CONTRIBUTIONS TO THE GEOGRAPHY OF THE UNITED STATES, 1926

PEDESTAL ROCKS FORMED BY DIFFERENTIAL EROSION

By Kirk Bryan

INTRODUCTION

Isolated rocks consisting of a larger mass above resting on a smaller base or pedestal and known generally as pedestal rocks form one of the most spectacular types of natural monuments. The processes by which such forms are produced are doubtless as numerous as the agents of rock destruction, and it is probable that all the varied methods of weathering and of abrasion play a part in the formation of some of these rocks. In two preceding papers [1] of these contributions the origin of certain pedestal rocks has been attributed to abrasion of the base of the rock by running water or to rain wash and differential weathering. In this paper additional examples of rocks formed in arid climates by differential weathering are described. The nice cooperation of chemical and mechanical weathering in Washington and the differential weathering of sandstone in New Mexico produce rocks that can, by detailed study, be distinguished from rocks described in the preceding papers that are due to differential rain wash or to abrasion by running water.

Pedestal rocks may be produced by the abrasive action of the water and suspended matter in streams, or by the work of waves of seas or lakes, or by the scour of wind-driven sand. The favorable conditions for the production of the form in a stream are (1) the introduction of a block of rock into the channel by its fall from above or by the lowering of the channel on both sides of a mass of rock in place; (2) a fairly constant flow of water without excessive floods which might in their violence snap off the pedestal; (3) sufficiently short duration of the process.

Abrasion and solution by streams are given by Martel [2] as the sole causes of pedestal rocks, of which he has described a large number in

[1] Bryan, Kirk, Pedestal rocks in the arid Southwest: U. S. Geol. Survey Bull. 760, pp. 1–11, 1925; Pedestal rocks in stream channels: Idem, pp. 123–130. See also Bryan, Kirk, Pedestal rocks: Eng. and Min. Jour. Press, vol. 119, pp. 172–173, 1925.

[2] Martel, E. A., L'érosion des grès de Fontainebleau: Services carte géol. France Bull. 127, 1910. In this bulletin several earlier papers dating back to 1886 are summarized.

various parts of France. He vigorously combats the idea that rain and wind erode such rocks, and he describes three rocks whose form has been produced by stream action—a rock in the bed of Velon River [3] that stands in the bottom of a partly destroyed pothole; a rock in a limestone cavern at Furfoos, Belgium,[4] protected from weather, rain, and wind, but so fragile that it can not be subject to abrasion and must be due almost wholly to solution; and a rock in Gibbon River, Yellowstone National Park,[5] also described by me.[6] He contends that rivers with strong and turbulent currents once flowed at the level of the plateaus of France and particularly over the plateau of Fontainebleau. Although these streams date back to Pleistocene or Pliocene time, their channel features still persist in the form of potholes, arches, and pedestal rocks. In limestone areas subterranean streams flowing through caverns also produce these forms, partly by solution and partly by abrasion, and subsequently erosion has brought them to the light of day.

The effectiveness of stream erosion in the making of such rocks is somewhat limited, as set forth above, and this conclusion is confirmed by the rarity of occurrences in the beds of present streams. Although the three examples cited by Martel seem entirely valid, his position in regard to other rocks in France represents a point of view which is not concurred in by others,[7] who attribute the rocks of Fontainebleau and Montpellier-le-Vieux to the work of weathering and rain wash.

The formation of isolated masses by the abrasive and plucking action of waves against a cliff is common, and such masses, to which the term stack is applied, have been described by a number of writers.[8] The notched stack is such a mass somewhat undercut by the waves. Ordinarily the notch is on the side exposed to the waves, but on some stacks the notch, because of a weakness of the rock at

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[3] Martel, E. A., op. cit., pp. 15–16, fig. 16.

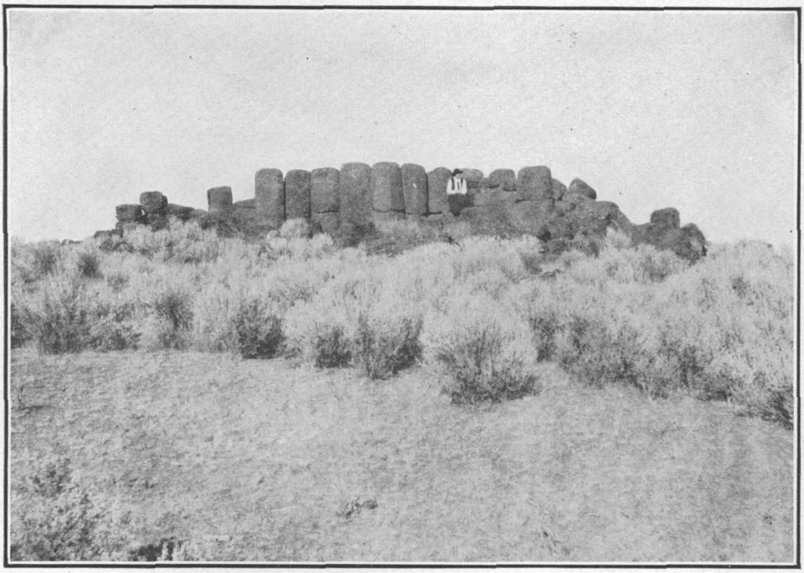
[4] Broeck, E. van den, Martel, E. A., and Rahir, E., Cavernes et les rivières souterraines de la Belgique, vol. 2, pp. 822–824, fig. 234, 1910.

[5] Martel, E. A. [Concerning the torrential origin of peduncular rocks]: Compt. Rend., vol. 159, pp. 87–89, 1914.

[6] Bryan, Kirk, Pedestal rocks in stream channels: U. S. Geol. Survey Bull. 760, p. 127, 1925.

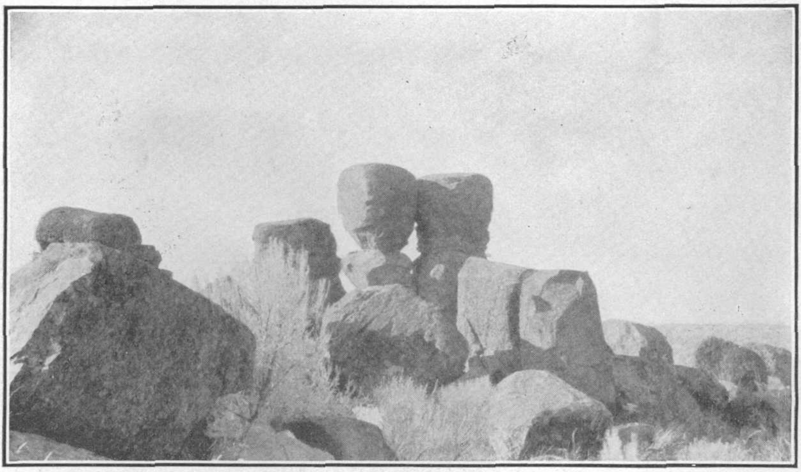
[7] Douvillé, H., Étude sur les grès de la forêt de Fontainebleau: Soc. géol. France Bull., 3e sér., vol. 14, pp. 471–481, 1886. Barré, O., Le relief de la forêt de Fontainebleau: Annales de géographie, vol. 11, pp. 295–314, 1902. De Lapparent, A., Leçons de géographie physique, 3d ed., pp. 90–91, Paris, 1907. Haug, E., Traité de géologie, vol. 1, p. 379, Paris, 1921.

[8] Geikie, Archibald, The scenery of Scotland, etc., pp. 67, 71, London, 1887. Fairbanks, H. W., Practical physiography, p. 411, fig. 342, Boston, 1906. Arber, E. A. N., The coastal scenery of North Devon, pp. 107–108, London, 1911. Atwood, W. W., Geology and mineral resources of parts of the Alaska Peninsula: U. S. Geol. Survey Bull. 467, p. 92, pls. 5, *B*; 9, *B*; and 12, *B*, 1911. Hobbs, W. H., Earth features and their meaning, p. 234, figs. 252–254, 1912. Johnson, D. W., Shore processes and shore-line development, pp. 278–279, pls. 34, 35, New York, 1919. Cotton, C. A., Geomorphology of New Zealand, pt. 1: New Zealand Board Sci. Art. Manual 3, p. 378, fig. 369, 1922. Dalmage, V., Post-Pliocene volcanics of the British Columbia coast: Jour. Geology, vol. 32, p. 41, fig. 4, 1923.



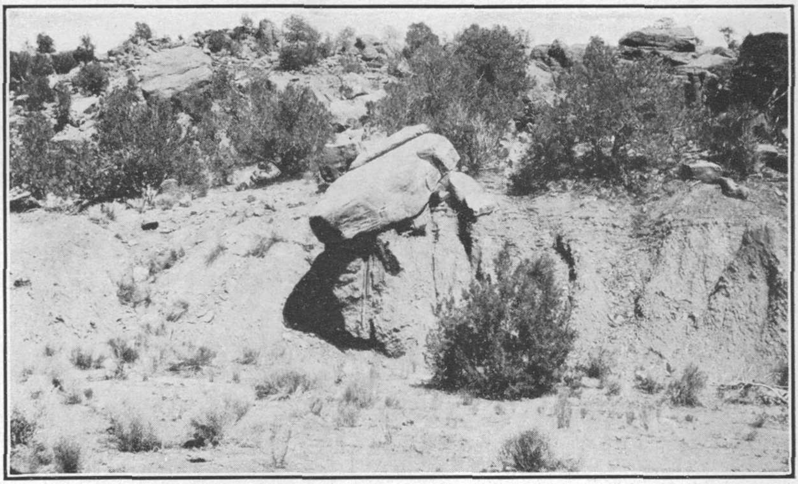
A. HILLOCK OF BASALT COLUMNS 6 MILES NORTH OF WHEELER, GRANT COUNTY, WASH.

A column on the left has the form of a pedestal rock. Photographed in 1923

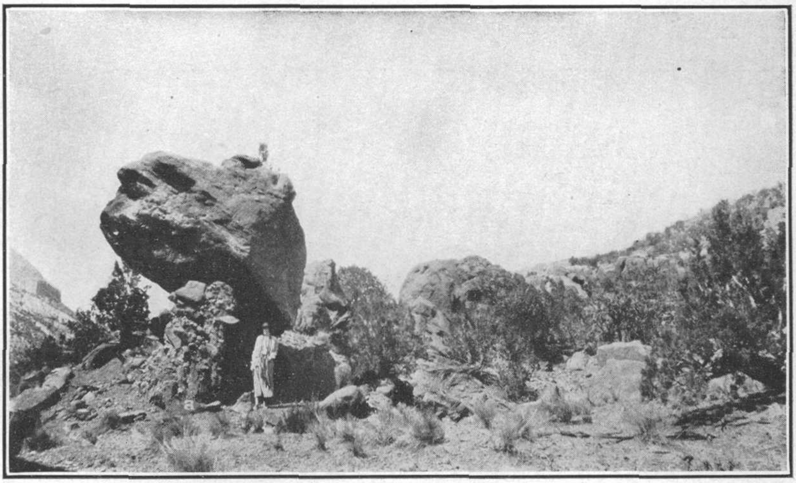


B. PEDESTAL ROCK FORMED BY MECHANICAL DISRUPTION OF BASALT COLUMN

Photographed in 1923



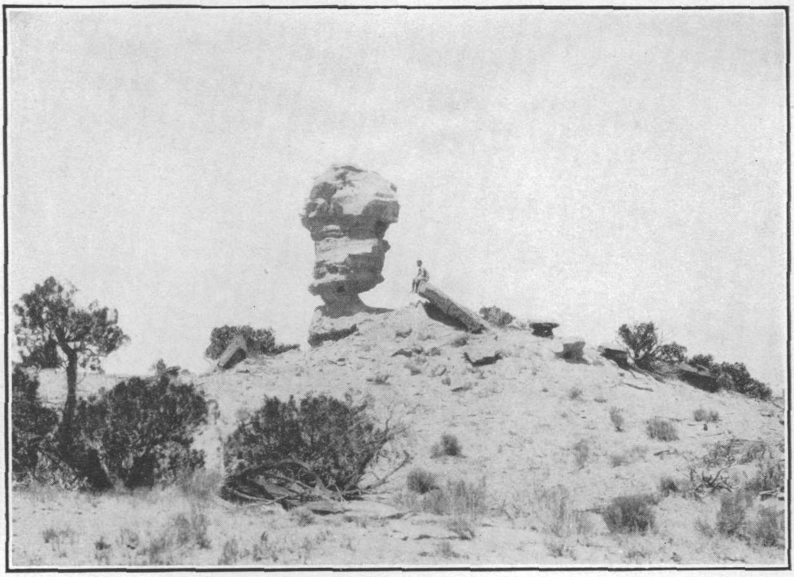
A. SANDSTONE BLOCK RESTING ON PEDESTAL OF SHALE DETACHED FROM THE BANK OF WHICH IT ONCE FORMED A PART



B. SANDSTONE BLOCK RESTING ON RUBBLE OF OLD TALUS ELSEWHERE STRIPPED FROM A SHALE SLOPE

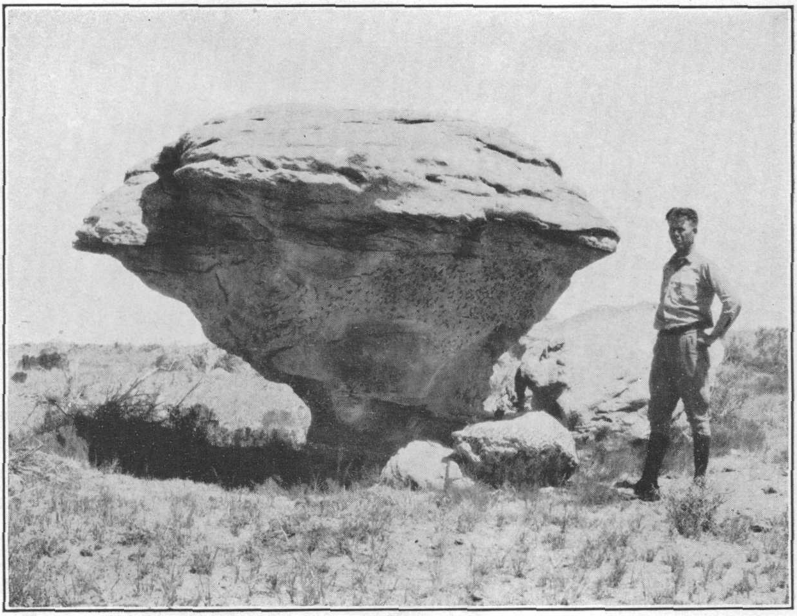
PEDESTAL ROCKS IN CANYON OF JEMEZ CREEK, N. MEX.

Photographed in 1923



A. PEDESTAL ROCK OF SANDSTONE NEAR SEVEN LAKES, McKINLEY COUNTY, N. MEX.

Photographed in 1924



B. PEDESTAL ROCK OF SANDSTONE NEAR McGILLVRAY'S RANCH, McKINLEY COUNTY, N. MEX.

Photographed in 1924

the position of greatest scour, extends all the way around the stack. Such notched stacks have the same form as pedestal rocks. Obviously, these rocks are structurally weak and are easily destroyed by the high waves of great storms. Direct abrasive action of wind-blown sand is asserted by a number of writers [9] to be the agent in the formation of pedestal rocks in deserts. Neither the descriptions nor the photographs presented by these writers are wholly convincing, except those of a rock on the coast of the Red Sea described by Wade [10] and of one in Southwest Africa described by Harger.[11] There is no inherent reason why the form can not be produced by this process, provided that winds and sand operate for a sufficient length of time on a favorably located mass.

The pedestal should show the marks of abrasion by wind-blown sand, but the possibility of polish by the pelts of grazing animals should be eliminated, as Karl Walther [12] has pointed out in describing a pedestal rock of granite which was produced by differential weathering in the plains of Uruguay.

Pedestal rocks in areas having various types of climate are due to differential weathering, and the object of this paper is to describe the particular processes of differential weathering which have produced certain pedestal rocks in areas having climates that differ in type but are comparatively arid. The examples from the State of Washington were studied incidentally in the course of a geologic examination of the Columbia Basin irrigation project in 1923. The rocks in the canyon of Jemez Creek, N. Mex., were seen while I was on leave in the same year, and the rocks in McKinley County, N. Mex., were visited during a geologic study of the recent deposits of Chaco Canyon for the National Geographic Society in 1924.

PEDESTAL ROCK IN BASALT

The pedestal rock in basalt here described is by no means perfect in form, but it is due to so curious a combination of circumstances that a description will doubtless be interesting to those concerned with the processes of arid regions. The rock lies at the north end of a small hillock 12 miles southwest of Adrian and 6 miles north of Wheeler, Grant County, Wash. This locality is in the west-central part of the Columbia Plateau. Quincy Basin, a structural depression, lies to the west, and the lavas of the plateau in this vicinity dip

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[9] A fairly complete list is given in U. S. Geol. Survey Bull. 760, p. 1.

[10] Wade, Arthur, Some observations in the eastern desert of Egypt, with considerations bearing on the origin of the British Trias (with discussion): London Geol. Soc. Quart. Jour., vol. 67, p. 248, pl. 14, fig. 2, 1911.

[11] Harger, H. S., Denudation in South Africa: South Africa Geol. Soc. Proc., 1913, p. xxxiv, and especially fig. 1.

[12] Estudios geomorfológicos y geológicos: Montevideo Inst. hist. geog. Revista, vol. 4, p. 109, footnote, 1924.

almost insensibly westward and pass under the gravel and sand that form this plain. Several waterless gorges extend westward from the higher land and fade out in the basin. Near the mouth of one of these gorges, Black Rock Coulee, long ago deserted by the glacial waters that excavated it, there is an area with numerous rocky hillocks projecting from the plain. The irregular rock surface, of which the hillocks are the high points, was doubtless carved by the glacial waters from Black Rock Coulee. Over this floor wind-blown dust from the flats of Quincy Basin or rehandled loess from the surrounding plateaus has settled.

The hillock with the pedestal rock consists of a group of basalt columns each of which is from 18 inches to 3 feet across. The columns are mostly six-sided and are unusually even and symmetrical. As shown in Plate 1, *A*, each column is separated from the neighboring ones by a space about 2 inches wide, yet each column, though it has the irregularities normal to such columns, fits its neighbors and evidently has not been displaced since its formation. At the base of the columns and below the ground surface the rock is continuous from column to column except for a medial crack. For an inch on each side of this crack the rock is soft, is greenish gray with rusty crevices, and gives the appearance of having suffered from chemical decomposition. The space between the columns, above ground, is obviously due to the removal of rock weakened in the same way. The projecting columns, though diminished in size, are hard and sound, and their faces are smooth and regular. They are little affected by corrosive processes but suffer disruption by spalling. The dense, tough rock breaks in spalls and chips, and to this spalling is due the pedestal rock shown at the left in Plate 1, *A*, and in more detail in Plate 1, *B*. This column has two incipient cross joints, and, as is well shown in Plate 1, *B*, spalling to these joints has produced the narrow neck that is surmounted by a block the full size of the column. The neighboring column is suffering from the same process, and some of the adjacent columns also show spalling from the corners. A few columns have lost from the sides, as well as from the corners, numerous thin rock chips, which litter the ground. These chips and the larger fragments broken from the corners appear to be fresh rock and ring when struck by the hammer.

Chips collected from the surface and dug out from between the columns have been studied by Clarence S. Ross, who has furnished the following statement:

The chips from the columnar basalt when studied under the microscope, both in thin section and as small grains embedded in immersion oils, show interesting characteristics, some of which were not suspected before examination. The rock is a normal basalt but little altered and is composed of calcic plagioclase, augite, and sparse olivine and magnetite.

The chips collected above ground have a dull weathered and pitted surface, but 1 millimeter below the surface they appear to be fresh, and they have the sharp metallic ring of a fresh rock.

The chips collected below the ground surface have a dirty greenish-gray appearance, and the laminae and cracks are filled with alteration products, among which opal is the most abundant. They do not ring but give a dull sound when tapped, and they present an appearance of rock decay.

In the chips collected above ground the plagioclase grains are entirely unaltered chemically, the augite grains are nearly as fresh, and the sparse olivine is only partly decomposed. A red-brown mineral secondary to olivine is present, but it was probably developed during the final cooling of the rock and is not a product of later weathering. A very small amount of limonitic material has developed which gives the rock a rusty appearance under the hand lens. This material lies in the cracks and cleavage planes of the minerals and as viewed under the microscope is a pale yellow-brown stain which accentuates the fractures and cleavage planes. The most striking characteristic is the development in the plagioclase and augite of countless small fractures, which are far more abundant and conspicuous than in a fresh basalt. On the surface of the chips minerals that appear nearly fresh under the microscope have become so fragile that they can not be picked up with the forceps, but just below the surface, although the fractures are nearly as conspicuous, the minerals are not so fragile. The fractures in general cut across the augite and olivine grains in random directions, but in most of the plagioclase grains they make an angle of 45° with the cleavage or follow a cleavage plane for a distance and then break across at an angle of approximately 45° to another cleavage plane, so as to form a rather regular network of fractures.

The minerals of the rock chips collected below the ground surface are surprisingly fresh considering the appearance of the rock in the hand specimen. The plagioclase grains are unaltered chemically, but the augite and olivine grains show distinctly more alteration than these minerals in the chips collected above ground. Both the plagioclase and the augite have only a few more fractures than are characteristic of the minerals of normal fresh basalt, and they do not have the abundant fractures shown by these minerals in the chips collected above ground.

The greater amount of weathering by chemical decomposition in the rock chips collected below the ground surface observed by Mr. Ross is confirmed by chemical tests carried out in the chemical laboratory of the Geological Survey by J. G. Fairchild. The results may be tabulated as follows:

Partial analysis of weathered basalt from hillock 6 miles north of Wheeler, Grant County, Wash.

	Sample taken above ground	Sample taken below ground
	Per cent	*Per cent*
Ferrous iron (FeO)	10.3	9.24
Loss on ignition (total H_2O)	1.06	2.32

The relative loss in content of ferrous iron of the rock chips from below the surface indicates that the olivine and augite have begun to break down, as is to be expected in the decay of basalt; and the increase in water content indicates that hydrous clayey minerals have been formed as a result of the decomposition of these minerals and perhaps also of the plagioclase, although under the microscope this mineral gives no sign of decomposition.

The intimate fracturing of the mineral grains of the rock chips from the surface brought out by Mr. Ross's study can be safely attributed to mechanical disruption, because the absence of decomposition products except for the small amount of iron oxide testifies to the almost complete lack of chemical change. The physical forces that can have caused the disruption are frost action and thermal expansion and contraction under the diurnal and annual fluctuations of air temperature. It seems improbable that sufficient water could penetrate into the mass of these otherwise unaltered mineral grains to disrupt them on its expansion in freezing, though no data are available in support of this contention. The fractures are, however, of a type that should arise if the grains were subjected to the stresses due to thermal expansion or contraction when at the same time they were confined by and stressed by other grains affected by the same forces. As the diurnal changes of air temperature are not only more numerous but because of their short period produce greater ranges of temperature in adjacent parts of the rock, they have doubtless been more effective than the annual changes in temperature in producing the cracks. It should also be noted that just below the ground surface the fracturing is absent, although there the annual changes in temperature should be just as effective.

The spalling of small chips and larger masses, to which the pedestal rock is largely due, is also a mechanical process. Spalling of this type is ordinarily attributed to thermal expansion and contraction, but Blackwelder[13] has recently expressed the doubts which it is evident from a review of the literature have lingered in the minds of geologists as to the validity of this process.

In this relatively arid locality conditions are favorable for numerous and rapid changes in air temperature, which, if such changes can disrupt rock, should produce the spalling that has been observed. Even if the changes in temperature of this locality are insufficient to disrupt a rock of normal strength the outer part of these basalt columns has already suffered from a minute internal rupture of its component minerals and therefore lacks part of the original strength and may have other quite distinct physical properties.

Frost action also can not be wholly eliminated, because the locality has a cold winter during which moisture that had collected in the fractures of the mineral grains might freeze and cause the spalling.

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[13] Blackwelder, Eliot, Exfoliation as a phase of rock weathering: Jour. Geology, vol. 33, pp. 793–806, 1925.

The relatively small amount of chemical weathering observed below the ground surface and between the columns may possibly be due to forces operative in the past. A little decomposition of this sort is evident in all the outcrops of basalt in the Columbia Plateau. Cliffs that are thought to have been formed by streams issuing from the ice of Wisconsin time appear to consist of fresh rock, but a close inspection shows that they have many zones of soft decomposed rock along vertical joints. The minerals that once filled the vesicles of the basalt have been leached out, and bands of opal in the cracks are more or less decomposed. Ordinarily, in the Columbia Plateau, surfaces formed in pre-Wisconsin time are underlain by rock that is softened and discolored by unmistakable chemical weathering. It may be that the chemical weathering of this locality began in the early Pleistocene and has been inherited from a time preceding the occupation of Black Rock Coulee by glacial waters,[14] which have removed at this place only a moderate thickness of rock. On the other hand the glacial channel in Black Rock Coulee may belong to the intermediate glaciation (Spokane of Bretz) or some earlier ice advance, and if so there has been ample time for chemical weathering to take place since the channel was formed. Chemical weathering may even be going on at the present time, for, although the climate is arid, the fine-grained soil is retentive of moisture.

The rock has formed in an arid climate, within the "dry spot" of Washington, a nearly circular region about 50 miles in diameter, in which the annual rainfall is less than 8 inches. The published observations of the United States Weather Bureau at Wheeler, 6 miles to the south and at about the same altitude, indicate, from an incomplete 7-year record, a mean annual precipitation of 7.12 inches. Most of this precipitation takes place in the winter months, November to February, though showers are also common in May and June. The moisture stored in the ground in winter, together with the spring rains, is sufficient to support sagebrush and a fair cover of grass. The vegetation has been sufficiently luxuriant to retain the fine loess-like soil. The capacity of this soil to hold moisture may, as already stated, provide suitable conditions below the ground surface for the small amount of chemical decomposition that has taken place between the columns.

Above the ground surface, however, the rain readily washes away the parts of rock that have been chemically decomposed even in a minor degree. During the long dry summer insolation has full play,

[14] Bretz, J. H., Glacial drainage on the Columbia Plateau: Geol. Soc. America Bull., vol. 34, pp. 573–608, 1923. The map of fig. 1 does not show Black Rock Coulee as a glacial channel. See, however, Bretz, J. H., The channeled scablands of the Columbia Plateau: Jour. Geology, vol. 31, pp. 617–649, 1923, especially p. 644 and pl. 3.

and the alternate contraction and expansion of the dense fine-grained basalt of the columns causes near the surface intimate fracturing of the component minerals. The same forces tend to bring about the flaking of chips from the sides and the spalling of the corners of the columns, but here frost action may come into play and may possibly be the dominant factor in disrupting the rock.

Thus this pedestal rock has attained its form by the action of both chemical and mechanical weathering on a basalt column having two incipient cross fractures. The combination of conditions necessary for the production of this rock is not wholly exceptional, for 3 miles northwest of Adrian there is a somewhat similar pedestal rock formed in an identical manner.

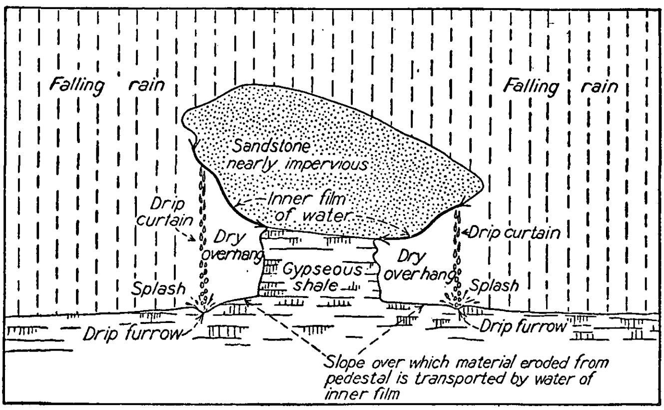

FIGURE 1.—Diagram illustrating differential rainwash on a pedestal rock consisting of an impervious block resting on an easily eroded mass below

DIFFERENTIAL RAINWASH

The violent showers characteristic of most arid climates will produce pedestal rocks by differential rainwash where blocks of impervious material rest on easily eroded material. The mechanism of this process was observed near Lees Ferry, Ariz., and has been described in an earlier paper.[15] The process is shown diagrammatically in Figure 1. The main work of producing the pedestal is done by the drip curtain, which excavates an annular groove around the rock. An inner film of water, however, clings by adhesion to the overhang of the rock and reaches the pedestal. It is largely the work of this film which erodes and thins the pedestal back of the drip curtain. In the rain observed at Lees Ferry the inner film reached just to the pedestal and wet its top. That this inner film may not only reach the pedestal but may, under suitable circumstances, cause erosion is evident from a pedestal rock in the canyon of Jemez Creek between the

[15] Bryan, Kirk, U. S. Geol. Survey Bull. 760, pp. 1–11, 1925.

towns of Canyon and Jemez Hot Springs, N. Mex., about 150 miles east of Lees Ferry, Ariz. The rock consists of a loose block of dense red sandstone, derived from outcrops farther uphill, that rests on a pedestal of red shale, as shown in Plate 2, *A*. On the face of the pedestal is a vertical roll of hardened mud similar in form and origin to the rolls of mud that form on the inside of an adobe house when the roof leaks. Obviously, the inner film of water traveling on the overhang, as shown in Figure 1, has reached and eroded the pedestal. Such a movement of water can have little scouring action, but if continued will lead to the removal of any material on the pedestal that is already loosened by weathering.

A rock near by (pl. 2, *B*) consists of a block of sandstone resting on a mass of rubble that in turn rests on red shale. The rubble and, doubtless, also the underlying block are the last remnants of a talus that once mantled the mountain side. The block has partly protected the underlying rubble in the process of differential erosion by rainwash, but the vertical grooves in the rubble bear mute testimony to erosion by water dripping over the face of the pedestal as an inner film. At the point marked "a" the rubble overhangs and protects the red shale which forms the lower 8 inches of the pedestal. The rubble is therefore more resistant to rainwash than the shale.

The climate of the area in which these rocks occur is not very different from that at Lees Ferry, except for lower temperature and greater precipitation, due to an altitude 2,500 feet higher. The mean annual rainfall amounts to 17.13 inches at Jemez Hot Springs, according to the record of the United States Weather Bureau over a period of 14 years, as compared to 5 inches, the estimated mean at Lees Ferry. This mean rainfall of 17.13 inches places the locality well within the arid zone as usually considered, yet it is evident that the rock shown in Plate 2, *B*, differs from the form of natural monument called earth pyramid, earth pillar, or demoiselle, only in having a larger block in proportion to the size of the pedestal. There seems, therefore, to be no essential difference in origin or method of erosion between earth pillars and pedestal rocks of this type. Yet earth pillars are generally admitted to be normal forms of erosion in humid regions, although they are doubtless less numerous there than in arid regions, where a slower rate of erosion gives each of them a longer life.

DIFFERENTIAL SAPPING

The overlying block in a pedestal rock formed by differential rainwash is relatively impervious to rain. If the upper block is porous, however, and absorbs part or all of the rain that falls on it, the circulation of water within the mass of the rock promotes weathering by solution. Sandstone is particularly susceptible to attack by water absorbed from rain. Generally, the water dissolves the cement and, traveling on original lines of easiest passage, emerges at the sides or base of the rock, where it runs out or is evaporated. At or near the point of emergence the rock crumbles into its original sand grains, which fall away or are carried off by rainwash. The intricacies produced by this process are truly marvelous. In general an excavation or eating back of the original mass takes place, and the process will here be called differential sapping.

Although characteristic also of the weathering of sandstone in humid regions the forms produced by this process in arid regions have been attributed by many to wind erosion. Gregory,[16] however, has invoked differential sapping as the method of formation of niches under dry waterfalls, of rock shelters, of windows, and of arches in sandstone in the dry climate of the Navajo country. Certain rock shelters and niches [17] in the Papago Saguaro National Monument of southern Arizona, where the mean annual rainfall is about 7 inches, have also been ascribed to this process.

PEDESTAL ROCKS IN SANDSTONE

LOCALITY AND CLIMATE

In northwestern New Mexico, in the areas underlain by sandstone and shale of Upper Cretaceous age, pedestal rocks are numerous. At each outcrop of sandstone one or more pedestal rocks may be found. These rocks are special forms of those monuments of erosion customarily isolated in the recession of cliffs. Their shape is due to the cooperation of a variety of structure in the original rock and several processes. The rocks that are most symmetrical in form are due to a nicety in this cooperation that may be considered fortuitous, but the great numbers of pedestal rocks which exist in this region indicate that certain conditions are dominant. The nature of the rock structure and the processes which act upon it in the production of pedestal rocks in the southern part of the San Juan Basin, near Crown Point, McKinley County, N. Mex., will be described in the following paragraphs.

The climate of the area is moderately arid and marked by cold winters and hot summers. An incomplete weather record extending over 11 years at Crown Point, where the altitude is 6,800 feet, as published by the United States Weather Bureau, gives a mean annual precipitation of 10.9 inches. In the five consecutive years for

[16] Gregory, H. E., Geology of the Navajo country, a reconnaissance of parts of Arizona, New Mexico, and Utah: U. S. Geol. Survey Prof. Paper 93, pp. 133–134, 1912.

[17] Bryan, Kirk, The Papago country, Arizona, a geographic, geologic, and hydrologic reconnaissance, with a guide to desert watering places: U. S. Geol. Survey Water-Supply Paper 499, pp. 91–93, 1925.

which this record is complete the precipitation ranged from 5 to 16.99 inches, indicating to some extent the great droughts and correspondingly wet years to which the area is subject. A large part of the winter precipitation is in the form of snow, and in the spring the ground is usually sufficiently moist to permit the growth of vegetation. In May and June rain sufficient to wet the ground is rare. In July the so-called rainy season begins. Heavy cumulus clouds drift over the country, and from these clouds fall violent local rains or cloudbursts. The areas in which these rains fall are sometimes small, but the heavier rains usually cover extensive areas. From a half to two-thirds of the annual precipitation falls during the rainy season, but this period of rain is uncertain in time and place. In years of generally high rainfall some areas receive little rain, and in many years the summer rains are delayed until September. In spite of the severity of these conditions for the growth of plants, the loamy and clayey soils developed on shale or on the overflow areas of ephemeral streams have a good growth of deep-rooted perennial grass, which makes its principal growth during the summer rains. The sandstone beds usually crop out as bare rock and have little soil except patches of wind-blown sand. Scanty grass grows on the sand, but the hardy juniper (scrub cedar) thrives in scattered groves, even on the bare rock.

The mean annual temperature at Crown Point so far as determined is about 50° F. The absolute range in temperature, however, is large, from −8° on January 2, 1919, to 95° on July 1, 1917. The daily range, especially early in the summer, is also large, probably amounting to as much as 60° or 70°.

This relatively severe climate, with its long periods of drought and violent rains, hot summers and cold winters, warm days and cold nights, has corresponding effects on erosive processes.

THE ROCKS

One of the most picturesque pedestal rocks of this area stands about half a mile off the road from Crown Point to Chaco Canyon near Seven Lakes. As shown in Plate 3, *A*, this rock rises from a small knoll in an area with a sparse vegetation of small bushes, grass, and junipers. The knoll lies in a small amphitheater in low cliffs of horizontal sandstone that is identical with the material of the pedestal rock. The rock is thus an erosion remnant between small valleys working headward into the cliffs and is remarkable only in the details of its form. An inspection of the photograph shows that joint faces are not entirely obliterated from the massive sandstone at the top, and the implication is that the isolation of the rock is due to erosion by weather and streams, along vertical joints. The remarkably slim pedestal is composed of laminated, somewhat clayey sandstone, and the constricted portion halfway up is of similar material. The capping sandstone is massive, as are the other projecting portions of the mass. It seems obvious that the laminated and clayey beds have suffered more from weathering than the remainder of the rock, and that the form is due to the distribution of the less resistant beds and the summation of the differences in the rate of weathering. That differential sapping, as defined on page 10, is the most active process, seems evident; first, because of the selective work against certain beds, which is effective irrespective of their thickness or position above the ground surface, and second, because at the time of visit, a few days after a rain, the surface of the slimmest part of the pedestal was damp, whereas that of the rest of the rock was dry and powdery.

Differential rain wash can not be solely accountable for this rock, because the differences in resistance of the different sandstone beds are too slight and the porous upper mass must absorb at least part of every rainfall. However, it seems likely that the inner film of water that creeps over the rock face during rainstorms is effective in removing loosened grains from all the intricate reentrants of the mass. Doubtless many of these loosened grains simply fall by gravity, and others are perhaps shaken loose during high winds. That the scour of sand carried by wind has any appreciable effect can be denied, for the base of the rock is too high above the ground for wind scour to be effective. All authorities are agreed that 2 to 3 feet above the ground surface is the limit of effective wind scour.[18]

The rock illustrated in Plate 3, *B*, stands near the road from Crown Point to Chaco Canyon, about 20 miles northeast of Crown Point. To the right of the view there is a rounded boss of sandstone eroded from the same horizontal sandstone bed, but the pedestal rock stands detached in a plain of sandy soil that within the area of the view merges into an alluvial sandy loam. Apparently the rock was once a mass approximating a cube in shape that was isolated along vertical joints, but the present form seems to be due to differential sapping. The upper part of the rock is separated from the remainder by a bedding plane, and it seems fair to assume that this upper sandstone has always been somewhat harder than the remainder of the rock. It is porous, however, and has a crumbly surface. Obviously it absorbs rain water, which emerges lower down from the pores of the sandstone of the pedestal. The surface of this lower portion is notably soft and friable, particularly near the ground. Here individual sand grains are loosened and fall by gravity or are

[18] Among others, see Hobbs, W. H., The erosional and degradational processes of deserts, with especial reference to the origin of desert depressions: Assoc. Am. Geographers Annals, vol. 7, p. 33, 1918.

washed off by the inner film during rains. Not only does the pedestal disintegrate into sand by the relatively slow solution of its cement but periodically large pieces fall off, as is attested by their presence at the base of the rock and by the scars left on the pedestal into which some of them can almost be fitted. It seems likely that frost action, when the pedestal is saturated after rains, aids in detaching these blocks. The wide range in temperature and the severity of the winter have been noted above.

Between the scars of recent falls there are somewhat more ancient surfaces that are minutely pitted. Each pit is about three-eighths of an inch in diameter and half an inch deep. Some of them contain dead insect pupae. It seems evident that wasps bore these holes as nests for their young under the overhang of the rock, where they are protected from the direct impact of rain. Thus animals contribute, in slight degree, to the erosion of the rock.

It seems impossible that wind scour can have had any important part in the formation of this rock. The pulverulent surface of the pedestal testifies to differential sapping; the scars, to frost action; and the pitted surfaces, to insect erosion. None of these surfaces could retain their characteristics under the sand blast, and they are in marked contrast to the firm, harsh surfaces of similar rocks in the region that are unquestionably scoured by wind-driven sand. The surrounding area is sandy, as might be expected where the local débris is all derived from the erosion of sandstone. Near by there are small accumulations of wind-blown sand, 6 inches to 2 feet thick, which are, however, more or less prevented from moving by the growth of grass. Near the pedestal rock sand is not moving in large amount or with violence, else the grass and sagebrush would be cut away, and the rock fragments lying at the foot of the pedestal rock would be shaped by wind scour.

PEDESTAL ROCKS IN HUMID REGIONS

The pedestal rocks described in this paper are all located in arid regions, yet the processes by which they have arisen are operative in humid regions. From a review of geologic textbooks one would gain the impression that pedestal rocks are characteristic of arid regions and do not occur in more humid lands. Aside from notched stacks on coasts and pedestal rocks formed in streams, whose origin is apparently independent of climate, a considerable number of pedestal rocks in humid regions have been described. In England [19]

[19] Hughes, T. McK., On some perched blocks and associated phenomena: Geol. Soc. London Quart. Jour., vol. 42, pp. 527–539, 1886; Notes on the geology of parts of Yorkshire and Westmoreland: Geol. Polytechn. Soc. West. Rid. Yorkshire Proc., vol. 4, p. 574, 1867. Bonney, T. G., The work of rain and rivers, p. 18, Cambridge Press, 1912.

and Ireland [20] certain pedestal rocks consist of glacial erratics of compact and insoluble rocks resting on limestone. Solution of the limestone except where partly protected by the erratic block has produced the forms. Estimates [21] of the age of the pedestal rocks and therefore of the time since glaciation, by comparison of the height of the pedestal with the rate of solution of limestone, have not been wholly satisfactory.

The mushroom rocks of New Red sandstone in Devonshire are thought by Kinahan [22] to be in part due to the work of rain driven horizontally by the wind, and the sandstone crags of Kinder Scout [23] provoked a discussion as to the relative effect of the scour of wind-driven sand and of differential erosion, and apparently no later investigator has published a definite conclusion.

In Indiana,[24] Illinois,[25] Arkansas,[26] and Wisconsin [27] are good examples of pedestal rocks that may be attributed to differential weathering and the subprocesses differential rainwash and sapping.

The life of pedestal rocks in humid regions is relatively short because of the rapidity of rock decay and, in the colder countries, because of the increased effectiveness of frost action due to the presence of moisture. Not only are the forms less persistent, but the presence of vegetation inhibits rainwash and much of the vertical cutting of minor streams, so that the rocks ordinarily occur as the result of exceptional conditions, such as the imposition of blocks of dense insoluble stone on limestone, or else in areas of porous sandstone and limestone. The erosion forms of porous sandstone in humid lands reproduce many of the spectacular features of arid regions, because areas of such rock resemble arid regions in having a scanty, sterile soil, a sparse vegetation, and a low water table. These features are well brought out in the literature on the Fontainebleau sandstone already referred to and in numerous works on the Quadersandstein and Buntsandstein areas of Germany. Similarly, limestones, particularly in areas having the Mediterranean type of climate, may

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[20] Kinahan, G. H., Valleys and their relation to fissures, fractures, and faults, pp. 53–54, London, 1875. Wynne, A. B., Notes on some physical features of the land formed by denudation: Ireland Roy. Geol. Soc. Jour., vol. 1, p. 258, 1867.

[21] Mackintosh, D., Results of observations in 1882 on the position of boulders, etc. (abstract with discussion): Geol. Soc. London Proc., Feb. 21, 1883, p. 67.

[22] Kinahan, G. H., op. cit., p. 83.

[23] Discussion of paper by Enys, J. D., Geol. Soc. London Quart. Jour., vol. 34, pp. 86–88, 1878.

[24] Dryer, C. H., Jug Rock, near Shoals, Ind.: Indiana Acad. Sci. Proc. for 1898, pp. 268–269, 1899. Logan, W. N., Geologic conditions in the oil fields of southern Indiana: Indiana Dept. Conservation Pub. 42, fig. 1, 1924.

[25] Bonnell, Clarence, The variety of physiographic material in a few counties of southern Illinois: Illinois Acad. Sci. Trans., vol. 9, p. 207, 1917.

[26] Hopkins, T. C., Marbles and other limestones: Arkansas Geol. Survey Ann. Rept. for 1890, vol. 4, p. 343, pl. 17, 1893.

[27] Alden, W. C., The Quaternary geology of southeastern Wisconsin: U. S. Geol. Survey Prof. Paper 106, p. 4, pl. 16, *A*, 1918.

produce somewhat similar forms, although in climates like that of the eastern United States areas of this type of rock are usually mantled by a deep soil.

CONCLUSIONS

The foregoing description of pedestal rocks in the widely separated States of Washington and New Mexico calls attention to the variety of processes involved in the formation of these minor but distinctive forms and emphasizes the accumulating evidence that many pedestal rocks, even in arid regions, are attributable primarily to other processes than wind erosion. The examples cited are due to processes which are also operative in humid regions. The fact that a relatively larger number are found in arid regions is probably due not so much to differences in the nature of the processes of weathering and erosion as in their rate, for in humid regions the formation of soil by chemical weathering and the growth of vegetation inhibit the formation of pedestal rocks in favorable places or rapidly destroy them when formed.

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CHANNEL EROSION OF THE RIO SALADO, SOCORRO COUNTY, NEW MEXICO

By Kirk Bryan

Deepening and widening of stream channels in the Southwest is a phenomenon that has taken place within the memory of men now living. It began at different dates from 1860 on and has progressed at different rates on several streams, as summarized in a recent paper.[28] The flood plains of numerous minor streams are yet undissected, but nearly every one of them is menaced by a deep channel, or arroyo, which visibly increases headward each year. These channels, or arroyos, not only grow headward through the smooth flood plains of the valleys but constantly widen by lateral cutting and the growth of minor tributaries. It seems inevitable that the present flood plains will eventually disappear and new flood plains will form at lower levels.

The consequences of these processes to native life and to agriculture, stock raising, and other activities of man are numerous and important. Interesting scientific problems are also raised. The various theories that have been advanced to account for this accelerated erosion are reviewed in the paper already cited.

Valid conclusions as to the merits of these theories can not be reached until historical data on the time at which erosion began have been accumulated. Knowledge of the date of the beginning and progress of this spectacular change in the regimen of streams is particularly necessary in arriving at a decision as to the effect on erosive processes of the introduction of cattle and sheep and the overgrazing that in most localities ensued. This paper presents, as a contribution to the necessary body of data, historical evidence, based on two reliable surveys made in 1882 and 1918, on the changes in the channel of a comparatively minor stream in New Mexico.

The Rio Salado, a tributary of the Rio Grande from the west, rises on the north side of the Datil Mountains and has a general

[28] Bryan, Kirk, Date of channel trenching (arroyo cutting) in the arid Southwest: Science, new ser., vol. 62, pp. 338–344, 1925. See also Swift, T. T., Date of channel trenching in the Southwest: Idem, vol. 63, pp. 70–71, 1926; Wynn, Fred, The West Fork of Gila River: Idem, vol. 64, pp. 16–17, 1926.

eastward course north of that range and thence through a narrow gap between the Socorro Mountains and the Sierra Ladron to a junction with the Rio Grande at the village of San Acacia. The Rio Salado is formed by the junction of Alamosa Creek, also locally known as Rio Salado, and a large stream from the north. The total length of this drainage line, if Alamosa Creek is considered the main stem, is 75 miles, and the basin drained by it lies almost wholly in Socorro County. The village of Puertecito lies 2 miles above the junction of the two streams, and Santa Rita (Riley post office), 7 miles below.

When Lorenzo Padilla, the first settler, who is still living at Santa Rita, came to the valley in 1880, the channel of the Rio Salado was inconsiderable, and the broad flat of the valley seemed a propitious place for farming. Consequently, others followed Padilla, and according to the survey notes of Daniel Curry, who in 1882 subdivided the townships into sections, Santa Rita had by that time grown to a town of 100 inhabitants. Curry recorded the width of the stream bed as ranging from 11.88 to 48.84 feet on a number of section lines.

Because the town of Santa Rita lies in one of the odd-numbered sections which was granted to the Atlantic & Pacific Railroad and therefore belonged to its successor, the Santa Fe system, the inhabitants of the town had a defective title to the land. In support of an application by them to the United States General Land Office to have this land declared a public town site, Paul B. Moore, of Magdalena, N. Mex., was employed to make a survey. The information contained in this note was supplied by Mr. Moore, whose interest in New Mexican geology is large and whose help in this and other matters is hereby acknowledged. During this survey in 1918 he found the course of the river radically different from that shown in Curry's survey of 1882, his measurements ranging from 330 to 550 feet in the same stretch of stream channel where Curry found widths of 11.88 to 48.84 feet. Some of these differences are tabulated below.

Width of Rio Salado at different points in T. 2 N., R. 4 W., 1882 and 1918

Location	1882	1918
	Feet	*Feet*
On line between secs. 23 and 24	13.20	525.0
14 and 23	18.48	330.1
14 and 15	11.88	441.3
15 and 16	48.84	550.0

According to the testimony of the local inhabitants to Mr. Moore, there was an exceptional rain and flood in 1883, which washed out a road and formed a new stream channel. Since that time the channel has constantly widened, and most of the agricultural land in the valley has been destroyed.

Unlike many similar streams in New Mexico, which have not only widened their channels but deepened them in the same period, the Rio Salado, at least in the vicinity of Santa Rita, has even yet banks that are only 3 to 10 feet high and average about 5 feet high. It is obvious, however, that the whole regimen of the stream is much different from that which existed in 1880.

But little is known of the progress of this erosion upstream. However, W. T. Thom, jr., during a survey of the Alamosa Creek valley,[29] witnessed, in August, 1923, headward erosion on Felipe Gilbert Creek, a tributary of Alamosa Creek. According to his notes, generously furnished for this paper, at a point in sec. 10, T. 2 N., R. 7 W., 12 miles west-southwest of the village of Puertecito, the arroyo of this stream worked headward into the undissected valley flat a distance of 40 to 75 feet as a result of a single storm, destroying the road crossing and necessitating a detour by the party to avoid the steep-sided gully. From this record we may conclude that the progress of the erosion begun near Santa Rita in 1883 has been, as measured in years, fairly slow and has not yet, 43 years later, affected all the minor tributaries.

Thoughtful men must naturally consider whether it is possible to check such erosion and whether it would be profitable or otherwise advantageous to do so. One of the necessary items of information on which such a decision must be based is the relative value of the land in a dissected or undissected flood plain. Many writers have deplored the destruction of these valley bottoms, but no one has attempted to put a monetary value on the loss that has occurred, yet such an estimate is necessary before it is worth while to consider remedial measures.

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[29] Winchester, D. E., Geology of Alamosa Creek Valley, Socorro County, N. Mex., with special reference to the occurrence of oil and gas: U. S. Geol. Survey Bull. 716, pp. 1–15, 1921.