiana Dept. Geology and Nat. Hist. Eleventh Ann. Rept., pp. 34–42, 1881.

stone in a building is to be reasonably uniform or if differences in color and texture are to be gradual and confined within certain limits.

GRADES OF INDIANA OOLITIC LIMESTONE

In order to establish a fair range in the variation of physical and chemical properties of the different grades of stone, samples were submitted by most of the quarry companies in the Bedford-Bloomington district, representing such grades as they produced. Each company was designated by a number. Each sample quarried was 28 inches long and 12 inches square. Two slabs, each 2 inches thick, were sawed from the ends of each sample, one slab to be stored for reference at the office of the former Indiana Limestone Quarrymen's Association, the other at the Bureau of Standards in Washington. The rest of each sample, after inspection of its color, texture, and structure, was shipped to the Bureau of Standards, sawed into test pieces, and used in determining physical properties.

The stone had practically always been classified as buff or "blue" (gray), and each class subdivided as No. 1, or fine, uniform grained, and No. 2, or coarser, less uniform grained stone; but each operator had his own idea of where the line of distinction between No. 1 and No. 2 should be drawn. Stone of mixed buff and "blue" (gray) color or of too coarse grain to be accepted as the loosely defined No. 2 stone was wasted or shipped for breakwater stone, furnace flux, and other by-products. The fact that the very fine, uniform-grained buff stone had been the principal variety marketed in the early days of the district and had become regarded as typical Indiana oolitic limestone created for many years an unfavorable impression toward other varieties of the stone that were much more abundant, and specifications for many large buildings insisted upon the fine, uniform-grained stone throughout the building, when in reality the difference in appearance between No. 1 and No. 2 stone was apparent only at close range. A conception had also grown in many minds that the No. 2 stone was not only coarser grained than the No. 1 stone but of inferior quality in other respects.

Consideration of these conditions by producers and leading architects, as well as the tendency to get away from strict monotone effects in buildings, gradually led to the adoption of the following more rational grading of the stone by the Indiana Limestone Quarrymen's Association in 1917:

Grades of Indiana oolitic limestone[42]

Buff stone:

- AA. Select buff statuary, of extra fine and uniform grain, especially adapted for carving.
- A. Select buff (formerly "No. 1"), of generally fine and uniform grain with a minimum of conspicuous "glass" spots or seams, shell holes, and other irregularities.
- B. Standard buff (formerly "No. 2"), of less fine and uniform grain, but not coarse grained; with only a few "glass" spots, shell holes, and other irregularities.
- C. Rustic buff (formerly "coarse"), of irregular, prevailingly coarse grain, usually with conspicuous fossil shells, shell holes, or "glass" spots, and other irregularities.

Gray (formerly "blue") stone:

- D. Select gray (formerly "No. 1"). Similar to A above.
- E. Standard gray (formerly "No. 2"). Similar to B above.
- EE. Rustic gray. Similar to C above.

Variegated (buff and gray) stone:

- F.[43] Select variegated (formerly "No. 1"). Similar to A above.
- G.[43] Standard variegated (formerly "No. 2"). Similar to B above.

Special grades:

- H. Special hard, as represented in Plates 41–44.
- I. Indiana travertine, cellular buff stone, too coarse grained for grade C.
- J. Old Gothic, unselected as to color and texture. Includes buff, gray, and variegated stone ranging from fine to very coarse but for the most part fairly coarse grained. Some pieces may have prominent shell holes, white or glassy streaks, tight crowfeet, and any other markings that exclude them from the other grades but do not affect soundness. This grade presents the widest variation in color and texture.
- K. Short length, sawed strip stone produced from a mixture of short mill blocks less than 6 feet in length or of such irregular shape that rectangular slabs exceeding that length can not be obtained from them. Equal to the regular grades in chemical and physical properties, and well adapted for range work and random ashlar.

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[42] After completion of this report the Indiana Limestone Institute, Bedford, Ind., comprising most of the companies operating in 1928, issued a report of its special committee on "grading and uniform classification of Indiana limestone." This committee adopts the same grouping as that given here, with the following exceptions: Grades F and G are combined under the term "variegated" stone; "special hard gray" and "special hard buff" stone are separately listed, and both have the same textural limitations as "select" stone; "Indiana travertine" is no longer listed, but much of the stone that used to be so classified is included in "rustic" and "old Gothic" stock. Specifications for most of the grades do not state sizes of grain but refer to samples or photographs of samples which show maximum and minimum fineness of grain and which agree closely with sizes stated in the table on p. 188. Some of the restrictions regarding shell holes, "glass" spots, and white or glassy streaks are slightly more severe and some slightly more tolerant than those in this report.

[43] Grades F and G were separate when the samples represented in Plates 41–44 were tested, but recently the term "variegated" has been used to embrace the entire range of texture represented by grades A, B, and C and is designated G in the classification. The finest and most uniform grained stone is separately designated as F, "variegated statuary" stock, and is similar in texture to AA.

The samples of different grade as designated by each company and submitted for testing are indicated in the table below. Tests of grades not represented would afford no additional significant data.

TABLE 10.—*Samples of Indiana oolitic limestone submitted for testing*

Key No.	Name of company	Location of quarry	AA	A	B	C	D	E	F	G	H
2	Bedford Stone & Construction Co.	Bedford		X	X	X	X		X		X
4	Chicago & Bloomington Cut Stone Co.	Bloomington		X							
5	Consolidated Stone Co.[a]	Dark Hollow	X	X	X	X	X	X	X	X	
6	Crescent Stone Co.[a]	Hunter Valley		X							
7	Doyle Stone Co. (Inc.)[a]	Dark Hollow		X	X		X	X	X	X	
8	Empire Stone Co.	Sanders		X	X	X	X		X		
9	Furst-Kerber Cut Stone Co.[a]	Needmore	X	X	X	X					
10	J. Hoadley & Sons Co.[a]	Hunter Valley	X	X	X	X					X
11	Hunter Bros. Co.	do		X	X		X				
13	Ingalls Stone Co.	Peerless		X							
13R	do	Oolitic		X							
14	Indiana Quarries Co.	do			X						
14x	do	Horseshoe		X	X	X		X			
14y	do	do		X		X		X			
16P	W. McMillan & Son[a]	Peerless	X	X	X	X			X		
16R	do	Reed Station		X	X						
16x, y	do	do		X							
16S	do	Sanders			X	X	X				
16x, y	do	do	X	X	X						
19	National Stone Co.[a]	Clear Creek		X	X	X	X	X			
20	C. S. Norton Blue Stone Co.	Spider Creek					X				
23	Shea & Donnelly Co.[a]	Eureka	X	X	X	X	X	X	X	X	

[a] Merged into Indiana Limestone Co., May, 1926.

CRITERIA FOR GRADING

The principal properties by which the stone is graded, as shown in the foregoing summary, are color and fineness of grain. Other characteristic markings, such as shell holes, "glass" spots, and veins or "seams," are usually regarded as objectionable in any of the select and standard grades, but as they are characteristic features of the whole oolitic limestone formation and likely to be found to some extent in any part of it, and particularly as they affect only the appearance of the stone at close range and are not at all objectionable with respect to durability, a certain degree of tolerance should be allowed for them. A few comments on these principal and minor features will emphasize the care and discretion that should be used in grading the stone.

Color.—Although only two distinct colors, buff and gray, are recognized, there are different shades of each color. Some of the buff is so pale as to be nearly white, some is light, and some is comparatively dark; but commonly only one shade of bluff is prominent throughout a considerable mass of stone, and where layers of different fineness of grain are of different shades of buff the two shades blend, especially on surfaces that are approximately parallel to the bedding. Even on exceptional stone, with alternating layers of nearly white and medium buff color, the contrast is marked only on surfaces at right angles to the bedding and decreases as the stone ages. In short, although it is conceivable that variation in the shade of buff may now and then be of some consequence in acceptance of statuary (AA) stock, it is rarely if ever of consequence in the acceptance of select (A) stock and never in the acceptance of standard (B) or rustic (C) stock.

Shades of gray range from rather light to dark in different quarries, but no noteworthy variation has been noted at any one place, and no further comment regarding them is necessary here. The substitution of the word "gray" for "blue" is advisable, as blue refers more to stone as seen in the quarries before it has dried, whereas gray applies to the dry stone as it appears in buildings. There has been an old prejudice against the word "blue," as quarrymen years ago were inclined to avoid or discard it in their efforts to produce the buff stone, more familiar to builders. Comments have been made and the writer has read a consulting engineer's report to the effect that the blue stone was not durable, owing to the presence of some organic matter. A building inspector was once heard to say that the blue stone was inferior to the buff because the buff color had been taken out of it, when in fact the reverse of this change was true. There is no difference between the gray (blue) and buff stone in durability. Theoretically leaching by water above the groundwater level should render the buff stone somewhat less strong than the gray stone, and this difference is generally but not entirely borne out by the comparative crushing strength of grades A: D and B: E, as shown in Plates 42 and 43.

The variegated stone shows without exception a sharp boundary between its buff and gray portions. As it is used where contrast within a single block is desired, no further comment is necessary.

Uniform

Fineness and uniformity of grain.—Deposition of the Indiana oolitic limestone in shoal water by shifting currents that were continually changing their velocity to a slight or considerable extent implies that absolute uniformity of grain is not to be expected. Where an approach to uniformity is desired, as in the statuary (AA) and select (A) grades, variations in fineness of grain should be small and should blend into one another. The blending is better obtained on surfaces cut about parallel with the bedding. Where single layers are as much as half an inch thick, and the stone is not cross-bedded, a surface may be cut entirely along one layer and may show marked contrast to a surface cut at right angles to the bedding. As small, flat shell fragments are easily floated and transported by moving water, it is common to find them in the finer-grained layers of the stone, which were deposited in comparatively quiet water. These shells prevent absolute uniformity of grain even in a single layer of stone but are not conspicuous in the finer-grained grades.

As the stone becomes coarser grained the uniformity of grain and the blending of adjacent layers decrease, and variation in texture is therefore to be expected in the standard grades (B and E). If a mill block is largely of one grade but contains considerable coarser-grained streaks at one end, it is the practice in the district to classify this block one grade below that of its prevailing texture.

The individuality of the coarse-grained stone (C) and the extra coarse grained "travertine" depends on marked lack of uniformity. If these stones are to be used in the interiors of buildings no thought need be given to their durability; but if they are to be used in conspicuous places out of doors they should be carefully inspected for very thin layers or films, some of them almost microscopic, of extremely fine-grained material, along which the stone may split if subjected to repeated action of frost. It is a curious fact that these extremely thin layers of the finest-grained material are more prevalent in the very coarse grained stone than elsewhere. This condition is due to deposition in shallow water, where relatively swift currents were occasionally interrupted by periods of quiet, during which films of limestone mud were deposited over the coarse-grained material. In places groups or nests of relatively large mollusks, with shells from half an inch to more than an inch in diameter, accumulated, and the interstices among them became filled with the limestone mud. The resulting stone is of such uneven hardness that it is discarded unless there is a special demand for it.

A few quarries have been opened in stone which is of fine enough average grain to be of standard or even of select grade but which contains an unusually large amount of extremely fine grained material, or "limestone mud," and therefore has an unusually low resistance to chemical and mechanical weathering. Chemical weathering rapidly dissolves this "mud," leaving isolated shell fragments in too prominent relief and wearing away the surface as a whole to a conspicuous degree. Frost action is likely to cause scaling along the surface of such a stone, no matter whether it is along or across the bedding. Seepage through imperfections in roof or backing will do far more rapid and serious damage to this inferior stone than to the recognized standard and select stone. Quarries of this kind of stone are soon abandoned, and there is extremely little chance that such material will be found in shipments from well-established quarries in the more productive areas of the region; but as new openings are made, especially in unproved areas, inspectors should assure themselves that the stone is free from objectionable quantities of this "limestone mud," either distributed throughout the stone or localized as almost invisible films along certain bedding planes.

Cross-bedding.—Cross-bedding in some degree is prevalent throughout the formation and may be expected in any grade of stone. In the grading of stone, cross-bedding should be regarded in the same way as ordinary bedding—that is, it should be determined

No cross bedding

whether the layers as a whole are of sufficiently fine and uniform grain or blend sufficiently to comply with the requirements for any particular grade. So long as these requirements are fulfilled, single blocks of stone may show both cross-bedding and ordinary bedding, if set on bed, without detracting from the appearance of the structure. If stones are set on edge, as is the more common practice, their surfaces bevel the layers of cross-bedding, and if some layers are distinctly coarser grained than others or contain a relatively large number of flat shell fragments, the variation in fineness of grain is emphasized. It is not very conspicuous, however, in the select and statuary grades, where the blending of layers is highly developed. In the standard grades it may be a prominent feature, and its appearance may be preferred by architects who wish to avoid the relatively monotonous uniformity of the select grades.

Objections to cross-bedding have been expressed now and then, to the effect that it indicates inferior weathering quality. It is true that certain cross-bedded stones of inferior weathering qualities may be cited from different parts of the world, and specific examples may be cited from certain places in the Indiana oolitic limestone; but this objection is not justified for the formation as a whole. The inferior cross-bedded stone, so far as noted by the writer, is mostly confined to the top and bottom of the formation, where conditions of deposition were the most variable and where films of " limestone mud " were most prevalent. Where these films were deposited between layers of cross-bedded stone there is the same tendency to split as was described on page 129. Where inferior stone of this kind has been exposed in outcrops or in the tops of quarry walls it has been split into parallel inclined slabs. Similar splitting has been noted at a few places in buildings, notably the steps of the State Capitol at Indianapolis, Ind.

These occurrences, however, are exceptional. Good stone with cross-bedding is exposed in many outcrops and old quarries. Where protracted erosion of outcrops along intersecting fissures or " mud seams " has reduced the originally continuous rock to a cluster of pinnacles, cross-bedded stone within any pinnacle is perfectly sound and will make excellent building stone if the pinnacle is large enough to permit economical quarrying. Cross-bedded stone that has not split after subjection to thousands of years of such natural weathering will be in no danger of splitting or scaling in a properly constructed building. To avoid the exceptional inferior cross-bedded stone, the same precaution is recommended as before—to watch for films of " limestone mud " and to discard the stone containing them, unless it is intended for interior use or is to be well protected from moisture and frost action.

Shell holes and "glass" spots.—Just as a few complete bivalve shells are found among the many broken shells on a modern beach, so a few complete shells are found among the shell fragments in the Indiana oolitic limestone. These shells appear on the surface of the stone as holes that range in diameter from that of pin pricks to half an inch or more. Their size varies directly with the texture of the stone, but their diameters are distinctly greater than those of the adjacent grains. As shown on page 171, they are everywhere too few to affect the strength or permeability of any grade of the stone, except perhaps some of the "travertine," where they are unusually abundant. Their only noteworthy effect is on the appearance of the stone at close range. They are more likely to be present in conspicuous amount in stone of standard than of select grade, but now and then stone otherwise of select grade contains an unusually large number of shell holes as much as 2 millimeters (0.08 inch) in diameter. Such a stone could not perhaps be accepted where minute details are very important, but in the ordinary use of select stone an occasional block containing several small holes will not seriously affect the appearance.

As "glass" spots are complete shells with the interiors filled by colorless calcite, the remarks in the foregoing paragraph apply to them also. Deposition of this secondary calcite tends to increase the strength of the stone and to decrease its porosity but has been too local for "glass" spots to be a reliable indication of superior strength. "Glass" spots, if very small, have no appreciable effect on the appearance. If comparatively large, as in some stone of standard grade, they may be objectionable where the stone is to be used in a very conspicuous place, but otherwise there can be no serious objection to them.

"Glass" seams and dense calcite seams.—"Glass" seams, as shown on page 139, are veinlets of colorless calcite that have filled cracks and thereby recemented fractured stone. All stages are possible, from empty cracks though partly developed to completely developed veins, and the degree of cementation differs accordingly. Imperfectly cemented stone is likely to crack again during quarrying or gang sawing and any stone with "glass" seams that passes these operations is not likely to give trouble. It is well, however, to be sure that "glass" seams thoroughly fill the cracks in which they have formed.

The seams or veinlets of dense buff or gray calcite were evidently formed before the stone became thoroughly solid and became thoroughly knit to the stone during consolidation. Although they resemble in appearance and composition the thin layers and films of "limestone mud" that are so objectionable along the bedding of the stone, they are much more thoroughly consolidated and present greater resistance to the saw than the stone itself does. No evidence of inferior strength or weathering quality has been noted along these seams, and, like the thoroughly developed "glass" seams, "glass" spots, and shell holes, they need be considered only with reference to appearance. They may be objectionable where detail is essential, but few of them are to be expected in any large shipment. If a block of otherwise select (A) stone contains a diagonal streak or seams of either kind of material and could be split into two "short-length" select blocks, it is the practice in the district to reduce this block to the standard (B) grade.

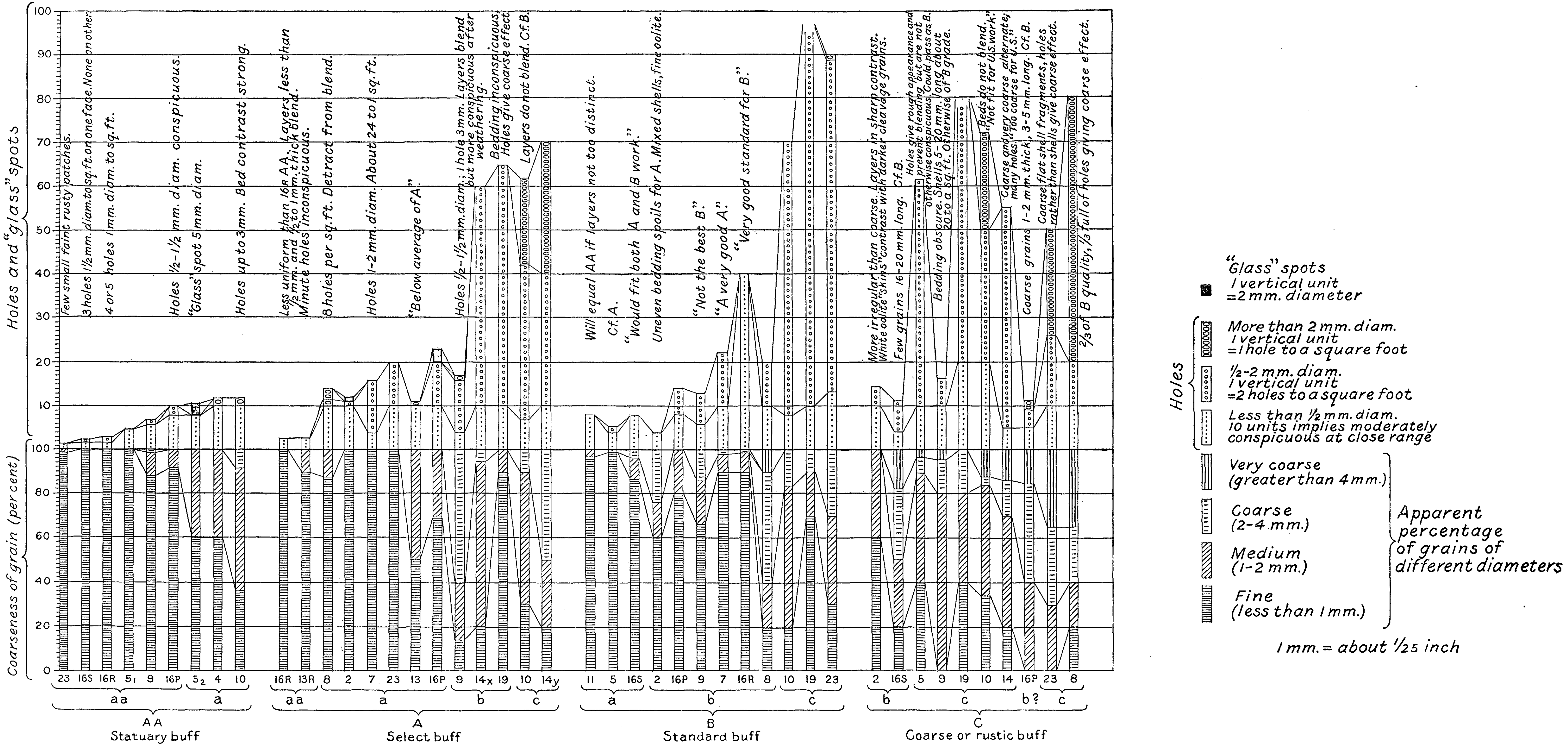
"*Crowfeet.*"—"Crowfeet" or stylolites, described on page 135, have little effect on the durability if they are very small, but as they consist of bituminous clayey material that is subject to rapid disintegration when exposed to the weather, stone containing them should be used with caution. Stone on parapet walls has been known to split along or close by "crowfeet" after exposure for a few winters. Even the smallest "crowfeet" should not be permitted in statuary or select stone. Only the smallest should be permitted in an occasional block of standard stone, and stones containing them should not be visible at close range, where the weathering out of the clay film will appear conspicuous. A stone set on edge may contain a "crowfoot" that does not come within an inch or two of the exposed surface. There is no objection to the use of such a stone, provided the "crowfoot" does not weaken the stone too much for the position in which it is to be set. "Crowfeet" that undulate very slightly and also thick "crowfeet" may contain sufficient soft shaly material to produce such a weakness, unless the projecting points of stone along both sides of them interlock over a distance sufficient to offset the weakening effect of the shaly material. The thick "crowfeet," however, are likely to be found only in shipments of "old Gothic" stone, which includes all varieties of reasonably sound stone found in the Indiana oolitic limestone.

CHARACTERISTIC FEATURES OF EACH GRADE AND RECOMMENDED SPECIFICATIONS

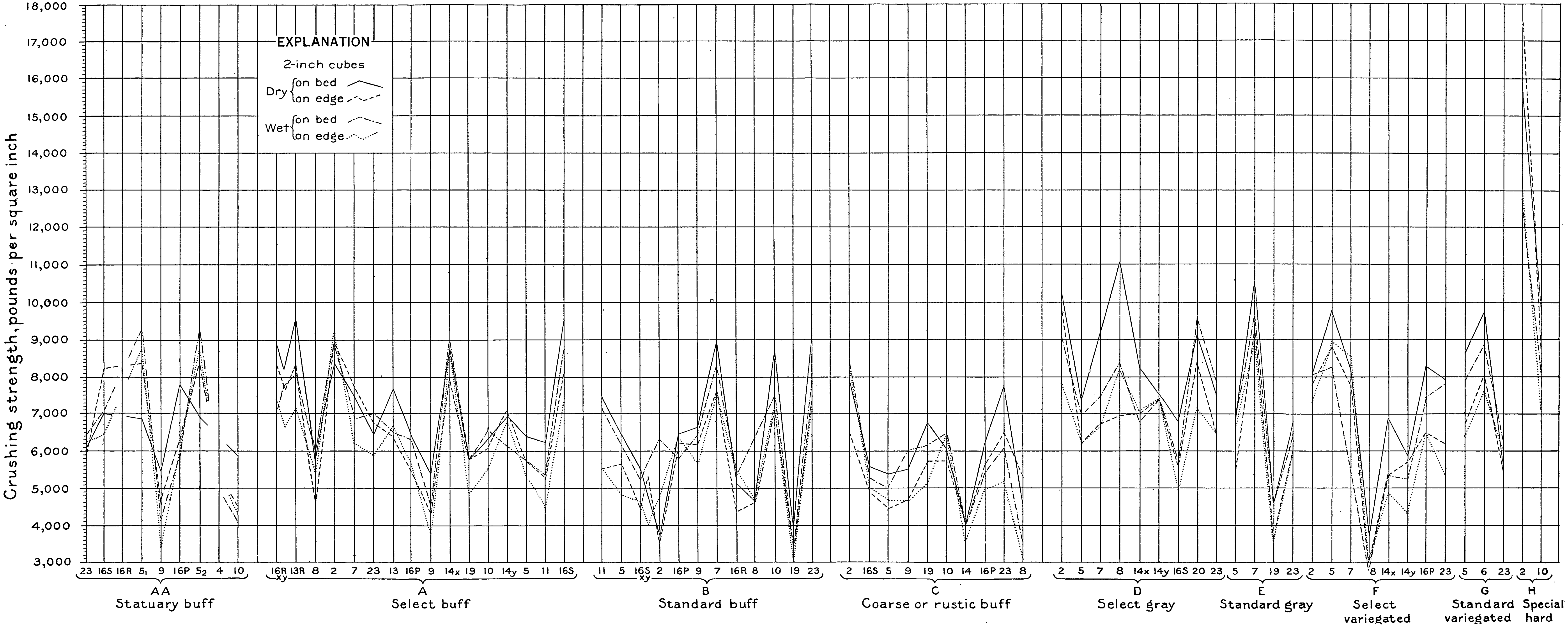
EXPLANATION OF DIAGRAMS

The characteristic features of each grade submitted, as represented by the samples, are described below and are represented diagrammatically in Plates 41–45. Proposed specifications for each grade follow the respective descriptions and are presented together in Table 11. Only Plate 41 needs a special explanation, as the other diagrams are ordinary curves representing the results of physical tests.

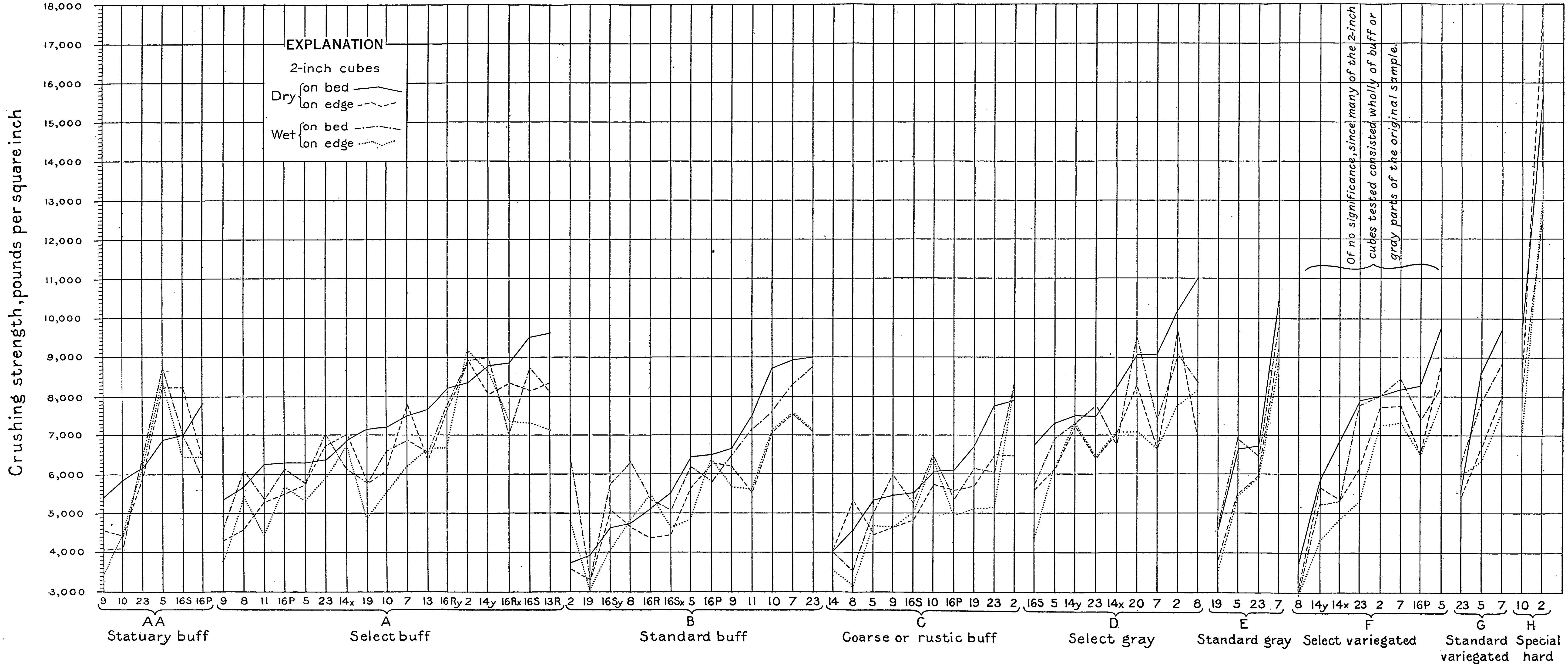
Plate 41 is intended to express graphically the relative appearance of the samples examined at Bedford, Ind., in 1917. Each company



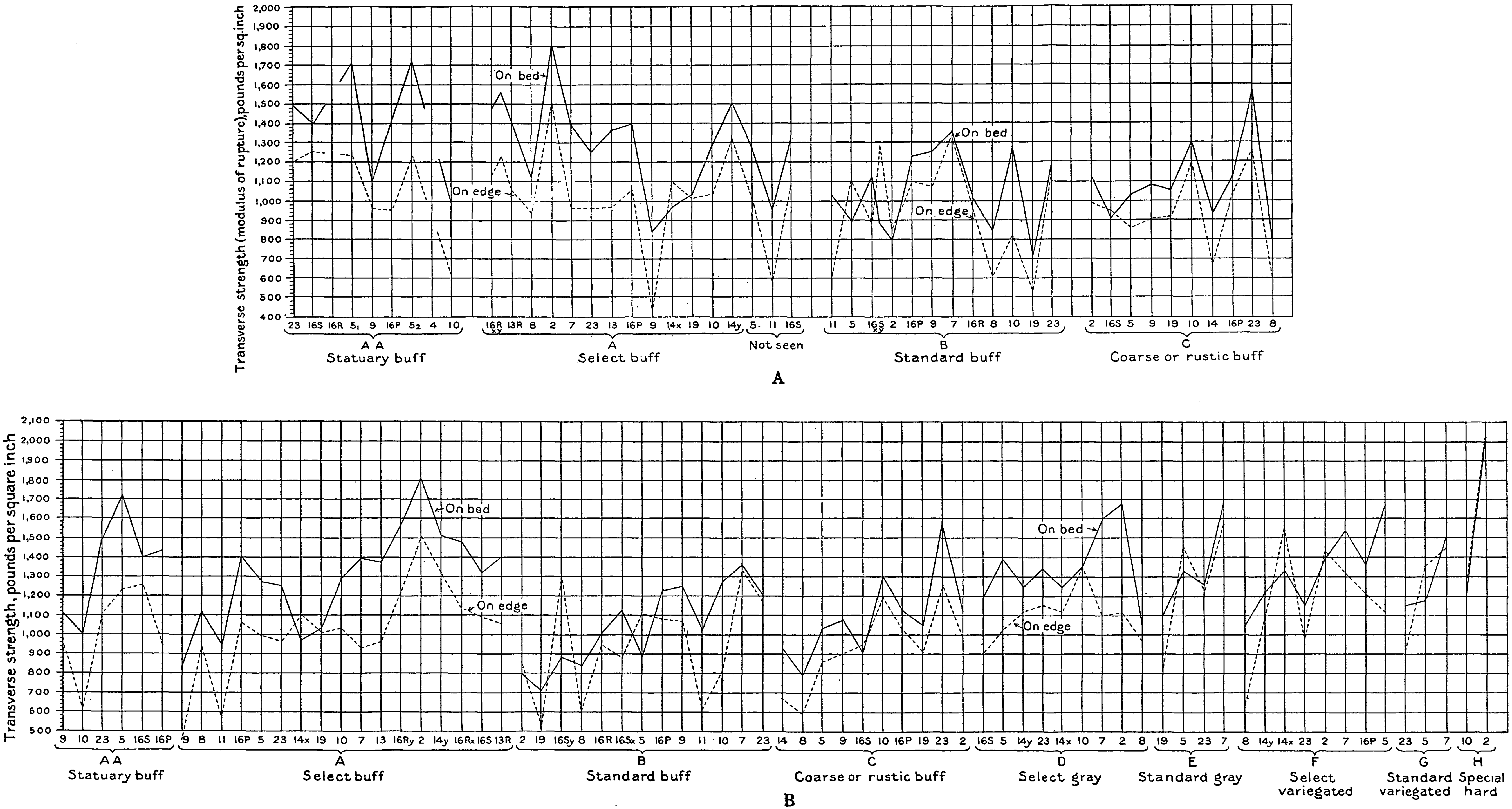
TEXTURE OF DIFFERENT GRADES OF INDIANA OOLITIC LIMESTONE



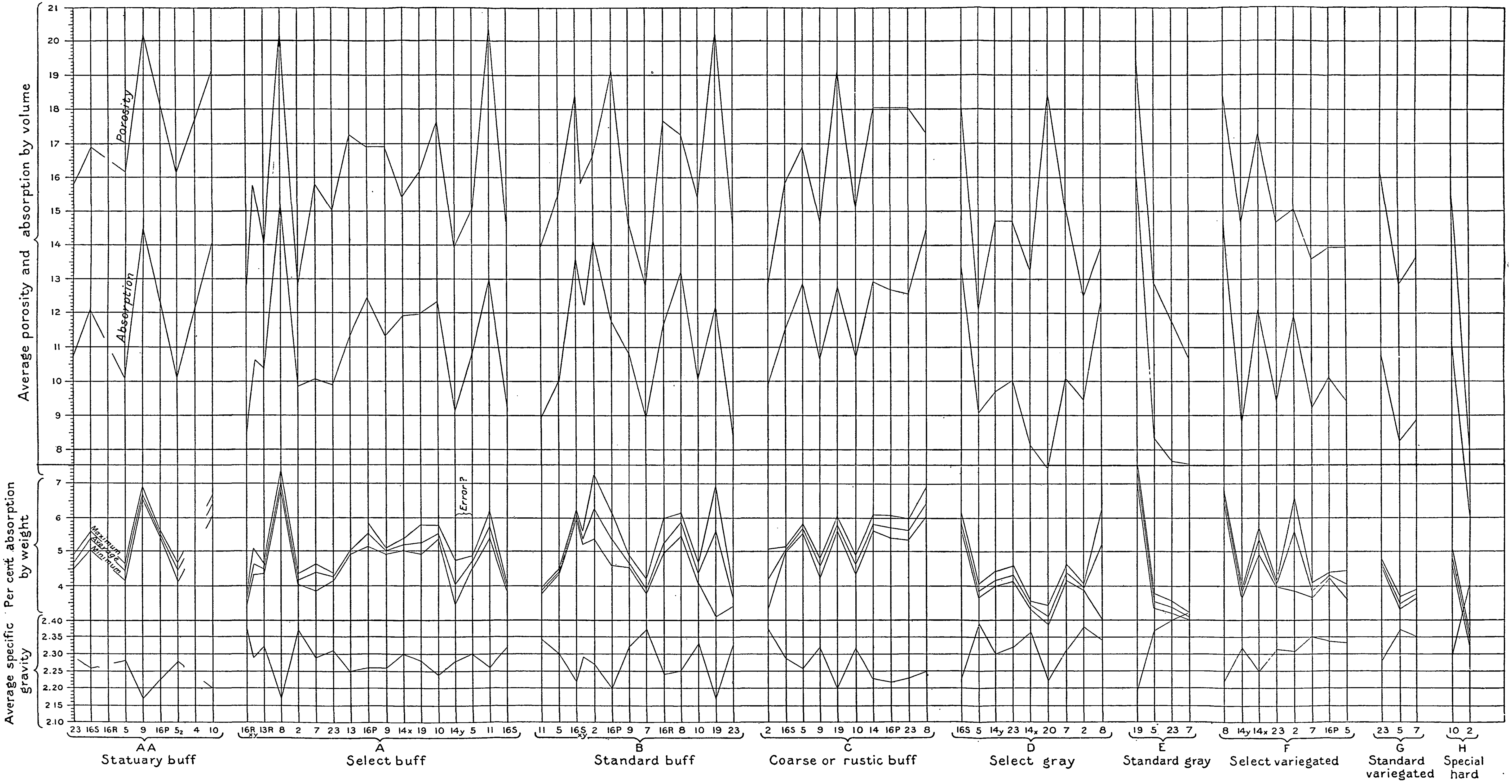
CRUSHING STRENGTH OF DIFFERENT GRADES OF INDIANA OOLITIC LIMESTONE, ARRANGED TO CONFORM WITH THE TEXTURE DIAGRAM IN PLATE 41



CRUSHING STRENGTH OF DIFFERENT GRADES OF INDIANA OOLITIC LIMESTONE, ARRANGED IN ORDER OF INCREASING STRENGTH OF DRY CUBES CRUSHED ON BED



TRANSVERSE STRENGTH OF DIFFERENT GRADES OF INDIANA OOLITIC LIMESTONE, ARRANGED (A) TO CONFORM WITH THE TEXTURE DIAGRAM IN PLATE 41, (B) IN ORDER OF INCREASING CRUSHING STRENGTH



POROSITY, ABSORPTION, AND SPECIFIC GRAVITY OF DIFFERENT GRADES OF INDIANA OOLITIC LIMESTONE

Grades AA to C conform with the texture diagram in Plate 41; grades D to H are shown in order of sample numbers rearranged according to Plate 43.

was given a number, and all the samples from one company were designated by the same number accompanied by a capital letter to designate its grading by the company. The diagrams representing the samples are grouped in Plate 41 according to the company's grading, and each grade is designated by a capital letter. This arrangement shows the general similarity of opinion regarding the different grades but also emphasizes differences in opinion. If a sample originally submitted in one grade proves after examination to belong to a higher or lower grade, the grade to which it should be transferred is indicated by a small letter; thus grade A, as originally grouped, contains stone designated aa, a, b, and even c, and a sample may be referred to by both number and letters, as sample 4 in Group AA (a), or as sample 19 in Group A (b).

The size of grain, expressed in apparent percentages, is based on a close but not too detailed observation, which can be made quickly. Exact measurements on these samples, as on rocks in general, would undoubtedly prove the actual average size of grain to be much less than the apparent average indicated by the diagram. For example, a sample consists of alternating fine and coarse grained layers. The finer layers, which contain no conspicuous grains more than 1 millimeter in diameter, constitute 60 per cent of the surface cut across the bedding; the coarser layers, in which grains from 2 to 4 millimeters in diameter or length are conspicuous, constitute the remaining 40 per cent. These percentages are expressed below the heavy horizontal line. (See sample 4 in Group AA (a).) If minute holes, less than 0.5 millimeter (one-fiftieth inch) in diameter, are abundant on close inspection, an arbitrary distance equal to 10 per cent of the graduated scale at the left of the plate is laid off above the heavy horizontal line. If larger holes are present they are represented on the upper end of the bar according to the explanation on Plate 41. As these holes are very conspicuous, even though few in number, they are represented on the diagram in a correspondingly conspicuous manner. Thus, sample 16S in Group AA contained one hole between 0.5 and 2 millimeters in diameter to a square foot of surface; sample 10 in the AA (a) group contained two holes to a square foot, each of them more than 2 millimeters in diameter. The calcite or "glass" spots are similarly treated. No sample examined contained more than one glass spot to 2 square feet of surface.

SPECIFICATIONS FOR DIFFERENT GRADES OF INDIANA OOLITIC LIMESTONE

The following table sets forth the characters of the different grades of Indiana oolitic limestone and gives the limits of variation within each grade according to the proposed specifications.

TABLE 11.—*Limits of variation for grades of Indiana oolitic limestone*

Grade and symbol	Percentage of grains of different diameters				Number of holes of different diameters per square foot			Number of "glass" spots of different diameters per square foot			Remarks
	1 mm.	1–2 mm.	2–4 mm.	4 mm.	0.5–2 mm.	2–4 mm.	4 mm.	2 mm.	2–4 mm.	4 mm.	
Statuary (AA):											
Range	100–80	0–20			0–4	0–1	0	0–4	0–1 in 10 sq. ft.		Layers must blend.
Tolerance [a]	70	30									
Select (A):											
Range	100–50	0–50	0–10		2–25	0–1 in 5 sq. ft.		0–10	0–1 in 5 sq. ft.	0–1 in 10 sq. ft.	Layers must blend. Maximum coarseness together with maximum number of holes or spots in a single block reduces stone to grade B.
Tolerance [a]	40	60	10								
Standard (B):											
Range	90–20	10–80	0–60	0–20	0–100	0–2	0–1 in 10 sq. ft.	0–20	0–2	0–1 in 5 sq. ft.	Blending of layers not necessary. The greater the number and size of holes, the finer should be the average grain. Maximum coarseness together with maximum number of holes or spots reduces stone to grade C.
Tolerance [a]	0	100			110	3	1	30	4	1	
Sub-B: [b]											
Sample 9, grade C	0	80	15	5	12	0	0				
Sample 16P, grade C	0	40	45	15	8	0	0				
Sample 14, grade C	20	50	16	14	100	0					
Rustic (C):											
Range	70–0	20–65	5–70	0–40	20–200	0–60	0–50	0–50	0–10	0–5	Blending of layers not necessary. No restrictions regarding relations between coarseness of grain and number of holes in determining maximum limit of coarseness.
Tolerance [a]		90	100	100							
Select gray (D)	Same as for grade A				Same as for grade A			Same as for grade A			
Standard gray (E)	Same as for grade B				Same as for grade B			Same as for grade B			
Rustic gray (EE)	Same as for grade C				Same as for grade C			Same as for grade C			
Select variegated (F)	Same as for grade A				Same as for grade A			Same as for grade A			Variegated stones of fine, medium, and coarse grain are now placed in one grade designated G; and F ("variegated statuary") is equivalent to AA.
Standard variegated (G)	Same as for grades B and C				Same as for grades B and C			Same as for grades B and C			
Extra hard (H)	No restrictions				Not even the most minute holes should be visible if stone is to be used as marble.			No restrictions			

[a] A few blocks with these textures may be used with discretion among blocks that fall within the limits of the respective grades.

[b] Grade sub-B includes stone that would not ordinarily be classed as grade B but that could with good judgment be used in considerable quantities with typical grade B stone.

The limits of each grade are necessarily expressed in definite figures, but it would be ridiculous to propose that an inspector should carefully measure each block in a large consignment. It is only reasonable, however, for the sake of uniformity in grading, for everyone concerned to grade the stone for a short time with the aid of a millimeter scale or an equivalent scale in inches (1 millimeter=one twenty-fifth inch) until his eye becomes trained. Thereafter a scale is not necessary, unless two persons experienced in grading differ in classifying a stone that is transitional between two grades. A few transitional stones may be found in any large shipment, as a single mill block (pl. 40, *B*) may range from one grade to another in texture. To avoid difficulty in disposing of such stones, a small percentage of them should be tolerated, and the limits of grain to be tolerated in any grade are suggested in the table. These limits may apply to mill blocks as well as to finished stone, and where the limit of toleration is exceeded, the present practice of reducing the stone one grade should be continued. (See pp. 183, 186.)

GRADE AA, "STATUARY BUFF"

Nine samples marked "AA" were submitted, and their numbers are shown in the accompanying diagrams. Although they were selected by the quarrymen as representative samples, it is not to be supposed that the best-appearing sample according to the diagram can be quite equaled by every block that may be offered as of grade AA from that particular quarry, or that a conspicuous hole or a "glass" spot in the sample submitted implies that every block from that quarry will contain a proportional number of holes or "glass" spots. It may be that a rough block free from holes or spots was selected at the quarry, and that the hole or spot was exposed after sawing. This further illustrates the need of a certain tolerance that is suggested below—less for grades AA and A than for other grades.

Of the nine samples submitted, four consisted almost entirely of fine-grained material, as seen on surfaces across the bedding; minute holes were not conspicuous, and in only two were holes with diameters of 0.5 to 2 millimeters as numerous as one to a square foot. It is noteworthy that sample 16R in Group A (aa) and sample 11 in Group B (a) are essentially equal to these four samples of Group AA, and that sample 16R of Group A appears even a trifle freer from holes than sample 16R in Group AA.

Samples 9 and 16P in Group AA consist of about 90 per cent of fine-grained and 10 per cent of medium-grained material, with very few or no layers that contain coarse grains. One sample is marred by conspicuous small holes, which may bring it somewhat below the desired standard AA for delicate carving that is to be viewed at close range.

The other three samples in Group AA(a) (samples 5_2, 4, and 10) contain more medium-grained material than is expected in AA stock. They also contain conspicuous holes, and in sample 10 the contrast between the coarser and finer grained layers is too distinct, not only for AA stock but even for A stock.

"Glass" spots, such as that in sample 5_2, are less likely to be found in the completely fine-grained stone than in stone with considerable medium to coarse grained layers; but they are to be expected here and there.

It is probable that some "glass" spots in AA stock can be eliminated during the carving or other finishing of the stone, and the retention in or rejection from grade AA of such a stone should depend on the frequency with which such spots are found in the quarry or in a certain ledge or floor of the quarry. If they are very scarce in the ledge from which the sample was taken, the prospect of eliminating a few scattered "glass" spots during carving is good; if they are numerous in the ledge the danger of exposing more during carving is equally probable.

It may be argued that stone represented by the samples containing considerable medium to coarse grained material will take carving about as readily as the fine, uniform-grained stone. This adaptability is amply demonstrated in new buildings. The difference in quality is brought out by weathering, and as stone of AA quality is presumably to be used only for statues, monuments, and the most closely viewed parts of monumental buildings, resistance to weathering is made the determining factor. Although both varieties of stone may yield an equal quantity of calcium carbonate to chemical weathering agents, the coarser-grained stone weathers unevenly, and the effects of weathering upon it are more evident.

After this consideration of the samples submitted and the uses intended, the following specifications for stone of grade AA are proposed:

The size of grain as a whole shall be generally uniform and for the most part not over 1 millimeter (1/25 inch) in diameter. (If a millimeter scale is not used, one graduated to twentieths of an inch will give a close approximation.) Layers of medium grain (1 to 2 millimeters in diameter), if they blend well with the fine-grained layers, may constitute as much as 20 per cent of the surface across the bedding. Where sufficiently large quantities of stone are used, a few blocks with as much as 30 per cent medium grain should be accepted. Holes, even the most minute, should be preferably inconspicuous, but numerous minute holes that can be noted only on close inspection are not objectionable. Holes as much as 2 millimeters in diameter may be as numerous as four to 1 square foot of area in a few blocks, though a predominance of blocks with so many holes should not be tolerated. Larger holes are objectionable, although a tolerance of one large hole to 10 square feet of surface is reasonable, provided the block containing it can be so placed as not seriously to mar the general appearance of the work. The same degree of tolerance should be applied to "glass" spots; as many as four to 1 square foot in a few blocks if the spots do not exceed 2 millimeters in diameter, but only one in 10 square feet if they are larger. There is opportunity for dispute where these defects are close to the limits of tolerance, but it is the quarryman's duty to keep well within the specified limits in work calling for such specially selected stone, as stone not quite up to this grade can readily be included in stock of the more extensively used stone of grade A. The price of AA stone should be sufficient to cover the additional cost of careful selection and to return a reasonable profit. The margin of profit on AA stone should be greater than that on stone which is called for in greater quantities and under less rigid specifications.

It is realized that in the Indiana oolitic limestone district it is not the ordinary practice to distinguish between grades AA and A. This practice is not surprising to one who has studied the quarries and noted the small percentage of stone that will meet the proposed specifications for grade AA. There can be no objection, however, to the call for such stone by consumers if they are willing to pay a proper price for this specially selected or statuary stock. It should be used only where it can be viewed at very close range; otherwise its special qualities will be wasted.

So far as results of laboratory tests are concerned, stones meeting the specifications of grade AA are not at all superior as a group to those of grade A. The strongest stone in Group AA (sample 5) is not up to specifications throughout in appearance. Only one (sample 23) possesses a high degree of uniformity in crushing strength, averaging between 6,000 and 6,500 pounds per square inch. Samples 16S and 16P also average well above 6,000 pounds per square inch, whereas samples 9 and 10 average less than 5,000 pounds. No tests are recorded for samples 16R and 4 in Group AA. Samples 16R and 13R in Group A, which are of AA quality, have an average crushing strength near 8,000 pounds, and sample 11 in Group B, also of AA quality, has an average strength of more than 6,000 pounds.

The percentage of absorption is not appreciably different on the whole in samples of Group AA than in the other groups of buff stone. The least absorption is shown by sample 5, the strongest sample, and the most by samples 9 and 10, the weakest samples. The other three samples range from 4.5 to 5.6 per cent, whereas samples 16R and 13R in Group A and sample 11 in Group B range from only

3.5 to 5 per cent. Specific gravity and weight per cubic foot, as should be expected, vary on the whole inversely to percentages of absorption and porosity. Sample 5 in Group AA is an exception, for it has a lower specific gravity and also lower percentage of absorption than sample 23, although its surface contains distinctly more of the small holes. This exceptional character is attributed to the complete sealing by secondary calcite of the larger pores or shell holes, only a few of which have been converted into " glass " spots. This process has strengthened the stone and made many of the pores air-tight without appreciably increasing the weight per cubic foot.

GRADE A, SELECT BUFF

As samples 16R and13R in Group A have already been shown to meet the specifications of Group AA, they may be dismissed here as more than meeting the requirements of Group A. The only further remark called for about these two samples is the noticeable though not great variation in physical properties of the two samples labeled 16R. These variations in the properties of stone of one grade from the same quarry are not at all surprising if the conditions of deposition and cementation of the stone are given proper consideration. Samples 5 and 4 in Group AA, samples 8, 2, 7, 23, 13, and 16P in Group A, and samples 11, 5, and 16S in Group B represent the proposed limits for select stone. Sample 9 in Group A, though comparatively coarse grained, consists of layers that blend so well that it could be used with due discretion as select stone; but it is likely to weather less evenly than the others after prolonged severe exposure, and its contrast with blocks of finer grain will then become more marked. For this reason it is reduced to class B, or standard grade. Nos. 14(1), 14(2), 19, and 10, because of prominence of holes, prevailing coarseness of grain, or lack of blending of the layers, are also reduced to standard grade.

The samples that best represent select stock are taken as a basis for the following proposed specifications for this grade. Fine-grained layers should constitute 50 to 100 per cent of the surface across the bedding; medium-grained layers from 0 to 50 per cent, and coarse-grained layers from 0 to 10 per cent. The layers must blend. Holes from 0.5 to 2 millimeters in diameter appear to be invariably present, though very inconspicuous in some samples. The minimum number observed, two to a square foot, is therefore specified. As many as 20 or 25 holes of this size to a square foot may be present in a few blocks without disqualifying them; but such blocks should not average more than 1 square foot in 5 of the surface of the structure. Holes from 2 to 4 millimeters in diameter should not be more numerous than one in 5 square feet. " Glass " spots less than 2 millimeters in diameter may be as numerous as 10 to a square foot. This maximum is less than that for holes of the corresponding size, as the spots tend to weather into relief after prolonged exposure, but as blocks with " glass " spots are likely to be more thoroughly cemented and stronger than the average, the advantage of having such blocks in places where strength is especially desired should not be ignored. It must be left to the builder to choose between strength and appearance at very close range. " Glass " spots from 2 to 4 millimeters in diameter may be as numerous as one in 5 square feet of surface, and larger spots as numerous as one in 10 square feet.

Although holes tend to increase in number and size with the coarseness of grain, the maxima specified above for grain and holes should not be permitted in the same block of select stock. A stone coarser grained than the average must be exceptionally free from holes or conspicuous spots to be classed as select. It is the combined effect of grain, holes, and spots that creates or destroys the select appearance.

The physical properties of the select samples vary much like those of statuary grade. Two samples (sample 5 of Group AA, which was transferred from the statuary group, and sample 2 of Group A) have high crushing strength—between 8,300 and 9,000 pounds per square inch. Sample 8 is comparatively weak (4,700 to 6,200 pounds per square inch), and the remainder are of medium strength. Of the samples reduced to grade B because of appearance, sample 9 is relatively weak, sample 14y is strong, and samples 14x, 19, and 10 are of medium strength. Of the three samples not seen by the writer, and therefore not represented in Plate 41, one is strong and two are somewhat below medium strength. External appearance therefore has no definite connection with crushing strength.

The ratio of absorption shows some tendency to increase with coarseness of grain, but it can hardly be called more than a tendency. It varies inversely with strength. The specific gravity, on the other hand, has a more marked tendency to vary directly with the crushing strength. Sample 23 is exceptional in having a higher specific gravity but lower average crushing strength than samples 7 and 13, which lie beside it in the diagrams. The relatively high specific gravity agrees with the relatively low ratio of absorption, but not particularly with the rather porous appearance of the sample. The discrepancy is presumably due to local variations, whereby the cubes crushed were weaker, lighter, and probably more absorptive than those used for determination of specific gravity and absorption. Sample 5 in group A is another exception. Its specific gravity is rather high and is higher than that of sample 5 in Group AA; but its average absorption is somewhat greater and its crushing strength much less.

Samples 5 and 16S in Group B, whose general appearance entitles them to consideration as select stone, are not far from the average of Group A in specific gravity and percentage of absorption but are below the average in crushing strength. Only one sample of 16S in Group B was seen by the writer and represented in Plate 41. It is not known whether samples 16Sx and 16Sy in Plates 42 and 43 represent different parts of this sample. The great range between the maximum and minimum values recorded for 16Sy would not be suspected from close inspection of the sample.

GRADE B, STANDARD BUFF

The standard grade covers a much broader range in texture than either of the preceding grades and represents what experience has shown can be produced from most quarries without too great a percentage of waste. A few quarries contain a considerable percentage of select as well as standard stone; others have little except standard stone or standard and coarse grained (grade C) stone in sight. The limits of variations in texture here proposed are based on the results of quarry study, as well as inspection of the samples. The variation in the opinion of quarrymen as to the limits of standard grade is if anything more marked than with those of grades A and AA. Some appear too ready to include stone in the select grade that will obscure the significance of the word select; others have classed samples as rustic (grade C) that tend to confine the meaning of the term standard within too narrow limits. With the practical significance of these terms in mind the writer has classed as standard stone samples 9, 14x, and 19 from group A; samples 2, 16P, 9, 7, 16R, and 8 from Group B; and samples 2, 16S, and tentatively 5, 9, and 16P from Group C. Those tentatively included have a general appearance that is about equally characteristic of rustic (grade C) and standard (grade B).

It is interesting to note here how impressions based on a general brief observation of an isolated sample may differ from those obtained by detailed examination. Sample 9 in Group B was mentioned by Messrs. Packard and Roberts, of the Supervising Architect's Office, as " not the best B," although its average grain was only slightly coarser and the holes in its surface no larger and no more numerous than unquestioned samples of Group A. The unfavorable impression was due to the conspicuous variation in grain of alternating layers, which was somewhat intensified by the holes present. Sample 7 in Group B was mentioned as " a very good A," although holes in its surface were more conspicuous than in sample 9. Its bedding, however, was more uniform and of finer average grain, and it is represented in the texture diagram as rather similar to several in Group A. Sample 16R was called "a very good standard for grade B," although its variation in grain is slightly less and its average grain slightly finer than that of sample 7, and its holes are distinctly smaller, though more numerous. Sample 8 brought forth no specific comment, although its variation in grain and average size of grain, as well as its number of holes, are distinctly greater than those of sample 9.

If these same samples could be seen well placed in a wall it would not be surprising if the remarks quoted should be slightly modified. The "very good A" (sample 7) falls within the limits of texture recommended for grade A and could undoubtedly pass careful inspection if used with good judgment in a job of A quality, but several blocks of such general character would not maintain the select appearance as well as the average of the proposed grade A. A few blocks like samples 9 and 16R could also be used with good judgment in work calling for grade A.

With the submitted samples as a basis, the following specifications for standard or grade B stone are suggested: Fine-grained layers, measured across the bedding, may constitute from 90 per cent to as little as 20 per cent of the surface; medium-grained layers from 10 to 80 per cent; coarse-grained layers as much as 60 per cent; and very coarse-grained layers as much as 20 per cent. Stone containing maximum percentages of coarse-grained layers should contain a minimum number of conspicuous holes, and the following maximum and minimum figures should be considered in a general way as inversely proportional to those indicating grain.

Holes ranging from 0.5 to 2 millimeters in diameter may number 100 or less per square foot. The more numerous they are the smaller must be their average size. Holes 2 to 4 millimeters in diameter should not exceed two per square foot. Where the grain is finer than the average, as in sample 19A, a tolerance of 10 per square foot may be allowed for the smaller holes and one per square foot for the larger holes. Holes more than 4 millimeters in diameter may number one to 10 square feet, with a considerable tolerance, according to the conspicuousness of the position of the stone in the building.

"Glass" spots may number for those less than 2 millimeters in diameter 20 per square foot; those 2 to 4 millimeters in diameter two per square foot; those still larger one in 5 square feet, with considerable tolerance according to the position of the stone in the building.

In Table 11 (p. 188) a sub-B grade is represented by three samples of grade C (samples 9, 16P, and 14). Samples 9 and 16P are ordinarily regarded as too coarse grained to be included in grade B but contain so few holes that a few blocks like them can be used with stock of typical grade B without arousing adverse criticism. They illustrate a judicious tolerance in the consideration of coarseness of grain and its relation to the prominence of holes. In contrast to them sample 14 of grade C falls within the maximum allowance for grade B, but the marked contrast between the alternating coarse and very coarse grained layers, together with the prominence of holes, gives a coarser appearance than the mere tabulation of data for coarseness of grain would indicate. Messrs. Packard and Roberts described this sample as "too coarse for United States Government work," but it could be used with due judgment along with regular standard stone and is therefore classed in grade sub-B.

The diagram representing crushing strength shows that of the 15 samples included positively or tentatively in grade B, three are distinctly stronger than the average for grade A, four are about equal to that average, and eight are below it. The number of relatively weak stones is greater than in grade A, but those of medium and superior strength are about as numerous as in grade A. The variation in strength of different samples is greater than for grade A, owing mainly to the unusually low strength recorded for sample 19. On the whole, however, there is too little difference in the crushing strengths represented for grades AA, A, and B to give marked preference to any grade.

The absorption diagram (pl. 45) shows the samples in grade B to have no greater an average percentage of absorption than those in grade A. None of them have quite so high a percentage as sample 8 in grade A, whereas sample 16Sy in grade B has a slightly lower percentage than any sample in grade A. In grade B samples 16Sy, 2, and 16P show greater variation in percentage of absorption than any samples in grade A, a feature apparently in keeping with the greater variation in size of grain; but it may be remarked here that such variations in single samples of grade C are not so conspicuous, a fact which suggests that the variations in the three samples of grade B are not necessarily characteristic. It is noteworthy that sample 2, which shows the maximum absorption for grade B, is placed in the texture diagram as one of the finer grained and least porous of the samples, although its uneveness of grain is marked. Sample 7, which has decidedly lower absorption than the average for any grade, is indicated in the texture diagram as having a moderate number of holes 2 millimeters in diameter or less. Sample 23, which contained so many holes of this size and was so coarse grained as to be reduced to grade C, proves to be one of the least absorptive of all the buff samples tested. There is evidently little relation between the number of readily visible holes and the percentage of absorption, and many of these holes must be so tightly sealed that their appearance on the surface is misleading. In absorption, as in crushing strength, there is little choice between grades A and B.

GRADE C, RUSTIC (COARSE) BUFF

The term "rustic" or grade C stone, formerly "coarse buff," includes stone too coarse grained or with too many large shell holes to be classed with standard stock but not so extremely coarse grained and open textured as the variety called "Indiana travertine." The samples assigned to grade C by the writer include samples 10 and 14y, which were transferred from Group A, samples 10, 19, and 23 from Group B, and samples 19, 10, 14, 23, and 3, which were originally submitted in Group C.

Comparison of the textures of these samples brings out the interesting fact that so far as coarseness of grain alone is concerned, all but two (samples 23 and 8) could be classed as standard stock, and even these two might be so classed under a reasonable tolerance. The difference from standard grade is almost entirely due to the prominence of holes. Samples 10 and 14y from Group A were reduced to grade C because their surfaces contained from 20 to 30 per cent of holes ranging from 2 to 4 millimeters in diameter, which gave an abnormally coarse-grained appearance. The three samples from Group B were reduced because their percentages of holes from 0.5 to 2 millimeters in diameter exceeded the maximum allowed for grade B and also gave an abnormally coarse-grained appearance. It may be that an injustice has been done to any of these five samples that were only rough sawed, as sawing tends to tear out grains and leave holes that would later be eliminated by planing, rubbing, or tooling. The specifications proposed in this report are for natural rock-face stone and finished stone and not for partly finished stone.

No "glass" spots were noted in the samples of grade C, but at several quarries coarse-grained "glassy" rock was discarded because of its appearance and great resistance to sawing. "Glass" spots, however, should be less objectionable in grade C than in grades of finer grain and are therefore considered in the following proposed specifications.

Fine-grained layers, measured across the bedding, may form 70 per cent or less of the surface, medium-grained layers from 20 to 65 per cent, coarse-grained layers from 5 to 70 per cent, and very coarse grained layers as much as 40 per cent. These limits are based on actual observation; the logical maximum for coarse and very coarse-grained layers is obviously 100 per cent. Holes 0.5 to 2 millimeters in diameter may range from 20 to 200 to a square foot, those 2 to 4 millimeters in diameter 60 to a square foot, and those still larger 5 to a square foot. With increase in the number of large holes the rustic stone grades into "Indiana travertine." "Glass" spots less than 2 millimeters in diameter may number 50 to a square foot, those 2 to 4 millimeters in diameter 10 to a square foot, and those still larger 5 to a square foot. It is not necessary to state tolerances for coarseness of grain or number of holes, as in work calling especially for coarse-grained stone the coarseness is the main feature.

The crushing strengths of samples of grade C are on the whole somewhat lower than those of grades B and A. Of the 10 samples, 6 are near the average and 4 below the average crushing strength of the entire series, though no further below than samples of grade B. Wide variations in strength in different parts of the same sample are as conspicuous as in grades B and A. The percentage of absorption averages somewhat higher in grade C than in grades B and A—a difference in general though not absolute agreement with the differences in crushing strength. These differences in physical properties are too small to be of serious consequence, but so far as they go they are in keeping with the suggestion to use select stone in the most closely observed parts of a building near street level, standard stone throughout the remainder of the lower stories, and coarse-grained stone in the upper stories.

GRADE D, SELECT GRAY

As the gray, frequently called "blue" varieties of the Indiana oolitic limestone have the same variations in coarseness of grain and presence of shell holes as the buff stone, and as fewer samples were submitted for study, no separate diagram of their textures has been made. All the samples submitted in Group D, except Nos. 14x and 14y, lie well within the limits proposed for grade A (select buff) and on the whole have even fewer conspicuous small holes (0 to 8 per square foot). Sample 20 in grade D could even be classed as of grade AA as regards texture. Samples 14x and 14y are so coarse grained as to be equivalent to grade C (coarse buff) and are therefore transferred to grade EE or rustic (coarse gray). On the other hand, sample 7 in Group E has all the qualifications for grade D, and samples 5 and 19 of Group E can be conservatively classed as sub-D.

To one without the opportunity for constantly comparing the differences in color, it is difficult to appreciate any contrast between pale-buff and light-gray stone. There is quite as much contrast between light-gray and dark-gray stone, both shades being present in some quarries. If a high degree of uniformity in color is required, specifications should be made accordingly, but there should be little or no difficulty in keeping the output from a single quarry for any particular job up to those specifications.

In crushing strength the select gray samples average somewhat higher than any of the grades of buff stone. This fact accords with the difference in origin between buff and gray stone, the buff stone owing its color to oxidation and partial leaching of the gray or dark coloring matter, which was accompanied by a little leaching of the calcium carbonate from the grains and matrix of the stone. The relatively low crushing strength of sample 16S, however, and the wide variation in strength of nearly all the samples in grade D show that original differences in the stone have far more to do with its crushing strength than the slight amount of leaching that took place during oxidation. The low crushing strength of sample 19E (grade sub-D) further emphasizes this point.

Percentages of absorption in grade D, as in other grades, vary on the whole inversely as the crushing strength. The average percentage is less than in grade A, although sample 16S, in grade D, has a higher percentage than any sample in grade A except sample 8. This exception once more emphasizes the original differences in the stone as controlling factors in the determination of physical properties. The differences in crushing strength, percentage of absorption, and related physical properties are too small to be very significant commercially, but as there has been in the past some tendency to regard the gray stone as inferior to the buff stone it is worth while to call particular attention to the slight superiority in physical properties of the select gray over all the other grades of Indiana oolitic limestone.

GRADE E, STANDARD GRAY

As only four samples of standard gray were submitted, three of which have qualified in grade D, not much significance can be placed upon the data afforded by the one remaining sample (23). Sample 23 is about equal to the average of grades B and C (standard and coarse buff) in both crushing strength and absorption, and the specifications for texture of grade B can therefore apply to grade E.

GRADE EE, RUSTIC (COARSE) GRAY

Rustic gray stone, equivalent to grade C, was not recognized as a distinct grade when the samples that form the basis of this report were prepared, but more recent quarry developments have shown, as was to be expected, that coarse-grained stone is about as abundant below as above the oxidized zone. This coarse-grained or rustic gray stone is therefore designated grade EE. The only samples studied that belong to this grade are samples 14x and 14y, reduced from grade D. They are superior to the average of grade C (rustic buff) in both crushing strength and absorption, but it is doubtful whether a larger number of gray samples would differ materially from the buff samples in these respects. The specifications for grade C therefore apply also to grade EE.

GRADE F, SELECT VARIEGATED

The term "variegated" is applied to blocks of stone which are partly buff and partly gray and which are taken from places in the quarry where the buff passes abruptly into gray stone. The two colors never occur mingled so as to give a mottled or composite effect, such as is characteristic of variegated marbles. Seven samples of grade F were studied. Sample 16P was not seen. Four of the seven samples (2, 8, 14x, and 14y) were sufficiently coarse grained in general appearance to be reduced to grade G, whereas sample 7, submitted in Group G, was raised to grade F. The contrast between buff and gray was very marked in some samples and very obscure in others. Some of the test cubes from any one of these samples are necessarily all of buff stone, whereas others from the same sample are entirely of gray stone, but no record of this difference was kept in the testing laboratory. The variations in crushing strength in grade F are therefore not expected to be distinctive, and they cover the same general range as those in the other grades. The percentage of absorption of grade F also compares favorably with those of grades A and D, a fact of interest to any who may have been skeptical regarding the relative physical properties of the variegated stone. It is also noteworthy that the ranges in strength and porosity for test pieces from any sample in grade F do not average greater than in grades A and D and further emphasize the fact that leaching during oxidation has not appreciably weakened the stone.

GRADE G, STANDARD VARIEGATED

Grade G is represented by samples 5 and 23 in Group G and samples 2, 8, 14x, and 14y, reduced from Group F. Sample 8, which had the lowest crushing strength of all the samples tested, comprised about 85 per cent of fine and medium grained layers and 15 per cent of coarse-grained layers. Minute holes were abundant, though none were conspicuous. Its specific gravity was low and its percentage of absorption high, though neither was extreme, and there was no apparent cause for the extremely low results of the compression test. Of the other four samples, two surpass and two fall below the general average in crushing strength and percentage of absorption.

Separation of grades F and G has been made on the basis of texture alone. As any differences in physical properties are insignificant, however, and as a demand for variegated stone implies a desire for diversity, which can be had in texture as well as color, there is no apparent need of keeping these grades separate, and the recent practice of using the term "variegated stone" to include the entire range of texture is thoroughly justified.

GRADE H, SPECIAL HARD STONE

Grade H was originally intended to comprise "special grades," or any varieties that did not conform in appearance or workability to grades AA to G, but the two samples submitted for examination were characterized by a much greater hardness than the rest, and the title given to grade H is therefore intended to apply to these two samples.

As one product that had apparently been neglected by producers and users of Indiana oolitic limestone was the unusually hard stone found at the top or bottom of certain quarries, producers were requested to furnish samples of this stone for testing, but only two samples (2 and 10) were submitted. Sample 10 was of varying texture. About three-fourths of it was of very fine, uniform grain (equivalent to grade AA), and the remainder was of medium to coarse grain (grades B and C) with very many fine holes and consisted of coarse shell fragments mingled with minute true oolites. Its crushing strength, as shown in the diagram, ranges between 7,000 and 10,000 pounds per square inch but averages near those of the stronger samples of other grades. Its specific gravity (2.30) is little if any above the average, and its percentage of absorption (about 4.6 to 5) is also near the average. The only features to account for an unusual degree of hardness are the large size of the shells, which are relatively resistant to sawing, and the unusually thoroughly cemented or "flinty" character of the true oolitic parts. This sample, like certain other blocks of similar texture, may have contained some disseminated microscopic quartz (silica), especially in the coarser-grained part, which increased its resistance to sawing.

Sample 2 ranks separately from all the other samples in physical properties. It consists of fine-grained stone (75 per cent) with very small lenses of medium to slightly coarse grained stone, thoroughly cemented. Not even the most minute holes can be detected. Glassy grains of calcite, the filling of former holes, constitute 10 per cent or more of the surface. Its crushing strength, from 1,270 to 1,740 pounds per square inch, is far greater than that of any other of the samples. Its specific gravity, 2.5, is also the highest, with one exception (sample 16S, grade A), and its percentage of absorption (2.27 to 2.53) is by far the lowest. These data testify to the unusually great degree of induration, which has practically converted the stone into a marble. Its hardness is due to the filling of original interstices with dense, tough calcite. So hard a stone is of course more expensive to work but is particularly adapted to steps that are subjected to much traffic as well as to base courses of buildings, where stone must sustain a maximum load and be subjected to more dampness and frost action than elsewhere. Sample 10, as well as certain other of the less absorptive and harder samples, may be recommended for steps supporting light traffic, but its variation in texture and porosity leaves some doubt as to its resistance to repeated subjection to dampness and frost action. The boundaries between extra dense and finely porous layers may be lines of weakness, and stone of such irregular texture and so considerable a percentage of absorption should be thoroughly examined for such lines of weakness before being offered for severe usage. The unusual hardness of the stone as a whole is no proof that partings likely to open under frost action are absent; on the other hand, the presence of unusually dense or " flinty " streaks should serve as a warning, because many of them are accompanied by extra fine pores, which retain moisture most readily and are therefore most likely to promote disintegration from freezing.

Although even the hardest limestone can not be regarded as the equal of granite in general in hardness and resistance to centuries of weathering, it is true that some granites whose feldspars are softened by the presence of considerable microscopic mica and which have been subjected to excessive tool work may lose the roughness of their tooled surfaces under foot abrasion quite as readily as limestone like sample 2 and may even show scaling before any roughening appears on the limestone. The scaling of the granite, however, is likely to cease after removal of the surface film that was minutely cracked by tooling, whereas the chemical weathering of the limestone, though slower at the start, will be continuous. Chemical weathering, however, proceeds so slowly that it is of little significance unless the stone is quite unprotected from attack by rain, and the structure in which it is placed is monumental in character and intended to stand for several centuries. This extra hard limestone is therefore recommended for steps and base courses, particularly in districts where superior grades of granite can not be obtained without great expense.

OTHER PRODUCTS

None of the other products of the quarries are represented by samples, and physical tests of them are not essential. The very coarsely porous " Indiana travertine " is intended mainly for ornamental work, where strength is of no significance, or for steps and floor tiles, where its open texture and more than average hardness are desirable. The " old Gothic " and " short length " products, including stone of all textural grades, are practically represented by the data already presented for those grades.