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SHALLOW FOLDING AND FAULTING AROUND THE BEARPAW MOUNTAINS.[1]

FRANK REEVES.

INTRODUCTION.

In a recent article in this journal on the structure of the Bearpaw Mountains[2] the writer described a belt of faulted folds in the plains adjacent to the mountains. As previously described, these folds are unusual in being almost universally faulted, in being uniformly of narrow width, in having between them belts, 1 to 3 miles wide, of practically flat-lying strata, and in their concentric relation in trend and extent to the Bearpaw Mountains, a circular area, about 35 miles in diameter, consisting principally of extrusive rocks. Some of these features are shown in Figs. 1 and 2. The character of the structure is shown in plan in Plate XIII of U. S. Geological Survey Bulletin 751.

Another unusual feature of these faulted folds is the probable shallowness of the deformation. The purpose of this paper is to present the evidence that this folding and faulting is shallow. The conclusions reached are, (1) that only the Upper Cretaceous and early Tertiary strata were involved in the folding and faulting; (2) that the intensity of the deformation continues undiminished to the base of the deformed series; and (3) that the underlying formations also were involved in the horizontal thrust but responded to it without being folded or faulted in any manner that has found expression in the structure of the outcropping beds. The writer's interpretation of the shallow phase of the structure is indicated in Fig. 2.

EXPOSED AND UNEXPOSED FORMATIONS.

The sedimentary formations in the area comprise about 2,800 feet of Paleozoic rocks consisting mostly of thick beds

[1] Published by permission of the Director of the U. S. Geological Survey.
[2] The structure of the Bearpaw Mountains, Montana: this Jour., vol. 8, No. 46, 1924, pp. 302-311.

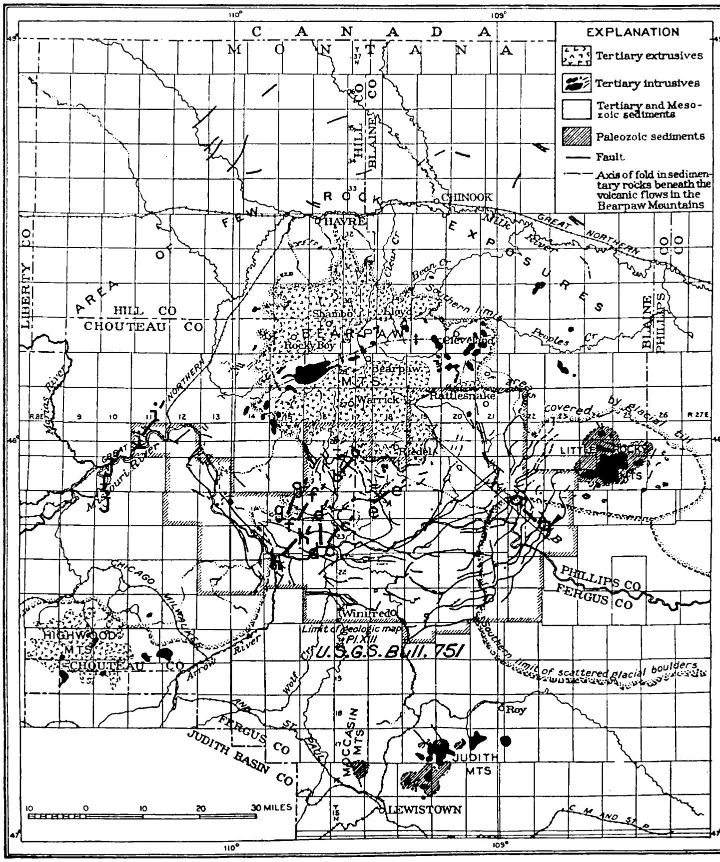


Fig. 1.—Map showing faults surrounding the Bearpaw Mountains and the locations of cross sections shown in Figures 2, 5, and 6.

of limestone overlain by some 5,000 feet of Mesozoic and younger beds, consisting largely of soft shales. The character and thickness of the individual formations are shown in Fig. 2. At the time of the folding several hundred feet of volcanic rocks probably overlay these sedimentary formations for a distance of 5 to 10 miles beyond their present limits in the Bearpaw Mountains. Since the folding, which occurred in mid-Tertiary time, the volcanic rocks and the underlying Lance formation have been eroded from the plains adjacent to the mountains except where they are preserved in some downfaulted blocks, that form a feature of the structure of the plains within a few miles of the mountains. A considerable thickness of older strata has also been eroded from the plains area, but because of the eastward tilting of the region, erosion has not reached as low stratigraphic levels in the eastern part of the area as in the western part. Thus, in the eastern part of the belt lying south of the mountains several

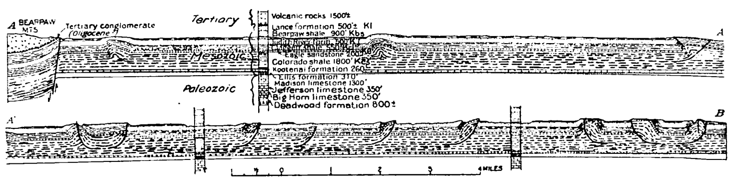
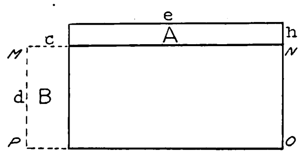


Fig. 2.—Cross section along line A-B of Figure 1, showing the probably shallow character of the folds and faults. Volcanic rocks 1,500′ ±; Lance formation 500′ ± Kl; Bearpaw shale 900′ Kbs; Judith River form 500′ Kj; Claggett shale 550′ Kcl; Eagle sandstone 200′ Ke; Colorado shale 1,800′ Kcs; Kootenai formation 260′; Ellis formation 310′; Madison limestone 1,300′; Jefferson limestone 350′; Big Horn limestone 350′; Deadwood formation 800 ±.

hundred feet of the Bearpaw shale is still present in the areas of flat-lying beds, whereas in the western part of the belt this formation, as well as the underlying Judith River formation, has been eroded, and the Claggett shale occupies most areas of flat-lying beds. Despite this difference in depth of about 1,500 feet stratigraphically to which the general region is eroded in the two areas, no deeper rocks are exposed in the crest of the folds in the one area than in the other. The lowest strata exposed in any of the folds are beds in the Colorado shale, occurring about 750 feet below the top of the formation and immediately underlying a red concretionary bed commonly known as the red chip zone. This red chip zone crops out in most of the folds in the western part of the area and in some of the major folds in the eastern part of the area. The fact that in so many folds that have been eroded to such varying levels no beds below a certain horizon are exposed suggests that the lowest beds exposed lie at the base of the strata involved in the folding. As this evidence as to the depth of the faulting and folding, however, appears more conclusive when viewed in the light of the theoretical considerations which led the writer to the conclusion that the folding and faulting, are shallow, these considerations will be presented next.

METHOD OF DETERMINING DEPTH OF FOLDING AND FAULTING.

The method used to determine the depth of the deformation is based on the principle, suggested by Chamberlin and Salisbury,[3] that in the folding of strata by horizontal thrust the crust involved, being shortened, is proportionately thickened, and that this thickening expresses itself in the elevation of the folded strata and is equal in amount to that elevation if it be assumed that no compacting of the beds or downward sagging of the crust accompanies the folding. Fig. 3 illustrates the principle. If M N O P of this figure, representing a cross section of the earth's crust composed of incompetent



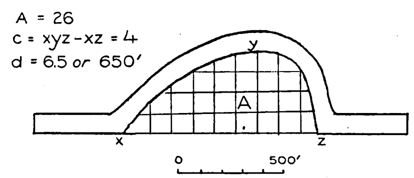


Fig. 3.—(Left) Diagram illustrating the principle that crustal shortening produces crustal thickening.

Fig. 4.—(Right) Use of equation $\frac{A}{c} = d$ for determining the depth of a fold.

beds, is shortened by horizontal thrust, by the amount c, then, if there be no compacting of the strata, the crust will be thickened and the cross-sectional area of the part added to the thickness of the crust will equal the cross-sectional area of the part subtracted from the length of the crust. That is

$$A = B$$

but as $A = he$ and $B = cd$

then $he = cd$ and $h:d = c:e$

and $A = cd$ or $\frac{A}{c} = d$

The structure in the area considered is such that it is possible to determine the amount of crustal thickening resulting from the crustal shortening in each individual fold at any stratigraphic horizon desired and to apply the equation $\frac{A}{c} = d$. In most folded areas this would be impossible, and it would be necessary to restore the structure of all the eroded strata and

[3] Chamberlin, T. C., and Salisbury, R. D., Geology, vol. II, pp. 125-126, 1906.

to apply the equation h : d = c : e, used by Chamberlin[4] in his studies of the depth of folding in the northern Appalachians and by Mansfield[5] in his estimates of the depth of folding in the Rocky Mountains of Idaho and Montana.

The use of the equation $\frac{A}{c} = d$ in determining the depth of the crust involved in a fold is illustrated in Figure 4. Here, instead of uniform thickening of the crust resulting from its shortening, the strata have buckled into a fold. The area of this upward bulge, A, measured in terms of the coördinate squares on which the cross section is drawn, is 26, and its crustal shortening, measured in the terms of the coördinate units of length, is 4. By substituting these values for A and c in the equation $\frac{A}{c} = d$, the depth of the folding is determined as 6.5 coördinate units or their equivalent, 650 feet. The values of A and c here and in Fig. 5 are determined by counting the number of coördinate units of area included between the bowed or faulted position of a bed and the line marking its former horizontal position and by measuring in terms of the same units the difference in length of the same bed in its bowed or faulted position and this line. As noted above, the equation is based on the assumption that there is no compacting of the beds during their compression and that the consequent thickening of the crust produces no subsidence of the area; in other words, that in Fig. 3, A = B. These assumptions will now be considered.

APPLICABILITY OF THE METHOD.

The possibility that the elevation of highly folded areas can be attributed directly to the thickening of the crust during periods of crustal shortening is rendered highly improbable by the data furnished by geodetic observations, which indicate that the earth's crust will sag under such marked addition of load. This conclusion is also corroborated by the geologic evidence, cited by Reid,[6] that the principal mountain systems of the earth have been raised up and not squeezed up and that the time of their elevation was distinctly later than the time of their folding.

[4] Chamberlin, R. T., The Appalachian folding of central Pennsylvania: Jour. Geol. vol. 18, 1910, pp. 228-251.

[5] Mansfield, G. R., Structure of the Rocky Mountains in Idaho and Montana: Bull. Geol. Soc. America. vol. 34, pp. 263-284, 1922.

[6] Reid, H. F., Isostasy and earth movements: Bull. Geol. Soc. America. vol. 33, pp. 319-323, 1922.

Thus it is evidently impossible to determine by the method suggested above the depth of folding in areas where there has been pronounced crustal shortening and consequent marked addition of material to the crust. Yet this objection evidently can not be raised to the application of the principle to the folds around the Bearpaw Mountains, for the individual folds here, being less than a mile wide, involve smaller cross sections of the earth's crust than geodesists believe must be in independent isostatic equilibrium. Consequently, if the added material in each fold is assumed to constitute a load that can not escape compensation, such compensation will not be all in the block directly under the fold, but will be distributed to at least such distances as probably to merge with the compensation of the adjacent folds, producing, if any, a subsidence of the whole area of the belt of faulted folds. That the individual folds have not been independently compensated is indicated by the fact that the beds in the belts between the folds continue up to the base of the folds without showing any downward deflection from the horizontal. Whether the total load of all the folds produced a subsidence of the entire area need not be considered, for neither general subsidence nor elevation of the area will change the size or height of the individual folds and thereby affect the problem. But it may be added that it is very doubtful that there was such a subsidence, inasmuch as the added material, if evenly distributed over the area, would represent a thickness of only about 100 feet, even if the improbable assumption be made that during the formation of these folds their crests were not in part eroded and a considerable amount of this added material removed from the area.

As to the possibility that the sediments were compacted during the period of folding as a result of squeezing out the included water: it is very doubtful whether the Cretaceous formations considered were appreciably further compacted when they were folded, inasmuch as they had been buried under a load of from 2,000 to 5,000 feet of strata during the long interval between the period of their deposition and that of their deformation, which was approximately that between mid-Cretaceous and mid-Tertiary time. This conclusion might be checked by comparing the porosity of the beds in the belt of faulted folds with that of the same beds outside of the belt if it were possible to determine to what extent the porosity was affected by the infiltration of cement material. Outwardly the sediments appear to have reached the same stages of consolidation.

If, however, it be assumed that during the period of folding the beds were further slightly compacted, then A. in Fig. 3 is admittedly less than B. But the value used for c is then also proportionately less than the true crustal shortening, as it does not include the shortening due to compacting. Consequently, the value obtained for d by the use of the equation $\frac{A}{c} = d$ can not vary much from the compacted value of d.

From the above considerations it would seem that no valid objection can be raised against using Chamberlin's principle for the determination of the depth of folding in the folds under consideration, provided, of course, it is admitted that these folds are due to horizontal thrust, but in the light of the data presented in the previous paper and that which will follow, such an admission is unescapable.

ACCURACY OBTAINABLE IN RESTORING THE STRUCTURE.

It is important here to consider the degree of accuracy which may be attained in restoring the folds in cross section and therefore in determining the true value of A and c. It is evident that an attempt to restore the cross sections of most folds produced by horizontal thrust is subject to much greater error than the attempt to restore the simple folds here considered, for most folds are a part of a series of folds of varying height, making it necessary, in order to show the structure of one bed, to restore, practically by guesswork, great thicknesses of folded beds that have been removed by erosion or that are concealed by hundreds of feet of overlying beds. Folds in which the Eagle sandstone was well exposed in the crest of the folds and for some distance down their flanks were selected for determining the depth of the folds. Detailed stadia traverses were made of these folds and the results were plotted on cross section paper. With these observations together with the knowledge of the thickness of the formations, little was left to conjecture in completing the structure of the folds in the Eagle sandstone except the amount of upward drag along the fault plane on the downdropped side of the fault and the inclination of the fault plane below levels of observation. But as most of the folds show little or no drag along either side of the fault plane, none was assumed for the unexposed beds unless the surface beds showed such drag. The fault planes are shown as slightly curved, in order to make them agree with the observation that in the eastern part of the faulted belt the dips are steep, most of them being

60 to 70°, whereas in the western part, where erosion has exposed the fault planes at lower levels, the dips range from 30° to 45°. Thus it is seen that there are sufficient controlling data to make it impossible to restore the folds in the Eagle sandstone that the form and size of the folds will be materially different from those indicated in the cross sections. The value given to A, is therefore, probably very close to its true value. There is greater possibility, however, of error in determining the amount of crustal shortening; yet the values used err, if at all, in making c too small, because they do not include the shortening due to possible minor sinuosities, small thrust faults, and the drag of the strata along fault planes. But to increase c in the equation $\frac{A}{c} = d$ is to lessen the value of d and consequently to arrive at a shallower depth for the folding than that indicated by the observed facts.

CONCLUSIONS REACHED AS TO THE DEPTH OF FOLDING FROM A STUDY OF THE LESS ERODED FOLDS.

The drawings in Fig. 5 show cross sections of folds which are examples of those used in arriving at a theoretical determination of the depth of the folding. These are typical of the major folds in the area south and southeast of the Bearpaw Mountains and were selected because of the good exposures of the Eagle sandstone across the crest of the fold. Their locations are shown in Fig. 1. The folds represented in cross section a-a′ and b-b′ occur in the area where the lower part of the Bearpaw shale is still present in the belts of flat-lying rocks between the folds. The depth of the folding below the Eagle sandstone as determined by the use of the equation $\frac{A}{c} = d$ is 903 and 727 feet, respectively. The inclination of the fault plane in cross section b-b′ is established by the data afforded by the logs of two wells drilled in the crest of the fold, which show that the fault plane was crossed in the wells at a depth about equal to that of the distance of the wells from the outcrop of the fault plane, thus indicating an inclination for it of about 45°. The cross sections c-c′ and d-d′ show two folds in an area where erosion has reached nearly to the base of the Judith River formation in the flat-lying rocks adjacent to the folds. The depth of the folding below the Eagle sandstone, as determined by the equation, is 1,058 and 1,075 feet respectively. Inasmuch as it is not assumed that the method used will give more than the approximate depth of the folding, the variation arrived at for the depth of the different folds may possibly be due to minor errors in determining the values of A and c. Probably in no fold does it vary markedly from an average of these depths. Of ten other folds so measured, the depth obtained varied from 700 to 1,300 feet below the Eagle sandstone, giving an average

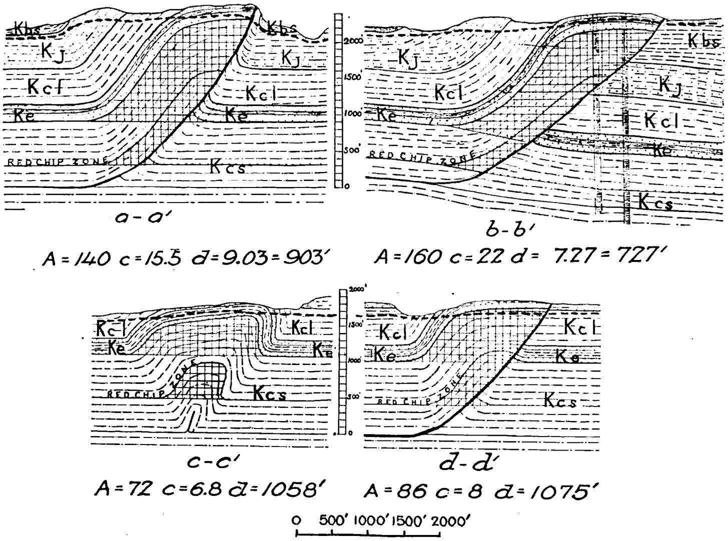


Fig. 5.—Cross sections illustrating how the restoration of the folds in the Eagle sandstone is used in determining the depth of the folding and faulting. Horizontal dotted lines indicate the depth to which the structure may be observed. For explanation of symbols see Fig. 2.

of 900 feet. In the lowest eroded folds the depths vary from 700 to 800, and as all the folds are very similar, it is doubtful whether any of them vary more than 200-400 feet from the average of 900 feet. If it were thought that the base of the folded series was the same for all the folds, an average of 750 feet would be assumed, inasmuch as this is approximately the depth indicated by the lowest eroded folds.

RESTORATION OF STRUCTURE OF THE RED CHIP ZONE.

Before considering the evidence furnished by the cross sections of the folds exposed to lower stratigraphic levels than those given above, let us consider what must be the structure of the red chip zone (see Fig. 5), a bed 600 feet below the base of the Eagle, if the folding is so shallow and the crustal shortening continues undiminished down to the base of the folded series. It should be clearly understood that the restoration of the structure at this horizon is a step in the restoration of the folds, which follows the determination of the depth of the folding arrived at from measurements of the folds in the Eagle sandstone, and is based on these determinations. The method used in restoring the structure of this bed was to draw a cross section with an equal amount of crustal shortening as that used for the Eagle sandstone in the same fold and an area equal to the product of this crustal shortening times the value given for the depth of the folding below the Eagle sandstone minus the coördinate equivalent of 600 feet, the red chip zone being 600 feet nearer to the bottom of the folded series than the base of the Eagle sandstone. Thus in a-a′ the value of c′ is 15.5 and of A′ 9-6 x 15.5 or 46.5. The use of a definite value for A′ and c′ and the necessity of the structure of this bed conforming also as nearly as possible to the structure in the overlying Eagle sandstone practically determine what form the folding in the red chip zone must take if the assumption as to the depth of the deformation be correct. The character of this structure as well as that of all of the beds in the basal part of the folded series is also shown in Fig. 5. In sections a-a′, b-b′, and d-d′ it will be noted (1) that at the horizon of the red chip zone the beds have the same inclination as the fault plane except for a narrow flexure where they end against the fault plane; (2) that the width of this flexed portion of each bed is equal to the stratigraphic interval between the bed and the base of the folded series and therefore becomes progressively narrower as the base is approached; and (3) that the inclination of the fault planes decreases with depth and merges with the bedding plane at the base of the folded series. In the unfaulted fold c-c′ it will also be noted that the folding becomes progressively narrower with depth, and that the width of the folds in each bed is slightly less than twice the interval between that bed and the base of the folded series. Such must be the character of the structure in the beds below the Eagle sandstone if the depths of the folding and faulting arrived at from the study of the folds in the Eagle sandstone are correct. If the folds that are exposed by erosion to these levels actually show these features, it is evident that the conclusion as to the depth of the deformation theoretically arrived at is then practically substantiated, for folds of only such shallow character can have such features.

RESTORED VS. OBSERVED STRUCTURE.

Six folds are shown in Fig. 6, in which the crests of the folds are eroded sufficiently to expose the red chip zone. It will be noted that the character of the structure is in all respects identical with that arrived at in restoring the structure of the red chip zone in the folds shown in Fig. 5. It will also be observed that the lowest beds exposed at the surface that are involved in the folding and faulting are those from 100 to

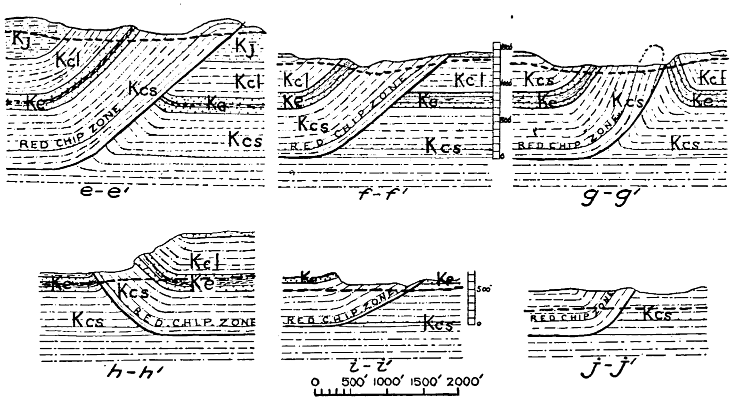


Fig. 6.—Faulted folds showing characteristic structure of the red chip zone in the deeper eroded folds. For explanation of symbols see Fig. 2.

200 feet below the red chip zone. The point may be raised, however, in as much as the observations do not go very deep, that other beds are turned up along the fault plane at lower levels. But such a suggestion ignores the facts arrived at in restoring the structure of the red chip zone in the cross sections shown in Fig. 5,—that is, that such structure can be the product only of such shallow deformation. However, as this may not be entirely evident except to those who actually carry out the restoration of the folds according to the method outlined above, this evidence may not appear to be conclusive. The assumption will consequently be made that the only rule that may be followed in restoring folds is to make the struc-

ture in the unexposed beds agree as closely as possible with that of the exposed beds. If this method be adopted and attempts are made to restore the structure in sections shown in Figure 6 so as to show that lower beds are involved in the folding and faulting than those exposed at the surface, it will be discovered that one of the two following assumptions has to be made to continue the faulting and folding down to greater depths; that the inclination of the fault plane becomes steeper at lower levels, or that the belt of tilted strata along the faults does not become progressively narrower at lower stratigraphic levels. But these assumptions are contradicted by all the field observations, and even if these or other improbable assumptions be made, it is impossible to restore the structure so as to show that lower beds are involved without showing for each successively lower bed a pronounced decrease in the amount of crustal shortening. This possibility is also contradicted by the following evidence. In the folds eroded to the lowest stratigraphic levels shown in Fig. 6 it is possible to measure the crustal shortening of the red chip zone in sections e-e′ and g-g′. The values obtained of 2,500 and 2,000 feet are equivalent to maximum values obtained for measurements of the crustal shortening in any folds in the Eagle sandstone. There is also no evidence that the crustal shortening is greater in the Judith River formation than in the underlying Eagle sandstone. It is obvious also that if the crustal shortening were diminishing in depth, the inclination of strata would become less in depth, which is contradicted by the evidence furnished by the deeper eroded folds.

If the foregoing evidence does not appear to be entirely conclusive that no beds are involved in the faulting below those observed, the bald fact remains that in the scores of faulted folds in which the Colorado shale is exposed no beds, as far as the writer has observed, are exposed which occupy a position more than 250 feet below the red chip zone, and he has examined probably 90 per cent of the folds and practically all those which have been eroded to the lowest stratigraphic levels. The red chip zone in these areas of the greatest regional erosion has the same attitude and relation to the fault plane as in the areas where erosion has just barely exposed this bed. This fact is graphically illustrated in Fig. 6. In e-e′ erosion has reached a level just low enough to remove the Bearpaw shale from the areas of flat-lying rocks adjacent to the fold. The red chip zone may be observed in the bluff of the creek where it bends over to meet the fault plane. At a 100-foot lower level it is inclined at the same angle as the fault plane and all the higher formations as well. In the succeeding sections of Fig. 6 erosion has reached progressively lower levels, so that in j-j′ it has attained a level 1,300 feet below that shown in e-e′. In all the folds the inclination of the red chip zone is parallel to the fault plane and there are only 250 feet or less of strata exposed between it and the fault plane. In section g-g′ an example of a faulted fold is shown in which there is more evidence of anticlinal folding than is shown in the other sections. In this, as in other similar folds observed in the field, the crest of the fold is clearly indicated by the two parallel outcrops of the red chip zone, which either have a vertical attitude or are slightly overturned. The distance across the crest of the fold between these outcrops is 200-400 feet. The shales occupying the crest of the fold also stand at angles of 90° or are slightly overturned. The thin beds of bentonite that mark the attitude of the bedding planes show no minor plications, as might be expected in such a series of plastic shales. In closed folds such as these, deeper beds than those exposed obviously are not included in the folding and in view of the fact that the evidence furnished by these folds as to the depth of the folding agrees so definitely with that furnished by the faulted folds and also with that arrived at by the use of the equation $\frac{A}{c} = d$, the shallow depth of the folding and faulting may be regarded as reasonably well established.

UNDERLYING BEDS INVOLVED IN THE THRUST.

This conclusion as to the depth of the folding and faulting makes it necessary to assume that the beds involved in this deformation were either thrust over the underlying strata or that the underlying beds were also involved in the thrust movement. Considering the fact that 80 per cent of the beds involved in the folding and faulting consist of plastic shales, that the thin Eagle sandstone is probably the most competent member of the series, and that between it and the base of the series there are 600-800 feet of shales, it seems improbable that the beds involved in this deformation could have transmitted the thrust for distances so long—the folds in the outer margin of the faulted belt being 30 to 40 miles from the obvious source of the thrust in the Bearpaw Mountains. If this conclusion be valid the alternative hypothesis must be accepted, namely, that the underlying beds transmitted these thrusts. This hypothesis is supported by the fact that the crustal shortening in the folded series continues undiminished down to its base and that the flat-lying belts between the faulted folds and other features of the structure are more readily explained on the assumption that the deformation is the result of the drag effects of the underlying beds moving beneath the folded and faulted series. The evidence cited in the previous article on the structure of the Bearpaw Mountains indicated that this movement must have been the result of a horizontal thrust from those mountains. What the origin of the thrust force was, however, and how the crustal shortening which it must have produced could have taken place in the beds underlying the folded series without those beds being folded or faulted in some manner that had an expression in the structure of the surface strata, are problems for which the writer can offer no adequate explanation.

U. S. Geological Survey,
Washington, D. C.