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The description and origin of the clastic dikes associated with Sheep Mountain Anticline in the Bighorn Basin, Wyoming

Albert John Warner

Iowa State University
THE DESCRIPTION AND ORIGIN OF THE CLASTIC DIKES
ASSOCIATED WITH SHEEP MOUNTAIN ANTICLINE
IN THE BIGHORN BASIN, WYOMING

by

Albert John Warner

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Signatures have been redacted for privacy

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INTRODUCTION AND PURPOSE

Sandstone dikes, also called clastic dikes, although seemingly anomalous phenomena, are actually fairly common and have been reported from many localities throughout the world. Most explanations for these peculiar features involve the formation of a suitable fracture, and filling from above or below by clastic material in a fluidized state. The foreign material lithifies to form a structure which is closely comparable to igneous dikes in general appearance (Peterson, 1966).

One of the earliest attempts made at an explanation of clastic dike intrusion was by Jenkins (1925), who by the use of an applied vertical force on a series of clays showed that the force of gravity of overlying sedimentary beds could force the clays down into pre-existing cracks.

This study is the outgrowth of one initiated in the summer of 1964 by G. Johnson, L. Garside, and the writer. During that particular investigation, several clastic dikes were observed on the flanks of Sheep Mountain Anticline in Bighorn County, Wyoming. A preliminary examination of the dikes indicated that they appeared to be related to the fracture pattern observed in the study area.

It is the purpose of this report to describe the clastic dikes associated with Sheep Mountain Anticline and related
structures and to determine their origin. The observed field relationships indicate that the dikes were forcefully injected into the underlying beds during the early stages of tectonism.
GEOGRAPHICAL AND PHYSIOGRAPHIC
DESCRIPTION OF THE AREA

The thesis area is located in Townships 53, 54, and 55 North and Ranges 93, 94, and 95 West, Bighorn County, Wyoming and occupies most of the Lovell NW quadrangle and one fourth of the Lovell SW quadrangle. The quadrangles lie completely within the Bighorn Basin of the Middle Rocky Mountain physiographic province. The area covers approximately 150 square miles in the northeastern part of the basin. The map (Figure 1) indicates the location of the area of study and of dike occurrences.

The most prominent topographic feature is the northwest trending Sheep Mountain, rising some 5000 feet above sea level and over 900 feet above the surrounding basin. It is approximately 15 miles long and 3-1/2 miles wide at its widest point.

The area is drained by the Bighorn River which flows generally north and is superposed upon Sheep Mountain cutting the axis at one-half the distance from the northern end. The remainder of the drainage is structurally controlled with many ephemeral streams occupying strike valleys and others cutting into the scarp and dip slopes of the bordering hogbacks.

The topography has generally rugged, sharp features
Figure 1. Index map of Bighorn County and the study area showing dike locations by area
characteristic of this arid region. The flanks of Sheep Mountain consist of flatirons which are common erosional features in the area.

Vegetation consists primarily of sagebrush and juniper which in the early summer give the desert a carpet of green, but in later months turns to gray and brown due to lack of rainfall. The rocks are well exposed and outcrops are continuous for miles, obscured only by cover related to drainage, terraces, and recent alluvium.
GEOLOGICAL SETTING

The Bighorn Basin is an irregular, approximately elliptical structural lowland limited on the west by the Absaroka and Beartooth Mountains, and on the south, east, and northeast by the Owl Creeks, Bighorn, and Pryor Mountains, respectively. All of these with the exception of the Absarokas, represent orogenic uplifts with exposed Precambrian cores, flanked by deformed strata.

The basin itself is underlain in its deepest parts by 2500 to 3200 feet of Paleozoic, 1500 feet of Triassic and Jurassic, and 7000 to 9000 feet of Cretaceous strata. In the central and western parts several thousand feet of Paleocene and Eocene strata are present (Eardley, 1962).

Stratigraphy

The oldest exposed formation is the Madison of Mississippian age which underlies the Amsden and Tensleep formations of Pennsylvanian age. The Madison is approximately 700 feet of massive limestone. The Amsden is 170 feet of dolomite and red siltstone which was deposited on a karst topography developed on the upper surface of the Madison. The Tensleep formation, which varies in thickness from about 40 to 110 feet, is predominately sandstone. The Embar formation consists mostly of 380' of red shales (lower) and
massive dolomite (upper) and rests disconformably on the Tensleep.

The Triassic Chugwater formation consists of about 700' of red siltstones and sandstones. The Jurassic rocks are subdivided into four formations and are, in ascending order: the Gypsum Springs, 170 feet thick; the Sundance, 350 feet thick; the Morrison, 150 feet thick; the Cloverly, 190 feet thick. The Gypsum Springs consists of red shale, limestone, and gypsum and rests disconformably on the Chugwater. The Sundance contains green shale, sandstone, and coquinoid limestone while the Morrison consists of variegated sandstones and shales. The Cloverly formation is primarily brightly colored white and purple siltstones and variegated sandstones.

The lower Cretaceous rocks are grouped into five formations and are, in order of decreasing age: the Sykes Mountain, 85 feet thick; the Thermopolis, 200 feet thick; the Muddy, 30 feet thick; the Shell Creek, 200 feet thick; and the Mowry, 300 feet thick\textsuperscript{1}. The Sykes Mountain consists of rusty colored sandstones and siltstones. The Thermopolis and Shell Creek formations, between which lies the white Muddy sandstone, are primarily black bentonitic siltstones containing some thin bentonite seams. The Mowry formation is a silver gray, siliceous shale containing a few thin sandstones and bentonite beds.

\textsuperscript{1}The first four of the above formations are also known as the Thermopolis group.
The Upper Cretaceous formations exposed within the thesis area include the Frontier, consisting of 500 feet of sandstone, black bentonitic siltstone, and bentonite, and the Cody which is predominately black or gray bentonitic shales with a few thin sandstones and bentonite. Figure 2 summarizes the stratigraphic column in the thesis area.

Structure

The structures within the thesis area are typical of the folds associated with the intermontane basins of the Wyoming Rockies. The predominant structure is Sheep Mountain Anticline which trends NW as do the other adjacent open folds. Other structures include Alkali Anticline and a triangular shaped syncline to the north of Sheep Mountain (Plates 1 and 3).

Sheep Mountain is a breached, asymmetrical anticline, plunging N 40° W and S 30° E. Dips on the eastern flank in the area range from 50° to slightly overturned, whereas those on the western flank range from 15° to 45°.

The stratigraphic units exposed on Sheep Mountain in the study area range from Madison in the core through Sundance on

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1The sandstone of the Frontier is mostly contained within two members, the Peay and the Torchlight. The Peay occurs approximately 40' above the Mowry-Frontier contact and varies in thickness from 50' to 100'. The Torchlight caps the Frontier and is approximately 50' thick.
Figure 2. Stratigraphic column of the rocks exposed in the thesis area
the eastern flank and through Cody on the western flank (Plate 1).

The formations exposed on Alkali Anticline are entirely Cretaceous in age, ranging from Thermopolis in the core to Cody on the flanks. Alkali Anticline is not as prominent as Sheep Mountain, having an elevation of roughly 4500 feet and dips on the flanks up to 30°. The structure plunges N 20° W and S 60° E and is cut by several NE trending normal faults.

The syncline which lies north of Sheep Mountain has the Cody formation exposed along its axis and was developed between Sheep Mountain, Spence Dome to the east and Rose dome further to the north.

The fractures, consisting of faults and joints of tectonic origin, are considered to be related to the early stages of folding and are discussed in detail in a later section of this report. The joints and faults are considered significant in the study since the field relationships suggest that there are two stages of fracture development; before and after the emplacement of the dikes. The major fracture sets represent the longitudinal, cross, and shear directions on an anticline (Badgley, 1965) and dikes were observed parallel to each of these trends.

History

The Bighorn Basin as well as other parts of Wyoming, acted as a shelf area of sedimentation until Cretaceous time
when considerable subsidence occurred in conjunction with more active Cordilleran tectonic activity to the west.

During Late Cretaceous to Eocene time, the sediments of the Northeastern Bighorn Basin were deformed into many northwest trending folds as the ranges surrounding the basin were elevated (Eardley, 1962).

Fanshawe (1947) postulated the tectonic genesis of the structures of the basin. He suggested that the folds and faults were the result of resistance to horizontal confinement which was set up in the upper sedimentary beds of the basin as regional compression warped the surface of the basement complex downward. This curvature caused the overlying sedimentary units to deform since they were forced to occupy less surface area.
METHOD OF INVESTIGATION

Since one of the major concerns of this study is to describe the dikes in some detail, it was necessary to make a detailed map of as many dikes as was feasible within the thesis area.

As a preliminary to this portion of the field work, a geologic base map was constructed on an acetate overlay from aerial photographs of the area. Approximately the first four weeks of the summer was spent on this undertaking. During this period of reconnaissance and mapping, 16 dikes were located, 14 of which were later mapped in detail.

The detailed mapping was done with plane table and alidade on a scale of 1" - 50' with two exceptions. This scale permitted the mapping of dikes which were in excess of 700' long on the 24" board, and at the same time allowed the detailed nature of the dikes to be recorded. Rod stations were taken at approximately 3' intervals on alternate sides of the dikes to insure accurate mapping. A lithologic description was also made at each rod station.

Sampling of selected dikes commenced upon completion of the plane table mapping. A tape and brunton compass traverse was used to tie into the plane table stations to locate sample sites.

Various structural features were recorded during this
phase of the work. These included fractures and slicken­
sides within the dikes, flow structures, and fracture patterns
in stratigraphic units in the dike areas.
OCCURRENCE OF THE DIKES

Spatial Distribution and Extent of the Dikes

Dikes were observed at 9 separate localities on the southwest flank of Sheep Mountain, the northwest nose of Sheep Mountain, the southeast nose of Alkali Anticline, and on the southeast nose of the triangular syncline. A total of thirteen dikes were mapped in these areas (Plate 2).

The dikes are easily visible, both on the ground and from the air since they have a relief of from 3 to 5 feet above the surrounding strata and generally intersect the well defined strike ridges at an acute angle or are nearly perpendicular to them (Figure 3a). The total topographic difference in elevation from the lower to upper end of most dikes is on the order of 100-200 feet (Figure 3b).

The spatial distribution of the dikes is limited to the area of exposure including the Shell Creek, Mowry, and Frontier formations. Stratigraphically, the dikes all occur within these three formations. In five of the areas, the dikes completely transect the Mowry formation and enter the underlying Shell Creek formation. In five locations dikes were observed in the basal Peay sandstone member of the Frontier formation. No dikes were observed other than in this stratigraphic setting.
Figure 3a. Aerial photograph of dikes #4 and #5 showing relationship to regional strike (looking S 45° W)

Figure 3b. A portion of a dike viewed parallel to the strike of the surrounding beds showing the topographic difference in elevation
The Peay sandstone is considered to be the source of the dikes. It is the nearest sandstone unit stratigraphically and spatially to the dikes and its lithology compares favorably with that of the dike rock. At the five locations where dikes transect the Peay, no dikes were observed to have gone through the Peay into the overlying siltstones. Furthermore, no dikes were observed that were related to the Torchlight sandstone member of the Upper Frontier or to the Muddy sandstone. These units are the nearest sandstones spatially and stratigraphically to the dikes other than the Peay. From this evidence, it is concluded that the dikes were intruded into a lower stratigraphic horizon.

The dikes generally followed one of three trends: due North, N 30° E to N 80° E (average N 56° E) and N 70° W. The dikes were generally vertical when they occur perpendicular to the strike of the surrounding beds. Dikes whose trends were at small acute angles to the strike of the country rock were observed to have dips of approximately 65° in the direction opposing the dips of the surrounding beds which are approximately 30°.

Eight of the thirteen individual dikes are located on the southwest flank of Sheep Mountain. Five of these intersect the regional strike at acute angles, two are nearly perpendicular, and a portion of one is nearly parallel.
One dike is located on the southeast nose of Alkali 
Anticline and has a strike of N 80° E (Figure 4).

The northern nose of Sheep Mountain contains the largest 
concentration of dikes. Four were mapped in this area. 
The plan view of these dikes show their relationship to the 
structural axes (Plates 1 and 2). It was noted that one of 
these dikes suggested fault control (Plate 2).

One mapped dike occurs on the southern nose of the 
triangular syncline. It is, like most of the others, not a 
complete unit, and is composed of several segments which, 
when viewed at a distance or from the air, give the 
appearance of a complete dike. A study of detailed maps 
of individual dikes indicates that these dike segments 
may be offsets of a more complete original dike after 
emplacement along systematic fracture sets. This point 
will be discussed later under the section concerning post 
dike fractures.

The major dikes in the study area had an apparent 
horizontal extent (length) ranging from 210' to 1800', 
averaging 770' and an apparent vertical extent ranging from 
55' to 250' with an average of 105' (Table 1). These 
dimensions are of the dikes as seen in their present position 
and are considered to be the minimum dimensions as measured 
in the field. Their true lengths are unknown, since dikes 
or portions of dikes may have been removed by erosion.
Figure 4. Clastic dike #9 transecting the axis of Alkali Anticline (looking S 10° W)
Thickness varied from several inches to local thickenings on the order of 2 to 5 feet.

The sedimentary beds surrounding individual dikes have dips ranging from 11° to 63°. The dikes occurring in areas of low dip have the longest horizontal extent (Table 1). A dike located east of the study area in the same stratigraphic setting has a horizontal extent of nearly 3 miles and the surrounding sedimentary beds dip on the order of 3° to 5°.

Although there is little direct evidence suggesting the direction of intrusion in terms of lineations, it has been established that the dikes were intruded into a lower stratigraphic horizon. The vector components of the intrusive direction may have ranged from vertically downward to lateral. The extent to which the lateral component of intrusion contributed to sand transportation would depend upon the time of the injection as related to the degree of development of the folding.

The simplest approach to determine the direction of sand transport is to consider the shortest distance that sand particles would take in traveling from the source of the sand to a location in the dike. This distance would be a perpendicular line extended from the source to a location in the dike.

Considering the above approach, dikes which were intruded
into areas of low dip would have a large vertical component and a small lateral component of sand transport. Intrusion would have occurred in the early stages of fold development. The magnitude of the horizontal extent of the dikes in areas of low dip further suggests that lateral transport of sand seems unlikely since the distances covered to the lower ends of the dikes extend to over one third of a mile.

In areas of steep dip, the possibility of a lateral transport component increases provided that the time of intrusion occurs when folding has progressed to the degree that the resolution of the transport vector, which is perpendicular to the source bed, produces a significant lateral component. Dips on the flanks of such a fold would exceed 30°.

Two lines of evidence suggest, however, that dikes located in areas of steep dip may also have been emplaced early in the folding and subsequently rotated to their present position. The dikes are related to the systematic fracture patterns observed in the Mowry formation and the Peay sandstone. The relationship of these fractures to bedding as discussed in a later section of this report show that they developed during the early stages of folding. The dikes mentioned above which dip at 65° in the direction opposing that of the surrounding beds occupy fractures which belong to systematic patterns as do dikes in areas of low dip. As mentioned
<table>
<thead>
<tr>
<th>Dike #</th>
<th>Bearing of dike</th>
<th>Attitude of the beds</th>
<th>Apparent H.E.</th>
<th>Apparent V.E.</th>
<th>Perpendicular distance from upper end of dikes to contacts</th>
<th>Distance dike penetrated into:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Km&lt;sup&gt;e&lt;/sup&gt; Km&lt;sup&gt;c&lt;/sup&gt; Km-K&lt;sup&gt;f&lt;/sup&gt; Km-K&lt;sup&gt;d&lt;/sup&gt; K&lt;sup&gt;e&lt;/sup&gt;H.V. K&lt;sup&gt;f&lt;/sup&gt;H.V. K&lt;sup&gt;d&lt;/sup&gt;H.V.</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>N55°E</td>
<td>N40°W 45°S</td>
<td>900'</td>
<td>180'</td>
<td>50' 460'</td>
<td>350' 50'</td>
</tr>
<tr>
<td>2</td>
<td>N50°E</td>
<td>N30°W 63°S</td>
<td>210'</td>
<td>55'</td>
<td>35' 255'</td>
<td>entirely in Mowry</td>
</tr>
<tr>
<td>4</td>
<td>N45°E</td>
<td>N40°W 50°S</td>
<td>700'</td>
<td>110'</td>
<td>50' 380'</td>
<td>200' 55' 80' 20'</td>
</tr>
<tr>
<td>5</td>
<td>due N</td>
<td>N40°W 45°S</td>
<td>900'</td>
<td>100'</td>
<td>70' 260'</td>
<td>275' 70'</td>
</tr>
<tr>
<td>6</td>
<td>N70°W</td>
<td>N30°W 30°S</td>
<td>1400'</td>
<td>165'</td>
<td>60' 515'</td>
<td>100' 20' 350' 5'</td>
</tr>
<tr>
<td>8</td>
<td>N70°E</td>
<td>N40°W 11°S</td>
<td>1800'</td>
<td>250'</td>
<td>30' 420'</td>
<td>250' 40' 325' 30'</td>
</tr>
<tr>
<td>9</td>
<td>N80°E</td>
<td>N22°W 25°N</td>
<td>800'</td>
<td>120'</td>
<td>40'(east flank) 150'(west flank)</td>
<td>125' 25'</td>
</tr>
<tr>
<td>10</td>
<td>N30°E</td>
<td>N60°W 35°N</td>
<td>375'</td>
<td>90'</td>
<td>25' 320'</td>
<td>entirely in Mowry</td>
</tr>
<tr>
<td>12</td>
<td>N80°E</td>
<td>due N 14°W 1100'</td>
<td>125'</td>
<td></td>
<td>70'(dowthrown block) 5'(upthrown block)</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>N5°E</td>
<td>N25°W 42°S</td>
<td>1800'</td>
<td>175'</td>
<td>60'(north flank) 380' 5'(south flank) 390'</td>
<td>130' 10'(S flank) 100' 20'(N flank)</td>
</tr>
</tbody>
</table>

<sup>a</sup>Apparent H.E. = apparent horizontal extent.

<sup>b</sup>Apparent V.E. = apparent vertical extent.

<sup>c</sup>Kf-Km = Frontier Mowry.

<sup>d</sup>Km-Ksc = Mowry Shell creek.

<sup>e</sup>Km = Mowry.

<sup>f</sup>Ksc = Shell treek.

<sup>g</sup>Kf = Frontier.
earlier, the dikes are fractured and offset on what also appear to be systematic fracture patterns. The relationship of these fractures to bedding shows that they also developed during early stages of folding. Since these fractures offset the dikes, they must be later than the dikes. The conclusion reached is that the dike intrusion represents a critical time in the early stages of folding.

In order to obtain the minimum extent and depth of intrusion of the dikes, it was necessary to rotate the surrounding beds to a horizontal reference position. Completion of this rotation indicated that the minimum horizontal extent ranged from 55' to 1740' with an average of 640' and the minimum vertical extent ranged from 150' to 800' at an average of 325' (Table 2). These data suggest that a forceful intrusion was needed to penetrate a depth of 800'.

The horizontal extent of the dikes was obtained by measuring the distance between perpendicular lines extended from the Frontier-Mowry contact to the upper and lower ends of the dikes (as seen in the field). This measurement was made on the surface of this contact after its rotation to the horizontal. The vertical extent was obtained by measuring the length of the perpendicular from the Mowry-Frontier contact to the lower end of the dike (Figure 5).
Table 2. Minimum dike dimensions obtained by rotating extent data to a horizontal reference plane

<table>
<thead>
<tr>
<th>Dike #</th>
<th>Minimum Horizontal Extent</th>
<th>Minimum Vertical Extent</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>460'</td>
<td>800'</td>
</tr>
<tr>
<td>2</td>
<td>55'</td>
<td>200'</td>
</tr>
<tr>
<td>4</td>
<td>400'</td>
<td>600'</td>
</tr>
<tr>
<td>5</td>
<td>750'</td>
<td>475'</td>
</tr>
<tr>
<td>6</td>
<td>1270'</td>
<td>550'</td>
</tr>
<tr>
<td>8</td>
<td>1740'</td>
<td>500'</td>
</tr>
<tr>
<td>9</td>
<td>730'</td>
<td>250'</td>
</tr>
<tr>
<td>10</td>
<td>280'</td>
<td>280'</td>
</tr>
<tr>
<td>12</td>
<td>1085'</td>
<td>150'</td>
</tr>
<tr>
<td>13</td>
<td>1540'</td>
<td>470'</td>
</tr>
</tbody>
</table>
Figure 5. Block diagram showing the relationship of the apparent horizontal and vertical extents of a dike to the minimum horizontal and vertical extents of the dike.
Perpendicular lines extended from the Mowry-Frontier contact to the upper ends of the dikes which occur in the Peay indicate that up to 60' of the basal Peay may have been involved in providing source material for the dikes.

Lithology

Megascopically, the dike rock is a medium grained, buff to light to bluish gray sandstone locally containing abundant chert pebbles ranging from 1/4" to 1-1/2" in the longest dimension. The dike rock has variable induration, however it is generally well cemented with calcite or silica and more resistant than the surrounding beds. The dike rock closely resembles the lithology of the Peay which is a light brown to gray sandstone, containing medium subrounded grains and black chert pebbles up to 2 inches long. It is generally cemented with silica and forms resistant ridges.

Structure

Controlling fractures

At each dike locality, a set of fractures was recognized which paralleled the strike of the dike or dikes at that locality. In one area, a fault was also recognized to be continuous with a dike and offset the Peay sandstone
(Plate 2). The displacement along this fault was approximately 15' vertically and 700' horizontally. These joint and fault trends can be related to the folded structures and are considered to be instrumental in controlling the emplacement and attitude of the dikes. The fractures occur in trends which occupy longitudinal, cross, and shear directions on the anticlines and syncline. A detailed discussion of the fracture pattern is included in the next section of this paper.

Post dike fractures

Detailed mapping illustrated the offsets of the dikes and the fractures within them. The offsets and fractures within the dikes indicate that small scale faulting on the order of several inches to several feet is more common than might be assumed from studying the geologic map of the study area. These faults are probably healed in the shales on either side of the dikes and the dike offset is the only remaining record of movement. In some areas the fractures are continuous from within the dike into the surrounding strata and are related to the regional structure. Many of the offsets of the dikes in the Shell Creek and the Mowry are parallel to bedding and are probably related to bedding plane faults, possibly along
the seams of bentonite which occur in these two formations. Other dikes such as the one discussed below have fractures which are not related to the fracture patterns of the surrounding beds but are related to the stress field discussed later.

Two sets of fractures measured within dike #9 have attitudes which become nearly vertical and horizontal when the surrounding beds are rotated to a horizontal reference position. The dike itself transects the axis of Alkali Anticline at a large acute angle. The vertical fracture set is also nearly normal to the walls of the dike and is the result of tension developed parallel to the axis of the anticline during its uplift. The fracture set parallel to bedding is the result of shear or sliding in response to stretching of the dike along its strike. The fractures which are parallel to bedding offset the vertical fractures slightly and are thus later. The dike outcrop looks very much like a concrete block wall. The relationships of the joints in this dike to the surrounding beds further indicate early intrusion followed by continued movement (Figure 6).

**Flow structures**

At one locality, flow structures parallel to the walls of the dike similar to those recognized by Vitinage (1954) in sandstone dikes in Colorado were observed. These structures
Figure 6. Vertical and horizontal joints developed on dike #9
have a curved cylindrical shape and vary in diameter from 1" to 1' and in length from several inches to several feet. The larger ones appear to consist of curved laminations which are reflected in the curved nature of the erosion surfaces. The structure has a bearing of S 13° E (the bearing of the dike §5 in this locality) and plunges 25° to the south. Rotation of the surrounding sedimentary beds to the horizontal gave a bearing (of the flow structure and the dike) of N 16° W and a plunge of the structure of 5° to the north.

In two other areas, planar or bedded structures were observed which might suggest flow. Rotation of the surrounding beds to the horizontal gave dip directions which coincide with the feature discussed above. That is, the down dip directions of these features pointed towards the axis of the anticline and were oriented nearly parallel to the strike of the dikes in which they occur. It is thought that the attitudes of these flow structures indicate lateral components of flow in an overall vertical flow direction.
FRACTURE ANALYSIS

In the course of the field investigation, it was noted that at the ten dike localities where fractures were measured, there was at least one set of systematic fractures which are parallel to the dike or dikes at that locality. One dike (#12) shows definite evidence of fault control. The fault has the same bearing as one of the major joint trends in the area and continues beyond one end of the dike. The joints of this set in the Peay sandstone increase in frequency as the dike is approached normal to its strike. Fault control is also suggested for dikes #8 and #9 by the observation that both dikes lie on nearly the same line and have similar bearings. An increase in the frequency of the joints of the set parallel to this trend is also noticed and begins approximately 3' to 5' on either side of the dike in the Peay sandstone. It is thought that other dikes in the area may also be related to faults associated with tectonic activity. Hence it appears that the dikes may be structurally controlled by faults or fractures of tectonic origin established before or during intrusion.

A study of detailed maps of several individual dikes indicated that offsets of the dikes and the fractures within them may be related to movement and adjustment along a
systematic pattern of fractures after the dikes were injected. In some areas the fractures are continuous from within the dikes into the surrounding beds thus indicating that a portion of the fractures in the area were established after emplacement of the dikes.

Badgley (1965) gives the geometric orientation of longitudinal, cross, and diagonal joints relative to fold axes and to the principal stress axes. (Figure 7) He defined longitudinal joints as those which are roughly parallel to fold axes and normally have steep dips. Cross joints are roughly perpendicular to fold axes and also normally have steep dips. They have been referred to as "extension joints" by Billings (1954) as they are related to slight elongation parallel to the axes of the folds.

Diagonal joints generally occur in paired sets arranged more or less symmetrically with reference to the longitudinal and cross joints of a region. The diagonal joints generally intersect to form an obtuse angle about the longitudinal joint trend and an acute angle about the cross joint trend. Their dips are generally steep.

Although the orientation of the principal stress direction cannot be directly observed, they may be inferred by observing the angular relationships between fracture sets. Thus it is convenient to relate joints and faults to the three principal stress axes (Badgley, 1965).
Figure 7. Geometric orientation of longitudinal, cross, and diagonal joints relative to fold axis and the three principal stress directions (Badgley, 1965)
Intermediate

Minimum

Maximum

STRESS SYSTEM

Longitudinal Joint

Diagonal Joint

Diagonal Joint

Cross Joint

Longitudinal Joint
Bucher (1920) was one of the first investigators to show the relationship of fracture patterns to the principal stress axes. In his example of a brittle body subjected to both horizontal compression and tension, shear planes develop which were similar to the anticlinal diagonal joints of Badgely. They are oriented in such a way that the maximum compressive stress bisected the acute angle between these joints and the joint dips are steep (Figure 8). Bucher's example is for a flat lying structure.

Badgley (1965) further states that rotation of bedding planes containing fracture patterns back to the horizontal using stereographic methods may alter the pattern significantly. He believes that because the rotated joint pattern more closely approached the idealized joint distribution normally expected on an anticline (Figure 7), much of the jointing, particularly the longitudinal variety, developed during the early stages of folding.

DeSitter (1964) contends that in an anticline of competent beds, there is a local tensional stress in the outer arc perpendicular to the axis. This would be considered the direction of the least principal stress, with the overburden constituting the median stress, and the greatest principal stress parallel to the axis (Figure 11). Tension joints would be developed parallel to the axis. In a syncline, the opposite would be expected with local
Figure 8. Shear planes developed in a brittle body subjected to horizontal compression and tension at right angles (Bucher, 1920)
compression in the direction perpendicular to the axis. In both cases a set of shear joints develops, with the acute angle bisected by the direction of the greatest stress, but differently oriented to axis direction (Figure 9a).

DeSitter outlines the type of joints one might expect in a competent unit subjected to moderate folding. Initially the sheet is in a simple stress condition, in which shear joints are forming at an acute angle with the deformative stress, and tension joints parallel to this stress (regional stress). (Figure 9b)

The next stage is the secondary stress condition, caused by elastic bending, which will cause a set of shear joints with their acute angle bisected by the anticlinal axis and tension joints parallel to the axis (Figure 9a).

Frictional shear joints may also occur as the result of the opposing stress on the top and bottom of the sheet. A couple on the other faces is needed to compensate for the rotational effects of the first couple. These joints are parallel to the fold axis.

Finally release tension joints may be expected after the stress has vanished. These will be parallel to the fold axis if they release the main stress or perpendicular if they release the secondary stress.

It is unlikely that all the above sets of fractures will
Figure 9a. Origin of joint and fault patterns in an adjoining anticline and syncline (DeSitter, 1964)

Figure 9b. Shear joints and tension joints developing in an unfolded sheet of rock (DeSitter, 1964)
Regional Stress

Tension Joints

Local Stress

Shear Joints

Anticline

Syncline
be present in any one folded rock unit. Whichever sets are dominant are probably determined by lithology, the position on the structure under consideration, the length of time that the stress has been acting, and the competency developed within beds as folding progresses.

Fractures were measured at ten dike localities in the Mowry and on the Peay sandstone of the Frontier. Fracture pattern data obtained from the 1964 study on the Tensleep and Sykes Mountain sandstones were also used to compliment the fracture pattern investigation.

The fractures were plotted on the geologic base map and using the methods of Phillips (1960) were rotated so that the surrounding beds were horizontal (Plate 3). It was noted that the vast majority of the joints were very steeply inclined or vertical upon completion of the rotation (Appendix 1). According to Badgley, this evidence indicates that the fracture pattern was established in the initial or early stages of folding.

Nearly all of the types of joints discussed above were recognized in this investigation. The shear joints measured in the Mowry and Frontier on the southwest flank of Sheep Mountain and on Alkali Anticline show both of the orientations discussed above. That is, some sets are oriented with their acute angle perpendicular to the axis, others with their acute angle parallel to the axis. The presence of these
two sets of shear joints suggest that although they were both formed during the early stages of folding, the latter, according to DeSitter would form slightly later than the former. This could be a critical point, particularly where the latter set of shear joints was recognized in some of the dikes on the southwest flank of Sheep Mountain. Joints measured in the competent Sykes Mountain sandstone on the northern nose of Sheep Mountain also show one member of a conjugate set of shear joints with its acute angle intersecting the fold axis.

In other areas where clastic dikes are reported to be structurally controlled, many joints of the set or sets which control the dikes are filled. The clastic dikes in Southern California reported by Duncan (1964) are characteristic. By comparison, it is significant that there are relatively few dikes in the study area. It is suggested that the dikes may be controlled by faults or major fractures developed in the Peay and a limited number in the Mowry during the initial stages of folding before the Mowry shale had attained enough competency during folding to undergo the brittle fracture as seen today. The nature of the fracturing and dike injection will be discussed in a later section of this paper.

A study of the geologic map of the study area shows that many of the dikes are located in areas where the Peay sand-
stone would probably be undergoing deformation more rapidly than in other areas. These include the noses of Alkali Anticline, Sheep Mountain, and the triangular syncline, and three locations on the southwest flank of Sheep Mountain where there is a change in the direction of strike of the beds.

It was concluded that the main compressive stress was acting very nearly horizontally in a NE-SW direction, with local secondary tension acting in the same direction as envisioned by DeSitter. This agrees favorably with the Laramide deformational history of the basin, where compressional forces from the W-SW thrust the miogeosyncline of the Cordillera onto the stable shelf (Thomas, 1949).

The cross joints observed were probably due to the tensional forces set up with longitudinal stretching parallel to the fold axis, (Billings, 1954) or caused by the release of the secondary stress system.

The longitudinal joints were probably due to either the local tensional forces set up in the outer surface of the fold or to the frictional shear mechanism proposed by DeSitter. The problem in determining if the first mechanism is valid is dependent upon what the outer surface of the fold and the depth of burial was at the time of deformation.

Joints whose dips do not approach the vertical upon rotation are generally unsystematic and may be due to gravity as described by Harris (1960).
Dikes were observed to have "filled" all three types of fractures: diagonal, longitudinal, and cross. The presence of NE trending normal (adjustment) faults on Alkali Anticline further indicates that a state of tension must have existed horizontally in a NW-SE direction.
ORIGIN OF THE DIKES

General Statement

It is now generally agreed that there are two different genetic types of clastic dikes (Duncan after Schrock, 1964): (1) Those which are the result of intrusive origin, and (2) those filled with material from above which is transported into previously formed fissures.

The clastic dikes in the study area are considered to be of intrusive origin and injected into a lower stratigraphic horizon. A simple filling mechanism wherein material is washed into fractures on the sea floor is negated for the following reasons:

(1) The vertical extent of the dikes ranges up to 800'. It is doubtful that fractures of this depth could exist on a sea floor where the sediments are water saturated and unconsolidated. It is also doubtful that any fractures which might exist on the sea floor would remain open for the length of time necessary to allow filling with the amounts of sand found in the dikes.

(2) The fracture pattern in the study area is related to the stress field. If the dikes were the result of filling of these fractures, the sea floor would have been subjected to uplift before the filling occurred. Material would then have been washed into the fractures by the
subsequent transgressing sea. No evidence for an erosion surface was observed between the Mowry formation and the Peay sandstone.

(3) The variations in the thicknesses of the dikes further negate a filling mechanism. It is doubtful that simple fillings would have thicknesses of more than a few inches (Donath, 1968)\textsuperscript{1}. The dikes have thicknesses that are locally on the order of several feet.

The dikes have been observed to penetrate the Peay sandstone to distances up to 60' above the bottom contact. At one location, a dike suggested control by a fault which offset the Peay. These lines of evidence indicate that the Peay was present and competent enough to form fractures before or during dike emplacement.

All authorities on clastic dikes agree that a fissure must be formed prior to formation of a dike. Smith (1952) mapped clastic dikes in the Big Badlands of South Dakota and showed that the resulting pattern is due to clastic material filling in a conjugate set of shear joints and tension joints both parallel and perpendicular to the regional compression. The fissures were due to a uniform stress field and its elastic release.

In the present study the fractures are considered to be

\textsuperscript{1}Fred A. Donath, Head, Department of Geology, University of Illinois. Modes of Deformation. Private communication. 1968.
of tectonic origin and caused by regional and local compressive stress acting in a NE-SW direction and its subsequent elastic release. The fracture pattern is considered to have developed in the initial stages of folding. This conclusion is based on the relationship of the fracture pattern to the anticlines and syncline. The fractures have longitudinal, cross, and shear directions typical of those found on folded structures. Dikes parallel to each of these trends were observed.

The Role of Pore Pressure in Dike Emplacement

It is believed that the effects of fluid pore or formation pressure play a major role, both in the development of fractures and in the subsequent dike injection.

Handin (1963) discussed the concept of effective stress in the deformation of rocks under pressure. In his derivation he placed a dry, homogenous, jacketed cylindrical test specimen under an initial external hydrostatic confining pressure, $P_c$. Then he designated $S_1$, $S_2$, and $S_3$ as the three principal total stresses, maximum, intermediate, and minimum. Compressive stresses are positive. Then:

$$S_1 = S_2 = S_3$$

Let the axial pressure $S_1$ be increased by an amount $\Delta S = S_1 - S_3$, the differential pressure, whereas the radial stresses all remain equal to the confining pressure. Then $S_1 > S_2 = S_3 = P_c$, $S_1 = S_3 + \Delta S = P_c + \Delta S$ in compression.
Now an internal hydrostatic pore pressure $p_p$ is applied. The concept of effective stress is expressed analytically as:

$$\sigma_1 = S_1 - p_p, \quad \sigma_2 = S_2 - p_p, \quad \sigma_3 = S_3 - p_p$$

where $\sigma_1$, $\sigma_2$, and $\sigma_3$ are the maximum, intermediate, and minimum principal effective stresses, respectively (Figure 10).

In a compression test:

$$\sigma_2 = \sigma_3 = (S_2 - p_p) = (S_3 - p_p) = (p_c - p_p); \quad \sigma_1 = (S_1 - p_p)$$

$$= (S_3 + \Delta S - p_p) = \Delta S + (p_c - p_p) \quad (1)$$

where $(p_c - p_p)$ is defined as the effective confining pressure.

Handin further showed that the internal friction is reduced because the normal pressure across the failure plane is lowered by the amount of pore pressure, not because the coefficient of friction is affected (Figure 11).

$$\tau = \tau_0 + (S_n - p_p) \tan \phi \quad (2)$$

where $S_n - p_p$ is the effective normal pressure.

From tests conducted at various pore and confining pressures, Handin concluded that the important mechanical properties—ultimate strength and ductility—are functions of the effective stresses. As the effective confining pressure is reduced, failure is facilitated, especially brittle failure by fracturing and faulting. Fracture implies total loss of cohesion and resistance to stress difference, separation into two or more parts and the release of stored elastic strain energy (potential energy) (Donath, 1968).²

²Ibid.
Figure 10. States of stress developed in dry (left) and fluid-saturated (right) homogeneous triaxial test specimens. Symbols $S$ and $\sigma$ denote total and effective stress, respectively. $p_c$ and $p_0$ denote confining and pore pressure, respectively. $\Delta S$ is axial differential stress. Angle $\theta$ measures inclination of faults relative to maximum principal pressure (Handin, et al., 1963).
$s_1 > s_2 = s_3 = p_c$

$s_1 = \Delta s + p_c$

$\sigma_1 > \sigma_2 = \sigma_3 = p_c - p_p$

$\sigma_1 = \Delta s + p_c - p_p$
Figure 11. Mohr diagram showing that an increase in pore pressure can cause failure because normal stress is lowered, while the coefficient of friction remains unaffected (Hubbert and Ruby, 1959)
When the effective confining pressure is low, frictional resistance is low, macroscopic shear failure occurs readily at low differential stress. High pore pressure cushions grains so there is little grain breakage. Intergranular movement is easy and porosity increases.

When the effective confining pressure is zero, the principal resistance to deformation is the low cohesive shearing strength (Equation 2). The rock deforms by intergranular movements and becomes dilatant.

Thus fracturing could be facilitated in the early stages of folding under moderate compressive stresses provided that the effective confining pressure is relatively low.

Hubbert and Rubey (1959) defined normal and abnormally high fluid pressures in sedimentary rocks. Normal fluid pressure is the water pressure in a given stratum which will support a static column of water extending to the surface of the ground or to the water table, that is the height equals the depth to the water bearing stratum. Abnormally high pressures may support water columns whose lengths are on the order of twice the depth. For such contrasts normal pressure may be considered hydrostatic. Formation pressure, whether normal or abnormal lowers the effective overburden pressure in porous rocks, thus strength is reduced at all depths. A system in which the formation pressure is "abnormal" has an excess of about 0.5 of the
formation pressure. This is not in equilibrium and must be isolated by some kind of permeability barrier (Handin, 1964).

Granular material cannot flow within beds unless the sediment is dilated by fluids to such an extent that individual grains no longer interlock (Duncan, 1964). Reynolds (1954) proposed that the industrial process known as fluidization, which is the transportation of solid or liquid particles by gas flow, as a geologic process that might be the cause of pebble breccias and pebble dikes. Fluidization, Reynolds continued, could conceivably cause selective transportation to allow subsidence of larger fragments and ascension of smaller ones—a process that has taken place in some pebble dikes. General or good fluidization of a bed is reached wherein each particle is surrounded by a liquid film and is in an agitated state although there is little or no mixing of solid particles (Shuster, 1952). As this state of general fluidization is reached, the fluid velocity increases and the pressure across the bed drops (Lewis, 1952).

In order for fluidization to occur within a sedimentary bed, the formation pressure in the bed must build up to the extent that the flotation limit of the overburden is reached (Duncan, 1964).

Hubbert and Rubey (1959) have demonstrated that it is possible for abnormal hydrostatic pressure to be built up due
to rapid accumulation of overburden and regional tectonic compression of the rocks and contained pore water.

Handin (1963) further stated that the commonest cause of abnormal pressure is the very rapid deposition of thick sections of fine-grained sediments which are impermeable to the extent that their connate water has not been fully expelled and the sediments are undercompacted. The interstitial fluid supports most of the weight of the superincumbent rock and very high disequilibrium pressures can be retained for long periods of geological time.

Abnormal formation pressures will strongly affect the deformation of the rocks in which they occur. The internal friction and hence the strength would become lower than the superadjacent rock. Deformation would tend to be localized within the high pressure zone. Here the rocks would also have low bulk densities and would be gravitationally unstable (Handin, 1963).

Mechanics of Intrusion in the Study Area

The sedimentary section in the area of study lends itself admirably to the foregoing ideas and conclusions (Figure 2). The Cretaceous section in the area is predominately one of thick black bentonitic siltstones, with the exception of the highly siliceous Mowry, and thin interbedded sandstones.

The relatively thin Peay sandstone itself is
overlain by a black bentonitic siltstone sequence. The Torchlight sandstone, another relatively thin unit, caps the Frontier and the 3000 feet of predominately black shale Cody formation lies above it. Subjacentely, the Peay is bounded locally by a thin bentonitic black shale. Directly beneath this occurs the very brittle, siliceous Mowry shale.

The black shales could act as an impermeable barrier which would effectively seal the Peay sandstone. With additional deposition and beginnings of compressive forces of the Laramide orogeny, water within the shales could have been expelled into the more porous sandstone and an abnormal formation pressure developed. This abnormally high formation pressure would have reduced the effective confining pressure to a low level or perhaps to zero. Thus a moderate horizontal compressive stress could rather easily have initiated fracturing with the resultant loss of cohesion and local increases in porosity and a dilatant bed. It was suggested earlier that, although all the fractures are considered to have formed early in the folding, the field evidence indicates that fractures formed both before and after dike emplacement.

During the initial stages of tectonism, pore water would be squeezed out of the Mowry into the Peay, thus increasing the Mowry's effective confining pressure, while at the same time, as mentioned above, the effective confining pressure of the Peay
would be lowered. This mechanism would necessitate increased tectonism to initiate faulting or fracturing in the Mowry. During this early phase the already abnormal pore pressure in the confined Peay sandstone would build up to the point where it would literally explode when released resulting in a forceful intrusion.

The dike emplacement represents a critical time or event in the early stage of folding. This critical time would occur when the Mowry became competent enough and the compressive forces great enough to allow development of the fractures which would trigger the release of the abnormal pore pressure in the overlying Peay sandstone. The critical timing and the forcefulness of the intrusion also suggests that the dikes may have opened their own fractures. Lemish (1958) suggested that pebble dikes in the Topia Mining District of Durango, Mexico opened their own fissure by forceful intrusion since there was a lack of definite relationship to the structural pattern.

It is felt that the dikes represent major fractures or faults developed in the Peay and underlying Mowry before the Mowry became competent enough to undergo the brittle failure that it shows today. The occurrence of these finely spaced joints in the Mowry and the dikes and the offsetting mentioned earlier would further suggest this time relationship.

The writer considers that fluidization of the Peay sand-
stone in and near these critical fractures took place with the release of the abnormally high pore pressure. The relatively small number of dikes suggest that the pore pressure was not uniformly distributed throughout the sandstone. In industry, an undesirable condition in a fluidized bed may provide a model of the conditions that occur in a relatively thin bed of granular sedimentary material. According to Flood and Lee (1968), stagnant regions can develop in a fluidized bed, which is quite thin with respect to its diameter. The solid material is fluidized only in the immediate vicinity of the holes of a gas distributor (Figure 12a). Furthermore, when a bed is not uniformly fluidized, a condition known as channeling results wherein the gas takes a preferential path through the bed (Figure 12b).

In a relatively thin bed of sedimentary granular material, the pore pressure would become nonuniform upon fracturing. The fractures would become preferential paths for fluidized materials and the pore pressure gradient would decrease towards the fracture. The portions of the bed between fractures could be analogous to the stagnant portions of a too shallow bed in industrial fluidization. In the Peay, distribution of pore pressure may have been further localized by its variable thickness and the more rapid rate of deformation in the areas of the noses of the folds and changes in strike.

The extent of fluidization and the effects of a pore
Figure 12a. Stagnant regions which develop in a fluidized bed which is too shallow. Only the particles of solid material near the holes of the gas distributor are well fluidized (Flood and Lee, 1968)

Figure 12b. Poor distribution of gas in fluidized bed can result in a condition called channeling (Flood and Lee, 1968)
Fluidized Regions

Stagnant Regions

GAS

Channel

GAS
pressure gradient on either side of a fracture may be partially reconstructed from the height that the dikes penetrated the Peay and the amount of sandstone in the dikes. As mentioned earlier, five dikes penetrated the Peay for vertical distances up to sixty feet above the contact. Using the average figures for thickness, 3', and horizontal and vertical extent, 640' and 325' respectively, the average dike contains approximately 625,000 cubic feet of sand. For every horizontal foot of extent, there is approximately 975 cubic feet of sand in the vertical direction. If the average thickness of the Peay is considered to be 50' (thickness varies up to 100'), the effect of the pore pressure gradient would be felt a minimum of 10' on either side of the dike and would probably be much greater than this since no abrupt thinning was noticed in the Peay as the dikes were approached.

Handin (1963) stated that material in the high pressure zone would be gravitationally unstable, that it would move upward and penetrate the overburden. It is felt here that the fluidized material would move downward because the Mowry achieved sufficient competency to allow fracturing before the overlying bentonitic black shales.

The mechanism here in discussed would be one of elastic expansion similar to one described by Reynolds after Walton (1954) wherein a clastic dike had intruded a dolerite sill. Water in the sediments below the sill was vaporized by the heat
of the intrusion. In response to a local decrease in pressure, caused by the fracturing of the sill, the water vapor expanded and swept the clastic material into the fracture as a suspen-
soid. The expanding vapor is likened to the release of abnormally high pore pressure.

Duncan (1964) envisioned sediments being put in a mobile condition by release of a confined high hydrostatic pressures in the emplacement of clastic dikes in California.

In describing a pebble-breccia dike, Bryner (1961) states that: "It would seem to have been produced by a milling action in which the rock fragments were actively suspended in an actively circulating medium such as water or gas. In this state this pebble breccia may have had intrusive mobility, although portions of it may have been formed more or less in place."
CONCLUSIONS AND SUGGESTIONS
FOR FUTURE STUDY

The conclusions reached in this study are:

1. The fracture pattern in the area was established in the early stages of folding by compressive forces acting horizontally in a NE-SW direction.

2. The clastic dikes were derived from the Peay sandstone of the Frontier formation and were forcefully injected down into the underlying beds during the early stages of folding. This injection was accomplished by fluidization of materials in certain critical zones of fracture upon release of an abnormally high pore pressure. The dike emplacement represents a critical time in the early stage of folding when the Mowry became competent enough to fracture and trigger the release of the abnormal pore pressure in the overlying Peay sandstone. The dikes were subsequently jointed and offset as continuing tectonism rotated them and the surrounding beds to their present position.

Future field work on this problem should include complete mapping of the fractures and faults in the areas of the dikes, more detailed mapping of the dikes for any linear features, and measurements on the Peay to determine thinning in the areas of the dikes. Other work should include some petrographic studies
on the flow structures to determine a preferential grain orientation with respect to the direction of flow.
LITERATURE CITED


ACKNOWLEDGMENTS

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## APPENDIX

### Joint Orientation Data

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Plate 1. Geology with dike areas
Missing Pages

Plate 1 was lost from the original text and therefore cannot be restored.
Plate 2. Individual dike areas with fracture rosettes
Plate 3. Structural axes with fracture rosettes
PLATE 3
STRUCTURAL AXES WITH FRACTURE ROSETTES
CORRECTED TO A HORIZONTAL REFERENCE PLAN

1-9. Fractures on the Mowry and Frontier
1a-10a. Fractures on the Sykes Mountain and Tensleep

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miles