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DEPARTMENT OF ENERGY, MINES AND RESOURCES

BULLETIN 205

COMPARATIVE STUDY OF THE CASTLE RIVER AND OTHER FOLDS IN THE EASTERN CORDILLERA OF CANADA

D. K. Norris

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By
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PREFACE

Much progress has been achieved towards the description of the broad geological framework of the eastern Cordillera of Canada; scientists must now turn their endeavors toward a better knowledge of the mechanisms of orogenesis. Toward this end, an anticline-syncline pair in the Foothills of southwestern Alberta has been studied in detail and compared with other folds in the eastern Cordillera, in the Ottawa-St. Lawrence Lowlands and in the northern Appalachians.

Certain well exposed fold- and fault-structures considered representative of the layered stack of unmetamorphosed sediments of this part of the orogen have been selected for careful field analysis and for physical and mathematical modelling. Fold and fracture mechanisms are thereby documented and simulated and provide the basis for geological concepts to improve the means of discovery and to predict zones of tectonically thickened coal. Such concepts also assist in the definition of the geometry of structural traps and in identifying geologically favourable areas for the accumulation of oil and gas.

Y. O. Fortier,
Director, Geological Survey of Canada.

Ottawa,
March 31, 1971

BULLETIN 205 — Eine vergleichende Studie über die Castle-River-Faltung und andere Falten in der östlichen kanadischen Kordillere

Von D. K. Norris

Diese Studie beschreibt die tektonische Analyse eines Paares von zylindrischen Biegefalten und vergleicht dieses Paar mit dem Aufbau anderer Falten in sedimentären Schichtfolgen der östlichen Kordillere, der Appalachen und der Ottawa- und St.-Lawrence-Ebenen.

БЮЛЛЕТЕНЬ 205 — Сравнительное исследование складок реки Кастл с другими складками Восточных Кордильер Канады

Д. К. Норрис

Производится структурный анализ изгиба со скалыванием одной пары цилиндрических складок в районе Кастл Ривер, Восточных Кордильер Канады. Эта пара складок сравнивается с другими складками слоистых осадочных толщ Восточных Кордильер, Аппалачских гор и низменности р. Оттавы — р. Св. Лаврентия.

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ABSTRACT

Meaningful physical and mathematical models simulating the structural evolution of orogenic belts must be based on detailed study of specific structures whose geometry and mechanical behaviour are represenative of the orogen. It is with the intent to create such models that certain fold- and fault-structures in the eastern Canadian Cordillera have been selected for careful study and analysis. A fold-pair, well exposed on Castle River, in the thrust belt of southwestern Alberta is designated a prototype for this modelling and various mesoscopic features of this fold-pair are compared with those examined in other folds in the southern and northern Cordillera, in the Ottawa-St. Lawrence Lowlands, and in the northern Appalachians.

Measurements of orthogonal bed thickness, bedding attitudes, inclination of axial surfaces and pitch of slickenside striae on bedding would suggest that the Castle River folds are typical for the clastic succession of the eastern Cordillera. Like most other structures examined, they are essentially flexural-slip, cylindrical folds. They are not truly parallel folds, but rather are intermediate in the continuum of styles from parallel (concentric) at one extreme to similar at the other. Original bedding thicknesses have not been significantly altered as a consequence of the folding but the sandstone beds characteristically have radii of curvature too small for their structural level; the folded layers tend, therefore, to retain a common form through larger stratigraphic intervals than required by the true parallel style. The folds do die out, however, in the direction of the detachments, which may be faults or décollements in low strength horizons such as shale, coal or salt. Some folds in the eastern Cordillera are symmetrical, inclined solely because of external rotation. Most are asymmetrical, inclined because their limbs are of unequal length. All may be externally rotated during translation on thrust surfaces or other detachments.

Interesting sidelights of this study relate to the accumulation of hydrocarbons and coal. The fact that folds die out upward and downward means that a specific fold form is characteristic of a given structural level. Whether symmetrical or asymmetrical, only the central lamina in a simple fold-pair or train can have a common radius of curvature at the hinge of the anticline and of the syncline. Higher structural levels will be characterized by broad anticlines separated by narrow synclines and lower levels by broad synclines separated by narrow anticlines. A basinward progression from low to intermediate to high structural levels is suggested in the fold forms at the top of the Middle Devonian limestones of the Nahanni Formation in Franklin and Mackenzie Mountains, and appears to represent different structural levels in one and the same fold style. Narrow anticlines separated by broad, flat-bottomed synclines buried beneath the northern Interior Plains may be important hydrocarbon traps because they may have served to localize significant quantities of oil and gas migrating up the regional dip from the intervening, broad, synclinal areas. Moreover, the characteristically small radius of curvature of sandstone beds in coal measures of the southeastern Cordillera requires transport of incompetent materials into the hinges. Thus, coal seams <u>throughout</u> the clastic succession may be expected to be tectonically thickened there and, depending on their suitability in rank or in ash content, may be selectively mined both by surface and underground methods.

RÉSUMÉ

Les modèles physiques et mathématiques qui simulent l'évolution structurale des zones orogéniques doivent être fondés sur l'étude détaillée de certaines structures particulières dont la géométrie et les mécanismes sont typiques de l'orogène à l'étude. Afin d'établir de tels modèles géologiques, l'auteur s'est livré à l'examen et à l'analyse systématiques d'un certain nombre de réseaux de failles et de plissements du secteur est de la Cordillére canadienne. Comme type structural, il a choisi une paire de plis de la zone de charriage du sud-ouest de l'Alberta, qui affleure très bien le long de la rivière Castle. L'auteur compare certaines caractéristiques mésoscopiques de ce pli à celles de divers autres plis du sud et du nord de la Cordillère, des basses-terres de l'Outaouais et du Saint-Laurent et du nord des Appalaches.

Les mesures de l'épaisseur des couches, de la disposition des lits, de l'inclinaison des surfaces axiales et de l'inclinaison des stries de glissement dans les plans de couche semblent indiquer que les plis de la rivière Castle sont typiques de la succession clastique de l'est de la Cordillère. Comme la plupart des autres structures étudiées, il s'agit essentiellement de plis de flexure cylindriques. Ce ne sont pas de vrais plis concentriques; ils seraient plutôt intermédiaires entre les plis concentriques d'un côté et les plis de cisaillement de l'autre. L'épaisseur originale des strates n'a presque pas été modifiée par le plissement, mais les lits de grès possèdent en général un rayon de courbure trop court pour leur niveau structural; les couches plissées tendent donc à conserver une forme commune sur un intervalle stratigraphique plus grand que ne l'exigerait un vrai style concentrique. Les plis s'effacent cependant en direction des solutions de continuité qui sont soit des failles, soit des décollements dans les horizons peu résistants de schiste, de houille ou de sel. Quelques plis de l'est de la Cordillère sont symétriques et doivent leur inclinaison uniquement à la rotation externe. La plupart sont asymétriques et doivent leur inclinaison à l'inégalité de leurs flancs. Tous peuvent avoir subi une rotation externe durant leur translation sur les surfaces de charriage ou autres surfaces de mouvement.

Un intéressant aspect accessoire de cette étude se rapporte à l'accumulation d'hydrocarbures et de houille. L'effacement des plis vers le haut et vers le bas indique que certaines formes de plis sont caracteristiques de certains niveaux structuraux. Que les plis soient symétriques ou asymétriques, seules les lamelles centrales d'une paire ou d'un faisceau de plis peuvent avoir le même rayon de courbure à la charnière de l'anticlinal et du synclinal. Les plis des niveaux structuraux supérieurs seront caractérisés par de larges anticlinaux séparés par des synclinaux étroits et ceux des niveaux inférieurs par des synclinaux larges séparés par des anticlinaux étroits. La forme des plis du sommet des calcaires du Dévonien moyen de la formation de Nahanni dans les monts Franklin et Mackenzie, laisse deviner une progression orientée vers le bassin depuis les niveaux structuraux inférieurs jusqu'aux niveaux supérieurs, et semble représenter des niveaux structuraux différents à l'intérieur d'un même style de plissement. Il se peut que les anticlinaux étroits, séparés par de larges synclinaux à fond plat, qui reposent sous le secteur nord des plaines intérieures constituent des pièges pétrolifères et gazifères importants, car les hydrocarbures remontant la pente régionale depuis les synclinaux plus larges qui séparent les anticlinaux s'y sont peut-être accumulés en quantités importantes. De plus, le rayon de courbure typiquement faible des lits de grès dans les charbons du sud-ouest de la Cordillère implique le transport du matériel incompétent vers les charnières. Il semble donc que les filons de houille de la succession clastique puissent s'épaissir tectoniquement dans les charnières et, selon leur qualité et leur teneur en cendres, ces charbons pourront être extraits sélectivement à ciel ouvert ou par des méthodes d'exploitation souterraines.

COMPARATIVE STUDY OF THE CASTLE RIVER AND OTHER FOLDS IN THE EASTERN CORDILLERA OF CANADA

INTRODUCTION

Since the reconnaissance study of the structural framework of the eastern Cordillera of Canada is almost complete, emphasis is now being placed on the nature and sequence of deformations that brought this framework into being. Specific types of geologic structures are being singled out and studied in detail. By means of an understanding of their geometry, deformational mechanics, and their spatial and temporal relations it is anticipated that it may be possible to create physical and computer models of the evolution of the eastern Cordillera. These models may be useful for substantiating the timing of folding and faulting relative to the migration of natural hydrocarbons and to the localization of these materials and coal in the hinges of folds or in other structural configurations.

Specific structures typical of the geometry and mechanical behaviour of component parts in the deformation will be the prototypes for this modelling. Anticline-syncline pairs with associated faults have been studied in detail at several positions in the eastern Rocky Mountains and Foothills in the vicinity of Crowsnest Pass. They occur in compositionally and mechanically anisotropic media, that is, in abundantly interlayered sandstones and shales; shales, sandstones and coal; and limestone and dolomite. These folds range in wavelength from a few feet to several tens of feet, and were selected on the basis of complete accessibility and of exposure close to a right section. It was, therefore, possible to survey their form accurately by plane-table with minimal error introduced through projection into the profile plane, to measure bed-thickness variations, to sample the fracture fabric in selected structural positions, to measure directions of relative displacement on bedding and other faults transecting bedding, to define precisely the position and shape of axial surfaces and of faults, to measure the attitude of bedding surface elements in any position on the structure, and to define the direction and magnitude of plunge of fold axes.

These measurements are essential to the definition of a structure and to the interpretation of the mechanics of its formation as it may be related to structural position in the Cordilleran orogen.

The textural and compositional layering is a fundamental property governing the deformational mode on the scale of the individual fault- or fold-structure. Individual beds have been detached from one another because of bedding slip, and faults show preferred inclinations with respect to the lithologic layering. Beds such as shale or coal, whose small shear strength and viscosity contrast with that of adjacent sandstones or limestones, commonly contain great numbers of faults ranging upward in scale from those of microscopic size. Differential displacement on these faults caused

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Plate I

Plate I. The Castle River prototype, an anticline-syncline pair in Lower Cretaceous clastic rocks exposed on the right bank of Castle River, Alberta. G.S.C. photo 117318.

or limestones, commonly contain great numbers of faults ranging upward in scale from those of microscopic size. Differential displacement on these faults caused anomalous and unpredictable thickening and thinning and, locally, complete destruction of the primary depositional fabric of the rock. Beds of large shear strength and viscosity, on the other hand, although commonly fractured in arrays (Stearns, 1964), may remain intact to play significant roles either in influencing the wavelength of folds (Currie et al., 1962) or as envelopes confining the folding or shearing deformation.

An understanding of these prototypes in the layered, sedimentary succession of the eastern Cordillera may assist in the prediction of location, size, and fracture fabric of host structures for coal within reach of modern methods of surface and underground mining and in the outlining of areas containing structures favourable for the entrapment of natural hydrocarbons at depth.

Few contributions to the literature on the geology of the eastern Cordillera in Canada treat in a meaningful way the geometry of folds or consider the significance of variations in fold style with tectonic environment across and along the Cordillera.

Two of the more significant contributions to our knowledge of the style of folding in the eastern Cordillera within the past decade are those of Dahlstrom (1960) and Price (1964). In them the principles of concentric folding are clearly portrayed schematically and with field examples from the Foothills and southern Rocky Mountains. By utilizing the two factors of constant bed length and bed thickness, Dahlstrom demonstrated that anticlines must die out upward and synclines downward and that simple folding cannot persist beyond the centre of curvature in concentric folds or the intersection of the axial surfaces of the flank flexures in box folds. Thereafter, according to Dahlstrom, "excess volume and length must be accommodated through non-concentric folding, flowage or faulting" (idem, p. 82) in the cores of the anticlines and synclines.

In his paper on the geometry and mechanics of formation of parallel and similar type folds, Ramsay (1962) examined a number of natural folds in strongly layered sediments and metasediments to see how closely they fit the theoretical types. Using the same two parameters of bed thickness and bed length, he demonstrated that many natural folds depart from the ideal parallel or similar form, having been modified by flattening. Measurements of bed thickness modifications were used by Ramsay to make exact quantitative estimates of flattening.

In the writer's experience, however, even in the non-metamorphosed, layered, sedimentary succession of the eastern Cordillera, parallel (concentric) folds are an ideal end member of a continuum of styles ranging from parallel at one extreme to similar at the other. Norris (1953, p. 1458) classified some of these folds in the coal measures of the eastern Cordillera as "similar" because the sandstone members tend to maintain a common radius of curvature upward or downward in a fold and the coal seams are usually many times their normal thickness in the hinges. There are, therefore, obvious departures from the true, parallel style for the combined sequence of competent and incompetent units. Nickelsen (1963, p. 20) reached the same conclusion from a study of folds in the coal measures of the Valley and Ridge Province of central Pennsylvania. He indicated that "At certain stratigraphic levels, thickened hinges are present with the result that the similar fold form is approached".

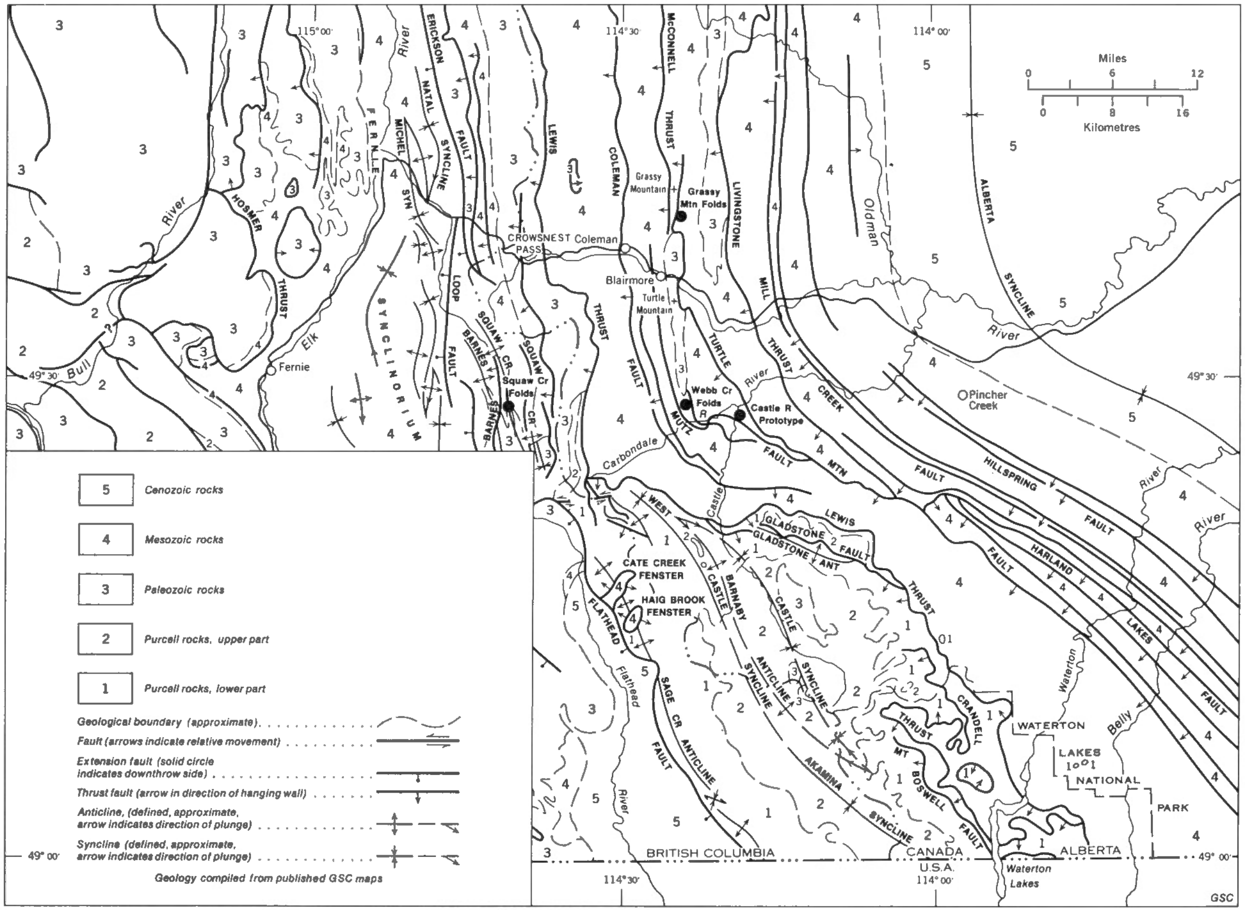

Figure 1. Geological environment of the Castle River, Webb Creek, Grassy Mountain and Squaw Creek folds in the eastern Canadian Cordillera.

Anomalous thickening of the coal in the hinges of some folds in the eastern Cordillera is of considerable economic importance and has led to several major strip mines, as will be seen, for example, on Grassy Mountain, Alberta.

ACKNOWLEDGEMENTS

The writer is indebted to D.G. Cook and N.C. Ollerenshaw of the Geological Survey of Canada for stimulating discussions leading to clarification of some thoughts expressed in this paper and to Professor M.R. Stauffer of the University of Saskatchewan for critically reading and commenting on the manuscript. Grateful acknowledgement is made also to the management of The Blue Coal Corporation, The Canmore Mines Ltd., and West Canadian Collieries Ltd. for making possible structural studies in the coal measures of the Northern Anthracite Field, Pennsylvania, and the Cascade and Crowsnest Coal Areas, Alberta; to R.A. Spillers for his perseverance and assistance in making measurements at the face of Number 2 pit, Grassy Mountain in 1950 and 1951; and to R.L. Emmerson and R.H.J. O'Brien for their help in completing the analysis of the Castle River and Webb Creek folds in 1961, 1963 and 1964.

THE CASTLE RIVER PROTOTYPE

Location and Geologic Setting

The Castle River prototype (Plate I) consists of an anticline-syncline pair flanked on the southwest by a series of three imbricate thrust faults. The structure is exposed on Castle River about one-half mile above its confluence with Carbondale River in the Foothills of southwestern Alberta, and is accessible via the road from Castlemount Ranger Station along the west side of the river. It was first drawn to the attention of the writer by Clow and Crockford (1951, Fig. 13) and examined in some detail a few years later (Norris, 1959a) in the course of his investigation of the structural relation of the Turtle Mountain and Mutz faults.

The geologic setting of this and other structures examined in detail in the vicinity of Crowsnest Pass is a series of thrust plates overlapping in section as well as in plan, and bounded above and below by major west-dipping thrust faults trending generally north to northwest (Fig. 1). The plates are commonly cut by splay faults and buckled into folds having wavelengths ranging from a few inches to more than a mile. The thrusts with associated splays and folds impart a strong north to northwest structural grain to the region. Vertical to west-dipping axial surfaces characterize the folds and, in conjunction with the thrust faults, impart a strong asymmetry to the structural geometry. The bulk shortening arising from thrust faulting and folding does not appear to vary appreciably in the Crowsnest Pass region because an increase or decrease in horizontal displacement on any one thrust is apparently compensated for by corresponding changes in displacement on adjacent thrusts (Norris, 1966, p. 193). Relative to the faulting, the folding does not contribute significantly to the total shortening.

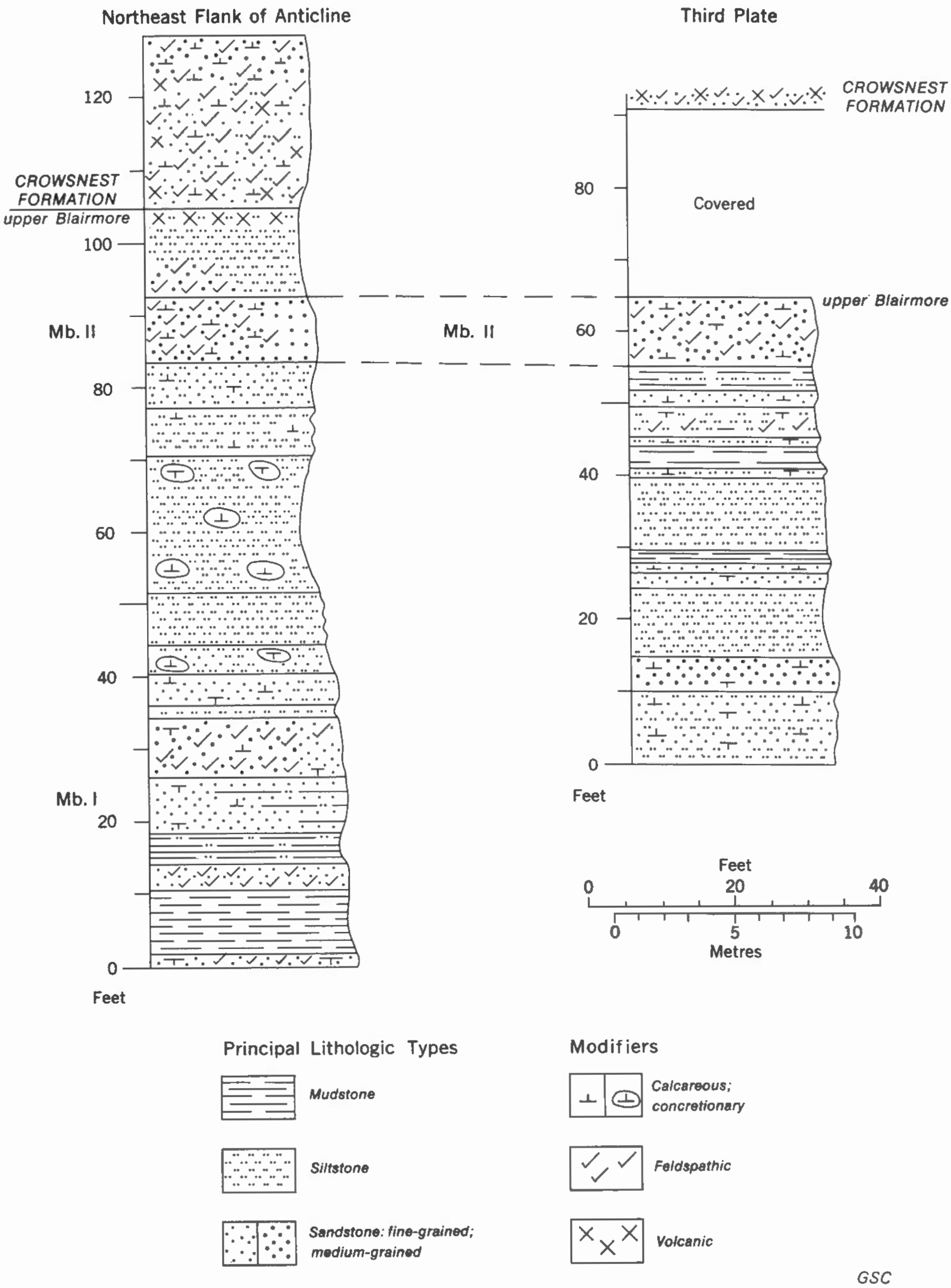

Figure 2. Stratigraphic succession of non-marine, Lower Cretaceous rocks comprising the Castle River prototype.

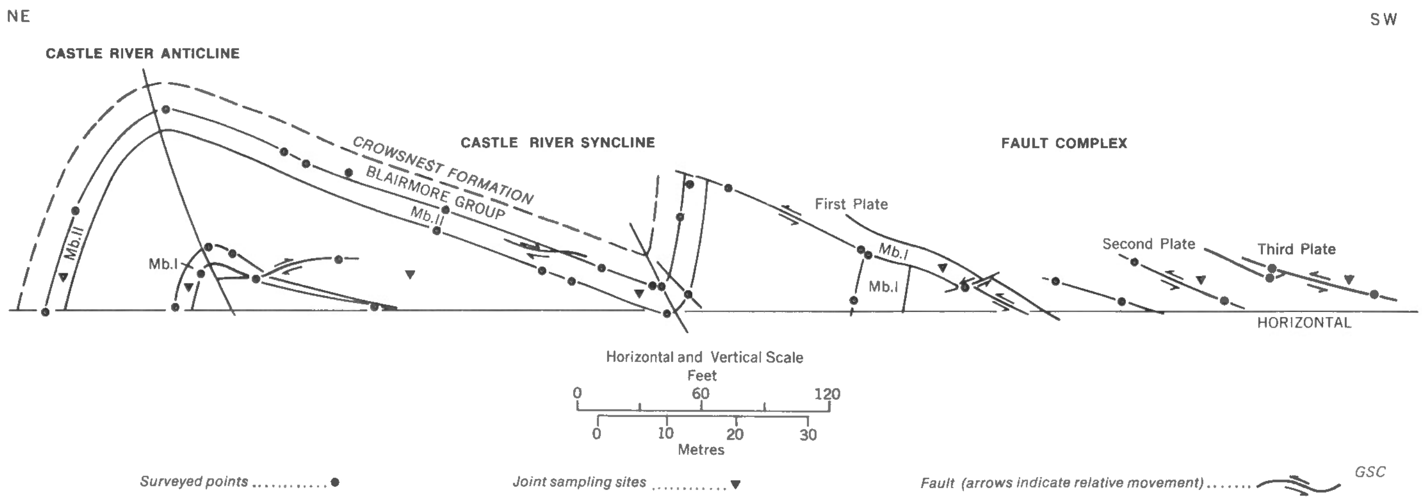

Figure 3. Right section of the Castle River prototype, Alberta, showing principal stratigraphic units used in establishing the fold geometry.

The Castle River structure, in the Turtle Mountain fault plate, is overridden along strike to the southeast by Mutz fault (Norris, 1959a). Mutz and Turtle Mountain faults merge at the surface about five miles to the southeast in Beaver Mines map-area (Hage, 1943).

The folds and faults of the Castle River prototype occur in the Lower Cretaceous siltstone, sandstone and shale succession at the top of the Blairmore Group and base of the Crowsnest Formation (see Appendix for rock description). Because of lateral variations in lithology many beds cannot be traced with assurance across covered intervals and from one thrust plate to the next. Two prominent sandstone ribs are traceable, however, throughout much of the structure and were valuable in defining the geometry of the deformation and the magnitude of the stratigraphic separation on the thrust faults. The lower sandstone will be referred to as Member I and the upper sandstone as Member II. Their bases occur at nineteen and eighty-three feet respectively above the lowest exposed rock in the core of the anticline (Plate II and Fig. 2) in the fold-pair. Stratigraphic sections measured on the northeast flank of the anticline and in the third splay to the southwest reveal these lithological variations. Member I, for example, grades rapidly southwestward into siltstone on the southwest flank of the anticline. It is thought that Member I is the near-vertical sandstone rib truncated abruptly in the immediate footwall of the first thrust and to be the sandstone bed which parallels the thrust in the hanging wall (Fig. 3). The stratigraphic position and separation on the second and third splays are such that the unit does not appear again in the structure. Member II, on the other hand, is conspicuous throughout the fold-pair and is correlated with prominent sandstones in the second and third plates to the southwest.

The Fold Style

Good exposure of the Castle River folds made it possible to measure form continuously from one fold to the other as well as to clarify the structural and stratigraphic relations of the folds to the series of three thrusts at their southwest extremity.

Because Castle River trends about 30 degrees from the ac fabric plane of the structure, the surveyed control points had to be projected to reconstruct the fold profiles in right section (Fig. 3). The fact that nearly all of the projected points fell onto a smooth curve would suggest that no significant errors were introduced in the reconstruction.

Two features of the Castle River folds are immediately apparent (Plates II and III). One is the pronounced northeastward asymmetry of both anticline and syncline (Fig. 4b) and the other is the subplanar nature of their adjoining flanks. Dips range from 75 degrees northeast on the steep flank of the anticline to 20 degrees southwest on the subplanar panel common to both folds, to near-vertical on the southwest flank of the syncline. At the structural levels exposed both axial surfaces are subplanar; that for the anticline dipping approximately 75 degrees southwest and that for the syncline approximately 60 degrees southwest.

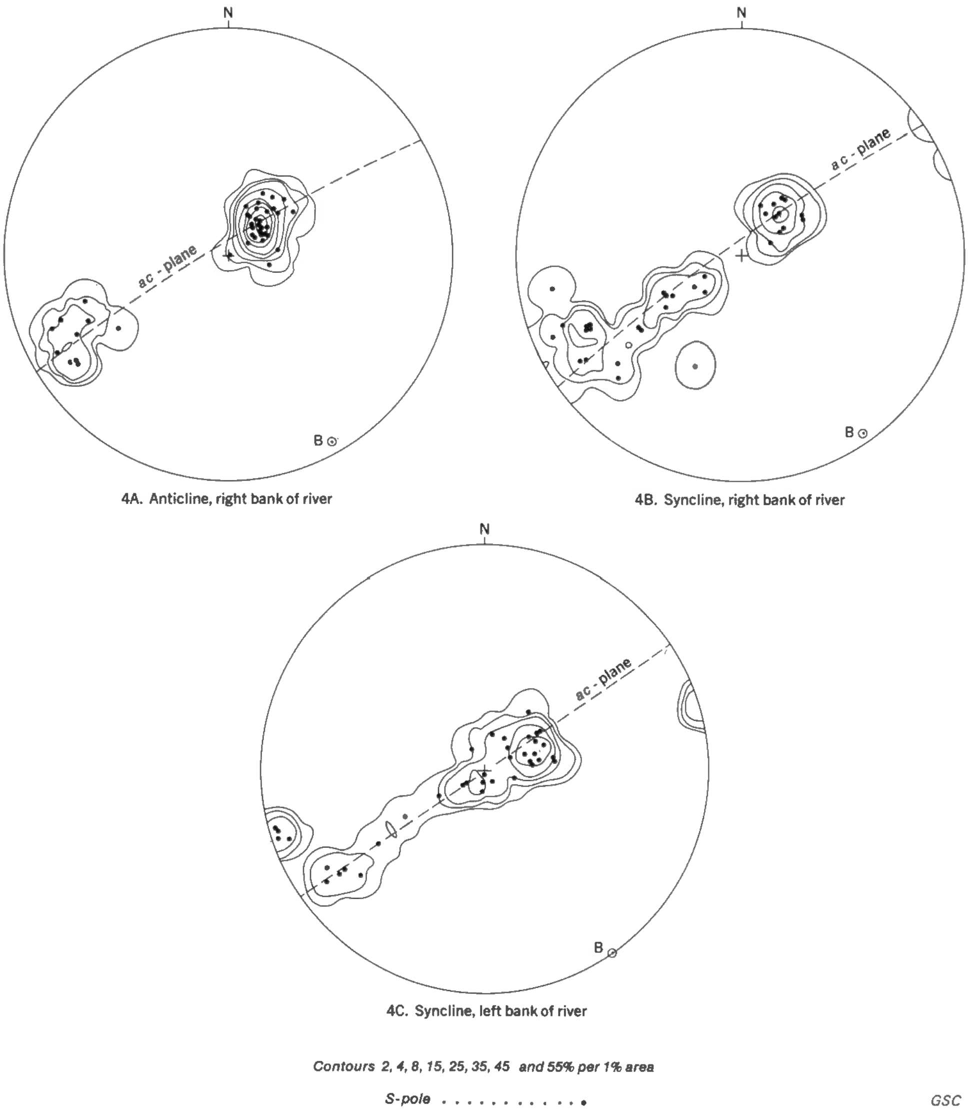

Figure 4. **S-pole diagrams for the Castle River anticline and syncline, with corresponding π-circles and defined fold axes B.**

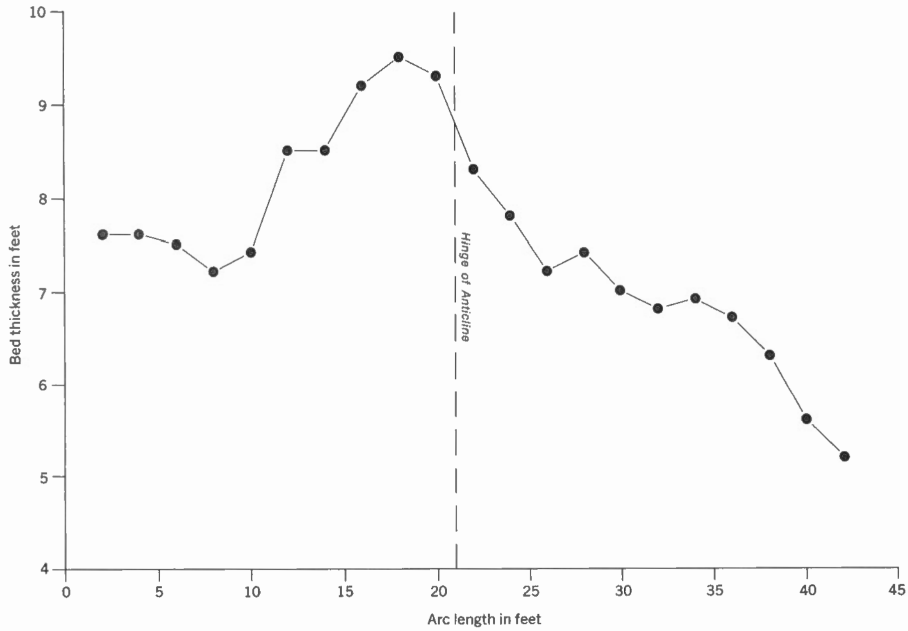

Figure 5. Variation in stratigraphic thickness of Member I as a function of arc length on top of the member in the Castle River folds.

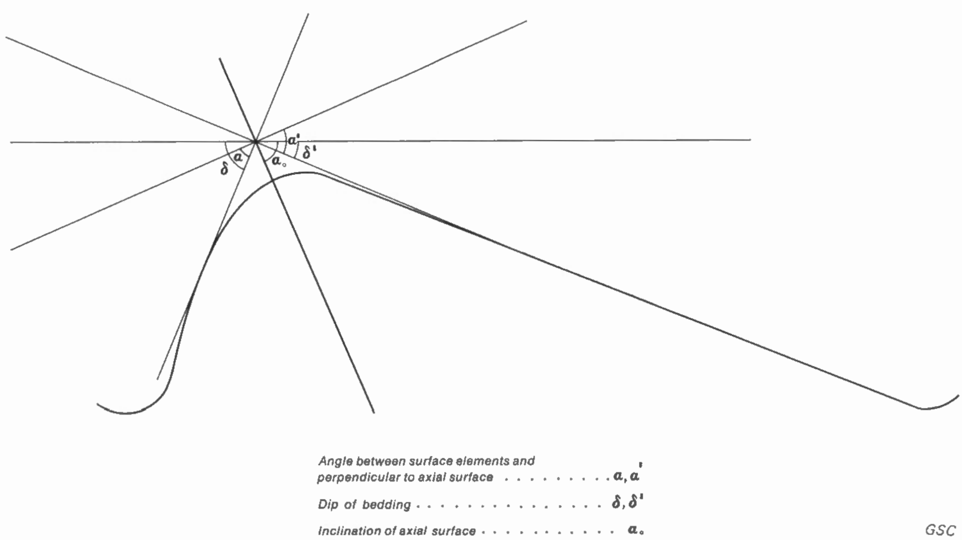

Figure 6. Geometrical relations among angles for an inclined fold in right section.

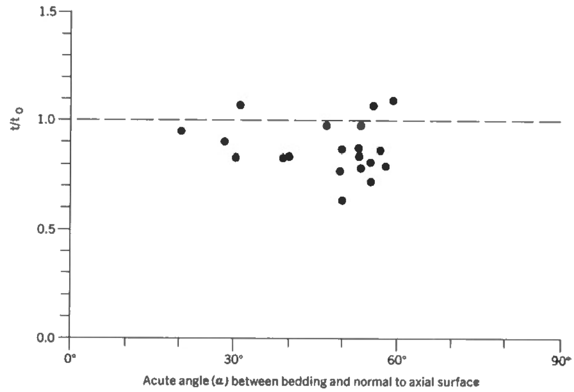

Figure 7. Variation in orthogonal bed thickness as a function of inclination of surface elements with respect to the axial surface of the Castle River anticline.

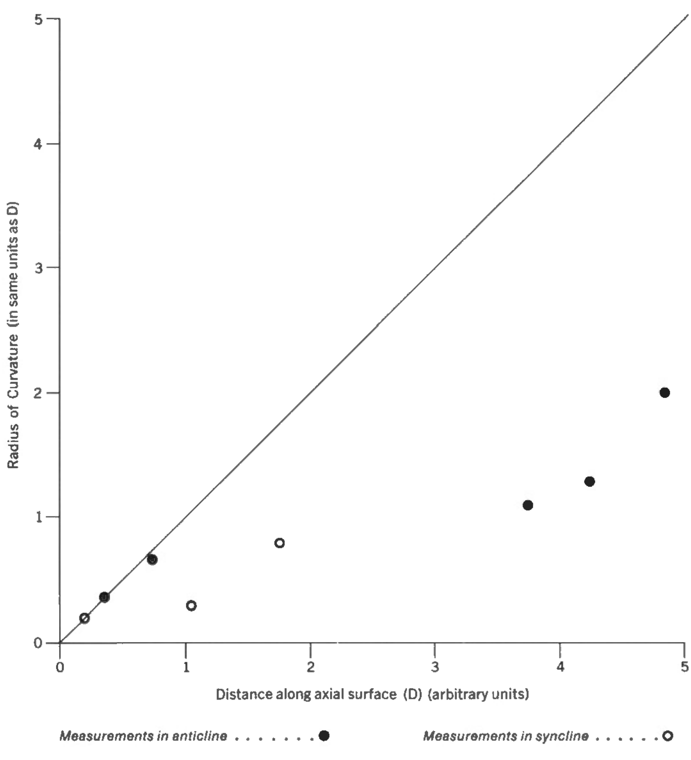

Figure 8. Variation in radius of curvature with structural level on the axial surface in the Castle River folds.

Although the terms wavelength and amplitude do not strictly apply to asymmetrical folds, the former will be considered to represent the linear distance between corresponding points on the northeast flank of the anticline and the southwest flank of the syncline, and the latter will be half the height measured in a direction perpendicular to any straight line joining corresponding points on the folds. The wavelength of the Castle River folds is, accordingly, 296 feet and the amplitude 85 feet. The axial plane separation (Matthews, 1958) at the long limb is approximately 195 feet, and the long limb height, measured parallel to the axial surface of the anticline, is 175 feet.

The orientation of fold axes at the outcrop was determined by means of bedding (S)-pole diagrams. The attitude of surface elements was systematically measured at two-foot intervals of arc length on the top of Member I for the anticline (40 poles) and on the top of Member II for the syncline (34 poles). These are plotted[1] in figures 4a and 4b respectively. π-circles of best fit were drawn through these plots and the azimuth and plunge of the fold axes determined. The anticlinal axis trends 150° and plunges 5° southeast, and the synclinal axis trends 145° and plunges 5° southeast. The two axes are, therefore, approximately parallel on the right (southeast) bank of the river. On the left bank (Fig. 4c), moreover, the trend of the synclinal axis is within two degrees of that determined above and its plunge is approximately zero degrees.

The strong clustering of S-poles for the anticline (Fig. 4a) reveals the subplanar nature of the flanks, and contrasts with the spread of poles along the π-circles for the syncline (Fig. 4b). Although the folds display variations in style they are both ideally cylindrical. The bending, however, is largely confined to the axial region of the anticline but is spread throughout the breadth of the syncline.

The assignment of folds to a particular style is largely based on constancy of bed thickness throughout the fold-pair and on change in radius of curvature with structural level on the axial surface. In parallel folds the thickness of individual layers may be expected to remain unaltered as a consequence of folding for large radii of curvature; any measurable changes are primary depositional or are owing to faulting. The radius of curvature of successive folded surfaces, moreover, will decrease downward in anticlines and upward in synclines and there is progressive departure from ideal parallel folding. Slip on individual detachment surfaces increases with external rotation. Ultimately beds no longer deform in harmony with their neighbours and faulting and crumpling of layers may occur in the cores of the folds.

The thickness of sandstone Member I was measured at intervals of two feet of arc length in a direction perpendicular to the hinge of the anticline (Fig. 5). It increases somewhat irregularly from seven and one-half to nine and one-half feet up the northeast flank, then decreases progressively across the hinge and down the southwest flank to five and one-half feet. The maximum thickness occurs approximately three feet northeast of the axis and well within the deformed sector. Close examination of the member reveals that the variations in thickness are the result of lateral facies changes to siltstone, a feature common to other resistant ribs in the fold-pair. The thickness variations are independent of folding, not because of it, and result in natural departures from the ideal parallel style.

[1] Data in Figures 4, 9, 10, 11 and 13 are plotted in equal-area, lower hemisphere projection.

These departures in style in the Castle River folds are revealed in a plot of the ratio (t/t_o) of the orthogonal thickness (t) of Member I at any point in the fold to its true thickness (t_o) in the hinge as a function of the acute angle of intersection (α) between the normal to the axial surface and bedding where the thickness has been measured. From the geometry (Fig. 6) a simple relation (circular measure) exists among α, the dip of the bedding (δ), and the inclination of the axial surface of the fold (α_o). For the general case of asymmetric folds the relation for beds on the steeper flank is: $\alpha = \delta + \alpha_o - 90$ and correspondingly for the gentler flank: $\alpha = \delta - \alpha_o + 90$. It should be noted that for folds with vertical axial surfaces the acute angle between bedding and the normal to the axial surface is equal to the dip of the bed.

For true parallel folds the ratio t/t_o must equal unity throughout the fold pair, regardless of the value of α. This ideal situation is shown by the dashed line in figure 7. The actual values of the ratios t/t_o, however, range from 0.6 to 1.1 and indicate that the fold at the stratigraphic level of Member I is not truly parallel. This deviation from parallelism is caused by the initial depositional variations in thickness rather than by variations due to the folding process.

The change in radius of curvature with structural level in the Castle River folds was evaluated from measurements on the five bedding surfaces in the anticline and the three in the syncline shown in figure 3. Radius of curvature (R) was plotted as a function of linear distance (D) along the axial surface in the c fabric direction[1] (Fig. 8), the starting point being the centre of curvature for the most acutely folded bed in the exposure. If the surfaces are concentric their radii of curvature (R) must equal the distance (D) from this common centre. The line drawn through the plotted points will be straight, will pass through the origin, and will have a slope of 45°. Points representing the smallest value of R for each fold necessarily fall onto the straight line because the distance from the origin to the corresponding surface is, in these instances, the radius of curvature.

The data suggest that the reference bedding surfaces in the Castle River anticline and syncline are not concentric and, therefore, the folds can not be truly parallel in style. Although the radius of curvature generally increases with distance along the axial surface, it is progressively too small to conform to the principle of concentricity.

It would appear, therefore, that on two counts, constancy of bed thickness and change in radius of curvature, the Castle River folds are not truly parallel in style.

Classification of the Castle River Folds

Because the distribution of S-(bedding) poles for both the anticline and syncline (Fig. 4) statistically defines a great circle, the attitudes of all the corresponding surface elements contain, within limits, the fold axes. The folds are, therefore, approximately cylindrical. Moreover, the axial surfaces in right section are subplanar at the structural level observed and the hinges are rectilinear for several tens of feet. The Castle River folds may be classified geometrically as plane cylindrical (Turner and

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[1] In this paper the c fabric direction is perpendicular to bedding, b is parallel to the hinge and a is perpendicular to b and c. Kinematic axes are not italicised.

Weiss, 1963, p. 110) within the width and depth of observation. Their style is neither truly parallel nor similar, but rather is somewhere between these ideal extremes. Because their axes are subhorizontal and their axial surfaces dip less than 90°, these plane cylindrical folds are classified according to geographic orientation as horizontal inclined (Turner and Weiss, idem, p. 119).

Structural Fabric of the Castle River Folds

The principal structural fabric elements examined in the study of the Castle River folds were joints that are perpendicular, subperpendicular and parallel to bedding, and slickensides and steps on faults parallel to bedding. Extension and contraction faults were few so that except for the joints, the structural continuity of successive beds is rarely interrupted.

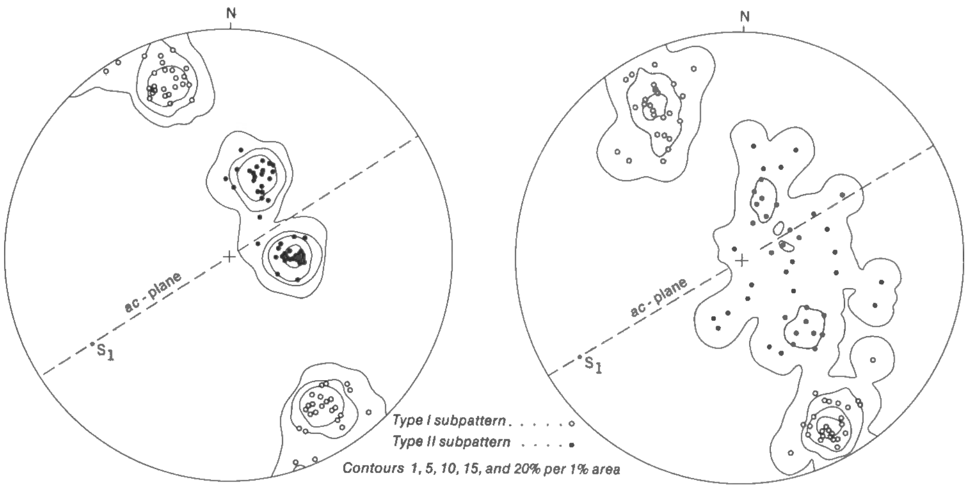
The fracture sets observed in this fold-pair may be identified with some of the subpatterns recognized by Stearns (1964) and treated in detail by him at a later date (Stearns, 1968, pp. 108-114). The two most common subpatterns or systems are composed of two intersecting sets. Type I consists of two sets intersecting at an acute angle bisected by the dip direction. Type II is made up similarly of two sets, intersecting at an acute angle bisected by the strike direction. All are perpendicular or subperpendicular to bedding. A number of joints were observed locally which did not conform to either of these subpatterns, but rather varied widely in inclination with respect to bedding. The two types are individually symbolized in figures 9, 10 and 11 portraying samples of the joint subfabric of the folds and associated fault plates bounding the structures on the southwest.

A conscientious attempt was made to measure all the macroscopic fractures in the rock at the sampling sites, in order that maxima on the fabric diagrams would not be a result of sampling bias.

The joint subfabric was sampled on both flanks of the anticline and in the three thrust plates to the southwest. The locations of these sites are shown on figure 3.

Four principal sets of joints were observed in Member II on the northeast flank of the anticline (see Fig. 9a). They are especially well developed on the left bank of the river (Plate IVa). All sets are perpendicular or subperpendicular to bedding. Two of the sets may be placed in Type I subpattern, and the other two in Type II. In both subpatterns a few joints are scattered between the two preferred orientations. The dihedral angle between the Type I sets is about 45° (Fig. 9a) and is bisected by the dip direction, that for the Type II sets is about 30° and is bisected by the strike direction.

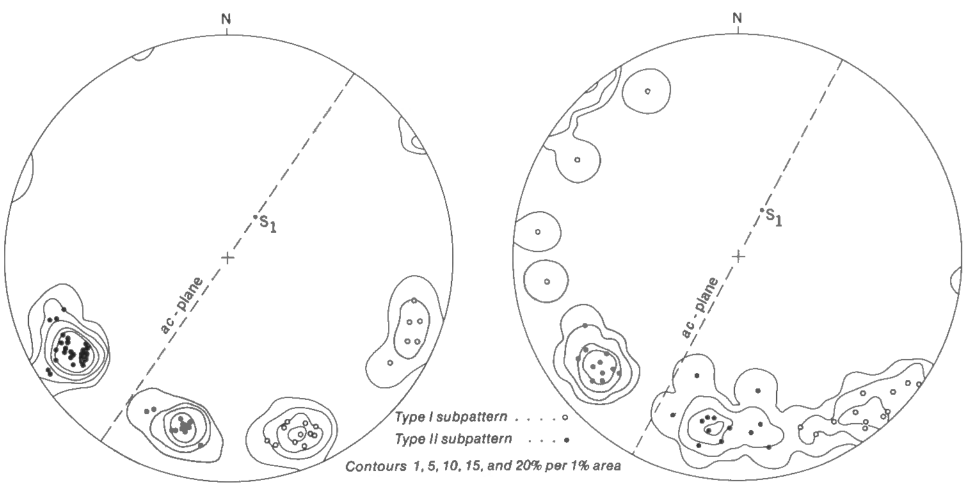
The joint subfabric of Member I on the northeast flank of the anticline is shown in figure 9b. Type I subpattern is very pronounced and the dihedral angle of 40° is bisected approximately by the dip direction. Type II subpattern is somewhat dispersed and the preferred orientations suggested by the 5 per cent contour are speculative.



9A. Member II, left bank of river (93 poles)

9B. Member I, right bank of river (93 poles)

Figure 9. Fracture patterns on northeast flank of Castle River anticline.



10A. 15 feet stratigraphically above top of Member I, right bank of river (55 poles)

10B. Member II, left bank (40 poles)

GSC

Figure 10. Fracture patterns on northeast flank of Castle River syncline.

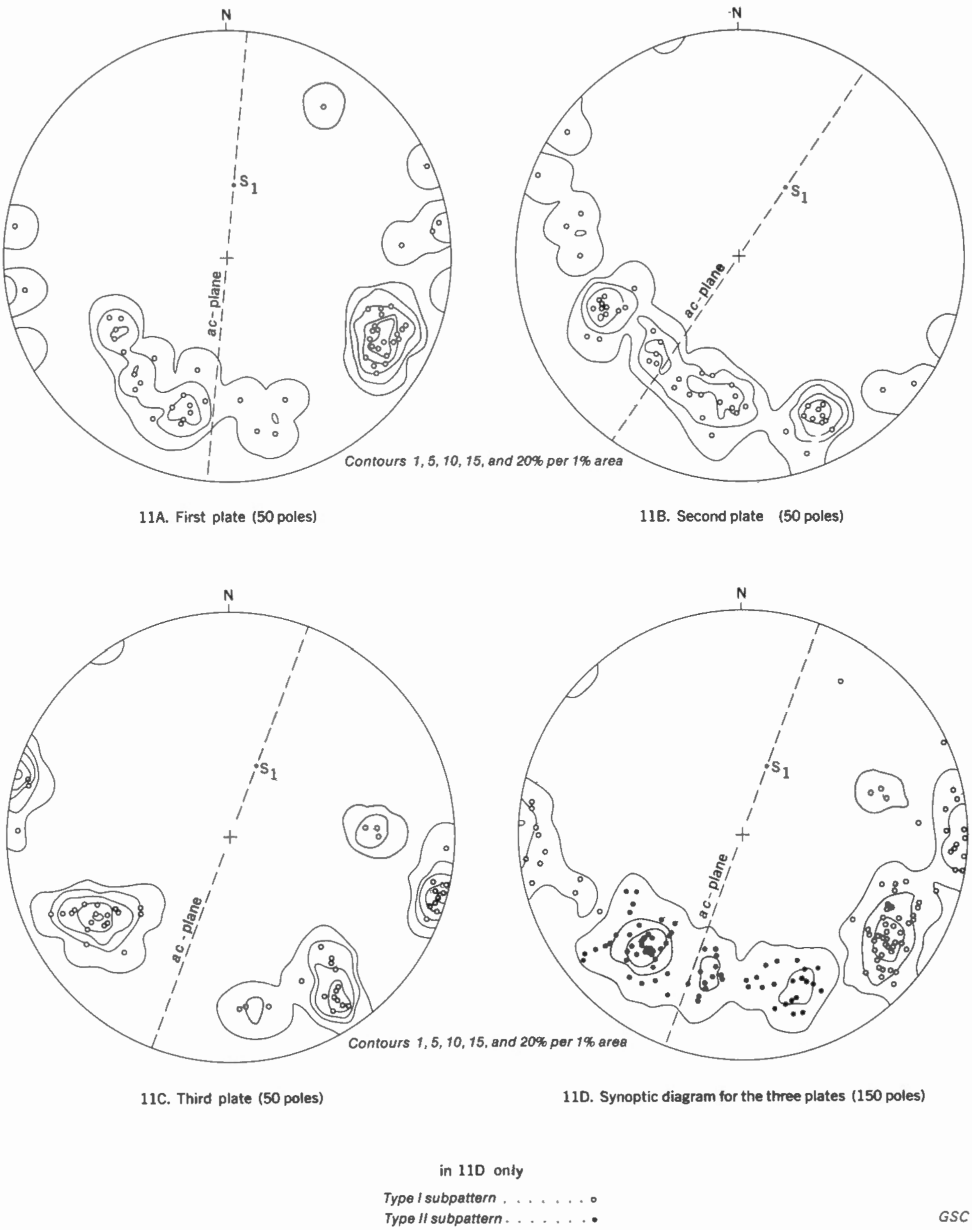


Figure 11. Fracture patterns in the three thrust plates to the southwest of the Castle River folds.

The joint subfabric was sampled also at two localities on the northeast flank of the syncline, one on each bank of Castle River. The data are represented in figures 10a and 10b. On the right bank (Fig. 10a) four distinct sets were recognized in sandstone beds fifteen feet stratigraphically above Member I. Two were assigned to each of the Type I and Type II subpatterns identified on the northeast flank of the anticline. The dihedral angle between the Type I sets is approximately 45°, the acute bisectrix trending 10° clockwise from the local a direction. For the Type II subpattern, the dihedral angle is about 40° and the acute bisectrix is in near coincidence with the local b direction. On the left bank of the river (Fig. 10b) the two sets of the Type II subpattern have almost identical orientation with their counterparts across the river, the dihedral angle being approximately 40° and the acute bisectrix coincident with the local b direction. One poorly defined set only of Type I subpattern was recognized lying intermediate in position between the corresponding maxima for the right bank and may be owing to overlapping of two sets. The preferred orientation for this subpattern is about 25° clockwise from the local a axis.

In spite of some scatter, therefore, the joints on the flanks of the folds on both sides of the river may be grouped in general into subpatterns each consisting of two principal sets symmetrically oriented with respect to the a and b fabric directions. By analogy with experimental studies these two sets may represent conjugate shears, with the few joints scattered between representing extension fractures or simply variations due to inhomogeneities in the rock. The a and b fabric axes would appear to coincide with the preferred orientations of the maximum principal compressive stresses during fracturing. For the Type I subpattern this stress was oriented approximately perpendicular to the fold axis and for the Type II subpattern parallel to it.

No surface features on joints appeared to characterize sets in a given subpattern. Thus it was not possible to identify joints as having originated through tension or shear. If the above analogy is correct, however, it is apparent that only the conjugate shears are strongly developed in the fold-pair and that the associated extension fractures paralleling the a and b directions are minor components of the fracture fabric. The fact that the joint sets are perpendicular or subperpendicular to bedding would suggest, moreover, that the maximum and minimum principal compressive stresses for both subpatterns were parallel or subparallel to bedding and that the intermediate stress was oriented orthogonally thereto regardless of the inclination of the beds.

In order to check the local persistence of the various joint sets recognized in the fold-pair, measurements were taken in sandstones of the immediate hanging-wall of the three thrust faults to the southwest, on the left bank of the river (Fig. 11). There the joints may be grouped into two or three sets at each sampling site and neither the strong preferred orientations nor the pronounced symmetry of joint maxima observed on the flanks of the fold-pair are immediately apparent. Individual sets vary in the strength of their development from site to site and it is difficult or impossible to define subpatterns composed of conjugate shears and associated extension fractures at any one site. If the three subfabrics are rotated to a common bedding orientation (276°, 27° SW) and are superposed on the one diagram, however, a joint pattern emerges which is very similar to that seen on either flank of the anticline (Fig. 11d). There are four maxima representing the conjugate shears of the Type I and II subpatterns and a scattering of joints between, possibly representing the extension sets. The latter are especially apparent in Type II, subparallel to the b direction. At all three sites, moreover, the spacing of the joints is noticeably closer than on the flanks of the anticline (compare Plates IVa and IVb).

Symmetry of the sets, strong maxima and wide spacing appear characteristic for the fold whereas a lack of pronounced symmetry, a scattering of joint orientations and a closer spacing appear to be associated with the individual thrust plates. Collectively, however, the joint subfabrics within the three plates are similar to those in the folds.

Thus far nothing has been said of joints in the ab fabric plane in the fold-pair although intuitively one might expect them to be important contributors to the fracture fabric where the bending stresses exceed the rupture strength of the rocks.

In order to evaluate the significance of ab or S-fractures in the Castle River prototype, the number of such joints visible to the naked eye was counted in a 23-inch thick sandstone bed in the vicinity of the hinge of the syncline on the left bank of the river (see Plate V). A plot of this number as a function of arc length measured along the bottom of the bed (Fig. 12) reveals a progressive increase from about twenty where the bed is essentially flat to sixty at the limit of outcrop where the bed is vertical to overturned. These joints appear to be spaced considerably more closely adjacent to the upper and lower surfaces of the bed than toward the middle. The maximum number observed does not occur at the hinge, but rather where the external rotation is greatest.

Two questions, therefore, immediately present themselves: why is the number of S-fractures not greatest where the radius of curvature is least, and what are the relative ages of these fractures and those perpendicular or subperpendicular to the lithologic layering? A careful examination revealed the presence of slickenside striae oriented perpendicular to the fold axis on many of these fractures. The striae, moreover, were traceable across the hinge, were especially abundant in the vicinity of the hinge between stations 2 and 4 (see Plate V), were fairly common between stations 4 and 5, and occasionally developed between there and station 9 on the subhorizontal flank. The data, therefore, would suggest flexural slip on these S-surfaces at the hinge and, consequently, that the hinge may have migrated progressively northeastward as the one flank was rotated through the vertical to the present overturned position. If this happened, the hinge may once have occupied the site of maximum observed number of fractures in the ab fabric plane and now be in the position of a somewhat lesser number of fractures. If, however, the amount of shearing strain was proportional to the external rotation (Norris, 1963b, p. 26), the number of fractures should increase and their spacing decrease in the rotating limb. This was observed to be the case.

The relative ages of the ab fractures and of those perpendicular or subperpendicular to bedding can best be established if offset relations among them can be recognized. It has just been demonstrated for the syncline on the left bank of Castle River that ab fractures are obviously related to the folding process. The question is, therefore, whether they offset joints that are oriented at large angles to bedding or are themselves offset.

Insofar as slip between layers is proportional to their deflection from initial dip it seems reasonable to conclude that the greater the fold flanks are appressed the more offset there will be of fractures at their intersections with kinematically active ab or bedding surfaces.

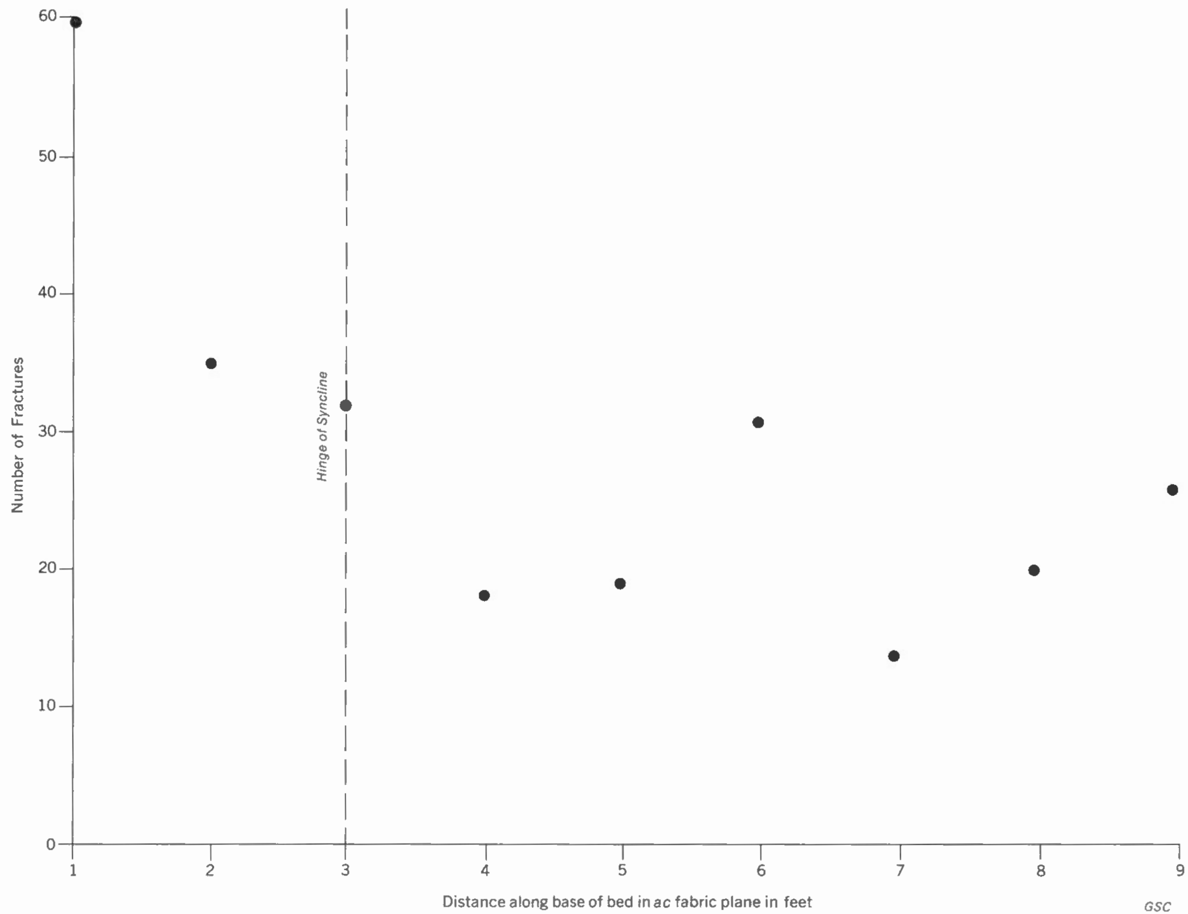


Figure 12. Variation in number of mesoscopic S-fractures in Member II as a function of arc length in Castle River syncline, left bank of Castle River.

Because only microscopic slip is required to produce slickensides (Norris, 1967, p. 313), the problem is not readily resolved unless the offset is apparent. A careful examination of the steep limb of the syncline on the left bank of the river revealed that many joints at large angles to bedding continue without offset at their intersections with the ab set. Because the slip on the latter in response to folding must be macroscopic, however, the Type I and Type II subpatterns appear to have been formed after folding of the layered succession was essentially complete.

The dip of sandstone Member I on the right bank of Castle River ranges from 75 degrees northeast to 25 degrees southwest. According to the formula (Norris, 1967, p. 318) relating magnitude of slip to thickness of layers and deflection, and using an average spacing of ten inches between successive slip surfaces, one might expect maximum offsets of the order of one foot on the northeast flank of the anticline and of one-third foot on the southwest flank. However, many prominent joints perpendicular and subperpendicular to bedding (see Plate IIa) pass unbent from top to bottom of the bed and without offset on ab fractures which they intersect. Others continue through as much as two-thirds of the bed before they terminate on such fractures. These prominent joints, therefore, also appear to have formed after folding. Like those in the syncline on the left bank of the river, their orientation and symmetry with respect to the fabric axes of the folds appear to have been controlled by residual stresses from the compressional phase of folding and faulting. They were, however, brought about by the lateral expansions and tensile stresses attendant upon uplift (Price, N.J., 1959, p. 167).

Kinematic Analysis of the Castle River Folds

The directions of motion in different parts of the Castle River folds are clearly revealed by slickenside striae on bedding, on intrastratal faults parallel to bedding and on faults at an angle to bedding. In most instances accretion steps (Norris and Barron, 1969, p. 150) were not observed so that usually it was not possible to determine the sense of relative displacement. However, the local ac kinematic plane could be defined.

For purposes of kinematic analysis, the Castle River structure was divided into four parts, three because of structural position and one because the river intervened. On the right bank the pitch of slickenside striae was measured in the anticline, the syncline and in the highly deformed beds in the hanging-walls and footwalls of the three thrust faults southwest of the fold-pair. On the left bank, pitch measurements were confined to the syncline. The data are presented in figure 13 as poles to slickensided surface elements in two distinct categories: those parallel to or coincident with bedding (o), and those inclined to bedding (Δ). The linear and curvilinear lines associated with the poles are slip linears, that is the projections of parts of the respective ac or deformation planes. The solid circles (•) are the piercing points of the b kinematic axes (axes of slip). Some surface elements were polished but not striated, and accordingly have no linears or axes of slip associated with them.

It is apparent from figure 13 that for both categories of poles the slip linears for the syncline and the anticline trend preferentially parallel or subparallel to the traces of the π-circle, that is approximately in the direction of the trace of the ac fabric plane. The fabric and kinematic axes would appear to have about the same orientation. For the syncline on the left bank of the river (Fig. 13a), for example, the a fabric and a kinematic axes are within 5 degrees of one another.

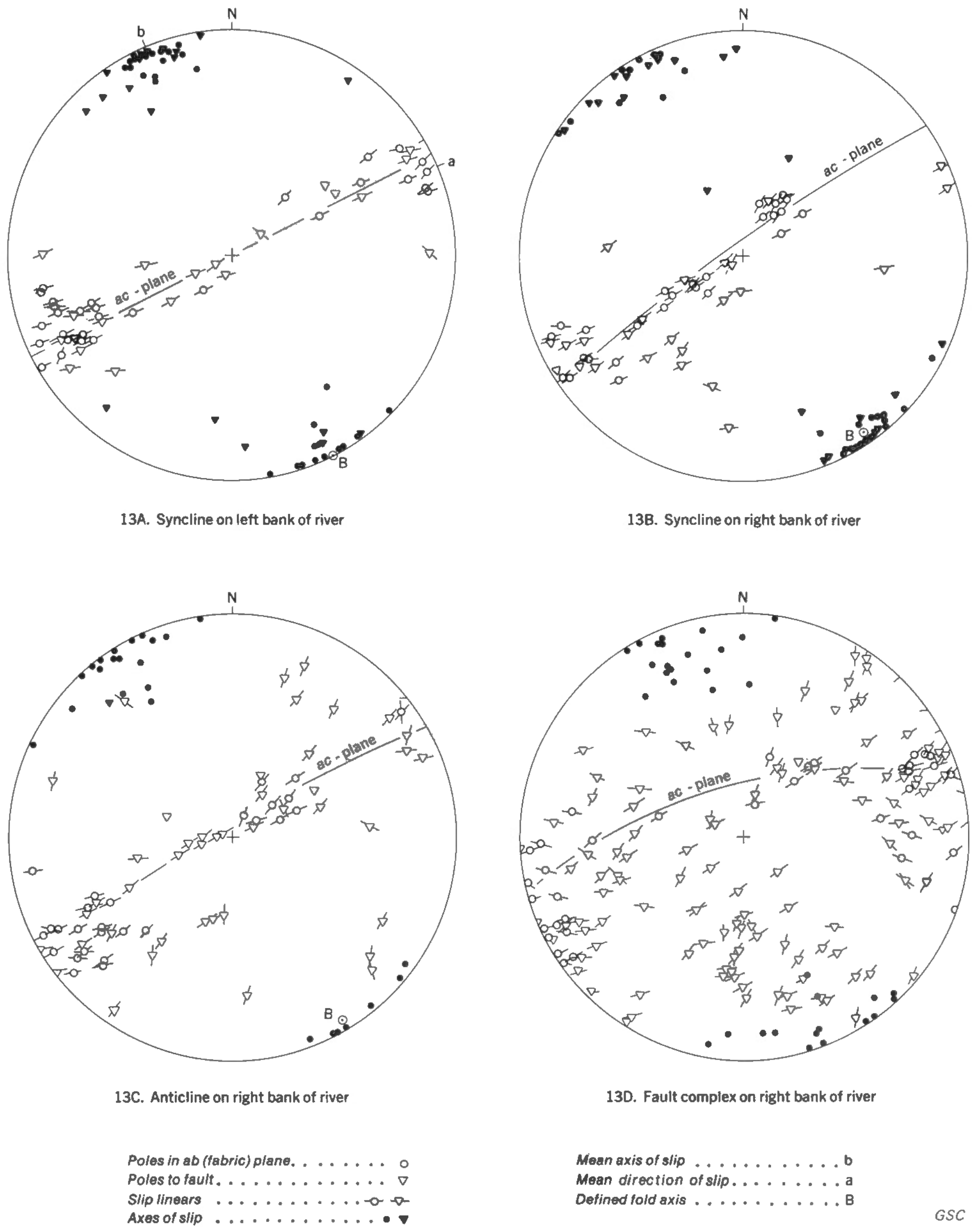


Figure 13. Poles to slickensided surfaces in Castle River prototype.

In contrast to the relatively simple geometric order of poles to bedding and faults and of their related slip linears for the fold-pair, the geometric and kinematic fabrics associated with the three thrust faults immediately to the southwest are complex (see Fig. 13d). There, also, slickensided surface elements are presented in two categories, those parallel to or coincident with bedding and those inclined to bedding. In spite of the disorder a π-circle for bedding can be approximated and would appear to represent a set of co-zonal surfaces whose statistical axis of intersection trends 165 degrees and plunges 20 degrees southeast. This is in contrast to the adjacent fold-pair whose mean axes trend 150 degrees and plunge less than 5 degrees southeast. Some of the poles to faults at an angle to bedding, moreover, tend to cluster along this π-circle, suggesting a crudely co-zonal set of slip surfaces statistically more or less with the same axis of intersection as the associated bedding slip surfaces. Others represent faults striking approximately at right angles to the trend of this zone axis but are commonly inclined northward at 50 to 60 degrees to it.

In order to establish and compare the basic structure of the kinematic patterns for slip on bedding in the fold-pair and in the thrust fault complex individual slickensided surface elements were rotated about their respective strikes into the horizontal and the new azimuth of the striae recorded. The frequency distributions of these azimuths were then plotted as histograms with common classes and class intervals.

The structure of the kinematic patterns for slip on bedding in the fold-pair and in the thrust fault complex is shown in the histograms in figure 14. That for the fold-pair is Gaussian in distribution, with an arithmetic mean azimuth of striae of 60 degrees;

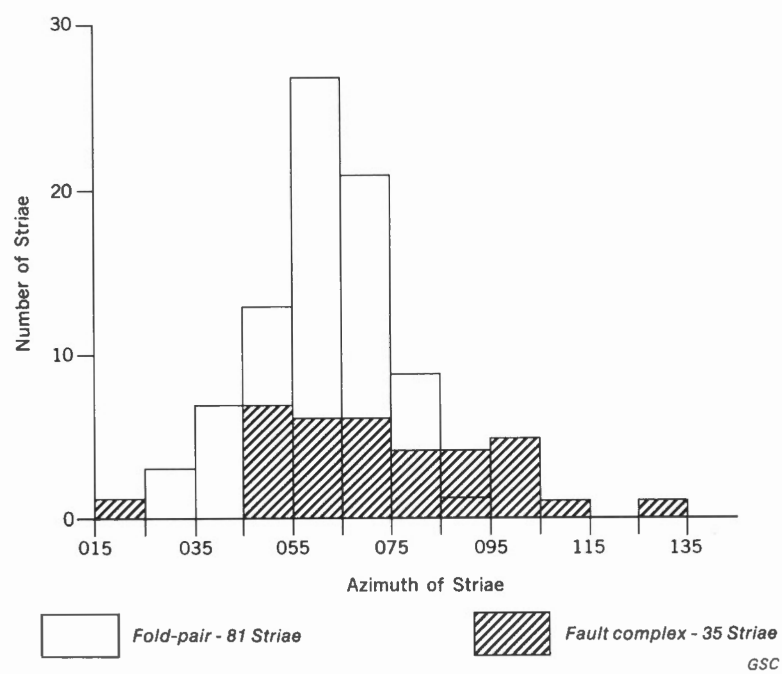


Figure 14. Frequency distribution of azimuth of striae in ab (fabric) plane in the Castle River folds, and in the fault complex.

the preferred direction of relative motion on bedding was, therefore, perpendicular to the fold axes, or in the a fabric direction. That for the fault complex, on the other hand, is difficult to assess because of so few measurements; the arithmetic mean azimuth is 73 degrees and the preferred direction of relative motion is essentially perpendicular to the axis of intersection of the set of co-zonal bedding surfaces on which these striae occur. Slip in both environments was for all practical considerations perpendicular to the respective fold or zone axis. The ten to fifteen degree difference in azimuth of relative motion on bedding between the fold-pair and the fault complex may not be significant in view of the great spread of azimuths for the fault complex. The spread for the latter is nearly twice that for the folds.

A comparative study of the distribution of kinematic a axes with tectonic environment was carried out by Norris and Barron (1969, pp. 160-162) in order to test whether there should be any fundamental differences in kinematic patterns in the thrust belt of the east-central Cordillera, the fold belt of the northern Appalachians and the craton of the St. Lawrence Lowlands. Their research indicated a consistent picture of slip in a variety of directions with a preferred motion perpendicular or subperpendicular to the strike of the fault or to the fold axis within each of these regions. The same conclusions seem to be valid for the Castle River folds and adjacent fault complex. The uniform but limited distribution of azimuths for the folds suggests that there was kinematic order so long as the strata throughout the structures remained physically continuous. With faulting the continuity was broken, each block became free to respond to the deforming stresses in its own manner and increased spread in azimuths of striae resulted. Some scatter is necessarily introduced because of the tenuous assumption that each bedding surface was necessarily rotated about its strike into its present attitude.

Thus far the analysis has been limited to the deformational behaviour of sandstone and shales by flexural slip in a structure where both the lower and upper detachment envelopes are inferred. Upward, the continuation of the Castle River folds is lost in the trees and downward the continuation is below river level. Repetition of the same part of the upper Blairmore succession in the three thrust plates on the southwest flank of the fold-pair strongly suggests that the faults become parallel to the layering within a few tens of feet of the base of Member I. This may well be the detachment surface for the Castle River folds so that the lower structural limit of the folds may not be far below river level.

The control of detachment surfaces on the style of deformation in the layered clastic succession within the eastern Canadian Cordillera is clearly revealed in several man-made exposures in the coal-bearing Kootenay Formation. One of these on the south face of Grassy Mountain, Alberta, will now be discussed in some detail not only because the nature of a detachment surface is displayed but, also, because it reveals an important principle of the transport of incompetent material (coal) in and out of the ac deformation plane during folding.

THE GRASSY MOUNTAIN FOLDS

High on the south face of Grassy Mountain, five miles north of Blairmore, Alberta, folds and faults in non-marine Jurassic and lower Cretaceous strata are clearly exposed. Coal was mined actively there about two decades ago and the resulting excavations in Grassy Pit No. 2 (abandoned) vividly reveal the nature of the deformation in these layered measures in right section. Fortunately these man-made exposures were photographed and surveyed while they were fresh because extensive sloughing from near vertical facies has occurred, resulting in loss in clarity of expression of the structures.

The folded and faulted Kootenay and Blairmore rocks shown in Plate VIa and VIb occur in the immediate footwall of Turtle Mountain fault and, therefore, lie structurally beneath and slightly farther east than the Castle River folds. The stratigraphic separation of the Turtle Mountain fault is approximately 500 feet and decreases rapidly northward. A knife-edge fault contact between the shales of the upper part of the Fernie Group and the conglomerate of the Cadomin Formation was at one time clearly exposed immediately beyond the area shown at the left (west) limit of Plate VIa.

To the east of Grassy Mountain is the Livingstone Range, having a resistant core of Late Paleozoic limestones and underlain by the Livingstone fault. The structures in Number 2 Pit are, therefore, between the Livingstone and Turtle Mountain faults and lie in a setting dominated by west-dipping thrusts and major folds with curviplanar axial surfaces dipping steeply westward (Norris, 1955).

The rocks exposed in the pit comprise part of the "lower Blairmore" (Norris, 1964, p. 520), the Cadomin Formation, and the Mutz and Hillcrest Members of the Kootenay Formation (Norris, 1959b, p. 232). They are a succession of shale, siltstone, sandstone, coal and conglomerate and, depending on their competence, display varying degrees of deformation. These rock units and the groups of beds within them are indicated on figure 15, based on a plane-table survey of the structures.

The deformation in Number 2 Pit is made up basically of two synclines and an anticline above the coal seam at the base of the Mutz Member, and two synclines and an anticline below the Member (see Fig. 15). The folds in the Mutz and Hillcrest Members are markedly disharmonic; the anticline in the Hillcrest, for example, rests beneath the more easterly syncline in the Mutz. The mean strike of the coal measures is approximately five degrees west of north and the plunge of the folds in the pit is close to zero degrees. Regionally, however, the structures in Grassy Mountain plunge northward because they lie on the north plunge of Blairmore Range (Norris, 1955).

The curviplanar axial surfaces of some folds exposed in Number 2 Pit dip steeply westward, congruent with the regional structural asymmetry, whereas others dip steeply eastward. Above the coal, folds with westward inclination commonly have sharp hinges and planar flanks (see Plates VIa and VIb) in the style of macro kink bands (see Faill, 1967, p. 214 and 1969, pp. 2539-2550). The thinly-bedded condition of the Mutz immediately above the coal (Beds 23 to 18) may have favoured this style. Below the coal, the folds are unfortunately masked with debris so that the inclination of axial surfaces and the curvature of flanks in the Hillcrest Member cannot be determined readily.

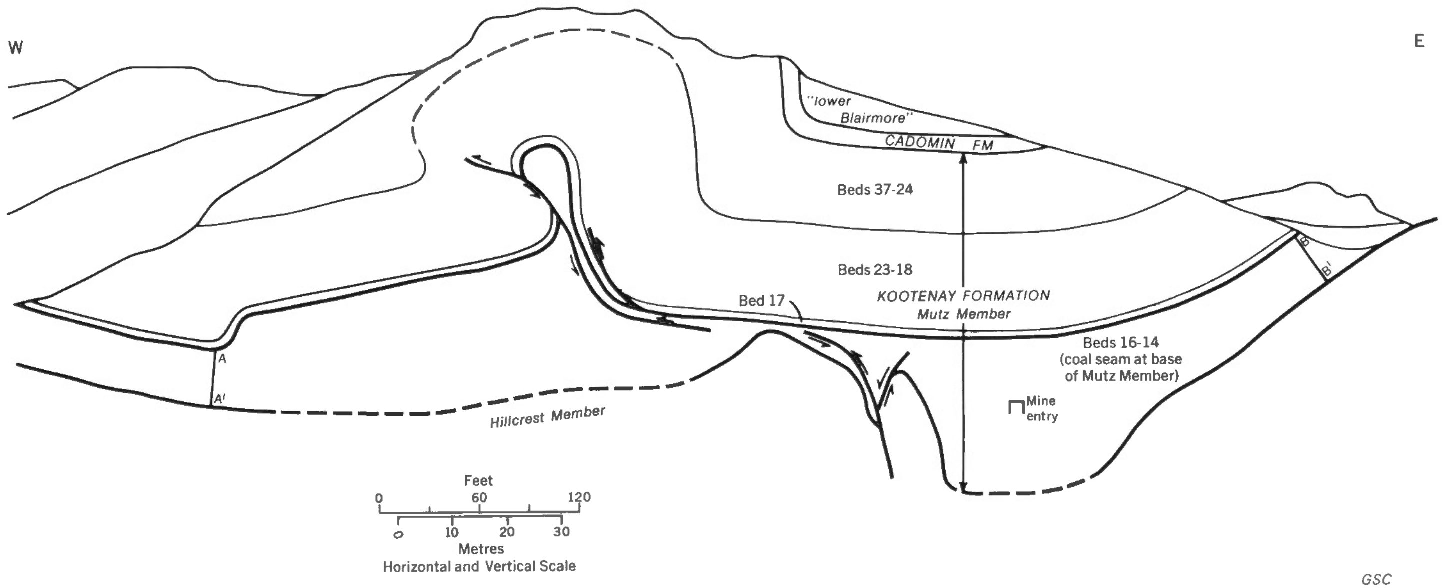


Figure 15. Right section of the Grassy Mountain folds, Alberta showing principal stratigraphic units used in establishing the geometry of the deformation in Number 2 Pit.

The primary depositional fabric of the coal has been largely destroyed because of slip between and across layers. The profusion of slickensided seam fragments and the many faults evident in the coal face attest to this. Whereas the normal, undisturbed thickness of the coal is about 34 feet (Bed 14, Norris, 1959b, p. 230), it is as much as 90 feet in the hinge of the more easterly syncline, and as little as about five feet where the anticline in the Hillcrest Member impinges on the roof of the seam.

The mechanism of tectonic thickening of the coal is clearly evident in the core of the anticline in the Mutz Member. Many east- and west-dipping shear surfaces are exposed, more or less symmetrically arranged with respect to the axial surface of the fold (see Plates VII and VIII). Offset bands within the coal, moreover, indicate that these and many other surfaces are bedding, thrust and high angle reverse faults. The coal was transported into the hinge on a myriad of discrete slip surfaces paralleling and transecting the depositional layering.

In conjunction with this remarkable thickening and thinning of the coal there is obvious shortening of hanging-wall and footwall beds, primarily through folding and secondarily through contraction faulting. A measure of this shortening is obtained by comparing the arc length of beds with their present horizontal length. Comparisons of the shortening of different layers can be determined by measuring the arc lengths at the upper and lower contacts of the coal between corresponding points (A, A' and B, B' of Figure 15) structurally removed from the tectonic thickening and thinning. With the faults removed, arc lengths AB and A'B' differ by only three per cent (800 vs. 780 feet respectively). In view of the possible errors inherent in surveying the contacts of the coal on the near-vertical face of the pit, the shortening in the beds immediately above and below the coal is for all practical purposes identical even though the two walls appear to have been deformed independently of one another. The present horizontal distance between points A and B is approximately 650 feet so that the amount of shortening accomplished by the folding and faulting of the coal measures is about 140 feet or 18 per cent.

With these measurements of arc length and original thickness of the coal, a simple test was performed to check whether the tectonic thickening of the coal within the limits of the structures was accomplished by simple transport perpendicular to the fold axes. The area of the seam measured in the right section between the limits AA' and BB' is approximately 40,000 square feet. On the other hand, the area of the undeformed seam in right section within these limits would be arc length AB times mean seam thickness or about 27,000 square feet. The observed area of the deformed seam is, therefore, approximately 48 per cent too large, a discrepancy which is not readily accounted for by small errors inherent in the plane-table survey.

The large area of coal in the section cannot be due only to reshaping of the seam as a consequence of shortening perpendicular to the regional strike. Coal must be transported into the section (ac deformation plane) on fault surfaces oriented perpendicular or oblique to the strike. The seam in Number 2 Pit, therefore, may be expected to thin ultimately in both directions away from the exposed section, and the folds to plunge accordingly.

The introduction of coal to the section in the b direction is important economically because of the anomalous thickening but it renders void any calculation of depth[1] to the detachment surface in the manner proposed by Goguel (1962). The sandstones and shales of the Mutz Member above the coal are obviously detached from the rocks of the Hillcrest Member below. A simple measurement of the area of the thickened coal above an arcuate envelope containing the upper contact of the seam between points A and B in conjunction with the measured shortening of 140 feet, would suggest that the detachment surface is about 107 feet stratigraphically below the top of the coal or about 73 feet below the seam. This is obviously incorrect because the disharmony in structures indicates that a detachment surface is within or at the base of the coal.

Calculation of depth to the detachment surface in cylindrical folds is extremely conjectural if the individual rheological properties of the rock formations comprising the folded succession are not taken into account. Where there is transport of material into the section the calculated depth to the detachment surface will be too great and correspondingly where the formations are thinned, the calculated depth will be too shallow.

FLEXURAL-SLIP FOLD MECHANICS

In classical, parallel, flexural-slip folds, each layer in the succession is free to slip over adjacent ones and the orthogonal bedding thickness of individual layers does not change significantly as a consequence of the folding. The flanks may be planar, curviplanar or curved provided that the orthogonal bed thickness remains constant. A theoretical figure involving three layers of equal and constant thickness and buckled into a fold-pair is shown in figure 16. The radii of curvature at the hinges increase systematically from centres C_1 and C_2 in the axial planes. Anticlines broaden and die out upward and synclines downward in the direction of detachment envelopes that confine the folding to a particular interval in a layered sequence. In a given fold, therefore, each layer will have a form slightly different from those adjacent to it. In a simple anticline-syncline pair, however, those layers equidistant above and below the central lamina will have the same form in reverse and upside down. This may be seen by superposing the two forms after the one has been rotated first end for end about a vertical axis passing through the common inflection and then bottom for top about a horizontal axis through the inflections.

It can be demonstrated both mathematically and by means of models that the arc lengths of successive beds are constant in each wavelength and independent of structural level. Thus, the progressively more acute folding toward the core of the anticline is compensated for by the progressively more open folding away from the core of the syncline. The centre line of the middle layer of the model is drawn to have a common radius of curvature for both the anticline and the syncline. Whether the folds are symmetric or asymmetric, only one such layer can possess this property in a given anticline-syncline pair. To one side or other of the middle band, however, the radius of curvature of a layer in the anticline must be different from that in the syncline; part of the layer may have curvature inside and part outside a stable configuration. Where the rate of curvature is greater than that for the ideal parallel, flexural-slip model, as in the cores of some folds, the layer or layers will undergo smaller scale folding and faulting.

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[1] "Depth" is a misnomer because there are usually an upper and a lower detachment.

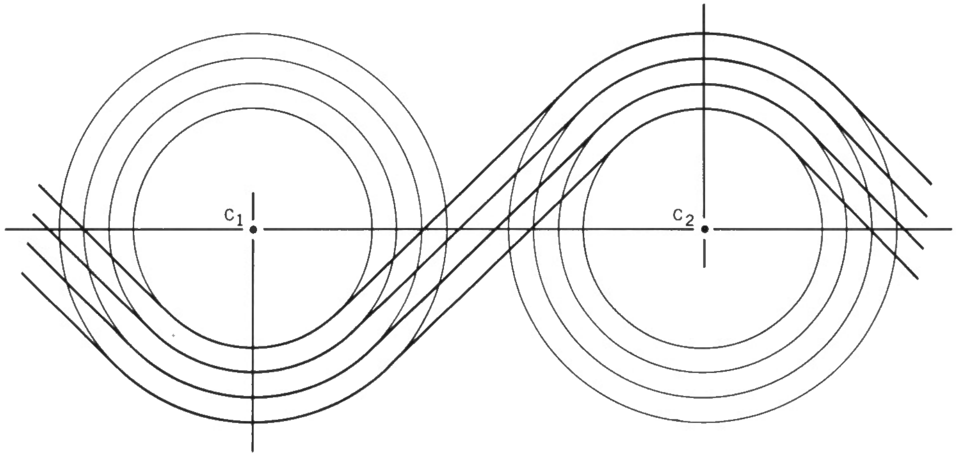


Figure 16. Theoretical, 3-layered model of parallel, flexural-slip fold-pair.

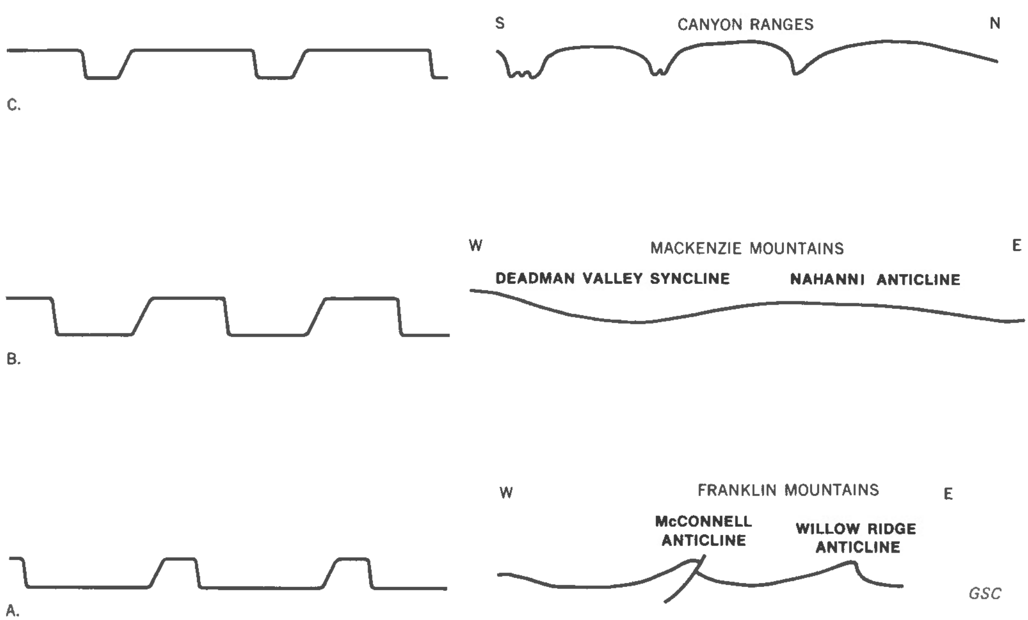


Figure 17. Comparison of theoretical forms from a concentric fold model (after Dahlstrom, 1960) with fold forms from the northern Cordillera.

Various fold forms may be observed in different parts of a region characterized by the same fold style, depending upon the structural level exposed (Dahlstrom, 1969, pp. 329-330). The folds may maintain the same wavelength and amplitude vertically through the succession but they must vary in curvature. Compare for example the three fold forms (Fig. 17) modified from Dahlstrom (1960, Fig. 1) with the three naturally occurring forms taken from structural studies by the writer in the northern Cordillera. From Dahlstrom's model it is apparent that flat-bottomed synclines and sharp anticlines are characteristic of structural levels close to the lower detachment envelope. An analogy to this situation may be seen just north of Willow Lake River toward the southern termination of Franklin Mountains in western District of Mackenzie. There, the middle and lower Paleozoic sedimentary succession is folded to form McConnell and Willow Ridge anticlines, pronounced structural highs in the Middle Devonian Nahanni Formation, connected by a wide area in which the rocks are essentially flat-lying (Fig. 17a). The basal detachment envelope is considered to be the salt beds of the Cambrian Saline River Formation, approximately 3,000 feet stratigraphically below. Farther west the formations are more numerous and thicker, and the structural level of the Nahanni Formation is progressively more removed from this detachment envelope. The matching curvature of anticlines and synclines in eastern Mackenzie Mountains, as seen for example in Deadman Valley syncline and Nahanni anticline (Fig. 17b) about half way between the North and South Nahanni Rivers, would suggest structural levels about mid-way between the upper and lower detachment envelopes. Still farther basinward folds at higher structural levels are complicated by thrusts and high-angle reverse faults. In northern Mackenzie Mountains, however, in an equivalent structural position in the sedimentary basin, east-trending, broad anticlines, exposing essentially flat-lying sedimentary rocks as old as Late Proterozic are interrupted by narrow, tightly folded synclinoria containing rocks as young as Late Devonian (Fig. 17c). The Cambrian salt beds are absent in this region and these folds are believed to lie at structural levels considerably above a lower detachment deep in the Proterozoic succession but close to an upper detachment in the Late Devonian Imperial shale. Thus the fold form occurring at an upper detachment is simply the mirror image of that occurring at a lower detachment.

The relation between radius of curvature and structural level for the Castle River folds will now be compared with that for the theoretical model and with four additional examples of flexural-slip folding. The latter comprise the Webb Creek folds, an anticline-syncline pair in siltstone and shale beds from 1 inch to 16 inches thick near the top of the Jurassic Fernie Group in the Maverick Hill fault plate (Norris, 1961, p. 180) of the eastern Cordillera of Canada; the Squaw Creek anticline (Price, 1964, p. 18) in the Fernie synclinorium of the Lewis thrust plate; the Queensway folds (Norris, 1967, p. 303) in limestone and shale beds from 1 inch to 30 inches thick in the Ottawa Formation of the Ottawa - St. Lawrence Lowlands; a fold-pair whose style has been accurately defined through studies underground in six coal seams in the Late Pennsylvanian Llewellyn Formation at the Sugar Notch Colliery in the Northern Anthracite Field of Pennsylvanian (Fig. 18); and Tipple syncline in the coal measures of the eastern Cordillera.

For each bedding reference surface the radius and centre of curvature at the hinges was determined graphically. The best fit curve through the centres of curvature defined the trace of the axial surface in the section and served to emphasize the misuse of the term "axial plane" so common in the literature of structural geology. The radius of curvature (R) was then plotted (Fig. 19) as a function of distance (D) from the centre of curvature of the highest or lowest reference surface or coal seam for the

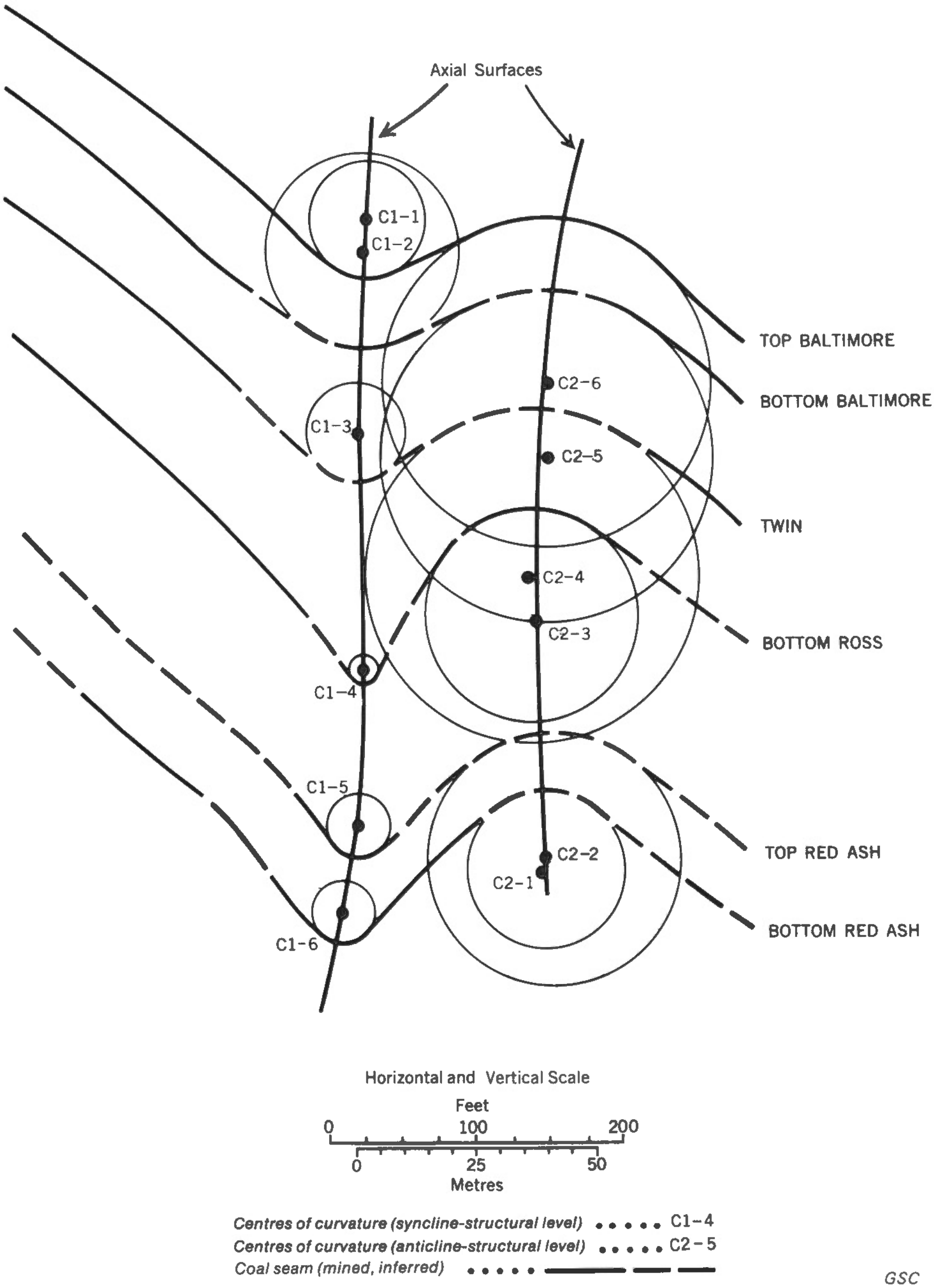


Figure 18. Right section of fold-pair, Sugar Notch, Pennsylvania.

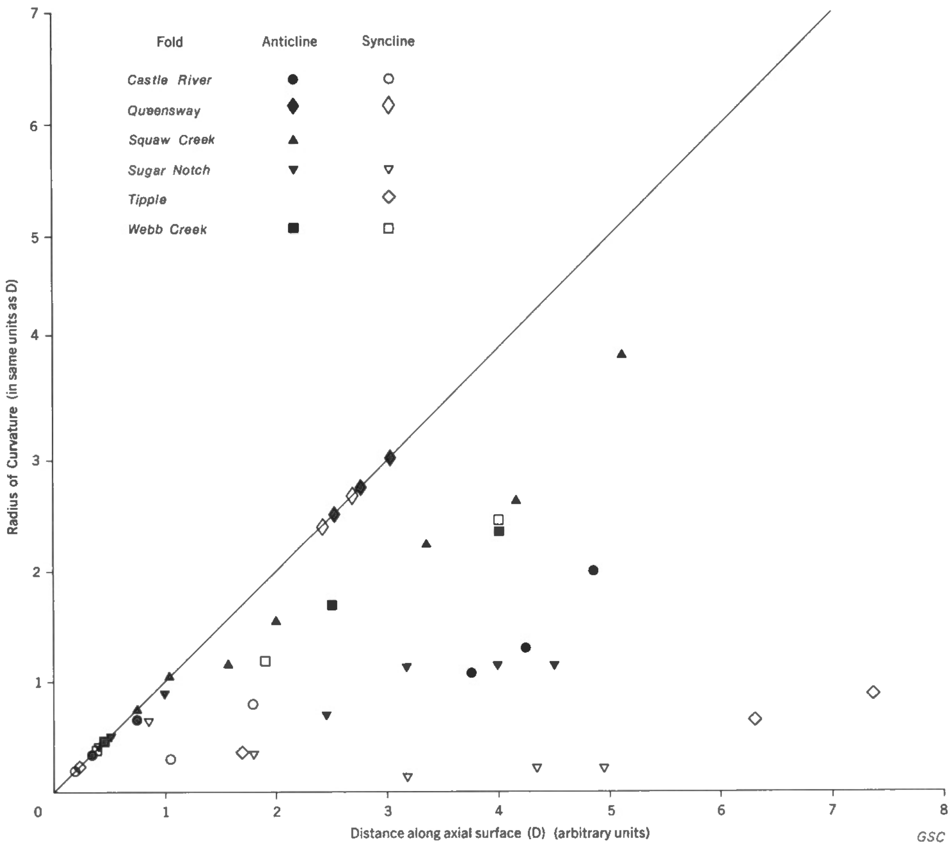


Figure 19. Synoptic diagram of variations in radius of curvature with structural level in the Castle River, Queensway, Squaw Creek, Sugar Notch, Tipple, and Webb Creek folds.

examples cited. Insofar as R and D are in the same units of measurement for the respective folds, the several examples may be compared on the one diagram regardless of their absolute dimensions. The straight line with a slope of 45° represents the relation for the theoretical, parallel fold model where, by definition, the radius of curvature of all surfaces must equal the perpendicular distance from a common centre of curvature to the surface at the hinge. Below and to the right of the 45-degree line would fall points representing surfaces with radii of curvature less than that required by the parallel model for structurally higher surfaces in anticlines and lower surfaces in synclines. Some of the forms represented by points in this region of the graph would fall into Ramsay's (1967, p. 366) Class 3 folds, in which the radius of curvature of an outer surface is always less than that of an inner one. There is dilatency in the hinges with concomitant extension of the axial surface in the c fabric direction. Above and to the left would fall points representing surfaces with radii of curvature progressively greater than that required by the parallel model. These would fall into Ramsay's (idem) Subclass 1A and 1C folds, in which the radius of curvature of an outer surface is always greater than that of an inner one. Thickening or thinning of the beds in the hinge is a necessary condition for the folds in these subclasses and the axial surface must extend or contract accordingly. For similar folds, the radius of curvature at the hinges is constant and independent of distance along the axial surface in the c direction. In the diagram they would be represented by a series of lines parallel to the horizontal (D) axis.

The folds plotted in figure 19 display a variety of styles ranging from parallel at the one extreme to similar at the other. The Castle River, Webb Creek and Squaw Creek folds show progressive departures from the theoretical, parallel model with increasing distance upward in the anticlines and downward in the synclines. The reference surfaces in them characteristically have radii of curvature that are too small for their structural level and the folds persist through larger stratigraphic intervals than would normally be the case for the truly parallel style. There is dilatency, therefore, at the hinges and extension of the axial surfaces in the manner of the folds containing the classical saddle reefs of Bendigo, Victoria (Stillwell, 1917). The Sugar Notch fold-pair and Tipple syncline, however, appear to be "similar" because their radii of curvature are more or less constant and independent of distance in the c direction on the axial surface. Of the several examples from a variety of tectonic environments, only the Queensway folds, whose flanks do not dip more than 15 degrees, appear to possess the geometric requirements of the theoretical model. This confirms the conclusion of Billings (1959, p. 58) that parallel style may be confined to folds with gently dipping limbs.

INCLINATION IN FLEXURAL-SLIP FOLDING

By definition, a fold is inclined if its axial surface dips less than 90° (Turner and Weiss, 1963, p. 119). The dip of the axial surface and, therefore, the fold inclination is defined with respect to external coordinates. Symmetry, on the other hand, is defined purely on the basis of fold form (Turner and Weiss, idem., p. 122). Thus a symmetrical fold may be inclined because of external rotation of the fold but an asymmetric fold is always inclined unless the axial surface is fortuitously in or rotated into the vertical. In asymmetric folds it is a simple matter of geometry to prove that the axial surface or plane must be inclined generally in the same direction as, but more steeply than the long limb, provided the fold has nucleated and grown in flat-lying beds or has not suffered external rotation.

The subplanar axial surfaces of the Castle River anticline and syncline dip approximately 75° and 60° respectively southwest. The folds are, therefore, inclined. The main factor causing this inclination is the asymmetry of the folds although they may have been externally rotated to a minor degree during translation on the Turtle Mountain fault or in response to deformation in an underlying plate.

The Castle River folds are one of a large family of asymmetric flexures whose axial surfaces are inclined characteristically in the direction of dip of the thrust faults of the eastern Cordillera. How are these asymmetric, flexural-slip folds nucleated and how do they grow? Are they initially symmetric so that asymmetry is an acquired characteristic rather than an innate one? Does an axial surface shift along the layering as a fold grows? What are the reasons for the association of westward-inclined axial surfaces with west-dipping thrusts in the eastern Cordillera? And why are some folds in the northern Rocky Mountains and Mackenzie Mountains inclined toward the foreland and others toward the interior of the Cordillera? These and other questions arose as a consequence of the study of the Castle River prototype.

Some answers are forthcoming through the critical examination of a physical model based on field observations in the Castle River, Webb Creek, Grassy Mountain, Queensway, Sugar Notch and Tipple folds. The model proposed for the nucleation and growth of these inclined, flexural-slip folds is that of a laminated plate, the laminae representing the layered sedimentary successions on the craton and in the miogeosyncline. Each layer is free to move along its upper and lower bounding surfaces during buckling and faulting. The plate as a whole is bounded by detachment envelopes which may represent faults transecting the layering or décollements in low strength horizons such as shale, coal or salt. The folding is, therefore, confined by the detachment envelopes and to a limited stratigraphic interval.

Axial surfaces are assumed to be generated at the initiation of buckling instability and to be oriented perpendicular or subperpendicular to the layering. Hinges are, therefore, in existence before significant external rotation of the beds, are assumed to be fixed in position on each bedding structural unit, and are moved toward one another with appression. There can be no transfer of material across the hinges through interlaminar slip so that flanks which are planar were probably always planar. The primary orthogonal thickness of the laminae is maintained down to a limiting value of the radius of curvature; below this limit the thickness may be significantly modified through secondary faulting and folding.

Several authors, for example, Seidl (1934), Kuenen and deSitter (1938), and Norris (1967, pp. 316-319) have discussed the mechanics of flexural-slip folding as revealed by layered models. Two such models are portrayed in figure 20; one representing a simple, symmetrical flexural-slip fold and the other an asymmetrical one. In both models there are ten layers and each layer has been divided about its centre line into ten equal parts between adjacent hinges. The reader can, therefore, readily visualize the different radii of curvature for the anticline and for the syncline as well as the sense and magnitude of interlaminar slip as functions of structural position at one and the same interface in the fold-pair.

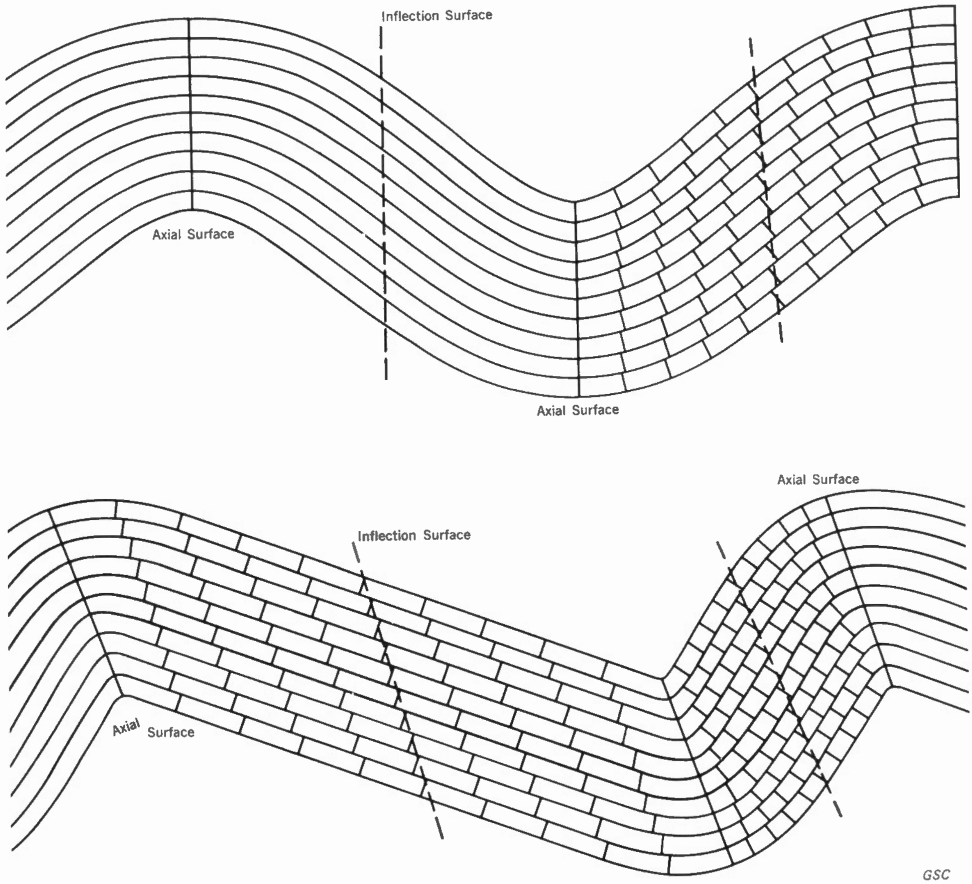


Figure 20. Schematic diagram showing variation in magnitude of interlaminar slip as a function of structural level in a ten-layered, symmetrical and asymmetrical model (after Price, R. A., 1965).

It has been shown quantitatively (Norris, idem., p. 318) that for the laminated model, flexural-slip and external rotation vary continuously throughout the fold-pair, reach their maximum values at the inflections, and reach zero at the hinges. For a given thickness of laminae they are independent of the size of the fold. Thus at the central (sinusoidal) interface of the symmetrical model (Fig. 20a) bedding surface elements in equivalent structural positions (equal arc length from a fold axis) on either side of the hinge will suffer interlaminar slip and external rotation equal in magnitude, but opposite in sense. As radius of curvature changes away from the central interface, layers are no longer sinusoidal in form so that external rotation and interlaminar slip no longer follow a simple trigonometric relation. This also is true for the asymmetrical model (Fig. 20b) where the fold form of all laminae is notably non-sinusoidal (eccentric). Here, surface elements which are equal arc length on either side of a fold axis have experienced external rotation and interlaminar slip proportional to their dip.

The variation in magnitude of slip for both models may be seen by following the offset of markers vertically through the succession as well as laterally along any of the lamina slip surfaces. Note the symmetry in these variations by comparing the offsets in the first column of markers to the right or left of the axial surface of the anticline with that to the left or right of the axial surface of the syncline. For the anticline the offsets increase downward and for the syncline, upward, the rate of increase being greatest toward the hinges and least at the inflections. Offsets, however, are maximum at the inflection and zero at the hinges.

The inclination and symmetry of simple folds originate at fold nucleation when spacing of axial surfaces is established. Even spacing results in limbs of equal length and consequently in symmetric folds. By the same token, uneven spacing results in asymmetric folds (see Figure 21). With increased appression the folds in a train decrease in wavelength, increase in amplitude and dilate the stratigraphic succession through forcing apart of the detachment envelopes. The hinges move toward one another and if any of the layers depart from the parallel style, the axial surfaces extend or contract in the direction perpendicular to the hinges.

In symmetric folds the axial surfaces may remain in the vertical as they move toward one another. If there is external rotation because of movement of the mass on an underlying curved thrust fault (Mountjoy, 1959), such folds may become inclined. In asymmetric folds, on the other hand, axial surfaces progressively rotate out of the vertical about axes parallel to the hinge and become more and more inclined in the direction of dip of the long limb.

The inclination of the axial surface at different stages in the growth of an asymmetric fold was calculated by means of the model shown in figure 22a. For simplicity the flanks are assumed to be planar and to meet abruptly at the hinge (C) in the manner of a kink zone boundary. Points A and B are the inflections defining the limits of the fold. The axial plane bisects the apical angle 2γ and is inclined at an angle i in the direction of the long limb. α is the dip of the long limb and β the dip of the short limb. The ratio of lengths of the long and short limbs l_1 and l_2 is a measure of the asymmetry of the fold and is arbitrarily assigned values 1, 1.5, 2, and 3. The inclination i of the axial surface was then calculated for several values of the dip (α) of the long limb for each ratio of limb lengths (Fig. 22b). The distance l_3 between the inflections is a measure of the appression of the fold. It assumes whatever values are required for the solution of the triangle once one of the angles (α) and two of the sides (l_1 and l_2) have been chosen. In turn, the functional relationship between the inclination

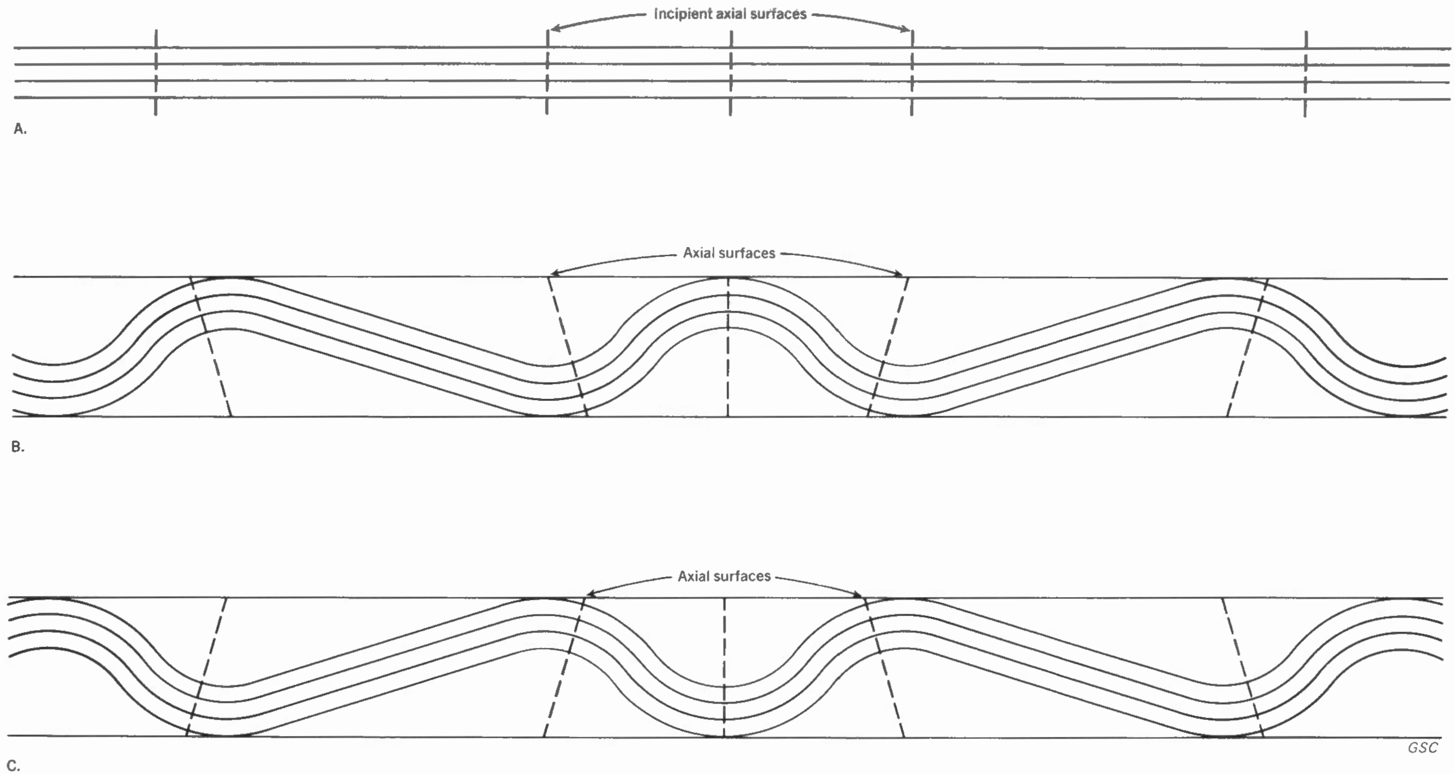
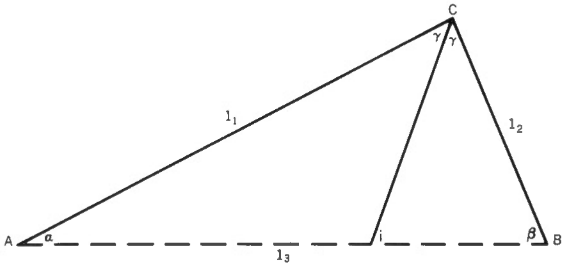
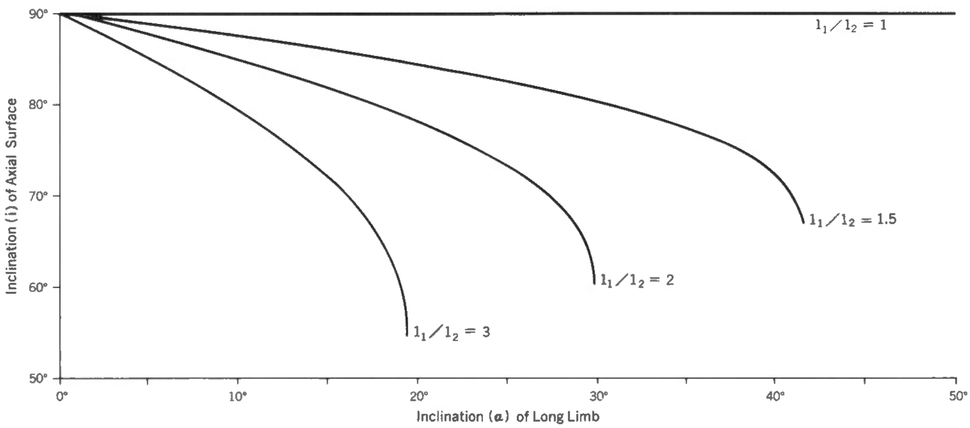


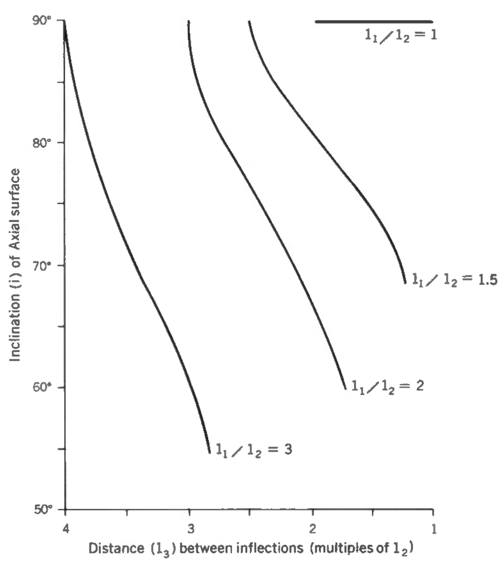
Figure 21. Schematic diagram showing relation between spacing of axial surfaces and fold symmetry.



22A. Angular relations in the asymmetrical model



22B. Inclination as a function of dip of long limb



22C. Inclination as a function of linear distance between inflections

GSC

Figure 22. Decrease in inclination of axial surface during growth of an asymmetrical fold.

of the axial surface and the distance l_3 was calculated (Fig. 22c). It is immediately apparent from the graphs that during the growth of an asymmetrical fold the inclination of the axial surface is not linearly dependent on the dip of limbs or on the distance between inflections. With regular increments in the dip of the long limb the inclination of the axial surface decreases first slowly and then more rapidly as the short limb approaches the vertical. For a given α, the greater the ratio l_1/l_2 (and hence the more asymmetric the fold), the greater is the rate of change of inclination of the axial surface. With regular decrements in l_3 (as might be the case with uniform appression) the axial surface rotates out of the vertical first rapidly, then relatively more slowly, and then somewhat more rapidly for all values of the ratio of limb lengths. The rate of change of inclination of the axial surface is greater, moreover, the larger the ratio l_1/l_2, for values of $i > 80° \pm$. In other words, the more asymmetric the fold, the greater the rate of change of inclination of the axial surface with α and with l_3 during the early stages of fold growth. During the growth of symmetric folds ($l_1/l_2 = 1$), on the other hand, the axial surface remains perpendicular to the detachment envelopes, so that its inclination is constant and independent of either the inclination of the limbs or the distance between the inflections.

In the southeastern Cordillera of Canada flexural-slip folds are intimately associated with the family of west-dipping thrust faults. The folds are characteristically inclined in the direction of relative motion of the thrust plates and are secondary to the thrusts in effecting horizontal shortening within the sedimentary veneer. In the northern Cordillera, on the other hand, flexural-slip folds are the principal structural element and are commonly inclined either toward or away from the craton; some are observed to reverse their inclination along strike. The high-angle reverse faults with which many of these folds are associated also show no preferred direction of dip so that the unidirectional structural asymmetry characteristic of the southeastern Cordillera is absent in the north.

The question of fold inclination has recently been discussed by Fitzgerald (1968, pp. 660-661) for anticlines in the foothills of the northern Rocky Mountains. There, he observed both box and curvilinear fold forms with all degrees of asymmetry and with about three times as many folds inclined away from the craton as toward it. He concluded that the lack of system in the inclination of folds in the area was owing to the presence of structurally weak material in the cores which was forced upward in the anticlines and, depending upon which direction the material moved, the fold was inclined either toward or away from the craton. Still farther north in Mackenzie Mountains, the same lack of system prevails, but the folds are commonly associated with the high-angle reverse faults.

The association of inclined folds with thrust and high-angle reverse faults in the foothills and mountains of the eastern and northern Cordillera would suggest a mechanical link between them. It has been shown that fold asymmetry and commonly also fold inclination is governed by spacing of axial surfaces. Thus it would appear that non-uniform spacing may be characteristic of successions deformed by thrust and high-angle reverse faulting. Whether the succession is externally rotated about a given hinge to form an anticline or a syncline (Fig. 21), and hence whether the corresponding axial surface will be inclined the one way or the other is dictated by the sense of motion on the fault or other detachment surface. The long limbs of these inclined flexural-slip folds are usually rotated so that the sense of interlayer slip on them is congruent to motion on the faults and the incongruity due to slip in the short limb is minimized. In terms of surface area on any one bed regionally involved in the folding, therefore, the more unidirectional the fold inclination, the greater the surface area on which the sense of slip is the same. Where the faults have a preferred direction of dip, as in the southeastern Cordillera of Canada, the associated folds have their long limbs inclined in the same direction as the faults and the asymmetry of the deformation is pronounced. On the other hand, where the faults dip in either direction, as in the Mackenzie Mountains, the axial surfaces of the associated folds also may dip in either direction and this asymmetry is lost.

CONCLUSIONS

A comparative study of the Castle River and other folds in the Jurassic and Lower Cretaceous clastic succession of the eastern Canadian Cordillera suggests that:

1. The Castle River folds are typical of the eastern Cordillera; they are not truly parallel but rather are intermediate in the continuum of styles ranging from parallel at the one extreme to similar at the other.

2. Interlaminar slip is the principal mechanism of relative displacement of structural units during buckling.

3. The textural and compositional layering is the fundamental property controlling the position and spacing of slip surfaces in the sedimentary succession.

4. The competent units tend to retain original bedding thickness throughout the fold whereas the incompetent units are sheared and transported into the hinges on numerous faults transecting the compositional layering. The fact that coal is commonly thickened in hinges emphasizes the commercial importance of additional exploration in these structural positions.

5. The thickening process, characteristic of materials such as shale or coal, is a passive phenomenon, is the result of buckling, and must take place concurrently with the growth of the folds.

6. The volume of material transported into the hinges is in some instances greater than can be accounted for by movement entirely in the deformation plane and hence significant quantities may have components of movement parallel to the fold hinges as well.

7. There is, accordingly, thinning and thickening along the hinge of a fold as well as across it.

8. Calculations of "depth" to detachment surfaces should be performed with the possibility in mind that material transport in the b direction may significantly alter the results.

9. The folded clastic succession tends to retain a common form through larger stratigraphic intervals than required by the true, parallel style because the competent beds assume radii of curvature which are too small for their structural level. The incompetent beds thicken to fill the volumes between.

10. The asymmetry of folds in the eastern Cordillera is established by the original spacing of axial surfaces at fold nucleation; even spacing results in symmetric, and uneven spacing in asymmetric folds.

11. Most folds in the eastern Cordillera are asymmetric, and inclined because their limbs are of unequal length; all may have been externally rotated to some degree during or after translation because of motion on faults or other detachments.

12. The fact that asymmetric folds characterize the southeastern Cordillera (where thrust faults are the dominant tectonic element) and symmetric folds are as common as asymmetric ones in the northeastern Cordillera (where folds are the dominant tectonic element) would suggest that regularity in spacing of axial surfaces may be inversely related to intensity of thrust faulting. Mechanical congruity in the layered succession, as it is deformed, is most complete when folds have their long limbs dipping in the same direction as the thrusts, because the sense of interlaminar slip in these limbs is the same as that on the faults; the incongruity due to slip in the short limbs is minimized.

13. Structural level in a fold-pair or fold train can be identified by the relative curvature of a given structural unit in an anticline and adjoining syncline; only the central lamina (in both symmetric and asymmetric folds) can have a common radius of curvature; higher structural levels are characterized by broad anticlines separated by narrow synclines and lower levels by the reverse situation.

14. Long, narrow anticlines separated by wide, flat-bottomed synclines in Franklin Mountains and western Interior Plains of the northeastern Cordillera may be favourable hydrocarbon traps where such structures occur at depth because they serve to trap hydrocarbons migrating from wide areas eastward up the regional dip.

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APPENDIX

Stratigraphic Sections

Appendix[1]

Stratigraphic Section
Northeast Flank, Castle River Anticline
right bank, Castle River

Unit	Lithology	Thickness (feet)	Height Above Base (feet)
	Crowsnest Formation		
17	Sandstone, volcanic, feldspathic, slightly calcareous, medium light grey speckled with red from volcanic fragments, very fine-grained matrix, moderately resistant, locally variegated with pale red. Coarse-grained in top five feet; scattered interbeds up to one foot thick of olive-grey, feldspathic siltstone	24	128.8
	Blairmore Group upper Blairmore		
16	contact gradational Siltstone, non-calcareous, green with pale red interbeds up to one foot thick and, locally, with patches of red; massive, rubbly weathering, recessive, gradational into Unit 15 vertically and to some extent laterally. Uppermost two to three feet appear to be contaminated with megascopic volcanic fragments	12.5	104.8
15	Sandstone, calcareous, feldspathic, pale greenish grey, medium-grained; locally massive as at water level on downstream flank of anticline; grades laterally into interbedded sandstone and rubbly weathering siltstone as seen, for example, on the southwest flank of the adjoining syncline	9.1	92.3
14	Sandstone, slightly calcareous, variably silty, pale greenish grey, fine-grained; in beds one-half foot to one and one-half feet thick; grades laterally into rubbly weathering, recessive, greenish grey siltstone as interbeds in the sandstone up to one-half foot thick; moderately resistant	6.1	83.2

[1] for graphic representations see figure 2.

Unit	Lithology	Thickness (feet)	Height Above Base (feet)
13	Siltstone, very slightly calcareous, medium grey, rubbly to platy weathering; some lenticular interbeds as much as one foot thick standing out as highly fractured ribs; fractures are parallel and perpendicular to bedding	6.4	77.1
12	Siltstone, variably pale green, greenish grey and locally pale red; massive, rubbly weathering; sparse chocolate-brown limestone concretions up to one foot thick, recessive	19	70.7
11	Siltstone, non-calcareous, greyish green, rubbly to splintery weathering; massive; rusty weathering on joint faces; some ribs locally very resistant	7.4	51.7
10	Siltstone, medium dark grey, rusty weathering, splintery; lenses of fine-grained sandstone up to one foot thick developed locally along strike; chocolate-brown weathering, dark grey, extremely calcareous concretions up to three feet long and one and one-half feet thick observed locally. Unit is slightly deformed so that thickness stated is average	3.8	44.3
9	Sandstone, slightly calcareous, pale greenish grey, fine-grained, massive, rubbly to chunky weathering; grades irregularly laterally into rubbly weathering siltstone	4.6	40.5
8	Siltstone, medium dark grey, massive, rubbly weathering, recessive	1.8	35.9
7	Sandstone, very slightly calcareous, feldspathic, greenish grey, medium-grained, massive, weathering into sheets and blocks one-half foot to three feet thick; grades laterally into the very fine-grained sandstone of Unit 6	7.9	34.1
6	Sandstone, slightly calcareous, medium dark grey, very fine-grained, massive; grades laterally from the base upward into silty, greenish grey mudstone on upstream flank of anticline; unit is cut off up the flank of the structure by a thrust fault	7.6	26.2
5	Mudstone, silty, greenish grey, massive rubbly weathering, recessive; gradational into Unit 6	2.7	18.6

Unit	Lithology	Thickness (feet)	Height Above Base (feet)
4	Mudstone, silty, green, massive, rubbly weathering, recessive, gradational into Unit 5	1.6	15.9
3	Sandstone, feldspathic, non-calcareous, green, fine-grained, massive, rubbly and spheroidally weathered; bedding poorly developed; moderately resistant; gradational into Unit 4	3.8	14.3
2	Mudstone, silty, variegated purple and green, rubbly and spheroidally weathered; locally moderately resistant as in core of anticline	8.5	10.5
1	Sandstone, feldspathic, very slightly calcareous, green, fine-grained, massive, forming the lowest exposed beds in the core of the anticline. Thickness exposed	2	2

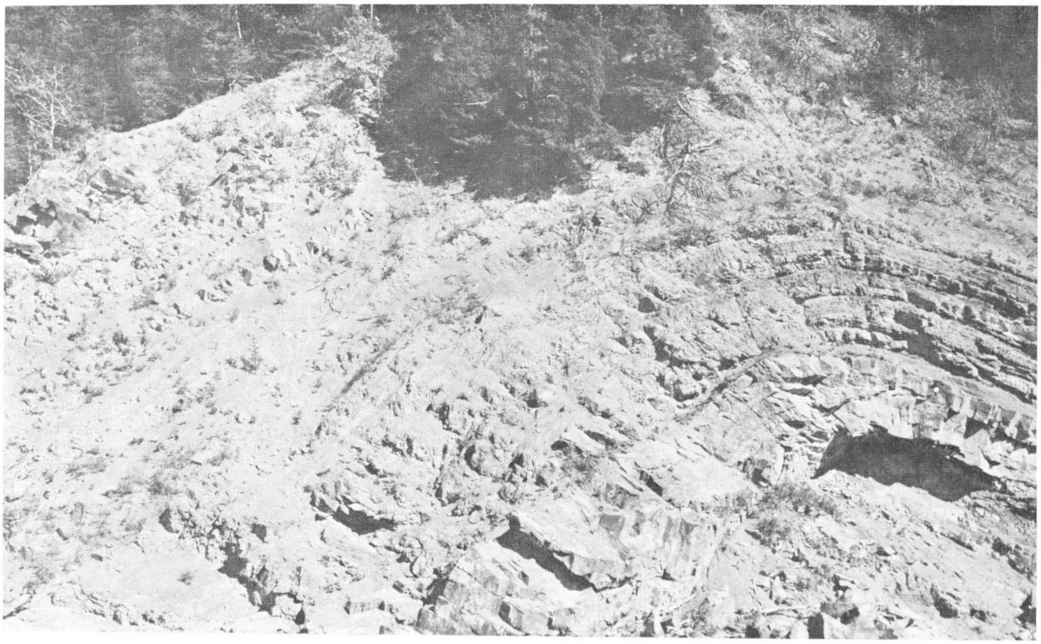
Stratigraphic Section
Hanging-wall of third splay, Castle River structure,
right bank, Castle River

	Crowsnest Formation		
16	Sandstone, volcanic, feldspathic, medium light grey	...	...
	Blairmore Group upper Blairmore		
15	Covered interval, estimated thickness	25	90.7
14	Sandstone, calcareous, slightly feldspathic, pale greyish green, medium-grained, resistant; local thin stringers and interbeds of moderately recessive, olive-grey siltstone; uppermost beds of unit platy weathering	10.5	65.7
13	Mudstone, slightly calcareous, olive-grey, moderately recessive; lenses of more resistant siltstone up to one-half foot thick	3.4	55.2

Unit	Lithology	Thickness (feet)	Height Above Base (feet)
12	Sandstone, calcareous, pale greenish grey, fine-grained, massive, resistant	2.5	51.8
11	Siltstone, slightly calcareous, feldspathic, massive, somewhat recessive	4.1	49.3
10	Siltstone, slightly calcareous, medium grey, massive, resistant	1.1	45.2
9	Mudstone, non-calcareous, olive-grey, massive, rubbly weathering, recessive	3.4	44.1
8	Siltstone, slightly calcareous, olive-grey, moderately resistant	0.9	40.7
7	Siltstone, non-calcareous, olive-grey, locally variegated with pale red, slightly resistant	10.3	39.8
6	Mudstone, non-calcareous, medium light grey, locally variegated with pale red, moderately recessive	1.7	29.5
5	Sandstone, slightly calcareous, medium grey, fine-grained, massive, resistant	1.4	27.8
4	Sandstone, slightly calcareous, medium grey, very fine-grained, platy weathering; pyrite filling cavities in the rock and staining it where weathered	2.1	26.4
3	Siltstone, olive-grey, massive, rubbly to platy weathering, considerably fractured, moderately recessive; pale olive-grey weathering in top two and one-half feet	9.5	24.3
2	Sandstone, very slightly calcareous, greyish green, medium-grained, in beds one-half foot to one foot thick; resistant	4.8	14.8
1	Siltstone and sandstone; interbedded slightly calcareous, olive-grey, platy weathering siltstone and olive-grey, fine-grained sandstone; the latter standing out as resistant ribs one-half foot to two feet thick. Thrust fault at base	10	10

Plate II.

a



b

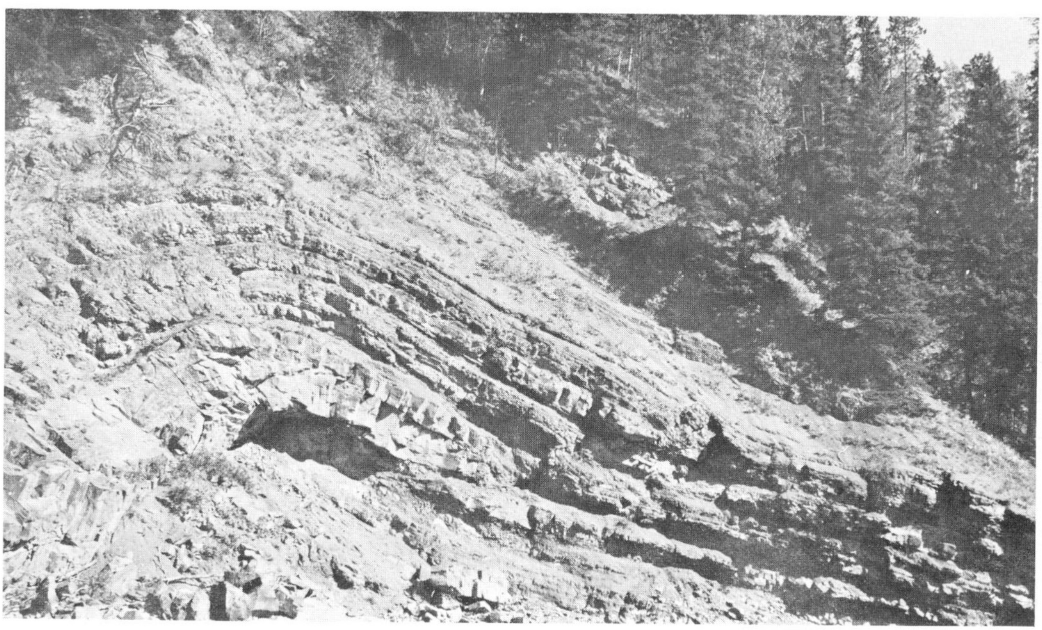


Plate II. The Castle River anticline showing structural geometry and fracture fabric. (a) the northeast flank, (b) the southwest flank. G. S. C. photos 132882 and 132881.

Plate III.

a

b

Plate III. The Castle River syncline (a) and part of fault complex immediately to southwest (b) showing structural geometry and fracture fabric. G. S. C. photos 132883 and 132886.

Plate IV.

a

b

Plate IV. Fracture arrays in the Castle River structure. Joint systems in Member II, northeast flank of anticline, left bank of river (a); joint systems in Member I, second thrust plate to southwest of fold-pair, left bank of river (b). Hammer handle in both instances is in direction of full dip. G. S. C. photos 127380 and 127403.

Plate V.

a b

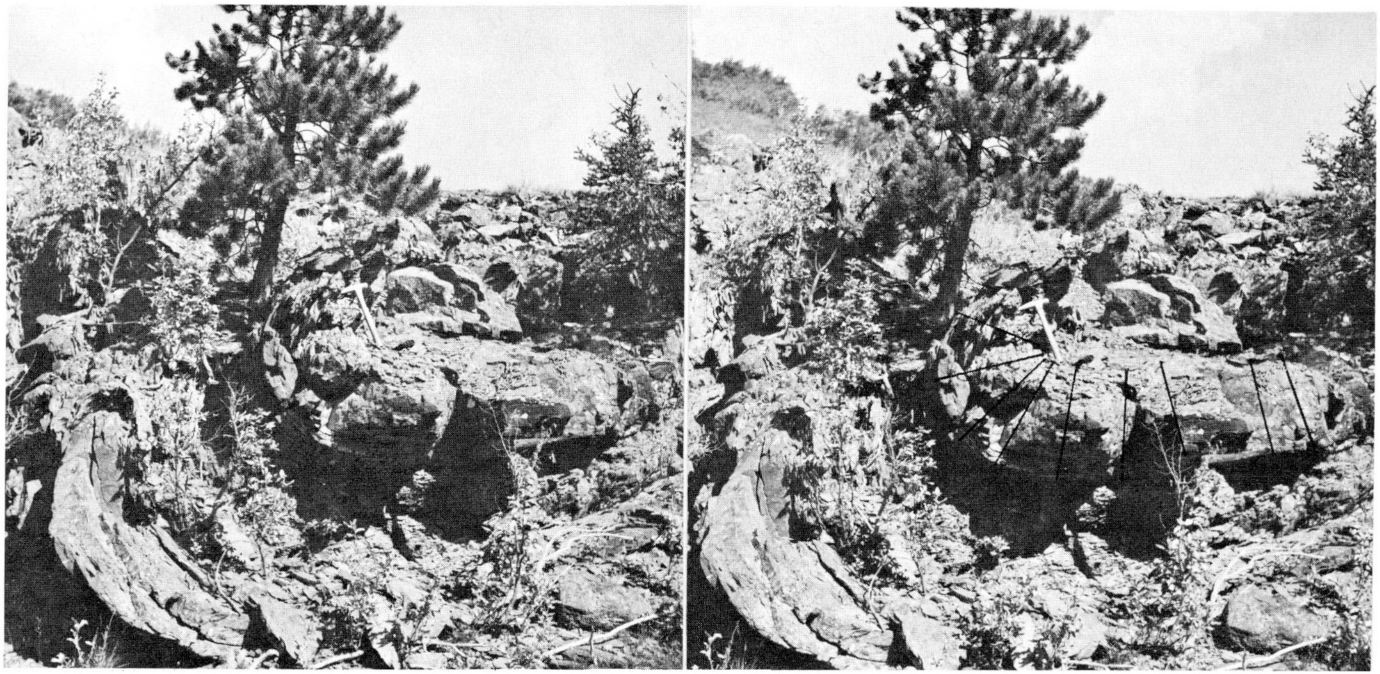
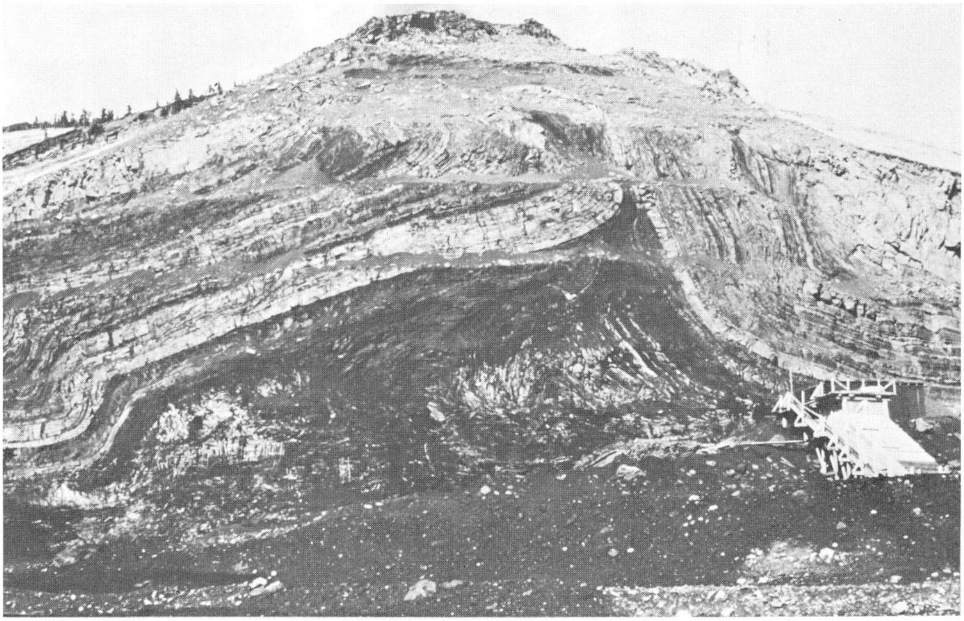


Plate V. Axial region of Castle River syncline, left bank of river, showing bedding (S)-fractures in Member II. Stereoscopic pair. G.S.C. photos 117483 and 117484.

Plate VI

a



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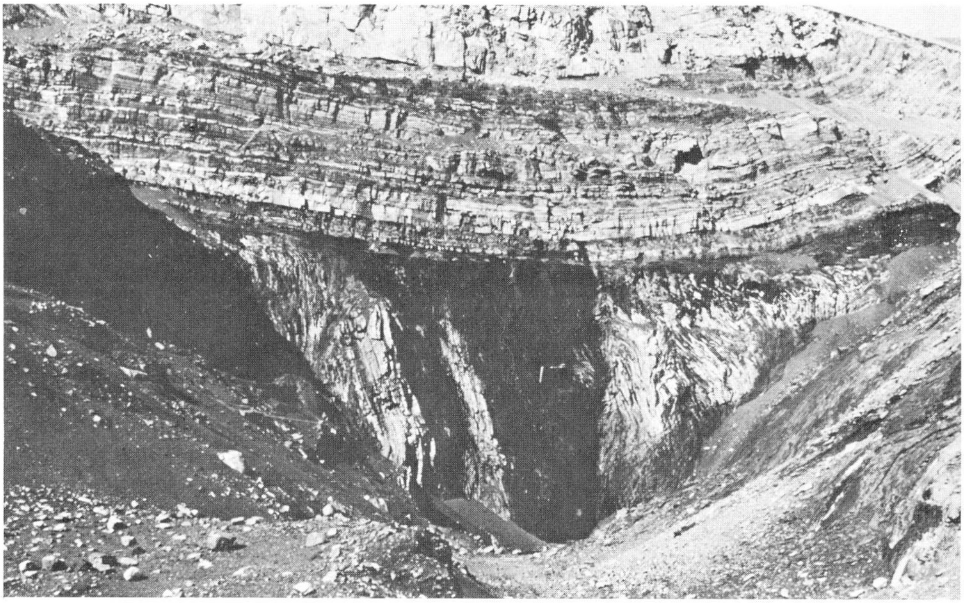

Plate VI. The Grassy Mountain folds, disharmonic structures in Jurassic and Lower Cretaceous clastic rocks exposed in Number 2 Pit, Grassy Mountain, Alberta. Grassy Mountain anticline (a) lies immediately to the left (west) of Grassy Mountain syncline (b). Entry in the coal in the syncline is approximately 6 feet high. G. S. C. photos 201686 and 201687 a

b

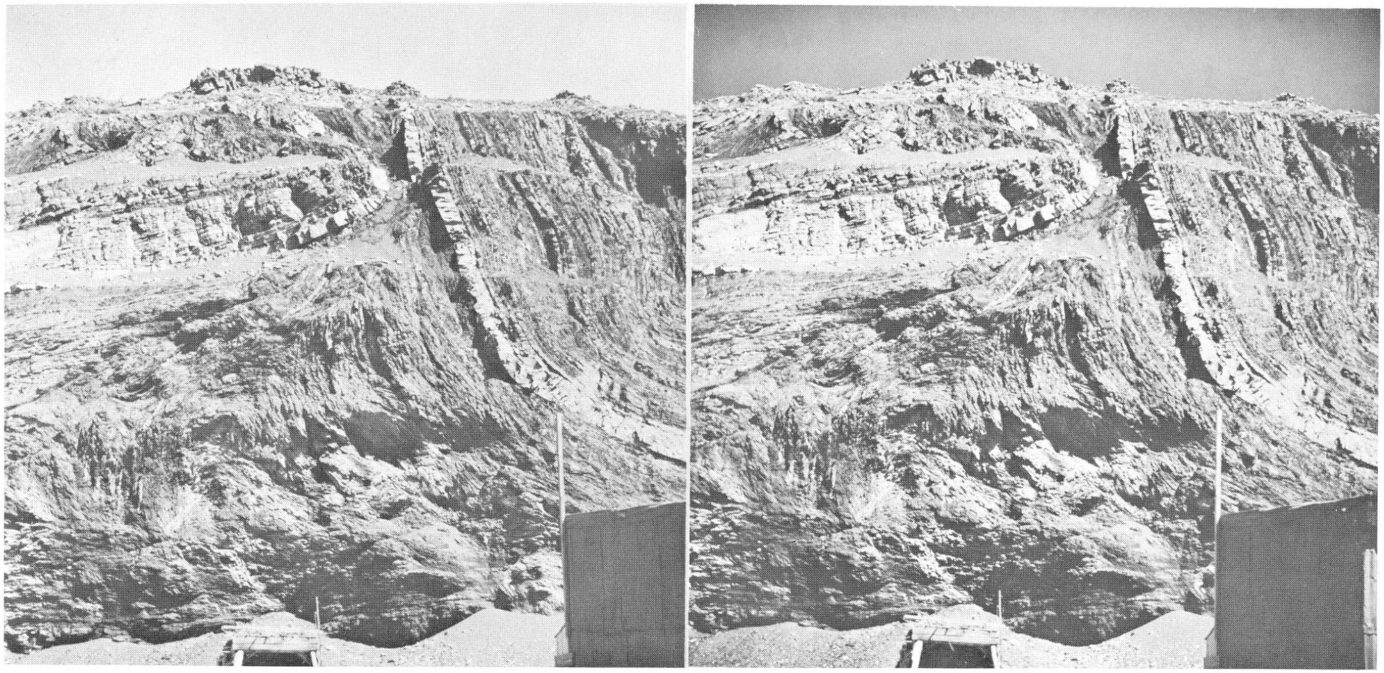

Plate VII. Grassy Mountain anticline showing tectonic thickening of coal and pinching of seam near crest of fold. Stereoscopic pair. G.S.C. photos 117434 and 117435.

Plate VIII.

Plate VIII. Axial region of Grassy Mountain anticline showing some of faults along which coal has been transported into the core of the fold. Sense of displacement on faults shown where it is known. G. S. C. photo 117434.

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