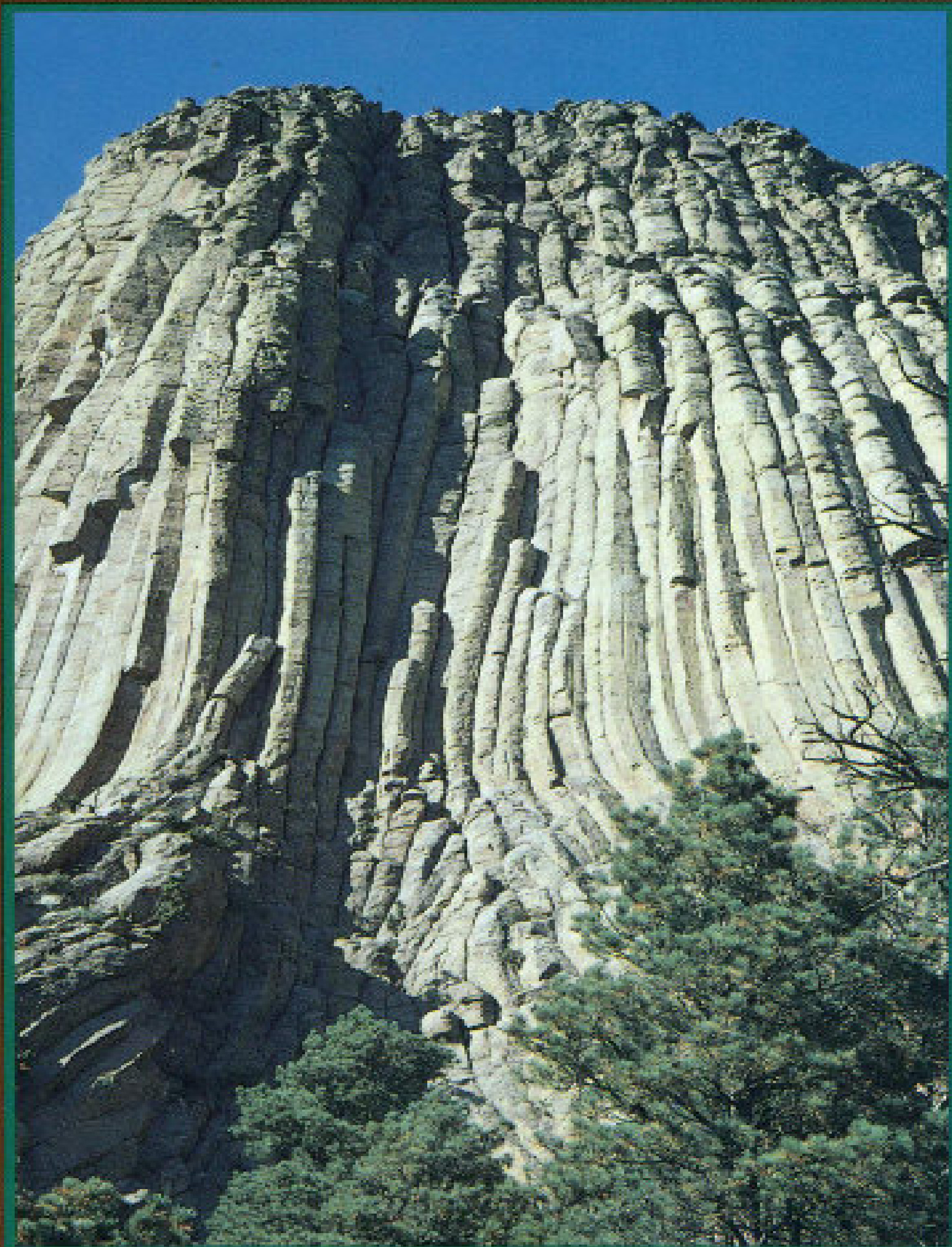
Geology of

DEVILS TOWER



The First National Monument

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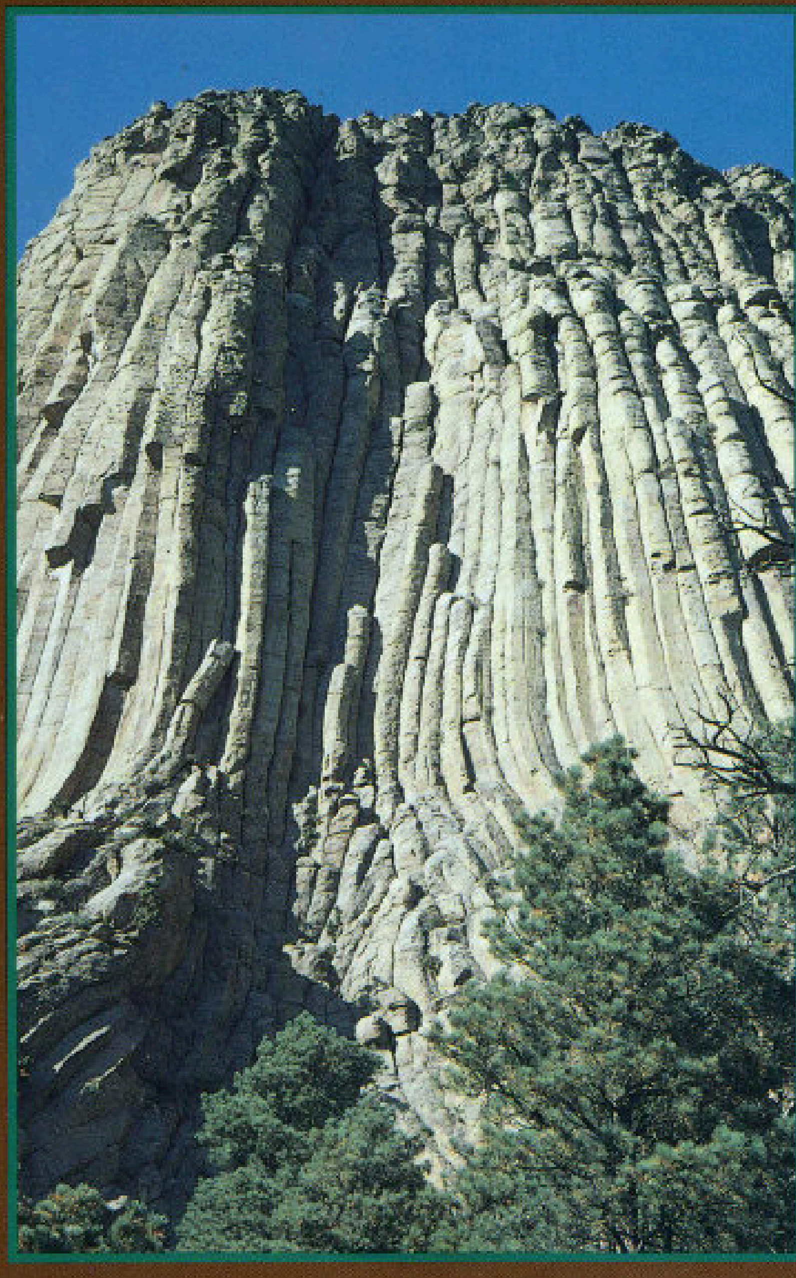

The First National Monument

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Geology of Devils Tower National Monument Wyoming

By CHARLES S. ROBINSON

A CONTRIBUTION TO GENERAL GEOLOGY

The National Park Service and the Devils Tower Natural History Association wishes to thank the United States Geological Survey for their kind permission to have this Bulletin reprinted with minor changes.

CONTENTS

ILLUSTRATIONS

A CONTRIBUTION TO GENERAL GEOLOGY

GEOLOGY OF DEVILS TOWER NATIONAL MONUMENT, WYOMING

By Charles S. Robinson

ABSTRACT

Devils Tower is a steep-sided mass of igneous rock that rises above the surrounding hills and the valley of the Belle Fourche River in Crook County, Wyo. It is composed of a crystalline rock, classified as phonolite porphyry, that when fresh is gray but which weathers to green or brown. Vertical joints divide the rock mass into polygonal columns that extend from just above the base to the top of the Tower.

The hills in the vicinity and at the base of the Tower are composed of red, yellow, green, or gray sedimentary rocks that consist of sandstone, shale, or gypsum. These rocks, in aggregate about 400 feet thick, include, from oldest to youngest, the upper part of the Spearfish formation, of Triassic age, the Gypsum Spring formation, of Middle Jurassic age, and the Sundance formation, of Late Jurassic age. The Sundance formation consists of the Stockade Beaver shale member, the Hulett sandstone member, the Lak member, and the Redwater shale member.

The formations have been only slightly deformed by faulting and folding. Within 2,000 to 3,000 feet of the Tower, the strata for the most part dip at 3°-5° towards the Tower. Beyond this distance, they dip at 2°-5° from the Tower.

The Tower is believed to have been formed by the intrusion of magma into the sedimentary rocks, and the shape of the igneous mass formed by the cooled magma is believed to have been essentially the same as the Tower today. Devils Tower owes its impressiveness to its resistance to erosion as compared with the surrounding sedimentary rocks, and to the contrast of the somber color of the igneous column to the brightly colored bands of sedimentary rocks.

INTRODUCTION

Devils Tower, a mass of bare rock that rises abruptly from the surrounding grasslands and pine forests, is one of the most conspicuous geologic features of the Black Hills region. Because of its scenic beauty and scientific interest, President Theodore Roosevelt in 1906 established Devils Tower and a small surrounding area as the first National Monument.

The Devils Tower National Monument covers an area of about 2 square miles near the center of Crook County in northeastern Wyoming (fig. 52). A paved road from the entrance of the National Monument goes south 7 miles to join U. S. Highway 14 at a point 29 miles northwest of Sundance, Wyo., and 33 miles northeast of Moorcroft, Wyo. The entrance to the National Monument may also be reached by a road (paved in Wyoming) that goes northeastward from the entrance, via Hulett and Aladdin, Wyo., to Belle Fourche, S. Dak., a distance of about 54 miles, where it joins U. S. Highways 212 and 85.

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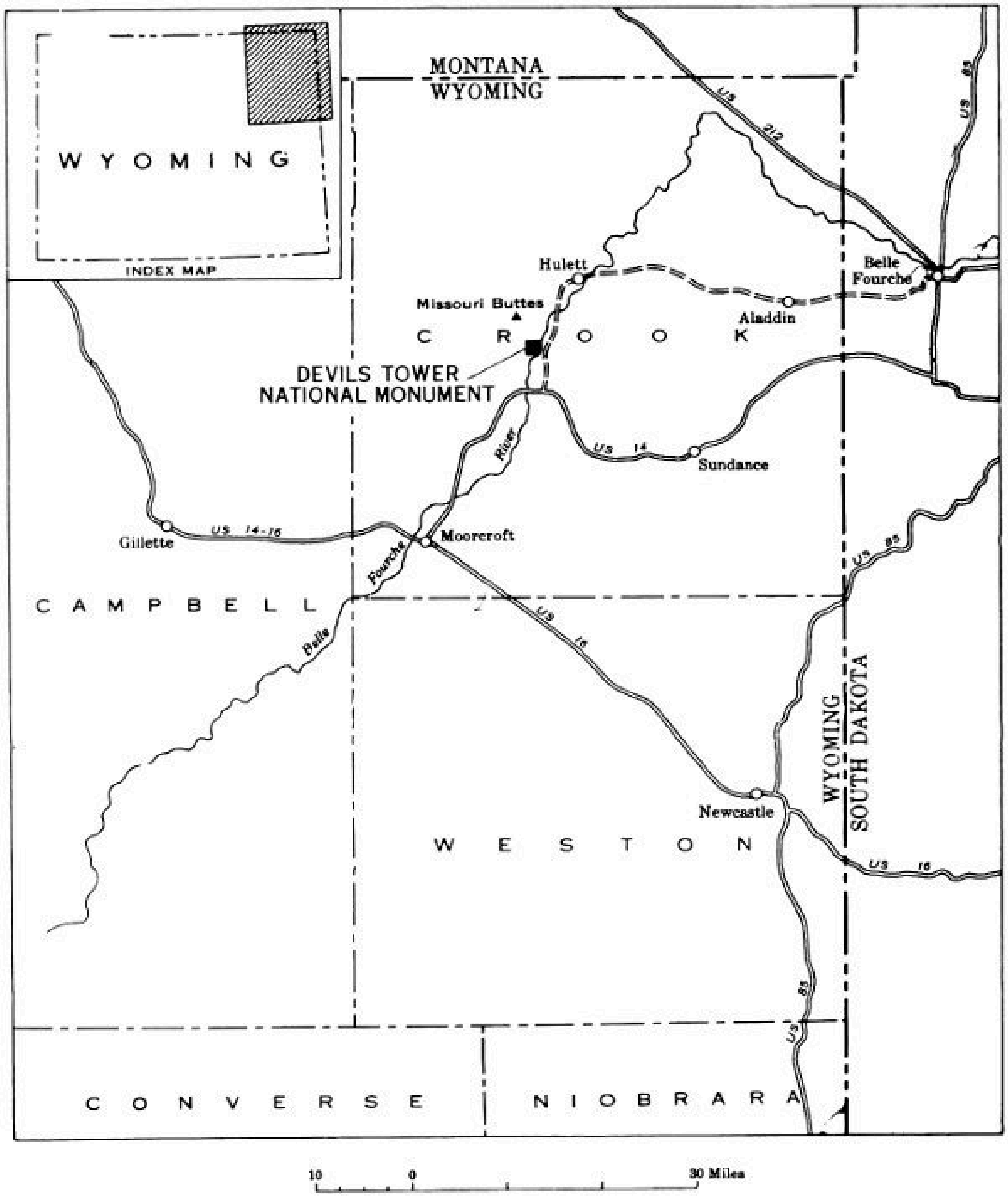


FIGURE 52.—Index map showing location of Devils Tower National Monument.

Public campgrounds and a natural history museum are maintained by the National Park Service at the base of the Tower about 3 miles by paved road from the Monument entrance.

The geology of the Devils Tower National Monument was mapped during the summer of 1954 by the U. S. Geological Survey in collaboration with the National Park Service. The work was part of a study of the geology of the northern and western parts of the Black Hills region conducted by the Survey on behalf of the Division of Raw Materials of the U. S. Atomic Energy Commission. The author wishes to acknowledge the assistance of the National Park Service and, in particular, Mr. Raymond McIntyre, Superintendent of Devils Tower National Monument.

GEOLOGY

The rocks exposed in the Devils Tower National Monument may be divided on the basis of their origin into two general types; igneous and sedimentary. The Tower itself is composed of igneous rock; that is, rock formed directly by cooling and crystallization of once molten materials. The rocks exposed in the remainder of the Monument are sedimentary; that is, they were formed by the consolidation of fragmental materials derived from other rocks or accumulations of chemical precipitates that were deposited either on the floors of prehistoric seas or near the shores of such seas. These rocks, which crop out around the igneous mass, are layers of shale, sandstone, siltstone, mudstone, gypsum, and limestone. Devils Tower owes its impressiveness to the differing rates of erosion of these rock types—the soft sedimentary rocks erode more easily than the hard igneous rock—and to the contrast of the somber color of the igneous column to the brightly colored bands of sedimentary rock that surround its base.

DEVILS TOWER

Devils Tower rises steeply for about 600 feet from a broad talus slope at its base. The top of the Tower, at an altitude of 5,117 feet, is about 1,270 feet above the Belle Fourche River. The Tower is about 800 feet in diameter at the base. The sides rise almost vertically from the base for a distance of from 40 to 100 feet and then slope in more gently to form a narrow bench. Above this bench, the sides again rise steeply, at angles of 75° to over 85°, to within about 100 feet of the top where the angle becomes less steep and the top edge of the Tower is somewhat rounded. The top of the Tower is almost flat and measures about 180 feet from east to west and about 300 feet from north to south.

One of the most striking features of the Tower is its polygonal columns (fig. 53). Most of the columns are 5 sided, but some are 4 and 6 sided. The larger columns measure 6 to 8 feet in diameter at their base and taper gradually upward to about 4 feet at the top. The columns are bounded by well-developed smooth joints in the middle part of the Tower, but as the columns taper upward, the joints between them, rather than being smooth, may be wavy and some of the columns may unite. Numerous cross-fractures in the upper part of the Tower divide the column into many small irregularly shaped blocks (fig. 53*A*).

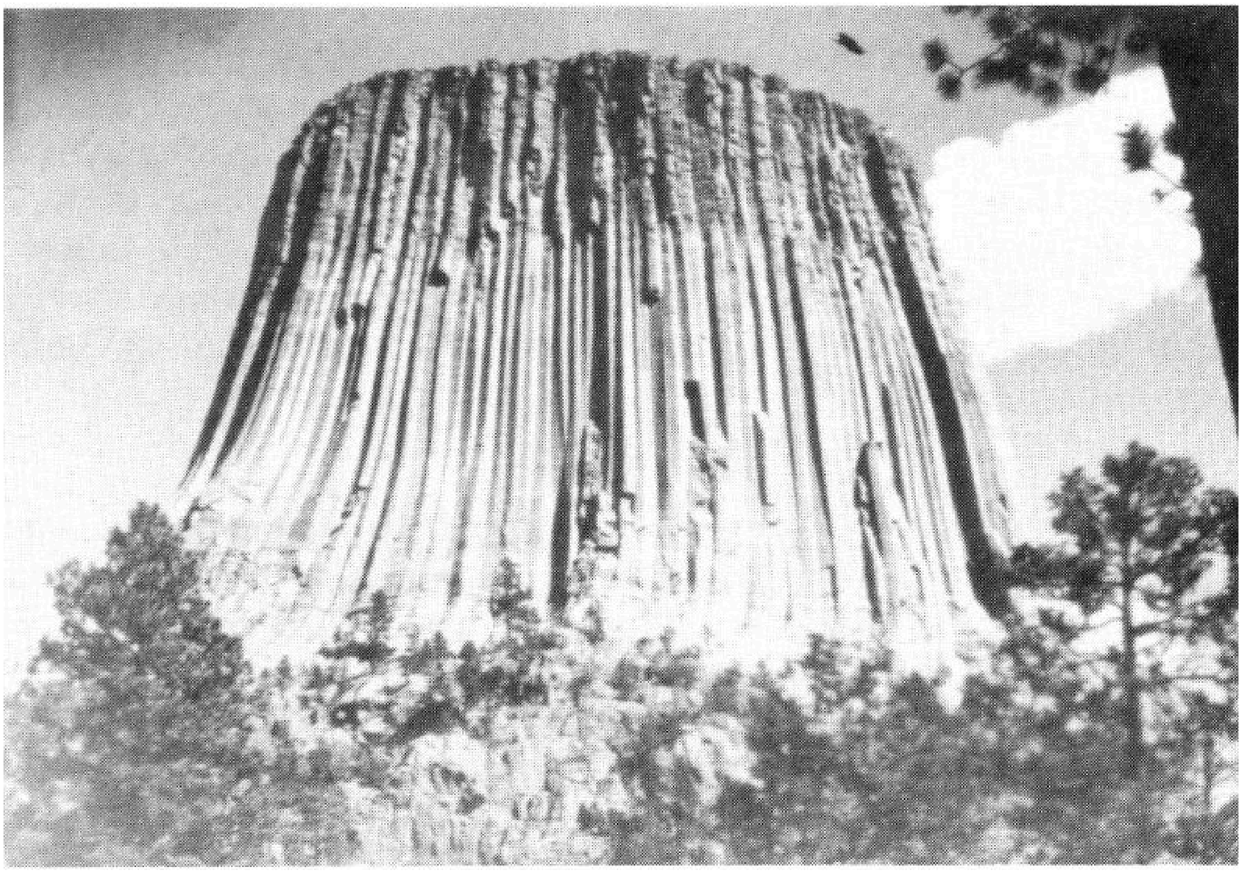


FIGURE 53.—A. Northwest side of Devils Tower showing how the columns taper or converge and in places unite near the top and are cut by numerous cross-fractures.

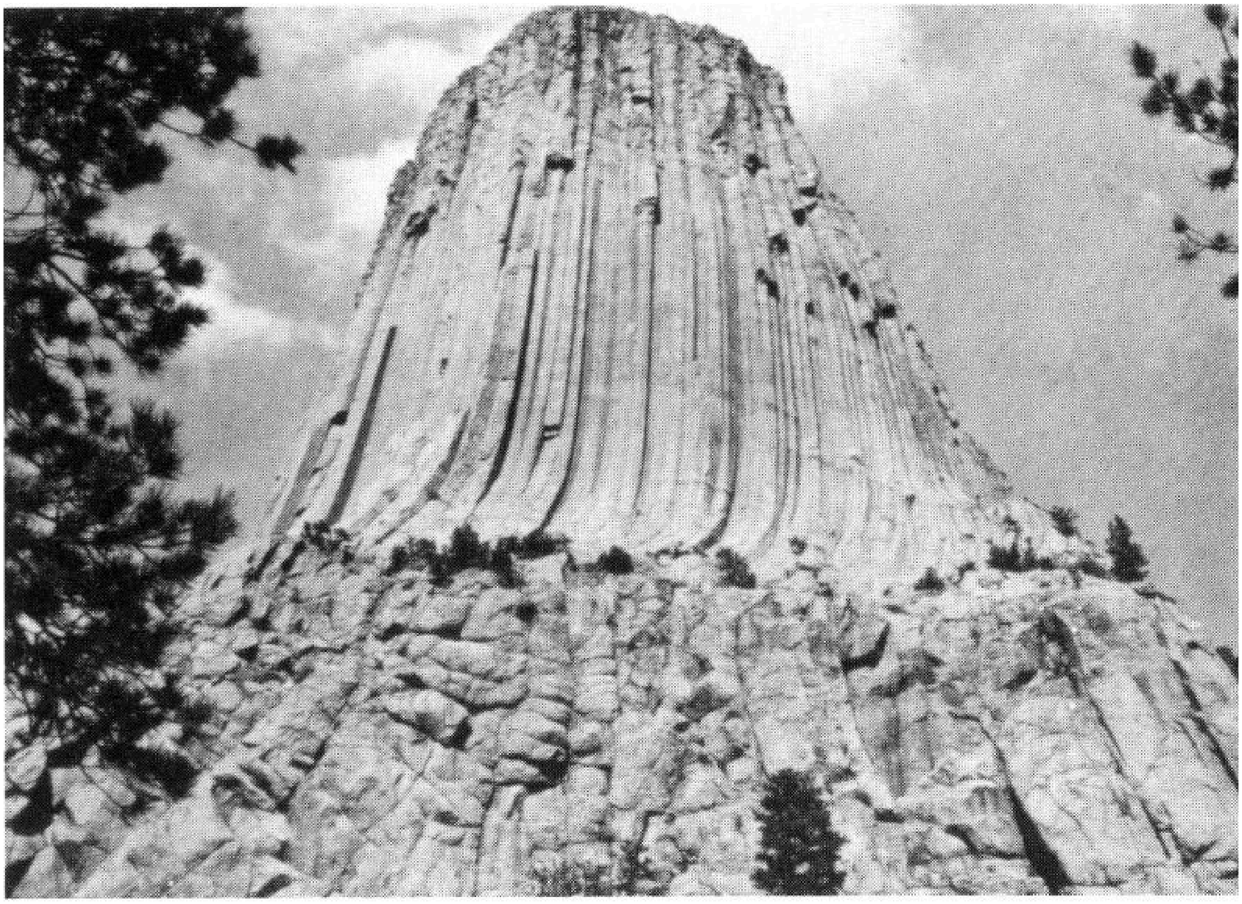


FIGURE 53.—B. Southwest corner of Devils Tower showing the columns flaring out and merging to form the massive base.

The columns in the central and upper parts of the Tower are almost vertical but flare out at the bench about 100 feet above the base (fig. 53*B*). On the southwest side the columns are nearly horizontal. Where the columns flare out, several columns may join to form a larger, less distinct column that merges with the massive base. 5

At the base of the tower, below the bench, the rock is massive and jointing, poorly developed. Here the joints form large irregularly shaped blocks rather than columns.

Columnar joints form as the result of contraction within a rock mass. In igneous rock the contraction is the result of cooling; that is, the cold solidified rock requires less volume than the same rock when molten. As a rock cools it contracts, and the resulting tension is in a plane parallel to the cooling surface. When rupture takes place, three fractures radiate from numerous centers in the plane parallel to the cooling surface. Ideally, the fractures are at 120° to each other. If the centers were evenly distributed, the fractures from different centers would join forming hexagonal (6 sided) columns. These fractures will go deeper and deeper into the rock as cooling progresses. This condition because of many factors, is seldom attained in nature, so the columns may have 4, 5, 6, or even more sides.

The rock making up Devils Tower is classified as phonolite porphyry (Darton and O'Harra, 1907, p. 6) and is of Tertiary age. The fresh specimens have a light- to dark-gray or greenish-gray very fine-grained groundmass with conspicuous crystals of white feldspar—commonly about one-fourth to one-half inch in diameter—and smaller very dark-green crystals of pyroxene. On the weathered surfaces the phonolite porphyry is a light gray or brownish gray. Lichens growing on the rock may give it a green, yellowish-green, or brown color.

Using a microscope, Albert Johannsen (Darton and O'Harra, 1907, p. 6) identified the feldspar crystals as a soda-rich orthoclase and the pyroxene crystals as augite with an outer zone of aegirite. In addition, phenocrysts of apatite and magnetite, were identified. The groundmass, according to Johannsen, consists of orthoclase laths in subparallel arrangement, needles of aegirite, possibly some nephelite, small cubes of magnetite, and secondary minerals of calcite, kaolin, chlorite, analcite, and a anisotropic zeolite.

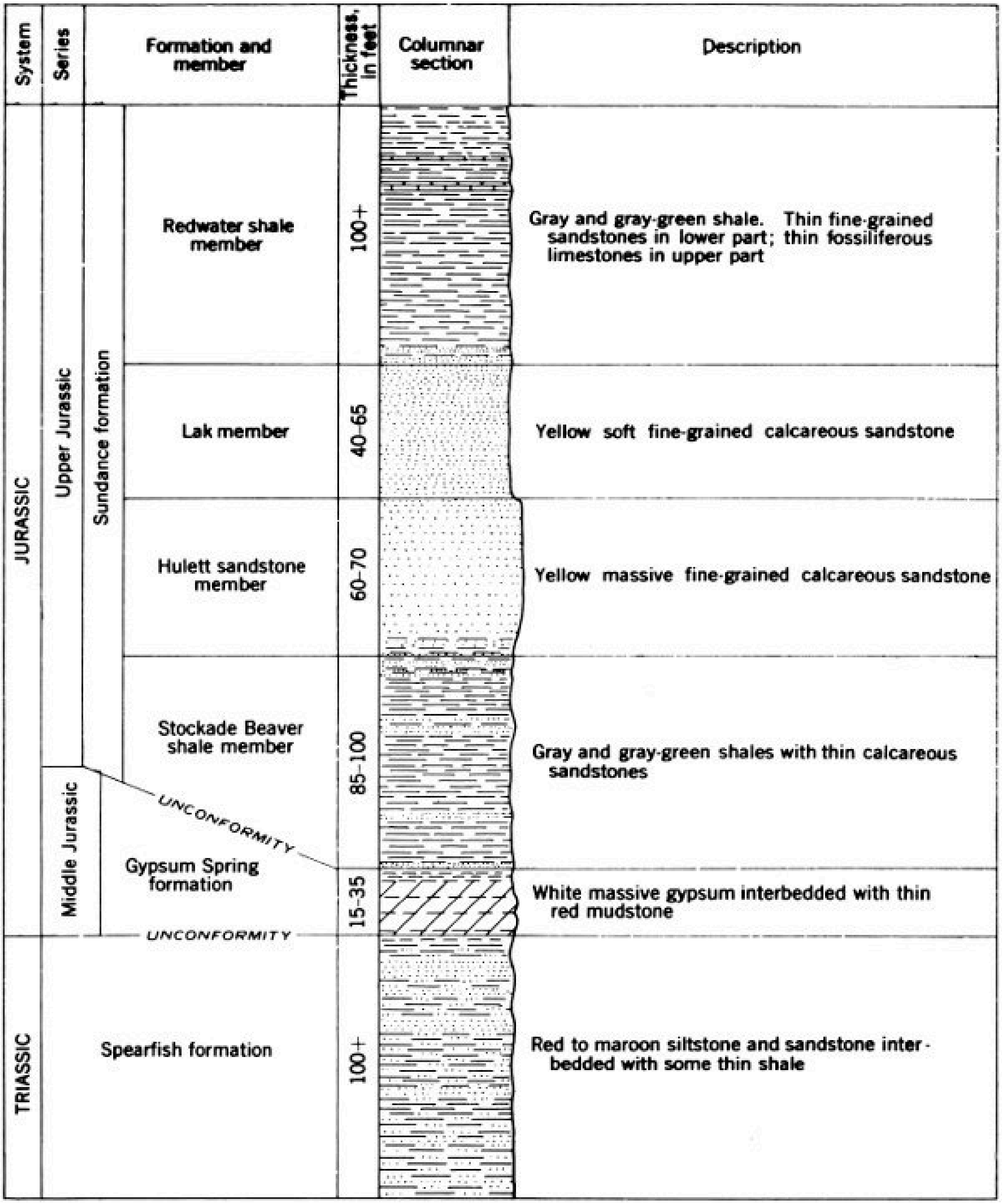


FIGURE 54.—Generalized section of the sedimentary rocks of the Devils Tower National Monument.

SEDIMENTARY ROCKS

The sedimentary rocks that surround Devils Tower have a total exposed thickness of about 400 feet. They are divided, from oldest to youngest, into the Spearfish formation of Triassic age, the Gypsum Spring formation of Middle Jurassic age, and the Sundance formation of Late Jurassic age (fig. 54).

SPEARFISH FORMATION

The Spearfish formation crops out in the southern and northeastern parts of the Devils Tower National Monument along the valley of the Belle 7
Fourche River and its tributaries and forms conspicuous brownish-red to maroon cliffs that border the Belle Fourche valley for several miles in the Devils Tower region. The formation is 450 to 600 feet thick in the northern Black Hills area (Darton, 1909, p. 28); however, only the uppermost 100 feet are exposed within the National Monument.

The Spearfish formation consists of red to maroon siltstone and sandstone interbedded with mudstone or shale. Locally, greenish-blue shale partings are found in the siltstone and sandstone. The formation is poorly cemented and weathers very easily forming, for the most part, gentle slopes, as on the northeast and southwest sides of the monument. Where it does form cliffs, as south of the Tower, the cliffs are cut by many sharp gullies.

No fossils have been found in the Spearfish formation in the Devils Tower region, but elsewhere in Wyoming, stratigraphically equivalent rocks contain land vertebrates of Triassic age.

GYPSUM SPRING FORMATION

The Gypsum Spring formation is exposed in a thin but almost continuous band around the Tower on the southwest to northeast sides. It also crops out near the top of the small hill at the eastern boundary of the National Monument, a few hundred feet north of the Registration Building. This formation is composed mostly of white gypsum, which stands out conspicuously between the red beds of the underlying Spearfish formation and beds of gray-green shale at the base of the overlying Sundance formation.

The Gypsum Spring formation ranges in thickness from about 15 to about 35 feet. It is thickest on the hill at the eastern boundary of the Monument. Here the formation is made up of a lower unit consisting of a bed of white massive gypsum 20 feet thick overlain by 14 feet of interbedded white gypsum and dark-maroon mudstone. The formation is 15 feet thick along the cliff directly south of Devils Tower. At this place, the formation consists of 12 feet of white massive gypsum interbedded with 1-6 inch thick beds of dark-maroon mudstone overlain by 3 feet of dark-brownish-red mudstone. The differences in thickness are primarily the result of erosion of the Gypsum Spring formation prior to the deposition of the Stockade Beaver shale member of the Sundance formation (Imlay, 1947, p. 243).

SUNDANCE FORMATION

The Sundance formation consists of an alternating sequence of greenish-gray shale, light-gray to yellowish-brown sandstone and siltstone, and gray limestone. The formation crops out above the gypsum and red shale of the Gypsum Spring formation on the bluffs and low rolling hills that surround the Tower. The formation consists of four members that are, in order of 8
age from oldest to youngest, the Stockade Beaver shale member, the Hulett sandstone member, the Lak member, and the Redwater shale member (fig. 54) (Imlay, 1947, p. 227-273).

Stockade Beaver shale member.—In general, this member, because it is composed mostly of shale, is poorly exposed. The best exposures of the lower part are on the hill at the east boundary of the Monument and along the steep slope south of the Tower. The upper part is fairly well exposed on the south side of the ridge north of the Tower, near the north boundary of the Monument. The member has a thickness of 85 to 100 feet.

The composition differs considerably in detail from one exposure to another, but in general it consists of gray-green shale with interbedded fine-grained calcareous sandstone. At the base of the member, at nearly all exposures, is a thin sandstone, 1 to 24 inches thick, containing black or dark-gray water-worn chert pebbles that have a maximum dimension of about 2 inches. Above the basal sand, the lower half of the member is composed mostly of gray-green shale, which locally contains some interbedded fine-grained calcareous sandstone, thin sandy and shaly limestone or dolomitic limestone, and rarely thin beds of red mudstone. The upper half of the member consists of dark-gray to gray-green shale with interbedded fine-grained calcareous sandstone that range from less than 1 foot to 6 feet in thickness.

The contact of the Stockade Beaver shale member with the overlying Hulett sandstone member is gradational. The sandstone becomes more abundant in the upper part of the Stockade Beaver shale, and the contact between those two members is placed at that point where the sandstone makes up more than 50 percent of the rocks.

Hulett sandstone member.—The Hulett sandstone member is resistant to weathering and forms a conspicuous, almost vertical, cliff that nearly encircles the Tower. This member ranges in thickness from about 60 to 70 feet.

The Hulett sandstone member consists, in general, of massive fine-grained glauconitic calcareous sandstone. It is typically yellow or brownish yellow but locally may be pink or red. In the lower 5 to 10 feet the sandstone is in beds from less than 1 inch to 2 feet thick separated by gray or greenish-gray shale partings of from less than 1 inch to 6 inches thick. Many of the sandstone beds at the base of the member are ripple marked.

The 50 to 60 feet in the middle of the member consists of massive beds that range in thickness from 5 to 20 feet. This portion is well cemented and forms the conspicuous cliff seen throughout the area. The upper 5 to 10 feet is thin bedded (beds from less than 1 inch to 6 inches in thickness) locally
shaly, and poorly cemented. This grades upward into the overlying sandstone and siltstone of the Lak member.

Lak member.—The Lak member crops out above the cliff of Hulett sandstone that almost encircles the Tower, and it underlies a broad rolling area in the northwestern part of the Monument. The member is rarely exposed because it is composed of soft sandstone and siltstone that usually weather to gentle slopes and become covered with vegetation. The best exposure is on the steep hill east of the Tower and northwest of the bridge across the Belle Fourche river.

This member is 65 feet thick a few hundred feet east of the Tower, but mapping within the Monument and measured sections within a few miles of the Monument indicate that the average thickness is about 45 feet.

The Lak member is typically poorly bedded soft, very fine-grained calcareous sandstone and siltstone with a few thin gray-green sandy shale partings. At the base and near the top of the member may be a few thin (less than 1 inch to 6 inches thick) well-cemented sandstone beds that form small ridges. The sandstone and siltstone grade almost imperceptibly from one to the other. The color ranges from light yellow brown and yellow to red. In the Devils Tower area, shades of yellow and yellowish brown are most common.

The contact of the Lak with the overlying Redwater shale member can be observed only in the exposure east of the Tower. Here, the upper 3 feet of the Lak is a yellowish-brown calcareous silty sandstone with a few discontinuous sandy shale partings (less than 1 inch thick), and the lower 3 feet of the overlying Redwater shale consists of dark-gray-green shale with interbedded, thin silty sandstone.

Redwater shale member.—This member encircles Devils Tower, but at most places it is covered by talus from the Tower. Even where it is not covered by talus, it is poorly exposed. It consists mostly of shale that weathers into gentle slopes, which are usually covered by vegetation. The Redwater shale is partly exposed on Fossil Hill, northwest of Devils Tower, and on the hill in the northwest corner of the Monument. The best exposures are on Fossil Hill.

The top of the Redwater shale member is not exposed within the limits of the Monument; consequently, the thickness could not be determined. In surrounding areas the Redwater shale ranges in thickness from 150 to 190 feet. It is at least 100 feet thick on the hill in the northwest corner of the Monument.

The Redwater shale consists mostly of light-gray to dark gray-green soft shale. In the lower 20 or 30 feet are beds of yellow soft sandstone, 3 inches to 2 feet thick. In the upper part, ranging from 50 feet above the base to the top, are lenticular beds of fossiliferous limestone 1 inch to 4 feet thick. Two such beds of fossiliferous limestone are exposed on Fossil Hill.

The Sundance formation contains clams, oysters, belemnites (squids), and other marine fossils that establish its age as Late Jurassic (Imlay, 1947, p. 244-264).

STREAM TERRACE DEPOSITS AND ALLUVIUM

Stream deposits (alluvium) are found in the valleys of the small streams around the Tower and, in particular, in the valley of the Belle Fourche River, that cuts across the southeast corner of the Monument. The deposits consist of unconsolidated gravel, sand, silt, and mud.

Along the Belle Fourche River, northwest of the river and between it and the main road, the river cut a terrace in the Spearfish formation. On the terrace were deposited gravel and sand.

TALUS AND LANDSLIDE MATERIAL

The talus and landslides are composed primarily of the material from the Tower and the Hulett sandstone.

Talus from the Tower forms a broad apron that completely surrounds the Tower. The talus extends from high on the shoulders of the Tower down to and across the sedimentary rock. Locally, landslides of this talus have extended through valleys in the sedimentary rock down almost to the level of the surrounding streams. The talus from the Tower is composed of fragments of the columns that range from a few inches in diameter to large sections of the columns as much as 8 feet in diameter and 25 feet long.

The cliff of Hulett sandstone that surrounds the Tower breaks off into rectangular blocks that form talus slopes at the base of the cliffs and locally large landslides down the hill below the cliffs. These blocks of Hulett sandstone range in size from a few inches to many feet in diameter. The talus material from the Tower has at several places overlapped the cliff of Hulett sandstone and become mixed with the material from the cliff.

About 1,400 feet north of the Tower are two patches of what is believed to be talus formed from sedimentary rocks that once surrounded the Tower. The talus consists of fragments of medium-grained brownish-white sandstone and, what is apparently, a highly silicified gray or white fine-grained quartzite. The sandstone resembles that found in the Lakota (Darton and O'Hara, 1907, p. 3) that lies about 200 feet stratigraphically above the Redwater shale in the area west of the Monument.

The sandstone and quartzite occur in angular blocks that range from less than 1 inch to several feet in diameter. The spaces between the blocks are filled with a yellowish or brownish-white sand.

The Lakota sandstone at one time surrounded the Tower and it is believed that these blocks are residual blocks that have not been removed by erosion.

STRUCTURE

The sedimentary rocks in the National Monument, and in the surrounding area, are gently folded into many small rolls, basins and domes, which locally are cut by faults of small displacement. These small folds are superimposed on a large dome that is collapsed in the middle.

Devils Tower is near the middle of the collapsed dome. From one-half to about a mile from the Tower the sedimentary rocks dip gently from 2° to 5° away from the Tower to form a broad dome. Within a radius of about 2,000 to 3,000 feet of the Tower, the dips change, and the rocks dip, in general, from 3° to 5° towards the Tower to form a shallow structural basin. In the basin itself and on the dome are several small folds. As an example, Spring No. 1 southwest of the Tower is in the center of a comparatively sharp syncline or down-fold at the edge of the basin. Fossil Hill northwest of the Tower is another small structural basin. The beds along the top and on the north side of Fossil Hill dip from 12° to 52° S. Those on the south side of the hill, north of the road, apparently dip very gently northward.

Three faults were observed in the area of the National Monument. Two of the faults are in the Hulett sandstone west of the main road and west of the Tower, and the third is in the northwestern side of the Tower near its base (pl. 30). The faults in the Hulett sandstone are probably vertical, and the displacement along them is believed to be less than 10 feet. The fault at the base of the Tower is a low-angle fault that trends northwesterly. The attitude of this fault at the point where it disappears below the talus is: strike, N. 41° W.; dip, 21° NE. The fault zone is 4 to 12 inches wide and is filled with a yellowish-green clay and sheared fragments of altered phonolite porphyry. The rock of the Tower below this fault is somewhat altered; the groundmass is a light greenish gray, and the normally shiny crystals of feldspar have a dull earthy luster.

GEOLOGIC HISTORY

The geologic history of the Devils Tower area is part of that of the Black Hills region. The uplift of the Black Hills and the subsequent erosion have exposed the rocks, from which the geologic history of the area may be interpreted.

Most of the rocks within the area around the Black Hills are composed of sediments deposited by water. These sedimentary rocks, which overlie much older rocks (Precambrian), were deposited in a series of successive layers during time intervals from the Cambrian period to well into the Tertiary period. Deposits in the ancient seas are represented by limestone, shale and some sandstone; deposits on low lands adjacent to seas, as flood plains 12
and deltas, by sandstone, siltstone, and some mudstone; and deposits along streams by conglomerate, sandstone and siltstone. Between the periods of deposition were intervals when the land was relatively high, and in certain areas all of the sediments of an earlier period were eroded away.

The oldest formation exposed in the National Monument, the Spearfish formation, was deposited during Triassic time along flat lands bordering the sea. Arms of the sea locally invaded the area to leave deposits of gypsum, which are found near the base of the Spearfish in areas outside the National Monument. The Gypsum Spring formation was deposited in the sea in Middle Jurassic time following a period of uplift and erosion that occurred after the deposition of the Spearfish formation. After the Gypsum Spring formation was deposited, the sea retreated, and another period of erosion followed before Late Jurassic time when the sea invaded the area again and the Sundance formation was deposited. The depth and conditions for deposition in this sea changed from time to time, as shown by the alternating beds of shale and sandstone in the Sundance formation.

Following the deposition of the Sundance formation, there were several periods when the area was above sea level and when the sea covered the area. During the periods when it was above sea level, the higher land was eroded, and the sediments deposited at a lower level. When the area was covered by the sea, marine sediments, principally shales, were deposited. Near the end of the Cretaceous period, the sea made its final withdrawal, and the sediments from late Cretaceous time to the present were deposited in fresh water.

The Black Hills uplift developed primarily during early Tertiary time, although it may have started in very late Cretaceous time. At this time the present general structural features of the Black Hills area were developed, and, probably, the igneous rocks, such as Devils Tower, were intruded (Jaggar, 1901, p. 266). Following this, the Black Hills area was repeatedly uplifted, and erosion exposed the older sedimentary and intrusive rocks. Even today streams continue to strip more and more rock from the country, leaving only local deposits, such as alluvium and terrace deposits, along the valleys.

ORIGIN OF DEVILS TOWER

The origin of Devils Tower has been a matter of speculation for many years, and even today after detailed geologic mapping of the area, no conclusive proof of its mode of origin can be presented.

Several theories of the origin have been proposed. One of the more popular of these is that it is the neck of an extinct volcano (Carpenter, 1888; Dutton and Schwartz, 1936). Another theory is that Devils Tower and Missouri Buttes (a mass of the same type of rock about 4 miles northwest of the 13
Tower) are the remnants of a laccolith (a tabular intrusive igneous body, thickest in the middle, and with a relatively level floor), the vent for which was under Missouri Buttes (Jaggar, 1901, p. 264). Darton (1901, p. 69) believed that the Tower is the remnant of a laccolith, smaller than the one proposed by Jaggar, the feeding vent for which was underneath the Tower.

Much more detailed geologic work will have to be done in the surrounding area before the mode of origin of Devils Tower may be proved conclusively. The evidence gathered during the present investigation, however, suggests that Devils Tower is a body of intrusive igneous rock, which was never much larger in diameter than the present base of the Tower, and which at depth (1,000 feet or more) is connected to a sill or laccolith type body. The bases for this theory are—

1. The exposed portion of the Tower is the result of recent erosion. At the time of its intrusion it was surrounded and probably covered by several hundred feet of sedimentary rock.
2. The mineral composition and texture are more typical of shallow intrusive rocks, which are formed at depth, than extrusive rocks, which are formed on the surface.
3. No evidence of extrusive igneous activity has been found in the surrounding area.
4. Missouri Buttes, about 4 miles to the northwest, and the Tower have the same composition so it is assumed that they were derived from a common

magma; possibly the magma of a large intrusive body, such as a laccolith or sill.

5. In a well drilled about 1½ miles southwest of Missouri Buttes, near the center of a structural dome, rock similar to the Tower and Missouri Buttes was encountered at about 1,400 feet below the base of Missouri Buttes. Inasmuch as the thickness of the sedimentary rocks in this area is normally much greater than this depth, the rock in the drill hole probably represents an intrusive body, rather than the Precambrian igneous rocks upon which the younger sedimentary rocks were deposited.
6. The relatively small amount of talus, slope wash, or terrace gravel derived from the Tower and Missouri Buttes suggests that they have not been extensively eroded, and therefore the original igneous bodies were not much larger than at present.
7. Columnar jointing is common in intrusive bodies formed at comparatively shallow depths.

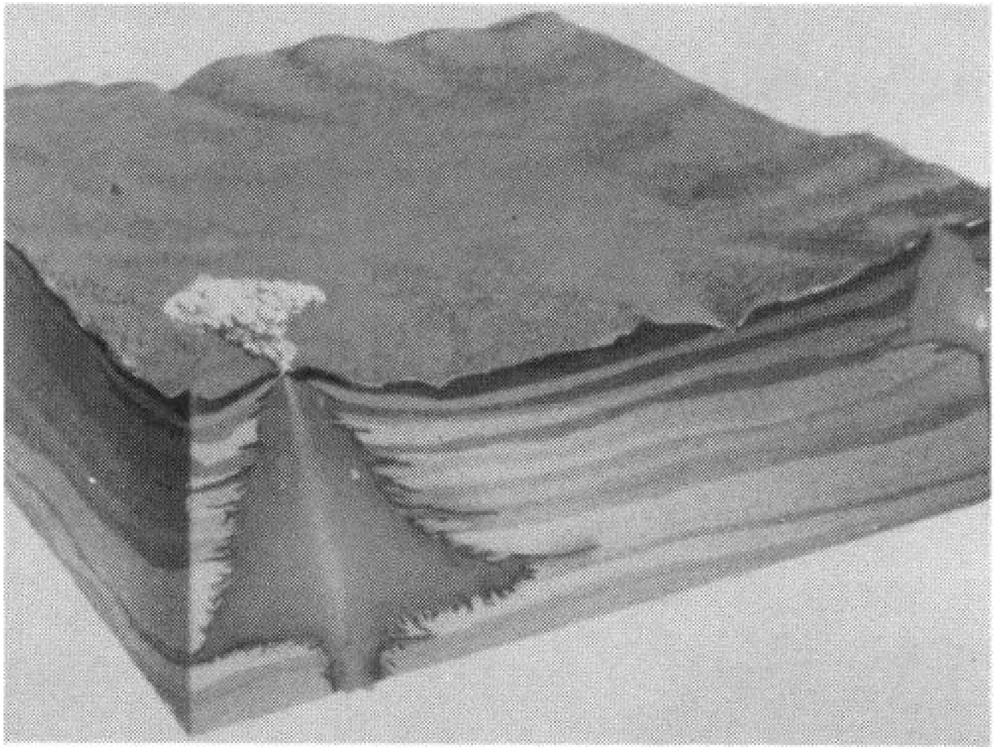
The following new material has been added to this booklet by the National Park Service (Devils Tower National Monument, 1985)

The most recent in depth, geologic study of Devils Tower was done by Don L. Halverson (1980) and presented in a dissertation, to the Graduate Faculty of the University of North Dakota.

He stated that, "The Missouri Buttes and Devils Tower, however, are necks of extinct volcanoes which have been exposed by erosion. This theory was first proposed by Carpenter (1888) and later expanded by Dutton and Schwartz (1936). The material which fed these volcanoes came from a minimum depth of 18 km. Evidence for this conclusion is listed in the following statements:

1. The alloclastic breccia in the vicinity of Devils Tower and the Missouri Buttes is definitely igneous in origin and probably represents periods of violent eruption.
2. A very definite similarity exists between these two features and the volcanic necks in the Taylor Mountain area of New Mexico.
3. The distinctive columns with basal flare are also found in the volcanic necks of the Taylor Mountains (Dutton and Schwartz 1936), but have not been reported in columnar-jointed laccoliths.

4. The Missouri Buttes and Devils Tower were intruded directly through horizontal sediments without disrupting them, even in the immediate vicinity of the igneous bodies.
5. Recent research indicates that many of the laccolithic intrusions in the Black Hills region may have been less passive than previously considered. Sundance Mountain may be a mixed volcanic cone consisting of welded ash fall, massive quartz latite, and ash flow tuffs. Nearby Sugarloaf Mountain is composed of layered tuffs (Fashbough 1979).
6. Collapse of materials into partly evacuated reservoir chambers accounts for the depressions surrounding the Missouri Buttes and Devils Tower. The 90 m of depression at the southern end of the Buttes is difficult to explain with a laccolithic model.
7. Flow directions deduced from oriented thin-sections and field observations indicate mostly vertical flow. It must be noted that in both igneous bodies orientation of some grains is horizontal; this could, however, simply indicate turbulent flow.
8. The stability field for the analcime-liquid system is 5 kbar minimum (Roux and Hamilton 1976), which indicates that the original melt of Devils Tower and Missouri Buttes rock had to originate at a minimum depth of 18 km.
9. It is unlikely that magma which had ascended from great depths and had just penetrated the resistant Hulett Member of the Sundance Formation, as well as the Lakota and Fall River Formations, would be stopped abruptly by the less resistant shales above. When the magma reached the shale beds, the weight of the column of igneous rock could have exceeded the strength of the shale, causing the magma to flow horizontally. No indication of horizontal spread, however, is observed. The continuously cylindrical shape of the intrusions indicates that the magma moved steadily upward and probably reached the surface.
10. Carbonatites have been found, and formally reported, in the nearby Bear Lodge Mountains, and also as fragments in the alloclastic breccias of the Missouri Buttes. Their presence suggest a high volatile content for the magma and the possibility of explosive volcanism."



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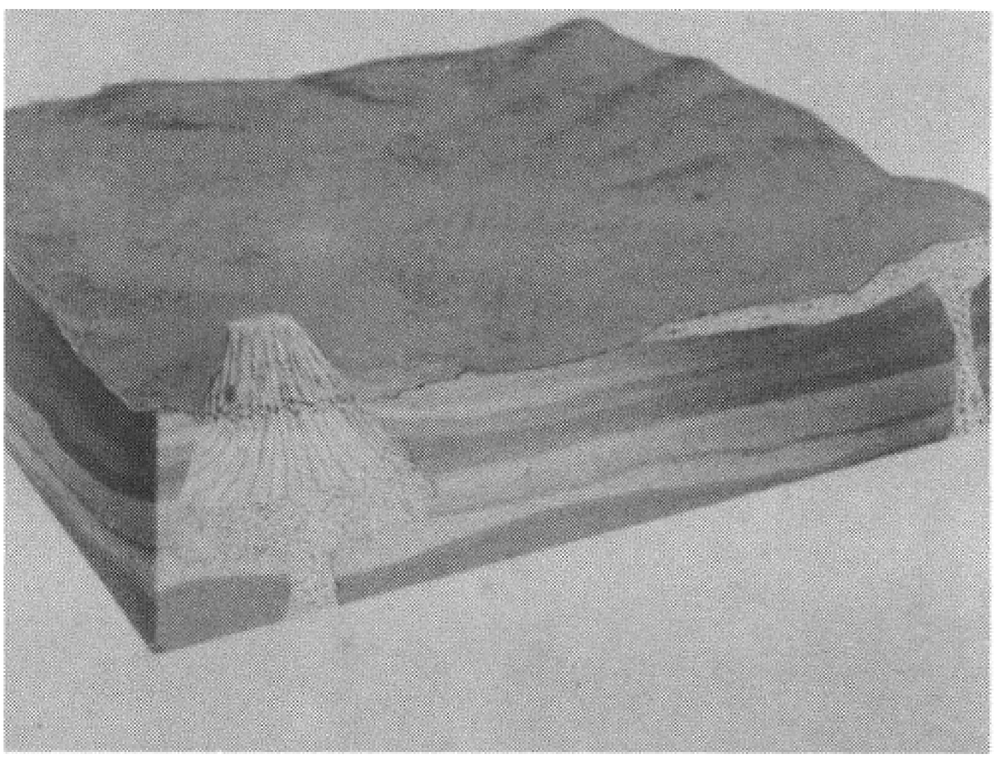

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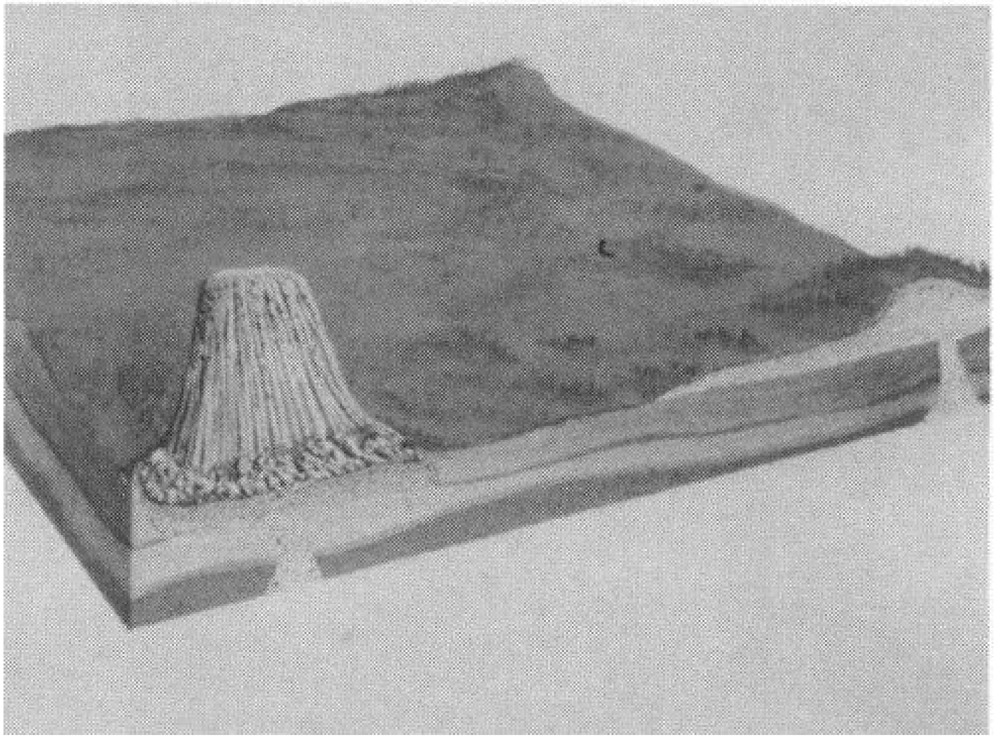

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