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STRUCTURAL STYLE OF THE KOOTENAY GROUP, WITH PARTICULAR REFERENCE TO THE MIST MOUNTAIN FORMATION ON GRASSY MOUNTAIN, ALBERTA

D.K. Norris

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PREFACE

Grassy Mountain, Alberta, is the site of several abandoned strip mines for Kootenay Coal. Geological structures involving this coal are spectacularly displayed in many pits and are amply illustrated and described in this report. They provide models for predicting tectonic thickening and thinning of materials with low shear strength, such as coal and shale. Application of the models can lead to more effective development and exploitation of other deformed coal measures in the Rocky Mountains.

Elkanah A. Babcock
Assistant Deputy Minister
Geological Survey of Canada

PRÉFACE

Le mont Grassy, en Alberta, est le site de plusieurs mines à ciel ouvert abandonnées de la société Kootenay Coal. Les structures géologiques dans lesquelles se trouve le charbon sont bien visibles dans nombre des houillères et sont abondamment illustrées et décrites dans le présent ouvrage. Elles fournissent des modèles qui permettent de prévoir l'épassissement et l'amincissement tectoniques de matériaux ayant une faible résistance au cisaillement, comme le charbon et le shale. Grâce à la mise en application des modèles, il sera possible de mettre en valeur et d'exploiter plus efficacement d'autres couches productrices déformées dans les Rocheuses.

Elkanah A. Babcock
Sous-ministre adjoint
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Abstract

Grassy Mountain, eight kilometres north of Blairmore, Alberta, lies within the Livingstone Thrust plate in the Front Ranges of the Rocky Mountains. On the mountain, strata of the Kootenay Group are highly sheared, thrust faulted, and cylindrically folded. Of the four coal seams contained within the Mist Mountain Formation of the Kootenay Group, the second highest, or No. 2 Seam, has been and will be the greatest resource on the mountain. Continuous exposures in the abandoned open-pit mines, as well as the many coal prospects in the No. 2 Seam, reveal two fundamental mechanisms by which the coal has been tectonically repeated, thickened, and thinned. These mechanisms are: ***imbrication****, resulting in layer-parallel piling up of the coal and associated roof and floor rock; and* ***flow****, resulting in mass transport of the coal on a profusion of discrete slip surfaces from one part of a seam to another. Imbrication does not necessarily rob the coal from immediately adjacent areas; flow does. These shearing mechanisms are end members of a continuum of structural styles that resulted in the progressive destruction of the primary depositional fabric of the seams as well as in the detachment of the seams from their roofs and floors.*

Imbrication and flow were concurrent responses to the same regional compressive forces of the Laramide Orogeny in the latest Cretaceous and early Tertiary. Imbrication made the Kootenay Group coals accessible to exploitation in numerous places, but also introduced structural complications that degraded the coals and limited the capacity of simple geological models to predict the presence of mineable coals at depth. The resource potential for medium volatile bituminous coal on Grassy Mountain is vast, and is largely confined to the No. 2 Seam.

Résumé

*Le mont Grassy se situe 8 km au nord de Blairmore, en Alberta, et fait partie de la nappe du chevauchement de Livingstone, dans les Front Ranges des Rocheuses. Les strates du Groupe de Kootenay y sont fortement cisaillées, chevauchées et déformées en plis cylindriques. La Formation de Mist Mountain du Groupe de Kootenay contient quatre filons houillers dont le deuxième plus élevé, soit le filon n° 2, a été et continuera d'être la ressource la plus importante du mont. Des affleurements continus dans les mines à ciel ouvert abandonnées et les nombreuses zones d'intérêt houiller dans le filon n° 2 indiquent que deux mécanismes fondamentaux ont provoqué la répétition, l'épaississement et l'amincissement tectoniques du charbon. Il s'agit de l'****écaillage****, qui a eu pour résultat l'empilement, parallèlement aux couches, du charbon et des roches associées du plancher et du toit; et du* ***fluage****, qui a provoqué le transport en masse du charbon d'une partie du filon à une autre, sur de nombreuses surfaces de glissement séparées. Contrairement au fluage, l'écaillage n'enlève pas toujours le charbon des zones contiguës. Ces mécanismes de cisaillement sont des termes extrêmes d'une série de styles structuraux qui ont entraîné la destruction progressive de la structure primaire des filons et provoqué le décollement des filons de leurs toits et de leurs planchers.*

L'écaillage et le fluage ont eu lieu en même temps en réponse aux forces de compression régionales de l'orogenèse laramienne à la toute fin du Crétacé et au début du Tertiaire. L'écaillage a produit des complications structurales qui ont dégradé le charbon et limité la capacité de prévoir, à l'aide de modèles géologiques simples, la présence de charbon exploitable en profondeur; néanmoins, c'est l'écaillage qui a rendu les charbons du Groupe de Kootenay accessibles à l'exploitation à de nombreux endroits. Les vastes ressources potentielles en charbon bitumineux à teneur moyenne en matières volatiles du mont Grassy sont largement confinées au filon n° 2.

Summary

Grassy Mountain, eight kilometres north of Blairmore, Alberta, lies within the Livingstone Thrust plate in the Front Ranges of the Rocky Mountains. At Grassy Mountain, the coal-bearing Kootenay Group is highly sheared, thrust faulted, cylindrically folded and broken into three, north-trending structural domains, herein referred to, from west to east, as the McConnell, Turtle Mountain, and Gold Creek blocks. These domains, or blocks, are separated by two regionally important thrust faults, the McConnell Thrust and the Turtle Mountain Thrust, each underlying the block that bears its name. The Turtle Mountain and Gold Creek blocks have been by far the most important in terms of their economic potential for medium volatile bituminous coal.

It is obvious that the coal measures on Grassy Mountain have been subjected to tectonic compression and extension throughout the emplacement history of the McConnell, Turtle Mountain, and other contraction faults. Insofar as the thrust blocks were in layer-parallel compression as they moved relatively eastward and upward over the flats and ramps in their footwalls, they were systematically folded and unfolded. Correspondingly, they were alternately compressed and extended. Moreover, there is widespread evidence of the fundamental control exerted by the layered anisotropy of the Kootenay Group on the localization of thick pods of coal and on the orientation of the extension and contraction faults cutting them.

Of the four coal seams contained within the Kootenay Group on Grassy Mountain, the second highest, or No. 2 Seam, has been and will be the greatest economic resource. Extensive and continuous exposures in the abandoned open-pit mines in this seam, as well as the many coal prospects and adits in the other seams, reveal two fundamental mechanisms by which the coal has been tectonically repeated, thickened, and thinned. These mechanisms are: *imbrication*, resulting in layer-parallel piling up of the coal and associated roof and floor rock; and *flow*, resulting in mass transport of the coal on a profusion of discrete slip surfaces from one part of a seam to another. Imbrication does not necessarily rob the coal from immediately adjacent areas; flow does. These shearing mechanisms are the end members of a continuum of structural styles that resulted in the progressive destruction of the primary depositional fabric of the coal as well as the detachment of the seams from their roofs and floors. Disharmony of folds is common because of these detachments, with anticlines sitting on top of synclines and vice versa, as seen, for example, on the north wall of No. 2 Pit.

Flow of coal into the hinges of folds appears to be simply an imitation, on a much reduced scale, of symmetrically arranged contraction faulting, with the faults verging toward the hinges of the folds. These small faults bound fragments of coal and rock as small as a few centimetres on each side, and the scale of the displacement of individual fragments may be correspondingly small. In spite of the highly sheared condition of the coal it is important to note that the Laramide deformation penetrated the rock mass selectively, to the scale of the individual grains, and that, while the organic constituents were deformed plastically, calcite ooliths remained unstrained.

A detailed study of the folds in No. 2 Pit revealed a surprising fact. There is considerably more coal (48%) in the plane of a right section through the pit than would be required if the structural thickening were due solely to the migration of coal within the plane of the section. If the coal was transported into the section from the sides, however, this process would have important economic and structural implications. First, the seam would have to thin along strike in order that the total volume of coal taking part in the thickening and thinning process remained the same. Second, the behaviour of the coal as a detachment horizon with unpredictable thickness variations means that any mobile rock unit (e.g., the No. 2 Seam or the Fernie Formation) can insulate structures above it from those below, and render the balancing of regional structure cross-sections difficult if not uncertain.

The single most important structure responsible for the thickening of No. 2 Seam on Grassy Mountain appears to have been the step in the footwall of the Turtle Mountain Thrust. Resistance by the step to movement on the fault resulted in the imbrication of the relatively incompetent

coal-bearing part of the Kootenay Group in the hanging wall, and the stacking of a succession of west-facing panels of coal. Compressive deformation of the footwall step, in turn, resulted in the folding of the coal-bearing beds and the flow of excessive quantities of highly sheared coal into the hinges. The folds probably originated as mega kink-bands that were subsequently modified to rounded forms as they became more appressed.

Measurements of the pitch of slickenlines at the contacts of the coal with the host rock indicate a single preferred azimuth of slip of 081° over the length of the mountain. This angle is within two degrees of the angle that I have established for the base of the Lewis Thrust plate in the Crowsnest Pass. The agreement of measurements from widely separated thrust plates, but in the same kinematic plane, supports the concept of interplay among plates to produce uniform crustal shortening along the Foreland Thrust and Fold Belt, as well as a statistically uniform direction of tectonic transport.

The resource potential for medium volatile bituminous coal above the 5000 ft. level on Grassy Mountain is vast. It is confined largely to the No. 2 Seam in the Turtle Mountain block and the west half of the Gold Creek block.

Sommaire

Le mont Grassy se situe 8 km au nord de Blairmore, en Alberta, et fait partie de la nappe du chevauchement de Livingstone, dans les Front Ranges des Rocheuses. Au mont Grassy, le Groupe de Kootenay est fortement cisaillé, chevauché et déformé en plis cylindriques; ce groupe houiller comporte trois domaines structuraux à orientation nord appelés ici, d'ouest en est, les blocs de McConnell, de Turtle Mountain et de Gold Creek. Ces domaines, ou blocs, sont séparés par deux failles de chevauchement d'importance régionale, le chevauchement de McConnell et le chevauchement de Turtle Mountain, qui reposent respectivement sous les blocs du même nom. Les blocs de Turtle Mountain et de Gold Creek sont de loin les plus importants pour ce qui est du potentiel économique en charbon bitumineux à teneur moyenne en matières volatiles.

Les couches houillères du mont Grassy ont manifestement subi une compression et une distension tectoniques tout au long de l'histoire de l'évolution des failles de McConnell, de Turtle Mountain et d'autres failles de contraction. Dans la mesure où les blocs chevauchés subissaient une compression parallèle aux couches au fur et à mesure qu'ils se sont déplacés relativement vers l'est et au-dessus des surfaces planes et des rampes de leurs lèvres inférieures, ils ont été systématiquement plissés et déplissés et donc tour à tour comprimés et allongés. En outre, de nombreux indices attestent du contrôle fondamental exercé par l'anisotropie stratifiée du Groupe de Kootenay sur la localisation de masses épaisses de charbon et sur l'orientation des failles de distension et des failles de contraction qui les recoupent.

Le Groupe de Kootenay du mont Grassy contient quatre filons houillers dont le deuxième plus élevé, soit le filon n° 2, a été et continuera d'être la ressource la plus importante du mont. Des affleurements vastes et continus dans les mines à ciel ouvert abandonnées de ce filon et les nombreuses zones d'intérêt houiller et entrées de mine dans les autres filons montrent que deux mécanismes fondamentaux ont provoqué la répétition, l'épaississement et l'amincissement tectoniques du charbon. Il s'agit de l'*écaillage*, qui a eu pour résultat l'empilement, parallèlement aux couches, du charbon et des roches associées du plancher et du toit, et du *fluage*, qui a provoqué le transport en masse du charbon d'une partie du filon à une autre, sur de nombreuses surfaces de glissement séparées. Contrairement au fluage, l'écaillage n'enlève pas toujours le charbon des zones contiguës. Ces mécanismes de cisaillement sont des termes extrêmes d'une série de styles structuraux qui ont entraîné la destruction progressive de la structure primaire du charbon et provoqué le décollement des filons de leurs toits et de leurs planchers. La disharmonie des plis est fréquente à cause de ces décollements, et on trouve des anticlinaux couronnant des synclinaux et l'inverse, par exemple dans la paroi nord du puits n° 2.

Le fluage du charbon jusque dans les charnières des plis semble n'être qu'une imitation, à une échelle très réduite, de la formation de failles de contraction symétriques, la vergence des failles étant orientée vers les charnières des plis. Ces petites failles limitent des fragments de charbon et de roche pouvant ne mesurer que quelques centimètres de côté; de ce fait, le déplacement des fragments particuliers peut être très faible. Malgré la condition très cisaillée du charbon, il importe de noter que la déformation laramienne a pénétré la masse rocheuse de façon sélective, à l'échelle des grains, et bien que les composantes organiques aient subi une déformation plastique, les oolites de calcite n'ont pas été déformées.

L'étude détaillée des plis dans le puits n° 2 a révélé un fait étonnant. En effet, il y a beaucoup plus de charbon (48 pour 100) dans le plan d'une coupe droite à travers le puits que ce à quoi il faudrait s'attendre si l'épaississement structural était attribué uniquement à la migration du charbon dans le plan de la coupe. Par contre, si le charbon avait été transporté dans la coupe à partir des côtés, le processus aurait d'importantes répercussions économiques et structurales. Premièrement, il faudrait que le filon s'amincisse parallèlement à la direction pour que le volume total du charbon touché par l'épaississement et l'amincissement demeure inchangé. Deuxièmement, le comportement du charbon en tant qu'horizon de décollement dont les variations d'épaisseur sont impossibles à prévoir, indique que toute unité rocheuse mobile (p. ex., le filon n° 2 ou la Formation de Fernie) peut isoler les structures sus-jacentes des structures sous-jacentes et rendre difficile, voire incertaine, la mise en équilibre des coupes transversales de la structure régionale.

Le gradin trouvé dans la lèvre inférieure du chevauchement de Turtle Mountain semble avoir été la cause première de l'épaississement du filon n° 2 dans le mont Grassy. La résistance du gradin au mouvement le long de la faille a provoqué l'écaillage de la partie houillère, relativement incompétente, du Groupe de Kootenay dans la lèvre supérieure, ainsi que l'empilement d'une succession de panneaux de charbon à vergence ouest. À son tour, la déformation par compression du gradin de la lèvre inférieure a provoqué le plissement des couches houillères et le fluage, jusque dans les charnières, de quantités excessives de charbon très cisaillé. Les plis étaient probablement à l'origine des «kink-bands» macroscopiques qui, par la suite, ont été arrondis au fur et à mesure de leur compression.

Les mesures du plongement des miroirs de faille aux endroits où le charbon est en contact avec la roche encaissante indiquent qu'il n'y a qu'un seul azimut de glissement préféré de 081° sur toute la longueur du mont. Cet angle est à 2° près de l'angle calculé par l'auteur pour la base de la nappe du chevauchement de Lewis au col Crowsnest. Cette concordance de chiffres tirés de nappes de charriage qui sont très éloignées l'une de l'autre mais qui se trouvent dans le même plan cinématique, appuie l'hypothèse selon laquelle le jeu réciproque des plaques a provoqué le raccourcissement uniforme de la croûte le long de la zone de plissement et de chevauchement de l'avant-pays et produit une direction de transport tectonique statistiquement uniforme.

Le mont Grassy contient de vastes ressources potentielles en charbon bitumineux à teneur moyenne en matières volatiles. Ces ressources potentielles se trouvent à une altitude supérieure à 5 000 pieds et sont largement confinées au filon n° 2 dans le bloc de Turtle Mountain et dans la moitié ouest du bloc de Gold Creek.

INTRODUCTION

Grassy Mountain (Fig. 1) is a north-trending ridge in the Crowsnest Pass region of southwestern Alberta, eight kilometres north of the town of Blairmore. At Grassy Mountain, the coal-bearing Jurassic Kootenay Group is repeated on major, west-dipping thrust faults and is acutely folded. Individual coal seams are locally structurally thickened and repeated, and have been of considerable economic importance as a source of medium volatile bituminous coal.

Coal production in the Crowsnest Pass region of Alberta began in 1899 and increased rapidly over the next decade as the demand for steam and metallurgical coals increased. The first underground mine was located at the, now abandoned, townsite of Lille, approximately six kilometres northeast of Blairmore, in Gold Creek Valley between Bluff Mountain and the Livingstone Range. Mining operations in No. 1 Seam[1] were carried out there between 1901 and 1912, but were ultimately discontinued because of thinning of the seam and because of faulting.

During this same period, extensive tunnelling and prospecting for coal was carried out on the east side of Grassy Mountain. Between 1904 and 1907, West Canadian Collieries attempted to mine some of the seams there. However, No. 1 Seam was found to be only about one metre thick and No. 2 and No. 4 seams contained too much ash. In the southward continuation of the Grassy Mountain seams, West Canadian Collieries opened its Greenhill Mine in 1914, the main workings being in No. 1 Seam. Coal seams, up to five metres thick, were encountered. The continuity of No. 1 Seam between Grassy Mountain and Blairmore appears to have been established.

Strip mining on Grassy Mountain was begun by West Canadian Collieries in 1947 and, over the next

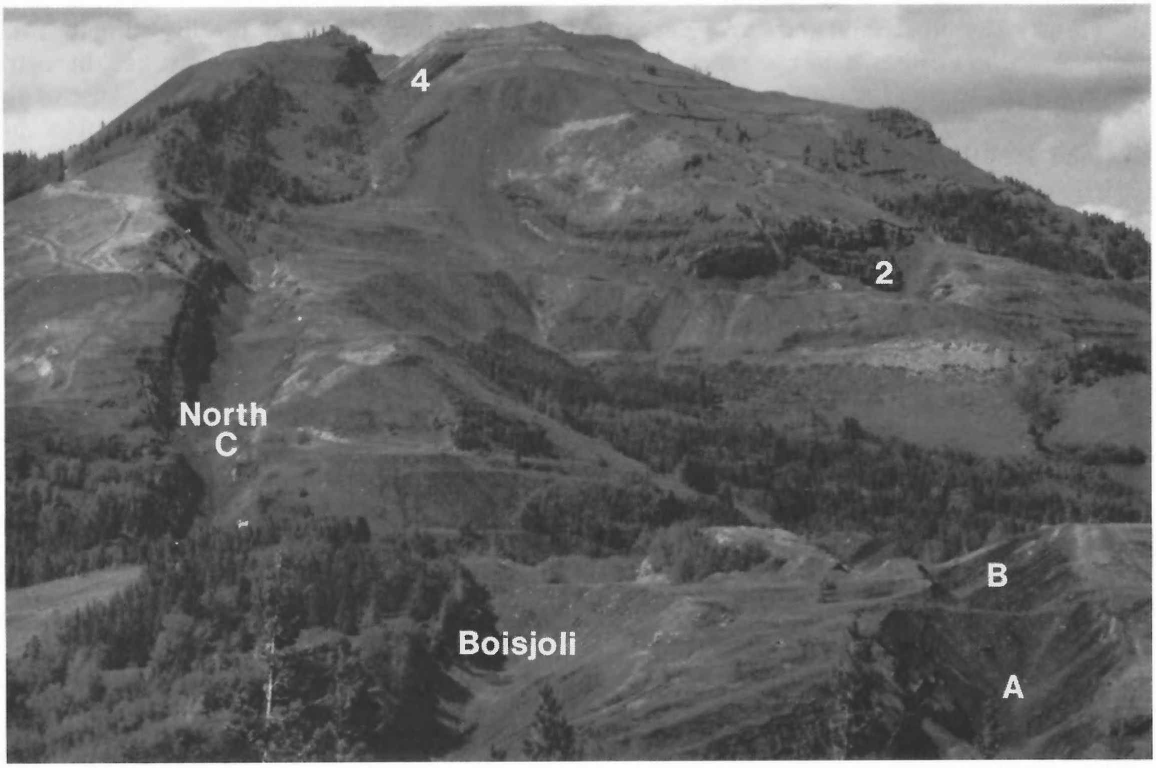

Figure 1. South face of Grassy Mountain, Alberta, showing deformed strata of the Mist Mountain Formation of the Kootenay Group. Coal was actively mined here by surface methods from 1947 until the early 1960s. Pits seen in this view include, from the south, A, B, Boisjoli, North C, No. 2, and No. 4. The No. 5 Pit is out of sight beyond the prominent notch of No. 4 Pit in the skyline. ISPG photo. 2398-14.

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[1] Seam numbers are as reported by MacKay (1933). They do not necessarily imply a one-to-one correlation from one part of the Blairmore area to another.

decade and a half, the coal resources were exploited throughout the length of the mountain. The property was subsequently acquired by Scurry-Rainbow Oil Company in 1966 and, in turn, by Consolidation Coal Company in 1973. Data generated by these companies, through extensive drilling programs, were of considerable value in finalizing the geological map and serial sections accompanying this report (see Gibson et al., 1983).

The first regional geological map of the Blairmore area, with serial structure sections, was published by Rose and Leach (1920), at a scale of one inch to one mile, demonstrating the position of Grassy Mountain in the Livingstone Thrust plate. These authors recognized the broadly anticlinal character of the mountain and the fact that it is cut by at least two west-dipping thrust faults. They showed that one fault decreases in stratigraphic separation southward and dies out in the Fernie Formation on the northwest corner of Bluff Mountain. They did not recognize that this fault is the northward continuation of the Turtle Mountain Thrust. The other fault (now recognized as the McConnell Thrust) causes a minor repeat of the Kootenay Group on the west face of Grassy Mountain.

In 1953 and 1954 I remapped the Blairmore area (Norris, 1992) at a scale of 1:50 000, incorporating advances in stratigraphic subdivisions and nomenclature, especially in the Paleozoic formations in the Blairmore and Livingstone ranges, and making use of important new stratigraphic and structural information from deep wells drilled in search of oil and natural gas. The northward continuation of the Turtle Mountain Thrust beneath Bluff Mountain, and thence onto Grassy Mountain, and the southward termination of the McConnell Thrust in the Kootenay Group on the northwest corner of Bluff Mountain were recognized (see Figure 2). In a preliminary report on the geology of the Fernie map area (East Half), Price (1962) incorporated the earlier mapping of the Blairmore and adjacent areas in a compilation of the geology of part of the southeastern Cordillera of Canada.

With the production of more detailed topographic maps of Grassy Mountain by the coal industry, it was possible to examine, and to portray on maps and cross-sections, the structural complications now exposed in the several abandoned strip pits. With the aid of a map (scale = one inch to 400 ft.), made available by Home Oil Inc., I extended the stratigraphic and structural control in the area and demonstrated principles of imbrication and flow that have important economic implications — through the structural thickening and thinning of coal seams in the Foreland Thrust and Fold Belt (Norris, 1986). The purpose of this report is to document these principles fully, in order that they may be applied by industry in the solution of structural problems in both underground and surface operations.

STRATIGRAPHIC SETTING OF GRASSY MOUNTAIN

The stratigraphic interval involved in the structure of Grassy Mountain extends at least from the Lower Carboniferous to the Lower Cretaceous (see Figure 30 and Table 1). The interval embraces a succession of sandstone, siltstone, shale, and carbonate rocks, collectively slightly more than 792 m thick. Its base is arbitrarily placed in the Lower Carboniferous Etherington Formation, although older (Rundle Group) strata undoubtedly form the core of the mountain.

The succession can be divided into two compositionally and genetically distinct lithostratigraphic assemblages below and above the base of the Jurassic Kootenay Group. The lower and older part of the succession embraces marine shale, sandstone, dolomite, and limestone of the Etherington, Misty, and Fernie formations. It is characterized by regionally persistent beds or groups of beds of uniform thickness and mechanical properties. The higher and younger part, embracing the Kootenay and Blairmore groups, consists largely of nonmarine sandstone, shale, and medium volatile bituminous coal. As a result of their depositional origins within subaerial deltas and adjacent coastal and alluvial plains, these strata are characterized by laterally discontinuous beds or groups of beds, especially in and proximal to old stream channels. For example, the massive sandstone bed in the middle of the Mutz Member, exposed high on the north wall of No. 2 Pit (Fig. 3), changes facies abruptly into interbedded sandstone and shale within regionally impersistent, interdistributary (overbank) clastic deposits of the Kootenay Group. The mechanical response of the laterally discontinuous strata in this succession to compressive stresses cannot be uniform (see Grassy Mountain Anticline, Figure 16). In fact, the only regionally persistent rock units in this part of the stratigraphic succession on Grassy Mountain are the Morrissey Formation, the No. 2 and No. 4 seams within the Mist Mountain Formation, and the Cadomin Formation of the Blairmore Group. These four units were indispensable in deciphering both the stratigraphic and structural complexities on the mountain.

The Rundle Group and overlying Misty Formation occur at the top of the Paleozoic, marine, shelf sequence, derived principally from cratonal sources to the east. The overlying, 170 m thick, Jurassic Fernie Formation embraces, in part, the marine, fine clastic succession (Fig. 4) of the epicontinental sea, trapped

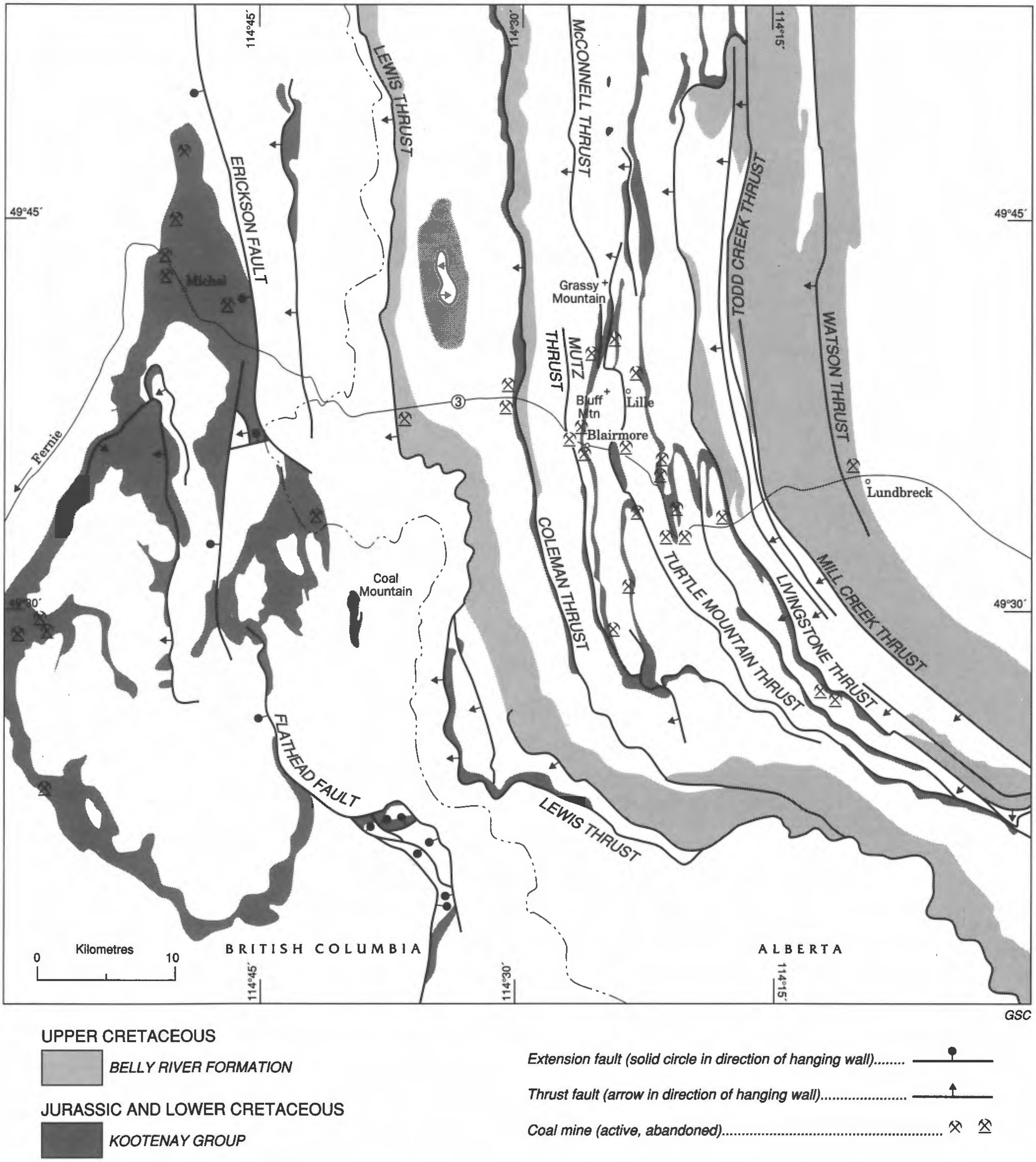

Figure 2. Location map, Grassy Mountain, Alberta, showing the structural setting of the mountain in the Foreland Thrust and Fold Belt. (Data from C.O. Hage, 1943, 1945; D.K. Norris, 1955, 1959; R.A. Price, 1962. After Norris and Bally, 1972.)

TABLE 1

Table of formations for rock units exposed on and adjacent to Grassy Mountain, Alberta

Lower Cretaceous	Blairmore Group	Beaver Mines Formation	≥150 m
		Gladstone Formation	
		"Calcareous member"	10 m
		Lower part	100–120 m
		Cadomin Formation	10–15 m
Unconformity			
Jurassic	Kootenay Group	Mist Mountain Formation	
		Mutz Member	0–90 m
		No. 1 Seam	0–1.4 m
		No. 2 Seam	0–10 m
		Hillcrest Member	20–30 m
		Adanac Member	20–30 m
		No. 3 Seam	0–4 m
		No. 4 Seam	0–2.7 m
		Morrissey Formation	
		Moose Mountain Member	20 m
		Weary Ridge Member	6 m
		Fernie Formation	
		"Passage beds"	20 m
		"Grey beds"	~120 m
		Lille Member	1 m
		Rock Creek Member	17 m
		"Unnamed shale"	14 m
Unconformity			
Carboniferous	Rocky Mountain Group	Misty Formation	40 m
	Rundle Group	(Undivided)	>300 m

between the craton and the compressional uplands flanking the ancestral western margin of the North American plate.

The Jurassic part of the Jurassic–Cretaceous Kootenay Group (Figs. 5–7), embracing the coal measures, lies in gradational contact with the Fernie Formation and marks the initiation of nonmarine sedimentation, predominantly from western sources, in the early stages of the Columbian Orogeny. It thickens and coarsens markedly westward in the direction of provenance, from its zero edge, close to the eastern margin of the Foothills, to approximately 1100 m on the western flank of the Fernie Synclinorium. It is overlain by the resistant, thick-bedded to massive Cadomin conglomerate and sandstone (Fig. 8), disconformably in the eastern Front Ranges and Foothills, and gradationally in the western Front Ranges.

Erosional truncation at the base of the Cadomin Formation systematically eliminates the Kootenay Group eastward, thereby erasing the younger, Cretaceous part of the section and, correspondingly, reducing its economic potential for coal. On Grassy Mountain, erosion at this level has removed the upper half of the Jurassic Mist Mountain Formation. Internally, erosional truncation at the base of the

Hillcrest Member (Fig. 6) has eliminated the No. 3 Seam from all but the vicinity of No. 2 Pit (around the type section of the former Kootenay Formation).

The overlying, light grey sandstone with interbedded varicolored shale of the Gladstone Formation of the Blairmore Group is distinctive for mapping purposes, as is the mildly resistant, grey weathering limestone (Fig. 9) of the "Calcareous member" at the top of the formation. The Beaver Mines Formation, although poorly exposed, is characterized by resistant, lenticular bodies of lithic arenite grading laterally into olive-grey siltstone.

STRUCTURAL SETTING OF GRASSY MOUNTAIN

Grassy Mountain lies within the Rocky Mountain Foreland Thrust and Fold Belt 6.5 km (4 miles) west of the surface trace of the Livingstone Thrust — the boundary between the Front Ranges and the Foothills structural subprovinces at the latitude of Crowsnest Pass. Grassy Mountain lies, therefore, within the succession of generally west-dipping thrust faults and associated folds with predominantly west-dipping axial surfaces that characterize this part of the Front Ranges (Fig. 2). It is located in the area of overlap of the McConnell and Turtle Mountain faults, where southward decreasing horizontal displacement on the McConnell Thrust is compensated by southward increasing displacement on the Turtle Mountain Thrust. Some semblance of uniform shortening of the supracrustal wedge appears to be taking place along this part of the Foreland Thrust and Fold Belt (Shaw, 1963, p. 235; Norris, 1966, p. 192, 193) as a result of this interplay between the faults.

North of Crowsnest Pass, the McConnell Thrust is in the Lower Cretaceous Blairmore Group. Toward the north end of Grassy Mountain it cuts downsection rapidly in its hanging wall to displace upper Kootenay Group over Gladstone Formation. It dies out in the Hillcrest(?) Member of the Mist Mountain Formation a few kilometres to the south on the west slope of Bluff Mountain. No. 2 Seam, in the hanging wall of the

Figure 3. Grassy Mountain Syncline, No. 2 Pit. The entry in the No. 2 Seam is approximately two metres high. Note structural discontinuity at top of seam, with a gently synclinal form in the floodplain and channel lithofacies above, and highly contorted and faulted coal below. Grassy Mountain Anticline lies immediately to the west (left). GSC photo. 201687.

Figure 4. Flaggy, dark grey siltstone of the mid-Bajocian Rock Creek Member of the Fernie Formation, exposed at the crest of Grassy Mountain Anticline in an abandoned railway cut at the base of the south face of Grassy Mountain. Staff is 1.5 m long. ISPG photo. 2214–61.

Figure 5. Interbedded sandstone and siltstone of the Moose Mountain Member of the Morrissey Formation at the type section of the former Kootenay Formation on Grassy Mountain. GSC photo. 117249.

Figure 6. Erosional contact between sandstone and siltstone of the basal Hillcrest Member and No. 3 Seam of the upper Adanac Member, Mist Mountain Formation (type section of the former Kootenay Formation), Grassy Mountain. The hammer head marks the contact. GSC photo. 117247.

Figure 7. Contact between sandstone and siltstone of the upper Hillcrest Member and the No. 2 Seam at the base of the Mutz Member, Mist Mountain Formation (type section of the former Kootenay Formation), Grassy Mountain. The hammer head marks the contact. GSC photo. 117248.

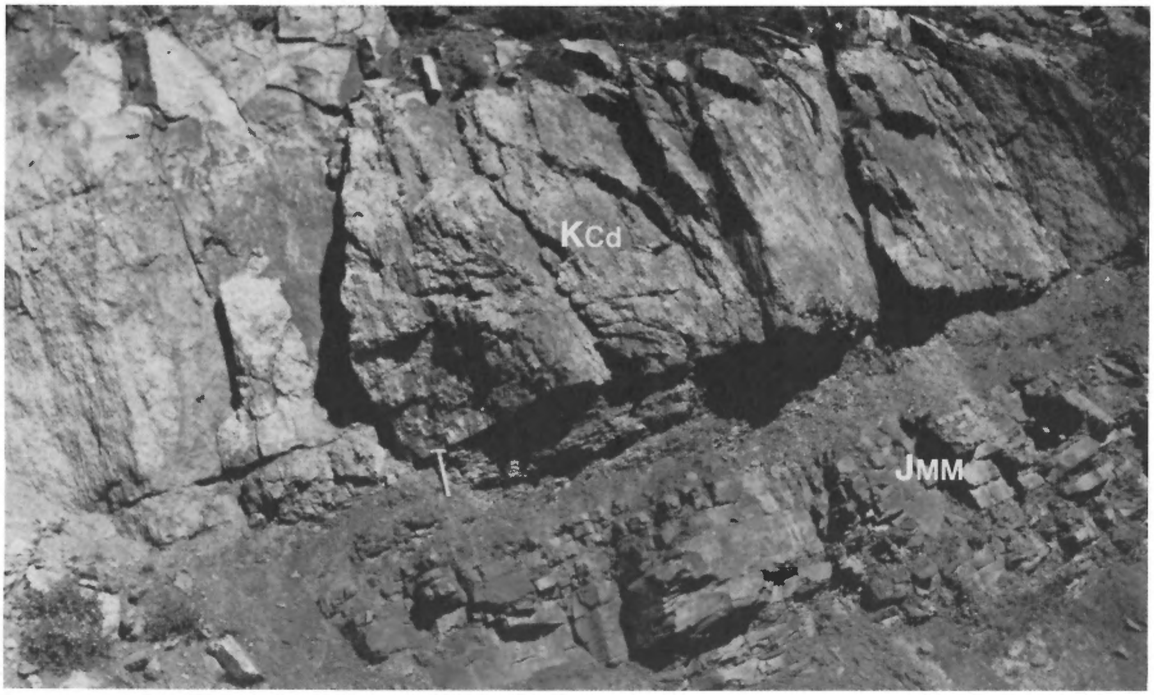

Figure 8. Disconformable contact between sandstone and shale of the upper Mutz Member (JMM) of the Mist Mountain Formation and chert- and quartzite-pebble conglomerate of the Cadomin Formation (KCd), at the type section of the former Kootenay Formation on Grassy Mountain. Note that the No. 1 Seam is absent here. The hammer head marks the contact. GSC photo. 117246.

Figure 9. Interbedded limestone and shale of the "Calcareous member" (KGc) of the Gladstone Formation, overlain by strata of the Beaver Mines Formation (KBM) in a roadcut at the southeast corner of Grassy Mountain. ISPG photo. 2398–58.

McConnell Thrust on Grassy Mountain, would appear, therefore, to be the same as the No. 1 Seam in the Greenhill underground mine on Bluff Mountain.

The Turtle Mountain Thrust, on the other hand, extends into Crowsnest Pass from the south. Lower and Upper Carboniferous limestone, dolomite and sandstone formations of the Blairmore Range occur in its hanging wall. South of Highway 3 the fault cuts abruptly from the east to the west flank of Turtle Mountain Anticline, thereby structurally truncating a large panel of vertical to overturned Carboniferous strata. This panel rested on vertical to steeply west-dipping, incompetent Fernie and Kootenay strata in the footwall of the fault, and the stage was set, some 65 million years ago, for this panel to fall away during the Frank Slide of 1903.

Northward from Highway 3, the Turtle Mountain Thrust cuts systematically upsection through the Carboniferous formations in its hanging wall to glide in the Fernie shale on the north slope of Bluff Mountain. An important transverse step occurs at this locality, as the Turtle Mountain Thrust eliminates the upper Paleozoic section from its hanging wall (Norris, 1955, 1992). The trace of the fault swings abruptly westward on the north flank of the step, then northward to Grassy Mountain, where the fault can be observed in No. 2 Pit. The thin band of Kootenay strata, mined beneath the fault at Frank, reappears in the saddle between Bluff Mountain and Grassy Mountain. The fault dies out in the Beaver Mines Formation a few kilometres to the north.

The stratigraphic path of the Turtle Mountain Thrust on Grassy Mountain (cutting upward through its hanging wall in an eastward direction), from a glide zone in the Fernie Formation abruptly upward through the Kootenay and lower Blairmore strata, indicates the presence of a longitudinal step. This step is of fundamental economic significance, because it localized imbrication of the Kootenay strata embracing the No. 2 Seam above it, and caused crushing and thickening of the seam in the Turtle Mountain Thrust plate, through resistance to displacement over the step.

FAULT NOMENCLATURE

Normal and reverse faults are defined (American Geological Institute, 1987, p. 452, 565) as follows:

Normal fault: "A fault in which the hanging wall appears to have moved downward relative to the footwall."

Reverse fault: "A fault on which the hanging wall appears to have moved upward relative to the footwall."

According to these definitions, the fundamental reference frame consists of three axes perpendicular to each other, two in the horizontal plane and one in the vertical. Thus, the terms hanging wall and footwall can be applied to the rock masses above and below the fault respectively, and the horizontal plane is the plane tangent to the gravity equipotential surface at any given point. The reference axes, therefore, have nothing to do with the origin, homogeneity or heterogeneity of the faulted rock mass. Accordingly, they apply equally well to igneous, metamorphic or sedimentary rocks, whether massive or layered, whether in the position or orientation in which they were intruded, extruded, altered or deposited, or whether externally rotated about a horizontal axis to the point where they are overturned and, at the limit, are upside down.

There are many geological situations — in the Canadian Shield for example — where it may be neither possible nor advantageous to designate the stratigraphic top of the rock succession. In these circumstances, there is little choice but to accept the horizontal and vertical reference axes, in spite of the disadvantages they present for deciphering the stratigraphic framework and, in turn, the geological history of the rock mass.

On the other hand, there are vast areas of both undeformed and deformed rocks in the sedimentary basins of the world where the stratigraphic succession is well ordered and where there is little doubt as to which is the natural top and bottom of a layer, bed, panel, formation, or larger sequence of rocks. The plane of the layering is the fundamental reference surface on which all biostratigraphic, sedimentological, paleoenvironmental, and structural deductions must be based. Moreover, on both megascopic (Rich, 1934) and mesoscopic (Norris, 1958) scales the layered anisotropy of these rocks imposes a fundamental control on the structural geometry of the supracrustal wedge, whether it be simple systematic jointing of the sedimentary succession on the craton, or extension and contraction faulting in the orogen.

Within the orogen, the strata with associated intrusions have been externally rotated, and the faults and folds no longer are in their initial orientation with respect to the horizontal and vertical. Rotation of the beds out of the horizontal by a few tens of degrees is common in thrust plates as the strata are displaced upward and over irregularities in the fault surfaces.

When the beds are more acutely folded, they may be rotated through the vertical to an overturned position, and, in the extreme, turned upside down and refolded. It is apparent therefore that, in deformed belts, the horizontal and vertical reference axes are no longer meaningful in deciphering the structural history of the mass. The simplest way of unravelling this history appears to lie in precise mapping of the effects of the deforming stresses on the rock mass — is the mass extended and thinned, contracted and thickened, uplifted or depressed, or rotated about horizontal or vertical axes external to the mass? The only pervasive reference surface that is useful in such mapping is the bedding or textural layering, so that one principal reference direction is the perpendicular to the layering. In sedimentary and volcanic piles the positive direction of this perpendicular is that of younger rocks. It may be designated arbitrarily in igneous and metamorphic assemblages.

The effects on fault nomenclature of the external rotation of a layered succession, where "tops" are known or designated, are illustrated in Figure 10. Beginning with an unrotated sequence (Fig. 10.1, 10.4), two faults are shown cutting the layering, one at 60° and another at 30°. The faults are, by definition, extension or normal, and contraction or reverse, respectively. In the former, the hanging wall is displaced relatively downward and in the latter, relatively upward. Should the normal fault be rotated through the vertical (Fig. 10.2) and the thrust fault through the horizontal (Fig. 10.5), the normal fault becomes, by definition, a "reverse" fault, and the thrust becomes a "normal" fault. With continued rotation of the "normal" fault (Fig. 10.3), it reverts, by definition, from a low-angle reverse fault to a "normal" fault in an overturned panel of rock as the fault passes through the horizontal. Correspondingly, the thrust fault, now in a "normal" configuration, changes to a low-angle reverse fault (Fig. 10.6) in an overturned panel as the fault passes through the vertical (younger rocks faulted onto older).

No measurable additional deformation has been introduced to the layered succession and the sense of relative displacement has remained the same, yet the faults have undergone two changes of name with respect to a horizontal and vertical reference frame. They remain *extension* and *contraction* faults, however, because the fundamental reference surface internal to the rock mass, the layering, has remained unaltered.

The use of an external reference frame, such as horizontal and vertical axes, for rock masses on a mesoscopic scale, where stratigraphic tops or other unique directional indicators are known, is clearly outmoded. It leads to confusion both in nomenclature and in attempts to unravel the structural history of the rock mass. The use of an internal reference frame is recommended. Extension faults (Fig. 11) simply extend and thin the rock mass in the fundamental reference plane (the layering), and contraction faults (Fig. 12) shorten and thicken it, regardless of the magnitude of external rotation. Moreover, the use of the terms "high-angle" and "low-angle" for reverse faults contributes little to our understanding of the structural history of a rock mass. Faults with these orientations may be simply stages in a continuum of external rotation, contributing nothing to the internal structural geometry of the rock mass.

It is recommended, however, that the terms "thrust" and "normal" be retained for megascopic structures like the Lewis and Flathead faults, respectively. Nevertheless, external rotation is associated with some of these megascopic structures. In the case of thrust faults, it has resulted in wholesale inversion of large panels of rock and the formation of some of the most spectacular geological structures in the eastern Cordillera of southern Canada (Norris, 1961).

STRUCTURAL GEOMETRY OF GRASSY MOUNTAIN

Grassy Mountain is made up of three north-trending structural blocks, separated by the McConnell and Turtle Mountain faults. They are termed, from west to east, the McConnell, Turtle Mountain, and Gold Creek blocks. The Turtle Mountain and Gold Creek blocks have been by far the most important in terms of their economic development for medium volatile bituminous coal.

The structurally highest domain is the McConnell block on the west flank of Grassy Mountain, and the structurally lowest is the Gold Creek block on the east flank. Structural complexity generally increases from west to east, ranging from the relatively simple homocline of the McConnell block to a domain of acute, asymmetric to overturned folds in the Gold Creek block.

Within the map area, the McConnell block basically comprises a west-dipping panel of Kootenay and Blairmore rocks. The McConnell Thrust beneath it cuts systematically downsection toward the south, so that the base of the block changes from Gladstone Formation at the north end of Grassy Mountain to the Hillcrest Member of the Mist Mountain Formation at

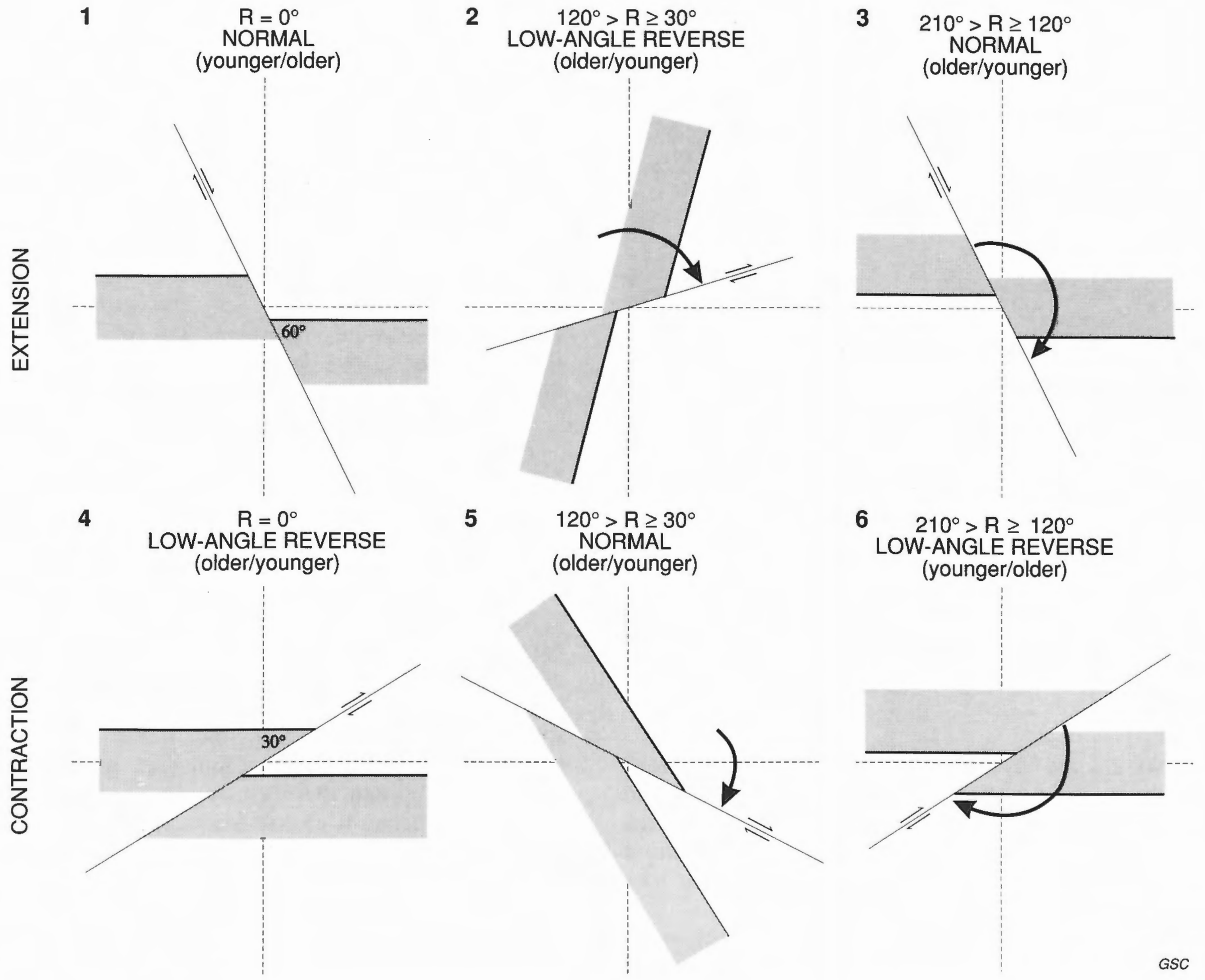

Figure 10. Stratigraphic relationships across extension and contraction faults, for unrotated and rotated layers (shaded). R = angle of external rotation. Curved arrows show the sense and magnitude of rotation. Split arrows show the direction of displacement. Horizontal and vertical reference axes are shown as broken lines. Stratigraphic (or otherwise designated) tops are identified by heavy lines. Slash (/) means "faulted over".

the south end. The gently north-plunging anticline, outlined by the Cadomin Formation toward the north end of the block on Grassy Mountain, is probably the result of drag on the fault.

The McConnell Thrust is exposed in the west wall of North C Pit where it follows an irregular stratigraphic path at the contact between the Kootenay and Blairmore groups (Fig. 13). At this locality, two discontinuous masses of crushed and recemented Cadomin conglomerate were isolated as the fault cut up- and downsection along strike, and the Gladstone and Cadomin were eliminated from the footwall of the McConnell block at the structural level of the pit.

Throughout the length of the block the McConnell Thrust decreases in dip separation as it cuts downsection in both hanging wall and footwall rocks. In structure section 3 (Fig. 30), the separation is shown as approximately 161 m and as about 104 m in structure section 8. From regional mapping the fault is known to die out as a bedding plane feature within the Kootenay Group (?Hillcrest Member) on the west flank of Bluff Mountain a few kilometres to the south. Thus, beyond the southern termination of the McConnell Thrust, the McConnell and Turtle Mountain blocks become one structural unit within the Turtle Mountain plate.

Figure 11. Family of extension faults in sandstone on top of No. 2 Seam on the east flank of the "Pod", No. 2 Pit, Grassy Mountain. GSC photo. 117445.

No. 2 Seam has been mined in the McConnell block at the surface in C–2 Pit, and both surface and underground in the Boisjoli Pit. Prospects along the length of the block reveal the presence of No. 1 Seam locally (see Figure 30).

The Turtle Mountain block is a generally west-dipping panel of Kootenay and Blairmore rocks complicated by splays from the Turtle Mountain Thrust. From north to south the entire Kootenay Group and the upper half of the Fernie Formation are brought to the surface as the Turtle Mountain Thrust cuts systematically downsection along strike. Gentle, north-plunging folds die out southward as the Turtle Mountain Thrust converges with the McConnell Thrust and the block narrows.

Beneath Grassy Mountain, the Turtle Mountain Thrust cuts abruptly upsection through footwall Kootenay and lower Blairmore strata from a glide zone within the "grey beds" of the Fernie Formation (see structure sections, Figure 30). A step was formed in the underlying Gold Creek block, thereby maximizing stratigraphic separation on the fault for any given dip separation. Resistance created by the step to movement on the fault resulted in imbrication of the relatively incompetent Mist Mountain Formation, with concomitant increased potential for tectonically thickened coal.

From north to south, the Turtle Mountain Thrust increases in dip separation as it cuts downsection in both hanging wall and footwall beds. In structure section 1, the dip separation is shown as approximately 107 m with the Beaver Mines Formation repeated at the surface. As shown in structure section 8, on the other hand, this separation is at least 300 m at the south end of the map area, with Fernie "grey beds" repeated within a glide zone of highly deformed, incompetent shales. Regionally, the Turtle Mountain Thrust increases in both dip- and stratigraphic-separation southward to become one of the major structures close to the eastern margin of the Foreland Thrust and Fold Belt (see Figure 2).

As many as four major repeats of the No. 2 Seam occur in the Turtle Mountain block. They have been exploited throughout the length of the mountain in the A, B, North C, No. 4, and No. 5 pits (see Figures 1 and 14).

The Gold Creek block has a complex anticlinorial form, cored by upper Paleozoic limestone and dolomite and embracing rocks as young as the Lower Cretaceous Beaver Mines Formation. The principal structure of the block is Gold Creek Anticline, extending from the position indicated in structure section 7 to beyond the north boundary of the map area. The anticline is characteristically asymmetric to overturned toward the east. It plunges northward at an angle of less than 5°, although in D Pit, midway between structure sections 1 and 2, the plunge is up to 15°. Its counterpart, Gold Creek Syncline, immediately adjacent to the east and outside the map area, is equally long (Norris, 1955) and plunges very gently to the south.

At its southern end, Gold Creek Anticline lies right hand en echelon with respect to Grassy Mountain Anticline, the two folds overlapping and mimicking on a small scale the right hand spatial relationship of the anticlinal form of the Blairmore and Livingstone ranges. In contrast to the general southward trend of Gold Creek Anticline, however, Grassy Mountain Anticline trends south-southeast. It diverges by as much as 20° counterclockwise from the average trend of most other structures on the mountain.

Grassy Mountain Anticline is defined largely at structural levels below incompetent Fernie Formation shales, whereas all other structures on the mountain are defined at structural levels above the Fernie. The divergence in trend, referred to above, between Gold Creek and Grassy Mountain anticlines strongly suggests the presence of a major detachment within the

Figure 12. West-dipping contraction fault (upper centre), repeating lower Mutz Member strata and gliding in the No. 2 Seam, North C Pit, Grassy Mountain. View is to the north. ISPG photo. 2398-125.

shales, similar to that observed beneath structures in Kootenay and younger rocks in the Fernie Synclinorium of the Lewis Thrust plate (Price, 1962, p. 52). The presence of disparate directions of tectonic transport at more than one structural level in the supracrustal wedge embraced within the Foreland Thrust and Fold Belt of southern Canada is, therefore, suggested. Consequently, the details of the anticlinal form of the upper Paleozoic rocks beneath Grassy Mountain, as well as in the valley between Grassy Mountain and Bluff Mountain, are inferred on the diagrammatic structure sections.

Between the positions designated by section lines 4 and 5 there may be a major disruption in the areal continuity of members of the Mist Mountain Formation, because of the apparent removal of the upper half of the Kootenay Group at the sub-Cadomin unconformity on the east flank of Gold Creek Anticline (see Figure 30). The Mutz Member, including No. 2 Seam, is interpreted as being absent south of this locality and the only coal present is No. 4 Seam.

The step along the west flank of the Gold Creek block in the footwall of the Turtle Mountain Thrust is economically important. It resulted in the imbrication of No. 2 Seam in the immediate hanging wall of the fault, and in spectacular thickening and thinning of No. 2 Seam coal in the footwall (Figs. 3, 15, 16), with wholesale detachment of folds and faults in the roof of the seam from their counterparts in the floor.

In No. 2 Pit, for example, the coal is thickened structurally from 10.4 m to 27.4 m in the hinge of Grassy Mountain Syncline; it is thinned to 1.5 m where the floor of the seam almost meets the roof on the west flank of the syncline; and it is thickened to 23 m in the hinge of the adjacent Grassy Mountain Anticline to the west. Additional structural complications, like the pod of coal (herein termed the "Pod") in the roof of No. 2 Seam (Fig. 17) defy the imagination of those attempting to prepare and balance structure cross-sections at depth, where control is minimal.

No. 2 Seam in the Gold Creek block has been exploited in the No. 2, E, E Extension, and D pits, where advantage was taken of tectonically thickened coal at or close to the hinges of Grassy Mountain Anticline and Syncline and Gold Creek Anticline.

MECHANICS OF SEAM THICKENING AND THINNING

The abandoned strip mines on Grassy Mountain show clear evidence of tectonic thickening and thinning of No. 2 Seam at the base of the Mutz Member of the Mist Mountain Formation. Because of the economic significance of variable seam thickness, I have examined some of the principles that may apply to the mechanics of seam deformation. Of particular importance are basic data on the level of strain penetration into the rock mass; the original, pre-Laramide thickness variations of coal seams from the same depositional and tectonic environments; and the magnitude and sense of shear to which the coal has been subjected through interbed slip.

The supracrustal wedge comprising the Foreland Thrust and Fold Belt was compressed, folded, faulted, tectonically thickened, depressed, and extended during the Laramide Orogeny. Structures attesting to this style of deformation are common throughout the Rocky Mountains and Foothills in rocks ranging from near the bottom to the top of the wedge, indicating the same kind of brittle response, regardless of scale, for a wide range of initial confining pressures. It is apparent, moreover, that this style of deformation selectively penetrates the rock fabric to the microscopic scale. Thin sections of ooids in dolomite collected from relatively undeformed strata of the Precambrian Altyn Formation in the Lewis Thrust plate, and of ooids from No. 2 Seam of the Kootenay Group in the Coleman Thrust plate, show no measurable distortion that could be attributed to the compressive forces of either translation or lateral spreading (D.K. Norris, unpublished data, 1964). However, clarite and vitrite in Kootenay coal are apparently deformed plastically by shear here and there (Bustin, 1981, 1982). The Laramide deformation, therefore, penetrated at least locally to the scale of individual rock grains, but the degree of penetration is clearly a function of the strength of the grains or of the ductility contrast between the grains and the host rock.

The coal-bearing part of the Kootenay Group throughout the southeastern Cordillera of Canada is interpreted as having been deposited as an extensive, fluvial deltaic/interdeltaic and fluvial/alluvial plain succession (Gibson, 1985, p. 71) along the western margin of the epicontinental Fernie Sea. It is assumed, therefore, that natural variations in depositional thickness of No. 2 Seam occur within the area of the

Figure 13. Horse of Cadomin Formation (KCd) along the trace of the McConnell Thrust, west wall of North C Pit. Both hanging wall and footwall beds belong to the Mutz Member of the Mist Mountain Formation. ISPG photo. 2398-136.

Front Ranges embracing Grassy Mountain. It can be expected, moreover, that seam thicknesses were modified by shearing.

Fortuitously, some unpublished thickness data are available from investigations underground a few kilometres west of Grassy Mountain in the Coleman Thrust plate. In the McGillivray and International mines, along strike from one another, No. 2 Seam occurs in a homocline over an area of more than ten square kilometres. This planar part of the seam was accessible along strike for about ten kilometres and, in some places, over a dip distance of as much as one kilometre.

The thickness of No. 2 Seam was measured and the percentage of sheared coal observed in the ribs at 36 locations spaced approximately 244 m apart, through both mines, over a strike distance of 9.5 km. In addition, 50 measurements of seam thickness were made, spaced every 6 m over a dip distance of 305 m, during an engineering survey in the McGillivray Mine. The objectives were to define the natural thickness variations of the seam in both the strike and dip directions where there were minimal structural complications, and to identify any possible relationship between seam thickness and the degree of destruction of the primary depositional fabric of the coal through shear.

A histogram of thickness variations of No. 2 Seam along strike, shown in Figure 18, appears to conform to a normal distribution. Thicknesses were observed to range from 3.9 to 13.1 ft. (1.2 to 4 m), and to average 7 ft. (2.1 m). The fifty measurements in the dip direction, moreover, conformed to a normal distribution, ranging from 2.7 to 7.8 ft. (0.76 to 2.4 m) and averaging 5.6 ft. (1.7 m).

Any possible relationship between seam thickness and percentage of sheared coal was investigated at the same 36 underground locations used for the thickness variation study in the McGillivray and International mines (Fig. 19). Analysis of these data suggests that shearing of the seam at different points ranges from 2 to 100 per cent, and that the locations where there is the greatest amount of shear are those with average or near average seam thickness. Moreover, where the seam is thinnest (4 ft./1.2 m) and thickest (13 ft./4 m) the percentage of sheared coal is neither maximum nor minimum, and is less than 30 per cent.

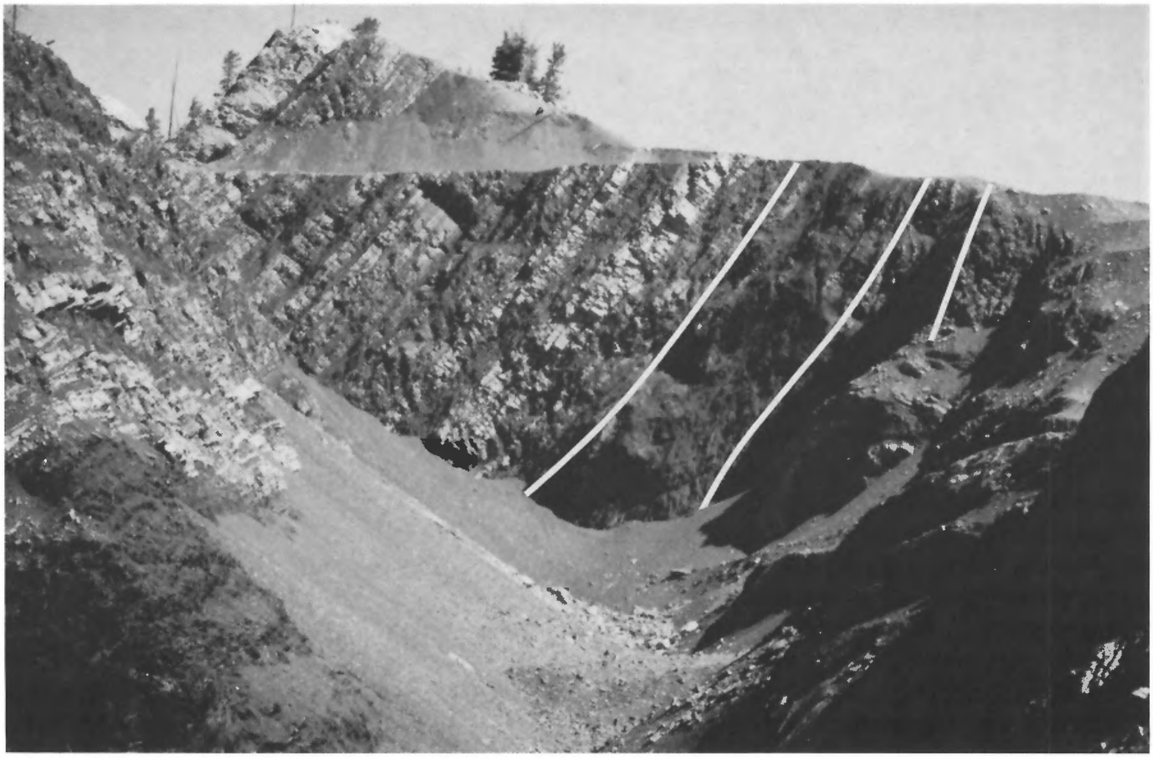

Figure 14. *Three or more splays from the Turtle Mountain Fault, imbricating the No. 2 Seam and associated sandstone and shale of the Mutz Member on the north wall of No. 5 Pit, Grassy Mountain. Note the complete section of the Mutz Member, capped by massive Cadomin Formation strata on the left skyline. ISPG photo. 2218-14.*

Invariably, the No. 2 Seam is sheared at its contact with both roof and floor, indicating the presence of regional detachment surfaces bounding the seam above and below. Sheared intervals of variable thickness at different levels in different locations lead to the conclusion that the seam contains a family of local, disconnected, overlapping detachment zones that collectively accommodates shearing strain imposed regionally upon the whole coal.

Petrographic studies indicate that the microfabric of sheared Kootenay Group coals is generally similar to that of the unsheared coal (Bustin, 1982). According to Bustin (op. cit., p. 81), "The finely granulated, sheared coal, on a microscopic level, consists simply of fragments of larger clasts with no evidence of internal deformation." Fragmentation of a seam appears to be due initially to brittle failure, forming blocks and chunks whose shapes are dictated by: i) the orientation and spacing of cleat sets perpendicular and subperpendicular to the layering, and ii) the presence of rock partings in the plane of the layering. With increased stress, tectonically oriented conjugate joint sets develop at acute angles to bedding (Norris, 1966). These joints dominate the structural fabric of seams and break them into polyhedrons up to one metre on a side. With incremental displacement and shear, the joints become slickensided and the blocks break down

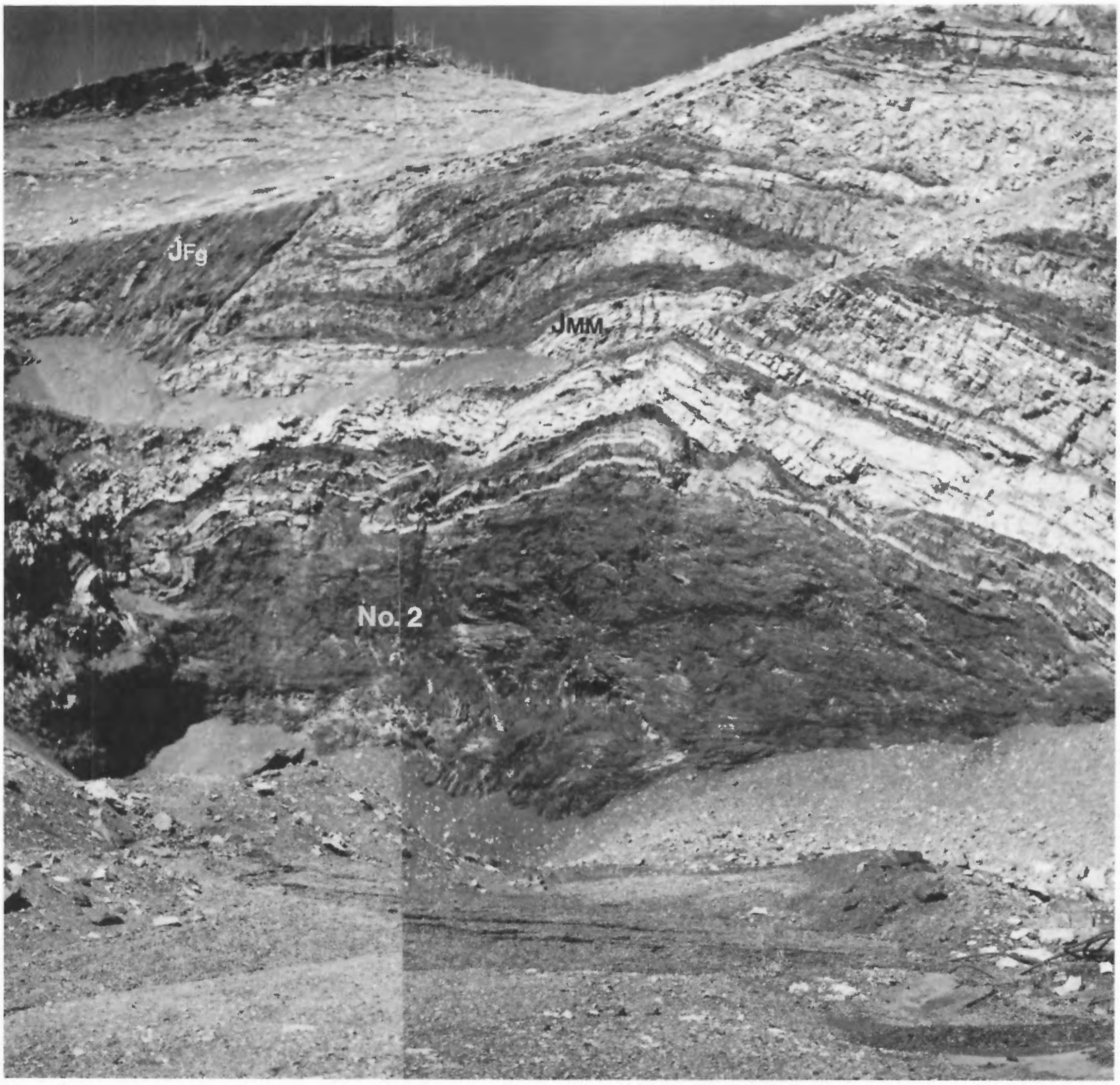

Figure 15. Step in the footwall of the Turtle Mountain Thrust at No. 2 Pit on Grassy Mountain, as it appeared in 1950. Hanging wall rocks are "grey beds" (JFg) of the Jurassic Fernie Formation. Footwall beds are No. 2 Seam and sandstone and shale of the lower Mutz Member (JMM) of the Mist Mountain Formation. (This fault is now covered with mine waste.) GSC photos. 117091, 117092.

into smaller, fault-faceted pieces of coal and rock. In the extreme, the primary depositional fabric of a seam is destroyed totally (as in parts of No. 2 Pit, Grassy Mountain) and the coal literally flows under tectonic compressive stress, through differential displacement on a myriad of small-scale, highly polished slip surfaces only centimetres apart and occurring throughout the seam (Fig. 20).

From the preceding discussion it may be concluded that, in an area in which it is apparently unfolded and unfaulted, a coal seam in the Foreland Thrust and Fold Belt can vary in thickness both along and across the strike. The No. 2 Seam in the Coleman Thrust plate, for example, is observed to triple its minimum thickness, over areas measured in square kilometres, where the seam is essentially planar. Where these variations are overprinted with imbrications due to drag across a longitudinal step in a thrust plate, there exists the potential for coal to be piled up tectonically in excessive quantities (as in No. 2 and 5 pits, Grassy Mountain) or, equally as likely, for the local development of areas that are devoid of coal or where the coal is thin.

Thickness variations also can be an innate depositional characteristic of a seam, or due to local, small-scale flow, since it is often observed that sections of underground mines where the coal is abnormally thin occur adjacent to sections where the coal is abnormally thick. It may never be possible, however, to assess the relative contributions of deposition and flow to these thickness variations because the entire area underlain by Kootenay strata was deformed to varying degrees in the Laramide Orogeny, so that tectonic thickening and thinning mask that produced by other factors. Moreover, the underground mines in which the coal seams were extensively and continuously exposed are now abandoned and most are flooded and inaccessible.

The stress regime required to compress and deform the Kootenay coal measures (Fig. 21) should be considered. The trajectories of the principal stresses (solid lines) can be viewed in the context of a structural cross-section of the Foreland Thrust and Fold Belt in the southern Canadian Cordillera. Moreover, the principal compressive stresses (σ_1, σ_2, σ_3) can be considered to have pervaded the layered rock mass from west to east, from regions of higher compressive

Figure 16. Structurally thickened No. 2 Seam in the hinge of the Grassy Mountain Anticline at No. 2 Pit on Grassy Mountain, as it appeared in 1950. Note the coal forming the "Pod" at the fold crest. GSC photo. 201686.

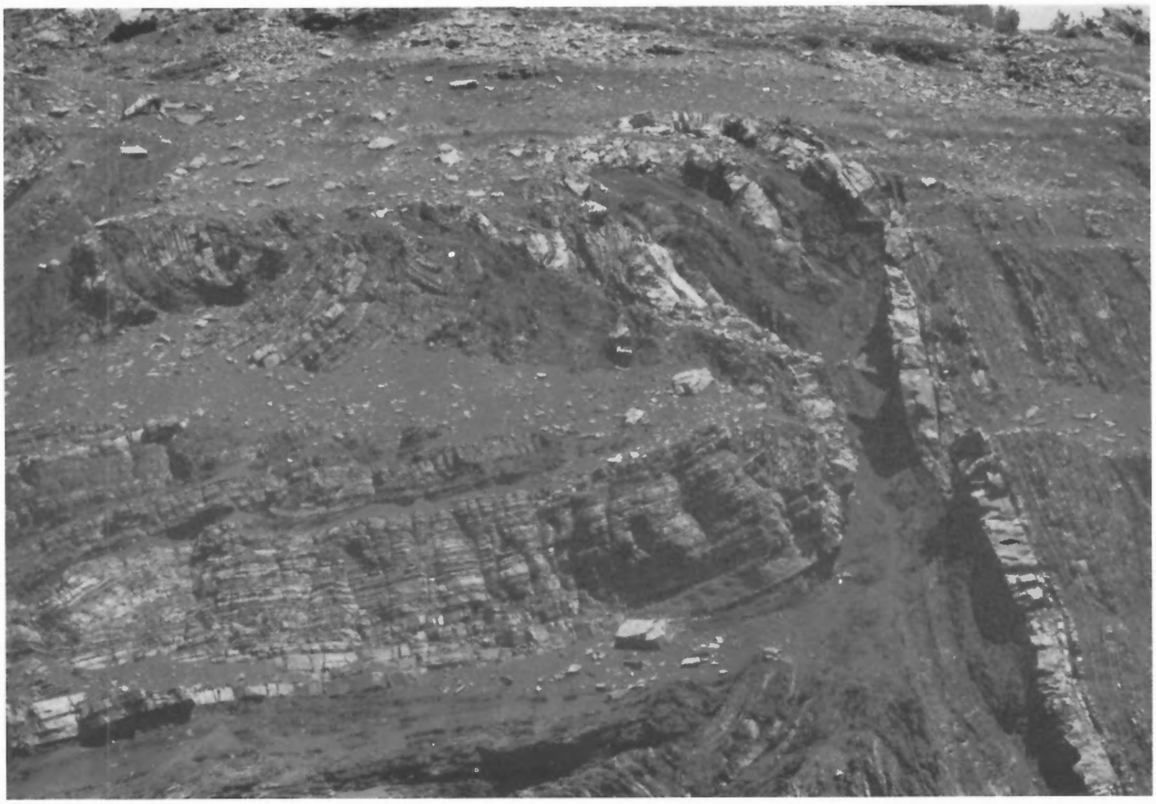

Figure 17. The "Pod" at the crest of Grassy Mountain Anticline in No. 2 Pit on Grassy Mountain. Necking in the lower Mutz Member forms the pod. Note the contraction faults offsetting the right (east) flank and crest of the structure. ISPG photo. 2398-121.

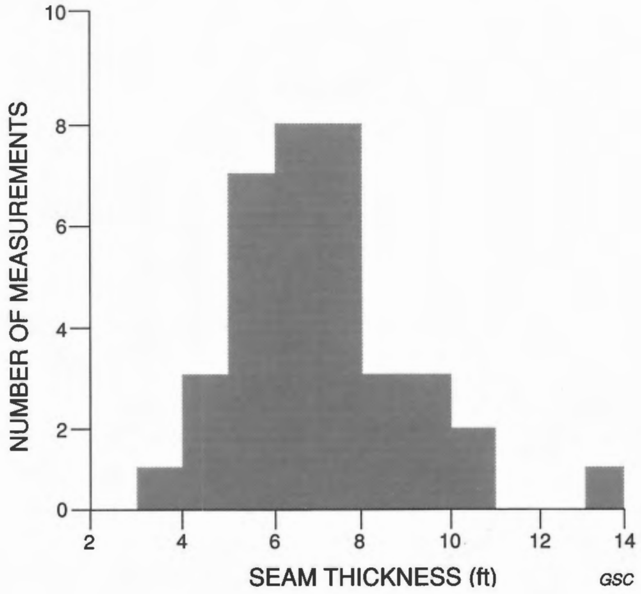

Figure 18. *Frequency distribution of thickness variations along strike in the No. 2 Seam, Coleman Thrust plate, McGillivray and International mines, Coleman, Alberta.*

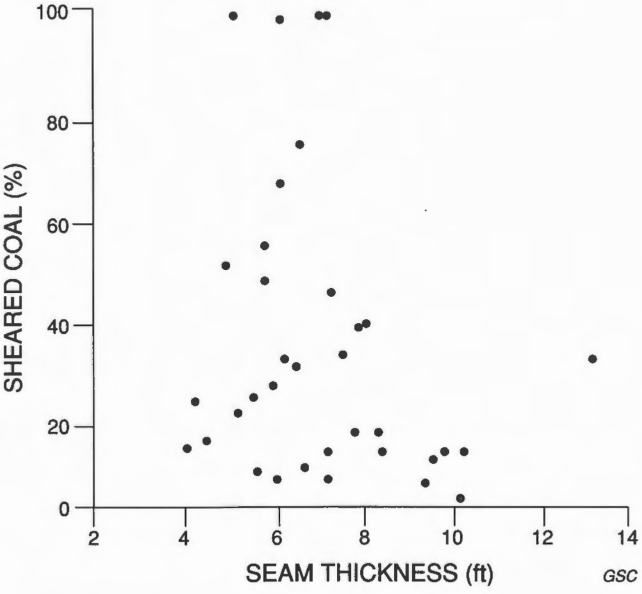

Figure 19. *Scatter diagram showing the relationship between the thickness of No. 2 Seam and the percentage of sheared coal along strike in the Coleman Thrust plate, McGillivray and International mines, Coleman, Alberta.*

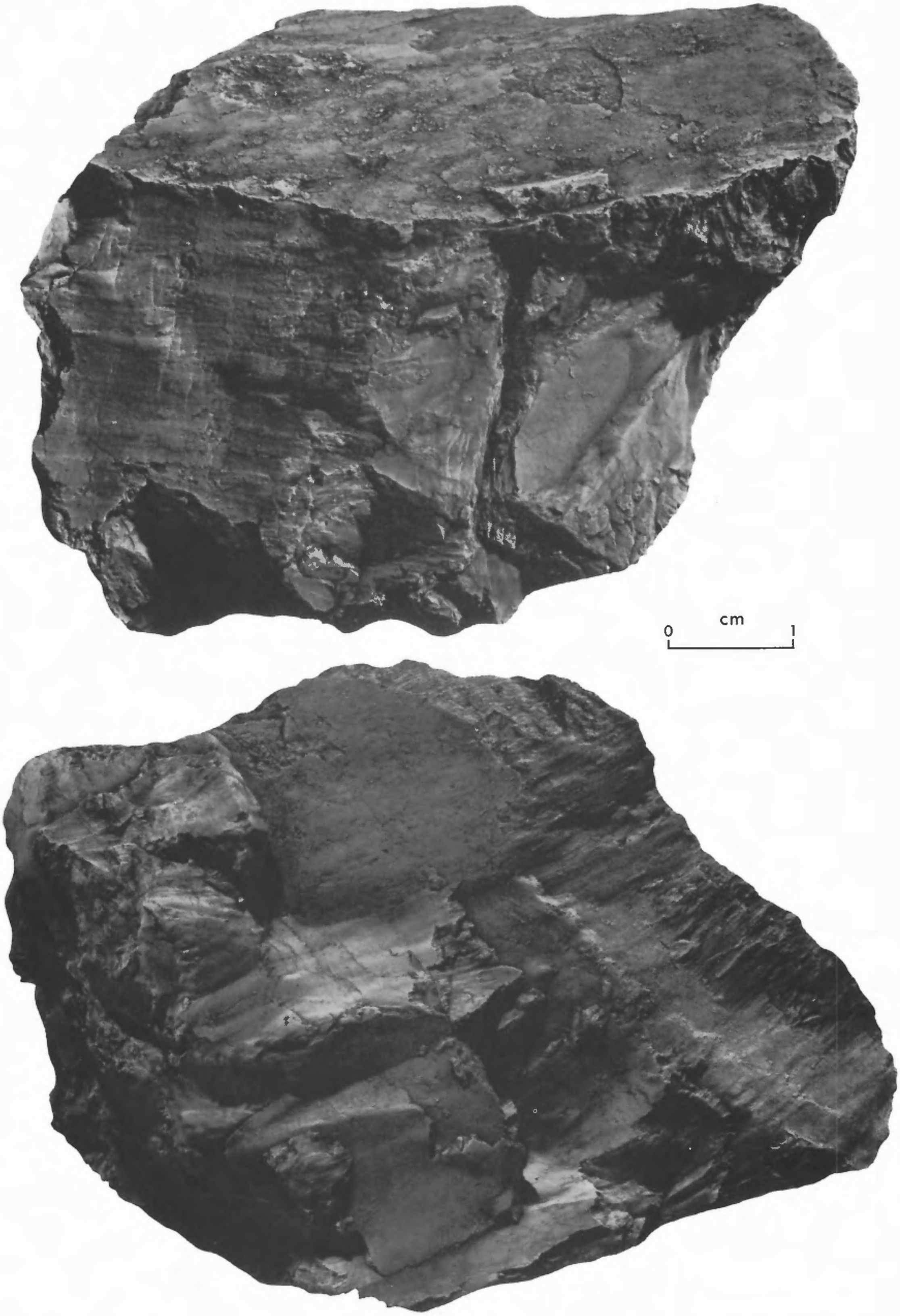

Figure 20. Two faces of a slickensided, lenticular fragment of coal from No. 2 Seam, Mutz Member of the Mist Mountain Formation, south wall of No. 5 Pit, Grassy Mountain. ISPG photos. 2703-1, 2703-2.

stress to regions of lower compressive stress, and to have been constrained by the sedimentary layering, whether the stratigraphic succession is undeformed or broadly folded. Thus, the σ_1 and σ_2 principal stress axes would tend to have been oriented in or close to parallelism with the layering, and the third (σ_3) would have been oriented perpendicular thereto. In layer-parallel compression for contraction faulting, the σ_1 and σ_2 axes will be in, or close to, the plane of the layering; and, in compression perpendicular to the layering for extension faulting, the σ_2 and σ_3 axes will occupy this fundamental position.

Under the stress conditions shown in Figure 21, with σ_1 horizontal or subhorizontal, potential contraction is accomplished on conjugate, curviplanar surfaces making angles of 30° to the σ_1 trajectories. With σ_1 and σ_2 tending to be constrained to the plane of the layering, potential contraction (or reverse) faults will be inclined at 30° to the layering and will strike perpendicular to the direction of regional compression. Correspondingly, if σ_1 were acting perpendicular to the layering, potential conjugate extension (or normal) faults would again make angles of 30° to this axis. These would be at angles of 60° to the layering and would parallel the regional strike of the layering only if σ_2 were also oriented parallel to the strike. The geometric similarity between actual imbricate thrust faults in the eastern Cordillera and the set of potential reverse faults dipping from right to left in the model is readily apparent.

The concavity of these potential contraction faults shown in Figure 21 is due to the divergence and curvature of the stress trajectories in a homogeneous material (Hubbert, 1951). However, the maximum principal compressive stress trajectories for potential contraction faults in the supracrustal wedge flow through an inhomogeneous stratigraphic succession in which individual layers are demonstrably variable in thickness and laterally discontinuous. The initial shape of potential contraction faults is, moreover, one of *flats* where the fault is parallel or subparallel to the layering, and *ramps* where the fault is cutting upsection in footwall beds in the direction of relative displacement (see Figure 22). A concavity will occur at each intersection of a flat with the ramp ahead of it and, conversely, a convexity will occur at each intersection of a ramp with the flat ahead of it. The overall shape of a contraction fault in cross-section, therefore, as it cuts upward through the stratigraphic succession in staircase fashion, is discontinuously concave upward. In the limiting case, as for example a massive, homogeneous stratigraphic unit, the spacing between the ramps and the height of the ramps each approach zero, and the contraction fault is continuously and smoothly concave upward, as in sand box experiments. Extension faults, on the other hand, appear to be more or less continuously concave upward, with no obvious steps interrupting them, as though the rock succession were responding as a homogeneous material in spite of its layered anisotropy.

Two important observations arising from detailed studies of extension and contraction faults in coal mines of the eastern Cordillera are: i) that extension and contraction faults show a preferred orientation with respect to the layering rather than to the horizontal and the vertical, and ii) that, on the mesoscopic scale of the mine, the stratigraphic succession is extended in the plane of the layering, in

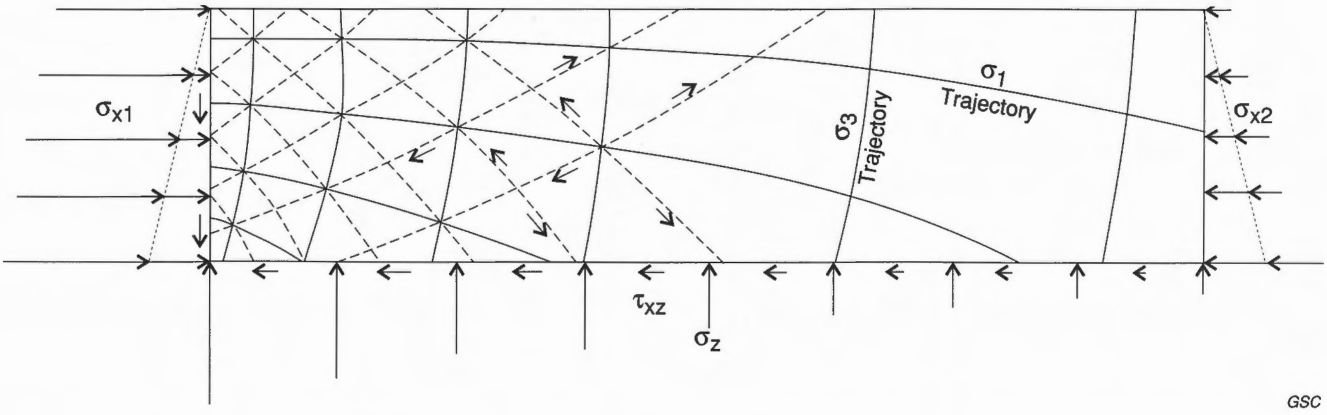

***Figure 21.** Trajectories of principal stresses (σ_1 and σ_3; solid lines), and of potential reverse-fault surfaces (broken lines) compatible with the boundary stresses (σ_{x1}, σ_{x2}, σ_z and τ_{xz}) for a two-dimensional stress system on a plane parallel to σ_1 and σ_3. Arrows indicate directions of potential slip. (After Hubbert, 1951, Figure 16.)*

stark contrast to the wholesale, megascopic contraction or shortening of the supracrustal wedge embracing the mines within the Foreland Thrust and Fold Belt.

Evidence that the layered anisotropy exerts a fundamental control on the orientation of the three orthogonal, principal compressive stress axes in extension and contraction faulting in the eastern Cordillera was demonstrated from the preferred angles at which these two types of fault cut the sedimentary layering (Norris, 1958). I was led to this fundamental conclusion by Raasveldt (Sax, 1946, p. 67, 68) who studied the frequency distribution of the *observed* dip of fault planes in the Willem Sophia coal mine in the Netherlands. Raasveldt reported that the most frequent dip of "normal" faults was 63°, and of "up- and overthrusts" was 22°. He noted that these preferred angles, measured with respect to the horizontal, were complementary. He did not relate them, however, to the plane of the layering.

Following Raasveldt (op. cit.), I plotted frequency polygons of the dips of extension faults in the No. 4 Seam at Canmore, Alberta, and of contraction faults (collectively) for all mines examined in the eastern Cordillera (Fig. 23A, B). The dips showed no single preferred values. However, when the sedimentary layering is designated the reference plane, and frequency polygons are plotted for the acute angle between the faults and the layering, there are preferred values for both extension and contraction faults.

Extension faults cut the layering at a preferred angle of 58° and contraction faults at 23°, the two angles being approximately complementary. In extension faulting, therefore, the major principal axis of compression is about perpendicular to the layering, and the intermediate and least principal compressive stress axes are in the plane of the layering. In contraction faulting, on the other hand, the greatest and intermediate principal axes for compression are in

Figure 22. No. 2 Seam (2), repeated above the McConnell Thrust in C-2 Pit (left) and above a splay fault in C-3 Pit (right), between Grassy Mountain and Bluff Mountain. Note the step in Mutz Member (JMM) sandstone and shale in the immediate footwall of the splay fault. ISPG photo. 2398-102.

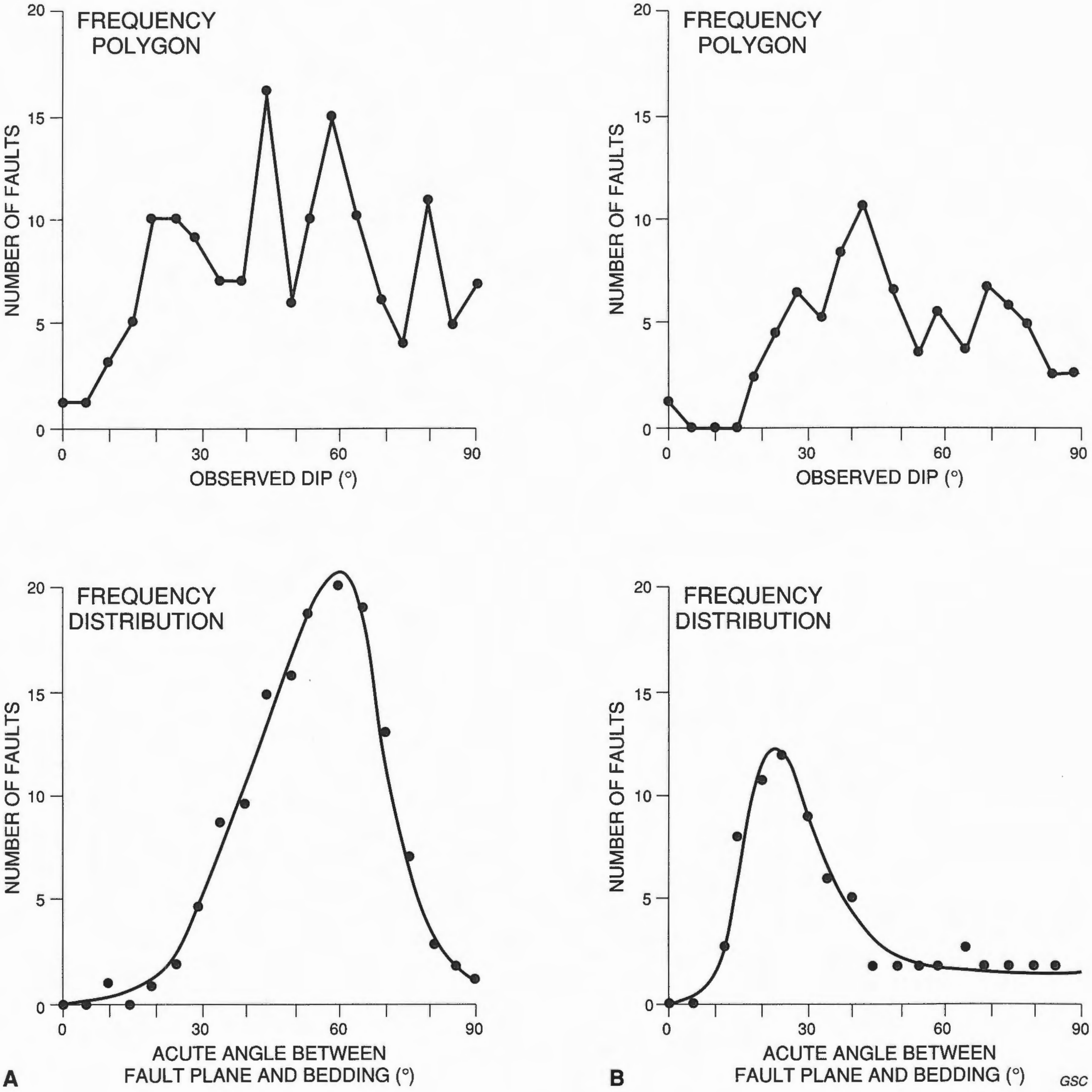

Figure 23. Frequency polygons and frequency distributions. (After Norris, 1958.)

A. Frequency polygon of the observed dips of extension faults, and the frequency distribution of these dips for horizontal bedding, No. 4 Seam, Canmore, Alberta.

B. Frequency polygon of the observed dips of contraction faults, and the frequency distribution of these dips for horizontal bedding in coal mines in the southeastern Canadian Cordillera. (After Norris, 1958, Fig. 5.)

the plane of the layering and the least principal axis, being orthogonal to the other two, is oriented perpendicular to the sedimentary layering. The simple practice of referring the faults to the sedimentary layering, rather than to the conventional horizontal and vertical reference frame, sheds light on the compressive regimes acting on the supracrustal wedge during Laramide shortening.

Insofar as an overriding thrust mass, such as the Turtle Mountain Thrust plate, was megascopically in layer-parallel compression as it moved relatively *eastward*, it was obviously folded (Rich, 1934, p. 1589) and unfolded (Norris, 1958, p. 31) as it was draped and moved over the successive flats and ramps in its footwall. The folds acted like standing waves as their axial surfaces remained more or less fixed relative to footwall ramps and, in effect, migrated relatively *westward* across the plate. Thus, with progressive displacement, the part of the overriding mass that was flexed initially into a syncline as it moved over the base of a ramp was then flexed into an anticline as it moved over the top of the ramp. Ideally, the strata were then straightened along a stratigraphically higher zone of bedding-plane slippage. In this manner, the overriding mass was first flexed one way, then the other, and any given point within it was alternately inside and outside the neutral surface of the folds. Correspondingly, it was alternately compressed and extended. Because of its strength in compression, the layered succession rarely broke to form contraction faults, but when it did, they commonly grew to be major tectonic features such as the McConnell and Turtle Mountain faults. Because of its weakness in relaxation, however, the succession failed on a profusion of generally small-scale extension faults. Extension faults outnumber contraction faults by a factor of ten (Norris, 1958) in the coal mines of the eastern Canadian Cordillera.

Structural markers, such as extension faults, are invaluable in providing unequivocal evidence of i) shear between the roof and floor of coal seams, ii) the minimum net slip in the plane of the seams, iii) the complicated displacement paths of beds in interbed slip, and iv) widespread drag within thrust plates as the hanging wall moved up and over footwall strata.

Many of these extension faults are offset in the plane of a coal seam and, in the majority of cases, these offsets are updip in the roof with respect to the continuation of the same fault in the floor. The coal seams, therefore, are tectonically detached from their host formations so that neither folds nor faults necessarily continue across them. Some of the most spectacular exposures of such detachments are seen in No. 2 Pit on the south face of Grassy Mountain (Figs. 3, 16). There, the folds and faults in the Mutz Member above No. 2 Seam are totally disharmonic relative to structures in the Hillcrest Member below the coal.

It is rarely possible to measure the offset of markers in the plane of a coal seam in open pit mines, because the roof of the seam is removed prior to gaining access to the coal. Underground, however, both roof and floor are commonly exposed continuously over strike-lengths of several kilometres and for dip distances of up to about one kilometre. During the course of my studies, extension faults in the roofs of many underground coal seams were matched with their counterparts in the floors, and in some instances they could not be matched. Many extension faults continue without interruption or offset across the seams, although abundant polish on roof and floor are obvious indications of detachment of the seams from their host rocks by shear. Other extension faults in the same area of the seam were observed to be offset either up- or downdip with respect to their continuations in roof or floor by as many as tens of metres, thereby substantiating small-scale interstratal displacement both in the direction of tectonic transport of the thrust plate containing them as well as in the reverse direction.

Abundant slickensided bedding in the Kootenay coal measures — in underground and open pit mines, in rock tunnels connecting seams, as well as in fresh roadcuts into formations of widely differing ages, rock types, and structural positions — substantiate the singular role played by the layering in the mechanical behaviour of the supracrustal wedge. Individual beds have limited areal extent, but regionally they overlap and interleave from the bottom to the top of the wedge. Collectively, they comprise a penetrative array of deformation discontinuities (faults) which was kinematically active during the Laramide Orogeny (Norris, 1966). Their overlapping nature across and along the strike contributed to the flexibility and integrity of the thrust plates as these plates encroached upon the western margin of the North American craton.

An exceptional example of the spatial and temporal relationship between interbed slip and extension faulting was mapped at No. 4 Jig, above No. 2 Gangway, in No. 4 Mine in the Kootenay Group of the Cascade Coal Basin near Canmore, Alberta (Fig. 24). At this locality, a relatively undeformed, west dipping panel of coal measures, embracing No. 4 Seam, occurs in the Lac des Arcs Thrust plate. Within the panel, slickensides on both roof and floor indicate that the coal was tectonically detached from the host strata. Moreover, offset of extension faults exposed in the jig document the displacement history of the roof over the floor in the last stages of the compressive Laramide Orogeny. The roof had moved relatively updip or

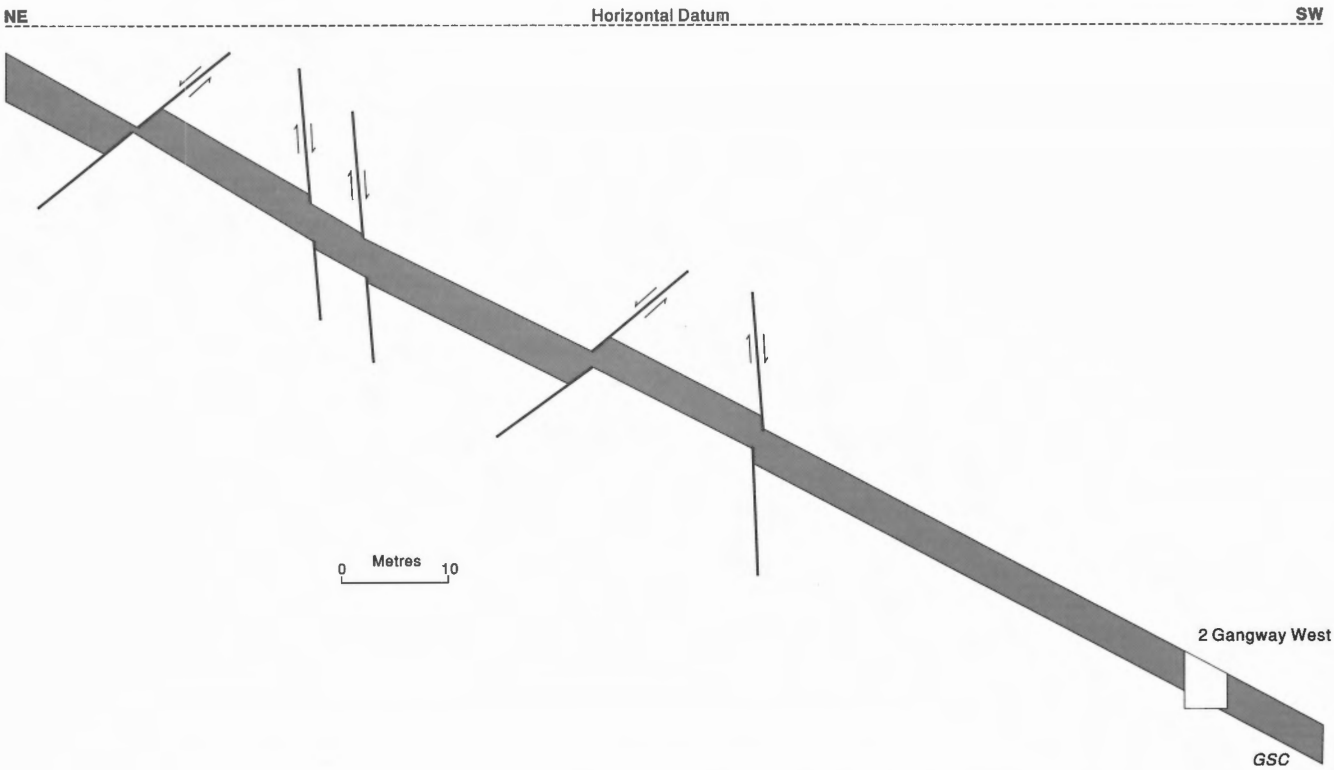

Figure 24. Structural cross-section of the Mist Mountain Formation at No. 4 Mine (No. 4 Jig, No. 4 Seam), Canmore, Alberta.

forward 2.4 m and had fallen back 1 m before the assemblage of floor, coal seam and roof was cut by three extension faults at the end of the orogeny. These faults were not offset in the plane of the seam by interbed slip. The fact that other extension faults in the roof and floor of the seam in the immediate area of the jig could not be matched would suggest a prior history of net offsets in the plane of the layering of several tens of metres, so that their continuations were not exposed by mining at the time of the survey. Moreover, the fact that a pattern of displacements identical to that observed in No. 4 Jig could not be identified throughout the mine and, indeed, throughout all four coal seams studied in the Cascade Coal Basin, strongly suggests that slip did not take place simultaneously over the entire bedding surface in the area of No. 4 Mine or, for that matter, among the several stratigraphic levels embracing the coal seams studied within the Lac des Arcs Thrust plate.

Measurements of offsets for the many extension faults displaced systematically updip in the plane of the coal, at several stratigraphic levels in the Kootenay Group, suggest that structurally and stratigraphically higher beds moved relatively farther than lower beds in the direction of transport of the thrust plates containing them. There was, therefore, an overall, forward, differential shearing movement within each plate, possibly because of drag along the bounding thrust faults (Norris, 1958). Moreover, the absence of a pervasive, matching pattern of roof and floor displacements (like that observed in No. 4 Mine) in all the mines studied suggests that forward slip did not take place simultaneously throughout any given plate, or throughout the several thrust plates embracing the coal seams examined in the eastern Canadian Cordillera.

Matching of extension faults between roof and floor of coal seams in the Cascade Coal Basin indicates, in addition, a complicated, cyclical movement picture including compression, forward displacement, pause, relaxation, extension, and fallback within and at the base of the Lac des Arcs Thrust plate. Supplementary data from other mines in the eastern Cordillera suggest that this type of motion may have continued throughout the entire kinematic history of this and other plates, as they were emplaced in the Foreland Thrust and Fold Belt. It took place in the manner of stick-slip (Brace and Byerlee, 1966), the total forward displacement of each plate being the net result of this forward and backward movement. Obviously, the net forward component on the major thrust faults was orders of magnitude greater than the fallback, in order that heaves measurable in kilometres could be attained by some of the plates.

KINEMATICS OF INTERBED SLIP

It has been shown that differential displacement at the coal/rock interface is of fundamental importance to the mechanics of seam thickening and thinning through shear and flow. The coal pits on Grassy Mountain are replete with examples of these displacements. In order to evaluate them, measurements were made of the pitch of slickenlines on the roof and floor of No. 2 Seam in five of the abandoned strip mines (see Figure 30 for station locations). To be representative, they were spread over the maximum possible strike distance (5 670 m), from No. 5 Pit in the north to A Pit in the south.

Pitches of striae along with attitudes of bedding were measured at as many points as possible over a strike distance of about 30.5 m at each of the five locations (Table 2). The number of measurements ranged from 10 to 25, depending upon the degree of weathering and preservation of the striae on the walls and floor of the pits. Altogether, 90 measurements were made.

Poles to bedding, with associated slip linears (Hoeppener, 1953), kinematic axes, and piercing points of the striae were plotted on the lower hemisphere of a Schmidt equal-area projection (Fig. 25). The piercing points were then revolved into the horizontal about axes representing the average strike at each station. No correction was made for the plunge of the folds at Stations I and III because it was less than five degrees. Azimuths of the striae for horizontal bedding were calculated, grouped into ten-degree classes and plotted as histograms. The arithmetic mean and mode of azimuth of striae were then compared, for all stations. For Stations II, III, and IV, the distributions appear to be normal. At Station V, at the southern limit of measurements, however, the sample could be bimodal, representing azimuths of slip of 070° and 090°, corresponding to the mean slip directions of Stations IV and III respectively. At Station I, the strong skewness of the sample toward higher values is attributed to the limited number (10) of measurements.

It is possible, as speculated by Price (1967, p. 48) from his measurements of slickensided fractures, other than bedding, at Station III, that a bimodality of slip direction may be present on Grassy Mountain and that it may be due to the superposition of two movement pictures, the one representing slip perpendicular to the north-trending leg of the Crowsnest Deflection (Norris, 1968), and the other perpendicular to its northwest-trending leg.

A careful search of the floor of A Pit at Station V, the only location of the five investigated that revealed any suggestion of more than one movement picture (see Figure 25, Station 5), did not reveal any intersecting striae. The relative ages of the two apparent populations of striae, therefore, could not be documented. Moreover, the samples from Stations I to IV on Grassy Mountain, as well as that from Vicary Creek Mine, 13 km to the northwest (60 measurements) (Norris, 1966), from a roadcut in the Carnarvon Member of the Lower Carboniferous Mount Head Formation on Highway 3 at Blairmore, Alberta (12 measurements), and from the Upper Devonian and

TABLE 2

Kinematic analysis, Grassy Mountain, Alberta

Station	Pit	No. of Observations	Mean attitude of bedding		Mean azimuth of transport	Structural setting	Comments
			Strike	Dip			
I	D	10	000°	60°E	092°	GM Anticline	skewed
II	5	25	004°	50°NW	079°	TMF slice	normal
III	2	15	000°	53°W	087°	GM Syncline	normal
IV	B	20	008°	44°NW	069°	TMF slice	normal
V	A	20	016°	43°NW	079°	TMF slice	(?)bimodal

GM - Grassy Mountain
TMF - Turtle Mountain Fault

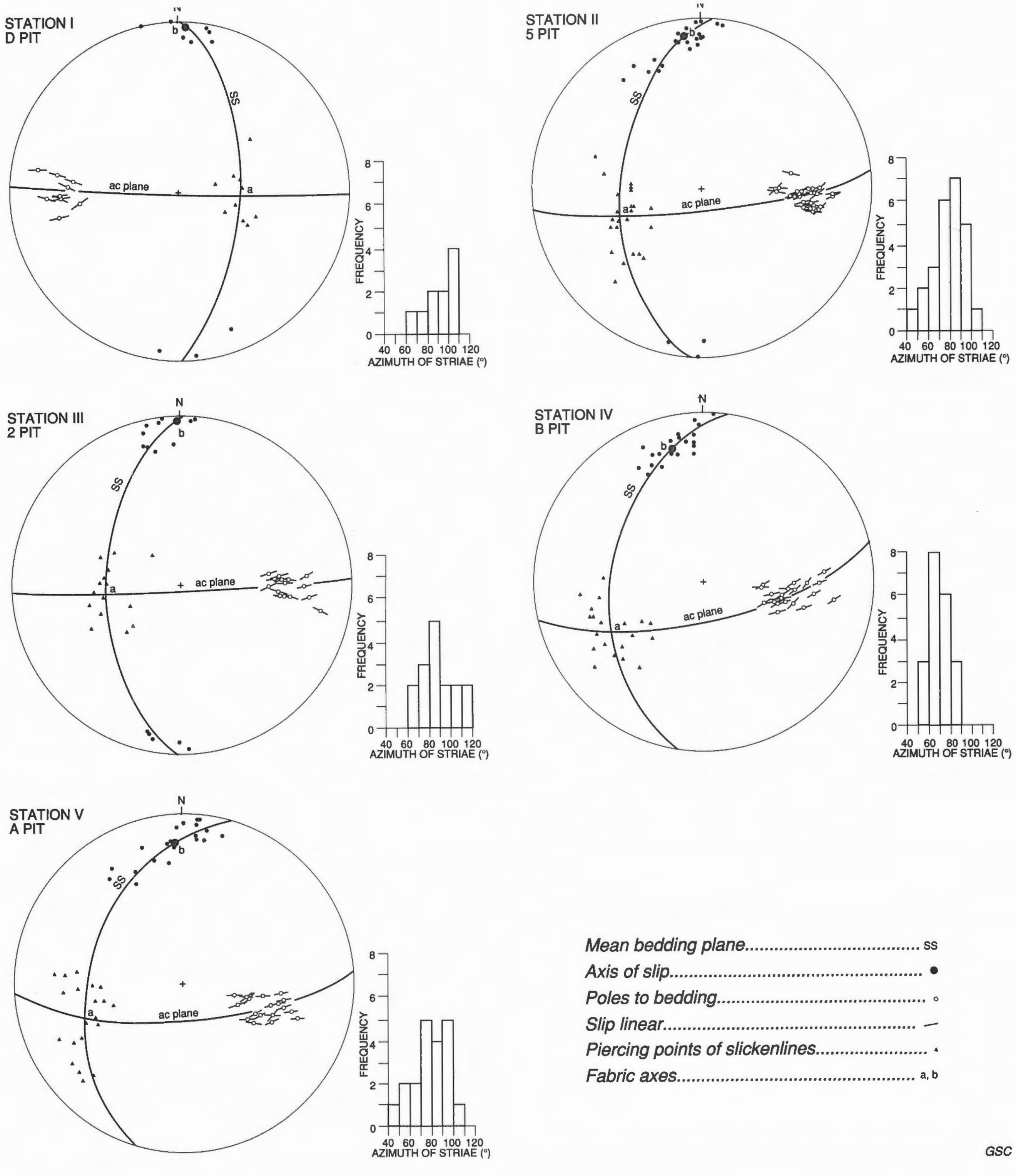

Figure 25. *Kinematic analysis of slickenlines on the roof and floor of No. 2 Seam at five locations on and immediately south of Grassy Mountain. See Figure 30 for station locations and Table 2 for summary of results.*

Lower Carboniferous formations exposed along Highway 3 at Crowsnest Lake near the British Columbia/Alberta boundary (71 measurements), can be represented by normal density functions with no suggestion of bimodality. There is, therefore, a very high probability that slickenlines, on bedding, at all locations in the Crowsnest Pass area, including Station V on Grassy Mountain, individually represent single kinematic patterns or movement pictures whose preferred directions of displacement are close to their respective arithmetic mean values. It is interesting to note that the preferred direction of slip (079°) for the Devonian and Carboniferous formations in the Lewis Thrust plate at Crowsnest Lake is within two degrees of azimuth of the average slip direction (081°) for all five stations in the Livingstone Thrust plate at Grassy Mountain, structurally well beneath the Lewis Thrust plate.

THE GRASSY MOUNTAIN FOLDS

The Grassy Mountain folds embrace Grassy Mountain Anticline and Syncline, and associated structures exposed in No. 2 Pit (Figs. 3, 6). The rocks in the walls of the pit include: i) shale, siltstone, and sandstone of the Hillcrest and Mutz members of the Mist Mountain Formation; ii) No. 2 Seam at the base of the Mutz Member; and iii) chert- and quartzite-pebble conglomerate of the Cadomin Formation. Varicolored shale and siltstone of the Gladstone Formation occur in the hinge of Grassy Mountain Syncline immediately north of the pit face. The stratigraphic interval between the base of the Hillcrest Member and the top of the Cadomin Formation is approximately 96 m.

The Grassy Mountain folds are made up basically of two synclines and an anticline in the Mutz Member above No. 2 Seam, and two synclines and an anticline in the Hillcrest Member below. The folds above and below the coal seam are markedly disharmonic; the anticline in the Hillcrest Member, for example, lies beneath Grassy Mountain Syncline in the Mutz Member and higher beds and, incidentally, divides the pit into two parts. The mean strike of the coal measures there is almost due north (Price, 1967, Fig. 4) and the plunge of the folds is, on the average, less than five degrees north. All folds are flexural slip and cylindrical, and, because of their tightness, few if any folds are parallel or concentric (Norris, 1971). They are broken by some contraction faults, one of which can be seen in the "Pod" at the crest of Grassy Mountain Anticline (Fig. 17), and another in the east flank of the anticline in the Hillcrest Member, in the floor of the pit. The latter fault has been rotated through the vertical to become a contraction fault with normal separation. Numerous extension faults cut the coal measures and most are evident where they offset the coal/rock interface (Fig. 11) (Price, 1967, Fig. 8).

Grassy Mountain Anticline and Syncline display contrasting structural styles. The anticline has a markedly planar west limb that is kink folded (Norris, 1971), while the syncline has typically rounded flanks. The difference in style appears to be due to the massive Mutz Member channel-sandstone in the hinge of the syncline, and the laterally equivalent but mechanically different succession of interbedded shale and sandstone in the hinge of the anticline. The anticline and its parasitic kink fold lean steeply to the west; the syncline, on the other hand, conforms to the regional pattern of eastward vergence of asymmetrical folds in the Foreland Thrust and Fold Belt.

The two most striking features of the folds are the marked thickening and thinning of No. 2 Seam, cited above, and the structural geometry of the "Pod". The thickness variations are clearly the result of the mass movement of the coal. The depositional layering of the seam was largely destroyed by interbed slip, so that faulted and folded remnants of shale, vitrinite, or fusinite bands only occur locally, and the remainder is a mass of disarticulated, highly polished and striated, overlapping pieces of coal, like that illustrated in Figure 20. In addition, many east- and west-dipping contraction faults can be identified in the seam because of the offset of these bands. In Grassy Mountain Anticline, for example, they comprise a family of shear surfaces arranged more or less symmetrically with respect to the axial surface, and they define at least two "herds" of horses converging from east and west on the hinge of the fold (Fig. 26). The infusion of coal consequent to this convergence stretched the host rock, creating a family of extension faults (Fig. 11), and thereby nucleating a protuberance that would ultimately evolve into the "Pod".

Structural thickening and thinning of coal in the Grassy Mountain folds appears to have been due to imbrication and flow, through transport of horses of coal and rock on contraction faults, synchronous with displacement on the myriad slip surfaces pervading the disarticulated coal mass. The result was widespread detachment of the roof and floor from the seam, concomitantly creating disharmony between the folds and faults above and below the seam. Evidence of the mechanical independence of floor from roof is seen, for example, where a large block of the seam floor has been inserted into the coal along a contraction fault on the west flank of Grassy Mountain Syncline (Figs. 3, 27). The same fault is not seen to cut the roof, and has been rotated into a position of normal separation.

Figure 26. Structural thickening of No. 2 Seam coal in the hinge of Grassy Mountain Anticline, No. 2 Pit, Grassy Mountain. White lines identify some of the contraction faults along which slices of highly sheared coal have been displaced, from both sides, toward the hinge of the fold. GSC photo. 117435.

The main question is how this thickening and thinning of the coal took place. Was it through migration of the coal entirely within the statistically defined *ac* kinematic plane for the structural domain of the mountain, or, is it possible that the coal moved in or out of this plane as well? In order to answer this question, the No. 2 Seam in the Grassy Mountain folds was surveyed using a planetable (Norris, 1971). This survey revealed the surprising result that there is 48 per cent too much coal in the plane of the section, if the structural thickening of the seam was due solely to migration of coal within the local *ac* kinematic plane. If the coal was transported into the plane of the section from the sides (i.e., from the "b" direction of the fold axes), the ramifications of such a structure would be important both economically and structurally. Firstly, it means that, because of the anomalous thickening of the coal in No. 2 Pit, the seam must thin along strike in order that the total volume of coal involved in the thickening and thinning process remains the same.

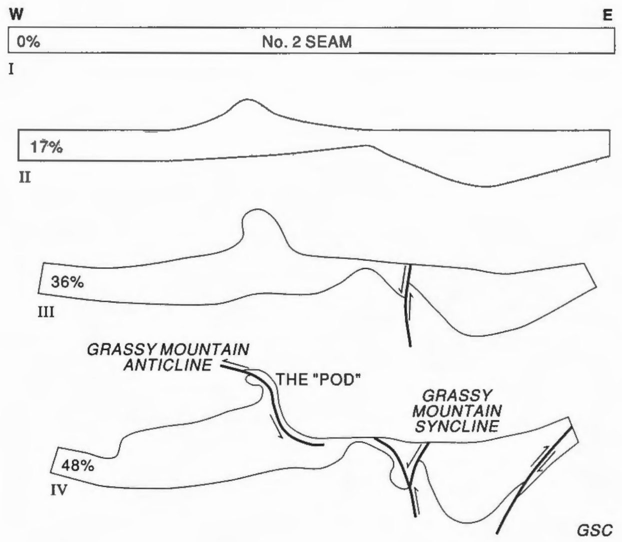

Figure 27. *Schematic development of folding and faulting of No. 2 Seam in No. 2 Pit on Grassy Mountain. Horizontal and vertical scales are equal. Right sections are balanced for bed length but not for seam area. Excess coal in Sections II, III, and IV is expressed as a percentage of the original area of coal outlined in Section I. (Section IV is after Norris, 1971.)*

Secondly, the behaviour of the coal as a detachment horizon containing unpredictable thickness variations, means that any mobile rock unit (cf. the Fernie Formation) can insulate structures above from those below and render the balancing of regional structure sections difficult if not meaningless. None of the structure cross-sections developed for the eastern Canadian Cordillera incorporate the structural style of the Grassy Mountain folds at depth. This is especially true for the "Pod". The disharmony of structures above and below the coal entice speculation as to how the Grassy Mountain folds evolved as one expression of structural style of the Kootenay Group.

The following stages are suggested for the development of the Grassy Mountain folds (Fig. 27). The model is based on the premises that the No. 2 Seam was initially more or less of uniform thickness across the mountain (Stage I), that the folds above and below the coal nucleated as mega kink-bands independently, and that successive stages in structural development leading to their present shape can be seen in the serial cross-sections (Fig. 30) drawn for strata along strike to the north and south where the folds die out. The planar segments on the west flank of Grassy Mountain Anticline are original features retained by the folds (Stage II). The curviplanar form of other segments developed later (Stage III).

The temporal relationship between folding and faulting is displayed particularly well in the "Pod" (Fig. 17). There, folding of beds adjacent to a fault offsetting the coal/roof-rock interface (Stage IV) would suggest that the hanging wall was dragged downward relative to the footwall (normal separation). The offset of the roof, on the other hand, is unequivocal evidence that the fault is contractional and that the hanging wall moved upward relative to the footwall. Folding, therefore, appears to have preceded contraction faulting, contrary to the generally perceived model for regional faulting and folding in the Foreland Thrust and Fold Belt (see, for example, Douglas, 1950, p. 84).

The excess coal outlined in the right section through No. 2 Pit (Fig. 27–IV) was then compared at face value with the excesses shown for Stages II and III, and was plotted as a function of the percentage shortening observed in the pit (Fig. 28). It was found that the excesses may not be a linear function of the amount of layer-parallel shortening. It could be nonlinear and extrapolated to some maximum value between fifty and sixty per cent for twenty-five per cent shortening. Neither the amount of coal migrating into a given *ac* kinematic plane nor the percentage shortening is boundless. The maximum transport into this plane is

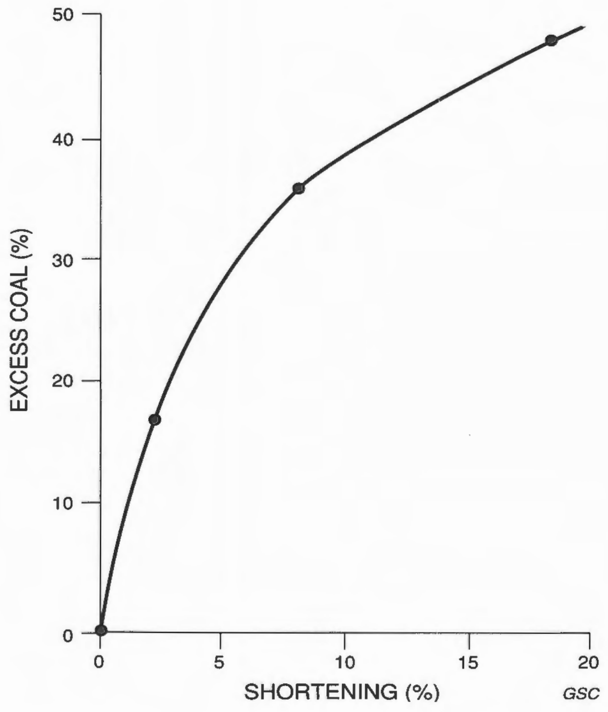

Figure 28. *Possible relationship between layer-parallel shortening of No. 2 Seam on Grassy Mountain and the amount of coal migrating into the* ***ac*** *kinematic plane.*

reached with the total collapse and isoclinal folding of the coal measures along strike to the north and south. The 48 per cent excess coal in No. 2 Pit is associated with 18 per cent shortening in the plane of the layering. Although data for the intermediate stages are speculative, they must represent a progression to zero excess northward as the folds die out and the seam assumes a more planar condition within the Livingstone Thrust plate.

A MODEL CROSS-SECTION OF GRASSY MOUNTAIN

The No. 2 Seam on Grassy Mountain has been structurally thickened and thinned by the two end members of a continuum of mechanisms. At one end of the continuum is *imbrication*, resulting in layer-parallel piling up of the coal and associated roof and floor rocks on discrete faults. At the other end is *flow*, resulting in mass transport of the coal, on a profusion of closely spaced slip surfaces, from one part of a seam to another. Regionally, the major thrust faults made the Kootenay coals accessible to exploitation at numerous places in successive fault blocks. Locally, however, the associated splays introduced structural complications that degraded the coals and limited the capacity of simple geological models to predict the presence of mineable coal at depth.

Imbrication, displayed on the north face of No. 5 Pit (Fig. 14), is in the style of the listric contraction or reverse faults characterizing the Foreland Thrust and Fold Belt. Upright panels of coal were stacked one upon another like shingles on a roof so that the deformation is decidedly asymmetric. In the hinges of folds like Grassy Mountain Anticline and Syncline, on the other hand, the deformation is approximately symmetrical, with families of contraction faults verging either away from the axial surfaces of the folds, as in Grassy Mountain Syncline (Fig. 3), or toward it, as in Grassy Mountain Anticline (Fig. 16). In the latter, the interaction of converging faults produced a complicated network of dislocated slip surfaces and associated horses of coal and roof and floor rock (Fig. 26). Imbrication does not rob the coal from immediately adjacent areas, but flow does.

Flow of coal into the hinges of the folds appears to be simply an imitation, on a much reduced scale, of symmetrically arranged slip surfaces verging toward the hinges of the folds. Slip surfaces or faults bound the fragments of coal and rock on scales as small as a few centimetres and the scale of the displacement of individual fragments may be correspondingly small. The net result of these displacements, however, is the widespread disarticulation and flow of the seam, along with slices of the roof and floor rock that may be caught up with them, into the hinges of the folds. Collectively, these fragments represent the composition of the seam, but individually they may be out of place with respect to their neighbours within the seam. Comparison of channel samples of coal through such highly sheared seams, therefore, may be of limited value for studies of lateral and vertical compositional variations.

Because of the intimate association of imbrication and flow on Grassy Mountain, these two mechanisms for coal seam thickening and thinning were amalgamated into a single cross-section that may have general application to deformed coal measures in the eastern Cordillera (Fig. 29B). The example of imbrication is taken from the north face of No. 5 Pit (see Figure 14), and the example of flow from the face of No. 2 Pit (see Figures 3 and 16). The composite section was then related to an initial state of undeformed Jurassic and Lower Cretaceous clastic rocks (Fig. 29A). With the section balanced as to layer length, but not as to the area of No. 2 Seam, it was found that the deformation observed in the combined No. 2 and No. 5 pits was the result of 17 per cent layer-parallel shortening. This is consistent with the 18 per cent shortening measured in No. 2 Pit and cited above.

The reason for the flow of excess coal into the structural position of what is now No. 2 Pit is not clear. This form of diapirism may have been due to differential compression of the longitudinal step in the coal measures in the footwall of the Turtle Mountain Thrust. The step is known to extend the length of the mountain (see the structure sections in Figure 30), whereas the excess coal accumulation is known to be localized in the position of the No. 2 Pit and its immediate vicinity on Grassy Mountain. It may be that, in association with compressive deformation of the footwall step as the Turtle Mountain Thrust plate overrode it, there was local vertical dilation, so that the mobile coal flowed naturally into the dilated zone from adjacent areas of higher pressure along strike both to the north and south. Should this be the case, deformed footwall steps may be useful indicators not only of other areas of anomalously thick coal near the surface, but also of potential reservoirs of oil and natural gas at depth.

Imbrication and flow characterize the mechanical behaviour of the Kootenay Group coals in the eastern

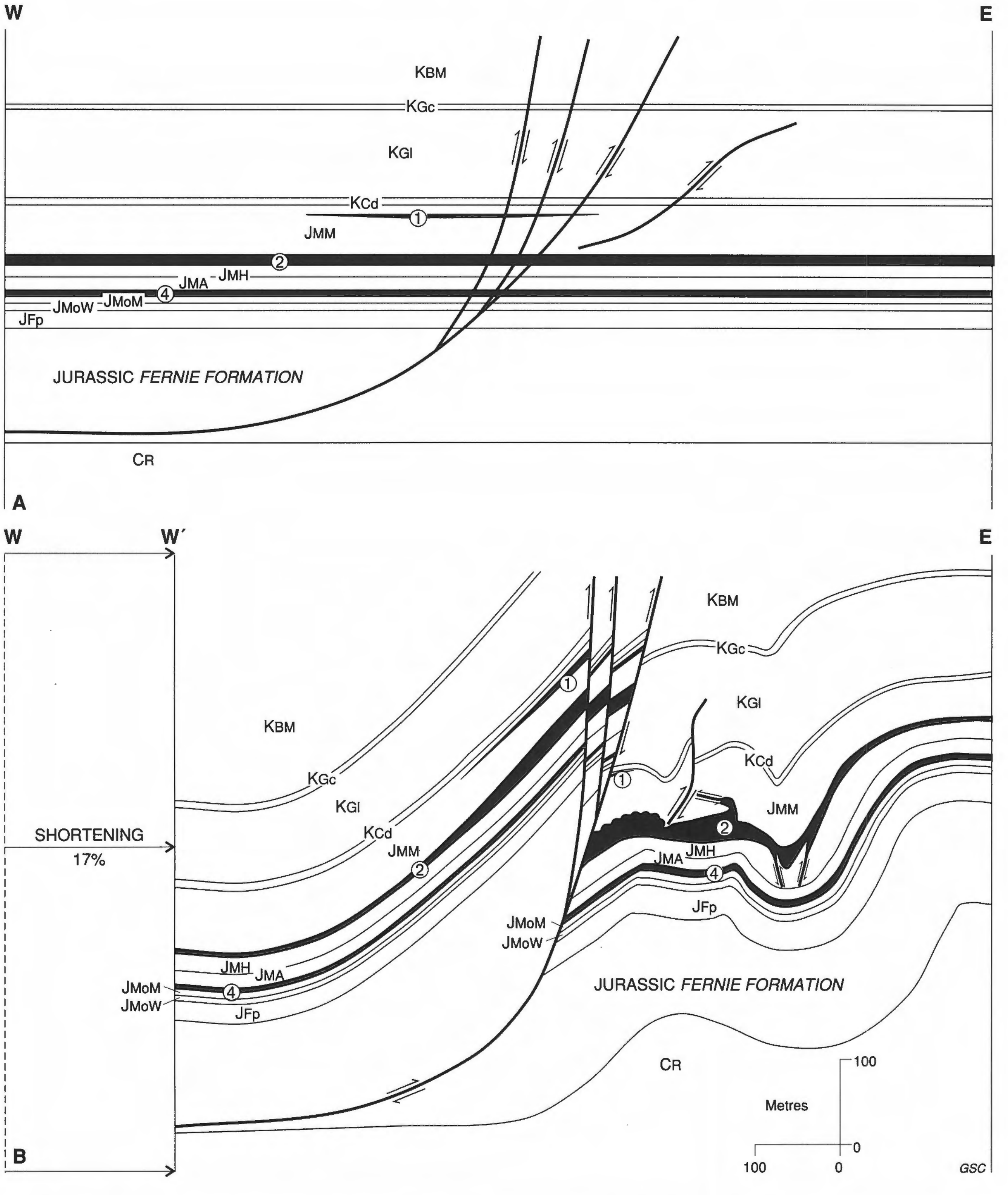

Figure 29. Model cross-section of Grassy Mountain, illustrating structural thickening and thinning of No. 2 Seam by imbrication and flow. The model was derived from structures observed in Pits 2 and 5. Restoration to initial state (A) was made by removing 17 per cent of layer-parallel shortening from the composite (B, final state). For legend, see Figure 30.

Cordillera. They were concurrent responses to the same regional compressive forces of the Laramide Orogeny in the latest Cretaceous and early Tertiary, and led directly to structurally thickened coal zones of considerable economic importance. It follows, in exploration and development work, that, if a coal seam is found to be structurally thinned, there may be a corresponding domain where the coal is structurally thickened. Judicious mapping of flow directions, both within the coal and at its contacts with roof and floor, could help locate hidden areas of thickened coal beyond the pit face.

CONCLUSIONS

The clarity of expression of structures involving the Kootenay Group on Grassy Mountain is such that the mountain can be used as a model for the thickening and thinning of coal seams in response to compressive deformation. Principles established here have application throughout the Foreland Thrust and Fold Belt, not only in the search for economically exploitable pods of structurally thickened coal, but also in the delineation of hydrocarbon-bearing structural traps.

Detailed mapping facilitates analysis of the underlying control of the lithological layering on the structural style of the deformed rocks, as well as the role of mobile units like coal and shale as detachment horizons that isolate structures above them from those below. The coal seams are invariably detached from their host rocks, so that they are free to be thickened and thinned independent of the faults and folds that bound them. Measurements, in the Coleman Thrust plate, of interbed shear associated with these detachments suggest that the locations of maximum shear are not necessarily where the coal is the thickest; rather, they may occur where the coal is of average or near average thickness.

The single most important structure responsible for thickening of the No. 2 Seam on Grassy Mountain appears to be the step in the footwall of the Turtle Mountain Thrust. Resistance by the step to movement on the fault resulted in imbrication of the relatively incompetent Mist Mountain Formation in the hanging wall and the stacking of a succession of west-facing panels of coal. Compressive deformation of the footwall step, in turn, resulted in the folding of the coal-bearing beds and the flow of excessive quantities of highly sheared coal into the hinges. The folds probably originated as mega kink-bands that were subsequently modified to rounded forms as they became more appressed. Some contraction faulting occurred in the later stages of fold development.

Imbrication and flow characterize the mechanical behaviour of the Kootenay Group coals in the eastern Canadian Cordillera. They were concurrent responses to the same regional compressive forces in the latest Cretaceous and early Tertiary. Up to 48 per cent excess coal has piled up in the hinges of some folds, suggesting oblique flow within seams as the strata were compressed and shortened.

Measurement of the pitch of slickenlines at the contacts of the coal with the host rock indicates a single preferred azimuth of slip of 081° over the length of the mountain, which is within two degrees of that established for the base of the Lewis Thrust plate in Crowsnest Pass. The agreement in measurements from widely separated thrust plates, but in more or less the same kinematic plane, supports the concept of interplay among plates to produce uniform crustal shortening across the Foreland Thrust and Fold Belt (Shaw, 1963, p. 235; Norris, 1966, p. 192, 193) as well as a uniform direction of tectonic transport. Moreover, the matching of extension faults from roof to floor of the coal seams suggests that the movement on the thrust plates was stick-slip, with fallback as the Laramide compressive stresses were spasmodically relieved within the supracrustal wedge. The culmination of this extension was reached in the early Tertiary with the development of the Flathead Fault system and backsliding on some of the major thrust faults, including the Lewis, thereby terminating the Laramide Orogeny in the southern Canadian Cordillera.

The coal resource potential for medium volatile bituminous coal on Grassy Mountain, above the 5000 ft. (1524 m) level is vast, but is confined largely to the Turtle Mountain block and the west half of the Gold Creek block. The eastern half of the Gold Creek block is essentially devoid of exploitable coal.

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