TYPES OF STRUCTURES
IN SOUTHERN SASKATCHEWAN

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by

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Written under the supervision of

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TYPES OF STRUCTURES IN SOUTHERN SASKATCHEWAN

By Jack Wild

ABSTRACT

Nontectonic structures in Saskatchewan comprise gravity, chemical, glacial and reef structures. Gravity structures are those due to slumping, unloading, caving, and features associated with unconformities such as compaction structures. Chemical structures include salt solution phenomena.

Tectonic structures, such as folds, faults, and jointing, can be observed in Southern Saskatchewan. Faulting is indicated in the Avonlea, North Portal, and Woodpile Coulee areas. Tectonic folds are found at Wood Mountain and Elbow. Jointing is common in several bedrock areas.

There is some evidence that both tectonic and nontectonic structures are in some places expressed on the present topographic surface through thousands of feet of sediment, despite the presence of a glacial mantle.

The study reveals that the origin of many structures is but little understood. Further research on some fundamental geological problems such as the magnitude of original dips, compaction, and salt solution is called for.

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INTRODUCTION

Subject of Thesis

This thesis deals with the various types of geologic structures encountered in the subsurface or at the surface in Saskatchewan outside the Precambrian Shield. Not all the known structures of the area are considered, but only a few of the more prominent are discussed to illustrate each structural type. An attempt was made to detect any surface expression of structures known only from subsurface information.

The structures are arranged according to their postulated origin (Table 1). The origins proposed for some of the structures may not be acceptable to all geologists, but alternative interpretations are considered. The author has placed polygenetic structures under what he considers the most common origin.

Location and Definition of Area

The region considered in this thesis comprises that portion of the province of Saskatchewan in which the bedrock is Cambrian or younger in age and which lies south of the exposed part of the Precambrian Shield. This region will be referred to as "Southern Saskatchewan". It is bounded to the south by the international boundary, to the east by the Manitoba-Saskatchewan provincial border, to the west by the Alberta-Saskatchewan provincial border, and to the north by the southern margin of the
TABLE 1. - CLASSIFICATION OF STRUCTURES IN SOUTHERN SASKATCHEWAN

<table>
<thead>
<tr>
<th>Class</th>
<th>Type</th>
<th>Subtype</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nontectonic</td>
<td>Gravity</td>
<td>Slump</td>
<td>Swift Current creek, Davis creek</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Unloading</td>
<td>Damsite, South Saskatchewan river</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Caving</td>
<td>Coleville-Buffalo Coulee</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Original Dip</td>
<td>Battle Creek</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Compaction</td>
<td>Nottingham</td>
</tr>
<tr>
<td></td>
<td>Chemical</td>
<td>Dissolution</td>
<td>Simple: Venn, Bladworth</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Compound: Cantuar</td>
</tr>
<tr>
<td></td>
<td>Glacial</td>
<td>Ice Thrust</td>
<td>Claybank</td>
</tr>
<tr>
<td>Sedimentary</td>
<td>Reef</td>
<td></td>
<td>Bladworth North</td>
</tr>
<tr>
<td>Tectonic</td>
<td>Fractures</td>
<td>Joints</td>
<td>Cypress Hills, Wood Mountain</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Faults</td>
<td>Woodpile Coulee, Elbow, North Portal, Avonlea</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Southwest, Avonlea</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Folds</td>
<td>Elbow, Wood Mountain</td>
</tr>
</tbody>
</table>
FIGURE 1. SOUTHERN SASKATCHEWAN

Horizontal scale approximately 1 inch to 300 miles
Precambrian Shield or roughly by a line extending from 101° long., 54° lat. to 110° long., 57° lat. (Fig. 1). The Precambrian Shield of Saskatchewan is in places covered by sediments which may be post-Precambrian in age, such as the Athabasca sandstone (Gussow, 1959), but these are not further considered. The rocks of Southern Saskatchewan range in age from Cambrian to Quaternary.

**Previous Work**

Structures of either surficial or deep-seated origin noticeable on the surface have been mapped by several geologists during field mapping in Southern Saskatchewan. The writer searched the literature for references to surface structures and the accompanying list is believed to include all pertinent titles. Bishop (1954) was the first to present a comprehensive treatment of all types of structures in Southern Saskatchewan.

It is held by many geologists that in Saskatchewan a thick mantle of glacial material obscures any expression of pre-glacial structural elements such as folds and faults. Kupsch (1956) showed, however, that deep-seated folds may be expressed at the surface. Lineaments in the Avonlea area are probable fault traces visible through a cover of glacial lake clay (Kupsch and Wild, 1958).

**Present Study**

The writer attempts to present a classification and discussion of all structural types encountered in Southern Saskatchewan.
Each structural type is first discussed in general terms. This discussion is followed by an example. Finally, a correlation of the subsurface structure with the present topography is, where possible, attempted.

Both surface and subsurface structural data were obtained from the literature, from personal communications, from geophysical and structural maps published by the Saskatchewan Department of Mineral Resources, and from maps and reports published by the Geological Survey of Canada.

Topographic control on a regional scale was supplied by a topographic map on a scale of 1 inch to 8 miles with 100 foot contours (Kupsch, 1958). More detail was provided by the sectional sheets on a scale of 1 inch to 3 miles and by the newer topographic maps on a scale of 1:50,000, both published by the Surveys and Mapping Branch, Canada Department of Mines and National Resources. Airphoto mosaics were supplied by Imperial Oil Limited.

Acknowledgements

This thesis was prepared under the supervision of Dr. W. O. Kupsch, Department of Geology, University of Saskatchewan, to whom the author is indebted for suggesting the topic together with guidance and constructive criticism throughout the preparation of the paper.

Thanks are due to the Texaco Exploration Company for assisting the writer with the collection of geologic material such as well
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Financial assistance in the form of a fellowship from the California Standard Company is gratefully acknowledged.

DEFINITION OF NONTECTONIC STRUCTURES

Nontectonic processes are defined by Billings (1954, p. 233) as follows:

"By nontectonic processes are meant those processes that are not directly related to movements within the outer shell of the earth. In many cases the term surficial processes would be equally good because the deformation is the result of movements near the surface of the earth under the influence of gravity. Even in these instances, however, the deformation is usually an indirect result of movements within the earth."

Billings (1954, p. 233) classifies nontectonic structures into three major categories: (1) those formed near the surface under the influence of gravity, including those formed by hillside creep, collapse structures, cambers, dip-and-fault structures, bulges, landslides, and differential compaction by sediments; (2) those related to chemical processes including salt solution phenomena and expansion due to change in volume; and (3) those related to glaciation.
These three categories will in the following be referred to as (1) gravity structures, (2) chemical structures, and (3) glacial structures. In addition the writer recognizes (4) sedimentary structures such as reefs.

GRAVITY STRUCTURES

Slump Structures

General description. - Removal of support causes faulting which is nontectonic in origin. Most of the slump deposits observed along major streams and rivers are a result of removal of support by the eroding stream. The blocks are separated from one another by fractures which are nontectonic faults (Fig. 2A).

Example. - Slumping may be observed along the banks of the Saskatchewan River at many points, mainly where the river has cut through the glacial deposits into the underlying Bearpaw formation. Where the bedrock under the glacial mantle is the Belly River formation, slumping does not occur even if the river cuts through the glacial deposits. It should be understood that the Bearpaw formation is mainly a shale, whereas the Belly River formation is predominantly a sandstone. Upon exposure, the Bearpaw shales take on water and gain volume with a consequent loss in shear strength. They are therefore more susceptible to slumping than the indurated Belly River sandstones which do not change in volume or strength when taking up water.

Surface expression. - Fig. 3 is a picture showing a typical
FIGURE 2. NONTECTONIC FAULT STRUCTURES

(a) Slump structure
(b) Unloading structure
(c) Caving structure
(d) Dissolution structure
slump deposit along Swift Current creek in southwestern Saskatchewan after Christiansen (1959, p. 22). Another more detailed view of slump structures along Davis creek south of Belanger in the Cypress Hills is presented in Figure 3a.

Unloading Structures

General description. - Faulting attributable to unloading is caused by removal of overlying sediments and subsequent rebound of the underlying rocks (Fig. 2B). Fracturing may occur at a point where a lateral facies change occurs, or where an incongruity of depositional structure exists, or where unloading has not progressed to an equivalent point.

Example and expression. - Peterson (1958) has described rebound effects in the Bearpaw shale at the site of the South Saskatchewan River dam now being constructed about 60 miles south of Saskatoon, Saskatchewan. He notes that the rebound can be divided into two phases, the first being elastic rebound which occurs immediately upon release of load and varies directly with the load, and a second or "time rebound" phase which takes place over many thousands of years. The time rebound involves swelling and increase in water content, and is the opposite of consolidation. Figure 4 is a reproduction of one of Peterson's illustrations (1958, pl. 1) showing the phenomenon. Note that the line separating the disturbed and unaffected areas may be considered a non-tectonic fault-line scarp.

The writer feels that Peterson's example is analogous to
FIGURE 3. SLUMPING ALONG SWIFT CURRENT CREEK

After Christiansen, 1959, p. 22
FIGURE 3a. SLUMPING ALONG DAVIS CREEK
FIGURE 4. UNLOADING STRUCTURES

Typical river-bank topography, South Saskatchewan river.

After Peterson, 1958, Fig. 2
slumping as defined previously. Undoubtedly the "time rebound" is an important factor in the formation of unloading structures, but the processes involved during "time rebound" are equally necessary in the formation of simple slump phenomena. Therefore, it is felt that if Peterson's example is one of unloading structure, it serves equally as well as an example of a slump structure. So closely allied are the two types that probably one type of structure, preferably slump structure, would suffice for a description of either phenomenon.

**Caving Structures**

**General description.**—Caving and cave faulting is a special case of slumping since commonly chemical processes precede the gravitational action. Slumping or faulting takes place in limestone caves where circulating groundwater has removed support by dissolving calcium carbonate to the point where the weight of the overburden exceeds the strength of the retaining walls (Fig. 2C). The faulting generally takes place along pre-existing joints in the limestone. Cave faulting has been postulated by some geologists in a few localities of Paleozoic rocks in Saskatchewan.

It should be noted that there is great similarity between faults formed by the above mechanism and collapse structures formed by solution of evaporites and subsequent collapse of overlying sediments. The difference exists only in the sediment which was dissolved.
Example. - In the Coleville-Buffalo Coulee area of west-central Southern Saskatchewan, structural contours on the Mississippian Exshaw formation show a northwesterly trending series of parallel anticlines and synclines. A number of closed lows are also present. Table 2 is a generalized stratigraphic section in the Coleville-Buffalo Coulee area. Reasoner and Hunt (1954, Fig. 2 and p. 1542) postulate that these structural features are due to caving during or following the post-Mississippian erosional interval. The two synclines mapped on the Exshaw formation approximately occupy deep river courses on the Paleozoic erosion surface and the anticlines occur in the interstream areas. Reasoner and Hunt (1954, p. 1542) believe that, once the streams had removed all the Mississippian cover in the channels while they were actively downcutting, the water was able to attack underlying Devonian Potlatch anhydrite. Leaching of the anhydrite would progress laterally as well as vertically, and hence there would be a gradational thinning of the Potlatch anhydrite toward the ancient valleys. The overlying Exshaw formation, when examined structurally, would therefore give the appearance of alternating anticlines and synclines provided the drainage channels were parallel. Reasoner and Hunt (1954, p. 1542) attribute the closed lows on the Exshaw surface as reflecting sinkholes on the Potlatch anhydrite. They also offer the alternate explanation that the anticlines and synclines may be caused by folding due to compression, but they believe that the structures are more probably a result of leaching and caving of the Potlatch anhydrites during the Paleozoic erosion.
### TABLE 2. GENERALIZED PALEOZOIC STRATIGRAPHIC SECTION IN COLEVILLE-BUFFALO COULEE AREA

<table>
<thead>
<tr>
<th>Period</th>
<th>Epoch</th>
<th>Group</th>
<th>Formation</th>
<th>Member</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mississippian</td>
<td></td>
<td>Madison</td>
<td>Lodgepole</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Exshaw (Bakken)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Three Forks</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Upper</td>
<td>Potlatch</td>
<td></td>
<td>Anhydrite Dolomite</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Saskatchewan</td>
<td>Nisku (Beaverhill Lake)</td>
<td></td>
</tr>
<tr>
<td>Devonian</td>
<td></td>
<td>Manitoba</td>
<td>Souris River</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Dawson Bay</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Middle</td>
<td>Elk Point</td>
<td>Prairie Evaporites</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Winnipegosis</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Ashern</td>
<td></td>
</tr>
<tr>
<td>Silurian</td>
<td></td>
<td>Interlake</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The present author believes that the anticlines and synclines are more probably the result of tectonism. Firstly, most drainage patterns are influenced to some degree by pre-existing bedrock structure, and some of the streams may occupy synclinal trends. Therefore it can be argued that the river channels on the Paleozoic erosional surface are likely to reflect some structural control. Secondly, although the Paleozoic erosional channels approximately coincide with the axes of the folds (Reasoner and Hunt, 1954, Figs. 2 and 3, p. 1541 and 1543) they are not exactly coincident, which would be expected if the channels caused the structural trends. The drainage pattern over the interstream areas is also suggestive of anticlinal structure. The Potlatch dolomite was exposed during Paleozoic erosion and the sinkholes evident on the Exshaw formation may be a result of groundwater circulating within this unit forming caves which collapsed leaving closed structural lows on the present Exshaw surface.

Modification of the structures at Coleville and Buffalo Coulee by leaching of the Potlatch anhydrite could well occur, but the writer believes that the structures are primarily tectonic in origin.

The possibility has been pointed out (Reasoner and Hunt, 1954, p. 1542) that these structures may be due to salt solution of the Middle Devonian Prairie Evaporites formation. The proof of any of these three possibilities for the origin of the Coleville and Buffalo Coulee structures, i.e.: Potlatch anhydrite solution, tectonism, or Prairie Evaporite salt solution, awaits detailed pre-Devonian subsurface control.
The Coleville-Buffalo Coulee area is the only area the present writer knows of in which caving phenomena occurs which is possibly due to causes other than salt solution. Since carbonates are widespread in the Paleozoic rocks of Southern Saskatchewan, other areas of carbonate caving are undoubtedly present, but undescribed.

**Surface expression.** Airphoto mosaics of the Coleville-Buffalo Coulee area show little topographic expression of the subsurface features illustrated by Reasoner and Hunt (1954, Figs. 2 and 3, p. 1541 and 1543). The southeastern part of the area shown on their map is covered by glacial lake sediments which effectively obscure any structural expression which may be present. The structural high shown on their Paleozoic erosional surface map in T. 33, R. 24, W 3 Mer. is coincident with both tonal halos and drainage anomalies on the airphoto mosaic, which may or may not be a surface expression of the subsurface structure. This is shown in Figure 5.

**Original Dip Structures**

**General description.** Some structures result from the deposition of strata having an original dip on the flank of a pre-existing topographic "high" or buried hill. Later compaction generally helps to emphasize such structures.

Wilson (1948, p. 1797) states that clays are least likely to accumulate on steep slopes and are more easily distributed by wave and current action. He also mentions that in other clastic sediments the coarser and more angular grains tend to stand on
FIGURE 5. AIRPHOTO MOSAIC AND PALEOZOIC STRUCTURAL CLOSURES

Coleville-Buffalo Coulee area

Structural closures after Reasoner and Hunt, 1954, Fig. 3
the steepest subaqueous slopes. Dake and Bridge (1952) show that sandstones can stand on slopes of 300 feet per mile and greater. They also point out that dips, which are believed to be initial, in limestones may be as high as 30°.

Example.— The Battle Creek area is located 45 miles south of Maple Creek in the extreme southwestern part of Saskatchewan. Figure 6 presents a Cambrian isopach in the area which shows that in the Battle Creek well a thinner than normal Cambrian section was encountered. This suggests the presence of a Precambrian buried "hill" which, however, is only insufficiently known for lack of information. The Shell Govenlock well did not penetrate the entire Cambrian section, but the section drilled is thicker than the entire Cambrian in the Battle Creek well. The isopach (Fig. 6) suggests that the "hill" is probably not a very high feature. A seismic map on the Precambrian surface was not available to the author, and hence it was not possible to gain an exact idea of the slope on the flanks of this buried hill. However, seismic maps on both Paleozoic and Mesozoic reflection horizons show a thinning in the overlying beds and a quaquaversal dip away from the point at which the Battle Creek well was drilled. The rate of dip decreases from roughly 100 feet per mile at the Nisku level to about 50 feet per mile at the Blairmore level. The Paleozoic structure as shown by seismic contours is illustrated in Figure 7.

In the Battle Creek area the Cambrian rocks are predominantly shale. This is noteworthy because shales are known to be easily compacted, and the structure may not be entirely due to original
FIGURE 6. CAMBRIAN ISOPACH, BATTLE CREEK AREA

Scale 1 inch equals approximately 20 miles
FIGURE 7. SEISMIC STRUCTURE AND STREAM DRAINAGE, BATTLE CREEK AREA

dip but may have been emphasized by differential compaction or it may have resulted entirely from differential compaction.

Although the predominant Cambrian rocks in the Battle Creek area are shales, in the Battle Creek well itself, the Cambrian section is much more sandy than in the other wells. This may be due to winnowing of the argillaceous sediments on the Precambrian topographic high, or, the section may represent the basal part of the Cambrian sequence which in most places is very arenaceous. If the basal sandy member was deposited in the area of the Battle Creek well, it is reasonable to assume that the sediments had an initial dip in order to explain the structure.

If the slopes on the flanks of the Precambrian high are assumed to have been twice those presently observed on the Nisku, which are 100 feet per mile, it is still possible that the sediments had an original dip because original dips of such magnitude have been reported from elsewhere (Dake and Bridge, 1932, p. 636-638).

Unfortunately, lack of close subsurface control makes it impossible to check for initial dip features in the various Cambrian units.

The Precambrian consists of granite in the Dorell well (Fig. 6) whereas it is quartzite in the Battle Creek well where the Precambrian surface is high. It is reasonable to expect that quartzite is more resistant to erosion, and thus stood above the surrounding terrain in Cambrian time when deposition took place.

The dip on the various higher reflection horizons of seismic surveys makes it reasonable to assume that compaction has also
taken place over the buried paleotopographic high, and also, perhaps, recent uplifts.

It has been suggested that the Battle Creek structure is due to doming of the sediments by an igneous plug. However, this suggestion is not held to be valid because no igneous rocks were encountered above the Precambrian in any of the wells. It is realized, however, that more well control is necessary to settle the problem of the origin of the Battle Creek structure. Other structures similar to that at Battle Creek may be seen on the isopach (Fig. 6).

**Surface expression.**—On the present-day erosion surface a radial drainage pattern surrounds the Battle Creek well location, indicating a topographically high area. The glacial mantle is thin in this region, and much bedrock is exposed. Figure 7 shows the drainage pattern in the area, as well as the Paleozoic seismic interpretation. Unfortunately, geophysical control was not available to the writer for the area to the west.

**Compaction Structures**

**General description.**—Compaction structures form as a result of loss of water by newly-deposited sediments during subsequent deposition with a consequent loss in volume by the deposit giving up water. Shales contain the most water when laid down and consequently lose a greater volume when under load. Also, shales are plastic by nature and tend to compress readily. Sandstones, on the other hand, are relatively incompactable, and will not
lose much volume. If sediments are deposited over an uneven surface such as an erosion surface, later compaction will cause structural deformation of these sediments, which will, in a modified and smoothed form, reflect the topography on the underlying erosion surface.

**Example.** - The Nottingham oil field in southeastern Saskatchewan is an example of a buried hill. Structure contours on top of the Mississippian erosional surface show a hill about 100 feet high and with an areal extent of about five square miles. Edie (1958, p. 111) states:

"Considerable topography is present on the Mississippian erosion surface and the topography is reflected in the reduced thickness of the Watrous redbeds over topographic highs."

**Surface expression.** - Regarding the expression in the present topography of the erosional hill on the Mississippian surface at Nottingham, Kupsch (1956, p. 73-74) states the following:

"An interesting tonal halo occurs in part of the Nottingham oil field in southeastern Saskatchewan.....Several producing wells provide data for a contour map on top of the Mississippian erosional surface.....If the tonal halo.....is superimposed on the contour map.....it becomes apparent that close agreement exists between the surface of the Mississippian and the present topography. The tonal halo lies on a low of the Mississippian surrounding a high area and the paleotopography is reflected at the present surface through a total of some 3600 feet of sediments, including at least 200 feet of drift....."

Other erosional hills similar to Nottingham are present at Alida, Arlington, Hastings, Queensdale, Ingolsby, and elsewhere.
CHEMICAL STRUCTURES

Dissolution Structures

General description.—Structures are common in the subsurface of Saskatchewan which involve only Devonian and younger sediments (Fig. 2D). These structures are believed to be the result of leaching of the Middle Devonian Elk Point evaporite beds which attain locally a thickness of as much as 600 feet in central Southern Saskatchewan. Subsequent slumping of the overlying sediments form the structures. These structures will vary depending on the time during which solution took place. The writer has classified the structures as simple dissolution if solution took place during one period. If there were several stages of solution, however, they are classified as compound dissolution structures. Along the flanks of these dissolution structures, minor faulting may be expected. These faults will affect the younger sediments to a greater or lesser extent depending on the amount of salt removed locally.

Bishop (1954, p. 474-485) described some of the structures which he believed due to dissolution, or "salt solution" as he called it. Milner (1956, p. 111) states:

"Local solution of the Devonian salt began some time after the deposition of the Mississippian Mission Canyon formation, but prior to the peneplanation of the Paleozoic rocks, and resulted in the development of downwarped blocks in which excess thickness of Mississippian beds were preserved from the post-Paleozoic erosion. Other areas have been recognized in which the
salt solution and subsequent downwarping took place after the post-Paleozoic erosion, but prior to the deposition of the Jurassic sediments.....

Cases of salt solution in post-Paleozoic but pre-Cretaceous times have also been found.....

Enormous areas of the Prairie Evaporite basin were affected by salt solution of relatively recent times.....

The possible sequence of events which took place in the formation of a compound dissolution structure are described by Milner (1956, p. 111) and are illustrated in Figure 8. In the first stage, the Mississippian strata were exposed to weathering, and salt solution occurred in the Prairie Evaporites salt beds. As the evaporites were removed, the section overlying these rocks began to subside until finally all the evaporites were removed, or solution ceased. Erosion of the Paleozoic rocks continued, leaving an abnormally thick succession of Mississippian strata in the area from where the evaporites were removed.

In the second stage, during Mesozoic sedimentation, strata of uniform thickness were laid down over the entire area. Isopachs of these overlying units show that abnormal thinning or thickening is absent, which by most geologists is interpreted as meaning that at the time of deposition of these overlying sediments, the depositional surface was more or less at the same elevation throughout the area.

In the final stage the flank salt of the Middle Devonian Prairie Evaporites was removed. This supposedly occurred in fairly recent times because Cretaceous beds have the same attitude as older Mesozoic strata. After the flank salt was removed, a "high" is
FIGURE 8. COMPOUND DISSOLUTION STRUCTURES

A. During sedimentation.
B. First stage of salt solution. Beginning of Paleozoic erosion.
C. End of Paleozoic erosion.
D. During Mesozoic sedimentation.
E. Removal of flank salt, pre-Pleistocene to Recent.
apparent in the area where the increased Paleozoic section was preserved.

An alternate solution can be advanced for features similar to those shown in Figure 8E. The Mississippian highs may represent erosional hills on the Paleozoic unconformity. Younger strata of uniform thickness but with some initial dip were then deposited on the flanks and over these hills. The variations in thickness of Devonian salt are in this interpretation believed to be either original or due to salt solution in pre-Mississippian time. Dake and Bridge (1932, p. 629) point out that in the area where they studied initial dip structures, these do not persist vertically more than roughly twice the height of the hill that caused the structure to form. In Saskatchewan, structures of the type as shown in Figure 8E, have abnormal dips persistent for several thousands of feet in the overlying Mesozoic beds on a Mississippian hill of only about a few hundred feet. It is noteworthy though that the dips of the overlying Mesozoic marker beds become less as the surface is approached. It is therefore possible that the structures are a combination of initial dip in the lower strata and compaction in the higher sediments.

Examples of simple dissolution structures.—The Venn structure was first described by Bishop (1953, p. 6), who states that the structure is one which involves the Devonian as well as the younger beds, but not any of the pre-Devonian strata. Figure 9 is a structural cross-section of the Venn area. Bishop (1954, Fig. 2) states that the dip of the section overlying the salt
HORIZONTAL & VERTICAL SCALE: 1 INCH = 1000 FEET

FIGURE 9. NORTH-SOUTH CROSS SECTION THROUGH VENN AREA
decreases progressively upward, and is approximately 175 feet per mile in the Upper Cretaceous sediments immediately underlying the glacial drift. He states further that it is difficult to date accurately the solution and channeling of the salt, but it appears likely that a considerable amount of the solution took place during Middle Devonian times since there is considerable thickening in the Middle Devonian section overlying the salt in the well which has been affected by solution. Further subsidence took place throughout Mesozoic times to account for the present structure.

It has been suggested that the Venn structure could be explained by normal faulting, but Bishop remarks that seismic studies have failed to reveal evidence of faulting (Fig. 9) and that a fault pattern to explain the structure completely would be so complex and require so many coincidences that it becomes unacceptable.

The Bladworth structure can be cited as an example of possible recent salt solution on a small, localized scale. A location map and structural cross-section are presented in Figure 10. Most characteristics of the Bladworth structure appear to be similar to those of the Venn structure, but only two wells were drilled to the pre-Devonian rocks on the Bladworth structure, and not as much information is available here as at Venn where three wells were drilled to the pre-Devonian. Note that a third well, Tidewater Davidson Crown #1, is present, but this well was not drilled to pre-Devonian rocks.

Figure 10 shows that all stratigraphic units which generally comprise evaporite beds have either lost these evaporites or are
Evaporites are shown in red
thinner in the Bladworth well than in the surrounding wells.

Probably fractures in the sediments overlying the Middle Devonian Prairie Evaporites allowed migrating water to remove evaporites from beds considerably higher in the stratigraphic column than the Prairie Evaporites. This leaching of evaporitic beds above the Prairie Evaporites has augmented the structure somewhat. The dip at the top of the Lower Cretaceous Blairmore formation between the two wells is about 155 feet per mile in a northerly direction. At the Milk River (Upper Cretaceous) top, the dip, again in a northerly direction, approximates 165 feet per mile. This increase in dip is due to a greater thickness of the section between the Blairmore top and the Milk River top in the Nash well which may or may not have been affected by salt solution. One theory that accounts for the depositional thickening in the Nash area involves salt solution. If during post-Blairmore deposition some dissolution of Jurassic and Paleozoic evaporites took place in the present location of the Nash well, but did not affect the Bladworth location, a depression would form at the depositional interface in the Nash area causing a depositional thickening in that area of the overlying Cretaceous strata. Sedimentational differences, without assuming salt solution, can also account for the thickening of the Blairmore to Milk River section from the Bladworth well to the Nash well. Firstly, it is known from regional mapping (Wiens, 1959, personal communication) that the direction of regional thickening in the Cretaceous section is southwesterly from the Bladworth location. Therefore, some of the thickening
in the Nash well may be accounted for by regional thickening. Secondly, if a local isopach map is drawn using all available well control in the area, and if the Milk River to Watrous interval is contoured, and it is assumed that after deposition of the Milk River the sea floor was relatively flat, it becomes evident that the Bladworth well location was a topographic high when Cretaceous deposition began. Therefore, it would be expected that depositional thinning would result over the topographic high. This would be accentuated by later compaction. The present writer favors the latter interpretation.

Seismic maps of the region north of the Bladworth and Venn areas indicate the presence of a great number of similar structures.

Example of a compound dissolution structure.—What is believed to be an example of a compound dissolution structure occurs about 20 miles northwest of Swift Current in the general Cantuar area. Figure 11A is a structure contour map on the pre-Devonian surface in this area, which shows that the No. 1 well is abnormally high. This is believed due to a high on the Precambrian surface as indicated from well-log studies in the area. The Cambrian is abnormally thin in the No. 1 well. Figure 11B is an isopach of the Upper Devonian. This shows the No. 2 well to have an abnormally thick Upper Devonian section. The structure map depicting the top of the Devonian (Fig. 11C) shows that the Devonian in the No. 2 well is structurally high even though it is east of the regional salt (Prairie Evaporite) edge. The Milk River (Upper Cretaceous) structure (Fig. 11D) shows this marker in the No. 2
FIGURE 11. CANTUAR AREA COMPOUND DISSOLUTION STRUCTURE

A. Structure contours on pre-Devonian surface; B. Upper Devonian Isopach values;
C. Structure contours on top of Devonian with regional salt edge. Triangles point in direction of present salt; D. Structure contours on top of Milk River.

Approximate scale 1 inch equals 6 miles
well to be still abnormally high.

The present writer believes the sequence of events necessary to account for such a structure may be as follows. After the Prairie Evaporites were laid down over the entire area Upper Devonian sedimentation began. During deposition of the Upper Devonian, salt removal began in the vicinity of the No. 2 well, allowing a greater thickness of Upper Devonian strata to be deposited at this location. Abnormal thickening in the overlying section is also present, and it is therefore assumed that solution of the Prairie Evaporites continued shortly after deposition of the Upper Devonian sediments causing thickening in overlying strata. Later (at least as late as post-Milk River), the remaining salt was removed from the area where the Nos. 1 and 2 wells were drilled, causing a structural "lowering" of the overlying strata.

It should be noted that this example, although similar, is not the same as that indicated in Figure 9. In the Cantuar area the top of the Devonian is not an erosion surface, and hence the thickening cannot be accounted for by erosion. A possible alternative origin is thrust faulting. However, examination of the Devonian section in the No. 2 well and comparison of it with the adjacent wells shows the No. 2 well to have a consistent thickening throughout the Upper Devonian section, and no repetition is present. The author believes, therefore, that this is a true example of compound dissolution.

Other compound dissolution structures occur at Hummingbird and Vanguard. Bishop (1956) believes the structures at Avoulea to
have formed in a similar manner, but the present writer interprets the structure at Avonlea differently. This is discussed later.

**Surface expressions.**- The Venn structure does not appear to be recognizable at the surface.

Aerial photographs of the Bladworth area suggest some correspondence between the seismic trends and the present topography (Fig. 12). This is mainly evident in the direction and curvatures of some large drainage channels. Two long, distinctive lineaments evident on air photographs are possibly the surface expression of faults. Neither well data nor seismic information require the postulation of faults in the subsurface, but it should be kept in mind that detailed subsurface information is not yet available.

The Cantuar compound dissolution structure does not appear to be directly indicated at the surface, but a tonal lineament (Fig. 13) is present in the area which may represent the present position of the regional salt edge as indicated by well control.

**GLACIAL STRUCTURES**

**General Description**

Bishop (1954, p. 483), and others before him, recognized that glacial structures are present in Southern Saskatchewan and states that they commonly exhibit strong folding and faulting which has not been shown to extend more than a few hundred feet below the surface. It is very difficult to show the depth to which structures of glacial origin may affect the bedrock because dense well
FIGURE 12. PALEOZOIC SEISMIC TRENDS AND AIRPHOTO IN BLADWORTH AREA
FIGURE 13. AIRPHOTO MOSAIC OF CANTUAR AREA WITH REGIONAL SALT EDGE

Triangles point towards area with salt
control would be needed to determine this depth. Such control is not available. Moreover, in most wells drilled in Saskatchewan surface casing is set to a depth which would generally be below the lower limits of glacial structures. Therefore, no or only very limited subsurface control is available for study of these structures.

Example

Byers (1959) has described in detail and presented evidence to support a glacial origin for the disturbed condition of the Mesozoic strata near Claybank. Regarding the physical aspects of the deformation, he states (1959, p. 5):

"The major structural features are three parallel overturned thrust folds which trend north 15 degrees east and whose axial planes dip at approximately 40 degrees to the west. They are characterized by thrust faults which also dip west, and by the almost total absence of any trace of an inverted or overturned limb. The beds above the thrust planes...are contorted into small asymmetrical folds, many of which are overturned to the east. The plunge of individual folds ranges from 20 to 35 degrees and may be either to the north or to the south. Thrust faults which can be followed down dip for any appreciable distance invariably become steeper with depth....

Estimates of the vertical extent of the deformation must be based on the thickness of the strata involved in the folding and on the projection of the fold structures......the minimum thickness of sediments is 208 feet. The maximum visible height of the folds in the outcrops is 356 feet. Reasonable projections of the fold structures both above and below the present surface show the maximum vertical extent to be at least 500 to 600 feet. The dip-slip component of movement on the larger thrust faults is estimated to be in the order of 150 to 200 feet."
Byers shows that topographic lineaments, ridges, and depressions parallel the trend of the deformed strata, and that the belt of deformation follows the outlines of a southward embayment in the northeast flank of the Missouri Coteau. Also, the dip of the beds is mainly towards the lowland areas indicating direction of movement or thrust normal to the sides of the embayment. Seismic records indicate the structures' superficial nature.

All of the observed phenomena can be accounted for by the glacial theory only. It is pointed out (Byers, 1959, p. 9) that landslides as a formative mechanism can be discounted because the deformation is not confined to the immediate area of an escarpment. Gravitational gliding may similarly be discounted as the deformation lacks the characteristics of gliding structures, and the superficial nature of the structures bars any explanation involving tectonic movements.

Byers' summary is as follows (1959, p. 10):

"...1. The structures near Claybank are overturned folds characterized by low-angle thrust faults typical of disharmonic superficial folding. 2. The structures involve a minimum of 208 feet of Upper Cretaceous strata and the amplitude of the folds is estimated to be in the order of 500 to 600 feet. 3. The deformation occurs in arcuate belts which parallel the margins of embayments which extend into the escarpment of the Missouri Coteau which faces northeast. 4. The deforming stress is considered to be due to basal slippage or boundary-layer flow of glacial ice within lobes which occupied the embayments. 5. Similar deformation of unconsolidated strata may be expected to occur throughout the prairie provinces wherever a reverse slope opposes the direction of glacial movement."

Other areas of similar deformation occur in the vicinity of Halbrite, 85 miles southeast of Claybank, in the Tit Hills and
Mud Buttes of east central Alberta and in the Misty Hills of east central Alberta (Byers, 1959, p. 8).

SEDIMENTARY STRUCTURES

General Remarks

Primary structures which owe their origin to processes of sedimentation are here termed sedimentary structures. These include sand bars, reefs, cross bedding, graded bedding, rhythmic bedding, ripple marks, mud cracks and other structures. Krumbein and Sloss (1953, p. 95) present a classification of sedimentary structures. The majority of the structures are small in scale and are not further considered in this paper. Only reefs will be discussed herein because of their relatively greater physical dimensions.

General description of reefs.—Mounds, which most geologists believe to be reefs, are common in the Middle Devonian Winnipegosis formation of Saskatchewan. Surface work in Manitoba and subsurface study in Saskatchewan has shown that large reefs grew in Middle Devonian times along a line extending from the Manitoba border to Prince Albert, Saskatchewan, and beyond. These reefs were later traced into the subsurface of the Williston Basin. Check (1956, p. 140) describes these reefs in the Winnipegosis formation as follows:

"Reef building in the formation was formerly believed to be restricted to a belt along the northern edge of the Prairie Evaporite salt. Additional drilling has shown that this original belt extends"
southward to the heart of the salt basin in south-central Saskatchewan. The reefs are believed to lie along general northwest-southeast trends. Maximum reef relief noted was 300 feet. The areal extent of the individual features is believed to be several square miles, but this has not yet been proved by drilling."

Walker (1956, p. 134) believes that the mounds in the Winnipegosis formation are not true reefs, but are formed as a result of incomplete metasomatic replacement of the carbonates by evaporites. He argues that no life could exist in a sea which was of the salinity necessary to deposit the Prairie Evaporites and he assumes that the Prairie Evaporites are contemporaneous with the "reefs". It is more likely, however, that the evaporites were not deposited contemporaneously with the reefs, but that they were precipitated during a later phase when the reefs had grown to such height and extent as to restrict the sea, thus causing evaporites to be deposited. Life was then extinguished, and the reefs ceased to grow. Sloss (1956, p. 11) has pointed out that reefs can grow under conditions of restricted circulation and evaporitic environment. The reefs will grow on the shallow shelf area where evaporation will take place. The heavier brine, however, will not remain in the vicinity of the reefs but will slip down into the deeper parts of the basin by gravity flow. Probably the best argument in favor of calling the mounds in the Winnipegosis formation reefs is the presence of reef-forming organisms found and described by MacLennan and Kamen-Kaye (1954).

The mounds in the Winnipegosis will here be considered true reefs.
Example.- Figure 14 shows a thickening in the Winnipegosis formation which is believed by the present author to represent an area of reefs. The material flanking the reef is somewhat less than 100 feet thick. The reef itself is slightly more than 300 feet thick in places. Insufficient seismic information is as yet available for study, and what is available on reflection horizons above the Devonian illustrates such a random character of anomalous closed lows and highs, that one suspects the effects of salt solution. The lack of velocity contrast between the various Devonian markers makes it impossible to receive reflections from these horizons. Therefore, in mapping reefs with the seismograph in areas such as this much of the interpretation must be based on reflections from horizons above the Devonian. Since these stratigraphically higher strata in this area appear to have been affected to a great extent by salt solution, it is difficult if not impossible to differentiate between anomalies caused by salt solution, and those caused by drape over reefs.

Surface expression.- Figure 14 shows the isopachs of the Winnipegosis overlain on the present topography. There is little indication of the reef on the present topography, and airphoto mosaics of the area which were examined by the author similarly show no indication of the underlying Winnipegosis structure. Because the regional seismic map published by the Saskatchewan Department of Mineral Resources suggests that this area has been greatly influenced by salt solution, it would be difficult to differentiate between features due to salt solution and those due to reefing in the Winnipegosis formation.
FIGURE 14. WINNIPEGOSIS ISOPACH AND SURFACE TOPOGRAPHY

Approximate scale 1 inch equals 8 miles
TECTONIC STRUCTURES IN GENERAL

Subsurface structures in Saskatchewan were at first believed to be present only on a regional scale. Bishop (1954, p. 481) states:

"It will be noted that no mention is made of major faulting at any place in the province, although from the information available it could be argued that many of the local structures could possibly be explained by faulting."

Bishop does not state what is meant by "major", but this is an important factor in consideration of tectonic structures. What may be considered as minor in one area may be regarded as major in another, less tectonically active, area. Further drilling in search of petroleum accumulations has pointed to the existence of many local structures, not all of which can be explained by non-tectonic origins.

The theory of salt solution structures led many geologists to consider any structure whose origin was in doubt as due to salt solution. As a result of this, it has been necessary for anyone advancing a tectonic origin for any given structure to have well control to rocks of pre-Devonian age in order to present adequate proof acceptable to all. Since this is very seldom possible, other criteria for recognition of tectonic structures must be presented.
FRACTURES

Joints

General description of joints. — Hills (1951, p. 99) states:

"A joint is a fracture in a rock mass, along which there has been extremely little or no displacement. At the surface, joints often become open fissures as a result of weathering, but below the zone of weathering they are closed, and sometimes sets of joints in the surface rocks are not represented in depth. Joints develop in sedimentary rocks from a variety of causes, including shrinkage accompanying dehydration, expansion due to weathering, tectonic deformation, and tidal effects in the crust."

The only type of jointing that will be discussed here is that believed due to tectonic deformation.

Examples and surface expression of joints. — Figure 15 is an airphoto mosaic of a portion of the Cypress Hills in extreme southwestern Saskatchewan. Two directions of jointing are easily seen because the joints control the local drainage pattern.

The strongest pattern appears in those areas where the bed-rock unit is the Oligocene Cypress Hills formation (Furnival, 1950, map), and where this formation is not covered by glacial deposits (Johnston and Wickenden, 1931, map).

The writer believes that the jointing is related to the folding in this area. Furnival (1950, map) shows the area in which the Cypress Hills formation outcrops to be anticlinal, and since the Cypress Hills formation is a competent unit (conglomerate and sandstone) it is reasonable to expect that any tectonic activity
Two directions of jointing are evident

FIGURE 15. JOINTING IN THE CYPRESS HILLS
in the area would leave strong fracturing in the unit.

The northeasterly trending joints (Fig. 15) approximate the strike of the beds as shown by Furnival, and are roughly parallel to the axial plane of the fold. The northwesterly joints are perpendicular to the axial plane of the fold.

Billings (1954, p. 117-118) shows how this pattern may result. The joints perpendicular to the axis of the fold may be extension joints resulting from slight elongation parallel to the axis of the fold, and the joints parallel to the axis of the fold may be release joints similar to those that form at right angles to the axis of compression when the load is released.

An alternative origin for the joints parallel to the axial plane of the fold is that they may be due to tension on the convex side of a bent stratum, in this case the Cypress Hills formation. The present author favors the latter interpretation for the formation of the axial plane joints because, as was previously explained, the Cypress Hills formation is composed of hard quartzites and conglomerates, and would ultimately fracture rather than bend under the influence of stress.

It is difficult to analyze properly the joint pattern in the Cypress Hills due to lack of field information and, so far as the author knows, they have not been described in the literature.

Figure 16 is an airphoto mosaic of the area immediately east of the Saskatchewan portion of the Bowdoin uplift. A strong north-northeast joint pattern is evident, with a somewhat weaker system trending north-northwest. As in the Cypress Hills, the drainage
FIGURE 16. JOINTING IN THE WOOD MOUNTAIN AREA
pattern is greatly affected by the joint pattern. The writer believes that this jointing is related to the Bowdoin uplift. The outcrop units belong to the Upper Cretaceous Eastend and Bearpaw formations and to the Tertiary Ravenscrag formation, and the joint pattern is most pronounced in an area of little or no drift (Wickenden, 1931).

As at Cypress Hills, the northeasterly joints parallel the axial plane of the fold (Fig. 19) and the northwesterly joints are approximately perpendicular to the fold axis. An origin similar to that at Cypress Hills is postulated for the Bowdoin joints by the author.

Faults

General remarks.—Faulting is present in several areas of Southern Saskatchewan. It has been found by surface investigations and by drilling. Seismic work by various oil companies has pointed out the existence of faulting, and in some areas examinations of aerial photographs lead observers to suspect the presence of faulting, even though supporting well control is not available.

Examples and expressions of surface faulting.—Woodpile Coulee is located in T. 1, R. 27, W 3 Mer. in extreme southwestern Saskatchewan. In this area, there occurs a small thrust fault which, although not evident on air photographs, is easily interpreted from an examination of the outcrops in the area. Williams and Dyer (1930, p. 85-86) describe this structure as follows:
"Signal Butte is a dome-shaped hill in Montana about 3½ miles south of the center of Tp. 1, Range 29, W. 3rd Mer.

It is a fine example of a quaquaversal structure, or dome, from which the arch has been eroded, exposing some 200 feet of Belly River sandstones and lignites below the bordering rim of Bearpaw shale. A well was bored on this dome for oil, but the record has not been seen.

The structures at Woodpile Coulee and Signal Butte appear to be of the same origin, and it is thought that pressure from the south caused doming in the one case and over-thrusting farther northeast. The faulting has consequently been interpreted as passing into a monoclinal fold forming an extension of the Signal Butte dome.

Bearpaw mountains are situated about 30 miles to the south and appear to bear a similar relation to the structures described above, as that of the Sweet Grass hills to the Sweet Grass arch."

Christiansen (1956, map) shows the existence of a bedrock lineament in the North Portal area of southeastern Saskatchewan.

Regarding this lineament Kupsch (1956, p. 68-69) states:

"A study of the air photographs of the Moose Mountain area (Christiansen, 1956, map) has subsequently revealed a non-glacial lineament more than ten miles long which is in front of, but parallel to the trend of the Missouri Coteau near the town of North Portal, Saskatchewan (Fig. 2). Field investigation of this lineament showed it to be most likely a fault-line scarp, with Ravenscrag beds dipping about 23 degrees to the southwest."

A dip of such a magnitude in this area is suggestive of a fault, because most markers in the stratigraphic column in this region show a regional dip less than 50 feet per mile to the southwest.

Some suggestion of faulting is evident in the Elbow area of central Saskatchewan. That tectonic structures do exist in this
area has been proved by drilling. One fold of considerable
vertical magnitude has been outlined (Fig. 20). Figure 17 is
an airphoto mosaic of the general Elbow area. Note the pronounced
lineament in T. 22, R. 7, W3 Mer. which is possibly the surface
expression of a fault. The folding in the Elbow area will be
discussed in the next chapter.

Lake of the Rivers is located approximately 32 miles southwest
of the Avonlea area. The lake itself occupies a portion of an
abandoned river channel, and hence is long and narrow in shape.
Figure 18 is an airphoto mosaic of the lake and adjacent terrain.
In the center of T. 10, R. 28, W. 2 Mer. a lineament transverse
to the lake's trend may be noted. This lineament strikes approxi-
mately north 30° east, and possibly represents a fault. The
Regina Sheet (Fraser et al., 1935, map) indicates that outcrops
of Eastend formation occur on both sides of this lineament, and
the accompanying report makes no mention of faulting. However,
Fraser et al. (1935, p. 25) do mention that in the area of Lake
of the Rivers, the thickness of Eastend varies considerably, and
that in this area the lower boundary of the formation is indefinite,
and difficult to separate from the underlying Bearpaw formation.
The author suggests that some of the thinning of the Eastend for-
mation in this area could be attributable to faulting, and not
to deposition. Further field work would be required to substan-
tiate or refute this contention.

The origin of the Lake of the Rivers lineament is possibly re-
lated to that of lineaments near Avonlea which will be discussed
FIGURE 17. AIRPHOTO MOSAIC IN ELBOW AREA

Note lineament trending northeasterly in the eastern portion of the mosaic (white arrows)
FIGURE 18. AIRPHOTO MOSAIC OF LAKE OF THE RIVERS

Lineament is indicated by white arrows
below. This is because the strike of the Lake of the Rivers lineament approximates that of the B set of lineaments in the Avonlea area (Kupsch and Wild, 1958, Fig. 3, p. 131).

Example and surface expression of subsurface faulting. Faulting in the Avonlea area of south-central Saskatchewan has been described and origins for the faulting proposed by many authors (Bishop, 1956, p. 235-236; Edie, 1956, p. 129-133; Fraser et al., 1935, 137 pp.; Wickenden and Graham, 1937, 13 pp.; Kupsch and Wild, 1958, p. 127-134). Warren (in Fraser et al., 1935, p. 61, and Regina map sheet) mapped two large surface faults south and east of the town of Avonlea. More detailed study was undertaken of the exposed bedrock by Wickenden and Graham (1937). Neither of these two surveys had the advantage of mapping with the aid of air photographs nor had they any substantial subsurface information from wells.

Although Bishop (1956, p. 235) suggests that the faults at Avonlea resulted from salt solution, Kupsch and Wild (1958, p. 133) present the following arguments in favor of a tectonic origin for the faulting at Avonlea:

"1. A fault zone, 35 miles long, is known from field work and study of air photographs near Brockton and Froid in northeastern Montana (Colton and Bateman, 1956, p. 1792). This zone is at the margin of the Middle Devonian Elk Point basin and according to Baillie (1953, pp. 70-71, and Pl. 6) no Elk Point evaporites were encountered in the nearby East Poplar Unit well No. 1. Although it is possible that all the salt was removed by solution subsequent to deposition, the marginal position of this well in respect to the basin makes it more likely that no salt deposition took place. The faulting near Brockton and Froid, similarly situated
as the Avonlea area in respect to the salt basin, is therefore likely to be tectonic.

2. The pattern of the lineaments in the Avonlea area is different from that to be expected if local salt collapse were the cause of the faulting. The distinctive conjugate pattern appears to be the result of stresses affecting the rocks over a wide area. Salt solution would tend to produce a rather irregular localized pattern with a radial tendency over solution caves.

The great length of the A fault (25 miles) and other lineaments parallel with it suggest a regional structure of considerable magnitude. Salt solution, as a possible explanation of assumed faulting in the subsurface of the Avonlea area, is restricted locally. Bishop (1956, p. 235) postulated removal of 400 feet of salt in well 1 at the end of Mississippian time and no removal of salt during that time from well 2 only 5 miles away. During post-Cretaceous time the same amount of salt was then dissolved from underneath well 2, whereas no solution took place in well 1. Such distinctly local phenomena occur in salt solution, but it is difficult to see how they can account for the regional structural framework. Tectonic faulting, on the other hand, equally well accounts for sharp local differences and in addition explains the over-all pattern.

3. The theory of solution collapse does not account for the fact that the faulting is in front of the Missouri Coteau. The part of the Missouri Coteau from near Garrington, North Dakota, to the vicinity of Lucky Lake, Saskatchewan, is a remarkably straight, well defined linear feature, more than 450 miles long.....The A lineaments parallel this trend and the observed A fault is thought to have caused the Missouri Coteau escarpment west of Avonlea. Similarly trending large faults, parallel with, and in front of the Coteau can be observed near Lignite, North Dakota (Townsend and Jenke, 1951, p. 855). Tectonic faulting, possibly of the wrench type, could explain the Missouri Coteau, but it is unlikely that faulting due to salt collapse could produce this major structure.

The presence in the Avonlea area of a Mississippian escarpment (Bishop, 1956, p. 235)
suggests that the Coteau structure was already a topographic feature in post-Mississippian - pre-Jurassic time.

4. The most compelling argument to believe in tectonic faulting in the Avonlea area is the May 15, 1909 earthquake (Heck, 1928, p. 37). The epicenter of this earthquake was at 105° W. Long., 50° N. Lat. This would superimpose the epicenter almost on the A2 lineament (Fig. 3). Even though this may be only a coincidence, the accuracy with which epicentra of earthquakes are calculated would still place the epicenter within the Avonlea area. The strength of this earthquake is recorded as 9 on the Rossi-Forel scale of intensities, which is described as an extremely strong shock. The earthquake was felt over an area of 500,000 square miles and that it did not cause greater destruction is mainly due to the sparsity of settlements in the area. An earthquake of this magnitude is not likely produced by a local mechanism such as salt collapse and a tectonic origin is indicated for the faulting."

It should be pointed out that the presence of faults, either of tectonic or salt-solution origin, is not accepted for the Avonlea area by some geophysicists based on their interpretation of seismic records (Sawatzky et al., 1959). On the other hand, at least one more geologist (Haites, 1959) has advanced compelling arguments in defence of a tectonic origin of subsurface faults in this area, which he believes to be of the wrench fault type.
FOLDS

General Description

Until recently, Southern Saskatchewan could be considered as a relatively unexplored area. At first oil companies operating in the province tested structures mapped at the surface. Although many of the mapped domes and anticlines were later regarded as nontectonic and the result of salt solution, some tectonic folds are present and have been mentioned as such in the literature.

For the most part, folds mappable at the surface involving sediments of Cretaceous and Tertiary age appear to be more numerous in the southwestern part of the province than elsewhere. This may be due to the greater number and better exposures and possibly to the influence of the Sweetgrass arch in southeastern Alberta, and other local uplifts such as the Bearpaw and Little Rocky mountains in adjacent Montana.

Example and Expression of a Surface Fold

The Wood Mountain area as here defined is located between T. 1 and T. 6, R. 10 and R. 19, W. 3 Mer. Figure 19 is a geological map of this area on which subsurface contours on the Mississippian erosional surface are superimposed.

The surface structure of the Wood Mountain area is that of a north plunging anticlinal nose which represents the northern
FIGURE 19. GEOLOGICAL MAP, WOOD MOUNTAIN AREA

Structure contours on top of Mississippian adapted from structural map published by Saskatchewan Dept. Mineral Resources. Surface geology adapted from Fraser et al., 1935, Regina Map Sheet.

Approximate scale, 1 inch equals 8 miles
extremity of the Bowdoin dome, the apex of which is located some 36 miles to the south in Montana. The outcrop pattern shows progressively older sediments appearing in outcrop toward the structurally higher area (Fig. 19). The dip on the structure is very low.

Regarding the structure in Montana, Perry (1953, p. 38) states:

"The Bowdoin dome is roughly circular, about 50 miles across, and has a structural relief (closure) of 700 feet or more. The top of the dome, about 8 by 20 miles across, is divided into eastern (Saco) and western (Bowdoin) parts by a structural saddle with about 100 feet relief, and minor folds extend away from the crests. Dip of strata in nearly all of the area is less than one degree, and in much of the area less than half a degree. Faulting has not been recognized in the domed area. The origin of this dome, 50 miles from other major uplifts, is problematical; some geologists have suggested that it may be the result of deep-seated igneous activity of a laccolithic type in the basal complex, however, no igneous dikes are known to be present."

The present writer feels that, because much additional drilling since 1953 has still not revealed any igneous rocks, a tectonic origin is more likely for the Bowdoin dome.

The low angle of dip of the structure at the surface is readily evident from the drainage pattern which shows little adjustment due to the doming of the underlying sediments. Comparison of the present surface topography (Fig. 19) with the structure on top of the Mississippian shows that the structure is a breached anticline. Elevations in the area of the Belly River exposures in T. 1, R. 13, W. 3 Mer. are similar to those found in T. 4, R. 11, W. 3 Mer. although in this locality the outcrop unit is the Ravenscrag. To
the northwest, in T. 4, R. 15 west to R. 19, W. 3 Mer., the surface elevations on the Ravenscrag are some 400 feet higher than in the area where the Belly River outcrops, but the stratigraphic interval Ravenscrag to Belly River is much greater than 400 feet, being about 1150 feet, indicating that the Belly River is considerably lower structurally in the northwestern part of the map area than in T. 1, R. 13, W. 3 Mer.

Other surface folds have been described in the Cypress Hills (Furnival, 1950).

Example and Expression of a Subsurface Fold

The Elbow structure is located in T. 23, R. 5 and 6, W. 3 Mer. in central Saskatchewan.

Figure 20 shows the present attitude of the pre-Devonian surface in central Saskatchewan. The Elbow structure is not due to drape over a pre-Devonian high, because the overlying beds show no thinning.

As may be seen from Figure 20, the structure shows considerable relief, approximately 550 feet on the pre-Devonian surface. Goudie (1956, Fig. 3) indicates about 600 feet of structural closure at the top of the Blairmore formation.

Goudie (1956, p. 19) offers two hypotheses for the formation of the structure. One hypothesis states that the structure is due to faulting, while the other attributes the folding to salt solution:
"In weighing the hypothesis that the structure has been caused by faulting, the seismic work done in the area must be considered. If a major fault existed in the area and were the primary cause of the structure, it should be detected by seismic shooting. Close control was used in shooting over the Elbow structure, and the resulting seismic pattern is clear and easily followed. The seismic contour map, therefore, does not bear out the premise of major faulting in the post-Paleozoic sediments being the cause of the structure."

Since the folding has been shown to affect the pre-Devonian sediments (Fig. 20) as well as the post-Paleozoic rocks, any faulting, if present, need not necessarily cut the post-Paleozoic sediments. If the faulting involved is a thrust cutting only the pre-Mesozoic sediments, it is highly unlikely that the fault would show on reflection seismic records, especially if it is of the low angle type. With the exception of the Cambrian, it is known that the velocity of shock waves in the Devonian and pre-Devonian systems in Saskatchewan is relatively uniform. This lack of velocity contrast makes it very difficult to detect any faulting in Paleozoic rocks by the reflection method. This lack of velocity contrast between the various Devonian and pre-Devonian formations would also make it almost impossible to detect a low angle thrust by the refraction method. Therefore, the absence of seismic criteria for faulting does not preclude the existence of faults which could be responsible for the Elbow structure.

Goudie states that the hypothesis of salt solution is a more plausible explanation for the formation of the Elbow anomaly. She used cross-sections to show that the structure can be explained
by salt solution, but these cross-sections are unacceptable to the writer. Sections 4 and 5 (Goudie, 1956, p. 20-21) show that no Mississippian exists in the Imperial Elbow No. 1 well, yet several hundreds of feet of Mississippian rocks are reported in the Schedule of Wells for the well in question (Anonymous, 1953, p. 28), and the writer on examining mechanical logs and stratigraphic logs has come to the same conclusion.

Figure 21 is a location map and a structural section across the Elbow structure. It should be noted that even though true scale is employed the feature is quite prominent. The values shown indicate formation or system isopachs. Although unit thickness variations do occur, the writer believes that essentially the systems and formations have enough uniformity in the three wells to indicate a lack of movement at least until post-Milk River time. The presence of the two unconformities can be used to account for the variations present. The possibility that Prairie Evaporites salt solution may have occurred thus causing minor formation thickness differences may not be denied. However, the theory of salt solution cannot account for the large elevation differential on the Ashern formation which directly underlies the Elk Point group, and this is the best argument in favor of a tectonic origin for the dome at Elbow.

Kupsch (1956, p. 67 and Fig. 1) holds that the Elbow structure is expressed at the surface as a topographic high. The fact that the highest point on the present-day hill does not exactly coincide with the highest point on the structure means little, as recent
Approximate scale (horizontal = vertical)
1 inch = 2000 feet

Figure 21. Structural section across elbow structure
Values indicate system or unit thicknesses
erosion could account for this.

The Elbow structure is the only known fold of this type in Saskatchewan.

CONCLUSIONS

Both primary and secondary localized as well as regional structures exist in Southern Saskatchewan, and some of them exert their influence on the present topographic pattern. Not only are such structures present in Southern Saskatchewan, but they are of many different origins. The present study of these has shown that the origin of many structures is far from clear and that further information, particularly with regard to the deeper strata, is needed for satisfactory explanations. Further research should be undertaken on such fundamental geological problems as magnitude of original dip, compaction, and salt solution.
REFERENCES CITED

Goudie, M. A., 1956, The Elbow area of Saskatchewan: Oil in Canada, April 30, p. 18 (14816) - 22 (14820).


