SCIENCE

A Weekly Journal devoted to the Advancement of Science, publishing the official notices and proceedings of the American Association for the Advancement of Science, edited by J. McKeen Cattell and published every Friday by

THE SCIENCE PRESS

11 Liberty St., Utica, N. Y. Garrison, N. Y.
New York City: Grand Central Terminal

Annual Subscription, $6.00 Single Copies, 15 Cts.

Entered as second-class matter January 21, 1922, at the Post Office at Utica, N. Y., under the Act of March 3, 1879.

VOL. LVI AUGUST 18, 1922 No. 1442

CONTENTS

GEOLOGY OF THE COLORADO RIVER BASIN WITH REFERENCE TO ENGINEERING PROBLEMS[1]

ANY account of the geology of the Colorado River basin falls naturally into two parts: that which deals with the life of the Colorado River and that which describes the preceding ages before the river began to flow. Professor Pack has presented the life history of the river. It is my task to sketch the earlier history of this part of the continent. With reference to the engineering problems, the geologist is concerned with three questions relating to the stability of the dam as affected by possible earthquakes, the nature of the foundation rocks, and the durability of the rocks used in construction. Reference will be made to these matters after the geology has been described.

We have become familiar with moving pictures, which present a succession of views, each one of which differs so slightly from the preceding that the eye sees their sequence as a continuous movement. The intervals are fractions of a second. The action is timed to our human scale. Geographic changes are exceeding slow. If we would present a moving picture of a succession of landscapes, the intervals between the views would be a hundred thousand or even a million years. Even so, the eye would see a continuous procession of views. Mountains would grow to majestic heights and waste away till their sites became plains. Rivers would develop and competing for territory would become master streams or tributaries according to the law of the strongest. Seas would invade the land and retreat from it after ages of occupation. Climates, floras and faunas would change. Such is the moving picture of geologic

[1] Presented in the Symposium on "The Problems of the Colorado River" at the Salt Lake City meeting of the American Association for the Advancement of Science and the Pacific Division.

history. It is timed to the march of the ages.

Even that slow movement of events is beyond our power to present in its continuity. We can at best represent widely separated conditions. And so, in attempting to sketch the history of the Colorado Plateau region, I can give you detached pictures only, some of them so unlike that imagination alone can link them together. It will be simplest to roll the broken film backward from the later, better known events to the earlier scenes, till knowledge becomes guess and guess fades into surmise in the mists of antiquity.

The Colorado River developed during a period before the present plateaus were elevated. So great a river system, like a great empire, is the result of many territorial conquests. The force by which it conquers is due to its fall, for by its fall it carves its canyons and extends its tributaries. Thus the earlier history of the river corresponded with an earlier ancient uplift of the plateau country. But that uplifted mass was first gashed by canyons, then became a land of broad valleys and mesas, and finally was eroded to a low plain. A later uplift has raised that plain to its present position, 7,000 feet above the sea, where it is the surface of the plateau.

The cycle of erosion just referred to is called the "Great Denudation." The time of its duration corresponded with the so-called early Tertiary. The early mammals drank from the growing Colorado. North America then, as now, stretched from the Atlantic to the Pacific, an undivided continent.

Stepping back a million years or so, we see North America divided. A broad, though shallow, strait stretched from the Gulf of Mexico to the Arctic Ocean along the Great Plains of to-day, dividing the continent into an eastern and a western land. The climate was mild and equable. Vegetation flourished in the warm humid atmosphere. It was the Coal period of Colorado and New Mexico. Great saurians dominated the life of the period, yet became extinct, apparently rapidly. Dull brutes, they were incapable of adaptation to changes of environment such as closed the period of their dynasty.

During this period, the so-called Cretaceous, the region of the Colorado plateaus was a watered land with rivers flowing from eastern coast ranges, on the site of the Rocky Mountains, toward the Pacific. Among them may have been the stream which eventually grew to the Colorado, but we can not identify it.

Still retreating down the aisles of time, we come upon the panorama of a wide North America, united from east to west, but submerged along the western margin even to Idaho. This, the Triassic and Permian periods of geologists, might well be called the period of the "Great American Desert." A red wind-swept delta plain covered the Rocky Mountain states from Montana to Arizona and extended southeastward over Oklahoma and Texas. Bleak and arid, it was like the plains of northern Siberia. Similar cold, barren lands existed widely throughout the continents. It was a time of stress for all living things and led to the evolution of higher forms than had previously existed when conditions bettered, just as the severe environment of life during the Glacial Period later led to the evolution of man from his ape-like ancestors.

The red muds and sands of the desert time reached far into the Colorado Plateau country and, in so far as they were not eroded during the "Great Denudation," they give the dominant color note to the upper gorges of the river.

Thus far in our retrospect we have found no epoch during which the plateau country was submerged beneath sea waters. Yet there is written in the strata of the canyon walls a very long record of marine conditions. Whoever has been down the Bright Angel Trail has seen it. The cliffs of sandstone shale and limestone demonstrate by their long horizontal lines of bedding, as well as by the fossils they contain, that they were laid down beneath the sea. It was never a deep sea, yet there gathered in the basin more than 4,000 feet of strata. Evidently the bottom sank gradually and the sediments gathered as the basin deepened. Far more impressive evidence of subsidence is found near Salt Lake. There the strata aggregate more than 40,000 feet in thickness and indicate a corresponding subsidence of the ancient foundation rocks.

It is clear from the great difference between 4,000 and 40,000 feet that we should not re-

gard the subsidence as uniform. On the contrary, it was an unequal warping of the surface, which indeed rose and remained land in the region southeast of the canyon, or was but temporarily submerged.

The invasion of the sea into western North America began with and extended through the so-called Paleozoic age, that vast lapse of time during which life evolved from the grasping crustacean to the ambitious reptile. It is one of the proofs of evolution that although the Paleozoic creatures are long since extinct, their mentalities still persist in individual men. According to geologists the Paleozoic was an era which began with the Cambrian period and closed with the Permian. Various intervening periods are distinguished, but for our study of the Colorado River basin, the Paleozoic stands for one event, the advance of ocean waters over much of the continent, their prolonged occupation of its area accompanied by numerous changes of front, and their retreat into the permanent ocean basins.

Back to the beginning of the Paleozoic era, including the Cambrian period, we have fairly complete records of the physical geography of the earth and we can trace the major lines of evolution of organic life. We can even attempt maps of the shifting lands and seas, follow the course of great climatic oscillations, and image in our minds the habitats in which our remoter and nearer ancestors lived. If we draw a parallel between human history and earth history we may compare the dawn of Assyria with the beginning of the Paleozoic. But the remoteness of Assyria is to be measured only in hundreds, whereas that of the early Paleozoic is to be estimated in as many millions of years.

Let us not think, however, that a hundred million years represents a large proportion of the earth's history, as it is recorded in the rocks of the Grand Canyon. Beneath the earliest Paleozoic strata lie other water laid deposits of sediment, the waste of ancient lands. Only a few fragments of those old records are known, but they testify unmistakably to the passage of unnumbered ages.

We are prone to think the earth must have been in a different state of cooling or had a different atmosphere in so distant a past. But no, the winds blew, rains fell, streams flowed, there was night and day, heat and cold. And within the earth there went on periodically those changes which occasion the rise and subsidence of continents, the growth of mountain chains. The Algonkian strata (such is the name geologists use to designate the era) were deeply buried, tilted up, invaded by masses of molten rock and eroded. They record activities identical in kind and intensity with those which are now active in the most youthful ranges, the Rocky Mountains and the Sierra Nevada. Though we look back two hundred million years we find earth-processes the same.

Even so we have not read the earliest chapter recorded in the rocks of the Grand Canyon. Beneath the Algonkian we come upon an older and different group of rocks. It is a group which never occurs anywhere but at the bottom. It is the foundation of the superficial crust. I speak of the so-called Archean, the oldest rocks known, though by no means necessarily the oldest rocks ever formed.

The Archean rocks are not surface rocks, not like the strata of the plateau country. They have risen from depths in the earth's crust where temperatures are high and pressures are enormous. The typical Archean are crystalline. Whatever the previous state of the minerals may have been, they have recrystallized. Some, which are called schists, have recrystallized in a solid state under overwhelming and unequal pressures. They have thus changed form, shortening anad lengthening to fit their Procrustean bed. Others, the granites, have been melted and have intruded as tongues of magma into surrounding masses, causing changes of crystalline form in them. Melting and recrystallizing, crystallizing and remelting, these rocks have undergone changes so complete that no one can tell what they may once have been nor through what sequence of kneading, mechanical shearing, folding, and chemical changes they may have passed.

The Archean rocks thus represent physical and chemical conditions which exist within the earth's outer shell. I say advisedly *exist,* not *existed.* For while it is true that we see only very ancient rocks of this character, there is every reason to assume that they are forming now beneath our feet. We know that the

earth, though solid, is very hot. We know that very great and unequal pressures exist at depths of a few miles beneath the surface. These are the conditions under which the Archean rocks formed and no doubt are forming.

In the laboratory of the Master no reaction occurs except according to law, and law is eternal, unchanging. There is, perhaps, no thought with which we may more appropriately approach the engineering problems of the Colorado River.

The engineers who will speak here of the utilization of the Colorado will describe works of great magnitude: dams surpassing any yet built; reservoirs impounding millions of acre feet of water; values of irrigated lands rising to hundreds of millions of dollars; powers which are to turn the wheels of industry from San Francisco and Los Angeles to Denver. But even so, they speak only as men, of the little works of men. In the laboratory of the Master their greatest accomplishment is infinitely small and transient.

A laboratory is a place where the forces of nature work changes in material compounds or crystal forms according to law. The mechanic, the physicist, the chemist arranges the conditions of some desired reaction and under the same conditions observes the identical effects recurring endlessly, unfailingly. If he makes an experiment the personality of the experimenter makes no difference. Even the Master works by law and can not work otherwise. Nor does time make any difference. A billion years ago the law of gravitation held the stars to their courses as it does to-day. In the earliest conceivable eon of the existence of matter the atoms moved to their places in molecules in the same order as now.

Yet there is a new development, no doubt also in obedience to law, but so subtle that we can not establish the relation. I mean the evolution of mind, which can investigate law, which can conceive and execute great works that rightly constructed will stand for ages. The mind can even trace its own evolution. Backward from human thought to animal instinct, from instinct to mere conscious existence, from consciousness to unconscious molecular reaction runs the chain. It runs unbroken. Life is its characteristic. But if thought is life, then is consciousness also; if consciousness is life, then is molecular reaction also life. In this sense minerals are alive, for they are chemical compounds which react to their environment. The earth is alive, for the reactions of its masses are evidenced in unending change.

The development of thought from unconscious reaction has recently evolved reason. Reason is so young, however, that it is still embryonic and in many humans is in a larval state. Nevertheless, no man becomes a scientist or engineer without having to some degree developed it and therein lies the hope of a successful solution of the extraordinary problems of the utilization of the Colorado.

The major difficulty in damming the Colorado is to establish the dam on a firm foundation. Investigations of the river's bed show that it is filled to depths exceeding a hundred feet with large boulders. The dam, if it be a masonry or concrete structure, must be welded to the solid rock in place. It will tax the resources of the engineer to the utmost to dig so deep through boulders and to place his foundation structure during the few months between floods, which, if unrestrained, will destroy it.

The presence of a boulder bed, of such depth and composed of rocks of such size, was not foreseen. It is due to the power of the floods. At low water the river ripples impotently around the stones. One can hardly conceive that in flood it moves rocks as large as cabins and buoys up a mass of them, rolling them over one another with irresistible force. But the evidence is there. It does. The bottom of the river in flood is a torrent of rolling rocks, of huge size. They roll, they jam, they temporarily resist. The river piles up its waters behind them. The rocks yield and are carried crashing down the channel to come to rest as the victorious waters roll on.

It is one of the most daring conceptions of modern engineering that this awful power may be used to build the dam that shall chain it. How, may best be stated in speaking of the types of dams that are under consideration.

The engineer and geologist are both cognizant of the power of floods. But there are

some facts regarding the structure of rocks which lie more exclusively in the province of geology. The first of these is what is called "jointing" in rocks. Jointing is a mechanical effect. It is produced by pressure in the case of massive rocks, like granite, or by torsion in the case of strata, when they are warped. All the rocks of the plateau region are jointed. In the magnificent architecture of the Grand Canyon, the vertical cliffs are the planes of joints. In the pointed forms which are characteristic of the deepest gorges in the granite, we see the effect of two or more intersecting joint planes. Now joints permit water to penetrate under and around a block of rock. The film of water may be very thin, but to the extent that it surrounds the rock it buoys it up, tends to lift it from its bed by virtue of hydrostatic pressure, and may free it from its firm foundations. Engineers are fully aware of this action. They seek to excavate to foundation rocks which show no open joints, or to seal visible joints by cement. Granite is regarded as one of the firmest foundations. It is liable, however, to blind joints, invisible planes on which there has been no actual parting, but the minerals have been strained and are ready to react to forces of decay. Water, not enough to wet, but just enough to moisten, is the agent that sets those forces to work. The engineer can not discover blind joints. Investigation of the minerals by the microscope, a study which is among the most specialized of geologic training, alone can demonstrate whether or not they are present.

We may think that the invisible is reasonably negligible. But the infinitely small is the infinitely powerful and also the infinitely patient. A film of water penetrating a plane of strained crystals may open the way to the ultimate destruction of man's mightiest work.

Minerals decay. That is not a familiar thought with many, although soil, a product of mineral decay, is familiar to every one. I said that minerals are alive. And it is because they are alive that they decay, decay being simply the reaction to a change of environment. Evidence of these facts is found in the rocks which the engineer must use in building a dam in the Canyon of the Colorado. The granites and schists of the ancient formations crystallized deep within the crust in an environment of very high temperature and great pressure. Elevated to their present positions at the surface they are in a cool environment, under little pressure. The change produced in every crystal a tendency to change, to disintegrate into forms and compounds better suited to their actual environment. Thus the seemingly solid granite of the Boulder Canyon site is pervaded with disintegrating forces, which will in the course of time, though probably long time, certainly cause it to crumble.

Let us now consider the two methods of building the proposed dam, which have been suggested. The first fascinates by its unusual character and its daring. It consists in blowing great masses of rock from the canyon walls into the river channel in such quantity that they will form the body of a dam three quarters of a mile up and down stream on the base and six hundred feet high. The blasting is not to be done all at once, but in sections from upstream downward and only to a part of the height at any one time. And the river is to be allowed to flow over the fallen rock masses in such manner that it will by its own power dig the deep hollows into which it shall also roll the great rocks. Thus the river shall work its will, but shall lay the masses where it can never move them again. It shall chain itself.

The success of this operation depends upon providing by blasting rock masses of such magnitude that the river can not carry them away. We have a report by Mr. Ransome, a geologist of the U. S. Geological Survey and one of the highest rank, to the effect that the granite of Boulder Canyon is considerably jointed. Conservative knowledge would suggest that there are many more joints than appear as actual fissures and that they would cause the granite to break into relatively small masses, in the blasting from the cliffs and subsequent rolling by the river.

Another question is how "solid" is the granite? That it is so described is natural, for "granite" and "solid" are almost synonymous terms to English speaking peoples. The significance of words depends upon our association with them and our experience of New

England granite says that it is the very symbol of solidity. But New England granites have been stripped by glaciers of every trace of decayed rock. They are solid because they are freshly exposed. That is not the case with granites in this western country.

For instance there is granite in the immediate vicinity of Salt Lake City. It seems solid. It is used in building. It will take a polish. But I am told it will not hold a polish more than three or four years, because the crystals have begun to decay. Professor Pack tells me that he has examined granite in this vicinity from the surface to a depth of 800 feet below it and found even at that depth that decomposition was in progress, as shown by the clouded appearance of certain crystals, the feldspars, under the microscope.

The granite of Boulder Canyon is decomposed on the surface. No one knows, as yet, to what depth. But the geologist has reason to suspect its solidity and must add his objection to those of conservative engineers against the suggestion that the dam be built by blowing the cliffs into the canyon.

The other type of dam proposed is to be built of reinforced concrete. Concrete may be described as a rock composed of minerals which are permanent under surface conditions because they form in that environment. Moisture promotes the consolidation of concrete. Age increases its strength. So far as the superstructure is concerned, a geologist must reason that a concrete dam will outlive a rock fill dam. The engineering problem in building a concrete dam is that of excavating to solid foundations. It is, in the judgment of conservative and experienced engineers, reasonably practicable to do so. But, if the conditions of jointing and decay of the rocks are considered as they should be, it will be the geologist rather than the engineer who shall determine whether they are solid or not.

The foundations are now being explored by drilling. It is not enough. A drill may bore out a core within a foot of a weak seam and not betray its existence. The preliminary examination will, no doubt, be followed by more thorough investigation and it may be suggested that a method of shafts and tunnel be employed. Shafts sunk, one on each side of the river, and connected by a tunnel at a depth of a hundred feet below the bottom of the channel, would enable a complete examination of the rock, inch by inch. Weaknesses could be excavated and filled. If they should prove too numerous at one hundred feet, the shafts could go deeper to a deeper tunnel. Eventually when solid rock was found, the rock above the tunnel could be cut away to the surface, stoped, as miners say, and the stope filled with concrete would form an impervious curtain wall. Working from the bottom up, the bed of the river would be approached and the deeper foundations would be laid without exposure to the risk of floods. It is not the province of the geologist to instruct engineers and I would not presume to, but the suggestion may stand to illustrate the problem of a deep and secure foundation, that the geologic conditions demand.

The Garden of Eden was created some five thousand or more years ago by the building of huge dams of earth to control the Tigris and Euphrates, and so well did those ancient engineers execute their task that the beauty of the garden became a tradition of all Eurasian races. The garden endured until the state fell. Subtle forces weakened the quality of its citizens as moisture attacks the minerals of the granite. Our engineers can build a dam to endure for thousands of years. What is the endurance of our state? What concrete foundations of national character are we laying to cut off the underground activities that would destroy it?

STANFORD UNIVERSITY BAILEY WILLIS

EXPEDITIONS OF THE MUSEUM OF NATURAL HISTORY

IN one of the corridors of the American Museum of Natural History the officials of that institution have hung a map of the world to which labels are attached showing the distribution of its exploring parties and field workers. During the present year a larger number of expeditions have been sent out than ever before. Intensive work is being pursued by each department.

In the department of geology, Dr. Edmund O. Hovey is at present on a trip through Cali-