OKLAHOMA GEOLOGICAL SURVEY
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TRAVERTINE DEPOSITS OF OKLAHOMA.

BY
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NORMAN.
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THE TRAVERTINE DEPOSITS OF THE ARBUCKLE MOUNTAINS, OKLAHOMA, WITH REFERENCE TO THE PLANT AGENCIES CONCERNED IN THEIR FORMATION.

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THE TRAVERTINE DEPOSITS OF THE ARBUCKLE MOUNTAINS, OKLAHOMA, WITH REFERENCE TO THE PLANT AGENCIES CONCERNED IN THEIR FORMATION.

INTRODUCTION.

STATEMENT OF THE PROBLEM.

The history of travertine is the history of a vast series of geographical changes. Geologically speaking, travertine is a rock of recent formation. The assertion that the present is the key to the past, in a wide sense, applies to a knowledge of travertine. We can expect to interpret the past where so much is obscure, imperfectly preserved, or not preserved at all, only in proportion as we understand the present where everything is open to investigation.

The history of travertine includes the general successive stages from the earliest beginnings of its existence, through its various periods of development, down to the present condition of things. In fact, the evolution of travertine involves a number of complicated processes which are better understood as we trace out the origin of the materials and the consecutive steps by which the materials have been conveyed into their present form and position.

One of the more important deposits of travertine in America is to be found in the Arbuckle Mountains of Oklahoma. At present there is a continuous development of travertine falls along two parallel streams, namely, Honey Creek and Falls Creek. These streams are fed from the underground waters of large springs. Many years ago the calcareous waters of these same springs probably supplied the mineral constituent of certain other isolated and widely distributed deposits, the presence of which indicates that large areas were formerly covered by travertine. These deposits must have had their origin at one time in the immediate vicinity of waterfalls, larger in size than those which are now present. The greater amount of the travertine formed during the past centuries was removed by differential erosion and consequently has had an important role in determining certain salient characteristics of the local topography. The data obtained from a study of the travertine that has escaped erosion, and the data obtained from observations of the travertine now developing in various places indicate clearly that certain plants and plant processes may be concerned in the deposition of this mineral. To the scientist the results of this investigation suggest two important problems: (1) the geological history of this travertine, and (2) the relation of certain plants to the formation of travertine and the older deposits of similar composition which are widely distributed throughout this region.

DEFINITION OF TRAVERTINE AND ITS SYNONYMS

Before taking up the geological history of travertine, in order to make clear the use of different terms in the discussion to follow, it will be necessary to define the various terms that are often used synonymously with travertine.

Travertine is deposited from the water of springs or streams holding calcium bicarbonate in solution, as white, gray, or brown concretionary calcium carbonate with a very cavernous and irregularly banded structure, soft and chalk-like to hard and crystalline, often containing fossil leaves, twigs, and mosses. The word travertine is derived from the Italian *travertino,* a corruption of tiburtino—Latin, *lapis tiburtinus*—the stone of Tibur. The city of Tibur, the modern Tivoli, is situated west of the Sabine Mountains near Rome on the river Teverone, Latin Tiberinus or Anio. At this city are the celebrated falls known as the "Cascatelle" where immense deposits of travertine have formed in that portion of the river which passes through the city.

A more ancient term for travertine is **Tufa,** which comes from the Latin *tophus,* and which was used by Vergil and Pliny in the same sense as the word travertine of the modern Italians. Tufa is a cellular variety of calcite in which the mineral matter has been deposited from the waters of calcareous springs around nuclei of algae, mosses, leaves, twigs, and other plant structures.

Frequently, too, the word travertine is used for materials such as **Stalactites,** the calcareous cylinders that hang from the roofs of limestone caverns, and **Stalagmites,** the same material covering the floor of limestone caverns. The water that drips through the roof or sides of the cavern holds a small amount of calcium bicarbonate in solution and leaves calcium carbonate to form the stalactites or stalagmites when evaporation takes place. The chemical composition of travertine is essentially the same, but in this case the deposition occurs only in springs or streams, whereas, stalactites and stalagmites occur only in limestone caverns. There are certain differences in the way in which the calcium carbonate is precipitated in these two kinds of deposits and these differences will be considered in detail later.

Another term which was used by Weed ('88) indiscriminately with travertine is **Calcareous sinte** a concreted calcium carbonate of various forms and composed of a series of successive layers, concentric, plane or undulated, and nearly or quite parallel. In its original sense, the word *sinter,* from the German *sinter,* meaning dross of iron, implies an initial process of heating before the deposition takes place but without a melting of the mineral. The deposits formed in the immediate vicinity of hot springs may be correctly termed *sinter.*

Another term which is applied to a great variety of rocks and soils with a considerable range of composition is **Marl,** from the old French *marle*—Latin *marga*—a kind of earth or a calcareous clay, a mixture of calcium carbonate, and argillaceous matter. The typical marls are soft and friable, of a white, gray, or brownish color, and are deposits formed in shallow lakes or open pools.

All of these different types of calcareous deposits, with the exception of sinter, are to be found in the Arbuckle Mountains. Stalactites and stalagmites are of frequent occurrence in the caves, but the amount of marl that is developed is relatively insignificant in this region.

REGION STUDIED.

GENERAL STATEMENT.

The Arbuckle Mountains, in which are included important deposits of travertine, are located in the south-central part of the State of Oklahoma. These mountains cover a triangular area approximately 35 miles on each side, with a fifteen mile arm extending westward from the southwest corner. This latter area, the Garrison plateau, bounded by the villages Hennepin, Woodford, Crusher, and Davis, and named after Garrison Creek, is the region in which the greater part of the present investigation was undertaken. The general name of Arbuckle Mountains is locally applied to this plateau which varies in elevation from 800 to 1,400 feet above sea level, or 100 to 500 feet above the bordering plains. It consists largely of limestone rock-prairies which along their margin gradually merge into an irregular series of low rounded hills with narrow and shallow ravines. Along with the change from hills to valleys there is a change in the nature of the flora and frequently this change coincides with differences in the surface formations.

ECOLOGY.

The weaker formations that develop shallow valleys, such as the Woodford chert of the Devonian or Mississippian, the Sylvan shale of the Silurian, and the Simpson formation of the Ordovician, together with the Reagan sandstone of the Cambrian, and granite-porphyry of the pre-Cambrian—of the east and west timbered hills—are all covered with a growth of shrubs and trees. In the narrow creek valleys and canyons which have developed in the Franks conglomerate of the Carboniferous, the Viola limestone of the Ordovician, and the Arbuckle limestone of the Cambro-Ordovician, trees appear on the alluvial deposits but rarely on the upland surfaces.

Aside from these evident differences in the vegetation, the various geological formations can be differentiated in part by the presence or absence of certain species of plants. A number of plants are more or less indifferent in regards to the substrata on which they grow, but certain other species appear either on silicious or calcareous formations to which they seem to exercise a decided preference. The forest trees of the granite-porphyry formation consist largely of the black jack oak (*Quercus marilandica* Muench.), with a small percentage of post oak (*Quercus stellata* Wang.) On the Reagan sandstone the same oak trees occur with other species in addition, but the proportion in numbers is just the reverse, that is, the post oak predominates. Other species of plants, which in this region are limited to the granite-porphyry areas, are: the buckthorn (*Rhamnus caroliniana* Walt.), the wild sweet pea (*Cracca Virginiana* L.), the butterfly pea (*Clitoria mariana* L.), large-bracted wild indigo (*Baptisia bracteata* Ell.), and (*Chaetopappa asteroides DC.*), A point of interest in the distribution of these plants is that the species *Baptisia bracteata* Ell. is found only on the granite-porphyry, whereas blue false indigo (*Baptisia australis* (L.) R. Br.) occurs indifferently on all the various formations In following out the selective appearance of trees to the Arbuckle limestone, it is found that along the smaller streams, pecan trees (*Hicoria pecan* (Marsh) Britton) and the black walnut (*Juglans nigra* L.) are as frequent if not more so than the various species of oaks.

In addition to forests, savannas occur on the Arbuckle limestone, especially in certain areas of the more crystalline rocks with the occurrence of the woolly buckthorn (*Bumelia lanuginosa* (Michx.) Pers.), the black oak (*Quercus nigra L.*), smooth sumac (*Rhus glabra* L.), and illscented sumac (*Rhus trilobata Nutt*). In a few places there develops a typical orchard savanna consisting only of the southern buckthorn. The savanna of the Franks conglomerate is characterized by such plants as the red cedar (*Juniperus virginiana* L.), the persimmon (*Disopyros virginiana* L.), the black oak (*Quercus nigra* L.), smooth sumac (*Rhus glabra* L.), black sumac (*Rhus copallina* L.), and illscented sumac (*Rhus trilobata* Nutt.). The savanna of the upper Viola limestone consists principally of the Chickasaw plum (*Prunus angustifolia* Marsh), the hop tree (*Ptelea trifoliata* L.), the black oak (*Quercus nigra* L.), and illscented sumac (*Rhus trilobata* Nutt.).

The transition from a savanna to a prairie often coincides with a minor change in the substrata. The rock prairies comprising the greater part of the Arbuckle limestone, Franks conglomerate, and the middle Viola limestone, are covered with a comparatively uniform flora. The principal grasses are: the plume grass (*Erianthus saccharoides* Michx.), the long awned aristida (*Aristida longiseta* Steud.), Bermuda grass (*Capriola Dactylon* (L.) Kuntze), soft-leaved prairie grass (*Panicum malacophyllum* Nash), and the buffalo grass (*Bulbilis dactyloides* (Nutt.) Raf.), the sppecies of mesquite grass and the tall gamma grass (*Antheropogon curtipendulus* (Michx) Tourn.), were found only on the Arbuckle limestone prairies. The principal herbaceous plants that are widely distributed over the prairies of these formations are: the chickweed (*Arenaria texana* (Robinson) Britton), wild flax (*Linum Lewis* Pursh.), and (L. *rigidum* Pursh.), (*Phyllanthus caroliniensis* Walt.), (*Croton Lindheimerianus* Scheele), the cacti (*Opuntia macrorhiza* Engelm.), and (*Echinocereus caespitosus* Engelm. and Gray), milkweed (*Asclepidora viridis* (Walt.) A. Gray), (*Evolvulus pilosus* Nutt.), (*Heliotropium tenellum* (Nutt.) Torr.), resinous skullcap (*Scutellaria resinosa* Torr.), Venus'-pride (*Houstonia angustifolia* Michx.), (*Tetreneuris linearifolia* (Hook.) Greene), and wavy-leaved thistle (*Cirsium undulatum* (Nutt.) Spreng.).

GEOLOGICAL HISTORY

The plants which have been listed above, in the course of time, have been aggregated into definite plant groups or societies. The differences existing between the various plant societies is due mostly to variations in the physico-chemical properties of the exposed geological formations. These rock masses vary in thickness and extent. Owing to the very nature of their origin, the geological record of the different formations is necessarily fragmentary, and further, has been obscured by the revolutions of successive ages. Even where the series of changes are continuous they are of unequal value in different places. In one case there is an unbroken succession of deposits many thousands of feet in thickness from which, however, only a few meagre facts of its geological history can be obtained. In another instance within the space of a few yards there is evidence of a varied and complicated series of changes in physical geography, as well as an abundance of fossils. The variation of over 10,000 feet of Paleozoic sediment, chiefly limestone that rests unconformably upon pre-Cambrian granite-porphyry, is due in part to the differential erosion and deposition which took place in this region during the Paleozoic era.

Some time after the early Paleozoic sediments had been laid down in an ancient sea the Arbuckle Mountains emerged and were uplifted to mountainous altitudes during the late Carboniferous period. The Paleozoic strata were successively exposed to erosion and base-leveled in common with the great Appalachian province east of the Mississippi River. Before the close of the Carboniferous period these strata either by erosion or subsidence or both were partly submerged and a late Pennsylvanian conglomerate was deposited upon their eroded surfaces. Both folding and faulting followed the deposition of the conglomerate, and continued up to the Permian period.*

During the Jurassic and Triassic periods, a long interval before the existence of the Comanchean sea, the Arbuckle Mountains were reduced almost to a flat plane, or peneplane. Cretaceous deposits were then laid down upon the submerged leveled surface. At the close of the Comanchean, late Cretaceous, or early Eocene periods, part of the streams were rejuvenated and the Cretaceous strata were removed over large areas. This erosion cycle terminated in a partial base-level in the Miocene age, but the superior hardness of the underlying rocks has resulted in the preservation of the exposed strata as a low plateau in the central part of the mountain group, whereas the bordering areas have been eroded to a lower level. This erosion cycle was interrupted

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*Reed, C. A., ('10): A report on the geological and mineral resources of the Arbuckle Mountains, Oklahoma, Okla. Geol. Survey Bull. No. 3, pp. 1-69, Pl. 1-23, 1910.

by another but differential uplift during the Pliocene age in which only the western part of the plateau was raised to a higher elevation. The streams were again rejuvenated and their development continued in common with the development of the broad valley of the Washita River during the Pleistocene age. That period of time beginning with the Pleistocene age and continuing up to the present is the period more particularly concerned in the history of the travertine of this region.

GEOLOGICAL HISTORY OF THE TRAVERTINE DEPOSITS.

DEPOSITION OF THE MATERIAL.

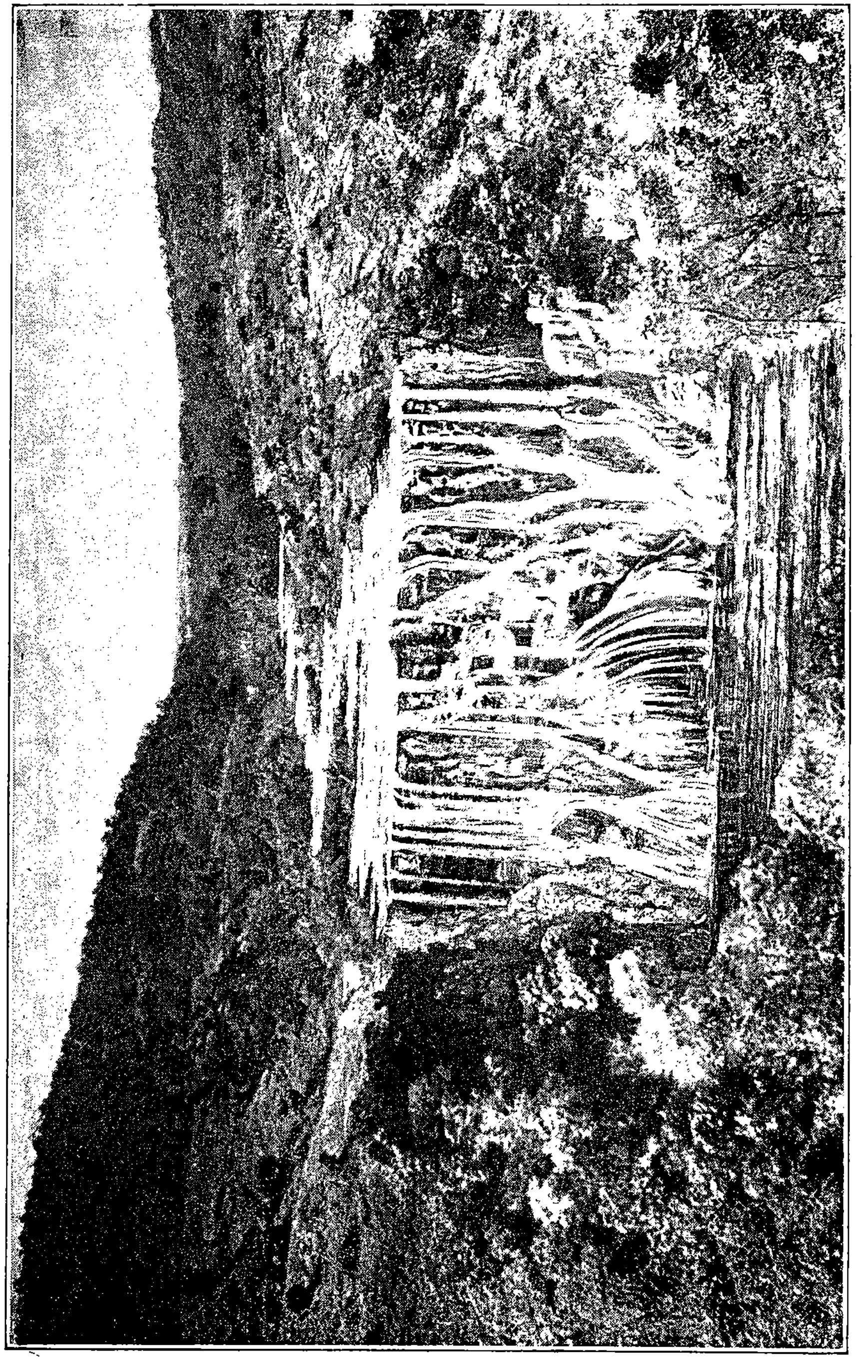
The deposition of the travertine that is now present in the Arbuckle region began soon after the removal of the Cretaceous strata and the consequent exposure of the underlying Paleozoic rocks. During the Pleistocene age the surface of the Garrison plateau was radially dissected by short streams with small flood-plains, rapids, and waterfalls. All of these youthful streams have a steep gradient wherever they flow over the limestone formations. The limestone is always found in layers varying from a fraction of an inch to many feet in thickness; in other words, there is a rough and incomplete stratification in the limestone as if it were a book, the leaves of which had stuck very closely together. The strata of these rocks readily split along these lines which are parallel with the bedding.

The position of the layers of rocks which constitute the bed of the streams is infinitely diverse. Sometimes they are tilted up vertically, sometimes horizontally, and again curved into wide channels. Wherever the streams flow through tilted strata, invariably they follow the strike; that is, they flow in the direction of a horizontal line parallel with the bedding. Where travertine dams occur the streams flow at right angles to the strike. With the exception of Eight Mile, Falls, and Honey creeks, all of the other streams which have their origin in this plateau are intermittent at least three months of the year.

In the intermittent streams and most places where seepage occurs only a small amount of travertine is found, and this is usually carried away by erosion as fast as it develops. The extensive deposits of travertine along incessant streams, especially Honey Creek and Falls Creek, indicate that in certain places the local topography has recently experienced a series of important changes. Certain of these changes were due to the development of travertine that attained its maximum period of growth in the construction of a number of falls, the largest varying from 60 to 100 feet in height, and from 300 feet to nearly a half-mile in width. The falls, however, were subjected to a period of erosion in which the rapid streams in times of flood cut through the soft deposits to a level lower than the original base of the travertine.

But in spite of the continued erosion, the formation of travertine continued with the building of a second series of smaller dams, attaining

PLATE I.



RECONSTRUCTION OF THE ORIGINAL TURNER FALLS.

a maximum height of 12 to 20 feet on Falls Creek, and 55 feet at Turner Falls on Honey Creek. The termination of the second construction period began about 67 years ago (1850), at a time when a gradual but slight erosion put an end to further development. This series, however, was followed by a third period which continues up to and includes the deposition of the new travertine.

Thus the travertine under discussion may properly be classified by three more or less distinct periods. These periods do not represent definite geological periods but only a convenient differentiation that can be adapted to show the result of local physiographic conditions.

TRAVERTINE OF THE FIRST PERIOD.

The deposits belonging to the first period of travertine formation occur principally on Honey Creek (1) in sec. 36, T. 1 S., R. 1 E., at the present site of Turner Falls; (2) at the head of one of the tributaries of Honey Creek in sec. 2, T. 2 S., R. 1 E.; (3) at the head of Falls Creek in secs. 32 and 33, T. 1 S., R. 2 E., and (4) a minor deposit near the head of Owen Creek in section 33 of the same township a half-mile south of Falls Creek.

RECONSTRUCTION OF TURNER FALLS.

Turner Falls is located on Honey Creek in sec. 36, T. 1 S., R. 1 E. In general, Honey Creek flows in a north-eastern direction, and finally empties into Washita River. It is deep in places, too; has a rocky or stony bed with sharp confining banks; and at times there are vertical cliffs between whose bases the clear water glides in a bubbling, noisy current. The stream runs swiftly and turns in sharp bends and angles, flashing light and color from its slowly undulating surface. There are also rapids and falls at different places, and where the bank turns sharply there is frequently a deep pool on the one side while on the other side we find rapidly running water.

The principal source of the water supply is from three large springs. During the rainy seasons a part of the water that falls on the Arbuckle limestone prairie penetrates through the crevices in the limestone strata, collects in subterranean caverns, and reappears from beneath huge masses of rocks as springs. The cool and clear water that issues from these underground sources holds in solution a small amount of calcium bicarbonate and free carbon dioxide. The water which does not sink through the fractured rocks is carried off as surface water by a number of intermittent streams that empty into Honey Creek. Continuing from the limestone prairies, this stream passes through the East Timbered Hills, over Reagan sandstone and Colbert porphyry and then proceeds into a small shallow valley of Arbuckle limestone. This valley rapidly narrows down into a deep gorge through which the stream is carried headlong by means of rapids and small waterfalls to the very end of the canyon, where there is a sheer drop of 60 feet to the valley beyond.

All through this valley, and along the steep sides of the canyon, there are large quantities of travertine. But the travertine of the first period is all above the present level of the stream bed. These deposits are 60 feet thick immediately above the natural falls at the lower end of the gorge, but as they extend back upstream for a distance of 150 yards they gradually diminish to only a few feet in thickness. To properly understand the structure of the falls during the first period of travertine formation, imagine this canyon filled to the very top with the older deposits for a distance of 200 yards above the falls. As the stream spreads out over the wide, elevated, and gently sloping surface, it would be deprived of any great power of erosion. It would gradually moderate in its flow to the edge of the inclined plane where the resultant thin film of water would fall like a flimsy spray for a distance of more than 100 feet into the deep pool in the valley below. The singular features of this ancient waterfall are vividly portrayed in the reconstruction on Plate I.

The details of this reconstruction are easily understood by a study of the contours, or lines representing changes in elevation, as given in the contour map (Plate II). At the edge of the falls the travertine of the first period extended from A to D and covered completely the Turner Falls that are now present at B to C. The top surface of the falls continued upstream to the point E, while that portion covered by water in which calcium carbonate was deposited is represented by the shaded sections of the map. That part of the travertine removed by erosion is represented by the less shaded area.

An obvious effect of the unequal surface of the resistant Arbuckle formation underlying the travertine that has escaped erosion is the unequal distribution of the deposits on the two sides of the stream. On the south side the travertine does not extend half as far upstream as on the opposite north side. This is due to the presence of a perpendicular cliff of limestone from H to M and the small amounts of travertine that may have been placed along its upper margin disappeared with the removal of the materials at the base of the channel. On the opposite side, from C to N the limestone makes up only a few feet of the base of the vertical wall facing the stream and the greater part of the steep cliff consists of travertine overlying the Arbuckle formation. The deposits are 60 feet thick at C, and from this point, in the general direction of C to N, they gradually decrease in thickness, and finally come to an end as soon as the elevation of the sloping limestone attains the same height as that of the top of the canyon.

The travertine that formerly occupied the canyon was gradually carried away many years ago by erosion. In times of flood boulders

CONTOUR MAP OF TURNER FALLS AND VICINITY.

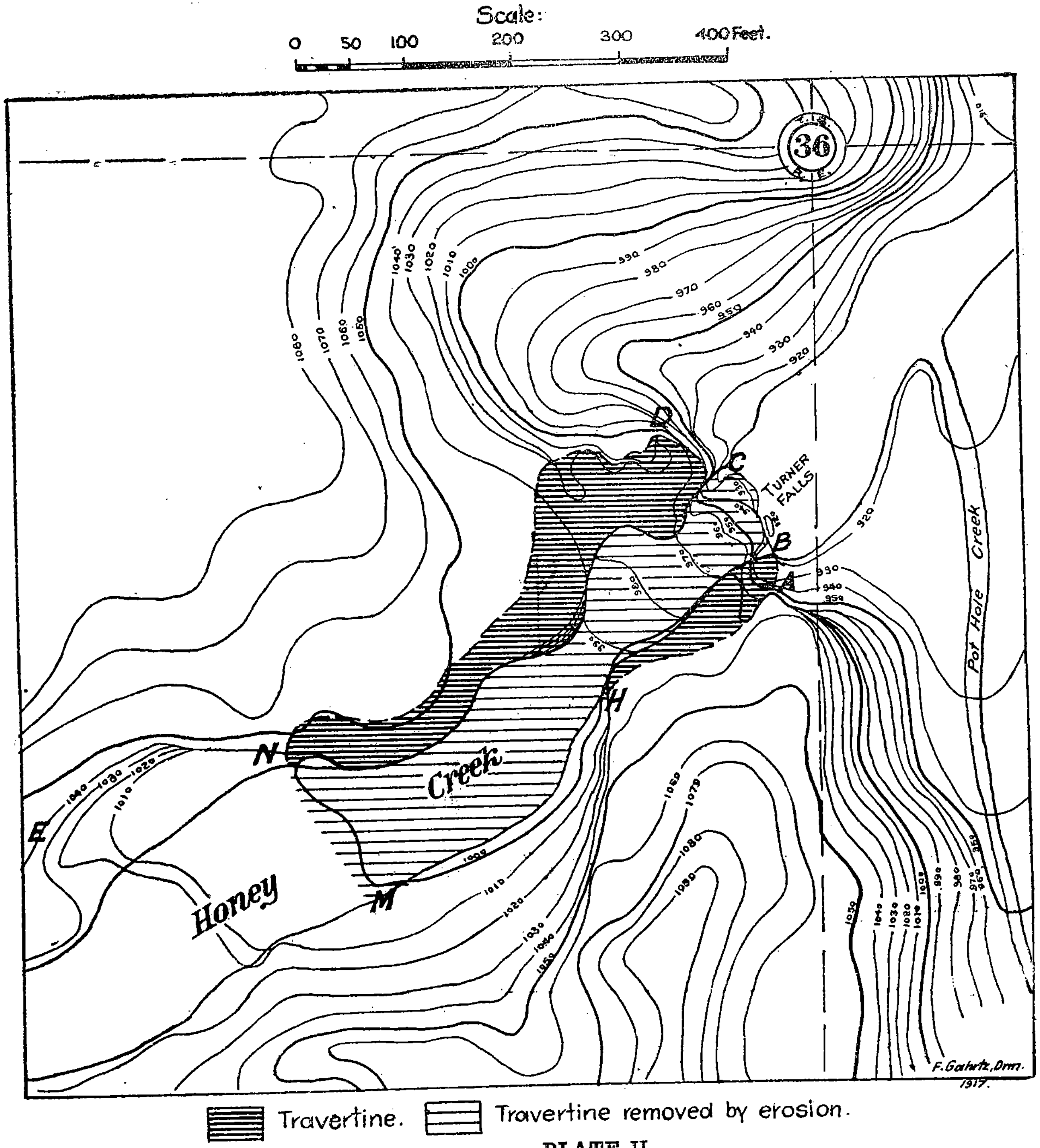


PLATE II.

from the granite-porphyry of the East Timbered Hills west of the falls, without doubt, supplied a part of the necessary tools for this work. The water in itself had small power to cut into the rock. Where there is no motion there is no wear. The real destructive power of the water on the soft deposits was in the sharp cornered boulders and gravel it could move, drive before it, and drag about from point to point. It may have taken centuries of this grinding and working in the water to produce a marked effect. In the stream bed we still find evidence of erosion continuing on today. Traces of wear are visible on the exposed surface of the travertine above the present bed of the creek. The channel of this stream became deeper as the fissures in the travertine and rock strata were pried open, extended, and widened into open passages. The soft portions of the rock crumbled away, the harder portions at the sides remained intact, the unwashed formation at the top was unaltered and the deep canyon was the result. The erosion continued in the bed of the channel until a part of the underlying limestone was worn away and finally ceased for a lack of boulders and other tools of abrasion. The rocks which fell into the water as boulders were ground to sand and gravel before they had been carried very far down Washita River. But in spite of the continuous erosion the travertine began a second phase of construction.

RECONSTRUCTION OF PRICES FALLS.

The reconstruction of Prices Falls presents a more difficult problem than that of Turner Falls on the Arbuckle limestone. In the vicinity of Prices Falls, travertine of the first period of formation covered an area of more than 60 acres, the mineral being deposited on four different formations that vary considerably from each other in their physico-chemical properties and consequently in the rate at which they will disintegrate. A reconstruction of Prices Falls appears on Plate III. This same region in its present condition is represented by a contour map (Plate IV). The Prices Falls travertine deposits at one time extended over the more or less rectangular portion included in the points A, B, C, and D. The position of the travertine now present is indicated on the contour map by a dark shading and the less shaded areas represent the places from which the travertine has disappeared. Also the boundary and extent of the different exposed formations is shown by numbered lines.

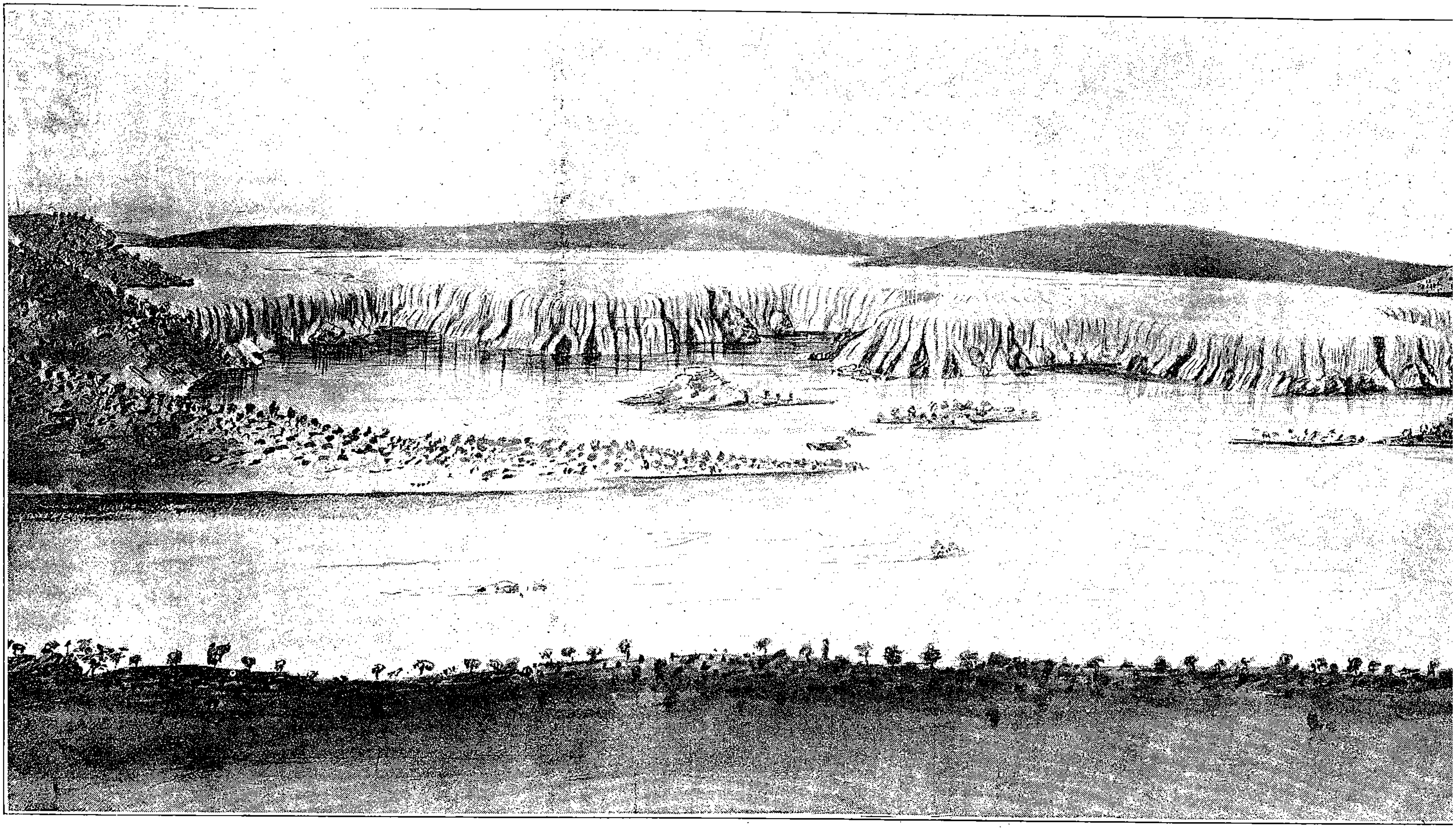
Immediately north of line 1 is Woodford chert; between lines 1 and 2 is the Hunton formation; between 2 and 3 is Sylvan shale; between 3 and 4 Viola limestone; and south of line 4 is the Simpson formation which extends south and west beyond the shaded areas. The lower edge of the reconstructed falls appears on the Viola limestone, Sylvan shale, and the Chimneyhill limestone (a part of the Hunton formation). The total width of the falls from A to D,—in outline very much like an inverted letter S,—is about four-tenths of a mile, whereas the upper margin of the deposits from B to C is approximately one-half a mile wide.

There is a gradual decrease in elevation from the posterior margin of the falls at point E, 958 feet, to the front margin of the falls at H, 908 feet, or a difference of 50 feet, in a distance of three-eighths of a mile. At the top of the falls, the travertine deposits at the points B, P, and E, are all of the same elevation or 958 feet, and they are nearly the same in thickness, varying from 6 to 10 feet. The points A and R are both of the same elevation or 930 feet. The large area H, D, I, is almost level and approximates 908 feet in elevation. The data obtained from the position and distribution of these deposits alone would indicate that at the time when the stream was flowing over the places mentioned above, the falls appeared like the reconstruction in Plate III.

Most of the water from the original stream that extended from B to C passed over the margin of the falls at G, D, I, after having flowed over that part north of E which is now a broad and shallow valley. Since part of the stream passed over the area north of E, he top of the falls was necessarily continued from B, P, and E, rth to some point of equal elevation near C. The absence of any extensive deposits of travertine near C may be accounted for by a more active and lateral erosion to which this place was subjected since it is on the outside curvature of the original stream.

But the strip of travertine on the so-called Table Mountain from E to R serves as the key to the entire problem. Here the travertine is of uniform thickness and was laid down on a section of Simpson limestone. There is a gradual change in elevation from one end of this narrow surface of travertine at the point E or 958 feet to the other end at R, or 932 feet. Similar deposits at levels corresponding to those on Table Mountain, but between the points A to B and C to I, have been removed by erosion and at the present time there are deep ravines between these places. The fact that the travertine from E to R is of uniform thickness and is lower at one end than at the other excludes the possibility of reconstructing this area by means of a series of narrow and connecting falls. The travertine at E R is in the center of the regional distribution of the deposits and was not subjected to the same amount of erosion as was the travertine on either side at the time when the stream was cutting deeper channels.

This erosion began to remove the deposits accumulated on the surface of the large falls simultaneously along two different routes. It began at first south of line 2 near the point G, where a great part of the Sylvan shale was undermined by seepage and easily washed away. After the shale began to wear away, the Chimneyhill limestone, which is very resistant to erosion, was exposed as a vertical cliff



RECONSTRUCTION OF THE ORIGINAL PRICE'S FALLS.

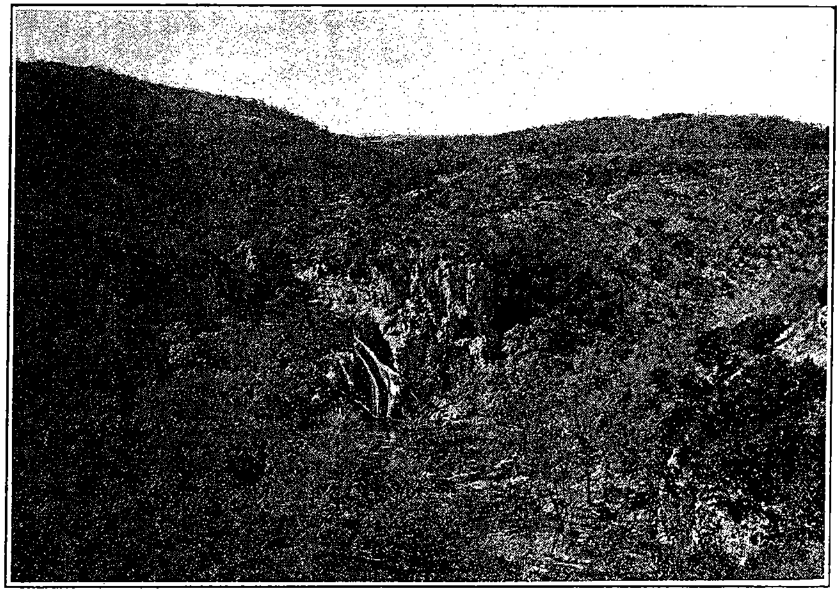
along the line of contact. The cutting of this new channel south of G then isolated the travertine area G, D, I, above water level. Consequently this elevated portion escaped the extensive erosion that continued in other places. The constant displacement of Sylvan shale along line 3 persisted until the stream bed was lowered to an elevation of 830 feet which at this point is the base of the original falls. In the center of this Sylvan formation, east of the point M, a shallow ravine continued to develop as a result of the erosive action of intermittent streams.

But as soon as the resistant Viola limestone was exposed at point M the deepening of the channel practically ceased. A part of the falls continued to recede upstream. Finally they disappeared, and at the same time the uninterrupted erosion carried away the travertine that was deposited above the present valley between E to C. During the time that the valley E to C was formed, a narrow and deep canyon was developed by the wearing away of the travertine and underlying strata between the points B and P, where Falls Creek is now located. However, during the initial stages of erosion, the section E to R called Table Mountain, remained unaltered in the central part of the original stream which consequently was divided into two nearly equal substreams. As the process of abrasion continued, after the valley had been widened by lateral erosion, the stream on the north side of E gradually lost its cutting power. But the stream on the south side of E was confined to a narrow channel and for this reason it continued to cut a canyon deeper than the valley on the opposite side of Table Mountain. Finally as the formation of the deeper channel progressed upstream, this part of the creek was able to carry off all the running water derived from the calcareous springs in the upper portion of the valley.

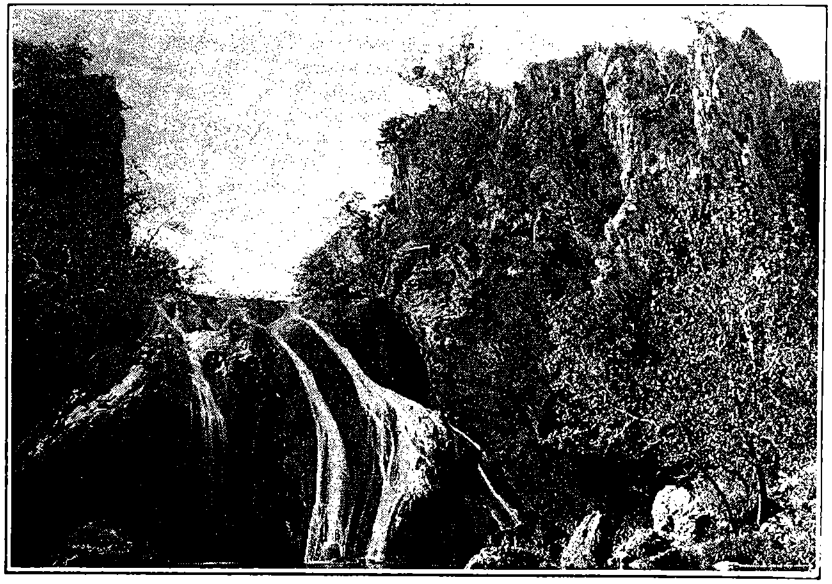
All the physiographic changes which have been described above account for the course now taken by Falls Creek, and due to this same change, the valley north of Table Mountain supplies only an intermittent stream. As soon as these streams had nearly completed the erosion of the less resistant strata down to the underlying resistant formations, travertine began to accumulate on the exposed rocks. This new phase of travertine which was in continuous process of development, will be termed the second period.

TRAVERTINE OF THE SECOND PERIOD.

Travertine of the second period may be found in any of the streams of the Garrison plateau with the exception of Garrison Creek. The amounts present in the intermittent streams are small and the location of dams is often limited to certain areas consisting of only a series of falls a few hundred yards in extent which are found near the sources of the streams. The largest amounts of these deposits

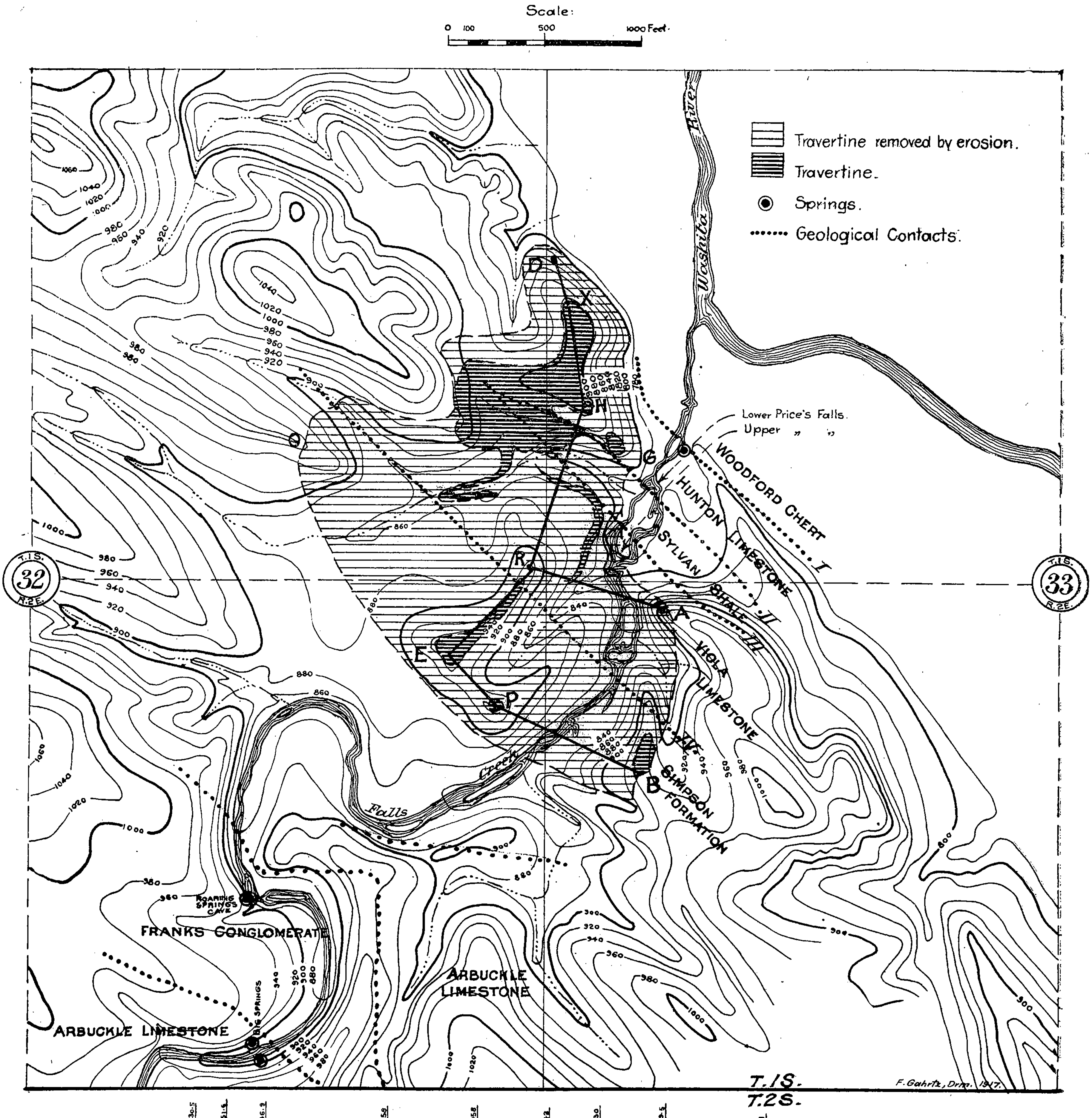


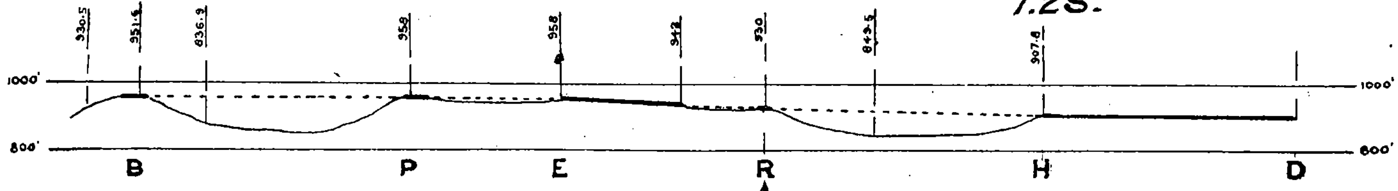
A. TURNER FALLS AND VICINITY.



B. DETAIL VIEW OF TURNER FALLS.

CONTOUR MAP OF PRICE'S FALLS AND VICINITY





PROFILE HEAD OF FALLS CREEK.

PROFILE HEAD OF PRICE'S FALLS.

PLATE IV.

occur in Honey Creek and in Falls Creek, where there are fourteen falls varying in height from 3 to 20 feet, within half a mile of Washita River. On Honey Creek above Turner Falls they are of frequent occurrence and vary from a few inches to 12 feet in height. The more typical of these deposits are to be found at Turner Falls and at Prices Falls.

TURNER FALLS.

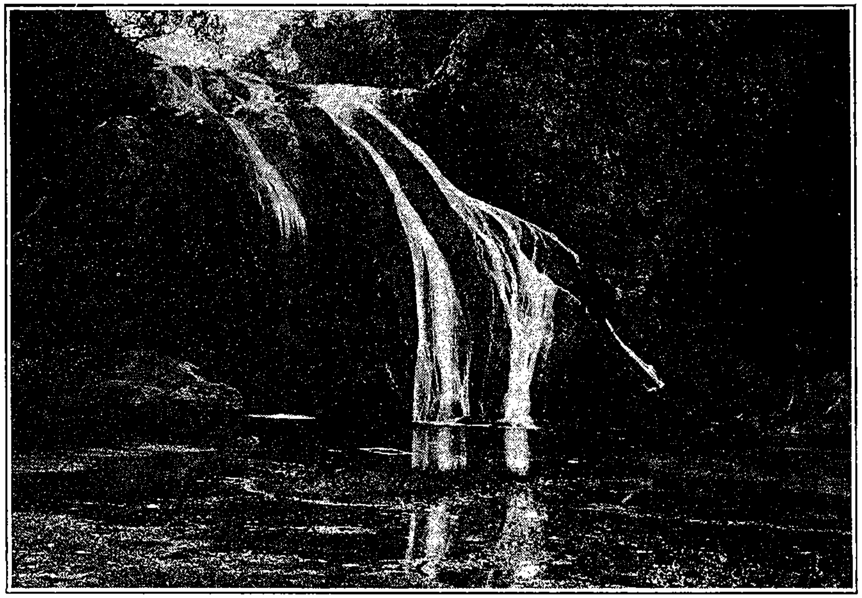
Turner Falls (Plates V and VI) is located on the Arbuckle limestone in sec. 36, T. 1 S., R. 1 E., on Honey Creek. It has a total height of 55 feet, but approximately 50 feet of the underlying formation is a natural fall with travertine developing on the top and the down-stream side in such a manner as to produce the present characteristic structure of the falls. The massive travertine on the face of the falls is very cavernous and a number of hollow cavities extend back 15 feet or more from the front surface. The deposits continue to increase in thickness on the down-stream side of the falls; but at places where there is a deep pool of water immediately below the projecting travertine, the large masses often weighing tons are unable to support their own weight and soon break off. But if the projecting travertine ledge rests on a support of Arbuckle limestone it will continue to grow in size. The addition of newly formed deposits is more rapid in low water when the falls are divided into a number of smaller streams. The position of these streams constantly shifts from place to place as the result of unequal erosion or the deposition of calcium carbonate.

PRICES FALLS.

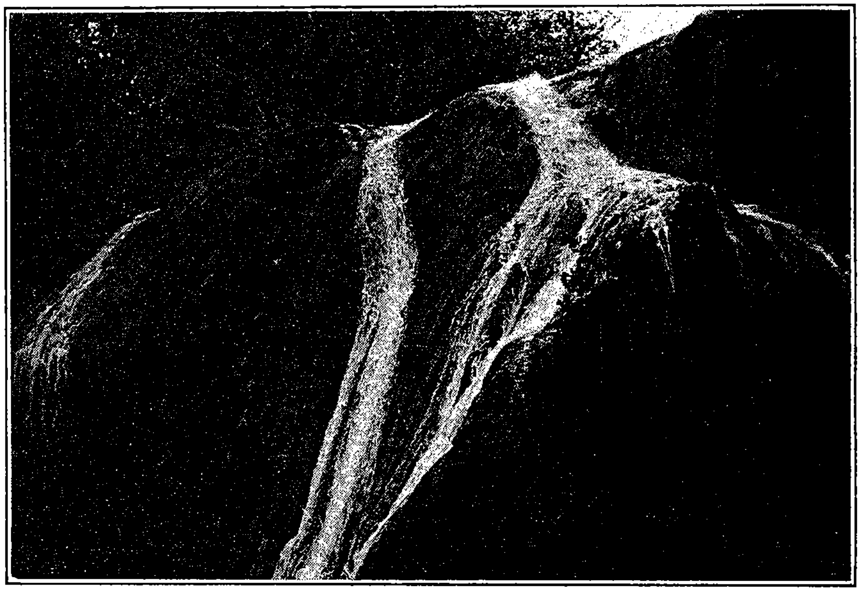
Physiographic changes similar to those found at Turner Falls are met at the lower Prices Falls on Falls Creek, 0.17 mile from Washita River. These falls, 14 feet in height, were altered by the deposition of travertine over the surface of a 10 foot natural fall on the Chimneyhill limestone. Deep channels have been eroded through the soft travertine on the top of this fall, so that the creek now normally passes over the falls in three streams. The water level of these streams during normal conditions is 3.15 feet below the highest point of the deposits and therefore the greater mass of the travertine is freely exposed to the air. The precipitation of calcium carbonate on these falls has practically ceased and the amount of erosion is gradually increasing.

The upper Prices Falls is only 130 yards from the lower falls. It has a total height of 19.3 feet with the highest point of the deposits 2 feet above the water level. These falls were developed by the accumulation of travertine over the surface of a natural fall on the Viola limestone. The creek normally passes over the falls only in one place, and calcium carbonate is now being precipitated in small amounts only in pendent masses of algae, various species of *Oedogonium*, and the mosses *Didymodon* and *Philonotis*, which soon break off with an increased weight of the mineral deposit.

PLATE VI.



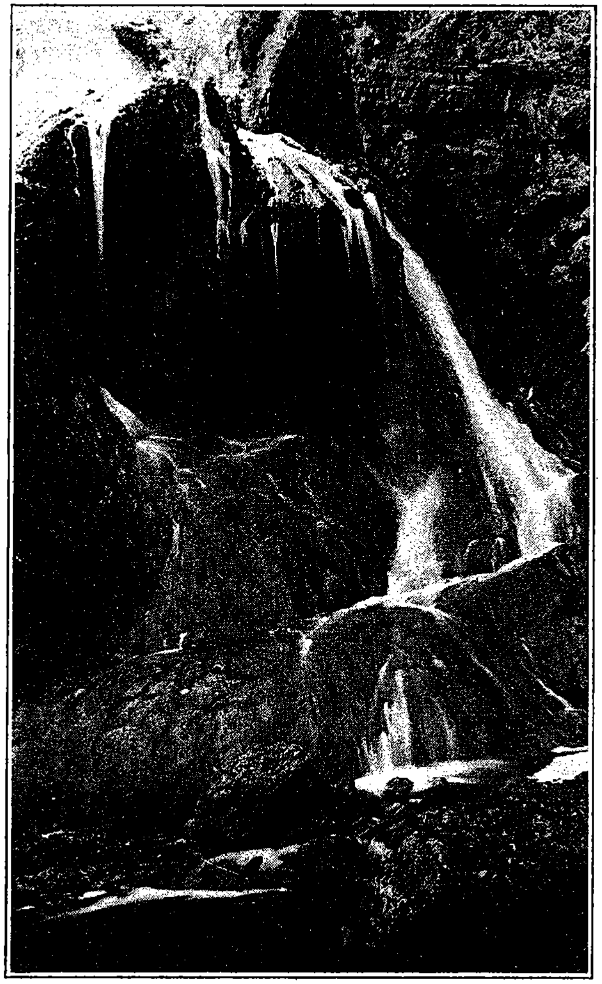
A. DETAIL VIEW OF TURNER FALLS.



B. DETAIL VIEW OF TURNER FALLS.

Large quantitites of the mineral deposits of the first period are found in the pool at the base of the upper Prices Falls and in the stream bed between the two falls. These large travertine boulders do not occupy their original position but were carried down from some point of higher elevation on the hills immediately west of the falls. As one goes farther upstream more evidences of newly formed deposits appear, but this phase of developing travertine will be considered as belonging to a third period of formation.

PLATE VII.



A. DETAIL VIEW OF TURNER FALLS SHOWING UNCONFORMITY OF TRAVERTINE AND ARBUCKLE LIMESTONE.

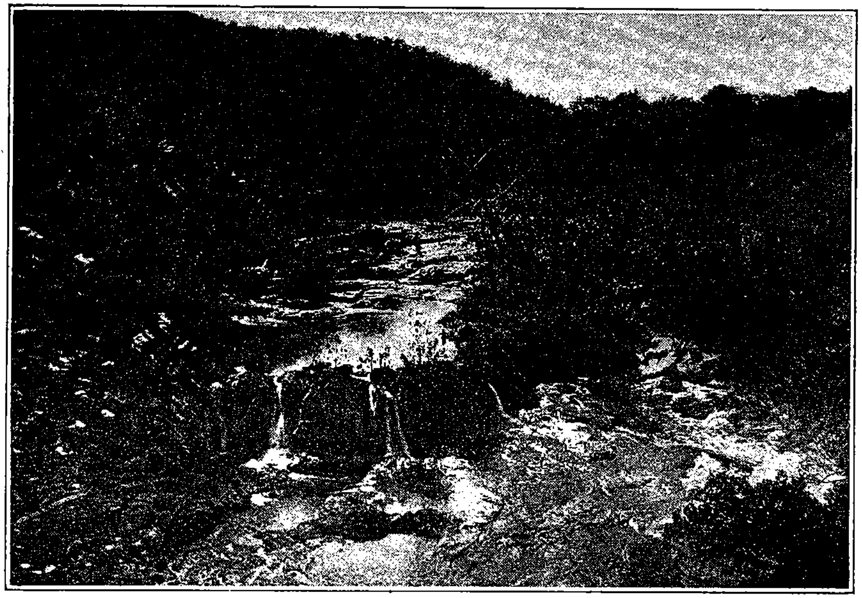
TRAVERTINE OF THE THIRD PERIOD.

Travertine of the third period, or the travertine which is now being formed, occurs in all streams, and in numerous places throughout the region where there is seepage. At first sight, and in certain instances, it is difficult to distinguish between travertine of the second and third periods, for they often merge into one another imperceptibly. However, this distinction can be most clearly shown in the deposits along Falls Creek. Here the largest falls and those first formed are near the head of the stream, and from this point upstream there is a progressive series of falls in all stages of development. After these dams attain a maximum height of 3 to 12 feet, the factor of erosion is greater than that of construction. This factor of erosion is more noticeable in the larger falls near the head of the stream, and it gradually becomes less with a corresponding increase of the construction factor as one passes upstream. Falls of the second period, then, may be defined as those in which the erosion factor is greater than that of construction; whereas the falls of the third period, or present formation, are those which continue to increase in size. It is evident that in this double series of falls the point of separation between the two types will gradually progress with time toward the source of the stream. The various points in detail are clearly brought out in a study of the data given in Table No. 1.

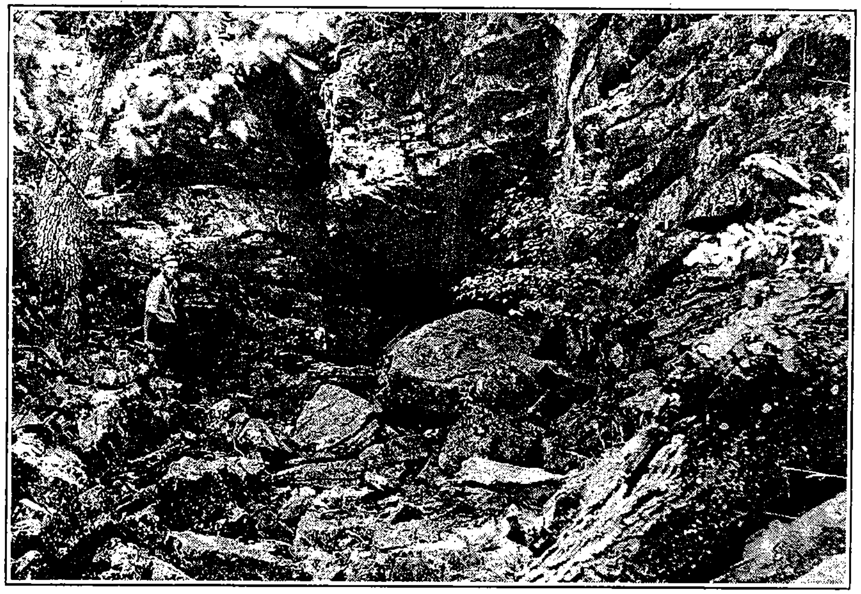
PLATE VII.

B. TRAVERTINE PLACED UNCONFORMABLY ON ARBUCKLE LIMESTONE, IN UPPER FALLS CREEK.

PLATE VIII.



A. TRAVERTINE FALLS ON HONEY CREEK, ABOVE TURNER FALLS.

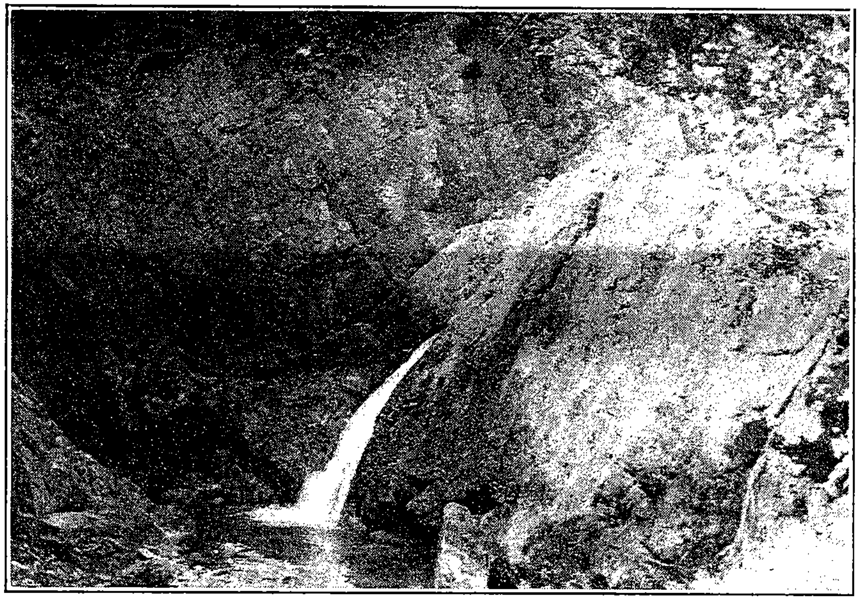


B. ENTRANCE TO A CAVE AT THE SOURCE OF HONEY CREEK.

DISCUSSION OF TABLE No. 1.

From an examination of Table No. 1 (Plate XV), the factors of erosion and construction, as indicated in the two columns specifying the height of the falls and the depth of the eroded surfaces, are represented by a very gradual and constant decrease in erosion, and an equally gradual increase of construction as one follows the creek for a distance of a mile from Washita River to the first large spring. The greatest amount of erosion, 3.15 feet, occurs in the second falls—the lower Prices Falls. From a point a half-mile from the river, the extent of erosion, 0.82 feet, rapidly decreases and two-tenths of a mile farther upstream there is no apparent wearing down of the deposits, but instead, the deposition of travertine is quite active on a series of dams that resemble a cascade in appearance. This cascade is one of the best examples in the Arbuckle region of the developing travertine in the initial stages of a waterfall construction (Plate V).

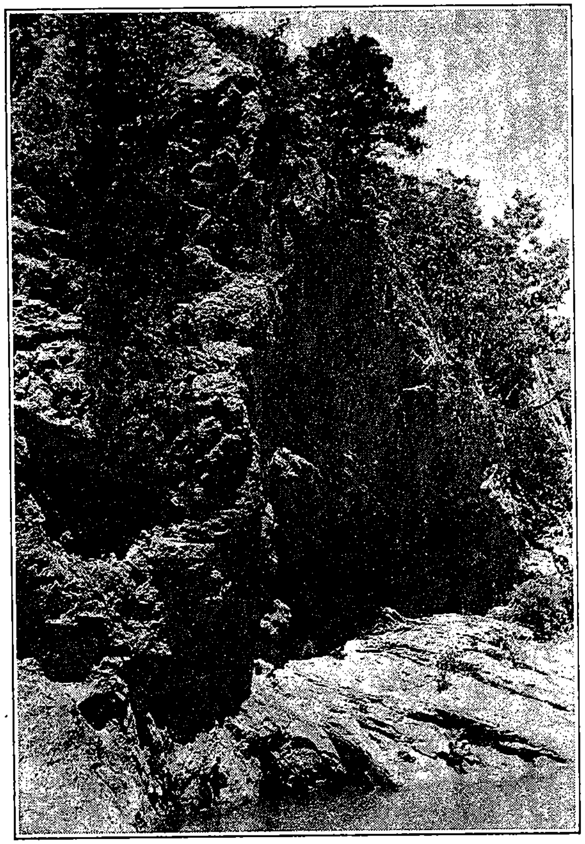
PLATE IX.



A. PART OF THE LOWER PRICES FALLS SHOWING THE UNCONFORMITY OF TRAVERTINE AND CHIMNEYHILL LIMESTONE.

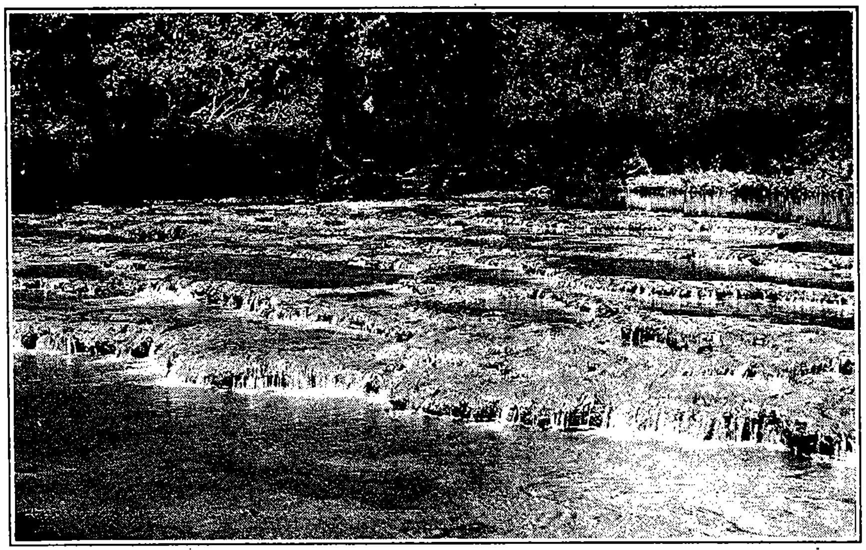
In a distance of one and one-fourth miles from Washita River, there are 20 travertine falls and 4 underground springs on Falls Creek. The first spring, 0.14 mile from the river, is a small spring fed by creek water. This water passes through beds of travertine and Sylvan shale for a short distance underground and reappears as spring water after it has worked its way around an outcrop of Chimneyhill limestone. Of the remaining three springs, one issues from the Franks conglomerate formation one mile from the river and is known as the Big Spring. The other two are only a quarter of a mile past Big Spring, one on each side of the creek, in the Arbuckle formation, at a point above which the stream is intermittent for about one-third of its total length. In the upper sources of Falls Creek there are a number of small springs that supply enough water during the dry seasons to keep the creek running for a distance of about a mile, and then most of the water passes underground to reappear, in part, at the last two large springs mentioned. In the upper part of the stream there are many small travertine dams but these are gradually being destroyed by erosion and partly by the cattle that frequent the stream while grazing on the rock prairies nearby. The presence of animal excrement in this region has undoubtedly proved no small factor in causing the disappearance of certain algae and water mosses that are common in other parts of this stream. Water inhabiting mosses are widely distributed in the creek valley in the vicinity of the first four springs mentioned, but of late these grounds have become a popular camping place for the people of the neighboring villages. The wear and tear of the travertine deposits, due to the unnatural conditions accompanying the presence of campers, and the gradually increased erosion, together with certain changes in ecological factors, has materially altered many of the falls. Under these conditions that are followed by the disappearance of water plants and an increase of erosion, it will be only a comparatively short time when the original beauty of these falls will be greatly impaired, if not altogether destroyed. The present condition of things is better judged from an account of the various deposits near the head of Falls Creek.

PLATE IX.



B. TRAVERTINE PLACED UNCONFORMABLY ON ARBUCKLE LIMESTONE, IMMEDIATELY ABOVE TURNER FALLS.

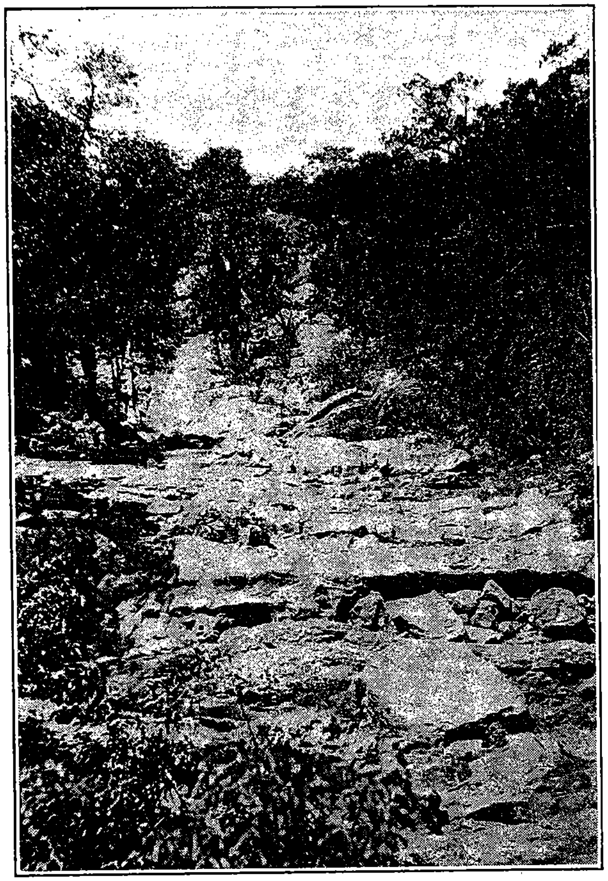
PLATE X.



A. FALL NO. 18 ON FALLS CREEK.

The first of the 28 falls has a height of 4.97 feet and is 150 yards from Washita River. This fall is located on the eroded vertically inclined strata of Woodford chert. The action of running water has cut three narrow channels through the soft travertine and at present there is no apparent plant growth or deposition of calcium carbonate at this place. Falls 2 and 3, the lower and upper Prices Falls, have been previously described. Fall 4 may be considered as the upper part of fall 3 with which it forms a connection on each side. In this dam there are two narrow cuts, the deeper one occurs on the more shaded side of the stream. From this fall on upstream to fall 19, there is a gradual increase of the width of the stream of water flowing over the falls, accompanied by an increase in vegetation and deposition of calcium carbonate. In the detail map of Falls Creek (Plate IV), the extent and shape of all the travertine falls

PLATE X.

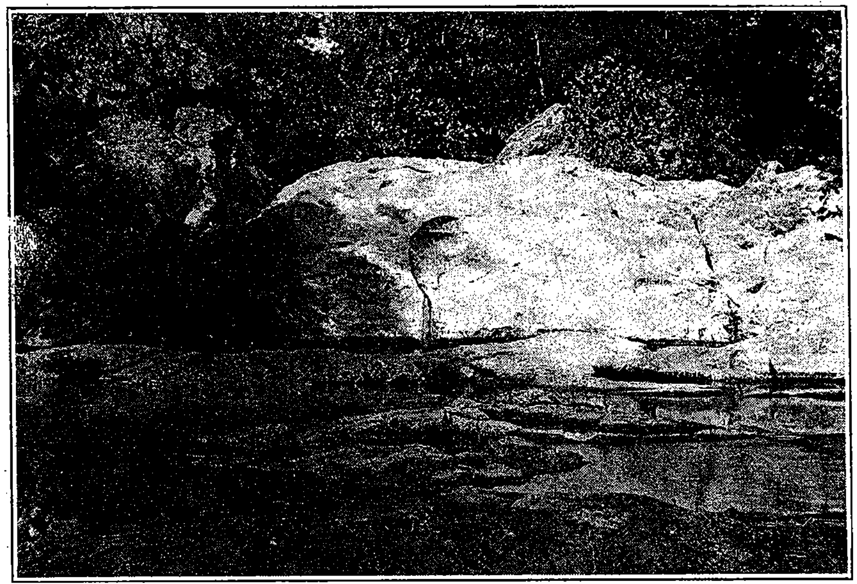


B. FALLS CREEK CANYON, SHOWING THE ORIGINAL CONDITION OF A STREAM BED AT THE BEGINNING OF TRAVERTINE DEVELOPMENT.

are indicated as well as the width of the various streams that flow through the eroded channels. However, in the present consideration, it is necessary to keep in mind the fact that the deposition of travertine can take place only in the immediate presence of water and that in the above mentioned falls the erosion that takes place in the narrow channels will prevent the accumulation of travertine at the top of the mineral deposits.

Water passes over fall No. 5 in two streams that are shallow enough to permit the growth of isolated tufts of mosses. Calcium carbonate is precipitated about the stems of these moss plants and this deposition keeps pace with the development of the plants to within a few millimeters of the growing tips. Fall 6 with its tufts of mosses and the stream divided into four channels is quite similar to the previous fall. Falls 7, 8, and 9 occur very close together. They are 5, 8, and 12 feet high, respectively. The seventh and eighth are connected by a wide strip of travertine and on each side of this lies a long narrow pool that connects with a third which is narrow, irregular in outline, and contains large boulders of travertine. The water either flows over a sloping terrace or over a series of cascades that have been caused by the breaking off of irregular pieces of sediment at the top of the falls. The development of algae and mosses, and the deposition of travertine, is not sufficiently active to keep up

PLATE XII.



A. A TRAVERTINE FALLS THAT HAS STARTED TO DEVELOP ON THE SURFACE OF A NATURAL FALL AS INDICATED BY THE DARK SURFACE ON THE LEFT SIDE OF THE PHOTOGRAPH.

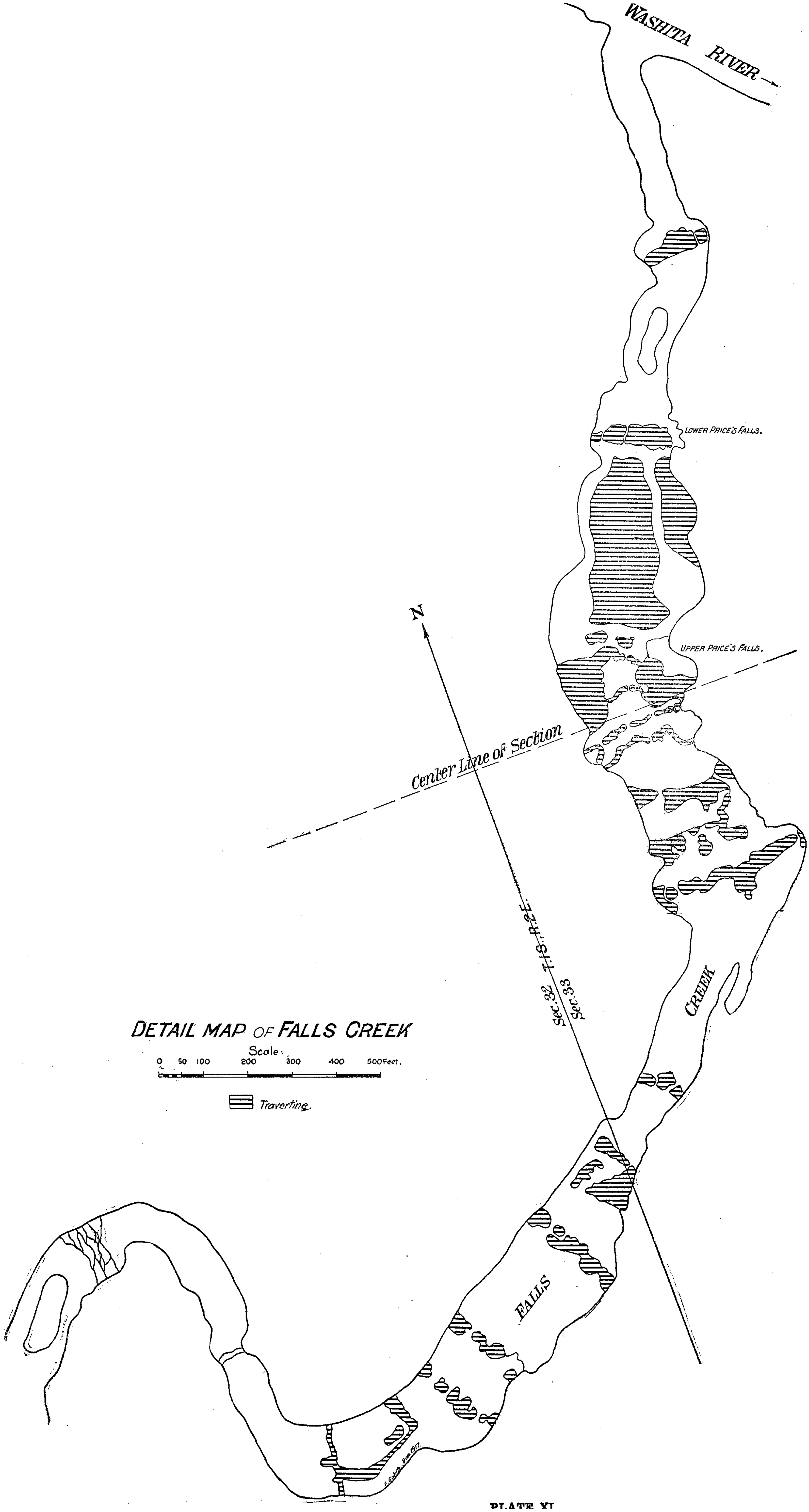
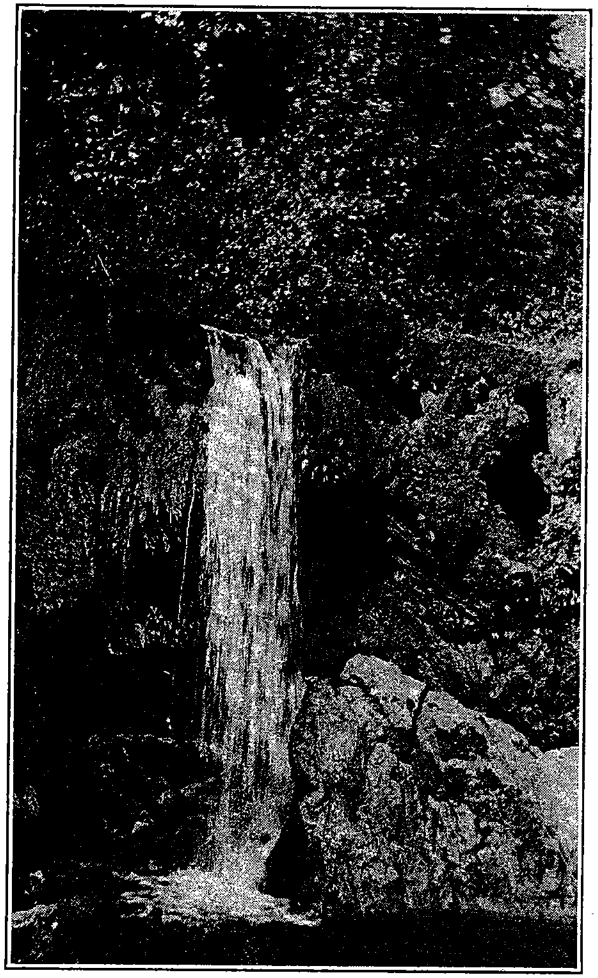

WASHITA RIVER
LOWER PRICE'S FALLS.
UPPER PRICE'S FALLS.
N
Center Line of Section
Sec.32 T.1S.,R.2E.
Sec.33
CREEK
FALLS
DETAIL MAP OF FALLS CREEK
Scale:
0 50 100 200 300 400 500 Feet.
Travertine.
F. Gobitt, Drn. 1917.

PLATE XI

with the amount of material removed by erosion. Most of these deposits are covered with large trees of sycamore (*Platanus occidentalis* L.), elm (*Ulmus americana* L.), and certain oaks, black oak (*Quercus nigra* L.), Schneck's oak (*Q. Schneckii* Britton), and red oak (*Q. rubra* L.).

PLATE XII.



B. A VIEW OF UPPER PRICES FALLS.

From this point, with a slight sedimentation of black soil, Falls Creek has developed a small flood plain where it passes through the Simpson formation. This limestone contains varying amounts of sand and shale. As a result of the water retaining properties of this kind of rock a dense growth of trees and shrubs have grown up along both

sides of the creek. The more common plants given in the order of their frequency are: trees, sycamore (*Platanus occidentalis* L.), post oak (*Quercus stellata* Wang.), basket oak (*Q. Michauxii* Nutt.), Schneck's oak (*Q. Schneckii* Britton), red oak (*Q. rubra* L.), white elm (*Ulmus americana* L.), cork elm (*U. alata Michx.*), and pig-nut hickory (*Hickoria glabra* (Mill.) Britton); shrubs, buck-bush (*Symphoricarpos symphoricarpos* (L.) Mac M.), smooth sumac (*Rhus glabra* L.), southern black haw (*Virburnum rufidulum* Raf.), and wild red plum (*Prunus americana* Marsh); vines, Virginia creeper (*Parthenocissus quinquefolia* (L.) Planch.), poison ivy (*Rhus toxicodendron* L.), sarsaparilla (*Menispermum canadense* L.), pepper vine (*Amelopsis arborea* (L.) Rusby), wild grape (*Vitis cinerea Engelm.*), and passion flower (*Passiflora lutea* L.); herbs, nettle-leaved vervain (*Verbena urticifolia* L.), snake-root (*Sanicula canadensis* L.), beggar-ticks (*Meibomia grandiflora* (Walt.) Kuntze, iron-weed (*Vernonia Baldwinii* Torr.), pale wild bergamot (*Monarda mollis* L.), purple lemond monarda (*M. dispersa* Small), meadow violet (*Viola papilionacea* Pursh.), blue cardinal flower (*Lobelia syphilitica* L.), cardinal flower (*L. cardinalis* L.), and wild carrot (*Daucus carota* L.); water inhabiting plants, water willow (*Dianthera americana* L.), water milfoil (*Myriophyllum heterophyllum* Michx.), and water cress (*Sisymbrium nasturtium-aquaticum* L.).

In the narrow valley of the Simpson formation where the plants mentioned above occur, one finds the falls 10 to 17. They are very much alike in size and structure. There is a gradual deposition of travertine about tufts of mosses, and filamentous and unicellular algae. But in passing upstream it is quite evident that the rate at which the calcium carbonate is precipitated is more rapid in each succeeding fall of the series. The variations in intensity of the light and shade caused by the dense growth of plants along the stream has a decided influence on the nature and amount of vegetation in the water on and near the falls. This influence is particularly noticeable in places where the travertine has been eroded, especially along the banks of the stream. In such cases, if the eroded area is fully exposed to sunlight, there is a tendency to check further damage by means of natural processes that begin with the formation of small fan-shaped dams immediately below the part eroded. In similar places, but with a continuous shade, there will be little or no plant growth and a corresponding lack of reconstruction of the falls.

Falls 18 (Plate XA) is the best example of a fall due entirely to the development of recent travertine. It consists of a series of small cascades arranged in an ascending series with a total height of 4.12 feet. Each cascade constitutes a fan-shaped segment, from 2 to 8 inches high, with a very cavernous and roughened surface. As the water spreads out into a thin sheet across the entire width of the falls, a distance of 120 feet, it divides into delicate sprays as it passes through tufts of the water mosses—*Didymodon tophaceus*

(Brid.) Jur., and *Philonotis calcares* B. & S., which grow at the very edge of the falls.

The roughened and more level surfaces of the travertine are covered with felt-like masses of algae, species of *Oedogonium* and *Spirogyra,* also *Vaucheria sessilis* (Vauch.) DC. and *V. geminata* (Vauch.) DC.—well-known members of the pond scums. These filamentous algae are fixed in a more definite position by the long-stemmed water moss (*Fissidens Julianus* (Savi) Schimp.). The pool immediately above this fall is crowded with plants of water milfoil (*Myriophyllum heterophyllum* Michx.), water cress (*Sisymbrium Nasturtium-aquaticum* L.), and water willow (*Dianthera americana* L.). All of the plants which have been mentioned above exercise a decided influence on the construction of these falls but the different forms and structure of the travertine falls is determined primarily by two dissimilar geological processes.

MECHANISM OF TRAVERTINE FALLS FORMATION.

All of the youthful streams of this region are very much like Falls Creek,—a part of which has just been described in detail,—in that they have a steep gradient. These streams with their valleys constricted where they cross the harder formations, flow over vertical and highly inclined strata of unequal hardness. In the stream bed of narrow valleys, travertine falls of various sizes are frequent, whereas the reverse is true in the more shallow places. The origin and subsequent form of these travertine falls is determined by one of two principal modes of development. In any of the larger streams there are many examples of these different types of falls that have attained various stages in their growth.

The travertine falls are to be considered as one of the following modifications: (1) previous natural rapids or waterfalls; (2) as transformations of boulder dams. In the first case, a stream flowing over stratified rocks at right angles to the strike would pass over the greatest number of cleavage planes in a given distance. Since the layers of unequal hardness in the stream bed are nearly vertical, the one less resistant wears more as the stream passes from the hard layers to the less resistant, and consequently gives rise to rapids. This phenomenon is well illustrated along Scudder Creek in sec. 32, T. 1 S., R. 2 E., where the stream passes from a narrow flood plain of the Simpson formation through the resistant Viola limestone, and then over the narrow flood plains of other less resistant areas. In the upper Viola formation, as a result of differential erosion, occurs a series of three rapids, each with an approximate gradient of 45°, and upon these sloping limestone surfaces travertine is now being formed. The continued addition of travertine on the surface of these connected rapids would ultimately result in the construction of one continuous and large rapid with an incline of 30° to 60°, and this accumulation of deposits of layered calcareous materials would place the rapids at a higher elevation and farther downstream than the original three natural rapids.

However, one of the necessary conditions for the formation of natural rapids like those on the upper Viola limestone, is a succession of strata with only slight differences in hardness. But in other instances the difference in hardness between two successive strata was great enough to develop falls. The origin of a natural fall due to considerable differences in hardness of successive strata is illustrated in part by the geological history of lower Prices Falls, at a place where the stream passes over the Hunton formation with its vertical bedding plane at right angles to the strike. At these falls the Hunton formation consists of a hard and resistant so-called Chimneyhill limestone, a bed of soft shale, and a comparatively soft limestone with marl. After the wearing away of the shaly layers by the action of running water there appeared a natural fall (Plate IXA) of about 15 feet on the Chimneyhill limestone. The addition of travertine on the top of the falls and on the downstream side of the exposed rocks, made a still higher and wider fall. It sometimes happens that the natural falls did not originate by differential erosion, but by faulting, in which a part of the strata of the stream bed was either elevated or lowered in such a manner as to produce sudden changes in elevation.

Aside from the origin of travertine falls as modifications of natural rapids or waterfalls, there is another process of formation in which boulder dams constitute the first stage of development. A large number of smaller falls near the sources of various streams have started in this manner. Boulders of various sizes tend to collect at certain places in the stream and by their aggregation form a series of rapids. As the travertine accumulates among the boulders they are cemented together into a conglomerate mass. As this process of cementation continues, a fan-shaped dam develops. The stream gradually changes, at the same time, from a series of rapid currents into a broad sheet of flowing water. The final result of this second process of development is a fall that has lost its original character to assume an appearance similar to the modified natural falls that have originated by the previously described methods. In all cases, the travertine primarily formed is afterwards transformed into a compact mass by the deposition of calcite in its interstices, and in times of flood this process is further changed by the addition of mud particles which are laid down with the calcareous sediment.

STRUCTURE AND COMPOSITION OF TRAVERTINE.

GENERAL STATEMENT.

Aside from the occurrence of differences in the formation of the travertine falls of the Arbuckle region, the material that goes to make up these falls is subject to a considerable variation in structure and composition. This particular travertine may be classified, according to its physical properties, into a series of representative types that differ by degrees in compactness and hardness,—ranging from a soft chalk-like mass to a banded crystalline mineral, or even to a form with the characteristics of a hard and resistant limestone. The cause for the occurrence of different types of the same travertine must be due to differences in the conditions under which the material was deposited. Such factors as the volume of mineral water that passes over the places where the calcium carbonate is precipitated, the position of the deposits in relation to the contact surface of the water, the temperature and agitation of the water, and the character of the plants associated with the calcareous formation, all have a decided influence upon the development of any particular type of travertine. The different types of travertine, may be conveniently arranged into three classes, and these classes have been termed "banded," "pisolitic," and "cavernous," according to their singular characteristics.

BANDED TRAVERTINE.

The banded travertine of the first period is the least common of these three types. The largest masses, from one to three feet in thickness, were found in the vicinity of Turner Falls and Prices Falls. Banded travertine consists of many parallel layers of crystals, plane or slightly undulating, that vary from a millimeter to a centimeter in thickness, and upon comparison with the color standards of Ridgway* ('12) are principally of a light buff or cinnamon brown color with frequent narrow streaks of a darker or mummy brown tint. It is easily fractured by a sharp blow with a hammer. The cleavage planes, along the faces of the rhombohedral crystals, are at right angles to the parallel dark colored bands. The dark color of the calcium carbonate crystals is due principally to the presence of iron compounds. The mineral is rapidly attacked by cold and dilute acids, carbon dioxide escaping with effervescence. A microscopic examination of this banded travertine, after treatment with dilute acids, revealed nothing to indicate the former presence of diatoms or other plant structures.

However, an examination of travertine of the third period, or recent formation, may indicate the possible origin of the older deposits. By placing pieces of the recently banded travertine in dilute hydrochloric acid, the calcium carbonate readily dissolves, leaving a collection of filamentous and unicellular algae that retain in general the outward form of the original mass. These algae are arranged in such a manner that under the microscope they present the appearance that one would expect in a section of lichen *thalli* with their tangle of fungous *hyphae* and scattered cells of unicellular algae. The filamentous algae, determined by Prof. George T. Moore*, were *Oscillatoria amphibia* Agardh, and *Lyngbya aerugineo-caerulea* (Kuetzing) Gomont. The cells of the unicellular algae are 20 to 24 *u* in diameter,** with a cell wall one-sixth the diameter of the cell. The wall is covered with rather distant, bluntish, warty projections, usually six or eight in number. Certain of these papilose cells contained non-motile reproductive cells, or *aplanospores*. Scattered among the vegetative cells were isolated *aplanospores* enclosed in loose, *hyaline* and membranous sheats. The general characteristics of this alga answer the description of *Trochiscia granulata* (Reinsch.) Hansgirg,—a form closely related to *Protococcus,* as given by Collins*** ('08).

This banded travertine which contained the filamentous and the unicellular algae described above, was collected on the upper surface of Turner Falls. During the summer season this type of deposit may accumulate at the rate of one millimeter in thickness a month. It readily separates from the underlying strata soon after its formation, peeling off in thin fragments that are readily broken and carried away by the running water.

PISOLITIC TRAVERTINE.

Algae of the same genera as those found in the recent banded travertine may have been concerned with the formation of the pisolitic travertine of the first period. The latter type of travertine, collected near the upper Prices Falls, is composed of aggregated granules varying from one to eight millimeters in diameter. The freshly broken surface of these granules is of a deep grayish olive color and in the spaces between them, there occurs a salmon-buff sediment, the color of which is due to the presence of iron. The weathered surface is of a light mineral gray. After the rock had been treated with dilute hydrochloric acid, the thin outer layer, composed principally of silica, remained insoluble. A thin section of these granules, viewed under the microscope, appears with characteristic zones of alternating light and darker areas that are produced by slight differences in the arrangement and aggregation of minute crystals. In figure 1, the outline of these parallel zones, magnified thirty times, indicates the general appearance of a section of the pisolitic granules.

Pisolitic granules of recent travertine may be found on most of the falls of the Arbuckle region. These granules consist of a soft calcareous deposit of which the constituents are held together by microscopic algae. Upon removing the calcium carbonate by means of dilute acids, the residue that still retains the general form of the original granules, consists of a tangle of *Oscillatoria* and *Lyngbya*

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*Ridgway, R.: Color standards and color nomenclature. Washington, D. C., Pl. 53, 1912.

*Director of the Missouri Botanical Garden, St. Louis.

**Italicized u used for Greek letter m, indicating a millionth part of a meter.

***Collins, F. S. Green Algae of North America, 1908.

filaments with a few cells of *Trochiscia* or some other unicellular green alga. Under certain conditions the calcareous granules may develop separately about colonies of unicellular green algae as well as if the calcium carbonate contained in the granules had precipitated about colonies of filamentous blue-green algae. It is not possible to specify the exact physiological conditions that determine the presence or absence of any particular alga, but from the relative distribution of various species of algae growing in the Arbuckle Mountains, it is evident that the conditions under which these different species grow are not the same for all of these minute plants.

During the early summer of 1916, a species of *Haematococcus* was very active in the formation of calcareous granules in Owen Creek. Wherever the calcareous granules are formed they enlarge and fuse into a homogeneous deposit that soon loses the original granular appearance of pisolitic travertine.

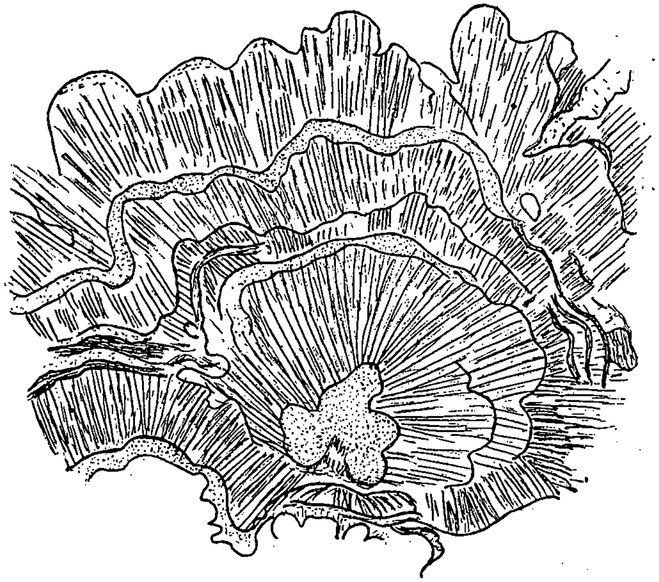

FIGURE 1. CROSS SECTION OF PISOLITIC TRAVERTINE X-15.

CAVERNOUS TRAVERTINE.

Cavernous travertine in general does not have the uniformity of structure that is characteristic of the banded and pisolitic types. It is usually without any particular kind of structure, but occassionaly, however, specimens are discovered that reveal the kind of plants that have been concerned in the formation of the mineral. An especially good specimen of cavernous travertine of the first period, retaining the general form of tufted mosses was located near the upper Prices

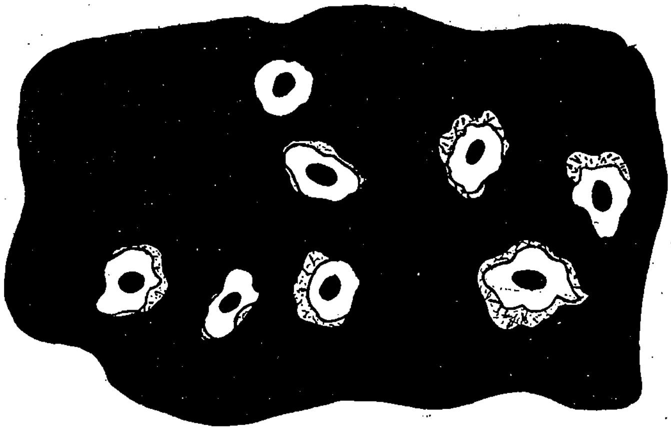

FIGURE 2. CROSS SECTION OF TRAVERTINE, SHOWING THE POSITION OF MOSS STEMS X-20.

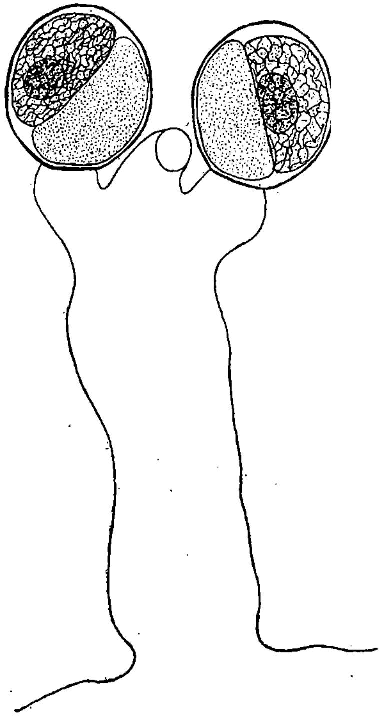

FIGURE 3. THE FRUITING BODIES OF **VAUCHERIA GEMINATA** FOUND IN RECENT TRAVERTINE X-275.

Falls. In longitudinal section this rock, with a freshly broken surface of a light buff to a ferruginous brown color, appeared like a tuft of parallel fossil mosses; and in cross section, the regularity in the position of the rust colored cylinders that replaced the original moss stems was very striking. Figure 2 is a reproduction from a camera lucida drawing of a thin section of this particular kind of travertine. In still other specimens of cavernous travertine, fossil leaves of various species of trees were common; petrified leaves of the same kind of trees that now grow along the stream banks. Aside from these fossils, indications of the former presence of filamentous algae are frequent.

Filamentous and unicellular algae are everywhere present in the recent formations of cavernous travertine. In the Arbuckle region, the most active formation of travertine occurs in the presence of the algae *Vaucheria gemminata* (Vauch.) DC. and *V. sessilis* (Vauch.) DC. On a number of rapids along Scudder Creek, cavernous travertine develops under optimum conditions at the rate of three to five inches during a single summer. The dense felt-like masses of *Vaucheria* grow upon the wet surfaces of the rapids in such a manner as to form little cup-like, or pocket-shaped hollows. The water which collects into minute pools in the cavities immediately above these masses of algae, slowly seeps through the tangled algous filaments, and at the same time, the calcium carbonate present in the water crystallizes about the plants in the form of a hard and brittle incasement. As the calcareous deposit accumulates and hardens in the seepage water, the young plants at the surface continue to grow, while the incased filaments gradually decay. Shortly after the formation of the travertine, all traces of plant structure disappear and nothing remains except the small hollow calcareous tubules that resemble in appearance a tangled mass of coarse fiber. Immediately below the surface of this travertine, fruiting bodies of *Vaucheria gemminata* (Vauch.) DC. are formed during the summer months. In figure 3 one of these fruiting bodies is represented as it appears under the microscope after the removal of the surrounding calcium carbonate by means of dilute acids. The contents of the filaments have already disappeared and only the cell walls remain. The filaments vary from 63 to 100 *u* in diameter, and the fruiting bodies occur on short branches 50 to 60 *u* wide and 200 to 250 *u* long.* There are two ellipsoid hemispherical *oogonia* 60 to 70 by 70 to 80 *u*, shortly stipitate, with a hooked cylindrical antheridium between them. The general appearance of the travertine formed by *Vaucheria* is represented in figures 4 and 5 in the camera lucida drawing of a cross section and a longitudinal section of the cavernous mineral. The arrangement and shape of the typical hollow calcareous tubules is quite evident. Travertine of this general character may also occur in the older deposits, and it is very probable that species of filamentous algae similar to *Vaucheria* were important agents in the development of travertine of the first period.

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*See footnote on page 37.

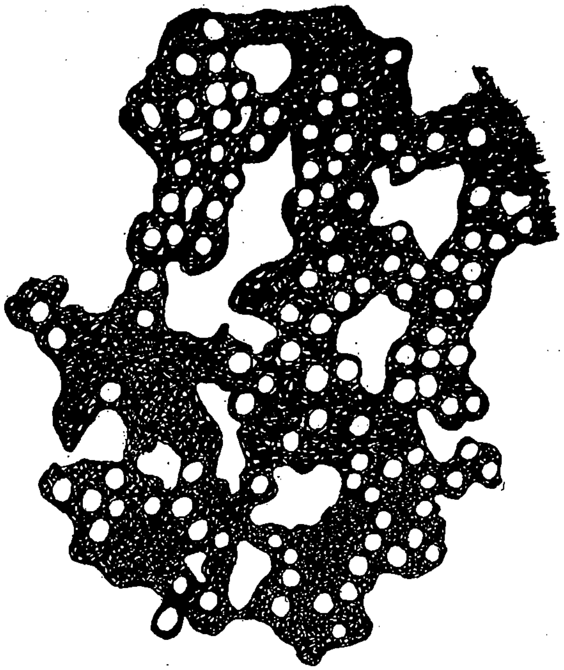

FIGURE 4. CROSS SECTION OF RECENT TRAVERTINE, SHOWING THE ORIGINAL POSITION OF VAUCHERIA FILAMENTS X-30.

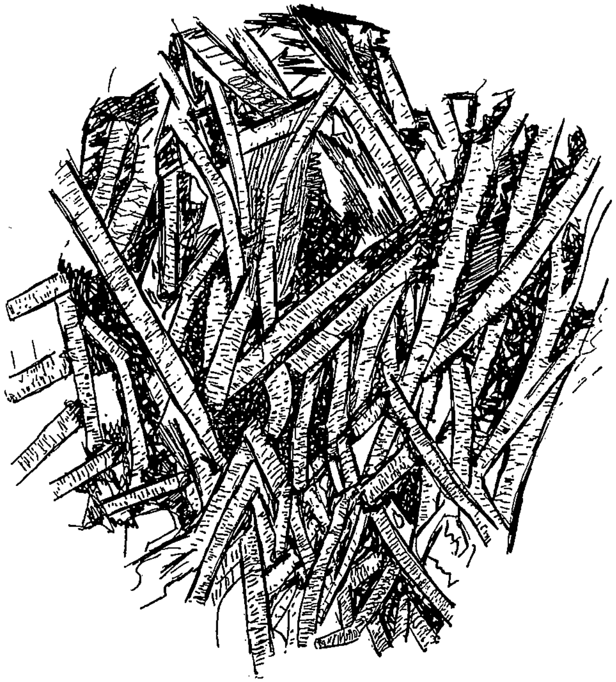

FIGURE 5. LONGITUDINAL SECTION OF RECENT TRAVERTINE, SHOWING THE ORIGINAL POSITION OF **VAUCHERIA** FILAMENTS X-30.

A number of other algae were present in recent cavernous travertine, and among those identified were: *Oscillatoria amphibia* Agardh., *Lyngbya aerugineo-caerulea* (Kuetzing) Gomont., *Lyngbya* species, *Rivularia* species, *Trochiscia granulata* (Reinsch.) Hansgirg, *Haematococcus fluviatilis* Flotow, *Oedogonium plagiostomum* var. *gracilius* Wittrock, *Oedogonium* species, *Cladophora glomerata* (L.) Kuetzing, and *Batracospermum* species.

Algae that were growing in quiet water and not contributing to the active formation of travertine include: *Zygnema pectinatum* (Vauch.) Agardh., *Spirogyra crassa* Kuetzing, *S. dubia* Kuetzing, *S. fluviatilis* Hilse, *S. gracilis* (Hass.) Kuetzing, *S. maxima* (Hass.) Wittrock, S. *porticalis* (Muller) Cleve, and S. *Weberi* Kuetzing. The most common alga occuring in seepage travertine was *Lyngbya aerugineo-caerulea* (Kuetzing) Gomont. The seepage travertine consists of a thin rust colored leathery crust containing filaments of *Lyngbya;* and beneath these plants there is a soft white chalk-like material containing only empty algous sheaths. The filaments of this *Lyngbya* break up into *trichomes* that vary from 4.6 to 6 *u* in diameter; the cells are 2.3 to 4 *u* long*; sheath firm and thin; the transverse walls often marked by granules; trichomes sometimes briefly tapering. Since algae of one species or other are present in all the recent calcareous deposits of this region, it will be highly important to consider the relation of these plants to the mechanism of travertine formation.

MECHANISM OF TRAVERTINE FORMATION.

In the mechanism of the deposition of travertine, one has to deal with the various factors involved in the precipitation and crystalization of calcium carbonate from nâtural waters containing calcium bicarbonate in solution. The factors of physico-chemical and biological processes are both concerned in the formation of travertine.

PHYSICO-CHEMICAL FACTORS.

A liter of pure water dissolves only .013 gram of calcium carbonate at 18° C., but calcium carbonate interacts with the carbon dioxide contained in all natural waters to form calcium bicarbonate, which, according to the equation $CaCO_3+CO_2+H_2O=Ca(HCO_3)_2$, is about thirty times more soluble. The amount of calcium carbonate dissolved in water increases with the partial pressure of carbon dioxide, to a maximum of 1.15 grams per liter at 15° C. According to Treadwell and Reuter** ('98) a liter of water saturated with carbon dioxide at 760 mm pressure and a temperature of 15° C. holds in solution .385 gram of calcium bicarbonate, which is equivalent to .238 gram calcium carbonate. The increase in solubility of calcium carbonate in waters

containing dioxide is to be accounted for by the formation of the univalention HCO_3. Every case of an increase in the solubility of a salt depends either on the decrease of the original ions or on the formation of new ions. The solubility of calcium carbonate in a tenth normal solution of sodium chloride is equivalent to its solubility in pure water.

If carbon dioxide is present in sufficient amount to form carbonates, it is also possible for magnesium carbonate and ferrous carbonate to remain in solution. Magnesium carbonate does not dissolve without the presence of free carbon dioxide, which in water at 15° C and with a partial pressure of carbon dioxide that is almost zero, contains 1.954 grams of magnesium bicarbonate, and .7156 gram of magnesium carbonate per liter. A liter of water containing carbon dioxide under six to eight atmospheres pressure will dissolve .73 gram of ferrous carbonate.

The precipitation of the carbonates of calcium, magnesium, and iron, takes place when from any cause the water parts with carbon dioxide. When the bicarbonic ion HCO_3 breaks up, losing carbon dioxide to the air, the normal carbonate of calcium or magnesium is formed, and being insoluble, is precipitated; whereas, the ferrous bicarbonate, under similar conditions, is broken up and ferric oxide or some corresponding hydroxide is formed by oxidation. These precipitations are modified by other substances which may be present in solution and the product is rarely pure, and the precipitation is not absolutely complete.

The dissociation pressure of carbon dioxide from the calcium bicarbonate, has probably a considerable value even at the ordinary temperature. When the ions Ca, CO_3, HCO_3 and OH come together, —as happens in the precipitation of a calcium salt with a soluble carbonate,—the solubility product of the calcium carbonate is much sooner reached than that of the hydroxide. The precipitate, therefore, consists of a normal carbonate in spite of the hydrolysis which occurs. In the precipitation of a magnesium salt with a soluble carbonate, the solubility product of magnesium carbonate is reached at about the same time as that of the hydroxide, so that the precipitate consists of a mixture of magnesium carbonate and magnesium hydroxide.

The best known deposits of calcium carbonate of purely inorganic origin are the stalactites and stalagmites of limestone caverns. Water percolating through the overlying limestone becomes charged with calcium bicarbonate. As each drop of the mineral solution gathers on the roof and begins to evaporate and lose carbon dioxide, the excess of carbonate, which can no longer be retained in solution, is deposited as a ring at the margin of the drop. At first the calcareous substance is soft, and when dry pulverulent; but by prolonged saturation and the internal deposition of calcite, it becomes crystalline by degrees. Aside from the stalactites and stalagmites, which are of a purely inorganic origin, there are other more extensive and important calcareous deposits that have been formed by the activity of organisms.

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*See footnote on page 37.

**Treadwell, F. P., und Reuter, M.: Uber die Loslischkeit der Bikarbonate des Calciums und Magnesiums, Zeit, f. Anorg. Chem. Vol. 17, pp. 170-204, 1898.

BIOLOGICAL FACTORS.

BACTERIA

Bacteria are active agents in the precipitation of calcium carbonate from the calcium salts present in solution in the seas of the American tropics. The formation of chalk and many varieties of sedimentary rocks composed of calcium carbonate, and also the cementation of coral fragments into compact rock, have been credited to bacterial agencies.

The precipitates of calcium carbonate, which Kellerman* and Smith ('14) obtained in their laboratory with cultures of certain bacteria, were formed by one of three different types of biological processes. In the first instance, ammonium carbonate is produced as a result of associative action of mixed cultures of bacteria, in which one species forms carbon dioxide and another species forms ammonium, either by decomposing a protein or by reducing nitrates to nitrites and ammonium. The ammonium carbonate thus produced reacts with calcium sulphate which may be in solution according to the equation $CaSO_4+(NH_4)_2CO_3=CaCo_3+(NH_4)_2SO_4$. In another instance, the production of ammonium by bacteria may bring about a precipitation of calcium carbonate in water charged with calcium bicarbonate according to the equation $Ca(HCO_3)_2+2NH_4OH=CaCO_3+2H_2O+(NH_4)_2CO_3$. Calcium carbonate may also be precipitated as a result of the bacterial decomposition of calcium salts of organic acids. Large crystals of calcite appeared in cultures of *Pseudomonas calcis* grown in media containing calcium only in the form of organic salts. With the exception of the nitrite and nitrate bacteria, no organisms are known which can utilize chemical energy in the production of organic food from carbon dioxide.

Murray** ('13) ascribes the precipitation of calcium carbonate in sea water to the interaction of ammonium carbonate, derived as a product of decomposing nitrogenous organic matter, with the calcium sulphate present in solution. This reaction has been shown to occur under experimental conditions wherever nitrogenous organic matter has been allowed to decay in sea water, yet this effect is purely local and confined to the immediate vicinity of the decaying organic material which gives rise to the formation of ammonium carbonate.

CULTURAL EXPERIMENTS WITH BACTERIA ISOLATED FROM TRAVERTINE.

The precipitation of calcium carbonate by bacteria suggests the possibility of travertine formation partly as the result of the activity of nitrifying bacteria by one or more of the different processes described above. In order to verify this supposition, pure cultures of bacteria were isolated from the deposits collected at Little Niagara Falls on Travertine Creek near Sulphur, Oklahoma. These bacteria were

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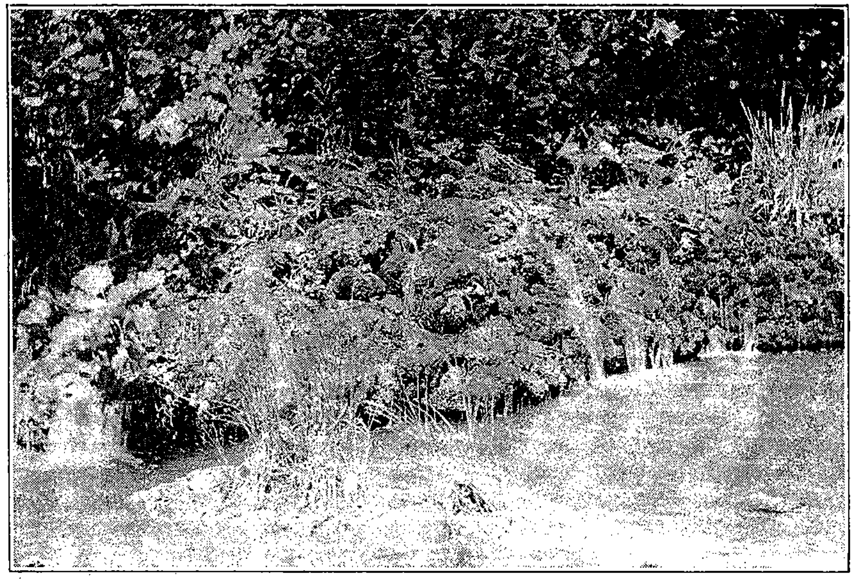
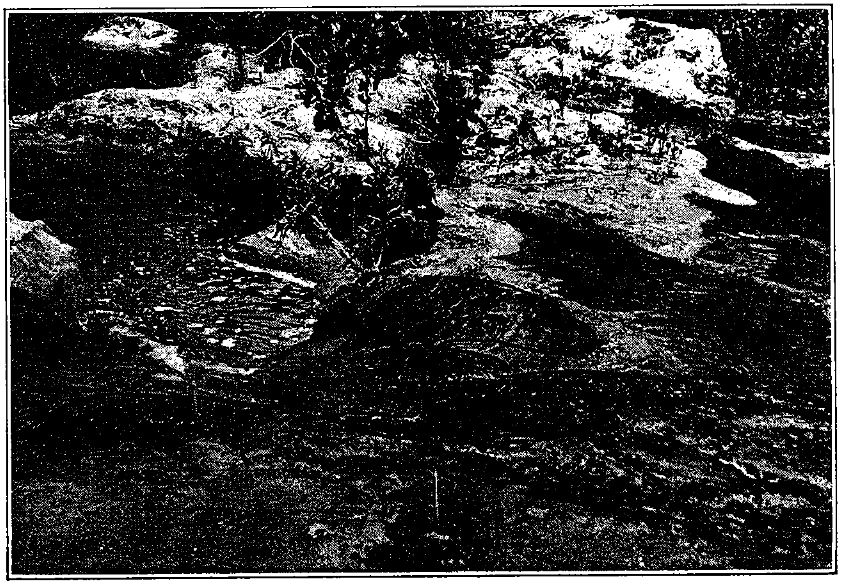
*Kellermann, K. F., and Smith, N. R., ('14): Bacterial precipitation of calcium carbonate, Jour. Wash. Acad. Sc. Vol. 4, pp. 400-402, 1914.

**Murray, Sir John, ('13): The Ocean, pp. 1-252, 1913.

PLATE XIII.



A. TRAVERTINE FALLS DEVELOPED BY TUFTS OF THE MOSSES PHILONOTIS AND DIDYMODON.



B. WATER FALLS ON HONEY CREEK, SHOWING LARVAE OF THE BLACK FLY SIMULIUM. THE POSITION OF THE LARVAE IS INDICATED BY THE CONTINUOUS LINES.

isolated by means of a mineral water agar, made by adding one per cent thread agar to the mineral water obtained from Falls Creek. Ten bacterial cultures were arbitrarily selected from the colonies of bacteria that grew on the mineral water medium, and were separately placed in 150 cc Erlenmeyer flasks containing 100 cc of a sterilized mineral nutrient solution. The mineral nutrient solution was either (1) the same kind as Winogradsky used for pure cultures of nitrogenous bacteria which assimilated atmospheric carbon dioxide without the aid of sunlight, containing: 1000 cc distilled water, 1 gram of ammonium sulphate, 1 gram of potassium dihydrogen phosphate, and 5 grams of basic magnesium carbonate; or (2) a nutrient solution containing an organic compound made up as follows: 1000 cc distilled water, .5 gram sodium dihydrogen phosphate, .2 gram magnesium sulphate, .5 gram calcium chloride, 2 grams sodium bicarbonate, and 1 gram sodium potassium tartrate. All of the ten pure cultures of bacteria in duplicates, were allowed to grow for eight days in solution 1, or three days in solution 2. After this length of time, the solutions containing the various bacterial cultures were titrated with tenth normal hydrochloric acid and tenth normal potassium hydroxide, using phenolphthalein and methyl orange as indicators. The results obtained from these cultures of bacteria, as given in the following table, are negative in that they do not show any change in the amount of bicarbonates due to bacterial activity. These results, however, are not considered decisive, for it was not possible at the time of this experimentation, to try the action of associative cultures or pure cultures of bacteria obtained from other sources and by other laboratory methods. In the following table the results of the titrations are given for the semi-combined carbonates in terms of cubic centimeters of tenth normal hydrochloric acid necessary to neutralize the 100 cc of nutrient solution in which the pure cultures of bacteria had been growing for eight days in solution 1, or three days in solution 2.

Solution No. 1. No. of cc n/10 HCl = 100 cc culture solution.		Solution No. 2. No. of cc n/10 HCl = 100 cc culture solution.
Culture No. 1	1.50 cc	2.3 cc
Culture No. 2	1.60 cc	2.3 cc
Culture No. 3	1.60 cc	2.3 cc
Culture No. 4	1.45 cc	2.5 cc
Culture No. 5	1.60 cc	2.3 cc
Culture No. 6	1.60 cc	2.3 cc
Culture No. 7	1.65 cc	2.3 cc
Culture No. 8	1.60 cc	2.4 cc
Culture No. 9	1.65 cc	2.2 cc
Culture No. 10	1.60 cc	2.3 cc
Control	1.60 cc	2.3 cc

ALGAE AND THE HIGHER PLANTS.

The ability by plants, to induce transformations of calcium compounds, is not limited solely to the activity of bacteria. Calcium is

essential for the development of the higher plants. Naturally, it is not taken up by plants as an element but in the form of one of its abundant salts, and constitutes not less than 2 to 8 per cent of the weight of their dried substance. Calcium plays an important role in the metabolic processes of plants, as a vehicle for certain other essential substances, and as a means of fixing and rendering harmless certain injurious by-products.

As a rule, all materials which are absorbed by water plants pass through continuous cell walls. In order that these various substances may enter the cell, they must be either in a liquid or a gaseous state. The plant nutrient solutions contain salts and other non-volatile compounds in solution; these on evaporation are left in the plant and gradually increase in quantity. At the growing points of most plants the cells, with their gradually increasing store of minerals, are separated from one another by extremely thin membranes which are practically of the same composition as protoplasm. Protoplasm is not a simple chemical substance. Active protoplasm generally gives an alkaline reaction, but under certain conditions it may be neutral.

Living protoplasm is not like the cell wall, equally permeable to all substances in solution, but on the contrary, completely excludes certain substances while allowing others to pass through more or less readily. It is also able to change its permeability according to circumstances. The outer protoplasmic membrane has the singular property of permitting the useful and essential substances to enter the cell, and at the same time exclude the non-useful or those substances which have attained a concentration sufficient for the needs of the cell. The same influence is exercised by these membranes in the transfer of substances in a reverse direction. On account of the selection thus exercised by protoplasm, the contents of a cell, in spite of continued osmotic pressure, are often of quite a different chemical nature from the immediate surrounding medium. To this same peculiar quality of the protoplasmic membrane is also due the selective power of cells manifested by the fact that different cells appropriate from the same nutrient solution entirely different compounds, so that, *diatoms*, for example, will take up chiefly silica, while *Chara*, for instance, will take up principally the calcium salts. Water is not only indirectly indispensable for the solution and transport of the products of metabolism, but also directly, in that its elements hydrogen and oxygen are used in the formation of organic compounds in plant nutrition. The more important service which water performs for plants consists in the conveyance and introduction into the plant body of the nutrient substances.

In order that substances may continue to enter the cell, it is essential that the absorbed material should become transformed into others that are indiffusible, either by the activity of the protoplasm, or by some other means. Under conditions favorable for these transformations, the osmotic currents toward the transforming cells will continue, and the altered and indiffusible substances will accumulate in them. In this manner inorganic substances are often deposited in large quantities in old cell walls. Among such substances silica, which is often met in the superficial cell walls of the grasses, sedges, horse-tail rushes, diatoms, and many other plants, will facilitate the formation of a very rigid skeleton. Calcium carbonate and calcium oxalate are also present, in crystal form, in many plants; as for instance, the *Characeae,* where the quantity of calcium carbonate in the cell walls is usually so great as to render the plants stiff and brittle. There are but few plants that do not possess crystals of calcium oxalate. These crystals are formed in the cytoplasm, within vacuoles which afterwards enlarge and sometimes almost fill the whole cell. In such cases the other parts of the cell become greatly reduced. The crystals may be developed singly in a cell, in which case they are of considerable size, or they may be so small and numerous as to appear like a crystalline sand filling the cell. As a general rule, the calcium oxalate deposited in crystal sacs represents an excretory product. Oxalic acid is formed in plants as a result of a variety of metabolic processes, particularly in connection with protein synthesis. But this acid is poisonous to the protoplasm, and is accordingly rendered harmless by its combining with calcium to form the very insoluble calcium oxalate.

Under certain conditions the precipitation of calcium carbonate may result from the activity of water plants in a manner more direct than in the formation of calcium oxalate. During the physiological processes of plant food manufacture, or photosynthesis, the water plant may assimilate either the dissolved free carbon dioxide gas, or the supply of carbon dioxide may be increased either as semi-combined carbon dioxide in the bicarbonates, or indirectly in the absorption of carbon dioxide by monocarbonates, from the air and that liberated during respiration. In all cases the carbon element contained in the carbon dioxide is made up into a constituent part of the living protoplasm. In one sense carbon is the most important material in plant nutrition. Every organic substance contains carbon, and there is no other element which could supply or take part in the formation of so many or such a variety of substances in living organisms. The carbon of all green plants is derived from carbon dioxide. Only cells that are colored green by chlorophyll are capable of assimilating carbon dioxide, for the chlorophyll bodies themselves are the laboratories in which this chemical process takes place. The chlorophyll, however, can only produce organic substances from carbon dioxide and water, with an incidental release of oxygen, by means of radient energy as expressed in the photosynthetic equation $6\ CO_2+6H_2O=C_6H_{12}O_6+6\ O_2$. The product of photosynthesis is usually a carbohydrate, sugar, or starch, but in certain algae it may be a fatty oil or a protein.

During the formation of organic materials in the cell, not all light rays are equally capable of inciting the activity of chlorophyll. The highly refractive chemical rays have little or no effect on photosynthesis; the red, orange, and yellow rays, that is, the so-called illuminating rays of the spectrum, are on the contrary the most active. All the rays of the mixed white light are usually at the disposal of plants, except the seaweeds found in deep water and which grow in a prevailing blue light. In the blue-green fresh water algae, the maximum of photosynthesis seems to take place in that part of the spectrum the color of which is complementary to their own. The pigments associated with the chlorophyll appear to act in the same way as the sensitive elements on the photographic plate; they attract light of a different wave length to cooperate in the chemical process.

Birge and Judy* ('11) found that the zone of photosynthesis in clear lakes may extend to the depth of thirty feet or more. The oxygen contents of this zone vary with the ratio of the liberated oxygen and that absorbed from the air, to that consumed by decomposition and respiration. In the region of photosynthesis, the oxygen may be present in sufficient quantity to saturate the water. Seyler concluded from experiments with Ulva that the photosynthetic process stopped before all of the half-bound carbon dioxide was used. Observations in Big Butternut Lake, Wisconsin, by Birge and Judy, demonstrated that plankton algae had removed about five-sixths of the half-bound carbon dioxide from the upper stratum of the lake.

Besides the synthesis of carbon compounds by chlorophyll bodies in algous cells, there is also an oxidation of various substances during respiration. In green plants respiration as a rule attains its greatest degree of intensity in the absence of light while the process of photosynthesis is at a standstill. The respiration of algae is essentially the same as that of the higher plants. During the metabolic processes, oxygen is consumed and carbon dioxide is set free in the water at all depths where plants occur. There is an accumulation of free carbon dioxide in the lower waters, increasing with depth, and a corresponding reduction of oxygen. Davis** ('00) offered an explanation for the precipitation of calcium carbonate by plants, and especially the algous genus *Chara,*—in water containing bicarbonates in quantities too small to be affected by the removal of all the free carbon dioxide present,—by presuming that the oxygen liberated during photosynthesis may cause this precipitation. However, this supposition does not hold under the conditions which usually accompany the formation of marl by *Chara* and other organisms. The calcareous incrustation of *Chara* is caused by the action of more than one biological process.

The fact that calcium bicarbonate is broken up and precipitated as the normal carbonate during the assimilation of carbon dioxide by water plants does not clear up all the plant processes involved in the formation of travertine. Hassak*** found that *Chara* gives an incrustation in solutions containing calcium sulphate, chloride, and other

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*Birge, E. A., and Judy, C., ('11): Inland lakes of Wisconsin, Wis. Geol. and Nat. Hist. Survey Sc. Ser. No. 7, Bull. No. 22, pp. 1-249, 1911.

**Davis, C. A. ('00): A contribution to the natural history of Marl. Jour. Geol. 8: 485-497, 1900.

***Hassak, cited by Oltmanns, F. ('05).

calcium salts, just as readily in the absence of calcium carbonate as when the carbonate is present. He also found that in light, algae decompose sodium bicarbonate and form the normal sodium carbonate. Frequently, too, one species of algae will differ from another species, and even individuals of the same species will not all be equally effective in the precipitation and secretion of calcium carbonate. These variations must be due to differences in the structure, chemical constitution, metabolism, and habitat of the plants in question. *Elodea, Vallisneria, Ceratophyllum, Potamogeton, Chara, Cladophora, Oedogonium* and certain other plants growing in water containing calcium bicarbonate become mineralized only in the presence of light and during the process of photosynthesis. Algae can remove and assimilate the carbon dioxide of the dissolved bicarbonates which are thereby transformed into the normal carbonates. According to Leitgeb* ('87) the incrustation of *Acetabularia* consists of calcium carbonate that constitutes the outer fine grained mass, and of calcium oxalate which makes up the inner portion of the deposit in the form of microcrystals. The carbonate is more abundant on the thallus and older parts of the plant. The oxalate appears first along the young curved tips, and especially in the actively growing parts.

The rapid growth in length which sets in a short distance from the growing point as a result of the increase in size of the cells must be accompanied by a corresponding growth in the surface of the cell walls. So long as this growth in surface continues, the cell walls remain thin. An increase in the surface of cell walls in algae often depends upon a passive extension of the preexisting lamella and a subsequent deposition of new layers, the area of which is naturally adapted to the increased surface available for deposition. In this case, the increase in surface is, strictly speaking, not affected by growth at all, but is due purely to passive extension.

After the cells have attained their ultimate size, the growth in thickness of the wall then begins. Growth of the cell wall, according to Strassburger** ('98 may take place in two ways: (1) by the introduction of new particles between those previously existing, which takes place during the surface growth and stretching of the cellulose membrane, termed growth by intussusception; and (2) by the laying down of new lamella on the surface of the older one, called growth by apposition. The later growth in thickness of most cell walls takes place by apposition. The cell wall, however, is not an excretion, but is formed by the direct change of portions of the protoplasm. The ash content of young cell membranes is not much different from that of living protoplasm.

Stratification, that is, the differentiation of a number of concentric layers differing among one another in respect to refractive index, is an almost universal feature of thickened cell walls. Very frequently a thickened cell wall may be seen to consist of several stratified layers, or complex strata, which differ from one another in chemical composition as well as in their optical behavior. The so-called primary, secondary, and tertiary thickened layers of most *Protococcaceae, Zygnemaceae, Ulotricaceae, Chaetophoraceae,* and *Siphonales* represent strata of this nature. In those algae that live submerged in water, the primary layer, a cuticle or similar structure, possesses only those features of a typical epidermis that are connected with its mechanical function or with its action as a light screen. A typical epidermis is scarcely ever present, and in these circumstances there is no reason why the photosynthetic system should not extend its influence over the outermost layer of the plant body. The secondary layers form a massive stratum which in soft tissues consists in part of a pectic compound of calcium. The tertiary layers are represented by a very thin, often highly refractive internal or limiting membrane. The stratification of the various layers of the cell walls are due to differences in the water content, to differences of a chemical nature, or they may be produced by a combination of physical and chemical factors. The gelatinous envelops or sheaths of certain algous cells are composed of substances that are closely related to cellulose. If these sheaths were condensed, they would form a firm cell wall. When a cell of the blue-green alga *Gloecapsa* divides, each daughter cell secretes a sheath about itself. As division continues, the sheath of the original cell remains enveloping the entire family. All of the sheaths formed at each successive cell division, remain in existence. The total number of sheaths present at the sixteen cell stage, for example, will be one less than twice the number of cells or thirty-one separate sheaths.

The cell wall of *Closterium Ehrenbergii* and *Closterium accrosum,* according to van Wisselingh* ('12) consists of strata of different ages. The older strata are on the outer side, while the youngest strata are on the inner side of the cell wall. At the beginning of development, the younger membranous layers are always thinner than the older ones, but as the cell matures the reverse condition is more prevalent. The primary or outermost layer contains little or no cellulose. The secondary layer contains a small amount of cellulose while the tertiary or the innermost lamella is very rich in cellulose.

The cell wall of the alga *Chara* consists of normal cellulose. The outer layers are more or less gelatinous and it is in these outer layers that the calcium carbonate is precipitated. In the red algae the same condition exists; but the layers are not as thick and the middle lamella is the first to become mineralized. As long as the cells are living, the protoplast is separated from the mineral deposit by a thin membranous sheath.

The stratified layers in the cells of many algae consist of pectin and pectin-like substances in pure form. Pectic acid combinations in algae

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*Leitgeb, H., ('87): Die Incrustation der Membran von Acetabularia, Sitz. d. Kais. Akad. d. Wiss. Math-Natur. Vol. 96, pp. 13-37, 1887.

**Strassburger, E., ('98): Die pflanzlichen Zellhaute, Jahrbucher fur Wiss Bot. No. 31, pp. 511-596, 2 pl. 1898.

*Van Wisselingh, C., ('12): Uber die Zellwand von Closterium, Zeit, f. Bot. Vol. 4, pp. 337-387, 1912.

are of general occurrence, mixed with the cellulose. In the gelantinous substances of *Laminaria,* there is present an acid that is combined with calcium, an acid that is closely related to pectic acid. Czapek* ('13) suggests that there is a possibility in many cases where calcium carbonate may be derived from the calcium pectinate contained in the cell walls. The deposition of calcium oxalate or the incrustations of calcium carbonate are the result of a primary precipitation or a transformation product derived from organic compounds.

The majority of the *Siphonales* and *Siphonocladiales* have a specific calcareous incrustation. There are also special structures of the red algae that become mineralized. The *Corallinaceae, Acetabularia,* and similar algae, growing in dense shade remain almost entirely free from calcium carbonate, but in well lighted habitats they attain a thick calcareous covering.

The occurrence in algae of minerals other than calcium has been known for a long time. One of the first discoveries in this particular field of investigation, was the detection of iron in the akinete membranes of *Conferva* and also the little iron-containing rods of *Penium.* Small quantities of iron have been found in certain species of the red algae and of the *Cladophoraceae.* By an examination of the investigations of Molisch** ('09) and Devaux*** ('01) on the fixation of minerals in water plants, one may gain an idea concerning a few of the many ways in which iron, calcium, and various other mineral salts accumulate in plant cell walls.

Molisch observed that the leaves of *Elodea* became brown in color if placed in water containing .015 per cent of the chloride, carbonate, or organic compounds of manganese; but very little change was noticed in the separate presence of other manganese salts such as the sulphate and phosphate. The coloration due to the presence of manganese carbonate was so great that the plant had the appearance of a new species. The entire mature leaf became brown black.

The young leaves in the tip of the plant remained free from the manganese precipitates and retained their green color. However, the stem and root epidermis also remained unchanged in the presence of any of the manganese compounds. The deposit, an oxide of manganese, begins to collect at the tip of the leaf and proceeds towards the base. The upper half of the leaf is often deep brown in color while the lower half is still green. This chemical change which is most probably connected with the process of photosynthesis, took place only in the light, not only in the red, but also to a less degree in the blue spectrum. The same result was obtained with the experimental plants in light either in water under normal conditions or in water free from carbon dioxide. The precipitate of manganese dioxide did not take place in all plants tested but only in a few species. In Elodea the mineral may appear first on the outer surface, on the inner surface, or in the center of the secondary layer and gradually extend throughout the entire stratum. Similar results, with the exception that the precipitate was colorless, were obtained with zinc, cobalt, and nickel sulphate, especially if the plants were placed in abnormal solutions.

According to Devaux compounds of potassium, lithium, sodium, calcium, strontium, barium, nickel, cobalt, cadmium, copper, and silver, mercury in traces, but not gold, platinum, or chromium, may be affixed to the cell walls of the water plants *Elodea, Lemna,* and *Ceratophyllum.* The amount of fixation of the metals is always slight and the fixed metals are easily displaced by alkalies and alkaline earth metals. The alkalies after fixation are displaced by dilute solutions of a calcium salt, even by natural water containing only five parts of calcium per million. Iron, on the contrary, is fixed in an insoluble state and therefore is not displaced in either alkaline or alkaline earth solutions.

A point of interest in regard to these observations is that the minerals are deposited only in the walls of mature cells and not in the walls of the young rapidly growing cells. The protoplast itself remains unaltered except in disintegrating or abnormal cells. It is evident that many physiological processes contribute to the mineralization of cell membranes, and that these numerous inherent possibilities give added weight to the importance of plants as rock-builders.

PLANTS AS ROCK BUILDERS.

The geologic work of plant life is not generally recognized, since it is less conspicuous on account of the absence of organic remains. Where the mineral matter preserves the form and structure of the plant, as in the case with silica forming the well known beds of diatomaceous earth, the origin of the deposits is apparent. Diatoms have an exceedingly wide distribution, occurring both in fresh water and in the sea. Diatomaceous deposits are now being formed in the Yellowstone National Park, where they cover an area of many square miles in the vicinity of active and extinct hot springs. In addition to this occurrence, the siliceous tests of diatoms may be found in certain argillaceous and other sediments. Tertiary species of diatoms show a very marked resemblance to living forms and the fossil deposits are not essentially different from those of recent development.

Rocks formed as sedimentary deposits are either composed of fragmentary materials derived from the breaking down of older rocks, or, they represent the more or less consolidated accumulations of organic and inorganic debris from plant and animal life. Of the different varieties of limestone, some are formed in lakes just as the calcareous marl of the present time; other kinds represent the calcareous mud and coral reefs of ancient seas; or, they constitute chem-

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*Czapek, F., ('13): Mineralische Einlagerungen in Zellmembranen, Biochemie der Pflanzen Vol. 1, pp. 680-682, 1913.

**Molisch, H., ('09): Uber lokale membranfarbung durch manganverbingdungen bei einigen Wasserplanzen, Sitz. Akad. Wiss. Wien. Vol. 118, pp. 1,427-1-441, 1909.

***Devaux, H., ('01): Generalite de la fixation des métaux par la paroicellulaire, Compt. rend. Acad. Paris Vol. 133, pp. 58-60, 1901.

ical precipitates of purely inorganic origin, being derived from water carrying in solution an excess load of calcium bicarbonate. When fresh waters, charged with carbonates, enter the sea, a direct precipitation of calcium carbonate may occur. This form of deposition is the exception. It happens only when the supply of carbonates is in excess of that which can be used by living organisms, and when the conditions of temperature and evaporation are such as to expel the carbon dioxide required to hold the carbonates in solution as bicarbonates.

In the present state of our knowledge, it may be said that the precipitation of great limestone formations in the ocean by chemical means is a speculation based upon the premised inadequacy of life to precipitate such amounts of materials in the early geological periods. It is necessary to explain only the limestones of pre-Paleozoic origin, the rocks of which contain very few fossils. But even these limestones may have been precipitated by organisms and the fossils destroyed by the process of recrystalization and metamorphism just as the fossils in many later formations have been changed.

As a general rule, limestones are ancient sediments formed in clear and comparatively deep water, composed largely of calcium carbonate; in certain cases with an addition of magnesium carbonate, and occassionally an addition of silica. In such rocks fossils of land plants are rare. There are, however, limestones which were formed wholly or in part by calcareous algae which grew in the form of submarine banks or in coral reefs. Occasionally the remains of these algae are clearly preserved, but more frequently in the formations of limestone in the ocean, all signs of plant structure have been destroyed.

The composition of the sea floor is not found to be of one kind of mud alone. The shallow water deposits are of fine gravel and sands washed down from the continental shelves and carried out to sea by meandering shore currents. But the deep sea beds, containing what is called the abysmal deposits, are not influenced by shore or land changes. In 3,000 feet or more of water, and far removed from land, the sea floor may be made up of the empty shells of organisms that live in and upon the surface of the water. With an increase in the depth of the water there is an increased pressure of carbon dioxide gas which dissolves and destroys these shells. Ultimately there remains only an ooze containing but a few traces of the organisms that go to make up the sediment. Apparently this process of sedimentation has not changed materially during the past geologic ages. Such forms of life as the brachiopods, the gastropods, and the crustacea, are practically the same today as in the earliest ages. It is a fair inference that organisms, including plants, not found in fossil forms because they are without shells or mineralized skeletons, existed also in the Paleozoic era.

At the present time the ocean and the connecting seas are not saturated with calcium, or even approximately so. It is certain that under present conditions the precipitation of calcium compounds in the ocean is accomplished principally by organisms. The animals and plants

living in the ocean and in lakes, abstract calcium carbonate from the water and build it into their hard parts. The number of species of organisms which are doing this work is enormous. The material deposited by animals may be amorphous or crystalline aragonite or calcite. The material deposited by corals and crinoids is crystalline, and in the form of aragonite; that formed by the mollusca is calcite and to a less extent of aragonite. The change from aragonite to calcite is so complete in rocks of moderate age that the presence of aragonite in the metamorphosed rocks is almost unknown. The continuous precipitation of calcium carbonate by organisms in the sea, and the building of organic deposits through geologic periods, combined with the mechanical rearrangement and recrystalliaztion, have resulted in great limestone formations.

The Arbuckle Mountains consist of approximately 10,000 feet of Paleozoic sediments, chiefly limestones that rest unconformably upon pre-Cambrian granite and porphyry. The Arbuckle limestone is the principal formation. It is composed largely of a hard, bluish-white and cream colored limestone and dolomite, interstratified with slightly argillaceous layers. Less common are the thin layers of cherty oolite and oolitic limestone. Oolitic limestone is very abundant in the Hunton formation. Beginning at the base of this limestone there are variable beds of white oolite consisting in part of coarse and fine spherical granules. Aside from the oolitic strata, the Hunton formation consists of a nearly pure white, cream-colored, or pink limestone, shaly limestone and marl. Limited amounts of marl occur in the Simpson formation which varies from a brown massive standstone to thin yellowish, bluish, or pure white and fossiliferous limestone interbedded with greenish clay shales. On the other hand, the Viola formation represents a continuous but slightly variable deposition of limestone. It is mostly of a fine and dense structure with a part made up of coarsely crystalline beds, and other strata that consist chiefly of shells and shell fragments. Up to the present time, only a few fossil plants have been discovered in the older formations of the Arbuckle region. A scarcity of fossil plants is generally the rule in all limestone formations.

To a botanist, the records of fossil algae are disappointing. Such genera as *Nematophycus* and *Pachytheca,* which may be regarded as extinct forms of algae, Seward* ('94), have been found in certain of the lower Paleozoic strata. Aside from these fossils, the recognition of fossil algae is limited to specimens that present only superficial resemblances to living species.

However, from a geological standpoint, the calcareous algae are of considerable importance as rock building agents. Certain rocks are definitely known to have been derived wholly or in part from the accumulations of calcareous plants, and in many cases where the plant structure is absent, facts may be presented which point to a phytogenetic origin.

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*Seward, A. C., ('94): Algae as rock-building organisms, Science Progress Vol. 2, pp. 10-26, 1894.

Nicholson* ('88), in a study of mocroscopic sections of a Silurian limestone from the Girvan district of Scotland, found in certain calcareous grains, abundant tubular structures suggestive of simple cylindrical plants which probably were connected with the precipitation of the calcium carbonate. At first he referred this fossil, *Girvanella problematica,* to *Rhizopoda,* as if related to the arenaceous foraminifera; but later he considered it as a representative of one of the blue-green algae. Wethered** ('89) found that fossils resembling *Girvanella* are present in many other rocks as well as those of Silurian age. In his sections of coralline oolite and pea-grit, there were present, centrally placed nuclei surrounded by concentric layers of numerous tubules. He did not hesitate to refer these structures to the genus *Girvanella.* Wethered explains the origin of pea-grit as a deposition on the sea floor of fragments of organisms, and about these fragments as nuclei, *Girvanella* tubules later collected, sometimes enclosing a fragment with a crust of tubules that ultimately gave rise to calcareous granules.

The discovery of *Girvanella* and allied forms in rocks from the Cambrian, Ordovician, Silurian, Carboniferous, and Jurassic formations, strengthens the point of view that oolitic structures in many cases are associated with the presence of tubular organisms. From the first examination of the microscopic structures of oolitic granules, certain investigators practically agreed that in the formation of oolitic structures, calcium carbonate had been deposited in concentric layers about a grain of sand or other nucleus by an inorganic process. According to Bornemann ('87), a fossil genus *Zonatrichites,* related to the family *Rivulariaceae,* has also been responsible for a number of oolitic structures. In this instance, concentric zones are formed, presumably by the periodic growth of algae, the older layers serving as a center on which the young filaments grow in radially arranged groups. The majority of marine calcareous oolites with regular zonal and radial structures are considered of plant origin by Rothpletz*** ('92). Sections of oolite from the Great Salt Lake in Utah, slowly dissolved in dilute acid, reveal dead cells of the blue-green algae *Gloeocapsa* and *Gloetheca.* According to Wallace**** ('13) the presence of certain areas of dolomite in Ordovician limestone of Manitoba is to be attributed to the agency of algae. The process of dolomitization during the hardening of calcareous ooze of an ancient sea, induced a local mineral transformation in the immediate vicinity of algae without affecting the crystalization of the surrounding limestones.

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*Nicholson, H. A., ('88): On certain anomalous organisms which are concerned in the formation of some of the Paleozoic limestones, Geol. Mag. N. S. Vol. pp. 15-25, 1888.

**Wethered, E., ('89): On the microscopic structure of the Jurassic pisolite, Geol. Mag. N. S. Vol. 6, pp. 196-200, 1889.

***Rothpletz, A., ('92): On the formation of colite, Amer. Geol. Vol. 10, pp. 179-282, 1892.

****Wallace, R. C., ('13): A contribution to the study of delomitization, Tran. Roy. Soc. Canada Ser. 3 No. 74, pp. 139-149, 1913.

Among the many kinds of algae living today there are numerous species of the *Cyanophyceae* and unicellular *Chlorophyceae* growing under conditions favorable for the formation of spherical masses of algae incrusted with calcium carbonate. It is probable that certain of the tubular structures found in different types of oolite, represent incrustations of calcium carbonate in the sheaths of certain species of blue-green algae.

Plants as well as animals are of importance in connection with the deposition of marl. The angiosperms, however, are of little value in this connection. The plant agencies here concerned are limited principally to certain blue-green algae, green algae, and the algae *Chara,* which grows in water varying in depth from a few inches to over a hundred feet. Schroter* ('02) found *Chara ceratophylia Wallroth,* a most vigorous form, growing in water 100 feet deep; always incrusted with calcium carbonate, stiff, hard, and brittle. The deposit consists of calcite crystals that are more or less scattered on the growing parts of the plants, and on the older parts, it constitutes a complete covering of uniform thickness.

Calcareous algae are noteworthy agents in the origin of limestone. In the *Chlorophyceae,* the green algae, almost all species of the *Siphonales* and *Siphonocladiales* have their specific hard coating of calcium carbonate. The fossil algae of this group are widely distributed and their presence indicates that calcareous algae have played an important role during the early geologic periods. Species of *Caulerpaceae, Codiaceae,* and *Dasycladiaceae* are of common occurrence in the tropical and subtropical seas; *Penicillus, Codium, Acetabularia, Cymopolia,* and *Halimeda,* are important types of recent genera.

In the *Rhodophyceae,* the red algae, species belonging to the genera *Corallina, Lithothamnium, Lithophyllum,* and Melobesia, take an active part in the building of coral reefs. In certain cases the coral reefs are largely, if not entirely, composed of algae. Walther** ('85) brought up, out of the Gulf of Naples, masses of *Lithothamnium* from depths of a hundred feet or more. Among the branches of the algae, Gastropods and other animals were completely enclosed by the growing plants. Water passing through these masses gradually destroy the structure of the algae and the whole is changed to a compact structureless limestone. On the other hand, if conditions are favorable for rapid mineralization, the external structure of the plant is permanently preserved.

The corals are confined more particularly to the warmer seas, but the calcareous marine plants, with a superficial resemblance to the corals, are widely distributed and according to Howe*** ('12) are very

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*Schroter, C., und Kirchner, O., ('02): Die Vegetation des Bodensees, Bodensee Forchungen Vol. 9, pp. 1-85, 1902.

**Walther, J., ('85): Die gesteinbildenden Kalkalgen des Colpes von Ucapel und die Entstehung structurloser Kalke, Zeit. d. Geol. Gesell. Vol. 37, pp. 229-240, 341-357, 1885.

***Howe, M. A., ('12): Reef building and land forming seaweeds, Proc. Phil. Acad. Sc. Vol. 64, pp. 137-138, 1912.

abundant in all latitudes from the equator to more than twelve degrees north of the Arctic circle. Investigations of certain coral islands indicate that the calcareous algae have been more important than the corals in the formation of these islands.

The study of calcareous algae in the vicinity of hot springs preceded the discovery of the relation of algae to the formation of coral islands. The variegated algous vegetation of hot springs attracted the attention of casual observers at a very early date. One of the oldest references to calcareous algae is in the ancient hymn of Boleslau von Lobkowitz, dating back to about 1500 A. D. and cited by Cohn* ('76). A part of this hymn describes in a poetic manner the many colored vegetation of the Carlsbad Hot Springs. Agardh** ('27) examined the algae of hot springs in the vicinity of Carlsbad and Triest. He came to the conclusion that the algae removed part of the carbon dioxide dissolved in the water and precipitated the normal carbonate by means of vegetative processes. Cohn ('62) agreed with Agardh but for the agents of precipitation he added two other factors; heating, and the dilution and mixing of the calcareous waters with atmosphere. At Carlsbad, Cohn reports that there were no living organisms in the water above 44°C; bacteria were present in water at 43° to 35°C; all the algae, principally *Oscillatoria terebriformis, O. viridis,* and *O. amphibia,* were growing in water below 37°C in temperature.

Aside from the springs of Carlsbad, Bohemia, Austria, calcareous hot springs are known to occur in Italy, Java, Japan, Luzon, Thibet, the Azores, New Zealand, Iceland, Virginia, Wyoming, Nevada, California, and Arkansas. At the baths of San Vignone in Tuscany, Italy, the travertine is deposited at the rate of 6 inches a year, while at San Filippo, Sicily, it forms at the rate of one foot in 4 months; the deposits at the latter place having grown to a height of at least 250 feet, and have formed a hill a mile and a quarter long and a third of a mile wide.

The extensive travertine deposits of the Yellowstone National Park were first described by Weed in 1888. From his observations of these deposits, he concluded that the formation of travertine, in this place, was due to the growth and activities of a brilliantly colored algous vegetation living in the hot mineral water. In the rapid currents the algae were filamentous, and in the more quiet water the filaments were united into membranous sheets or in masses of jelly which were inflated by the gas bubbles that became entangled in the plant tissue. If the temperature of the water exceeded 150°F a white filamentous "alga" coated with sulphur was the only species present. Farther from the source of the spring the vegetation, coated with calcium carbonate, changed to a pale greenish yellow growth that was more abundant and

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*Cohn, F., ('76): Kryptogamen Flora von Schlesien, Abh. Schles. Gesell. Vol. 1, pp. 47-53, 1876.

**Agardh, ('27): Aufzahlung einiger in den Ostreichischen Landern gefundenen neuen Gattungen und Arten von Algen, nebst ihrer Diagnostick und beigefugten Bemerkungen, Flora. Vol. 10, pp. 625-640, 1827.

more deeply tinted in the cooler waters. Associated with the green algae were plants of a red and orange color. However, he notes that the formation of travertine was less rapid in the presence of the green algae and was very active about filaments of the white and red colored plants at a temperature of 100°F. Among the various factors that cause the precipitation of calcium carbonate from the mineral water of these hot springs are: the relief of pressure as soon as the water reaches the outer surface of the subterranean passage with a subsequent diffusion of carbon dioxide into the atmosphere, a lowering in temperature of the water, and evaporation. The cementation of the calcareous grains, which takes place in the older and deeper layers of algous masses, Weed* ('83) considered due largely to processes independent of plant life.

The value of plants as agents of calcium carbonate precipitation in hot springs has been overestimated by Weed. Under conditions similar to the formation of the calcareous deposits in the immediate vicinity of the hot springs of the Yellowstone National Park, there is no question but that travertine would be formed from the hot mineral water even if the plant life were absent. The vegetation in this particular instance, by its presence, acts only as a passive agent in determining the form and structure of the deposit, and does not necessarily take an active part in the precipitation of calcium carbonate.

Davis**, in 1897, visited the same region of the Yellowstone National Park and was able to make a brief study of the plants growing in the hot springs. The green plants were present in the warm water at a temperature of 55° to 65°C. As the temperature of the water increased, the green color was less intense and finally when the water was about 80°C, the plants all appeared light yellow in color. In the hottest water there were only long white filaments in the running streams, and a delicate fungous mat upon the bottom of quiet pools. The colorless or white plants were all *Schizomycetes.* The filaments were elongated *zoogloea,* or colonies of *Beggiatoa,* consisting of innumerable bacteria imbedded in a gelatinous matrix. The filaments of gelatinous consistency, at first delicate and flexible, soon became coated with small sulphur crystals and calcium carbonate, making them into stiff fibers along the edges of the hot pools and upon the bottom of the streams.

Associated with the bacteria, extensive growths of blue-green algae are often contained in a stiff and gritty jelly-like mass. The peculiar elevated runs about pools of hot water are colored by the presence of *Phormidium* and *Spirulina,* while in the cooler parts, *Anabena* and *Gloeocapsa* are usually present.

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*Weed, W. H., ('88): The formation of travertine and siliceous sinter by the vegetation of hot springs. U. S. Geol. Surv. Ann. Rept. 9: 619-676. 1888.

**Davis, B. M., ('97): The vegetation of the hot springs of Yellowstone Park. Science, N. S. 6: 145-157. 1897.

The mere presence of the algal filaments as foreign bodies does not facilitate the precipitation of calcium carbonate, but only produces the variegated colors and slight modifications in the surface of the calcareous terraces of the Yellowstone National Park. If no plants were present the travertine formations would grow just as rapidly, but only as so many coats of whitewash. As the water emerges from the orifices of the hot springs and spreads out in the shallow streams and pools there is an immediate escape of carbon dioxide from the supersaturated mineral water, a lowering of the temperature of the water, a release in pressure followed by a proportionat loss of carbon dioxide, and evaporation. All of these factors, exclusive of plant agencies, determine the precipitation of calcium carbonate of the hot springs of the Yellowstone National Park as a dazzling, white deposit of travertine.

The calcareous deposits associated with algae of cool water habitats are somewhat different in their formation from the deposits of hot springs. Penhallow, in 1896*, reported the formation of calcareous pebbles in Michigan ponds about the algae *Oedogonium, Gleocystis, Calothrix, Sirosiphon, Dichothrix,* and *Schizothrix.* Tilden, in 1897**, discovered a fungus, resembling *Pseudohelatium granulosellum,* associated with algae growing in a calcareous matrix. The water in which the calcareous pebbles were formed contained only 18 grains of calcium carbonate and 17.5 grains of calcium sulphate per gallon.

The travertine formations of Benestad, Sweden, are described in detail by Kurck*** ('00). These deposits occur along the water courses of certain valleys and on the hillsides where water issues from calcareous springs. The travertine is hardest wherever evaporation is taking place most rapidly, especially on the slopes near the springs; but along the streams, in the valleys, the travertine remains moist and consequently is soft and granular. Kurck gives the distribution of the flowering plants growing on various travertine areas without mentioning any lower plant forms such as mosses and algae which undoubtedly were present. Deposits of a similar nature, the tufa deposits of the Salton Sink, are considered by Jones**** ('14) as having been formed primarily by the activity of algae. The presence of algae, the porous and dendritic character of the deposits were taken as indications of its vegetative origin.

Among the many algae that have been reported living under conditions favorable for the formation of travertine are numerous species belonging to the genera: *Anabena, Aulosira, Calothrix, Chantransia, Chroococcus, Dichothrix, Fischerella, Gloeocapsa, Gleocystis, Hapalosiphon, Lyngbya, Inactis, Nostoc, Oscillatoria, Palmella, Phormidium, Plectonema, Pleurocapsa, Schizothrix, Spirulina, Stigeoclonium, Stigonema, Symploca, Synechococcus,* and *Urococcus.* These algae and certain other plants are able to remove by various processes, the calcium carbonate contained in most natural waters; but the relation of these calcareous plants to the active formation of travertine will vary with the locality and the conditions under which they are found. The many geological transformations, chemical reactions, the plants and their part in the precipitation of calcium carbonate, all have an important role in the continuous and complicated cycle included in the formation of travertine in the Arbuckle Region.

TRAVERTINE CYCLE OF THE ARBUCKLE REGION.

The ultimate source of the calcium carbonate out of which the travertine of the Arbuckle region is precipitated can be traced back to the large areas of exposed Paleozoic limestones that constitute the principal geological formations. The spring water that issues from these limestone areas contains, in solution, not more than seventy parts of calcium bicarbonate per million parts of water. Limestone is very sparingly soluble in pure water, but water containing carbon dioxide gas dissolves this rock to an appreciable extent. Rain water, in falling through the atmosphere, takes up a small amount of carbon dioxide, oxygen, and other gases. The amount of carbon dioxide which is normally present in the air, varies at different times and places from 2 to 3.6 volumes in 10,000 of air, while close to the ground, the amount increases to as much as 12 parts per 10,000. Aside from the absorption of carbon dioxide, rain water takes up additional substances while passing through the soil, the products of plant decay and mineral acids. As the water sinks deeper into the earth, the corresponding increase of pressure enables it to hold, in solution, greater quantities of gases, acids, and salts; all of which greatly increase the dissolving power of water. This rain water, charged with acids and gases, makes its way downward through the joints and bedding planes of the limestone, exerting its solvent action upon the walls of these crevices. One result of this solution is to make the rock porous. In extreme cases of porosity, the prolonged abstraction of calcium carbonate develops an elaborate system of subterranean tunnels, caverns, and sink-holes.

Numerous sink-holes may be found in various parts of the Arbuckle limestone prairies. The majority of these sink-holes, with irregular passages of only a few feet in diameter, extend 25 to 40 feet below the surface. Some of the sink-holes are directly connected with large caverns. The largest caves of this region and those which have been formed by the action of water, are near the sources of the streams, in close proximity to springs. Important data would be obtained in a calculation of the amount of calcium carbonate that has been carried away by the water of these springs. A part of

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*Penhallow, D. P., ('96): Note on calcareous algae from Michigan Bot. Gaz. 21: 215-217, 1896.

**Tilden, J. E., ('97): Some new species of Minnesota algae which live in a calcareous or siliceous matrix, Bot. Gaz. Vol. 23, p. 95, 1897.

***Kurck, C., ('99): Om Valktuffen vid Benestad, Bihong K. Svenska Vet.-Akad. Handlingar Vol. 26, Afd. II, pp. 1-79, 1900.

****Jones, J. Claude ('14): The tufa deposits of the Salton Sink. Carn. Inst., Wash. D. C. Pat. Vol. 193: pp. 79-84, 1914.

the dissolved limestone was transformed into travertine while the remainder was retained in solution and finally discharged into the sea. If one were to take into consideration the quantity of the deposits along Honey Creek, also the size of the caverns at its sources, and if the spring water flowing out of these caves during the past centuries contained calcium carbonate in the same or amounts greater than at present, it would appear reasonable to intimate that not less than 25 per cent of the dissolved limestone was again precipitated in the streams as travertine.

At the present time, there is evidence of the dissolving action of water on limestone in all of the caves in which the underground water is able to move on and reappear at the surface as springs. Large stalactites and stalagmites are found in those caverns, or in parts of the larger caverns in which only a small amount of water seeps through the overlying strata. The upper cavities of the cave at the source of Garrison Creek contain abundant stalactite formations; but in the lower cavities of the same cave, the water is still widening its underground passages. A cave that is a half mile from the source of Honey Creek contains numerous stalactites but very little water. Another cave at the source of the same creek contains a pool of water that supplies a large spring, and on the walls of this cavern small hollow cavities indicate that the dissolving action of water is still effective. A cave on Cedar Creek, with a room approximately 80 feet long and 30 feet high does contain water, and stalactites are beginning to appear in various places. The conditions under which these caves have been formed are conditions that favor a rapid solution of limestone; that is, the supply of water is charged with carbon dioxide, and after it has remained in contact with the limestone a sufficient length of time to bring about solution, it is able to move onward.

It has been shown previously that calcium bicarbonate is held in solution by the excess of carbon dioxide in the water, and that any agent which causes the abstraction of this carbon dioxide also brings about the precipitation of calcium carbonate. In order to estimate the rate at which the calcium carbonate was formed into travertine, a number of test objects, cylinders of wood, pieces of stone, and heavy cord, were fixed in various places along Falls Creek and Honey Creek. The average result of these tests indicated that there was an increase of about two millimeters of travertine a month. On Scudder Creek, cavernous travertine developed, under optimum conditions and in the presence of *Vaucheria plants,* in masses of 3 to 5 inches during a summer season. Under the present conditions of a continued deposition of travertine and without taking into consideration the effect of erosion, it would require approximately 4,000 years for the construction of the former Turner Falls and the original Prices Falls. As affording a definite chronology, such calculations as these are of no value, but they have much use in fixing one's attention upon a possible minimum.

The rate at which these falls developed may have been influenced by the work of certain animals and the agencies of water plants. The only animals that have been found in large numbers on these deposits are the larvae of the black fly *Simulium.* These insects, Howard* ('02), known as black flies, sand flies, or buffalo gnats, are small biting flies with broad wings and rather short legs. The eggs are laid on the moist surface of the travertine in light yellow, very sticky, and gum-like masses. The larvae hatch about eight days after the eggs are laid and in this stage the insects may be found at any season of the year. The larvae are aquatic and occur most abundantly during the early summer, on the surfaces of the travertine falls in the well-aerated and swiftly running streams. They are fastened to the rocks by the posterior end of the body; they assume an erect position and move the head with a circling motion. As they grow larger or if the water becomes too shallow, they allow themselves to be washed into deeper water, holding by a thread which they spin as they go. This thread is spun from the mouth but is attached along the side of the body to the different segments. When full grown, the larva spins its cocoon, firmly attaching it to the travertine and also to adjacent cocoons. The length of the pupae stage is about three weeks. The newly issuing insect, surrounded by a bubble of air, quickly arises to the surface of the water and flies away instantly.

During the period of time that the black flies pass through these various changes, only the larva and pupa stages need to be considered in connection with the formation of travertine. The larvae often occur in numbers sufficiently large to cover a part of the surface of the falls. (Plate XIII B.) These larvae generally occur where filamentous algae and mosses do not grow; that is, in the deeper channels where erosion is most active. At present, there is no evidence of travertine formation due to their activity, as would be expected, since they normally take up oxygen and secrete carbon dioxide. After the larvae develop into pupae, these insects do not assist in the development of travertine except indirectly, in cases where the water is sufficiently shallow and thus permits a continuous evaporation of water from the surface of the cocoons.

The animals living in the Arbuckle region are ineffective in the formation of travertine, but various species of water plants take an important part in this process. Upon careful observation, plants were found wherever travertine was being formed, and in places favorable for its formation, the absence of travertine was apparently due to the absence of plant life. In this region the deposits of calcium carbonate are not formed, as generally supposed, on dead leaves and branches of trees that have fallen into the water, and on submerged dead grasses, as such; but wherever deposits are found on submerged leaves and dead grasses there is usually a growth of algae present, whereas, other submerged dead leaves without the covering of algae remain

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*Howard, L. O., ('02): The insect book, New York, pp. 120-123, 1902.

unaltered in respect to travertine. The roots of trees extending into the water are especially noteworthy. The smaller and actively growing roots which normally secrete carbon dioxide remain unaltered by travertine, but the older parts of the roots which are covered with a cortex of cork tissue will be incrusted with calcium carbonate, usually accompanied by a growth of algae.

Among the plants that are of little importance in the formation of travertine are the *Angiosperms,* the flowering plants. In the shallow water along the banks of loose soil, the water willow, *(Dianthera americana L.),* sends up its erect stems with leaves spreading above the surface of the water. Only the submerged green portions of this plant become slightly coated with calcium carbonate. The greater part of the water cress *(Sisymbrium Nasturtium-aquaticum L.),* appears above water and on the wet rocky slopes immediately above springs. Water milfoil *(Myriophyllum heterophyllum* Michx.) is entirely submerged in pools of quiet water and is usually covered with a slight incrustation except along the growing tips. Dense mats of the stonewort, the alga *Chara,* always with a hard and brittle covering, occupy the deep pool just below Turner Falls on Honey Creek. However, the calcareous fragments of the *Chara* plant accumulate only for a few months, and in times of flood the loose sediment is readily washed away.

The sediment that collects in the crevices of the overhanging ledges of the travertine falls maintains a variety of ferns; principally *Woodsia obtusa* (Spreng.) Torr., *Asplenium platyneuron* (L.) Oakes, *Adiantum Capillus-Veneris L.,* and *Pellaea atropurpurea* (L.) Link. These ferns appear only on the older deposits and assist in no way in their formation, but to a slight extent, to their disintegration. In a like manner the liverworts *Marchantia polymorpha* L., *Reboulia hemisphaerica* (L.) Raddi, *Plagiochasma Wrightii* Sull., *Fossombronia salina* Lindb., *Porella pinnata* L., and *Anthoceros laevis* L., which were found in moist places along various streams were ineffective in the formation of travertine.

On the other hand, water mosses are active agents in building up travertine dams. Their habit of growing in dense tufts of green along the marginal slopes of rapids, influences the construction of small cascades. Among the thousands of mosses, there are only a few species which appear to exercise no selection, that is to say, are indiscriminate in regard to their substrata. The existence of all other mosses is more or less dependent upon the nature of the substrata. Any attempt to arrange mosses into groups according to a single type of geological formation would lead to indefinite results, for the apparently characteristic plants of one formation would later be found, to some extent, on still other kinds of rocks. According to the chemical relation of the substrata, mosses may be arranged into a class living in calcium-free habitats, and another class inhabiting the calcium-containing soils. Of the three principal mosses, *Didymodon tophaceus* (Brid.) Jur., *Philonotis calcares* B. & S., and *Fissidens Julianus* (Savi.) Schimp., that grow in moist places of the Arbuckle Mountains, both

Didymodon and *Philonotis* appear in other regions with a restricted calcareous habitat. The third species, *Fissidens Julianus,* occurs in different parts of the United States and in varying conditions. *Barbula unguiculata* (Hud.) Hedw., is abundant in the Arbuckle region on the older travertine formations. None of the three water mosses were found in fruiting condition, and their descriptions are necessarily limited to the vegetative characters.

The most common of the three rock-forming mosses is *Didymodon tophaceus* (Brid.) Jur. This moss grows in dense tufts; the stems vary in length from one-half inch to 4 inches, often branched; leaves olive green in the upper parts of the stem, changing to a brown color or covered with a white calcareous incrustation, leaves spreading from an erect base, oblong lanceolate or lingulate, obtuse, margin resolute, entire; costa stout, vanishing below the apex; cells at the apex small, the marginal cells rectangular or nearly square, at the base of the leaves the alar cells are distinct and 3 to 6 times longer than wide, thick walled, pellucid, very distinct; the upper cells slightly papillose.

Didymodon tophaceus appears in very moist and more or less shaded habitats, whereas *Philonotis calcares* generally grows in better lighted places. *Philonotis calcares* B. & S. appears in compact bright green tufts; stems ½ inch to 3 inches high, robust, the lower part incrusted with calcium carbonate; leaves crowded, secund, ovate-lanceolate, varying in length and width, acute, loosely areolate, costa excurrent into a short bristly point, margin serrate more toward the apex; papilose; cells at the base scarcely large, narrowly rectangular and chlorophyllose. Capsules have not been found.

These mosses, *Philonotis calcares* and *Didymodon tophaceus,* are to be found only in calcareous habitats, but *Fissidens Julianus* is not restricted in this manner. *Fissidens Julianus* (Savi.) Schimp., is widely distributed in the United States and does not require a description other than its aquatic habitat and its resemblance to *Fontinalis.*

There are three or more general physiological processes by means of which these mosses assist in the mechanism of travertine development. The water which contains calcium bicarbonate is taken up as a mineral nutrient solution by these plants, either through the rhizoids or from the surfaces of the leaves. *Didymodon* and *Philonotis* are only partly submerged; but the upper leaves and the growing tips are kept moist with seepage, the tufts retaining water like a saturated sponge. Water evaporates from the leaf surface, and at the same time the calcium salts concentrate in the cells and in the moist film surrounding the leaves. During the process of photosynthesis, carbon dioxide is removed from the bicarbonate contained in the moist film about the leaves and from the bicarbonate in the cell. This reaction assists in the precipitation of calcium carbonate in the outer layers of the cell walls and on the outer surface of the leaves. A part of the calcium salts absorbed, unite with oxalic acid and other harmful by-products that are formed during the process of metabolism. Briefly stated, calcium bicarbonate and other calcium salts in the water enter the cells in various ways and there concentrate; a part of these salts unite with oxalic acid and hurtful by-products formed during metabolism, which are changed into harmless or useful substances; a part of the bicarbonate is precipitated as the normal carbonate in the outer layers of the cell walls and on the outer surface of the leaves and stems during photosynthesis. The travertine first formed represents a direct precipitation of the calcium salts contained in the mineral water, or it is derived principally by evaporation and to a much less degree as a transformation product from various salts contained in the cells. While *Chara* deposits the calcium carbonate within its own cells, the mosses precipitate the mineral as an inorganic incrustation outside their leaves and stems. It appears to arise first from the decomposition of the dissolved carbon dioxide and bicarbonates by the living plants and it proceeds along their growing parts. Subsequent evaporation and loss of carbon dioxide causes the calcium carbonate to be precipitated over the tufts of mosses and algous tissue until the substance becomes a soft crystalline limestone.

Algae develop travertine in a manner similar to the mosses. Species of *Spirogyra* and *Zygnema* are the least effective in this development, since they grow in quiet places, usually floating on the surface of the water, and the calcareous crystals formed by these floating plants fall to the bottom of the streams as a loose and fine-grained sediment. Plants of *Oedogonium* and *Vaucheria* which are often attached like green pendants to the overhanging ledges of falls, become hardened with an incrustation of calcium carbonate. At first there is nothing brittle about these algae. Their long filaments bend and apparently stretch like rubber. Add to this a glossy, slippery surface and you have a growth that comes to no more harm than the bending ferns on the projecting mountain ledges. Upon examination of *Oedogonium* and *Vaucheria* plants under the microscope, minute crystals of calcium carbonate appear scattered along the surfaces of the filaments. These crystals, at first isolated and small, increase in number, enlarge, and fuse into a soft chalk-like mass that later hardens with the deposition of calcite in its interstices. The unicellular grass-green algae and filamentous blue-green algae grow in more compact aggregations, and the travertine formed by them is more condensed than that formed by *Vaucheria*.

As these algae precipitate the calcium carbonate in the form of travertine, there is a change in the concentration of carbonates of the mineral water in which the rock is formed. This change is represented by the data on the water analyses made along Falls Creek and here given in Table No. 1. The analyses were made at intervals of tenths of a mile, and at each fall and each spring. 100 cc samples of water were titrated with n/20 KOH, potassium hydroxide, and n/20 HCl hydrochloric acid, using phenolphthalein and methyl orange as indicators. Methyl orange is unaffected by carbon dioxide and hence the bases present in the water as carbonates or bicarbonates may be titrated by standard acids. $Ca(HCO_3)_2+2\ HCl=CaCl_2+2\ H_2O+$

$2CO_2$. The carbonates are alkaline, the bicarbonates are neutral, but free carbon dioxide is acid in reaction with phenolphthalein. Free carbon dioxide in water can be titrated with standard potassium hydroxide, the solution becoming neutral when the alkali is converted into bicarbonates. $CO_2+KOH=KHCO_3$. If a water is neutral to phenolphthalein the half-bound carbon dioxide is equal to the fixed, and the volatile carbon dioxide is equal to the sum of the fixed and the free carbon dioxide.

The free and semi-combined carbon dioxide in the water of Falls Creek were determined with the same 100 c.c. samples, titrating the free carbon dioxide first with n/20 KOH, phenolphthalein as indicator, then methyl orange was added and the titration continued with n/20 HCl. In the calculation of the semi-combined carbonates, the number of cc KOH used is of course subtracted from the number of cc of HCl required to neutralize the 100 cc of water, methyl orange as indicator.

According to Treadwell and Reuter l. c., a liter of water free from carbon dioxide will hold in solution .358 gram of calcium bicarbonate at 15°C. The following table gives the solubility of calcium bicarbonate in a liter of water at 15°C with varying amounts of carbon dioxide.

Partial pressure of CO_2 in mm mercury	Free CO_2	Grams of calcium bicarbonate
0.0	.000	.385
0.6	.000	.402
1.9	.029	.595
3.1	.047	.821
6.0	.145	1.249
13.1	.243	1.331

From a comparison of this table of solubilities with Table No. 1, it is seen that the amount of bicarbonate present in the Falls Creek water varies from 10 to 17 per cent of the amount of calcium bicarbonate that would be present if the solution were saturated. The largest amount of free carbon dioxide present is in the spring water at the source of the streams. The immediate loss of carbon dioxide from the spring water is due to a rise in temperature, about 6 degrees, which in itself is sufficient to explain this loss. From the Big Spring to fall No. 18, there is a decrease of free carbon dioxide equivalent in terms of n/20 KOH of 1.2 to .4 cc and in the bicarbonates a decrease from 14.52 to 13.09 cc in terms of n/20 HCl, and a rise of 18.5° to 24°C in temperature. The stream between the two points mentioned is filled with *Myriophyllum* plants, which accounts for a part of this loss of carbon dioxide. From fall 18 to fall 7, the amount of carbon dioxide in the water remains constant at an equivalent of .4 cc KOH, the bicarbonates decrease in amount from 13.09 to 11.99 cc, while the temperature remains the same in all places. The gradual decrease of bicarbonates in the water with the amount of free carbon dioxide remaining the same, indicates that the precipitation of calcium carbonate on these falls is the result of a change in the carbonic ion HCO_3, either by a physico-chemical process or by the activity of plants.

Plants obtain the carbon of which their tissues are built by decomposing the carbon dioxide derived either from the air or from the water according to the mode of life of the plant. It is thus obvious that where aquatic life is abundant, a great deal of carbon dioxide will be abstracted from the water with a consequent deposition of calcium carbonate if the concentration of calcium salts is sufficient. Algae are the most effective plant agencies in the precipitation of calcium carbonate. Different algae accomplish this separation in different ways. Frequently the calcareous deposit appears in minute crystals in the gelatinous matrix between the vegetative filaments and upon their surfaces. At first the crystals are separate and small, but by a continued increase in numbers star-like clusters are produced, and these, by enlargement, grow into calcareous grains. Further growth results in the union of these grains into a soft mass of travertine.

A very effective mode of increasing the size of the particles of a fine precipitate is to allow them to remain for a considerable time in contact with the liquid in which they are formed. The result of this condition is a recrystallization in which the finer crystals disappear and the coarse grains enlarge at their cost. The cause of this change is to be sought for in the surface tension which exists on the boundary surface between solids and liquids. This tension acts in such a way that the surfaces of a large number of small crystals are reduced by the enlargement of individual crystals, the total amount of material remaining the same. Calcium carbonate comes down amorphous at first and in that state is perceptibly soluble in water, but on standing, the precipitate becomes crystalline (calcite) and at the same time much more insoluble. This process of crystallization would be effective in the formation of travertine in the Arbuckle region if the calcareous spring water was concentrated by evaporation alone. It is evident that if the travertine deposits were due to evaporation, they would be distributed more or less along the edges and shallow parts of the water courses. It is certainly remarkable that this calcareous substance may be observed incrusting fibrous branches of mosses and filamentous algae in water containing only .013 per cent of carbonates.

However, the mechanism of travertine formation is more clearly indicated by the results of certain experiments and observations on the development of this rock in various parts of the Arbuckle mountains. A number of experiments were made in Owen Creek to determine how much of the developing travertine was formed by algae and other plants. The method of experimentation was to restrict the growth of algae to certain areas by means of copper and by keeping certain other places in almost total darkness. At the top of a rapid, a coil of copper screen containing granular copper was placed in such a manner that all of the stream had to pass over metallic copper. The algae below the rapids were killed by means of a copper sulphate solution, but mosses growing in the same water with these algae were not affected by this dilute copper solution. Test objects, pieces of wood and stone, were fixed in the running water above and below the copper screen. The purpose of this metallic copper was to prevent the reappearance of algae on the lower surface of the rapids, all other conditions remaining the same as normal, and thus determine their influence on travertine formation. Another test above the rapids consisted of pieces of stone and wood placed under a felt cloth two feet square, elevated in the center by a wooden support eight inches high, and weighed down at the edges with heavy rocks placed in such a manner as to permit the running water to pass under the cloth, and at the same time keep out most of the light. Three weeks after starting the experiment the stream nearly stopped running and the test objects were removed. The test objects that had been placed in the dark under the felt cloth, and on the lower surface of the rapids below the copper screen were unchanged. On the upper surface of the rapids above the copper screen and in the light, algae were starting to grow on the test objects and a slight amount of travertine had formed about the plants. The water at this place contained .33 parts of free carbon dioxide, and 10.67 parts of semi-combined carbonates per million parts of water. Since the results obtained on Owen Creek were unsatisfactory, the experiments were removed to Honey Creek.

At the top of Turner Falls a cylinder of wood attached to a strong cord was placed under a felt cloth that was fixed on two sides to the surface of the travertine in such a manner that the water could enter at one end and out at the other. This experiment eliminated the factors of diffusion and the resultant loss of carbon dioxide, and the activity of green plants. These conditions would not affect the growth of bacteria, the diffusion of carbon dioxide, and the mixing of oxygen with the water. This experiment was partly destroyed by unknown persons a few days before it was intended to be removed and the results obtained were not considered decisive and the experiment was repeated.

The following series of experiments were all placed in a position that was almost inaccessible and not likely to be visited by anyone, on the upper projecting ledge of Turner Falls on Honey Creek. In order that the results of one experiment could be compared with those of various other tests, the apparatus was set up in such a manner that all test objects were under practically the same conditions in regard to the amount of water flowing over them. The materials were examined at frequent intervals and the results of the experiments are indicated in the photographic reproduction on Plate XIV. The materials used in these tests consisted of cheese cloth of approximately 30 threads to the inch, copper gauze of 100 mesh, granulated copper, limestone pebbles of a size equivalent to that of the granulated copper, 3/16-inch fiber rope, 5/16-inch cotton rope, 1/4 to 3/8-inch wood cylinders 3 inches long, wire nails, and felt cloth. Although these materials were all used in one place, the object, the varying conditions, and the results of the various tests will be enumerated separately.

1. The ease and rapidity of travertine formation is well indicated by the coating or impregnating of various objects that are placed in the calcareous running water. The deposition on a piece of 5/16-inch cotton rope was very rapid at first and well formed after 3 days. At the end of 2 and 3 weeks, the rope was entirely covered with a hard calcareous coat, varying from 1 to 3 millimeters in thickness, on the surface of which were unicellular green algae in sufficient number to give it a light green color. The algae were not present with the first appearance of the travertine and the amount of calcium carbonate deposited varied with the extent of the absorptive surfaces exposed; that is, the greater the absorptive surface, the greater is the amount of travertine formed, as indicated by the mineralization about the frayed ends of the rope.

2. If a piece of 5/16-inch cotton rope were placed in the same conditions as in the preceeding test, but under a felt cloth in order to prevent the appearance of algae, the rope, however, still became coated with travertine. The amount of travertine formed in this case depended upon the conditions that influence evaporation; if the felt cloth were immediately above the rope the amount of evaporation was limited and only a small quantity of calcium carbonate was precipitated; if the felt cloth were elevated sufficiently so as not to seriously interfere with evaporation, the amount of calcium carbonate apparently equaled that of the control experiment under normal conditions.

3. A comparison of the results obtained with cotton rope with those brought about with wood cylinders will indicate the effect that the kind of material and the character of its structure and surface have upon the formation of travertine. Small wooden cylinders attached to fiber ropes, placed in calcareous running water under normal conditions and beneath a felt to exclude the light are nearly equally coated with calcium carbonate, providing the conditions for evaporation are the same. The structure and appearance of the newly formed travertine is alike in both cases with the additional presence of unicellular green algae on the wooden cylinder placed under normal conditions in the light.

4. Materials like those used in the previous experiments, such as cotton, fiber rope, and wood, do not interfere with the growth of bacteria and algae. However, certain metals, and especially copper, are very toxic to algae and bacteria, and under certain conditions will prevent their development. In order to test the formation of travertine in the absence of bacteria and algae, copper gauze and granulated copper were used in various ways. Two pieces of copper gauze, 2 by 3½ inches in size, with 4 thicknesses of cheese-cloth placed between them in a manner like a sandwich, were nailed with their flat surfaces against the falls. Under normal conditions the copper screen soon became coated with calcium carbonate, which was followed a week later by the appearance of unicellular green algae. At the end of the third week there was a calcareous covering one millimeter in thickness, which retained the matted impression of the screen. The cheese-cloth extending beyond the copper screen was stiff, hard, and covered with travertine. The cloth immediately between the two pieces of copper screen was only slightly altered by the presence of loose crystals of calcium carbonate, which may be accounted for by the rapid formation of a calcareous cover on the top surface of the copper screen.

5. A similar apparatus of cloth and copper screen placed beneath a felt cloth, under conditions that would almost prevent evaporation, was slightly coated with calcium carbonate but not enough to hide the separate threads of the cloth or copper gauze. The same type of test object beneath a felt cloth, but under conditions that favor evaporation, was coated with travertine to an extent equal to the test object under normal conditions.

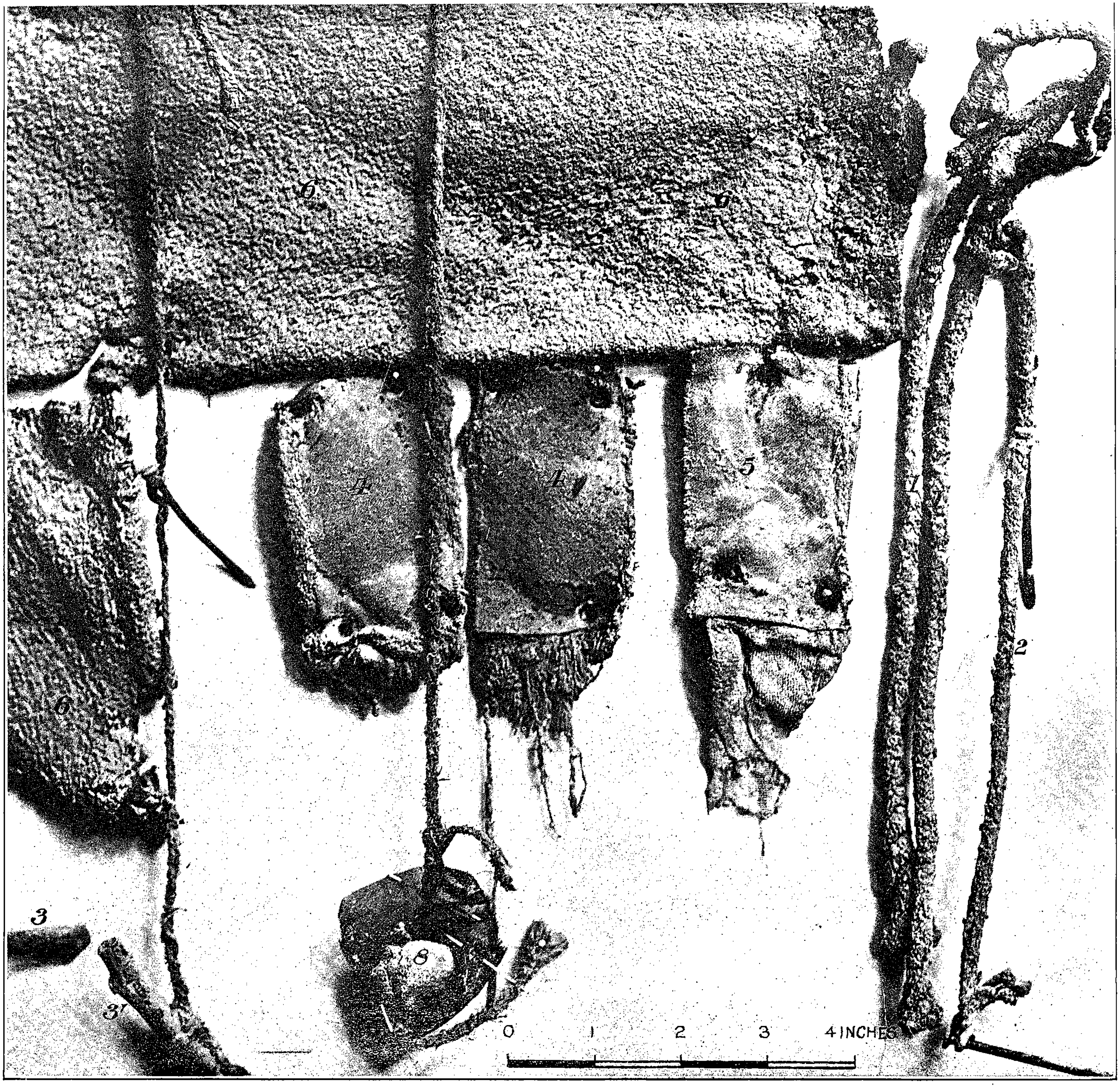
6. The felt cloth which was used in some of the experiments mentioned above became impregnated with travertine very soon after it was placed in the calcareous running water. After 3 days it was of the same general outward appearance as the surrounding surfaces of newly formed travertine. In cases where there was a double fold of the felt cloth, the lower fold was impregnated with calcium carbonate to the same extent as the upper, but without the characteristic light green color of freshly formed travertine, which is due to the presence of unicellular grass-green algae.

7. Additional tests with metallic copper included the use of a small cheese-cloth bag, about 1½ inches in diameter, containing granulated copper and fixed in the running water by means of a short piece of rope nailed to the surface of the falls. A similar bag containing limestone pebbles instead of granulated copper was placed in a like position. After these objects had been in the running water for 3 weeks time, they had become entirely coated with travertine. The spaces between the copper granules and limestone pebbles were tightly packed with calcite crystals so that there was essentially no difference in the amount or kind of deposition in either case.

8. A similar experiment consisted of granulated copper placed in a cheese-cloth bag ¾-inch in diameter, entirely covered with one or two folds of copper screen. This object was suspended in the calcareous running water for 10 days before it was removed. There was no change in the appearance of the copper screen, but after removing this screen the underlying cheese-cloth was found entirely covered with calcium carbonate (travertine) and masses of calcite crystals were also present between the granules of the copper. Bacteria and algae were entirely absent.

DISCUSSION.

The results of the experiments placed on Turner Falls on Honey Creek indicate the relative importance and value of physico-chemical and biological agencies in the formation of travertine in the Arbuckle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region. Under conditions that favor evaporation travertine will form as readily in the dark as in the light. Bacteria and unicellular grass-green algae are nearly always present in newly formed travertine but their presence is not an essential aid to its formation. That evaporation alone is effective in the development of travertine is also shown by a more careful examination of the recently formed deposits. The deposition of calcium carbonate occurs to a slight degree along the margin of the streams and in places where the water is shallow. This precipitation may take place on limestone surfaces without the presence of algae but the quantity of sedimentation is small because limestone does not absorb water readily and the loose calcite crystals or calcareous mud that appears on its surface soon wears away on account of the erosive action of water, in times of flood, and for this reason, the apparently insignificant formation of travertine may escape notice. With the appearance and development of travertine there is a natural cycle of plants to accompany these changes. During the earliest stages of development the unicellular grass-green algae and blue-green algae are present, followed by filamentous blue-green algae with the later appearance of filamentous grass-green algae that grow in felt-like masses and water mosses that are aggregated in dense tufts, partly submerged and saturated with water like a wet sponge. The rate of travertine development depends on the kind and amount of moist surfaces available for the evaporation of water. This evaporation of calcareous water and the consequent formation of travertine is greatest about those plants that are best adapted to take up large quantities of water. Travertine would be formed in the Arbuckle region if there was a continuous renewal of absorptive surfaces, for example, the continued addition of layers of felt cloth would induce a very rapid formation of travertine without the aid of plants. It is true that the development of travertine in the Arbuckle region would not exceed that removed by erosion in the absence of water plants, but the role of water plants is principally to renew and supply suitable moist surfaces for the evaporation and consequent diffusion of carbon dioxide from the calcareous spring water, thereby causing the precipitation of calcium carbonate in the form of travertine.

CONCLUSIONS.

The travertine of the Arbuckle Mountains presents two problems: (1) the geological history of travertine and (2) the relation of certain plants to the formation of travertine.

The travertine deposits of the Arbuckle Mountains have been classified into three more or less distinct periods of formation.

Travertine of the first period occurs above the water level of the present streams.

Travertine of the first period includes the reconstruction of Turner Falls and Prices Falls.

Travertine of the second period occurs in all streams of the Arbuckle Region except Garrison Creek, and is present in all of the travertine falls in which the erosion factor is greater than that of construction.

Travertine of the second period is well represented by the deposits of Prices Falls and Turner Falls.

Travertine of the third period of formation or of present development includes all travertine deposits and falls in which the mineral continues to accumulate.

The travertine falls of the Arbuckle Region are: (1) modifications of previous natural rapids or waterfalls, or, (2) modifications of boulder dams.

Travertine may be differentiated into three classes as banded, pisolitic, and cavernous.

In the mechanism of travertine formation, evaporation and the consequent diffusion of carbon dioxide are the principal physico-chemical factors.

Algae and mosses induce the development of travertine (1) principally by providing moist surfaces suitable for the evaporation of calcareous spring water; (2) by the abstraction of free carbon dioxide and by the decomposition of the bicarbonic ions, and (3) to a slight degree by means of transformation products derived from the calcium compounds contained in the plant cells.

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CHART SHOWING WATER ANALYSES OF

Falls Creek.

DISTANCE IN MILES FROM WASHITA RIVER.	GEOLOGICAL FORMATION	TOTAL HEIGHT OF FALLS. FEET	AMOUNT OF EROSION. FEET	No.CC. N/20 KOH ⊕ 100 CC. WATER. PHENOLPHTHALEIN.	FREE CO₂ PARTS PER MILLION.	No.CC. N/20 HCL ⊕ 100 CC. WATER. METHYL ORANGE.	SEMI COMBINED CO₂ PARTS PER MILLION.	TEMPERATURE CENTIGRADE.	REMARKS.
0.0				0.3	0.33	10.3	11.0	24.2	
0.09	Cwf	4.97	1.67	0.3	0.33	10.3	11.0	24.2	FALLS No. 1
0.10				0.3	0.33	10.4	11.11	23.5	
0.14	Dh/Sh			0.6	0.66	10.65	11.05	20.	SPRING
0.17		14.0	3.15	0.3	0.33	10.45	11.16	23.5	LOWER PRICE'S FALLS.
0.20	Ss			0.3	0.33	10.6	11.33	24.	
0.25	Sv/Ov	19.32	2.0	0.3	0.33	10.7	11.44	23.6	UPPER PRICE'S FALLS.
0.26		3.4	1.6	0.3	0.33	10.95	11.71	24.0	FALLS No. 4
0.27		6.15	1.65	0.3	0.33	11.1	11.88	24.4	FALLS No. 5
0.28		3.48	1.56	0.3	0.33	11.1	11.88	24.4	FALLS No. 6.
0.30				0.4	0.44	11.25	11.93	23.8	
0.31		5.27	1.67	0.4	0.44	11.3	11.99	24.0	FALLS No. 7
0.33	Sv/Ov	8.16	1.74	0.4	0.44	11.5	12.21	24.	FALLS No. 8
0.35		12.25	1.85	0.4	0.44	11.6	12.32	24.2	FALLS No. 9
0.40	Osp			0.4	0.44	11.75	12.48	24.8	
0.43		4.67	1.75						FALLS No. 10
0.46		3.2	1.62	0.4	0.44	11.75	12.48	24.	FALLS No. 11
0.47		3.75	1.62	0.4	0.44	12.0	12.76	23.7	FALLS No. 12
0.50				0.4	0.44	11.7	12.43	24.	
0.53		4.7	0.82	0.4	0.44	11.9	12.65	24.5	FALLS No. 13
0.56		4.21	0.37	0.4	0.44	12.0	12.76	24.5	FALLS No. 14
0.59		3.25	0.25	0.4	0.44	12.2	12.98	24.	FALLS No. 15
0.60				0.4	0.44	12.2	12.98	23.8	
0.61		2.25	0.25	0.4	0.44	12.3	13.09	23.8	FALLS No. 16
0.65		1.20	0.36	0.4	0.44	12.35	13.14	24.	FALLS No. 17
0.70		4.12	0.0	0.4	0.44	12.3	13.0	24.0	FALLS No. 18
0.80	Osp			0.6	0.66	12.7	13.31	24.	
0.83		1.75	0.0	0.7	0.77	12.8	13.31	23	FALLS No. 19
0.87									
0.90	Of	1.50	0.0	0.7	0.77	13.0	13.53	22	FALLS No. 20
1.0				1.0	11.0	14.1	14.41	18.5	FALLS No. 21
1.01				1.2	13.2	14.4	14.52	18.5	BIG SPRING
1.02		3.58	2.25						FALLS No. 22
1.05		1.50		0.3	0.33	11.0	11.77	24.5	FALLS No. 23
1.06		1.17							FALLS No. 24
1.08		0.5		0.3	0.33	11.25	12.04	24.	FALLS No. 25
1.10									
1.13		1.75 3.50		0.4	0.44	11.6	12.32	22.	FALLS No. 26
1.18		1.35		0.4	0.44	11.9	12.65	22.	FALLS No. 27
1.20	Of					12.2	12.76		
1.23		1.50 2.40		0.6 0.8	0.66 0.88	12.3	12.65	19.5 19.0	FALLS No. 28
1.24	Oa/Єa			1.0	11.0	12.5	12.65	18.0	SPRING
				1.0	11.0	12.6	12.76	18.5	SPRING

F. [illegible], Arm. 1917.

— Falls. ⊙ Springs.

Owen Creek.

Sv/Ov			0.3	0.33	10.0	10.67	26.	

Honey Creek.

Oa/Єa			0.3	0.33	9.4	10.01	24.	TOP OF TURNER FALLS.
			0.3	0.33	9.2	9.79	24.	BASE " " "
			0.3	0.33	8.5	9.02	23.6	100 YDS. BELOW "

Cwf = Woodford Chert. Dh/Sh = Hunton Limestone. Ss = Sylvan Shale.

Sv/Ov = Viola Limestone. Osp = Simpson Formation.

Of = Franks Conglomerate. Oa/Єa = Arbuckle Limestone.

PLATE XV.

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