THE FALL OF THREATENING ROCK

S. A. SCHUMM* and R. J. CHORLEY**

ABSTRACT. In 1941 a huge monolith of Cliff House Sandstone toppled and damaged a portion of the ruins of Pueblo Bonito, Chaco Canyon, New Mexico. For 5 years prior to the fall of the rock, measurements of its movement had been made by National Park Service personnel. These data indicate that the movement of the rock was an exponential function of total precipitation and that the rate of movement was seasonal, being relatively faster during the winter. It is estimated that the rock began moving away from the cliff at about 550 B.C.; therefore, the movement and collapse of the rock may be considered a contemporary process.

INTRODUCTION

On January 22, 1941, Threatening Rock, or Braced-up Cliff as it was known to the Navajo Indians, finally fell. This monolith of Cliff House Sandstone, which rose behind the ruins of Pueblo Bonito in Chaco Canyon National Monument, New Mexico, was a source of concern to the National Park Service personnel, as it had been to the inhabitants of Pueblo Bonito in the eleventh century, who had taken steps to stay its fall (pl. 1-A). This primitive effort in preventive engineering and the threat that the rock presented to Pueblo Bonito caused it to be one of the most famous rocks in the Colorado Plateau region.

Because of the concern that fall of the rock would severely damage Pueblo Bonito, National Park Service personnel began in 1935 to measure the distance between the rock and the cliff from which it had been detached. The measurements were continued until the fall of the rock in 1941 and are recorded in the Superintendent’s Monthly Narrative Reports at Chaco Canyon National Monument. These data will be used here to document the movements of Threatening Rock before its fall and to provide information on the type of movement, its rate, and the approximate time of the origin of the movement.

The courtesy and assistance of the National Park Service personnel at Chaco Canyon National Monument are gratefully acknowledged. In particular, the assistance of Lynn A. Robbins made the collection of data on movement of the rock an easier and more enjoyable task. Mr. Robbins and M. S. Johnston of the National Park Service and R. F. Hadley, Geological Survey, have reviewed the manuscript.

DESCRIPTION OF CHACO CANYON

Chaco Canyon is located in northwestern New Mexico on the upper Chaco River, a tributary of the San Juan River (fig. 1) at an altitude of about 6200 feet. within the Navajo Section of the Colorado Plateau physiographic province. The canyon has been cut through the Cliff House Sandstone, the upper formation of the Mesaverde Group in this area and into the underlying Menefee

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Formation, both of Late Cretaceous age. The formations dip north and east at about 2 degrees.

The Cliff House Sandstone, which at present forms the main canyon walls, is composed of two massive sandstone units separated by a thinly-bedded sandstone unit, which is associated with a topographic bench. The upper unit of the Cliff House Sandstone has weathered into rounded forms, contrasting strikingly with the vertical cliffs supported by the lower sandstone unit. This lower sandstone unit is about 140 feet thick, and the whole of the Cliff House Sandstone is about 369 feet thick (Bryan, 1954). The lower unit of the Cliff House Sandstone is intersected by widely-spaced joints, and this mechanically weak (unconfined compressive strength is only 2500 psi) and permeable (porosity is about 28 percent) rock forms a relatively unbroken line of ragged cliffs on the north side of the river.

The underlying Menefee Formation is composed of shale with thin sandstone and coal members. On the south side of the canyon the Menefee Formation is exposed from 50 to 100 feet above the canyon floor (pl. 1-B). The shale is exposed less in the north wall of the canyon, where the position of the top of the shale varies from slightly above to below the alluvium of the canyon floor.

In the vicinity of Pueblo Bonito the width of Chaco Canyon ranges from half to three quarters of a mile. At least 40 feet of Recent alluvium lies within the canyon. During the last 100 years, this alluvium has been trenched to a depth of 20 to 30 feet by the Chaco River (Bryan, 1954).

Along the north wall of the canyon huge joint blocks of the Cliff House Sandstone can be observed in the various stages of detachment from the cliff.

Fig. 1. Index map of Chaco Canyon National Monument.
The Fall of Threatening Rock

(pl. 1). Bryan (1954, p. 19) has proposed that the erosion of this cliff is due to rainwater passing down through the porous Cliff House Sandstone and seeping out at the basal junction with the Menefee Formation, particularly where this junction lies at or above the alluvial valley fill. This natural undermining causes the Cliff House Sandstone joint blocks to become detached, move away from the cliff face, settle, and collapse (pl. 1-A, C, D). The movement of the joint blocks away from the cliff allows other joints to open up some distance back from the face of the cliff.

Average precipitation at Chaco Canyon is 8.29 inches (U. S. Dept. Agr. 1941, p. 1014), although it averaged about 9 inches during the 5 years when rock movement was measured (table 1). Generally, more precipitation falls during the summer than during winter months. Killing frosts occur during 7 months of the year (table 1), and snowfall is common during the winter months.

**Table 1**

Climatological data 1936-40 Chaco Canyon National Monument
(from U. S. Weather Bureau 1935-41)

<table>
<thead>
<tr>
<th>Year</th>
<th>Annual precipitation (inches)</th>
<th>Snowfall (inches)</th>
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</thead>
<tbody>
<tr>
<td>1936</td>
<td>9.66</td>
<td>15.0</td>
</tr>
<tr>
<td>1937</td>
<td>7.78</td>
<td>12.5</td>
</tr>
<tr>
<td>1938</td>
<td>9.06</td>
<td>23.8</td>
</tr>
<tr>
<td>1939</td>
<td>7.71</td>
<td>24.3</td>
</tr>
<tr>
<td>1940</td>
<td>12.18</td>
<td>2.2</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Year</th>
<th>Date of last killing frost</th>
<th>Date of first killing frost</th>
</tr>
</thead>
<tbody>
<tr>
<td>1936</td>
<td>May 1</td>
<td>Sept. 29</td>
</tr>
<tr>
<td>1937</td>
<td>*May 1</td>
<td>Sept. 26</td>
</tr>
<tr>
<td>1938</td>
<td>May 23</td>
<td>Oct. 17</td>
</tr>
<tr>
<td>1939</td>
<td>June 18</td>
<td>Oct. 2</td>
</tr>
<tr>
<td>1940</td>
<td>May 2</td>
<td>*Oct. 10</td>
</tr>
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</table>

* Estimated.

**THREATENING ROCK**

Threatening Rock was a block of Cliff House Sandstone 150 feet long, 100 feet high, and about 30 feet thick, weighing about 30,000 tons (Judd, 1959). Prior to its fall, it rested on a base of shale of the Menefee Formation. An earth and masonry terrace had been constructed by the Indians to prevent erosion at the base of the rock and to support it. Trees wedged beneath the rock by the Bonitians were dated at 1057 and 1004 A.D. (Judd, 1959).

Threatening Rock (pl. 1-A) was described by Keur in 1933 (ms) as "... now entirely detached from the cliff. It is slightly wedge shaped, with its greatest width at midheight. The vertical split between the rock and the canyon wall is from 10 to 12 feet wide at the top and from 3 to 4 feet at the base. This
A. Threatening Rock before its fall. Note rubble from pre-1877 rock fall and wall of Pueblo Bonito on lower left (National Park Service photograph).

B. Threatening Rock after its fall. The rock broke into numerous fragments on impact. Ruin of Pueblo Bonito is at foot of rock fall. The arroyo of the Chaco River and the south wall of Chaco Canyon are visible in the background.
C. Monoliths of Cliff House Sandstone tilting to west (left) at rear of Hungo Pavie ruin, Chaco Canyon National Monument.

D. Separation of monoliths of Cliff House Sandstone from canyon wall along joints. About 100 feet of sandstone is resting on shale, sandstone, and coal of the underlying Menefee Formation, Chaco Canyon National Monument.
difference in width at top and base is not entirely due to the leaning forward of the rock but rather to the weathering and loosening of smaller sandstone blocks from the surfaces of the cleft. The space between rock and canyon wall is partly filled with these loosened rocks . . . " Keur pointed out that not only had the rock moved out from the cliff but that it had settled about 8 inches.

"The front part of the rock shows a fairly uniform though weathered surface. One large vertical crack, 40 feet from the east end, is visible extending from top to base. Several other smaller cracks are present in the front surface. The base of the rock is far from uniform, showing a deeply extending erosion in spots. This undercutting extends in one place from 14 to 16 feet, which is almost to the gravity axis, the width of the rock at midheight being 34 feet . . . The overhang at the base of the rock is greatest at the west end where over a length of 60 feet the undercut varies from 4 to 15 feet. The overhang of the remaining 110 feet is much less, ranging from 3 to 6 feet" (Keur, ms, p. 2).

Photographs of the rock before it fell (pl. 1-A) suggest that the approximately 100 feet of Cliff House Sandstone rested on about 15 feet of shale, which was exposed beneath the rock. Undoubtedly, both basal weathering of the sandstone and erosion of the shale caused the development of the overhang at the base of the rock.

**MOVEMENT AND FALL OF THREATENING ROCK**

Of interest here are the measurements of the progressively increasing distance between the cliff and the rock made by T. C. Miller and L. T. McKinney, custodians of Chaco Canyon National Monument. The measurements are recorded in the Monthly Narrative Reports of the Superintendent for the years 1935 through 1941. Miller had two steel bars set in concrete in November 1935, one on the cliff and the other on the rock. His first measurement was made 5 months after installation and the second in December 1936. McKinney’s first measurement was made in March 1937, and subsequent measurements were made almost every month until the rock fell in January 1941. Additional measuring points were established in 1936, and all were replaced in 1940. All measurements were made near the top of the rock.

Precipitation records from Chaco Canyon (U. S. Weather Bureau 1935-41) have been used in an attempt to relate weather conditions to rock movement. In figure 2 cumulative rock movement and cumulative precipitation are plotted as a function of time. Although precipitation was well above average during the latter part of 1940, the precipitation curve does not show progressively greater increments with time as does the curve of rock movement. The rock appears to have been stationary for consecutive periods of several months, but for unit increments of time the rock moved progressively farther as time passed. The curve showing rock movement against time of figure 2, therefore, resembles some of the strain-time diagrams obtained by subjecting rocks to uniform stress (Griggs, 1940, fig. 5). The irregularities of the curve of figure 2, however, suggest an intermittent application of stress. Although the movement of Threatening Rock is not analogous to the deformation of a solid, the similarity between the curves, which are characteristic of solid failure under shear or tensile stress and for the movement of Threatening Rock, suggests that
Fig. 2. Cumulative movement of Threatening Rock (solid line) and cumulative precipitation (dashed line) plotted against date of measurement or time. Vertical lines, drawn at dates of first killing frost of the fall and the last killing frost of the spring for the years of record, indicate cumulative movement which occurred during periods of freeze and thaw. Freeze-thaw periods are designated f.
catastrophic geomorphic or erosional events of this type are probably preceded by events of progressively increasing magnitude until failure occurs.

The plot of cumulative rock movement against cumulative precipitation is revealing (fig. 3). When these data are plotted on semi-logarithmic paper, a straight line could be fitted to the plot, indicating that cumulative movement is an exponential function of cumulative precipitation. However, a straight line was not fitted, for it is the irregularities or steps which appear, when the points are connected, that are of interest here. Starting at the lower end of the plot,

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Fig. 3. Relation between cumulative rock movement and cumulative precipitation. Irregular line drawn to connect plotted points is bracketed by dashed spring and fall lines. Data measured in late winter and spring plot near the upper dashed line. Data measured in fall and early winter plot near lower dashed line.
five treads and five risers which comprise a stepped pattern can be counted. It appears then that there were 5 periods when rock movement was relatively rapid and 5 periods when the rock moved relatively less or not at all. If the amount of precipitation falling were the only factor influencing rock movement such variations in the rate of movement might not be expected to occur. The periods of relatively rapid movement (risers) always coincide with winter months.

Daily temperatures were not published for the Chaco Canyon weather station; however, the dates of the first killing frost of the fall and the last killing frost of the spring were recorded (U. S. Weather Bureau, 1935-41). These dates are listed on table 1 with annual precipitation for the years during which measurements of rock movement were made.

The steplike appearance of the plot of figure 3 is recognizable also on the plot of rock movement against date of measurement on figure 2. Figure 2 shows that the most rapid rates of movement occurred between the dates of killing frosts or during the winter, whereas the periods of slight movement occurred during the summer months. This conclusion is in accord with measurements of soil creep made on shale slopes in western Colorado (Schumm, 1964), where frost action was a major factor causing seasonal mass movement.

Seasonal frost action, although effective in promoting surficial creep of the lithosols of western Colorado, could not be expected to be as effective in moving a 30,000 ton block of sandstone. It may be that the opportunities for wetting of the contact between the rock and the shale were greater during the cooler winter months, when evaporation would be less. Probably the higher precipitation of summer, an average of 6.2 inches for each period of least movement on figure 2 in contrast to an average of 3.2 inches for each winter period of greater movement, was less effective in causing wetting of the shales than the snows of winter, an average of 14.6 inches of snow for each period of greater movement on figure 2 in contrast to an average of 1.9 inches for the periods of less movement. A factor which may have been an important cause of seasonal movement was the collection of snow in the space behind the rock. Melting of this snow would wet both the shale beneath the rock and the contact between the sandstone and shale, which would accelerate rock movement. In addition, movement of water along the contact would cause sapping, where it appeared at the front of the rock (Bryan, 1954).

Between December 23, 1940 and January 22, 1941, the rock moved outward 10 inches and settled 4 inches. Previously it had settled about 3 inches between August 1937 and August 1939. The following description of the final movement and fall is abstracted from information supplied by R. C. Heyder, Acting Superintendent at Chaco Canyon National Monument (written communication). On the evening of January 21, 1941, a large rock fragment fell from near the top of Threatening Rock. It was estimated by McKinney that the rock moved outward 9 inches during the night of January 21, probably at 9:15 p.m. when the rock fragment fell. While McKinney was making his regular monthly measurements of rock movement, beginning at 12:40 p.m. on January 22, he could hear the rock popping and cracking, and it moved outward 1/32 inch during his measurement. At 3:24 p.m. Threatening Rock fell
with a sound like distant thunder, and a dust cloud rose about 130 feet into the air.

When the rock fell three Indians were chopping wood about 300 feet southeast of the rock. According to their description as recorded by the National Park Service, "The Indians on the woodpile heard the rock groan and looked up to see dust shooting out of the cracks in it. The slab leaned out about 30 or 40 feet from plumb, settled sharply, and when it hit solid bottom, rocks from the top of it were broken loose and propelled into the ruin. The lower two-thirds then pivoted on its outer edge and fell down the slope toward the ruin. The whole mass broke into many fragments and an avalanche of rocks catapulted down the slope and into the walls of the back portion of Pueblo Bonito" (R. C. Heyder, written communication).

The final measurements by McKinney showed not only an outward movement of 10 inches and a settling of 4 inches but also a westward movement of 14 inches during the final month. Thus the rock was sliding toward the southwest. It is significant that the rock had been undermined to a maximum depth on the west end (Keur. ms). At the point of greatest undermining, as shown on a field sketch prepared by Blom in 1924 and published by Judd (1959), the rock was undermined about 15 feet where it was 32 to 33 feet thick. The additional outward movement of the rock since 1924 was sufficient to reduce greatly the support on the western end.

It is not certain what type of rock movement actually occurred during the period of measurement. The measurements were made near the top of the rock, and it is possible that the movement was a tilting of the rock away from the cliff rather than a movement of the entire rock on the shale base. Keur (ms, p. 2) stated that the distance between the rock and cliff was from 10 to 12 feet at the top but only from 3 to 4 feet at the base. He indicated, however, that much of this difference was the result of weathering at the top of the rock and cliff. In plate 1-A the rock doesn't appear to be leaning away from the cliff to any great extent. The fall of the rock, according to the eyewitness accounts, was a combination of tilting and sliding. The final movements of the rock probably shifted its center of gravity beyond the shale support beneath the overhang and tilting naturally occurred. Nevertheless, the earlier movements appeared to be a combination of settling and movement away from the cliff rather than tilting (McKinney, 1963, oral communication).

**RATE OF MOVEMENT OF THREATENING ROCK**

The movement of the rock during the last 5 years of its reign over Pueblo Bonito has been recorded, showing that the rate increased until the rock fell. It is known that the rock moved outward 10 inches during the month before it toppled and a total of 22 inches during the 5 years preceding its fall. The rock at the base was about 4 feet from the cliff in 1933 (Keur, ms); therefore, the rock must have moved slightly more than 70 inches, about 6 feet in all, away from the cliff before it fell. On figure 4 an attempt has been made to project the existing data backward in time to give an estimate of the duration of time between the initial separation of the rock from the cliff and its final fall, the abscissa of figure 4 being time before fall in years and the ordinate
Fig. 4. Relation between distance to be moved and time before fall of Threatening Rock. For example, one year before the fall of the rock an additional 16 inches of movement was required. Extending the regression line until it intersects the horizontal line representing total rock movement before fall, 72 inches, yields an estimate for the time required for this movement (about 2500 years).
distance to be moved before fall (a maximum of 72 inches). When the data on distance to be moved is plotted on logarithmic paper for the last month, for the 5 years prior to fall, and for Keur’s measurement of 4 feet in 1933, a straight line can be drawn through the points. This straight regression line can then be extended until it intersects the line for 72 inches of movement. When a vertical is dropped from this point of intersection it crosses the abcissa at about 2500 years before 1941 or about 550 B.C., indicating that movement of the rock away from the cliff may have begun at about this date.

Objections can be raised concerning the validity of extending the regression line of figure 4. Its extension is based on the assumption that the climate of the 2500 years prior to the fall of the rock was not greatly different from that of the present and that the engineering effort of the Pueblo Indians did not significantly retard the movement of the rock. Climatic fluctuations must have occurred during the period of the movement of Threatening Rock, but Antevs (1948) has concluded that the climate of this relatively cool and moist period was sufficiently similar throughout to place it in one climatic phase, the Medithermal, lasting from about 2000 B.C. to at least 1850 A.D. In addition, Deevey and Flint (1957) suggest that the warm and dry Hypsithermal interval ended about 600 B.C. when a relatively cooler and moister period began, which would be favorable for rock movement. The effectiveness of the Indians’ structures cannot be evaluated; however, they probably slowed the weathering and erosion of the overhang. What effect this had on the rates of movement it is not possible to evaluate.

From the regression line of figure 4 the time required for each foot of movement away from the cliff can be estimated as follows:

<table>
<thead>
<tr>
<th>Movement</th>
<th>Years required</th>
</tr>
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<tbody>
<tr>
<td>1st foot</td>
<td>1600</td>
</tr>
<tr>
<td>2nd foot</td>
<td>650</td>
</tr>
<tr>
<td>3rd foot</td>
<td>200</td>
</tr>
<tr>
<td>4th foot</td>
<td>60</td>
</tr>
<tr>
<td>5th foot</td>
<td>8.0</td>
</tr>
<tr>
<td>6th foot</td>
<td>0.2</td>
</tr>
</tbody>
</table>

These values are averages that obscure the seasonal nature of the movement of the rock which is clearly shown on figures 2 and 3.

Archeologists have found evidence of earlier rock falls from the canyon wall at the rear of Pueblo Bonito, for blocks of sandstone were discovered beneath the floor of the earliest dwelling at this site (Judd, 1959, p. 509). A more recent fall buried part of the terrace built during the eleventh century (Keur, ms: Judd, 1959, p. 509). A photograph taken in 1877 shows the debris from this fall (Judd, 1958, pl. 2), and mention is made of it by Jackson in 1877 but not by Simpson during his visit in 1849 (Judd, 1959, p. 509). The occurrence of two major falls since 1100 A.D. from the cliff to the rear of Pueblo Bonito indicates that the fall of the sandstone blocks is a geologically frequent event in Chaco Canyon.
CONCLUSIONS

A unique record, obtained by National Park Service personnel, has been used to demonstrate that the monoliths of Cliff House Sandstone at Chaco Canyon National Monument are moving under the present climate. If these data are representative, they indicate that the rates at which mass movements of this type occur are an exponential function of the weathering or erosional agent, in this case precipitation. The rate of movement is seasonal, being relatively slow during the summer and relatively fast during the winter. Frost action and wetting of the shale by snow melt are considered to be important factors causing movement of the blocks.

The occurrence of infrequent geomorphic events of high intensity has always presented problems. In that observation is generally difficult and in that the long time intervals between them raises the fundamental question of what constitutes a “contemporary” process. The well-documented collapse of Threatening Rock represents a record of unusual completeness for a catastrophic geomorphic event, but the second problem remains. Bryan (1954) classed the collapse under “present geologic processes.” On the other hand, a completely different interpretation of the collapse of the joint blocks is possible if it is assumed that erosion was much more rapid at some earlier (pluvial?) phase of erosional history, during which the detachment, collapse, and weathering of the joint blocks proceeded at a much more rapid rate. Under such an interpretation the presently-observed infrequent cliff falls would represent the final failure, partly under the action of long-term creep of the underlying shales, of blocks which were essentially undermined and detached from the cliff during the last stages of the more active past processes. In short, under this assumption the fall of Threatening Rock might almost be termed “posthumous erosion”. However, the estimate that rock movement began about 550 B.C. suggests that in this case the movement and fall is a contemporary process.

The general question of the magnitude and frequency of forces in geomorphic phenomena has been well treated by Wolman and Miller (1960), who pointed out that . . . “The effectiveness of an event of given frequency in terms of its performance of work is measurable both by its magnitude and by the frequency with which it recurs . . . On the other hand, although related to the form of the landscape, the ranking of events in terms of the relative amounts of work performed is not necessarily directly correlated with their relative importance in the determination of . . . (form) aspects of the landscape” (1960, p. 55). The failure of the cliffs at Chaco Canyon provides a rather special instance of the manner in which the character of the medium may control both the magnitude and frequency of major erosional events. Wolman and Miller (1960, p. 54) noted that . . . “Almost any specific mechanism requires that a certain threshold value of force be exceeded. However, above this threshold or critical limit there occurs a wide range in magnitude of forces . . . ”. Where this threshold value is low, such a wide range in magnitude of forces is obviously possible, but the tendency of the lower Cliff House Sandstone to break up preferentially into huge joint blocks along a low erosional cliff implies a strong bias in favor of infrequent, high intensity, large-scale failure. Indeed, much of the erosion of the Chaco Canyon cliffs can occur only in a catastrophic
manner by the collapse of huge, cliff-high blocks. The final fall of these blocks marks the termination of a multitude of events of low intensity and high frequency (figs. 2, 3); however, in terms both of work accomplished and of the resulting topographic forms, the dominant mechanism seems to be of characteristically high intensity and low frequency.

References

Keur, J. Y., ms, 1933, A study of primitive Indian engineering methods pertaining to Threatening Rock: manuscript on file at Chaco Canyon National Monument.