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J.D. HUGHES
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SUMMARY

A complete, undeformed outcrop section of the coal-bearing, Jurassic-Cretaceous Kootenay Group is exposed on the northeast face of Mount Allan, near Canmore, Alberta, in the Cascade Coal Basin. One thousand two hundred and twenty-three metres of section, including 1038 m of Kootenay and 185 m of the overlying Blairmore Group, were measured and sampled in detail. Sedimentary features recorded in the field, and from slabbed surfaces of samples in the laboratory, were used to subdivide the succession into component sedimentary facies. Coal samples collected over 873 m of section show a regular gradation in rank from semi-anthracite at the base to medium volatile bituminous at the top.

The Kootenay and Blairmore groups form a westward thickening clastic wedge, the sediments of which were derived from rising mountain ranges to the southwest and west. Sedimentation commenced with northeastward progradation of wave-dominated delta systems into the Fernie sea, forming a widespread basal sheet sand known as the Morrissey Formation. Laterally extensive, coal-forming swamps of the overlying Mist Mountain Formation developed on top of this sand at many localities within a coastal plain – lower deltaic plain setting. Interchannel deposits of crevasse splay, lacustrine, levee and swamp-marsh origin predominate within the Mist Mountain Formation. Channel deposits fine upward and are lenticular in the southeast-trending exposure afforded by Mount Allan, suggesting they may form "shoe-string" sand bodies in plan view, and were deposited by low sinuosity rivers or rivers meandering within narrow, stable meander belts on deltaic and alluvial plains. Upsection, within the overlying Elk Formation, coal seams become thinner, the ratio of interchannel to channel deposits decreases, and channel deposits become coarser grained and more laterally continuous, suggesting a change in channel morphology to high sinuosity, meandering or braided, and sedimentation on more proximal parts of an alluvial plain. The overlying strata of the basal Blairmore Group are conglomeratic, lack coal seams and plant remains, and contain red-weathering claystones, suggesting a change to a more arid climate, and sedimentation proximal to the mountain front on mid- to distal-portions of alluvial fans. Unconformities of unknown magnitude may be present on Mount Allan beneath the Pocaterra Creek Member (at the base of the Blairmore Group), and between the Pocaterra and the rest of the overlying Cadomin Formation. Blairmore strata overlying the Cadomin Formation are less conglomeratic and contain minor plant remains, suggesting a return to sedimentation on an alluvial plain.

As determined by vitrinite reflectance, coal ranks within the Mount Allan section range from semi-anthracite at the base to medium volatile bituminous at the top. Reflectance data for the section follow a second-order curve; that is, reflectance change per unit of depth is greater in the lower parts of the section. The section has higher rank values than several other sections within the Kootenay Group, but has similar reflectance gradients, with the exceptions of sections at Canmore, 12 km north of Mount Allan; Mist Mountain, 50 km southeast; and Line Creek, in the Upper Elk Valley. This suggests that the geothermal gradient at Mount Allan may have been similar to gradients at other widely separated localities in the Kootenay Group, and that variations in rank between these locations may be attributable to variations in sedimentary and tectonic loading, rather than to variations in geothermal gradient.

SOMMAIRE

Un profil houiller complet non déformé du groupe de Kootenay dont l'âge s'étend du Jurassique supérieur au Crétacé inférieur, est exposé sur la face nord-est du mont Allan près de Canmore, Alberta dans le bassin houiller Cascade. On doit noter que 1223 m de profil y compris 1038 m appartenant au groupe de Kootenay et 185 m du groupe superposé de Blairmore ont été mesurés et échantillonnés en détails. Les accidents sédimentaires ont été identifiés sur le terrain et aussi à partir d'échantillons analysés en laboratoire afin de déterminer les successions des faciès sédimentaires. Des échantillons de charbon pris sur plus de 873 m de profil montrent une gradation régulière du degré de métamorphisation à partir du semi-anthracite à la base jusqu'au charbon bitumineux mi-volatil au sommet.

Les groupes de Kootenay et Blairmore forment un biseau clastique s'épaississant vers l'ouest, les sédiments consituants proviennent de fronts orogéniques du sud-ouest et de l'ouest. La sédimentation a pris naissance par une progradation dirigée vers le nord-est de complexes deltaïques à prédominance ondulatoire dans la mer de Fernie formant, de ce fait, à la base, une couverture sableuse identifiée à la formation de Morrissey. Des marécages latéralement extensifs de la formation de Mist Mountain superposée et destinés à la formation du charbon, se sont développés au-dessus de ce sable à plusieurs endroits, à l'intérieur d'un milieu de plaine côtière et de plaine deltaïque inférieure. Des dépôts entre les chenaux d'origine, des dépôts de crevasse, des dépôts lacustres, des bourrelets et des marécages prédominent dans la formation de Mist Mountain. Des dépôts de chenaux affinent vers le haut de la formation; ceux-ci sont lenticulaires dans l'affleurement orienté vers le sud-est, le long de l'axe du mont Allan, ce qui indique qu'ils forment des corps sableux configurés en "lacet de chaussure", lorsqu'ils sont étudiés en perspective de plan. D'ailleurs, ils se sont déposés par des rivères à basse sinuosité ou par des rivières qui serpentaient en dedans des zones de méandres étroits et stables à l'intérieur des plaines deltaïques et alluviales. Vers le haut du profil à l'intérieur de la formation d'Elk superposée, les filons houillers deviennent plus minces, le rapport des dépôts entre les chenaux à des chenaux diminuent, et les dépôts des chenaux sont à plus gros grains et plus continus latéralement, ce qui indique un changement de morphologie de chenal caractérise par des méandres à sinuosité élevée et une sédimentation sur des régions partiellement éloignées à plus éloignées. Des discordances de grandeur inconnue sont présentes au mont Allan au-dessous du membre de Pocaterra (à la base du groupe de Blairmore) et entre le membre de Pocaterra et le reste de la formation de Cadomin superposée. Les couches de Blairmore qui recouvrent la formation de Cadomin sont moins conglomérées et contiennent moins de matières végétales, ce qui indique un retour à un régime sédimentaire sur la plaine alluviale.

Les degrés de métamorphisation du charbon déterminés par la réflectance vitrinite du profil du mont Allan, fait que ce charbon passe de semi-anthracite à la base à un charbon mi-bitumineux au sommet. Les données relatives à la réflectance pour le profil suivent une courbe de second ordre; ce qui fait, que le changement de réflectance par unité de profondeur est plus élevé dans les parties inférieures du profil. Le profil a les degrés les plus élevés que la plupart des autres profils du groupe de Kootenay, mais possède des gradients de réflectance semblables, à l'exception des profils situés à Canmore, à 12 km au nord du mont Allan, de ceux du mont Mist, à 50 km au sud-est du ruisseau Line dans la haute vallée de l'Elk. Ces costatations suggèrent que le gradient géothermique au mont Allan est peut-être semblable aux gradients d'autres localités éloignées les unes des autres du groupe de Kootenay et ces variations du degré de métamorphisation entre ces localités sont peut-être dues à des variations d'ordre sédimentaire et tectonique plutôt qu'à des variations du gradient géothermique.

The Mount Allan section lies in the immediate footwall of the Rundle Thrust and was overridden at one time by Paleozoic and possibly post-Paleozoic rocks in the hanging wall of this fault. A series of time-burial models were developed, incorporating assumptions about the thickness of post-Kootenay/pre-Laramide sediments, the thickness and position of the Rundle Thrust plate, and the timing of events. Theoretical reflectance values and gradients were calculated using the Lopatin techniques for each model, utilizing several geothermal gradients. Curves relating reflectance to geothermal gradients were developed for each model and used to calculate the geothermal gradients required to produce the ranks observed in the section. By comparing the degree of similarity between geothermal gradients calculated from two observed rank values and the rank gradient of the section, an assessment of the validity of each model was obtained.

The best correspondence to the observed rank data was achieved using a model with a maximum depth of burial of 4200 m and a maximum geothermal gradient of 4.3°C/100 m. This yields a maximum temperature for the lowermost coals of 200°C, a value in agreement with studies based on other lines of evidence.

Le profil du mont Allan se trouve dans la lèvre inférieure et immédiate de la faille inverse de Rundle et antérieurement, le profil du mont Allan était recouvert de roches paléozoïques et probablement post-paléozoïques à la lèvre supérieure de cette faille. Une série de modèles "chronologie-enfouissement" a été conçue de telle sorte qu'elle inclut des hypothèses au sujet des sédiments post-Kootenay à pré-Laramide, l'épaisseur et la position de la plaque de butée de la faille inverse de Rundle et la succession chronologique des événements. Les valeurs de la réflectance théorique et des gradients ont été calculées à partir des méthodes de Lapatin pour chacun des modèles utilisant plusieurs gradients géothermiques. Les courbes reliant la réflectance aux gradients géothermiques ont été adaptées pour chaque modèle et utilisées pour le calcul du gradient géothermique requis pour donner les degrés de métamorphisation observés dans le profil. En comparant la similarité entre les gradients géothermiques calculés à partir des deux valeurs du degré de métamorphisation et à partir du gradient du degré de métamorphisation, ceci permet une évaluation de la valeur de chacun des modèles.

La meilleure correspondance aux données du degré de métamorphisation observées s'est réalisée en utilisant un modèle à profondeur d'enfouissement maximum de 4,3°C/100 m. Ceci donne une température maximum de 200°C pour des charbons plus inférieurs, valeur qui concorde avec des études basées sur des entités similaires.

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Abstract

A complete, undeformed outcrop section comprising 1038 m of coal-bearing, Jurassic-Lower Cretaceous Kootenay Group and 185 m of overlying Blairmore Group strata was measured and sampled in detail on the northeast face of Mount Allan near Canmore, Alberta. Sedimentary structures, lithologic composition and vertical sequences of lithologies were used to identify depositional environments. Coal rank data were utilized to determine the post-depositional burial history of these strata.

Sedimentation commenced with deposition of a tabular sheet sand (Morrissey Formation) by northeastward prograding, wave-dominated delta systems. Overlying coal-bearing strata of the Mist Mountain Formation accumulated in coastal, deltaic and alluvial plain settings within fluvial channel, crevasse-splay, lacustrine, levee and swamp-marsh depositional subenvironments. Within the Elk Formation sedimentation by fluvial processes occurred on more proximal parts of an alluvial plain. Overlying conglomeratic sediments of the basal Blairmore Group accumulated proximal to the source on mid- to distal-portions of alluvial fans.

Coal rank data for the section follow a second order curve and coals range from semianthracite at the base to medium volatile bituminous at the top. A comparison of rank gradients indicates absolute differences in rank between Kootenay sections may be attributable to variations in geologic and burial history rather than to variations in geothermal gradient, as proposed by earlier workers. High ranks at Mount Allan may be related to loading by the Rundle Fault Plate. Models incorporating assumptions about the geothermal gradient and burial history indicate maximum temperatures reached by the lowermost coals were about 200° Celsius.

Keywords: Coal, Sedimentation, Clastic Depositional Environments, Coal Rank, Burial Models, Kootenay Group, Cascade Coal Basin, Vitrinite Reflectance.

Résumé

Un profil houiller complet et non déformé qui comprend 1038 m de couches du Jurassique-Crétacé inférieur et 185 m de couches du groupe de Blairmore susjacent a été mesuré et échantillonné en détails sur la face nord-est du mont Allan près de Canmore en Alberta. Les structures sédimentaires, la composition lithologique et des séquences verticales ont été utilisées pour l'identification de la sédimentation du milieu. Les données relatives au degré de métamorphisation du charbon ont été utilisées pour la détermination de la phase d'enfouissement post-sédimentaire de ces strates.

La sédimentation a commencé par le dépôt de sable tabulaire (formation de Morrissey) en progradation dirigée vers le nord-est suivant des complexes deltaïques ondulatoires. Des dépôts de plaines côtières et de plaines deltaïques se sont développés dans divers milieux de sédimentation, dont les chenaux fluviaux, les crevasses, les milieux lacustres, les levées et les zones marécageuses. En ce qui a trait à la formation sédimentaire fluviatile d'Elk, elle apparaît sur davantage de zones proximales de la plaine alluviale. Les sédiments conglomératiques superposées du groupe de Blairmore se sont déposées sur des portions moyennes et rapprochées des cônes de déjection.

Les données relatives au degré de métamorphisme du charbon pour ce profil suit une courbe de second ordre et de telle sorte que les charbons passent de semi-anthracite à la base à des charbons bitumineux à volatilité moyenne au sommet. Une comparaison des gradients du degré de métamorphisation indique de nettes différences dans le métamorphisme entre les profils de Kootenay, ceci peut-être attribué aux caractéristiques géologiques et aux phases de sédimentation plutôt qu'à des variations du gradient géothermique, hypothèse antérieurement proposée. Les degrés de métamorphisation élevés au mont Allan sont peut-être liés à la pesanteur due à la plaque faillée de Rundle. Les modèles d'étude impliquant le gradient géothermique et les phases de sédimentation indiquent un maximum de température de 200°C pour des charbons situés plus en profondeur.

Mots clés: charbon, sédimentation, milieux de sédimentation clastique, degré de métamorphisation, modèles d'enfouissement, groupe de Kootenay, Bassin houiller Cascade, réflectance vitrinite.

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INTRODUCTION

The Late Jurassic to Early Cretaceous Kootenay Group, long important for its commercial coal deposits, is well exposed on the northeast face of Mount Allan, 12 km southeast of Canmore, Alberta, in the Cascade Coal Basin (Fig. 1). This section is unique in that coal-bearing lower and middle Kootenay strata, which at most other localities are poorly exposed and/or deformed, due to their recessive, structurally incompetent nature, are well exposed for a strike length of 2 km, with only minor structural complications.

The Mount Allan section was measured and described during the 1972 field season, at which time 1108 samples were collected. Small scale sedimentary structures, which in the field were often obscured by the highly weathered nature of these rocks, were visible on slabbed surfaces of many of these samples. Thirty-eight coal samples, collected over an 873 m stratigraphic interval, show a regular gradation from semi-anthracite rank at the base to medium volatile bituminous rank at the top.

The purpose of this report is to describe the lithologic succession on Mount Allan from the base of the Kootenay Group to the lower part of the overlying Blairmore Group, to review inferences regarding the depositional setting of these strata, and to present the coal rank data, which may provide a reference coalification curve for this area.

This report is based on fieldwork conducted by J.D. Hughes in 1972 during the preparation of an M.Sc. thesis at the University of Alberta, and subsequent studies. A.R. Cameron performed all rank determinations and calculations for the time-burial models and wrote most of the section on coal rank variations. The geological scenarios utilized in the coal rank section and their implications on coalification history are based on discussions between Hughes and Cameron over the past several years.

Acknowledgments

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Thanks are also extended to Carol Boonstra, of the Institute of Sedimentary and Petroleum Geology, who drafted several of the figures, and to W.B. Sharman, of I.S.P.G. photography unit, for his patience in working with numerous much-less-than-perfect photographs.

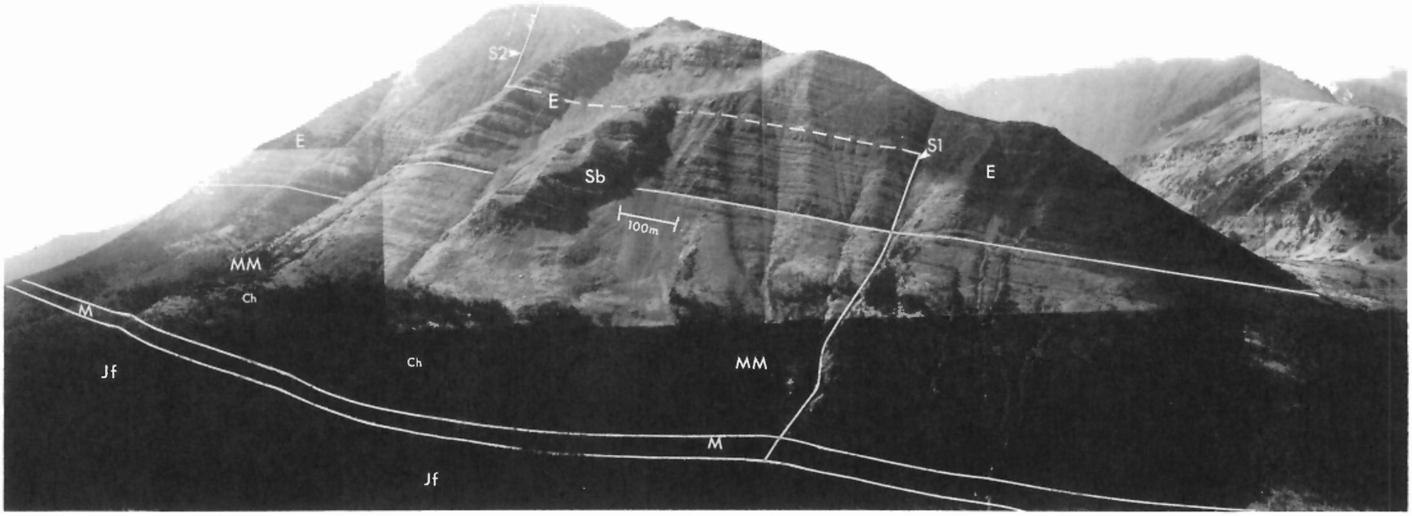


Figure 1. *Northeast face of Mount Allan, viewed from Pigeon Mountain. Jf = Fernie Formation; M = Morrissey Formation; MM = Mist Mountain Formation; E = Elk Formation; S1, S2 = segments 1 and 2 of measured sections; Sb = slump block; Ch = sandstone unit referred to in text; dashed line indicates bed traced to Segment 2.*

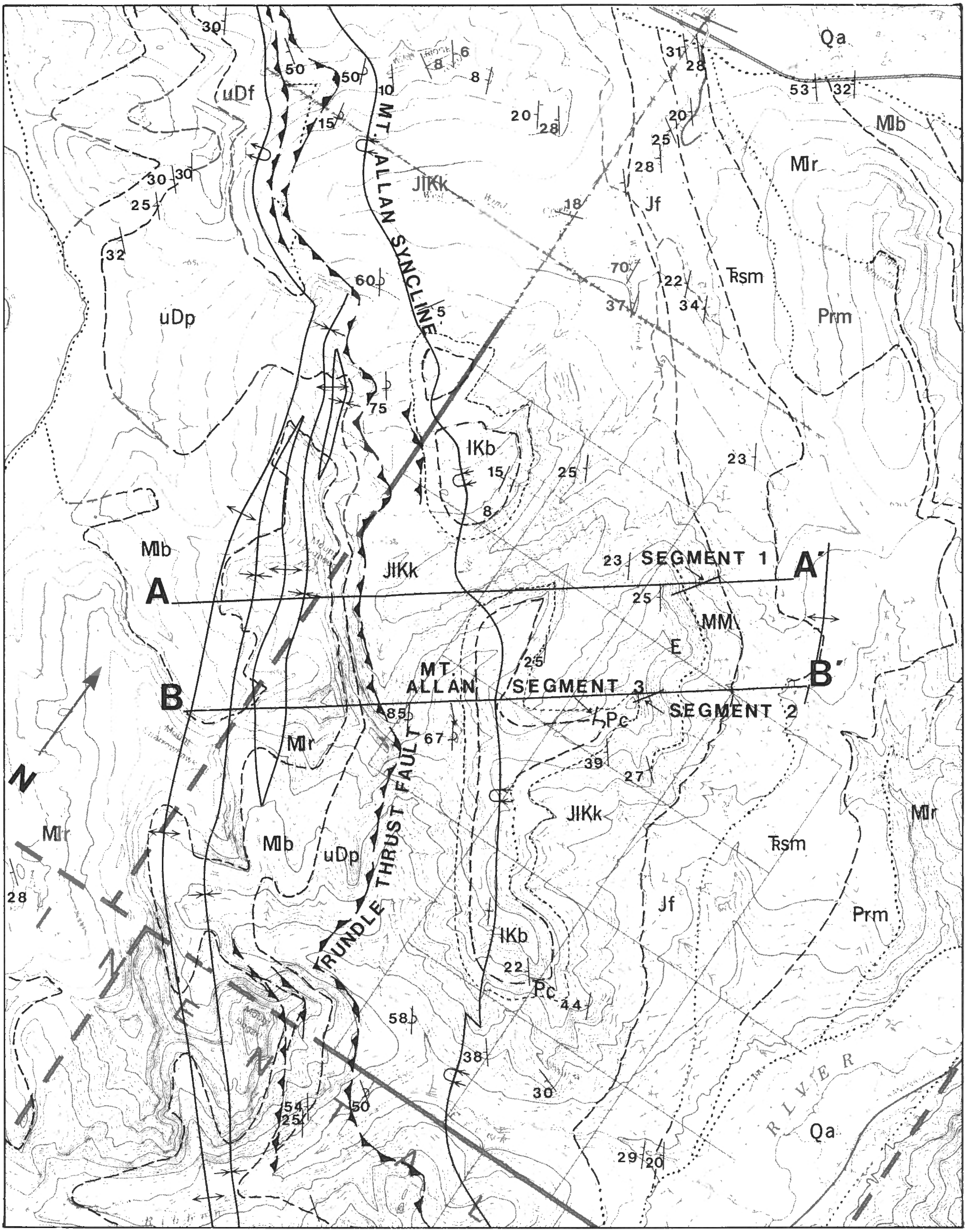
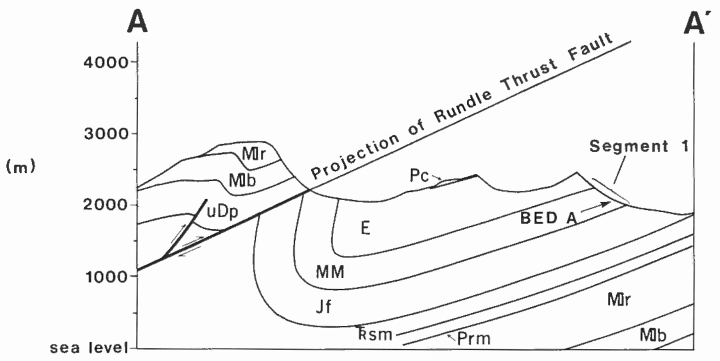
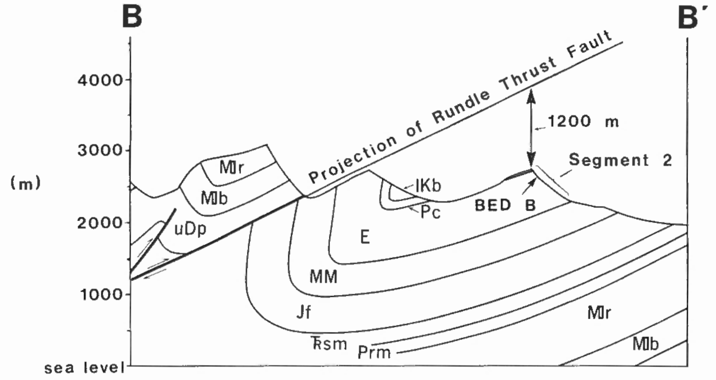


Figure 2. Geological map and cross-sections of the Mount Allan area, showing location of the three measured section segments. Kootenay Group subdivisions are labelled as in Figure 1. The plane of the Rundle Thrust Fault has been projected at 25° in cross-sections A-A' and B-B' to determine its former position above the measured section. Beds A and B refer to coal seams discussed in text. Geology after Bielenstein (1969) and Price (1970); boundaries of Elk and Mist Mountain formations and Pocaterra Creek Member added by Hughes.





LEGEND

(cross-sections and geological map)

QUATERNARY

Qa	Till, gravel, silt

LOWER CRETACEOUS

lKb	BLAIRMORE GROUP: sandstone, siltstone, mudstone, basal conglomerate
Pc	POCATERRA CREEK MEMBER: sandstone, siltstone, shale, conglomerate. Included in Blairmore Group by Allan and Carr (1947).

JURASSIC AND LOWER CRETACEOUS

JlKk	KOOTENAY GROUP: sandstone, siltstone, mudstone, coal

JURASSIC

Jf	FERNIE FORMATION: shale, limonitic siltstone and sandstone

TRIASSIC

TRsm	SULPHUR MOUNTAIN FORMATION: dark grey siltstone, silty mudstone, shale

PERMIAN AND PENNSYLVANIAN

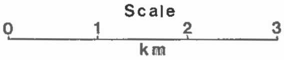
Prm	ROCKY MOUNTAIN GROUP: sandstone, arenaceous dolomite, massive chert

MISSISSIPPIAN

Mr	RUNDLE GROUP: limestone and dolomite
Mb	BANFF FORMATION: dark to light grey limestone, dark grey shale

UPPER DEVONIAN

uDp	PALLISER FORMATION: massive, mottled dolomitic limestone
uDf	FAIRHOLME GROUP: dark to light grey, crystalline dolomite



(Conventional structure symbols used)

Previous work

Coal mining began in the Cascade Coal Basin in the early 1880's with the opening of seams along the Cascade River near Banff (Dawson, 1886), and has been more or less continuous until the closure of Canmore Mines Ltd. in July, 1979. Early workers in the basin included Dawson (1886), Dowling (1907), MacKay (1934) and Allan (1943). Crockford (1949) measured the Kootenay section on Mount Allan, as did Norris (1957), although the latter dealt mainly with the structure of the mining area near Canmore, some 10 to 15 km northwest. Coal rank variations within the mining area and regionally within the Kootenay Group are discussed by Norris (1971) and Hacquebard and Donaldson (1974). Regional studies of the lithostratigraphy, sedimentology and depositional setting of the Kootenay Group include those of Norris (1964), Rapson (1964, 1965), Jansa (1971, 1972) and Gibson (1977a, b, 1979, and in press).

STRATIGRAPHY

Geological setting

The Cascade Coal Basin comprises a linear, northwest-trending area about 70 km long, underlain by the coal-bearing Kootenay Group (Norris, 1971). Kootenay strata in the basin are flanked on the southwest by Cambrian, Devonian and Mississippian carbonates in the hanging wall of the Rundle Thrust, and on the northeast by homoclinal Jurassic, Triassic and Paleozoic strata (figs. 2, 3). The Rundle Thrust cuts downsection along strike in its footwall to the northwest and southeast of Mount Allan, progressively truncating Kootenay strata toward the extremities of the basin.

The Mount Allan section is in the northeast limb of a major northeastwardly overturned fold, the Mount Allan Syncline, which lies parallel to and in the immediate footwall of the Rundle Thrust (figs. 2, 3, 4). Blairmore Group strata, which form the core of this fold on Mount Allan and the ridges immediately to the northwest (Fig. 2), are the youngest rocks preserved in the Cascade Coal Basin. Strata east of this synclinal axis form a southwest-dipping (25°-35°) homocline, and include rocks as old as Devonian underlying Pigeon Mountain to the northeast, in the hanging wall of the Lac des Arcs Thrust. Structural disturbance within the section is limited to a small, southwest-dipping thrust fault in the lower Blairmore Group, which repeats about 10 m of strata, and a southwest-trending, high angle fault, with about 15 m of apparent normal displacement, in the upper part of the Kootenay Group (Fig. 5). The remainder of the section is essentially undisturbed.

The structural geology of the coal measures in the mining area near Canmore is complicated by numerous folds and faults (Norris, 1957, 1971), and the stratigraphic order and separation of coal seams there is understood only because of the extensive subsurface data available from mining and drilling.

The Rundle Thrust is a major structural feature in the area, and it may have had a significant effect on the coalification history of the basin (Fig. 4). Lateral displacement on this fault, measured from a section at Three Sisters Mountain (Price, 1970), about 10 km northwest of Mount Allan, is in the order of 7 km, with the hanging wall block moved northeastward relative to footwall strata. Cross-sections by Bielenstein (1969) at Mount Lougheed and Ribbon Creek, about 3.4 km and 4.8 km northwest and southeast of Mount Allan respectively, suggest a similar amount of displacement. Estimates of the dip on the fault plane at the present topographic surface vary from 35-40° southwest at Ribbon Creek (Crockford, 1949), through 35° southwest at Three Sisters Mountain (Price, 1970), to 26° and 7° southwest at Mount Lougheed and Ribbon Creek respectively (Bielenstein, 1969).

If these estimates of fault plane orientation and displacement are correct, it is apparent that Kootenay Group rocks within the Cascade Coal Basin were at one time overridden by Paleozoic and Mesozoic rocks in the hanging

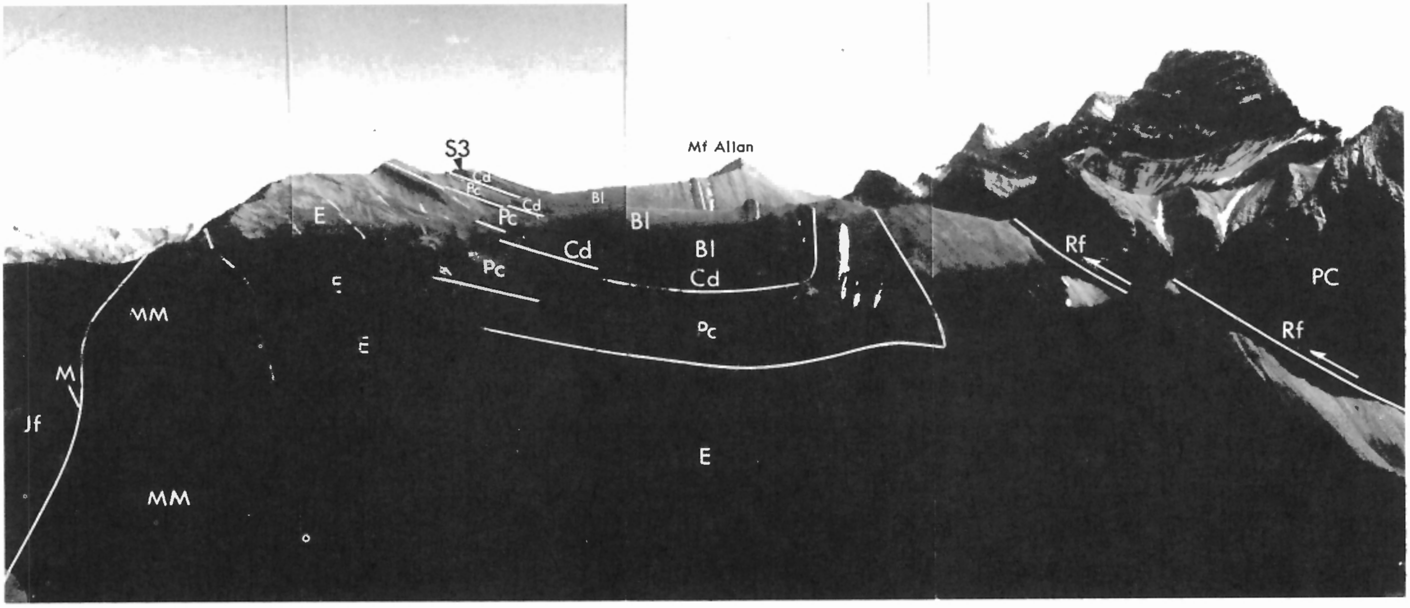


Figure 3. Mount Allan viewed from Wind Ridge (about 7 km northwest), along axis of Mount Allan Syncline, showing major structural features and location of Segment 3 (S3) of measured section. Labelled as in Figure 1; Pc = Pocaterra Creek Member; Cd = Cadomin-equivalent conglomerates; Bl = undifferentiated Blairmore Group; PC = Paleozoic rocks in hanging wall of Rundle Fault; Rf = Rundle Fault.

Figure 4. *Rundle Thrust Fault and hanging wall plate viewed toward northwest from summit of Mount Allan. Vertical and overturned Kootenay and Blairmore strata form the immediate footwall in the foreground. The fault plane is defined by the contact between light-coloured Paleozoic carbonates and vegetated, darker coloured Kootenay Group rocks on the right.*

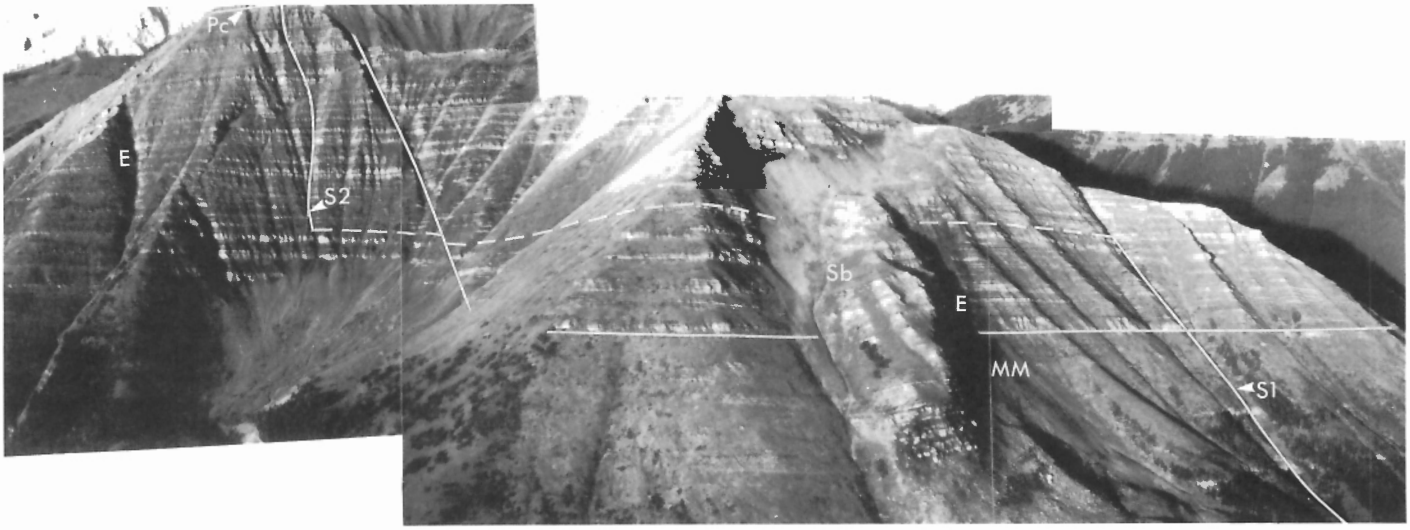


Figure 5. *Aerial view of northeast face of Mount Allan showing slump block, segments 1 and 2 of the measured section, and the traverse line between the segments. A fault with apparent normal displacement offsets the traverse line near Segment 2. Strike length along face is about 2 km. Labelled as in Figure 1.*

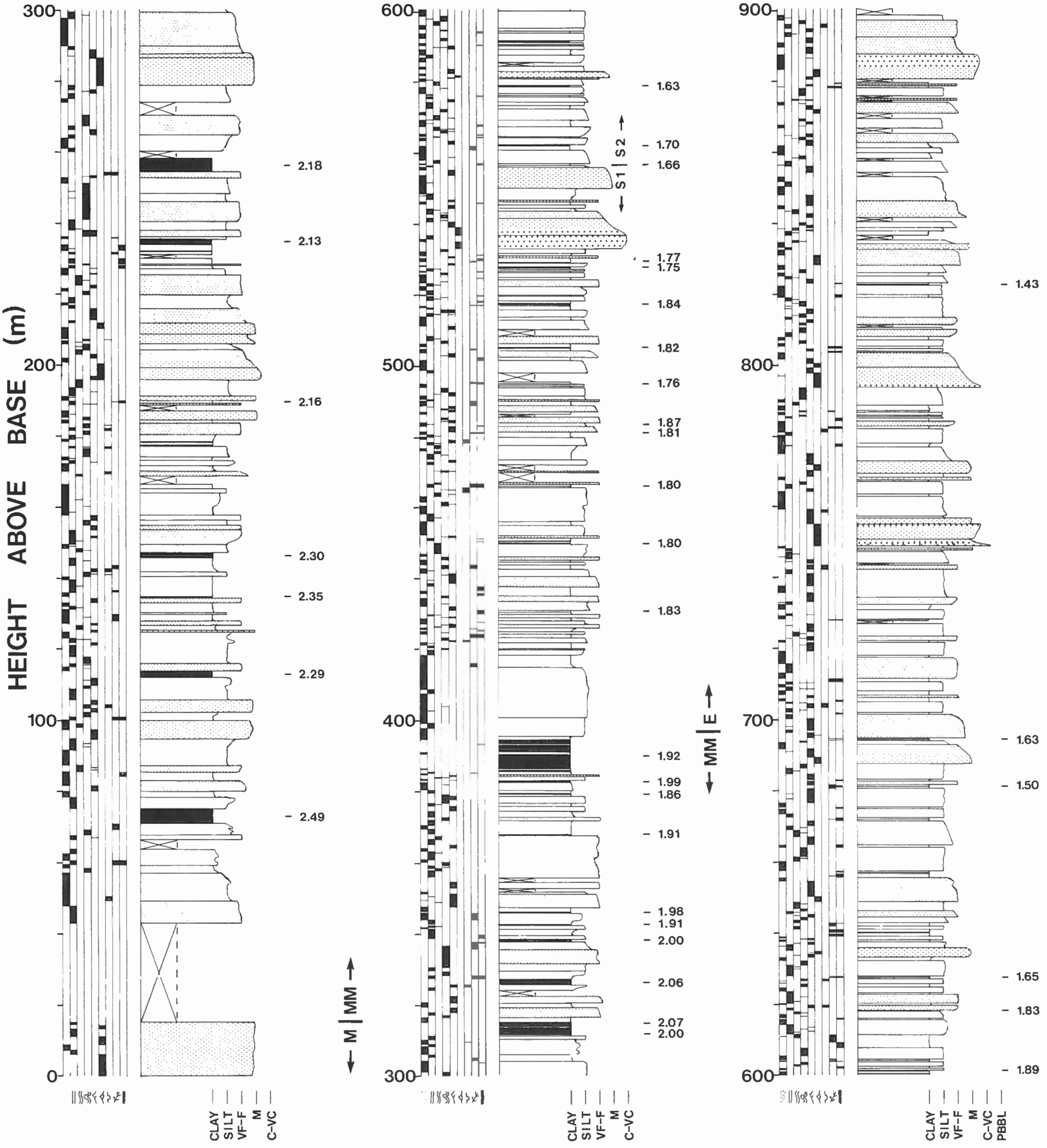
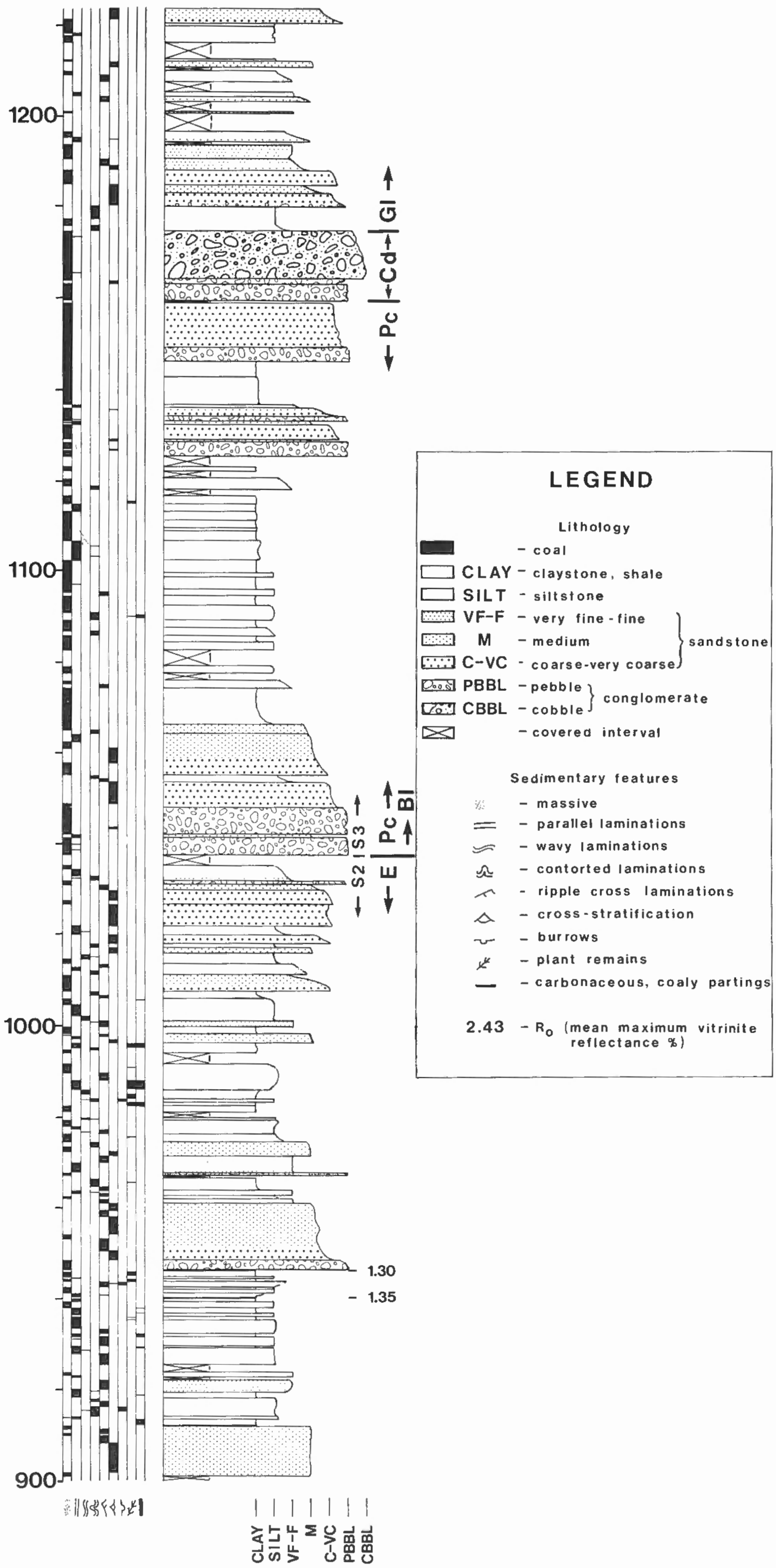


Figure 6. *Geological section on Mount Allan measured at locations shown in Figure 2. Pc = Pocaterra Creek Member of Allan and Carr (1947); Cd = equivalent to Cadomin Formation of McLean (1977) farther north; Gl = undifferentiated overlying strata of Gladstone Formation of Mellon (1967). Pocaterra Creek Member and overlying strata are included in Blairmore Group (Bl). Section segments and remaining formations are labelled as in figures 1, 2, 3. Numbers at right are mean maximum vitrinite reflectance values, in per cent, for coal and carbonaceous beds. Columns at left include data from samples collected at 1.5 m intervals and at all major lithologic breaks. Some units contain interbedded lithologies.*


1200
1100
1000
900
Pc
Cd
Gl
S2
S3
E
Pc
Bl
1.30
1.35
CLAY
SILT
VF-F
M
C-VC
PBBL
CBBL
LEGEND
Lithology
- coal
CLAY - claystone, shale
SILT - siltstone
VF-F - very fine-fine
M - medium
C-VC - coarse-very coarse
sandstone
PBBL - pebble
CBBL - cobble
conglomerate
- covered interval
Sedimentary features
- massive
- parallel laminations
- wavy laminations
- contorted laminations
- ripple cross laminations
- cross-stratification
- burrows
- plant remains
- carbonaceous, coaly partings
2.43 - R$_o$ (mean maximum vitrinite reflectance %)

wall of the Rundle Thrust. The thickness of this overriding fault plate would presumably have been variable, with the thickest values occurring near the present outcrop trace of the fault and progressively thinner values occurring to the northeast, reflecting the observed tendency for thrust faults to cut upsection in both hanging wall and footwall rocks in the direction of hanging wall displacement (Bally et al., 1966). The hanging wall plate is estimated to have been at least 2500 m thick above the Mount Allan section. This estimate is based on the assumption that the plate comprised all stratigraphic units between the Mississippian Rundle Group and the base of the Blairmore Group, and that these units were similar in thickness to those presently observed in the area. If a dip of 25° southwest on the fault plane is assumed at Mount Allan, the projected former position of the fault plane is approximately 1200 m above the uppermost part of the Kootenay Group in the Mount Allan section and 2300 m above the base of the section (Fig. 3). The effect of loading by this fault plate on the coalification history of the basin is examined in the final section of this report.

Nomenclature

The Kootenay Group conformably overlies the marine "Passage Beds" of the Jurassic Fernie Formation and is overlain, in places disconformably, by strata of the Lower Cretaceous Blairmore Group.

The nomenclature of Kootenay strata has been recently revised (Gibson, 1979), with the former Kootenay Formation being raised to group status, and subdivided into three formations. The Morrissey Formation at the base of the group comprises two members. The lower, termed the Weary Ridge Member, is approximately 7.5 m thick on Mount Allan. The upper, termed the Moose Mountain Member, is about 15.5 m thick. The Mist Mountain Formation contains the coal-bearing portion of the succession, and includes about 380 m of strata between the top of the Morrissey Formation and a prominent change in lithology associated with a topographic break above the uppermost major coal seam. This break defines the contact between the Mist Mountain and the overlying Elk Formation (Gibson, 1979). The Elk Formation includes the remaining, essentially non-coal-bearing strata of the group, and is about 643 m thick on Mount Allan.

At Mount Allan, the Blairmore Group consists of: the Pocaterra Creek Member of the Cadomin Formation at the base, a 120 m-thick unit previously recognized only at Mount Allan and in the Highwood-Elbow area to the south (Allan and Carr, 1947), but which has recently been reported in the Crowsnest Pass area (Gibson, 1977); thick, resistant conglomerate beds equivalent to the Cadomin Formation of McLean (1977), which at most other localities form the basal unit of the group; and overlying less resistant strata of the Gladstone Formation (Mellon, 1967). Only the lower portion of the Blairmore Group has been preserved within the core of the Mount Allan Syncline (figs. 2, 3).

Geological section

The stratigraphic section shown in Figure 6 comprises three partial sections, which were measured on the northeast face and along a ridge crest near the summit of Mount Allan (figs. 1, 2) at locations previously described by Hughes (1978). The section includes 1225 m of strata from near the base of the Moose Mountain Member to the lower Gladstone Formation. The more resistant Elk Formation is almost completely exposed for a distance of 2 km along strike, whereas underlying Mist Mountain strata are partially covered over this distance and exposure of the "Passage Beds" of the underlying Fernie Formation is limited to major creek gullies (figs. 1, 5). Segment 1 of the section comprises Morrissey, Mist Mountain and lower Elk strata, which were measured near the northwest end of the area of exposure (figs. 1, 5, 7). Segment 2 includes overlying Elk Formation strata which were measured within the headwall of the cirque about 2 km to the southeast of Segment 1 (figs. 1, 5, 8). A major slump block of Elk Formation strata, which could be mistaken for in place material because of its coherent nature and similar bedding attitude, occurs between segments 1 and 2 (figs. 3, 5). This block has dropped approximately 100 m downslope from its original position. The top of a sandstone bed which was traced along strike to connect segments 1 and 2, lies within unaffected Elk strata in the headwall of the slump scarp (Fig. 5). Segment 3 of the section consists of lower Blairmore Group strata from the base of the Pocaterra Creek Member to the lower Gladstone Formation, and was measured along and on the northwest side of the ridge crest above the cirque section (figs. 2, 3, 9).

LITHOLOGY

Morrissey Formation

On Mount Allan the Morrissey Formation comprises 23 m of fine- to medium-grained sandstone, subdivided by Gibson (1979) into a lower Weary Ridge Member (7.5 m thick), and an upper Moose Mountain Member. Sandstones of the Weary Ridge Member are slightly argillaceous, moderately sorted and parallel laminated to massive with minor ripple crosslaminations. Hamblin and Walker (1979) reported low angle scours and rare burrows within this unit. Sandstones of the Moose Mountain Member are better sorted, more siliceous and resistant, and contain small- to medium-scale trough cross-stratification with minor parallel laminated beds. The contact between the two members is sharp and locally scoured. The lower contact of the Morrissey Formation is sharp and overlies the "Passage Beds" of the upper Fernie Formation, a thick coarsening-upward sequence of interbedded siltstone, shale and sandstone, which has recently been studied in detail by Hamblin and Walker (1979). The upper contact of the Morrissey Formation is not exposed at the section location, however, at localities farther south it is reported to be sharp and is commonly directly overlain by coal or carbonaceous rocks (Gibson, 1977b).

Although only the Moose Mountain Member of the Morrissey Formation is shown on the lithologic section in Figure 6, the underlying Weary Ridge Member and the "Passage Beds" of the Fernie Formation are well exposed. Figure 10 illustrates the weathering nature, contact relationships and coarsening-upward character of these strata.

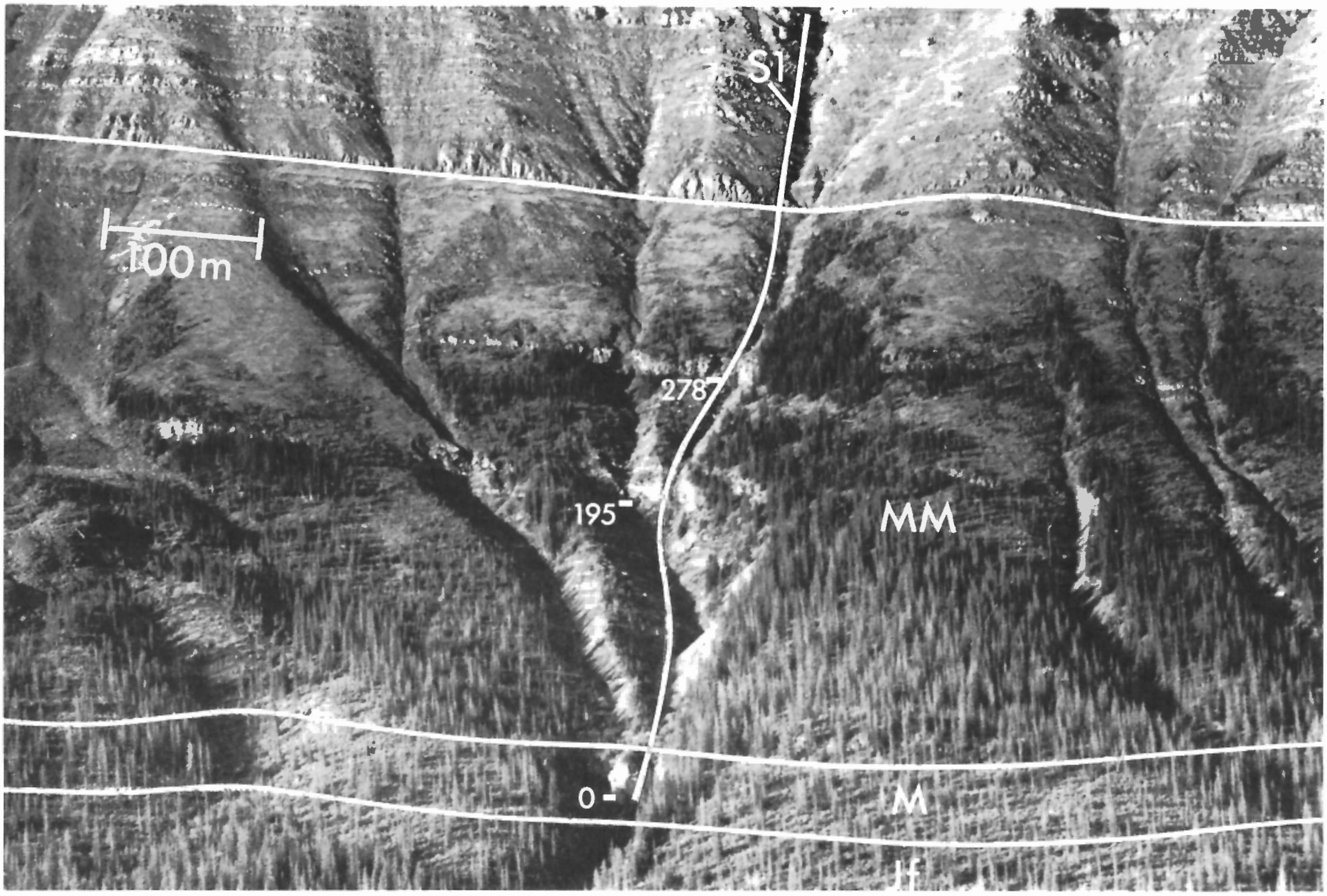


Figure 7. *Segment 1 of the measured section at Mount Allan, comprising Morrissey, Mist Mountain and lower Elk strata. Note lateral continuity of sandstone units in middle and lower parts of Mist Mountain Formation. Section interval measurements (see Fig. 6) of major sandstones are indicated. Labelled as in Figure 1.*

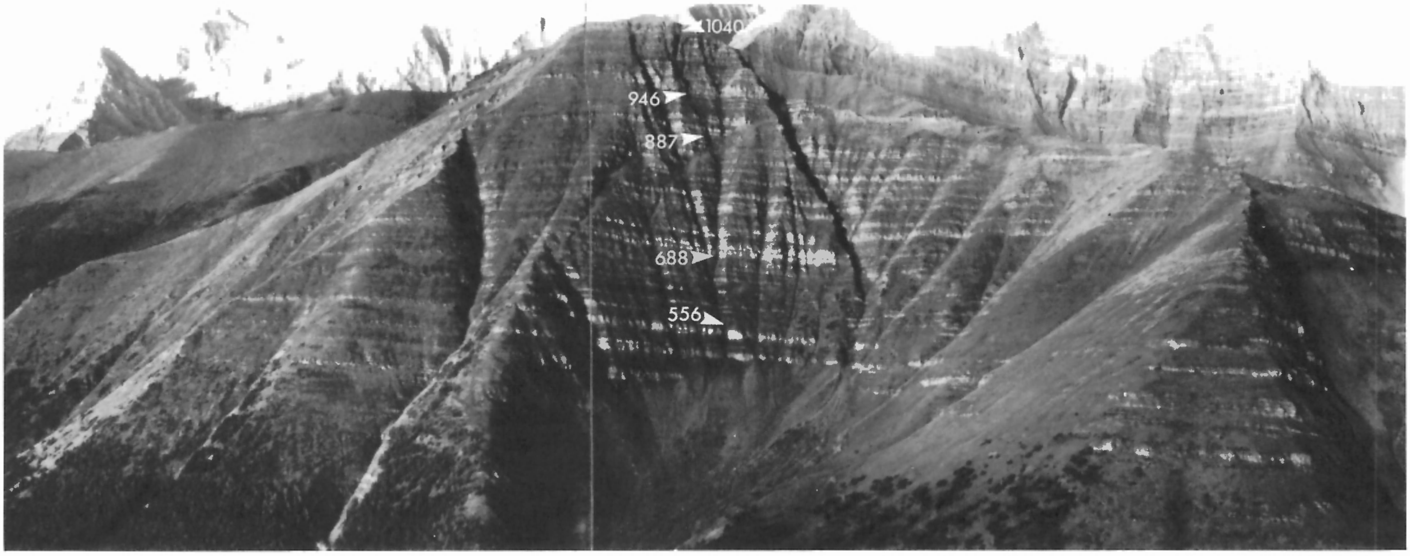


Figure 8. *Segment 2 of the measured section at Mount Allan comprising Elk Formation strata. Section measurements (see Fig. 6) for segment limits and some of the major sandstone units are indicated. Note lateral continuity of some of the light-coloured sandstone units, and their relative scarcity as compared to the darker coloured, finer grained units.*

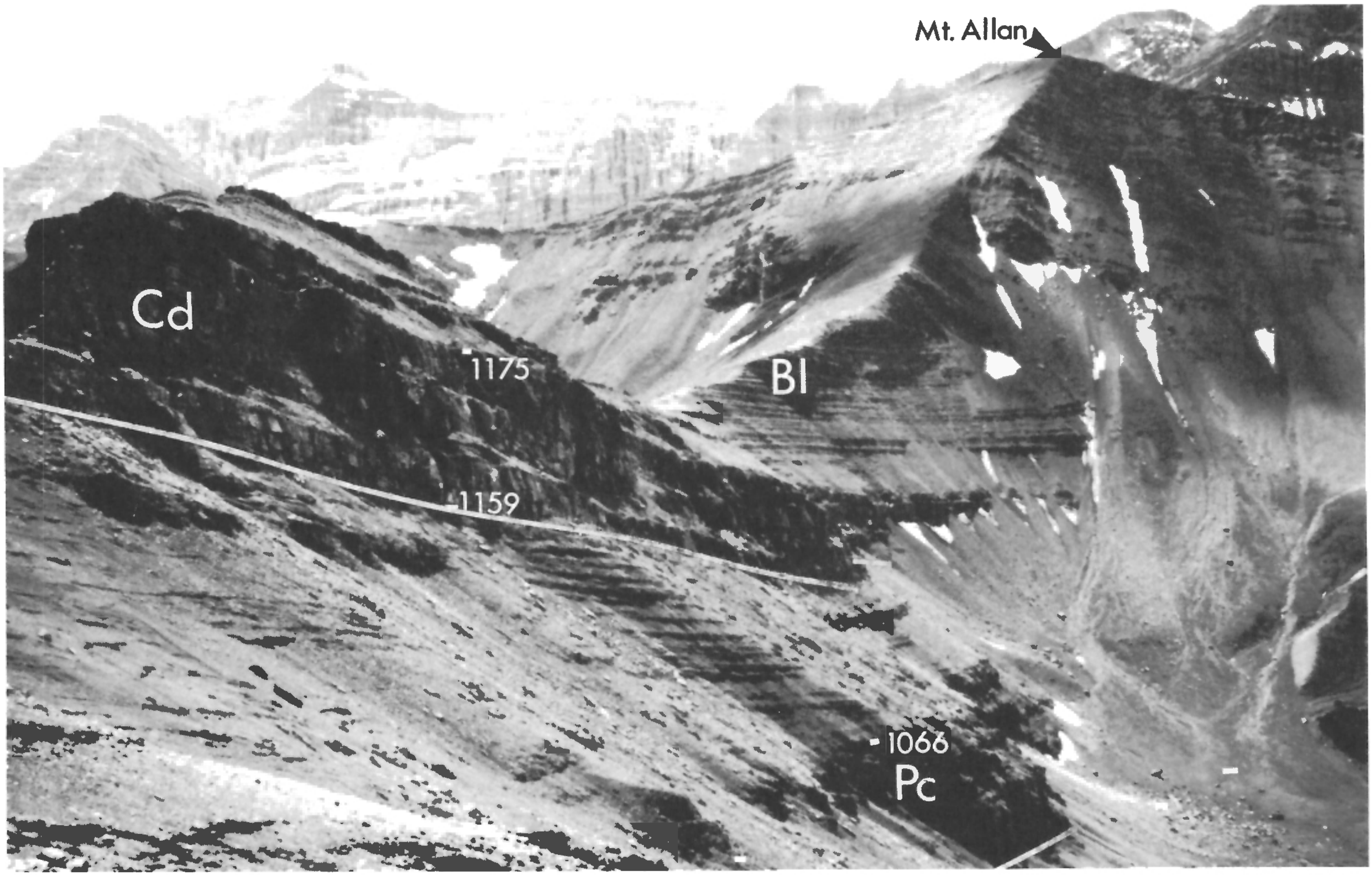


Figure 9. *Segment 3 of the measured section at Mount Allan, comprising Pocaterra Creek Member (Pc), Cadomin equivalent conglomerates (Cd), and overlying strata of the Blairmore Group (Bl). Numbers correspond to section measurements in Figure 6.*

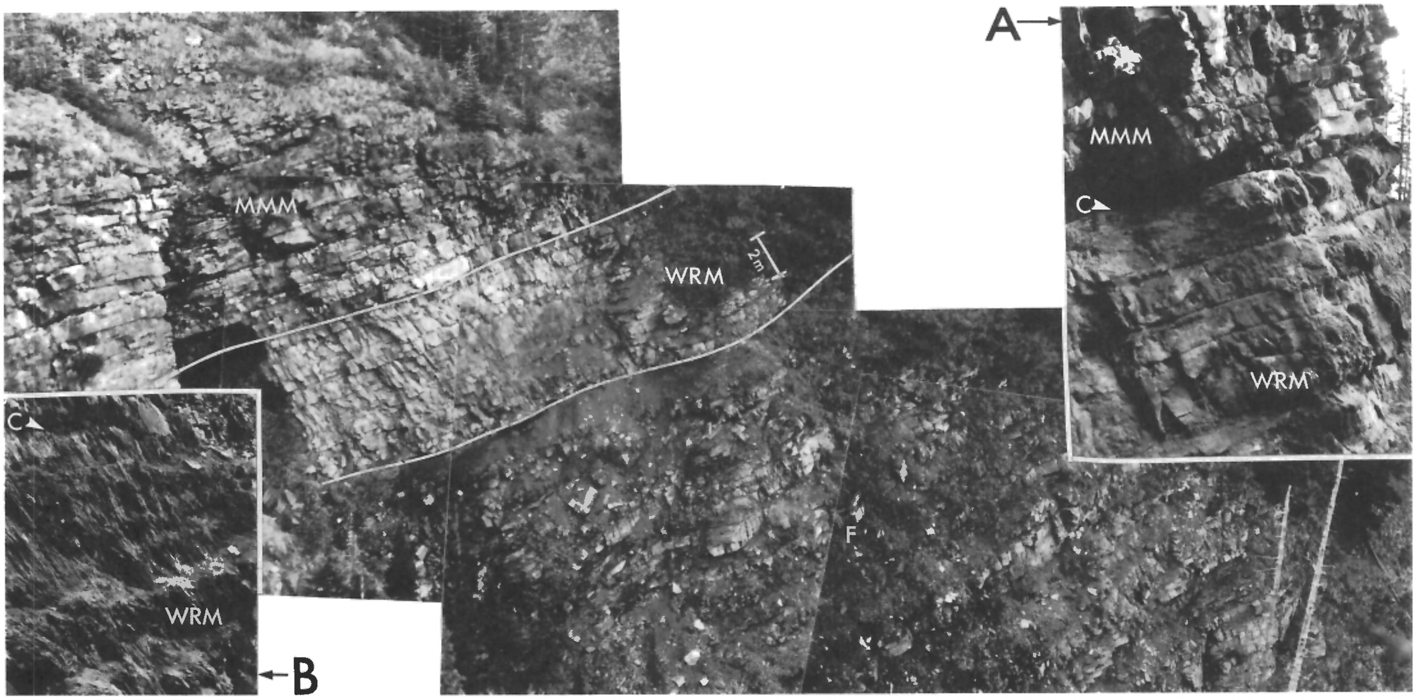


Figure 10. *Morrissey Formation and underlying "Passage beds" of Fernie Formation. MMM = Moose Mountain Member; WRM = Weary Ridge Member; F = Fernie Formation. Inset A = MMM/WRM contact (C) and weathering character. Inset B = detail of WRM weathering character.*

Mist Mountain Formation

The Mist Mountain Formation is made up of 380 m of interbedded siltstone, sandstone, claystone and coal (figs. 1, 5, 7). Siltstone is the most abundant rock type, comprising approximately 34 per cent of the strata, followed by very fine grained sandstone (28%), claystone (14%), fine grained sandstone (10%), coal (9%), medium grained sandstone (4%) and coarse grained sandstone (1%). The contact between the Mist Mountain and the overlying Elk Formation is defined by Gibson (1979, p. 194) as "...the base of the first major sandstone or conglomerate above the last or uppermost major coal seam...". On Mount Allan, Gibson (pers. comm., 1979) placed this contact at a prominent topographic break above the uppermost major coal seam, a break which here coincides with the base of a 20 m thick siltstone bed (Fig. 6).

Claystones occur in beds ranging from a few centimetres to several metres in thickness. They vary from black to dark grey or grey on fresh surfaces and weather grey to grey-brown, with darker colours reflecting a higher content of carbonaceous matter. They are most commonly massive or parallel laminated, although wavy and contorted laminae and ripple crosslaminations occur. Massive beds commonly display a hackly weathering character and a subconchoidal fracture. Plant remains and carbonaceous or coaly partings are common; burrows are rare. Most beds are non-calcareous, although a few slightly- to very-calcareous claystones occur in the upper part of the formation.

Siltstones also occur in beds ranging from a few centimetres to several metres in thickness. They are generally slightly lighter in colour than claystones, ranging from dark grey to grey on fresh surfaces and weathering grey to grey-brown. Thicker beds are usually parallel laminated to massive; whereas thinner beds commonly display ripple crosslaminations and/or contorted laminations. Plant remains and carbonaceous or coaly partings are present but are generally less abundant than within the claystones. Burrows were noted in two beds. Most siltstones are slightly calcareous, although both non-calcareous and very calcareous beds are present. They are generally more calcareous toward the top of the formation.

Sandstones within the formation are commonly somewhat lighter in colour than the finer grained lithologies, ranging from grey to grey-brown to dark grey on fresh surfaces and from grey to grey-brown or light grey on weathered surfaces. They become more calcareous toward the top of the formation and less calcareous with increased grain size: very fine grained varieties are commonly slightly to very calcareous, whereas fine- and medium-grained varieties are non- to slightly-calcareous. Plant remains and carbonaceous or coaly partings are present in some of the finer grained sandstones but are less abundant than in the claystones and siltstones. Burrows are rare. Very fine- and fine-grained sandstones occur in thin beds within finer grained units, and as thicker beds lying gradationally on coarser sandstones. They very commonly display ripple crosslaminations and/or contorted laminations. Less common are massive, evenly laminated and wavy laminated beds. Medium- and coarse-grained sandstones occur in the lower portion of relatively thick fining-upward units with erosional basal contacts, and as rare, thinner beds. They are commonly massive or display ripple crosslaminations or small- to large-scale trough cross-stratification. Contorted and wavy laminae and parallel laminated beds are less common. Wood molds and casts are locally present in the thicker sandstone units.

Ten coal seams, ranging from 0.5 to 9 m in thickness, and numerous thinner seams and carbonaceous beds occur within the formation. Some of these coals are blocky and relatively undeformed whereas others are friable and weathered in outcrop. Numerous polished and slickensided surfaces visible in the latter at both mesoscopic and microscopic scales indicate extensive shearing.

The number of major coal seams and the thickness of the Mist Mountain Formation [using Gibson's (1979) definition] on Mount Allan differs from that within the mining area at Canmore, 12 km northwest, where Norris (1971) reported 15 seams greater than 0.5 m in thickness within the lower 500 m of the Kootenay Group. It is probable that lateral equivalents of the uppermost seams noted by Norris lie within the lower Elk Formation on Mount Allan, as the overall thickness of Kootenay strata inferred for both areas is similar, and lateral variation in seam thickness is to be expected. The apparent change in thickness of the Mist Mountain Formation between these areas is thus a result of the arbitrary definition of its upper contact, which at the Mount Allan location is based on the position of the uppermost major coal seam rather than a significant change in depositional regime.

Elk Formation

The Elk Formation consists of 643 m of interbedded siltstone, sandstone, claystone, minor conglomerate and coal (figs. 1, 6, 8). The formation is more resistant and somewhat coarser grained than the underlying Mist Mountain Formation, particularly in its upper part. However, the predominant lithology is also siltstone (42%), followed by very fine grained sandstone (17%), claystone (14%), fine grained sandstone (10%), medium grained sandstone (9%), coarse- to very coarse-grained sandstone (5%), coal (2%), and pebble conglomerate (1%). Its contact with the overlying Blairmore Group lies at the base of an 11 m thick unit of pebble conglomerate and minor sandstone (Fig. 6).

Claystones occur in somewhat thinner beds than in the Mist Mountain Formation and are most abundant in the lower 250 m of the formation. They are similar in colour and weathering character to claystones of the Mist Mountain Formation. Massive beds predominate over parallel laminated varieties. A small proportion of beds display contorted or wavy laminations or ripple crosslaminations. Plant remains and coaly or carbonaceous partings are common. Slightly- to very-calcareous beds are most abundant in the lower part of the formation although most claystones are non-calcareous.

Siltstones are also similar in colour and weathering character to those in the Mist Mountain Formation. Contorted laminae and ripple crosslaminated and massive siltstone beds are generally more abundant than within the Mist Mountain Formation; whereas parallel laminated, coaly and carbonaceous siltstone beds are less abundant. Most siltstones are slightly- to very-calcareous, and non-calcareous beds are rare.

Sandstones are more abundant and include coarser grades than within the Mist Mountain Formation, and tend to be somewhat lighter in colour on both fresh and weathered surfaces. Medium- to very coarse-grained sandstones occur in units from 2 to 15 m in thickness, and are most abundant in the upper part of the formation. As in the Mist Mountain Formation, these units commonly have a fining-upward vertical profile and erosional bases, although reverse grading is evident in some beds. Pebble conglomerates are present at or near the base of some sandstone units near the top of the formation. Medium scale trough cross-stratified or massive beds are common in the middle and lower parts of these units; ripple crosslaminations, parallel and contorted laminations occur in the finer grained upper parts. Very fine- and fine-grained sandstones lie gradationally on coarser sandstones or occur as relatively thin beds bounded by finer grained units. They are very commonly ripple crosslaminated. Contorted laminae, parallel laminated and massive beds are less common. Wood molds and casts are present in some of the thicker sandstone units. A similarity to the sandstones of the Mist Mountain Formation is apparent: very fine grained sandstones are slightly- to very-calcareous; medium- to very coarse-grained sandstones are non-calcareous to slightly calcareous. All size fractions tend to be more calcareous in the lower part of the formation.

Conglomerates are a minor component of the formation and, with the exception of a thin bed at the 748 m level (Fig. 6), are confined to the uppermost 100 m of the formation. They occur in beds with erosional lower contacts overlain by coarse sandstone units, as previously mentioned, and as rare thin beds overlain by fine grained sandstone units. They are generally matrix supported. Clasts within the conglomerates are predominantly moderately well rounded, black and dark grey chert, with minor quartzite. Clasts rarely exceed 4 cm and average about 2 cm in diameter.

Blairmore Group

Blairmore Group strata exposed on Mount Allan include the basal Pocaterra Creek Member, the Cadomin Formation, and the lowermost 100 m of the Gladstone Formation, the lower 45 m of which are shown in Figure 6.

The Pocaterra Creek Member has not formally been included within the Cadomin Formation, or given formational status on its own, and thus is somewhat of an anomaly in Blairmore nomenclature. It was first defined by Allan and Carr (1947), who applied the name in the Highwood-Elbow area south of Mount Allan to strata below a quartzite-pebble conglomerate which they correlated with the "basal Blairmore conglomerate" or "Cadomin conglomerate" of other workers to the east and south. At this locality, these strata consist of a basal chert-pebble conglomerate, generally finer grained and with less quartzite than in the Cadomin, overlain by greenish-grey and maroon shales characteristic of Blairmore strata elsewhere. Allan and Carr suggested that, although there may have been minor erosion of uppermost Elk strata below the Pocaterra Creek Member (*op. cit.*, p. 29), there was evidence for major erosion of Pocaterra Creek Member strata on the erosion surface underlying the Cadomin, resulting in a southeasterly decrease in thickness from 112 m to 5.7 m.

The unconformity of greater magnitude in this area thus appears to correlate with the basal Blairmore unconformity elsewhere, and Pocaterra Creek Member strata are, as Allan and Carr pointed out (*op. cit.*, p. 29), ". . .earlier in age than any other strata assigned to the Blairmore [Group] in the foothills of southwestern Alberta. . .". Gibson (1979) has subsequently recognized the Pocaterra Creek Member in the Fernie area of southeastern British Columbia, where he included it with the Blairmore Group on the basis of (*op. cit.*, p. 783) ". . .very light grey, well-indurated quartz sandstone, olive-grey to reddish-brown siltstone and mudstone, and light- to medium-grey quartz-chert-pebble conglomerate. . ." which, with the exception of the conglomerate, is atypical of the underlying Elk Formation.

On Mount Allan, relationships within lower Blairmore strata are similar to those reported by Allan and Carr (1947) to the southeast. The Pocaterra Creek Member is readily recognized, and consists of a basal conglomerate, about 11 m thick (Fig. 6), overlain by 23 m of interbedded conglomerate and sandstone, 60 m of olive-grey to reddish weathering claystones with interbedded medium grey to light grey weathering siltstones, and an upper sandy and conglomeratic unit 34 m thick. The weathering character of these major units is illustrated in Figure 11. The conglomerates of the Pocaterra Creek Member are readily distinguished from those of the overlying Cadomin Formation (Fig. 12). Clasts are predominantly moderately to well rounded, dark grey to black chert with minor varicoloured cherts and quartzites. They are typically 2 to 3 cm in diameter, ranging up to 8 cm. In contrast, the Cadomin Formation conglomerate consists of up to 60 per cent light grey to white, moderately to well rounded quartzite clasts between 10 and 12 cm in diameter, ranging up to 16 cm, with subsidiary smaller clasts of black, dark grey and green chert and varicoloured cherts and quartzites. Mean clast size within the Cadomin Formation decreases to 3 cm near the top and 6 cm near the base. Except for their thickness, the conglomerate beds of the basal Pocaterra Creek Member are similar in composition and clast size to conglomerates of the underlying Elk Formation. This suggests that the magnitude of the hiatus beneath the Pocaterra Creek Member if present, is small compared to the unconformity which may be present at the base of the Cadomin. Thus the lithologic similarity of the finer grained rocks is the sole basis for including these strata within the Blairmore Group.

If the red weathering claystones within the Pocaterra Creek Member are related to oxidization of iron particles in an arid or semiarid environment (Walker, 1967), there must have been a gradual change in climate from the humid or temperate conditions associated with the coal-bearing Mist Mountain Formation. This is supported by the general lack of plant fragments and carbonaceous partings within the Pocaterra Creek Member and the upward decrease in abundance of thick coal seams within the underlying Elk Formation. A hiatus may be present between the Pocaterra Creek Member and the Elk Formation; alternatively, the erosion surface below the basal conglomerate may be the result of normal channel scouring, and Pocaterra Creek Member strata may represent the first appearance of semiarid conditions during a period of gradual climatic change and continued sedimentation. Overlying Cadomin Formation conglomerates indicate a change in the rocks exposed in the source area and sedimentation more proximal to the source, suggesting there may be a significant hiatus beneath them.

Pocaterra Creek Member strata are indeed caught in the middle: they are apparently removed to the east, along with Kootenay strata, by pre-Cadomin erosion, yet bear more lithologic resemblance to the Blairmore Group than to the underlying Kootenay Group. A solution may be to define them as a formation separate from either group. The Pocaterra Creek Member is currently being examined regionally by Ricketts and Sweet (in press) in an effort to resolve this problem.

Claystones occur in relatively thick beds in the middle of the Pocaterra Creek Member (figs. 6, 11). They weather dark grey through olive-grey to reddish brown and red, and are dark grey to light brown or red on fresh surfaces. Most

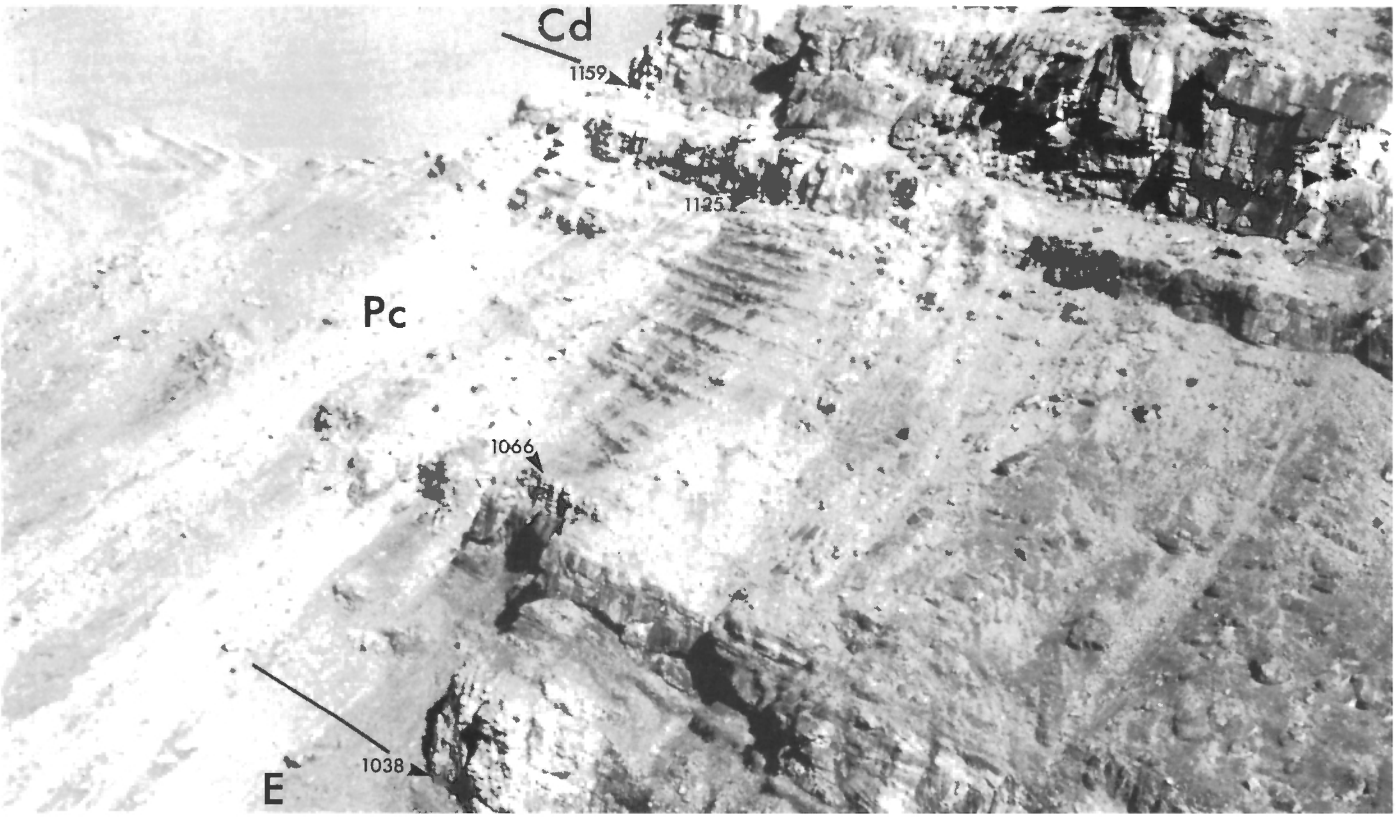


Figure 11. *Pocaterra Creek Member (Pc) and overlying Cadomin equivalent conglomerate (Cd), exposed in Segment 3 of the measured section at Mount Allan. Numbers indicate section measurements in Figure 6. E = Elk Formation.*

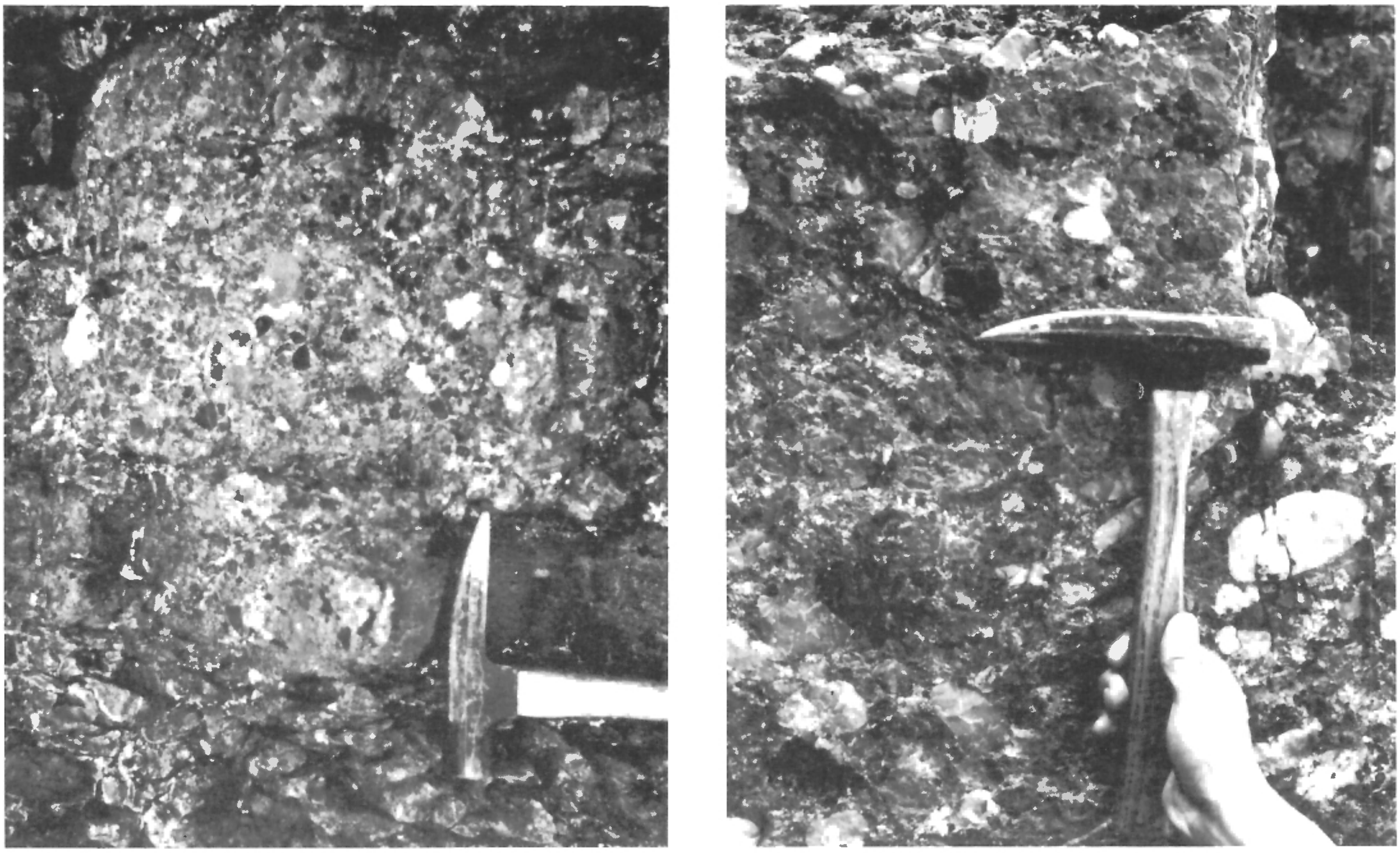


Figure 12. *Conglomerates of the basal Pocaterra Creek Member (A) and upper member of the Cadomin Formation (B). Note smaller clast size and relative lack of quartzite (light-coloured clasts) in Pocaterra Creek Member conglomerate.*

are non-calcareous, although a few very calcareous beds with calcite-cemented concretions are present near the top of the member. Slabbed surfaces of these claystones commonly show a mottled character with no recognizable laminations which, along with the limestone concretions, may be indicative of paleosol development and subaerial exposure (Collinson, 1978). A few parallel-laminated claystones are also present. Plant remains were found in only one bed.

Siltstones occur interbedded with claystones in the lower part of the Pocaterra Creek Member and above the Cadomin conglomerates (Fig. 6). They weather grey and dark grey to grey-brown and red-brown, and are dark to light grey on fresh surfaces. They are predominantly non-calcareous, although a few slightly calcareous and rare very calcareous beds are present. Most siltstones are massive although some contorted laminae and ripple crosslaminated beds were observed. Carbonaceous partings were noted in one bed.

Very fine- and fine-grained sandstones occur as interbeds within finer grained rocks and as thin beds overlying coarser lithologies. They weather grey to grey-brown and are dark grey or grey on fresh surfaces. Generally, they are ripple crosslaminated, or display contorted or parallel laminations, and are non-calcareous to slightly calcareous. A distinctive, very light grey, very hard, quartzose variety of sandstone found in the Pocaterra Creek Member and overlying Blairmore strata is not found in the underlying Elk Formation (Gibson, 1977; pers. comm., 1980).

Medium- and coarse-grained sandstones occur as interbeds within pebble conglomerates and within the upper parts of conglomeratic fining-upward sequences. They weather light- to medium-grey and are medium grey to dark grey on fresh surfaces. They are commonly crossbedded, with less common massive, parallel laminated and convoluted beds, and are generally non-calcareous.

As a rule, conglomerates form the basal unit of fining-upward sequences (Fig. 6) and have erosional basal contacts. They are massive with minor sandy interbeds and can be distinguished by clast composition and size, as discussed previously. The proportion of sand-sized matrix is variable, and examples of both matrix- and framework-supported conglomerates can be found. The conglomerates weather grey to brown and are the most massive and resistant beds in the section (figs. 6, 11). Although individual beds may be lenticular laterally, composite bed sets of conglomerates at the base of the Pocaterra Creek Member and in the Cadomin Formation form near vertical cliffs which can be traced laterally for several kilometres (figs. 3, 4).

LITHOLOGIC TRENDS

The section was sampled at 1.5 m intervals and at each major lithologic change. The 1108 samples collected were slabbed and examined under a binocular microscope. Mean and range of grain size; proportion of clasts, matrix, and cement; approximate composition of clasts; sedimentary structures; and colour were recorded, where possible, for each sample. These data were then examined for vertical trends. Grain size and sedimentary structure data are incorporated into Figure 6.

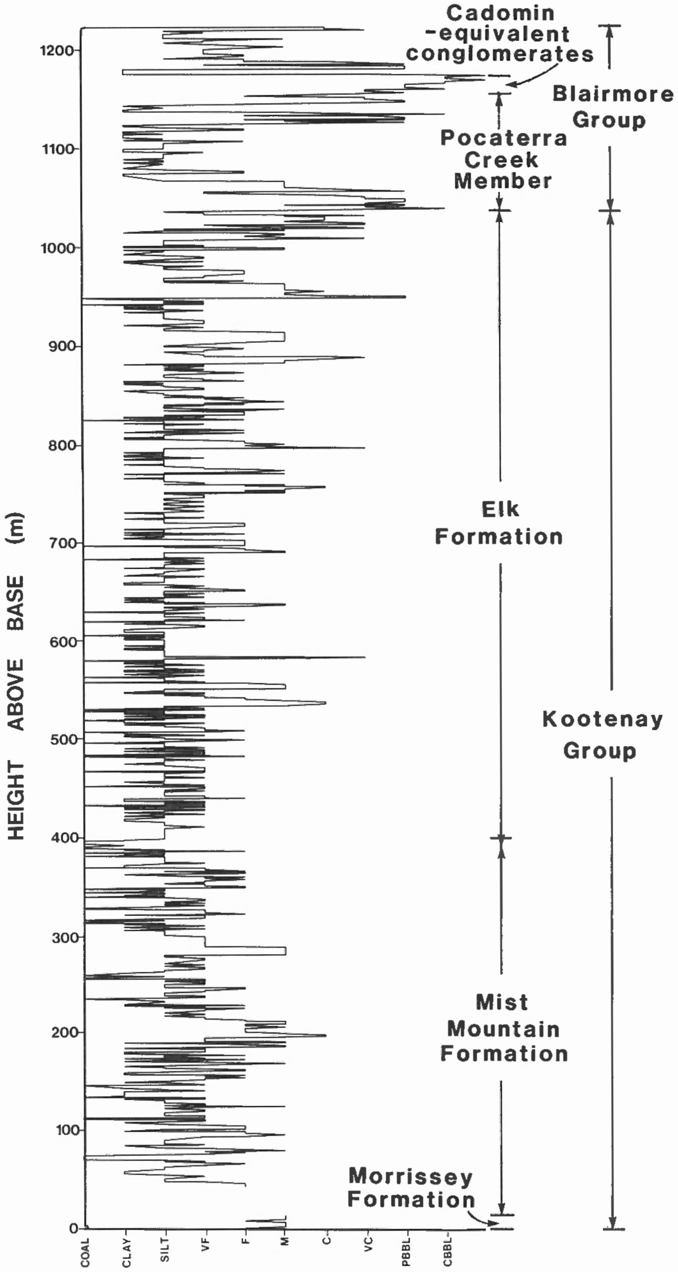


Figure 13. *Mean grain size of samples collected from Mount Allan section. Lithology codes along abscissa are explained in Figure 6.*

Grain size

The most obvious trend within the section is a general upward increase in the grain size of sandstones and the abundance of sandstone units, accompanied by a decrease in the number and thickness of coal seams. Clast size in the finer grained lithologies also increases upward from predominantly clay/silt to silt/very fine grained sand. This trend is illustrated in Figure 13, which shows the position of coal seams in the section and the mean grain size of all samples collected, and in Figure 14, which shows the abundance of coal and each grain size class in the Mist Mountain and Elk formations, and in the Pocaterra Creek Member and overlying Blairmore Group strata.

The morphology of the thicker sandstone units also changes upsection. Sandstone units within the Mist Mountain Formation are lenticular, and of limited lateral extent in the southeast trending exposure afforded by Mount Allan, whereas overlying Elk Formation sandstones are more laterally persistent, some extending throughout the 2 km of strike length visible on Mount Allan.

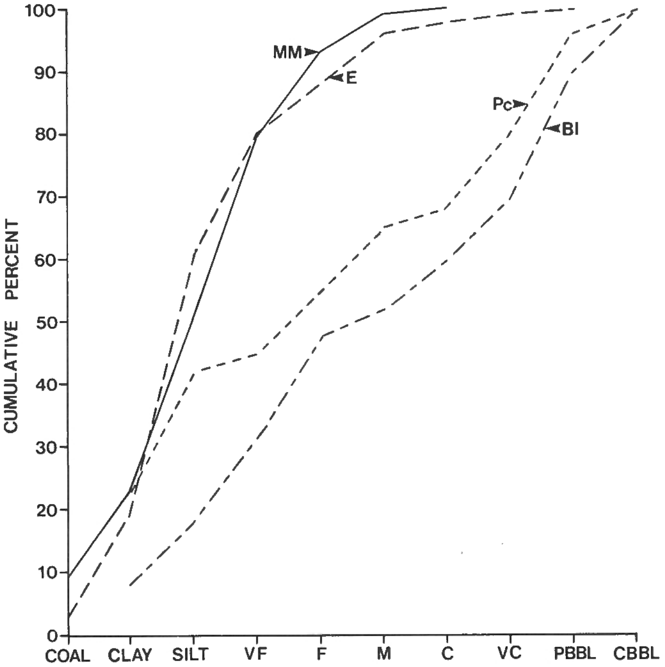


Figure 14. *Cumulative grain size, by formation, for the Mount Allan section. Lithology codes along abscissa are explained in Figure 6.*

Sedimentary features

Figure 15 summarizes the frequency of occurrence of the sedimentary features noted in Figure 6 with respect to grain size and stratigraphic position. It is evident from these graphs that the frequency of occurrence of some of these features is strongly controlled by grain size, and that there are vertical trends in frequency of occurrence of certain features within a given grain size class. As the grain size of sediments is directly related to the energy of the transporting medium, sedimentary structures indicative of high energy, such as small- and medium-scale crossbedding and upper flow regime plane beds, are confined mainly to medium- and coarse-grained sandstones. Very fine- and fine-grained sandstones are commonly ripple crosslaminated or parallel laminated; claystones and siltstones are massive or display parallel-, wavy- or contorted-laminations. Within beds of a certain grain size class, upward trends are toward higher energy structures. For example, within the claystones massive and parallel laminated beds decrease upward, whereas contorted laminae and wavy-laminated beds increase; within the siltstones there is a slight upward increase in the abundance of ripple crosslaminations; within the very fine- and fine-grained sandstones, there is an upward increase in ripple crosslaminated beds accompanied by a decrease in contorted laminae and wavy laminated beds; and within medium grained sandstone, there is an upward increase in small- and medium-scale cross-stratified beds and a decrease in ripple crosslaminated beds. The environmental significance of these trends is discussed in a later section.

Mineralogy

Although a detailed petrographic study was not done, thin sections were cut from 70 representative samples to determine major clast, matrix and cement components. A binocular microscope was used to estimate these quantities from slabbed surfaces of all samples coarser than claystone. Clasts are predominantly moderately well rounded and moderately sorted, and make up on average from 80 to 90 per cent of the very fine- to coarse-grained sandstones. The mean clast composition for each of four grain size classes (very fine, fine, medium, and coarse to very coarse) was determined. The range in mean clast composition between these size classes is as follows: 44 to 53 per cent light coloured quartz and quartzite, with standard deviations (sd) of 13 and 18 per cent respectively, and with the higher values occurring in the coarser sandstones; 13 to 24 per cent dark grey to black chert and quartzite (sd 9 and 7 per cent respectively), also with the higher values occurring in the coarser grades; 6 to 12 per cent rock fragments (sd 3 and 5 per cent respectively); minor amounts (<1%) of carbonaceous material, which occurs primarily in the finer grained rocks; and detrital carbonate, including both dolomite and calcite, which comprises between 9 and 31 per cent of clasts.

The clastic carbonate component is of particular interest, because its abundance appears more strongly related than that of other components to grain size and stratigraphic position. Figure 16 shows the abundance of clastic carbonate in all size classes from siltstone through coarse grained sandstone. The mean abundance of clastic carbonate increases from 9.5 per cent (sd 8.4 per cent) in coarse grained sandstone to 31.1 per cent (sd 12.2 per cent) in very fine grained sandstone and 33.3 per cent (sd 17.0 per cent) in siltstone. This is related to the relatively low resistance of carbonate to erosion and weathering during transport as compared to siliceous clasts, resulting in a concentration in the finer size fractions. The fact that the standard deviation increases and correlation coefficients of the best fit regression lines decrease in the finer grained lithologies may be related to the relatively high surface area to volume ratio of the smallest clasts, making them more chemically reactive and, therefore, more susceptible to the geochemical environment in which they are deposited. Carbonate clasts deposited in a back-swamp or forested setting would be exposed to acidic groundwater in the presence of humic acids associated with decaying vegetation, and carbonate might be leached out to be concentrated within underlying layers. On the other hand, carbonate clasts deposited in standing bodies of water on the floodplain, or within rapidly buried units with a short residence time in the vadose zone, would be less affected. All size fractions in Figure 16 show similar vertical trends in carbonate abundance, with maxima in the middle of the Kootenay Group. Jansa (1972, his Fig. 4)

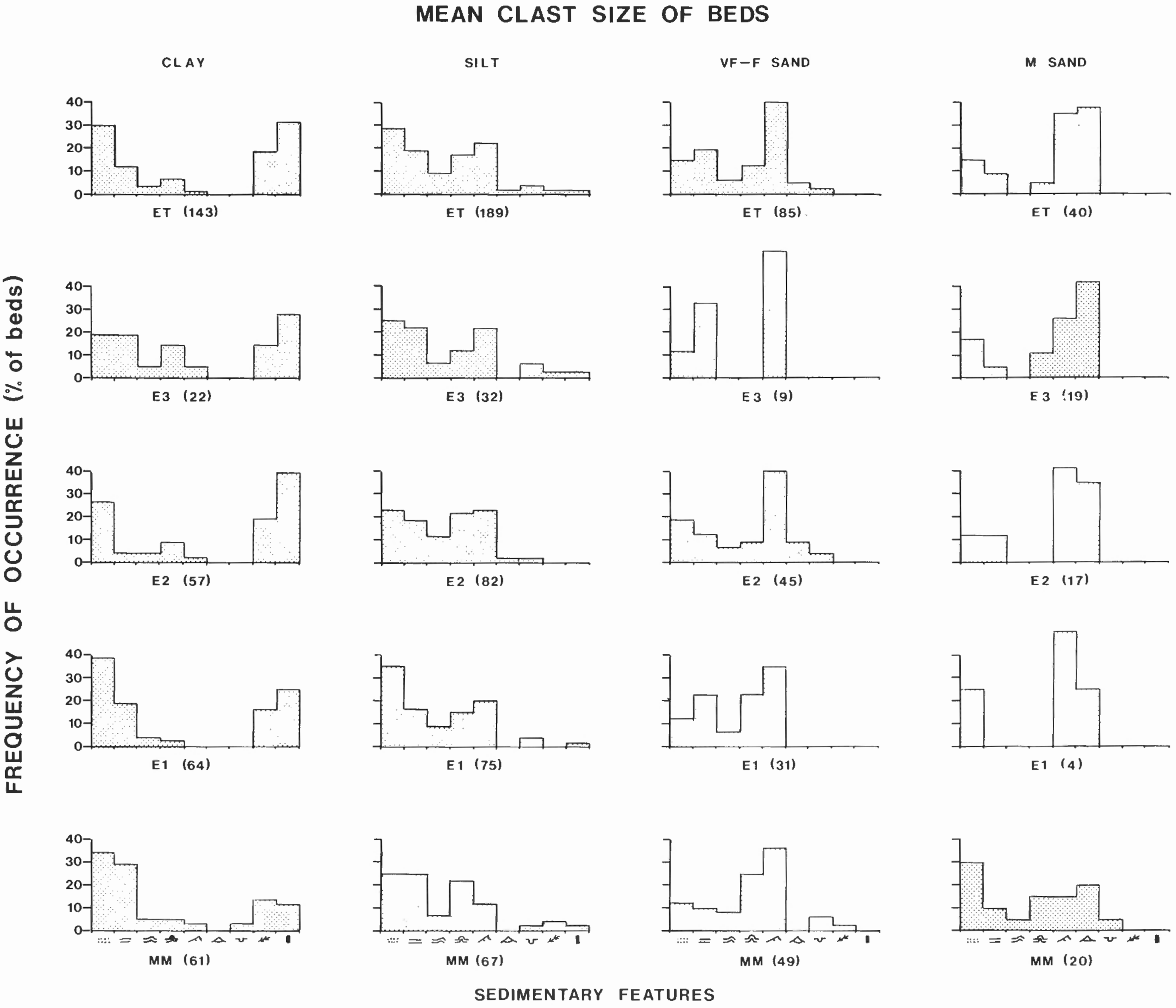


Figure 15. *Frequency of occurrence of sedimentary features noted in Figure 6 as a function of grain size and stratigraphic position. MM = Mist Mountain Formation (15–400 m); E1 = 400–600 m; E2 = 600–900 m; E3 = 900–1038 m; ET = Total Elk Formation (400–1038 m). ( ) indicate number of beds considered. Lithology codes are explained in Figure 6.*

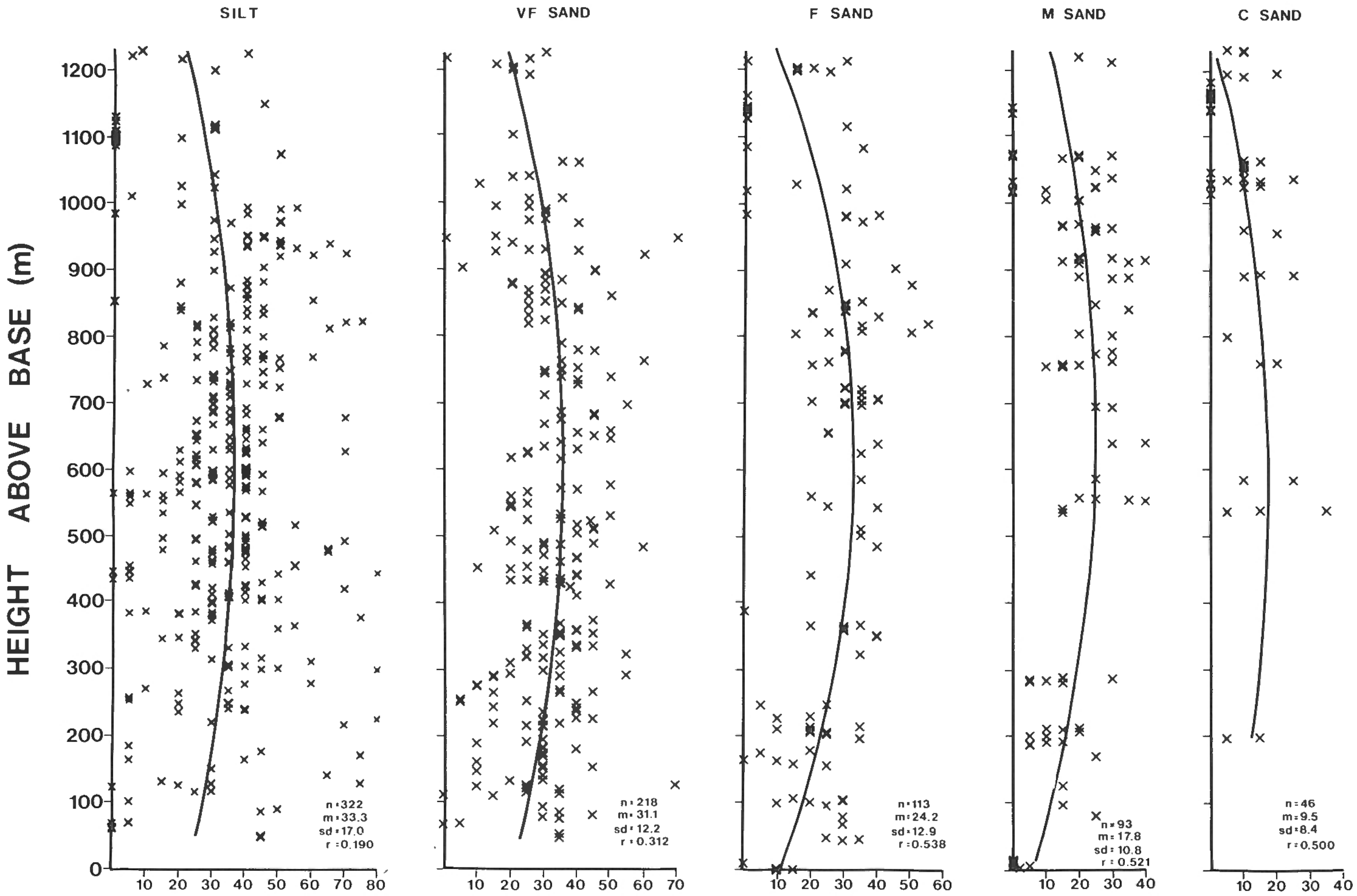


Figure 16. *Clastic carbonate content, estimated using a binocular microscope, subdivided by mean clast size of samples. Fitted curve is a second-order polynomial. n = number of samples; m = mean; sd = standard deviation; r = correlation coefficient.*

reported a similar trend in carbonate content in the Panther River section of the Kootenay Group. This trend is best approximated by the second-order polynomial curve shown for each size class, as higher order polynomials did not improve the correlation coefficient. It appears to reflect a change in the rocks exposed in the source area, and may be related to unroofing of Devonian to Pennsylvanian dolomites and limestones to the south and west. This is in accord with observations of other workers (e.g. Rapson, 1964, 1965; Schultheis, 1970; Schultheis and Mountjoy, 1978; Jansa, 1972; Gibson, 1977b; McLean, 1977) who suggested that, with the exception of the metamorphic and minor volcanic clasts, which may have been derived from the Shuswap metamorphic complex (Rapson, *op. cit.*), suitable source rocks exist in the Paleozoic and lower Mesozoic sedimentary strata presently exposed in the Main Ranges of the Rocky Mountains (Cambrian quartzites; Devonian to Pennsylvanian carbonates and minor chert; Permian phosphatic cherts and minor carbonates; Triassic carbonates and clastic sediments).

Silica forms the most common cement, particularly within the coarser sandstones and conglomerates. Carbonate cement is also important in the finer grained lithologies where clastic carbonate is a major component. Clay minerals form rare cements in siltstones and sandstones, although they are significant components of claystones (Jansa, 1972; Gibson, 1977b).

DEPOSITIONAL SETTING

Morrissey Formation

The Morrissey Formation and underlying "Passage Beds" of the Fernie Formation constitute a regressive, coarsening-upward sequence marking the commencement of uplift and erosion in their source area to the south and west. Although the thickness of component rock units varies widely, these strata are very persistent laterally and are found over an area at least 380 km by 160 km (Gibson, 1977b). Most workers attribute the Morrissey sequence to delta systems prograding either in a northerly to northeasterly (Gibson, 1977b; Hamblin and Walker, 1979) or an easterly (Jansa, 1972) direction, although a diversity of opinion exists as to the morphology of these deltas and the interpretation of the Weary Ridge and Moose Mountain members of the Morrissey Formation.

The "Passage Beds", which generally include more abundant sandy interbeds and less bioturbation upward, comprise the "prodelta" facies of these delta systems, with stratigraphically higher beds being deposited in progressively nearer shore locations. Within the lower part of this sequence, thin sandstone and siltstone beds, commonly with sharp bases, gradational tops and oriented sole marks, are interbedded with bioturbated shales, and are interpreted as turbidite deposits by Hamblin and Walker (1979). The overlying "hummocky cross-stratified" sandstones of Hamblin and Walker (*op. cit.*), which also display sole marks and bioturbation, are interbedded with siltstones and are interpreted as storm deposits, originating below fair weather wave base. As such, they may represent proximal deposits of density currents which, in more distal locations, formed the more typical turbidite deposits represented by the underlying strata (Walker, 1979, Fig. 15).

Interpretations of the Weary Ridge and Moose Mountain members of the Morrissey Formation must account for:

1. Their lateral persistence and thickness.
2. The moderately to well sorted, quartzose character of the Moose Mountain Member, as compared to the more argillaceous, less resistant Weary Ridge Member.
3. The parallel laminations and minor ripple crosslamination and small- to medium-scale low-angle cross-stratification of the Weary Ridge compared to the generally larger scale and more abundant trough and festoon cross-stratification of the Moose Mountain Member.
4. The lack of bioturbation in these units.

Through the study of many modern deltas, Coleman and Wright (1975), and numerous other workers, have shown that delta morphology is related to the complex interaction of fluvial and marine processes. Type of sediment, the rate and annual variation in the discharge of distributaries (which are largely a function of climate), the source rocks exposed, and the size and geometry of the drainage basin, constitute the primary variables affecting the fluvial system. Tidal range, wave power, longshore currents and the tectonics and geometry of the receiving basin are the primary marine variables. Of fundamental importance are the relative energies of fluvial, wave, and tidal forces. For this reason, Galloway (1975) constructed a tripartite delta classification scheme based on the contribution of each. To better understand the hydrodynamic conditions of deposition of ancient deltas, the lateral and vertical lithological relations within them can be compared with those of modern deltas.

The high lateral continuity of sands in the Morrissey Formation suggests that wave energy was a prominent factor in moving sand from the mouths of major distributaries to interdistributary areas. Reworking of sands by wave action would remove fines normally associated with distributary mouth bar complexes in fluvially-dominated deltas, and contribute to the highly quartzose and resistant nature of the Moose Mountain Member. Littoral drift could also have been a factor in moving sands from distributary mouths, particularly if prevailing onshore winds intersected the coastline at an angle other than 90°. High wave energy implies moderate to steep offshore slopes (Wright et al., 1974) which allows most of the energy to be expended at the coastline. Steep offshore gradients would enhance the probability of density currents removing sediments to deeper water, and would inhibit the development of offshore barrier island complexes.

Facies models with similar vertical profiles to those of the Morrissey Formation include the regressive barrier model of Reinson (1979, Fig. 24), and models of the modern, wave-dominated São Francisco (Brazil) (Wright and Coleman, 1973) and Rhone (Mediterranean) (Oomkens, 1967) deltas. Differences in the thickness of units within these vertical profiles are related to subsidence rates and to the relatively low rate of sediment supply in nondeltaic (Reinson, *op. cit.*) as compared to deltaic settings, although the sequence of lithofacies is similar in each case. In these vertical sequences, the predominantly parallel laminated sands of the Weary Ridge Member, containing minor crosslaminations and rare burrows, would correspond to upper shoreface and foreshore deposits of a beach, as suggested by Hamblin and Walker (1979), or to the distal portions of distributary mouth bar complexes. Shallow scours reported by Hamblin and Walker (1979) within and at the top of this unit, may relate to storm activity. Overlying, clean, massive to trough cross-stratified sands of the Moose Mountain Member represent backshore deposition on beach ridges and dunes, rather than within a braided channel complex as suggested by Hamblin and Walker (1979, p. 1683). Thin, fine grained, commonly carbonaceous horizons, reported by Gibson (pers. comm., 1980) to occur within the Moose Mountain Member at some localities, may represent swale fills between dunes or beach ridges. Although burrowing is present in upper shoreface and foreshore deposits of modern regressive barrier systems such as Galveston Island (Bernard et al., 1959, 1973; Davies et al., 1971), it is much less common than in middle and lower shoreface deposits, and is still less common in these facies in the above mentioned wave-dominated delta systems. This may be due to higher sedimentation rates and higher energy conditions (sufficient to transport medium and coarse sands in the case of the Morrissey Formation as opposed to very fine and fine sands on Galveston Island). The rare burrows reported by Hamblin and Walker (*op. cit.*) in the Weary Ridge Member, and the complete lack of burrowing in the Moose Mountain Member, are therefore not inconsistent with a beach-beach ridge-dune origin.

The presence of a laterally extensive coal seam at or very close to the top of the Moose Mountain Member at many localities (Gibson, 1977b), suggests the existence of widespread peat-forming swamps in close proximity to the beach and that sands at these locations were accreted directly to the coastline rather than to an offshore barrier system separated from the coastline by a lagoonal evironment. Gibson (1977b, p. 785) states that there is "...no conclusive paleontological evidence... ...to indicate any major or even minor marine influence or intertonguing in the lower coal-bearing member...". Nevertheless, in the area south of Banff, at localities where it is not directly overlain by coal, some of the finer grained strata above the Moose Mountain Member may represent a lagoonal facies and hence indicate the presence of an offshore barrier system. Unfortunately, these strata are not exposed where the section was measured on Mount Allan. The absence of facies commonly present in mesotidal barrier systems, such as tidal channels exhibiting bidirectional crossbedding and tidal delta complexes, suggests a low, probably microtidal (<2 m), tidal range, and a resultant low tidal influence in the delta-forming process.

Mist Mountain Formation

Strata of the Mist Mountain Formation are attributed by most workers (e.g. Gibson, 1977b; Jansa, 1972) to deposition within the subaerial portions of deltas (the subaqueous portions of which are represented by the underlying Morrissey Formation) in lower and upper deltaic plain settings. As previously mentioned, no marine or brackish deposits have yet been recognized within the formation in this area. Mist Mountain strata can be subdivided into a coarse grained facies, consisting of thick (>4 m) sandstone beds and related overlying finer grained units, attributed to deposition within and proximal to river channels; and a fine grained facies, comprising interbedded claystone, siltstone, coal and thin (<4 m) sandstone beds, which accumulated on floodplains adjacent to these channel systems by in situ growth (coal) and overbank sedimentation during periodic flooding. The ratio of channel to floodplain sediments within the section on Mount Allan is approximately 1:10. Each of these major groups can be further divided into several subenvironments.

Channel deposits

Thick sandstone units interpreted as channel deposits occur within the formation above the 195 m and 278 m levels of the section. These sandstones are lenticular in the southeast-trending exposure afforded by Mount Allan, thinning and grading laterally into finer grained sediments. They can be traced along the face for about 800 m (Fig. 7). Finer grained lateral equivalents of a third major sandstone, which occurs about 50 m above the base of the formation one kilometre along strike to the southeast (Ch in Fig. 1), may be represented in the section by the very fine grained sandstone unit above the 45 m level, although intervening strata are covered. Although the lateral terminations of these channel units are not well exposed on Mount Allan, they may be very abrupt, as is the case at Harmer Ridge in the Fernie Basin (about 140 km south of Mt. Allan), where a channel unit in the lower part of the Mist Mountain Formation lenses out over a few metres and exhibits an angular, erosional contact with underlying floodplain sediments, suggesting a cutbank formed on the outside of a meander bend.

The lower sandstone unit (Fig. 17) is 34 m thick and consists of two separate fining-upward sequences with erosional bases, and thus represents a "multistoried" channel complex. Each sequence has a lower, generally fining-upward, medium- to coarse-grained, massive to cross-stratified sandstone sub-unit, 6 to 8 m thick (Fig. 6). These sub-units are gradationally overlain by very fine grained sandstone and siltstone, commonly displaying ripple crosslaminations and convolute bedding and, less commonly, wavy- and parallel-laminations and massive beds. The upper sandstone unit comprises a single fining-upward sequence, with a lower, medium grained, massive to parallel laminated and trough cross-stratified sandstone sub-unit, 7.6 m thick, which grades upward through 12 m of massive to ripple crosslaminated, fine- to very fine-grained sandstone, into siltstone, claystone and coal.

Similar fining-upward sequences have been reported by numerous workers from ancient and modern fluvial deposits (e.g. Allen, 1965; Jackson, 1976). They are commonly attributed to deposition by meandering rivers, although similar sequences can result from braided rivers (Cant and Walker, 1978). The dominance of fine grained overbank sediments, which would tend to resist lateral migration of channels, and the lenticular nature of sandstone units indicated from the section on Mount Allan, favour low sinuosity or meandering channels confined to narrow meander belts, rather than braided channels.

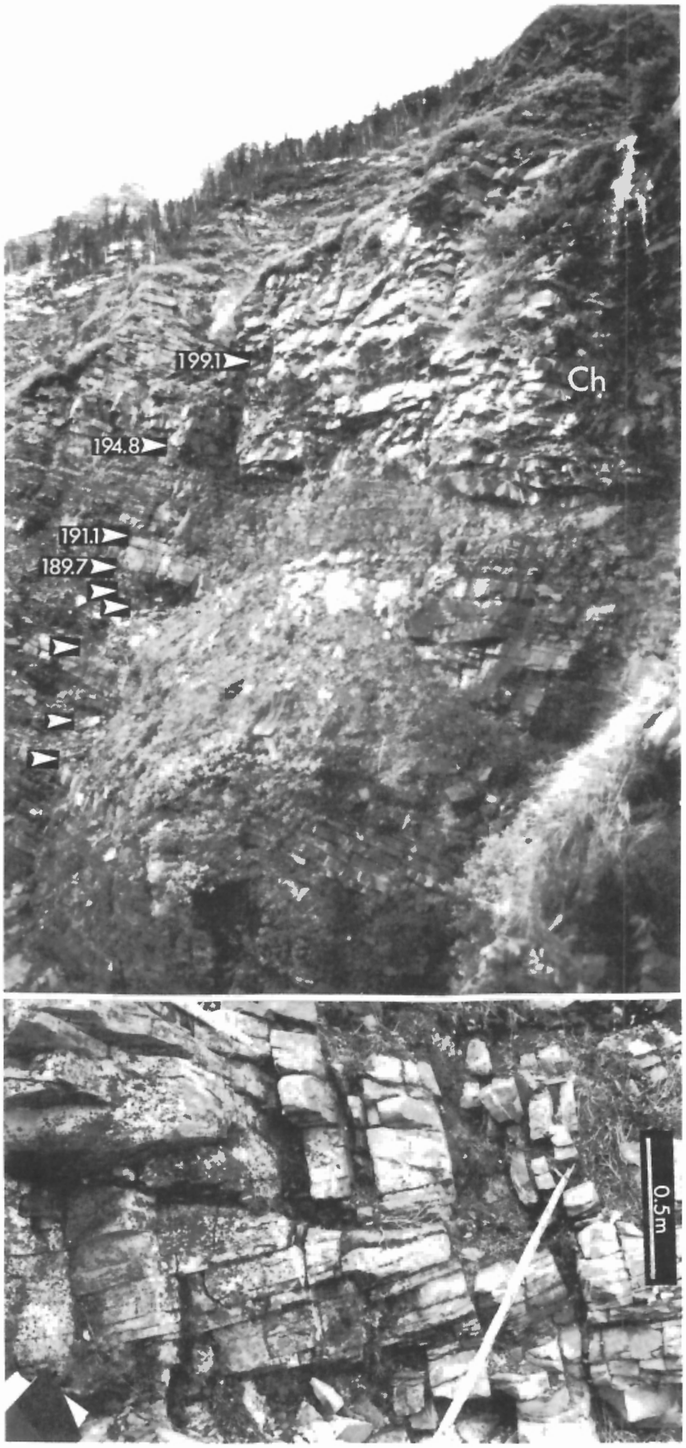


Figure 17. *Channel sandstone (Ch) with erosional base cut into floodplain deposits, Mist Mountain Formation. Inset at base shows medium- to large-scale trough cross-stratification in lower part of sandstone unit. Numbers and arrows correspond to unit boundaries and section measurements shown in Figure 6.*

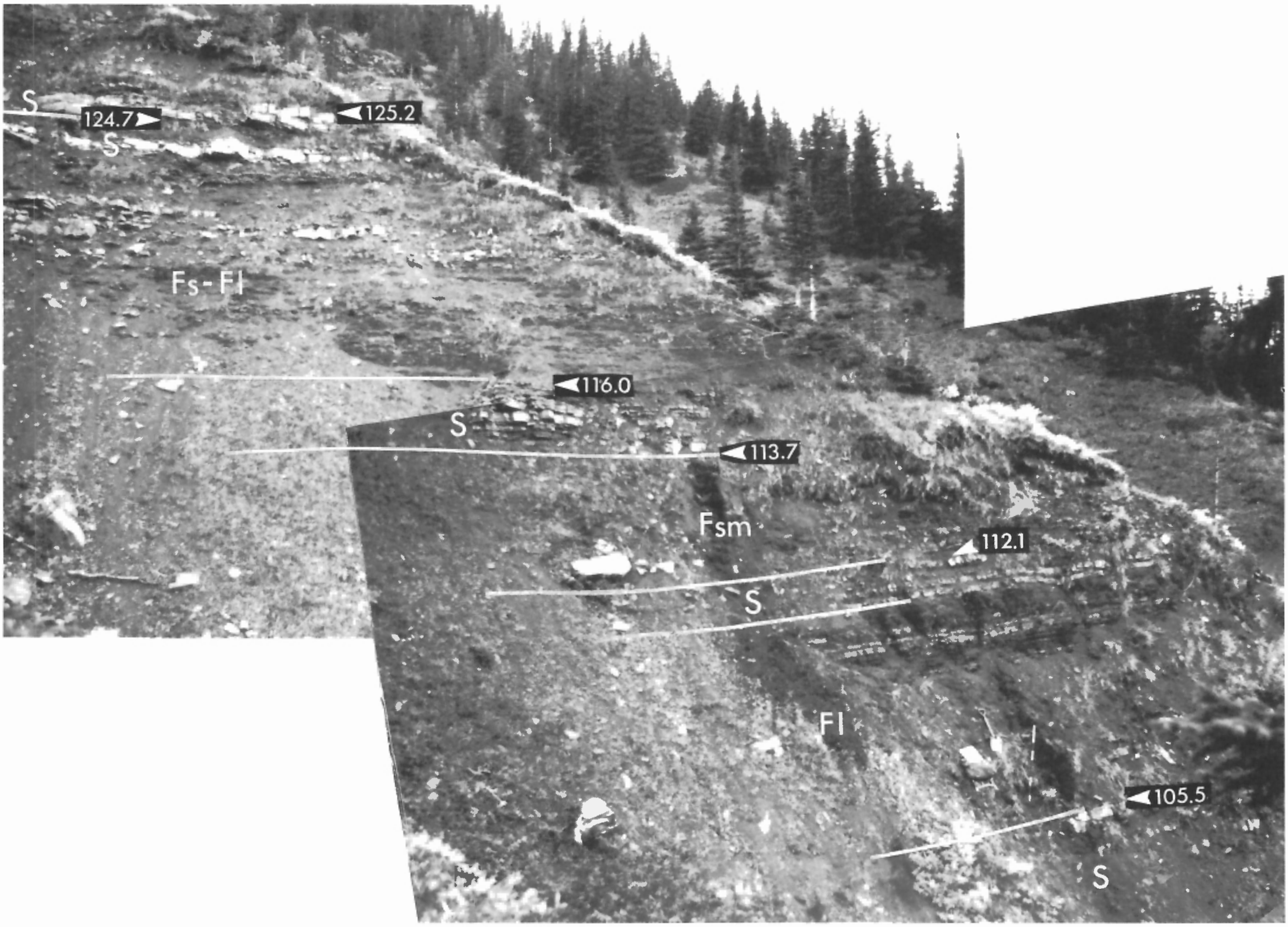


Figure 18. *Floodplain deposits of probable crevasse splay (S), subaerial flood basin (Fs), swamp-marsh (Fsm) and lacustrine (Fl) origin, in lower part of Mist Mountain Formation. Numbers and arrows correspond to unit boundaries and section measurements in Figure 6.*

The lower sandstone unit within these sequences represents high energy channel fill deposits. Overlying finer grained units represent deposition in lower energy settings on point bars as the main channel migrated laterally. Lateral accretion sets or "epsilon" crossbeds, a diagnostic but not particularly common feature of point bar deposits (Allen, 1965, 1970; Collinson, 1978), were not observed within channel facies on Mount Allan, although they have been observed (by Hughes) at Harmer Ridge in the Fernie basin. Channel lag deposits, comprising small pebbles and fragments or casts of branches and logs are present, and have been reported from the base of equivalent units in the Crowsnest Pass area by Gibson (1977) and Gibson and Hughes (1981).

Floodplain deposits

The remainder of the formation comprises overbank sediments deposited within flood basins between major channels or distributaries during periodic floods. These sediments may be divided into levee, crevasse splay, subaerial and subaqueous flood basin, and swamp or marsh deposits. Coal, which accumulates in interchannel areas primarily by in situ growth between flood events, is included with floodplain deposits because of its close association with them.

Depending on the subenvironment, the lateral continuity of floodplain sediments is generally greater than the main channel deposits. For example, the lateral continuity of the swamp-marsh subenvironment represented by the major coal seam (Balmer) near the base of the formation in the Crowsnest Pass area is in the order of several tens of kilometres (Gibson, 1977b). Overlying seams of mineable thickness can generally be correlated within individual coal areas, over distances of 5 to 15 km or more; however, seam lenticularity and the absence of identifiable marker horizons preclude correlation between areas. The lateral continuity of overbank and marsh-swamp deposits is related to lateral uniformity of local subsidence rates, which in turn is related to the distribution of underlying fine and coarse deposits. The widespread sand sheet at the base of the Kootenay is the laterally most persistent and uniform unit in the group, and it follows that subsidence rates would be relatively uniform laterally immediately following its deposition, as compared to later periods, when local subsidence rates would be influenced by differential compaction associated with more laterally restricted fluvial facies. Coal formed on top of the basal sand should, therefore, be the most laterally persistent of the succession. More variable local subsidence rates higher in the succession should contribute to a greater variety of overbank subenvironments within interchannel areas, and hence less lateral persistence of coal seams.

Overbank flooding may occur through widespread topping of levees flanking the channel and point bar facies of the meander belt, and/or by concentration of floodwaters within crevasse channels breaching the levee at scattered points. Deposition is most rapid nearest the channel during waning periods of flooding, and grain size can be expected to fine toward the flood basin.

Levee deposits, because of the wide range of flow conditions under which they accumulate, display a wide diversity of rock types and sedimentary structures. Evidence of rapid deposition, such as climbing ripple cross-stratification and convolute bedding, are common, as are thin fining-upward sequences, grading from ripple cross-stratified sand into silt, then into clay and finally into coal, reflecting waning flow and establishment of vegetation on levees during low water periods. The preservation potential of levee deposits within meandering channel systems is low, as they are commonly best developed on the convex, actively eroding side of meander bends (Collinson, 1978). Deposits of possible levee origin in the section may be represented by some of the interbedded claystone, siltstone and very fine grained sandstone overlying point bar deposits of the major channels discussed above.

Crevasse splay deposits accumulate within relatively narrow channels where they breach the levee, and as widespread deposits farther into the floodbasin. Grain size within individual splays generally decreases with distance from the main channel and also vertically (Horne and Ferm, 1978; Reineck and Singh, 1975). Near the main channel, splays may be represented by thin channel deposits containing sediments coarser than flanking levee deposits but finer than the main channel fill. Farther into the floodbasin, they are represented by sands and silts bounded by finer grained sediments, and may display ripple crosslaminations and/or convolute bedding, and a graded, fining-upward vertical profile. The most distal and uppermost portions of splays comprise massive to laminated clays and silts, reflecting very low energy conditions with sedimentation primarily from suspension. Splays deposited on the subaerial portions of the floodplain may become vegetated and display signs of rooting or contain carbonaceous interbeds. Where splay channels prograde into standing bodies of water on the floodplain, small-scale deltas with coarsening-upward vertical profiles may develop.

Siltstones and sandstones of probable crevasse splay origin constitute about half of the overbank sediments in the formation. They occur mainly as thin (0.3-2 m thick) beds of siltstone or very fine- to fine-grained sandstone, commonly with ripple cross-stratification and/or contorted laminations, bounded by finer grained rocks. Both fining- and coarsening-upward grading is evident, reflecting waning flow conditions and progradation of small scale deltas into standing bodies of water, respectively. The coarsest and thickest beds represent deposition proximal to channels; thinner, finer grained, massive to parallel- or wavy-laminated beds represent deposition in more distal locations.

The finest grained overbank sediments, herein termed "floodbasin", deposits, were deposited primarily from suspension in areas removed from current action. They may be extensively root-bearing and contain carbonaceous or coaly interbeds where they accumulated in subaerial "back-swamp" or marsh settings, or may be massive to laminated where they accumulated within nonvegetated subaerial or subaqueous lacustrine settings on the floodplains.

Claystones and siltstones of floodbasin origin compose the remainder of the overbank sediments in the section on Mount Allan. Relatively thick (>3 m), massive to laminated claystone and siltstone beds, devoid of root material and carbonaceous interbeds, occur in the lower part of the formation (figs. 6, 18) and may represent subaqueous deposition in lacustrine settings distant from river channels. Some of these beds coarsen upward into overlying fine grained sandstone of crevasse splay origin, possibly as a result of small-scale, splay-fed deltas prograding into and across the lacustrine environment. The remaining claystone and siltstone beds, which are generally thinner and carbonaceous, are bounded by coarser rocks and/or coal, and represent deposition on the subaerial portion of the floodplain. The fact that some of these beds are root-bearing, mottled, or contain coaly interbeds suggests development of soil horizons and vegetation in a forest or swamp-marsh setting.

Laterally extensive coal seams represent accumulation and preservation of plant material within interchannel areas over relatively long periods of time by comparison to other floodplain deposits. For example, several tens of centimetres of crevasse splay sediment may be deposited during a single major flood event in parts of the floodbasin. Such flood events may have periodicities of several to hundreds of years, depending on climate and drainage basin characteristics. One metre of bituminous coal, on the other hand, represents peat accumulation over a period of 6000 years, assuming peat accumulation rates of 1 mm/yr. (typical of temperate-climate peats) and a peat to bituminous coal compaction ratio of 6:1 (Stach et al., 1975). The formation of thick, laterally extensive coal seams, therefore, requires the presence of the following conditions for periods of several tens of thousands of years:

1. Isolation from sedimentation during overbank flood events on major channels. This may result from physical distance and/or topographic elevation of peat accumulation areas with respect to these channels, or from flocculation of floodwater-borne sediments in close proximity to channels, due to the acidity of groundwater within the coal swamps (Horne et al., 1978).

2. A delicate balance between subsidence rates and peat accumulation rates. If peat accumulation rates exceed subsidence rates, peat builds above the water table and is oxidized. If they are less, coal swamps are drowned and a lacustrine setting forms.

3. Lateral uniformity in the above conditions. This is a function of the spacing of major channels within the floodbasin, and the distribution of underlying fine and coarse deposits, as previously discussed.

The presence of claystone, siltstone and minor sandstone partings of variable thickness within some coal seams (Fig. 6), however, indicates periodic interruption of peat accumulation. These partings most commonly represent sedimentation during overbank flood events, but may, in some cases, represent altered volcanic ash deposits or "tonsteins", as reported in the Crowsnest Pass area by Meriaux (1972).

Elk Formation

Most workers infer that Elk Formation strata accumulated in an alluvial plain environment at a distance from any coastal influence. There is no abrupt lithological change at the Mist Mountain - Elk boundary; sedimentary environments in the lower Elk were, apart from the disappearance of major coal-forming environments, similar to those in the upper Mist Mountain. Lithologic trends within the Elk do suggest, however, a gradual change in the morphology and abundance of river channels, the stability and areal extent of overbank areas, and the position of the section with respect to the source areas to the south and west.

Upward changes of environmental significance in the Elk Formation include:

1. An increase in the mean grain size of sand units.
2. An increase in the abundance of thin- (<4 m), medium- and coarse-grained sandstone units.
3. An increase in the mean grain size of the fine grained facies.
4. A decrease in the fine: coarse facies ratio, from 8:1 in the lower 300 m to 4:1 in the upper 300 m.
5. An increase in the apparent lateral continuity of thick sandstone units.
6. An increase in the depositional energy level as evidenced by sedimentary structures within rocks of a given grain size class.

Increases in grain size are consistent with either a progressively closer proximity to the source area in the southwest, or to an increasing rate of uplift and erosion in a source area of fixed location. Bally et al. (1966), Price and Mountjoy (1970) and Price (1980) suggest that deformation, including northeastward directed thrust faulting, commenced in what is now east-central British Columbia in the Late Jurassic, providing a source area for the detritus of the Kootenay-Blairmore clastic wedge. Primary source terrains in this case would be the uplifted leading edges of northeastward-moving thrust plates comprising Precambrian to lower Mesozoic sedimentary rocks; and thus, at any given location east of the active deformation front, upward trends within derived sediments should reflect a progressively closer source.

The absence of thick coal seams in the Elk and the presence of redbeds in the overlying Pocaterra Creek Member suggest a gradual change to a more arid climate. Changes in channel unit geometry and the fine: coarse facies ratio may be related to changes in discharge regimes of river channels caused by this climatic change, and to an increase in paleoslope which may have occurred as the deformation front advanced.

Channel deposits

Channel deposits in the Elk Formation consist of numerous medium- to very coarse-grained, generally cross-stratified sandstone units ranging from 2 to 15 m in thickness. These units commonly display a fining-upward vertical profile, although reverse grading is evident in some beds (e.g. at 750 m, 880 m; Fig. 6), and there is no obvious grading in others (e.g. at 910 m; Fig. 6). Lower contacts are commonly erosional, and scoured surfaces occur within some units. Lag deposits, consisting of pebbles and/or casts of wood fragments, are also present within some of these units. Two examples of fining-upward channel sandstones bounded by finer grained overbank strata are shown in Figure 19. The lateral and vertical relationships of a massive sandstone unit in the upper Elk Formation to finer grained floodplain sediments is illustrated in Figure 20.

Channel deposits within the Elk vary in thickness laterally but appear to have greater continuity in a southeastward direction than channel deposits of the underlying Mist Mountain Formation. Thick sandstones at the base of the cirque section (Segment 2; figs. 5, 6, 8) have lateral continuities greater than the 2 km of exposure afforded by Mount Allan, although they vary in thickness over this distance. Lateral thickness variations within overlying sandstone units can be seen in figures 5 and 8. The greater continuity of channel deposits within the Elk compared to those in the Mist Mountain Formation suggests a change in channel morphology from stable, low sinuosity channels, or channels meandering within relatively narrow and stable meander belts (which tend to produce linear, sinuous channel deposits), to high sinuosity meandering or braided channels, which tend to produce more tabular channel deposits (Allen, 1965; Collinson, 1978).

Given uniform subsidence rates during the time of deposition of the Mist Mountain and Elk formations, the increased abundance of sandstones in the Elk can be related to any of the following:

1. More closely spaced channels on the alluvial plain and correspondingly smaller floodplain areas between channels.
2. A change in channel character from stable to laterally migrating, with erosion of most of the overbank material.
3. A combination of the above factors.

The presence of a number of rather thin channel sandstone units suggests a range in the scale of the depositing channel systems. If a relatively constant discharge prevailed in the drainage basin, the presence of smaller channels would suggest that numerous closely spaced channels existed at any one time on the alluvial plain, and would support point 1. This factor, plus the change in channel morphology evident from the continuity of the sandstone units, indicate that point 3 is the most probable alternative.

Floodplain deposits

Floodplain deposits of the Elk Formation differ from those of the Mist Mountain Formation in that they are less abundant, contain a larger proportion of ripple crosslaminated siltstone and very fine grained sandstone beds, and have only thin associated coal seams. Thick claystone beds are absent. The presence of more abundant and less stable, laterally migrating channels suggests individual floodbasins were smaller in physical dimensions and existed for shorter periods of time. Much of the ripple crosslaminated siltstone and very fine grained sandstone probably formed as crevasse splay deposits in relatively close proximity to channels. Parallel-laminated to massive siltstones and claystones, indicative of deposition from suspension in standing bodies of water or in areas distant from channel influence, are less abundant, suggesting areas

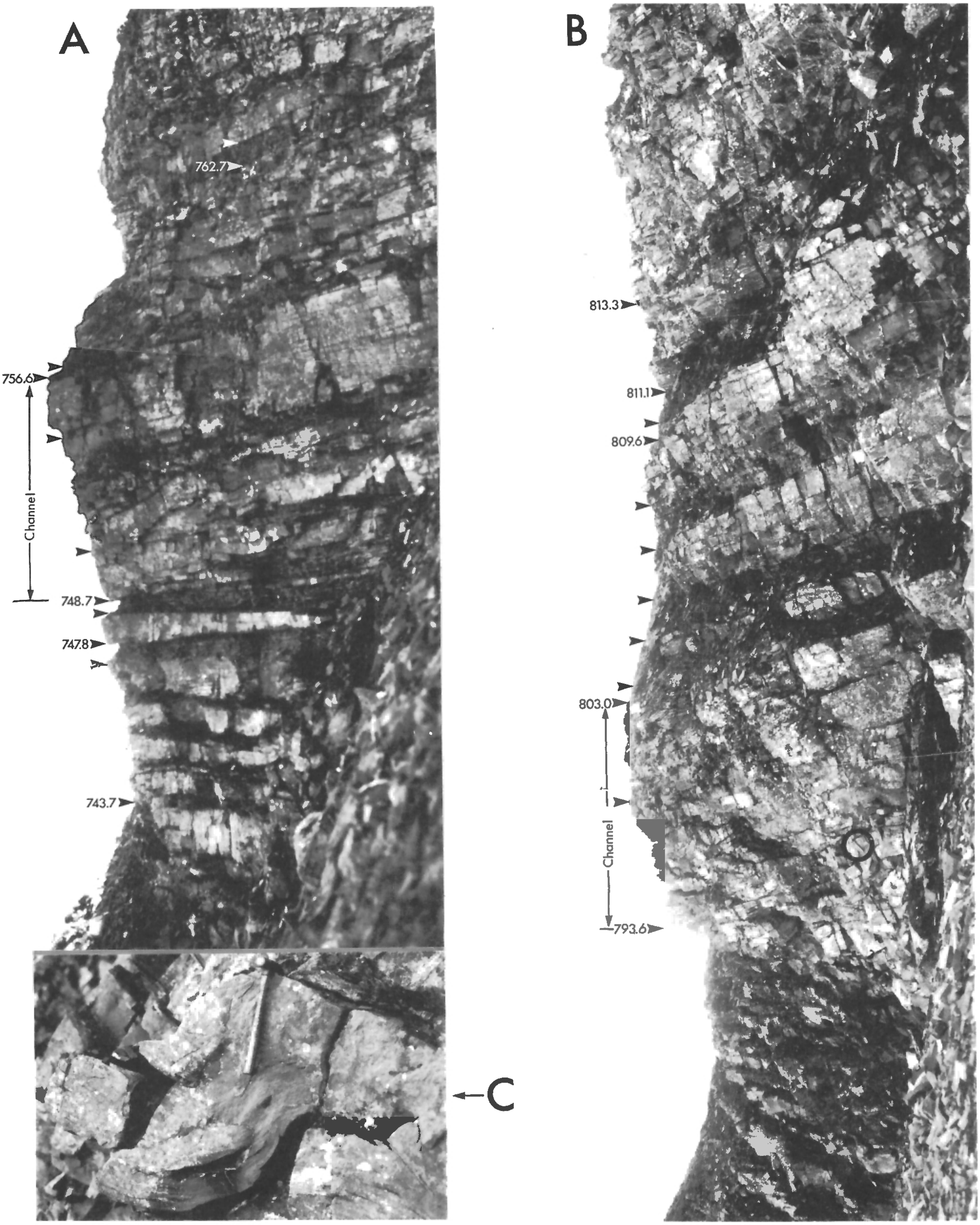


Figure 19. *Two fining-upward channel sandstones, bounded by finer grained floodplain deposits, in Elk Formation (A, B). Numbers and arrows correspond to unit boundaries and section measurements in Figure 6. Note lenticular sandstone unit of crevasse splay origin at 747.8 m. Inset C = soft sediment deformation within lower part of channel sandstone at 793.6 m. Hammer (circled) locates position of Inset C within sandstone unit.*

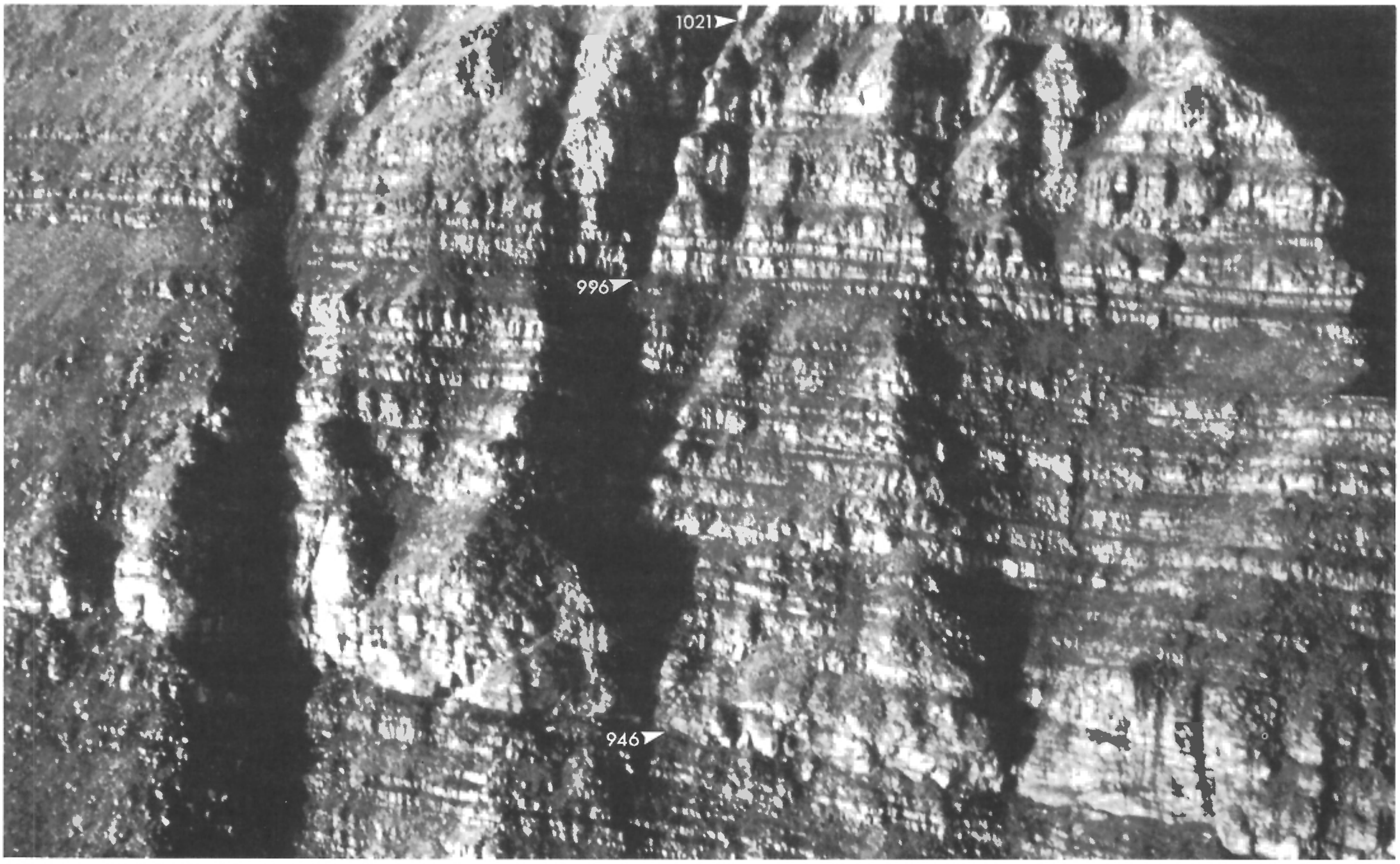


Figure 20. Aerial view of massive to trough cross-stratified channel sandstone unit and floodplain deposits in upper part of Elk Formation. Numbers indicate section measurements in Figure 6. Sandstone unit at 946 m grades from pebble conglomerate at base to very fine grained sandstone and siltstone at top. Note erosional lower contact with underlying floodplain deposits; and low angle cross-stratification in basal part of sandstone unit on left-hand side of Figure, which may represent lateral accretion sets or "epsilon" crossbeds. Note also the relatively thin bedded nature of the floodplain deposits, and the lenticularity of the fine- to medium-grained crevasse splay sandstone unit above 996 m.

suitable for their accumulation formed a relatively small part of individual flood basins. One exception is a 22 m thick, laterally persistent, parallel laminated to massive, thinly bedded siltstone unit of probable lacustrine origin, whose base forms the Elk - Mist Mountain contact on Mount Allan (figs. 1, 5, 6, 21).

The presence of smaller and more abundant braided channels situated nearer to the source area suggests discharge may have been more irregular during the deposition of the Elk Formation than during that of the Mist Mountain, with a resultant increased rate of occurrence of periods of overbank flooding. Depositional conditions suitable for the accumulation and preservation of coal within flood basins must, therefore, have been of relatively short duration in the Elk compared to those of the Mist Mountain Formation, being interrupted by frequent overbank flooding and lateral encroachment of channels, resulting in the relatively thin and laterally restricted coal seams observed within the Elk Formation.

Blairmore Group

The depositional setting of conglomeratic lower Blairmore and upper Elk strata has been briefly considered by Rapson (1964), Mellon (1967), Jansa (1972), Gibson (1977b) and Gibson and Hughes (1981). The Cadomin Formation has recently been considered in more detail by Schultheis (1970), McLean (1977) and Schultheis and Mountjoy (1978).

At western localities in the southern Rocky Mountains, where a thick conglomeratic facies is developed, most authors attribute the conglomerate beds to deposition by braided streams on the middle to distal parts of alluvial fans. Farther north, in northeastern British Columbia and northwestern Alberta, McLean (1977) reported a proximal alluvial fan facies. To the east, where pre-Cadomin erosion is great and the Cadomin Formation is generally represented by a relatively thin (4-8 m thick) conglomerate bed, McLean (1977) and Schultheis and Mountjoy (1978) suggested that the conglomerate accumulated over a long period of time on a pediment surface of low relief, with continuous reworking of the conglomeratic material.

McLean (1977) advocated the humid climate, alluvial fan model of McGowan and Groat (1971) for thick Cadomin sections in central and northwestern Alberta and northeastern British Columbia, where these conglomerates and associated strata contain plant remains and coal seams. At localities in southwestern Alberta and southeastern British Columbia, Blairmore strata are not coal-bearing and commonly contain red-weathering shales (Mellon, 1967), suggesting different climatic conditions toward the south during this period.

Although, as Glennie (1970) pointed out, the presence of redbeds is not unequivocal evidence of a semi-arid or arid climate, geochemical conditions favouring the diagenetic oxidation of iron-bearing grains commonly exist in such climates and many ancient redbed deposits have been related to semi-arid or arid conditions. Walker (1967) listed several conditions necessary for red colouration, including: the presence of iron-bearing grains; post-depositional conditions and Eh-pH interstitial environments favouring interstratal formation of ferric oxide; sufficient time for the formation of ferric oxide; absence of subsequent reduction; and, possibly, elevated temperature. Arid and semi-arid climates provide such conditions, as they typically have seasonal rainfall with low water tables and, therefore, oxidizing conditions near the surface, and either do not have, or rapidly oxidize, organic material that would otherwise reduce ferric compounds.

The general lack of plant remains and coaly partings, and the presence of red weathering claystones within the Pocaterra Creek Member on Mount Allan, may thus indicate a change in climate from the more humid conditions represented by the typically grey weathering strata of the underlying Elk Formation. This change appears to have been gradual and probably does not represent true arid climate conditions, as grey and dark grey weathering claystones are also present, and red claystones form a volumetrically small part of the member. Dryer conditions may have been related to a rain shadow effect caused by rising mountain ranges to the west, as suggested by Peterson (1966, p. 129) for Blairmore-equivalent strata in Montana.

The laterally extensive conglomerate beds of the Pocaterra Creek Member and Cadomin Formation probably represent deposition by braided streams, as suggested by earlier workers. The moderately- to well-rounded, mechanically resistant clasts within these conglomerates suggest significant transport, which favors a middle to distal, rather than a "proximal to intermediate", location on alluvial fans, as proposed by Schultheis and Mountjoy (1978, p. 329). Schultheis and Mountjoy (*op. cit.*, p. 335) suggested maximum transport distances of 48 km for clasts of the size found in the Cadomin Formation on Mount Allan. Smaller clasts, within Pocaterra Creek Member and Elk Formation conglomerates, reflect greater transport. The change in clast size and composition between Cadomin and older conglomerates indicates that a significant period of nondeposition or erosion may have occurred prior to deposition of the Cadomin Formation on Mount Allan.

Claystones and siltstones of the finer grained, middle and upper parts of the Pocaterra Creek Member are commonly mottled and contain calcite cemented concretions. This implies accumulation on inter-channel or inter-fan floodplains, in part within ephemeral lakes, with prolonged periods of subaerial exposure.

Figure 21. *Thin bedded siltstone of probable lacustrine origin, which forms basal unit of Elk Formation. Person (see arrow) near base for scale.*

COAL RANK VARIATIONS WITHIN THE MOUNT ALLAN SECTION

Sampling and analytical methods

The thick sequence of unfaulted Kootenay strata exposed in the Mount Allan section provided an excellent opportunity to carry out a rank study on samples of its coals collected by Hughes. The stratigraphically lowest sample examined was from a 3 m thick seam located 57 m above the Morrissey-Mist Mountain contact and the highest was from a thin seam occurring 91 m below the Elk-Pocaterra Creek contact (Fig. 6). The zone of study thus covers a stratigraphic interval of 873 m, making it one of the thickest Kootenay sections examined to date for rank variation.

Rank determinations were made by microscopically measuring the reflectance of the maceral vitrinite. Measurements were carried out using oil immersion at a magnification of 600X. Preparatory work involved crushing the coal samples to minus 20 mesh (<0.84 mm). For each sample, a representative split of this crushed material was formed into a pellet by bonding with resin. Specimens were then polished according to standardized procedures (ASTM Standard 2797, 1979). For each sample, 50 points of maximum reflectance were measured and these raw data were then used to calculate a mean maximum reflectance (R_o) and standard deviation.

The beds from which the samples were taken varied from thick, relatively clean coal seams to thin, impure, coaly layers. Because all of the samples were collected at or near outcrop surfaces, there was concern that some might be so badly weathered as to be unusable. Microscopic examination showed that, although nearly all samples displayed some evidence of weathering, it was possible, by careful selection, to find large particles seemingly unaffected and to carry out reflectance determinations near the center of such particles. In most instances, reflectance histograms showed good unimodal distribution patterns. In a few samples, the abundance of mineral matter forced prolonged searches for vitrinite masses large enough to provide reliable measurements.

Results

Thirty-eight samples from coal seams or from beds containing coal were examined, and their mean maximum reflectance values and standard deviations are presented in Table 1. Standard deviations for individual samples range from 0.04 to 0.13. The mean values are also plotted in Figure 22, which is a depth-reflectance profile. The plotted curve in Figure 22 is a computer generated, best fit, second-order regression line with a correlation coefficient of 0.968. Despite evidence of weathering in a number of samples, the plotted points lie along a fairly well defined path. The two samples obtained from near the 600 m level are exceptions. They show reflectivities considerably higher than would appear warranted for their position in the section. These samples were re-analyzed but no appreciable changes in their values were obtained. Neither one shows weathering characteristics markedly different from most of the other samples. In any case, weathering would probably lower the reflectance values rather than increase them (Bustin, 1980; Marchioni, 1983). Repetition of strata by an undetected thrust fault or a local increase in bireflectance may result in the presence of anomalous reflectivities.

The reflectance values obtained for the total suite of samples range from 1.30 to 2.49 and represent coals of medium volatile bituminous to semi-anthracite rank. The reflectance boundaries between these ranks are plotted on Figure 23 and follow the relationships shown in Davis (1978). To a certain degree, such boundaries should be viewed as approximations, since volatile matter-reflectance relationships are affected by variations in the maceral contents of the coals. ASTM rank boundaries above high volatile A bituminous are based on volatile matter contents determined on the whole coal, whereas reflectance determinations are made on vitrinite only and, in a strict sense, can only be related to the volatile matter of the vitrinite. Because the major maceral constituent in most coals is vitrinite, the errors involved are not great and diminish with increase in rank. However, for coals with high contents of other maceral groups (inertinite and/or liptinite), the relationship between reflectance as determined on vitrinite, and volatile matter as determined on the whole coal, may show a wider discrepancy. This point has been made in the published work of a number of authors including McCartney and Teichmüller (1972), Pearson (1980), and Marchioni (1983).

The relatively smooth profile shown in Figure 22 substantiates the field evidence that this particular Kootenay section is internally undisturbed in a structural sense, with the possible exception noted earlier at the 600 m level. If most of the coalification had taken place prior to faulting, major faults would show up in such a profile as sharp displacements of the trend line either to right or left. Thrust faults would result in a repetition of rank values in the profile, whereas normal faults would result in omission. If the major part of the coalification occurred after faulting, then the structural effects may be largely masked in the smoothness of the reflectance-depth profile.

TABLE 1

Summary of reflectance data on Mount Allan samples

Position* (m)	$R_o$max	Standard Deviation	Position (m)	R_o max	Standard Deviation
929.8	1.30	0.06	433.3	1.80	0.06
922.6	1.35	0.07	413.0	1.83	0.06
804.5	1.43	0.04	376.6	1.92	0.06
676.3	1.63	0.04	364.8	1.99	0.06
663.0	1.50	0.04	362.3	1.86	0.06
609.2	1.65	0.05	349.6	1.91	0.05
599.4	1.83	0.04	327.8	1.98	0.06
585.8	1.89	0.07	324.5	1.91	0.07
559.6	1.63	0.05	320.3	2.00	0.07
543.0	1.70	0.07	308.7	2.06	0.07
537.9	1.66	0.07	297.1	2.07	0.11
511.1	1.77	0.06	295.8	2.00	0.08
508.4	1.75	0.05	255.0	2.18	0.18
499.3	1.84	0.05	232.0	2.13	0.08
487.2	1.82	0.05	171.6	2.16	0.07
476.6	1.76	0.09	122.8	2.30	0.13
464.1	1.87	0.06	122.2	2.35	0.10
462.4	1.81	0.05	95.5	2.29	0.06
447.4	1.80	0.04	57.0	2.49	0.09

*Height in metres above base of Mist Mountain Formation - add 15 m to compare to section measurements in Figure 6.

Comparison with other Kootenay sections

Rank data on coals of the Kootenay Group have been reported by several other authors. Norris (1971, p. 30) prepared a plot of fuel ratio versus depth for coals in the Canmore area of the Cascade Coal Basin. Hacquebard and Donaldson (1974) described rank-depth profiles for six Kootenay sections including the Canmore field. Graham et al. (1977) published reflectance data for coals cut in a series of boreholes in the upper Elk Valley of British Columbia (EV-holes), and Pearson and Grieve (1978, 1979, in press) discussed various aspects of rank variations in the Fernie Basin and Elk Valley. Rank data for sections at Barrier Mountain (NTS Map 82 O/12E) and at Mist Mountain (NTS Map 82 J/10W) can be found in Gibson (in press). The geographic locations of these sections places them roughly on a northwest-trending line, 266 km long, extending from the Natal-Sparwood area of southeastern British Columbia (about 190 km south of Mount Allan), to Barrier Mountain in Alberta (about 80 km northwest of Mount Allan). This line of section is within the Rocky Mountains and roughly parallels their trend.

In Table 2, some of the data from these earlier studies are summarized and compared with those obtained at Mount Allan. In this table, a wide variation between sections is evident from the reflectance ranges (column 2) and first order reflectance gradients (column 4). Reflectance values vary from a low of 0.64 in the Elk Valley holes to a high of 2.65 at Canmore. Reflectance gradients vary from a low of 0.068/100 m in the Elk Valley holes to 0.200/100 m at Canmore. First order reflectance profiles for these sections are illustrated in Figure 23, which shows a clear segregation, by virtue of their higher rank, of the northern sections from the sections to the south. Most of the coals in the southern Kootenay sections are medium- to high-volatile bituminous in rank, with some low volatile coals reported by Pearson and Grieve (1978, 1979). Most of the coals in the Canmore, Barrier Mountain and Mount Allan sections are low volatile bituminous to semi-anthracite.

Reflectance data from the Mount Allan section have been plotted as a second order curve in Figure 22, so that a common phenomenon in these profiles can be shown more clearly; that is, reflectance values show more change per unit of depth with the deeper, more mature coals. If, for example, the profile on Mount Allan is divided into upper and lower straight line segments, as shown in Figure 24, the reflectance gradient of the former is 0.104/100 m, and of the latter is 0.165/100 m. Rank gradients between sections can therefore be compared only for similar rank values, as was stressed by Diessel (1975). Variable gradient, second-order reflectance profiles have been noted elsewhere in the world within coals of similar ranks to those of Mount Allan (see for example Diessel, *op. cit.*). This variability is to be expected from what is known of the exponential increase in coalification reactions with increasing temperature.

To compare Mount Allan with the other Kootenay sections, best-fit, second-order regression curves were derived for all sections, and rank gradients were determined for the overlapped portions of these curves (columns 5, 6, 7 in Table 2). The ratio of gradients between Mount Allan and the other sections can be used as an indicator of the degree of similarity between gradients, and appears in column 8 of Table 2. From these ratios it is evident that rank gradients on Mount Allan are similar to those in the sections at Sparwood, Fording River, Natal and Barrier Mountain (within 14%); and are markedly lower than at Mist Mountain (36% greater), Line Creek (61% greater) and Canmore (40% greater). No comparative calculations were made for the EV (Elk Valley holes) section, because there is no overlap with Mount Allan; or for the Highwood section, because rank values for this section were determined from chemical analyses.

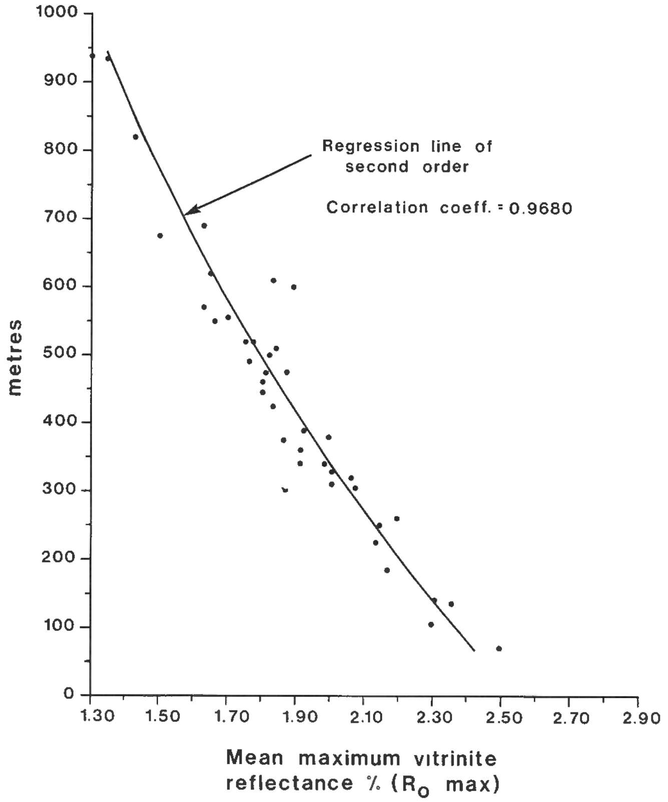


Figure 22. *Depth-reflectance profile for the Mount Allan section. Seam position is measured from base of Mist Mountain Formation. Add 15 m to determine section position in Figure 6.*

The considerable difference in coalification gradients between Mount Allan and Canmore (the sections are only 12 km apart) is anomalous. Table 2 shows that for comparable parts of the two sections the gradient is 0.197/100 m for Canmore and only 0.141/100 m for Mount Allan. There are, however, differences in the sources of the samples: the Mount Allan samples are from outcrop, and, as indicated earlier, may show varying degrees of weathering; many of the Canmore samples were collected in mine workings or test adits, and, therefore, are presumably somewhat fresher. Marchioni (1983) has indicated that for the Rocky Mountain coals investigated during his weathering of coal study, all the outcrop samples showed lower reflectances than their fresh counterparts, and he suggested that, in order to arrive at an approximate value for the fresh coal, one should add up to 10 per cent to the reflectance determined on the weathered coal. This was done with the Mount Allan samples. According to this procedure, adjustments were made for those samples where the degree of weathering had been indicated as severe and for which the reflectivity histograms showed a diffuse or bimodal character. Regression analysis for the whole section including those adjusted values showed little change. The correlation coefficient was 0.932 and the first-order reflectance gradient was 0.118/100 m, compared to 0.123/100 m for the unadjusted section. The procedure was repeated but this time all the Mount Allan values were

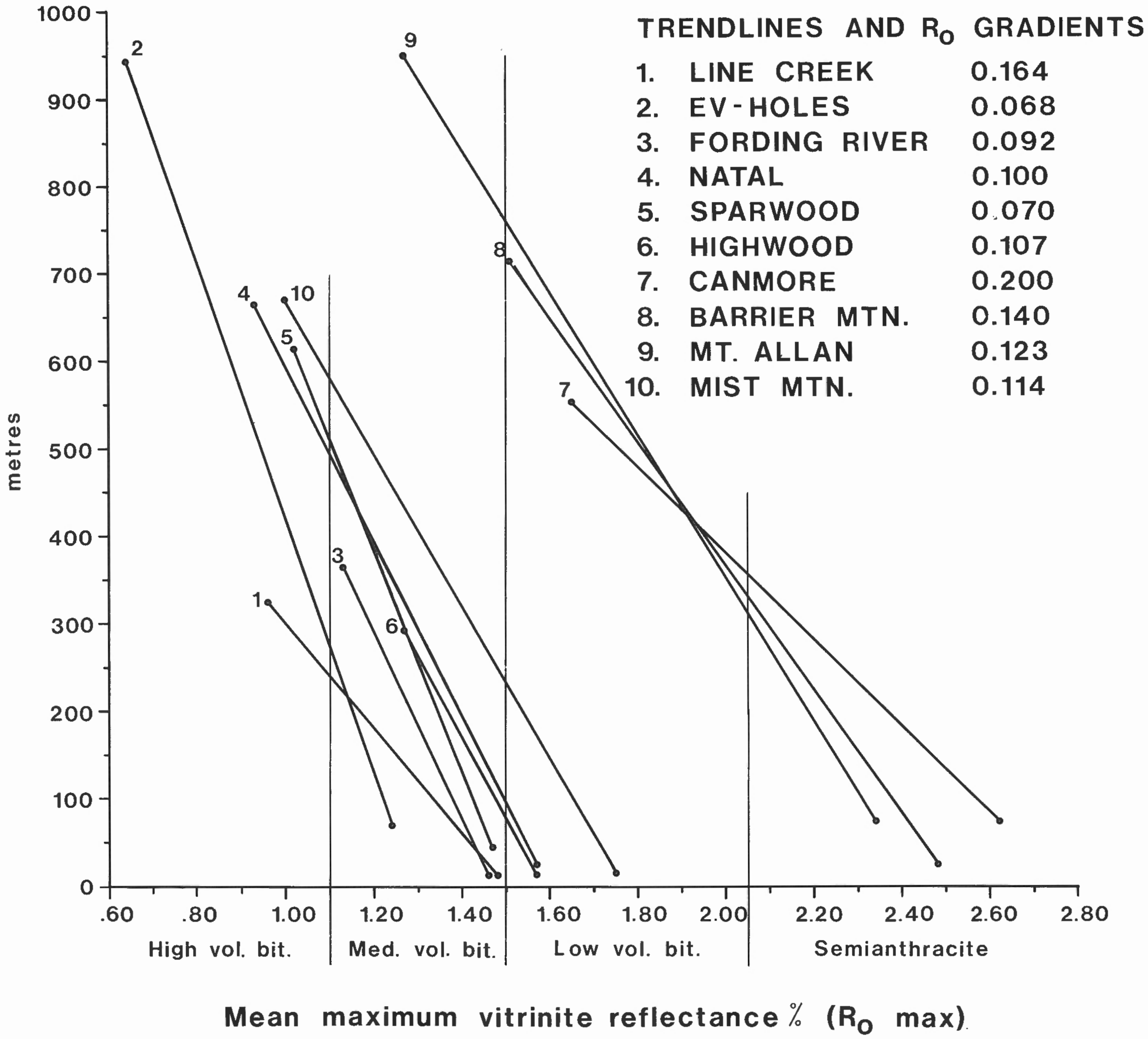


Figure 23. *First order, depth-reflectance profiles for Kootenay sections in the southern Canadian Rocky Mountains (see Table 2 for raw data). "O" metres = base of Mist Mountain Formation.*

adjusted upward by 10 per cent. The calculated gradient was increased somewhat by this manipulation to a value of 0.136/100 m. A plot of the adjusted trend is shown in Figure 25. A possible explanation for the Mount Allan-Canmore discrepancy may be that rank data from the Canmore profile were composited from several locations. A complete section is not exposed at any one locality due to the largely covered and structurally complex nature of the coal-bearing strata in the area, hence stratigraphic separations between seams for this profile may have been underestimated.

Discussion of rank-burial relationships

The published literature on relationships between temperature, depth of burial, duration of burial and resulting rank of carbonaceous material has become quite voluminous. Much of the recent impetus for research on this problem has come from the interest in oil and gas exploration. The same basic principles apply in studies relating to rank changes in coal-bearing sequences. In fact, early studies on the subject were related to coal rank change per se. Some of the more important papers dealing with this subject have been those of

TABLE 2

Comparison of rank data from Mount Allan section with other Kootenay sections

1 Section	2 R_o max[1] Range (%)	3 Stratigraphic Interval (m)	4 First order R_o max gradient[2] (%/100 m)	5 R_o max Range of Overlap with Mount Allan[3] (%)	6 Mount Allan[4] R_o max gradient For overlap (%/100 m)	7 Other section[4] R_o max gradient For overlap (%/100 m)	8 Gradient Ratio Other sections/ Mount Allan
Mount Allan	1.30-2.49	873	0.123	-	-	-	-
Highwood	1.28-1.58	282	0.107	-	-	-	-
Fording River	1.13-1.43	337	0.092	1.30-1.43	0.080	0.069	0.86
Line Creek	0.97-1.49	308	0.166	1.30-1.49	0.083	0.134	1.61
Natal	0.94-1.50	639	0.096	1.30-1.50	0.084	0.074	0.88
Sparwood	1.04-1.45	573	0.078	1.30-1.45	0.081	0.074	0.91
Canmore	1.67-2.65	477	0.200	1.67-2.49	0.141	0.197	1.40
EV-holes	0.64-1.24	875	0.068	-	-	-	-
Barrier Mountain	1.48-2.50	692	0.140	1.48-2.27	0.124	0.122	0.98
Mist Mountain	0.98-1.74	668	0.114	1.30-1.74	0.98	0.128	1.36

[1] measured reflectance values

[2] from first order regression equation

[3] R_o range from best-fit second order curve

[4] R_o gradient from best-fit second order curve

Data in columns 2 and 3 from Hacquebard and Donaldson (1974) for Highwood, Fording River, Line Creek, Natal, Sparwood, and Canmore sections; from Graham et al. (1977) for EV-holes.

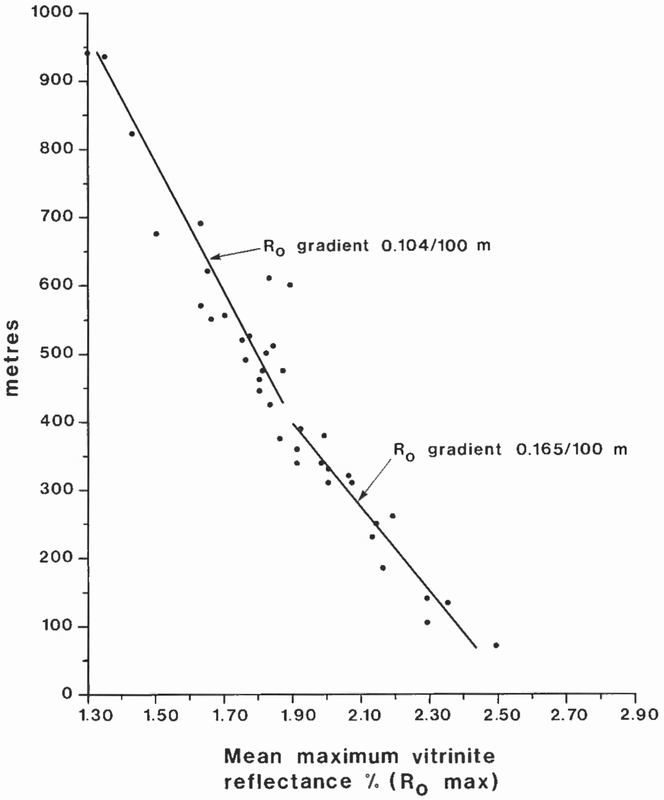


Figure 24. First order reflectance gradients for upper and lower parts of the Mount Allan section. Seam position measured from base of Mist Mountain Formation. Add 15 m to determine section position in Figure 6.

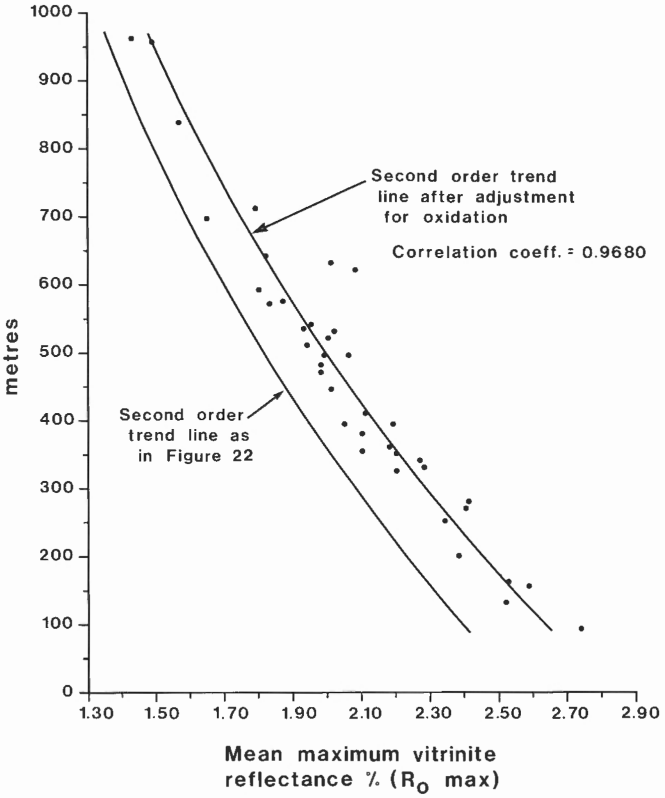


Figure 25. Mount Allan depth-reflectance profile corrected for oxidation. Seam position measured from base of Mist Mountain Formation. Add 15 m to determine section position in Figure 6.

Huck and Karweil (1955), Karweil (1956), M. Teichmüller and R. Teichmüller (1966, 1979), and Bostick (1974). Bostick (1979) summarized much of the current thinking in a review article. An important additional reference is a publication entitled Inkohlung und Geothermik (editor H.D. Hilden), also published in 1979.

From the literature, the following two important principles have emerged:

1. Time and temperature, at least to a certain extent, are interchangeable in producing a given rank; that is, burial for a short time at a relatively high temperature will produce the same degree of coalification as longer burial under lower temperatures.
2. The exponential effect of temperature increase on reaction rate implies that the maximum temperature reached is very important in determining the final rank of a coal, and in many cases the major part of the coalification of a given seam appears to be conferred by the last few 10° increments of temperature increase.

Though supported by field evidence in many instances, there is risk of oversimplifying the concept of exponential effect, as coal maturation is not a single reaction but is the product of an aggregate of reactions complexly influencing one another. However, the important factors in determining the rank of a coal seam appear to be depth, duration of burial, and geothermal gradient.

The post-depositional geologic history of the Kootenay coal seams is complex, hence resultant burial histories of individual coal seams and regional coalification patterns can also be expected to be complex. Kootenay sedimentation was followed by deposition of varying thicknesses of the Blairmore and Alberta groups and the Belly River Formation, and an unknown thickness of younger Cretaceous sediments. All these sediments were deposited within westward thickening clastic wedges, thus burial depths should increase westward. Tectonism, culminating in the late Cretaceous to early Tertiary Laramide Orogeny deformed Precambrian to early Tertiary rocks, resulting in the complexly deformed terrains presently exposed in the Rocky Mountains. Uplift and erosion since early Eocene time has removed unknown thicknesses of late Cretaceous and early Tertiary sediments deposited during and subsequent to this period of tectonism, as well as older sediments.

Several authors have studied regional coalification patterns in the southern Canadian Rocky Mountains, and have offered possible explanations for the rank variations they observed. Norris (1971, p. 31) suggested that coalification was primarily a result of pre-Laramide sedimentary loading. He also suggested that the high ranks at Canmore may be due to a higher geothermal gradient in that area compared with localities farther south, as the style of deformation and pre-Laramide burial history for the two areas appear similar. Norris (*op. cit.*) suggested that this elevated geothermal gradient may relate to a metamorphic halo (Price and Mountjoy, 1970), outlined by biotite, garnet, and staurolite-kyanite isograds, which extends up to 15 km into the western Rocky Mountains between Valemont and Golden, about 150 km west-northwest of the Mount Allan area. Hacquebard and Donaldson (1974) also suggested that coalification was primarily a result of pre-Laramide sedimentary loading, and related the high ranks and rank gradient at Canmore and the high rank gradient at Line Creek to elevated geothermal gradients. They postulated on these grounds (*op. cit.*, p. 89) that there have been marked variations in the geothermal gradient throughout the Rocky Mountain and Foothills regions. In contrast to earlier authors, Pearson and Grieve (1978) suggested, on the basis of rank variations noted within inclined seams in the Fernie basin, that at least part of the coalification had occurred during and subsequent to deformation of the coal seams. They noted that the coal rank varies with topographic position and also across thrust faults, and suggested (*op. cit.*, p. 11) that "... tectonically uplifted coals have been subjected to lesser amounts of burial cover, and hence have received relatively small amounts of post-faulting coalification".

On the basis of rank data published by Hacquebard and Donaldson (1974) and Graham et al. (1977), and unpublished data provided by A.R. Cameron for the Mist Mountain and Mount Allan sections, one of the authors (Hughes) suggested that, if a portion of coalification in the Kootenay Group is post-deformational, as indicated by Pearson and Grieve (*op. cit.*), loading by overthrust fault plates may have been an important factor in the coalification history of areas in the footwall of major thrust faults, and may be responsible for much of the regional rank variations observed within the Kootenay Group. Evidence in support of this theory is as follows:

1. Sections with anomalously high ranks at Canmore and Mount Allan lie in the immediate footwall of the Rundle Thrust Fault, and were undoubtedly overridden by the hanging wall plate. This is true also of the section at Barrier Mountain, which lies in the footwall of the Clearwater Thrust, the hanging wall plate of which is similar in thickness and lateral displacement to that of the Rundle Thrust.
2. The section at Mist Mountain, in the footwall of the Lewis Thrust, shows much higher ranks than the section in the EV-holes located 10 km west in its hanging wall, suggesting that loading by the Lewis plate may have elevated the ranks at Mist Mountain.
3. Coals at the base of the Kootenay Group in the Crowsnest Pass area of Alberta, in the footwall of the Lewis Thrust, have similar ranks to coals in its hanging wall at Corbin and Tent Mountain. If coalification is related only to pre-deformational sedimentary loading, the Tent Mountain and Corbin coals should have higher ranks because overlying Kootenay, Blairmore and younger strata are much thicker there than in the Crowsnest Pass area (Norris, 1964; Price, 1962). Loading by the Lewis or other fault plates may have provided the additional depth of burial required in the Crowsnest Pass area to account for the ranks observed there.
4. Reflectance-depth profiles for the Mount Allan section appear to follow a second-order curve, in common with coals of similar rank elsewhere in the world. If rank gradients between Kootenay sections are compared over similar reflectance ranges, gradients between all sections except Canmore, Mist Mountain and Line Creek are similar (within 14%), suggesting that geothermal gradients in these areas were similar. If the high ranks at Canmore are related to greater loading there than at the other locations, it is not necessary to invoke a higher geothermal gradient in this area to explain them. Differential loading between localities could result from different pre-Laramide sedimentary thicknesses, or the presence or absence of an overthrust plate, or a combination of both factors.

The important element which distinguishes pre- from post-deformational coalification is that in the former case iso-rank lines are oriented parallel to bedding and that, as the amount of post-deformational coalification increases, the iso-rank lines intersect bedding lines in inclined strata at increasingly larger angles (see Figure 21.8 in Diessel, 1975). If some coalification post-dated deformation, the orientation and position of iso-rank surfaces would depend on the geothermal gradient, the proportion of pre- and post-deformational coalification, and the duration of specific burial regimes. In addition, the rank gradients and ranks noted at a specific location would depend on bedding orientation and orientation of the line of section. A detailed study of these relationships in the southern Canadian Rocky Mountains is currently being conducted by the authors.

Rank-burial relationships in the Mount Allan Section

An interpretation of coalification at Mount Allan is fraught with many uncertainties because of the complex stratigraphic and structural history of the area. Important pieces of information are missing and only approximations can be made for them, based on the overall history of the Kootenay Group and post-Kootenay events in the Cascade Coal Basin. These missing or uncertain data fall into the following categories:

1. The maximum thickness of post-Kootenay sediments.
2. The role played by the Rundle Thrust Fault.
3. Timing of events and hence the duration of burial regimes.
4. Geothermal gradients.

In view of the uncertain nature of these variables, several possible geological scenarios for the Mount Allan section were developed, and the burial history and geothermal gradients in each were used to calculate theoretical ranks and rank gradients utilizing Lopatin techniques (1971). These theoretical ranks and rank gradients were then compared with the observed values to test each scenario's validity.

The Lopatin model involves the calculation of a time-temperature index (TTI) and the correlation of this index with some rank parameter such as vitrinite reflectance. The model is based on the assumption that coalification is an exponential process and that the rate doubles for every 10°C rise in temperature. A description of the Lopatin technique and an evaluation of its application to oil and gas exploration has been published recently by Waples (1980). According to Waples, calculated TTI values consistently agree with other maturation indices.

The TTI is obtained by dividing the temperature history of a given stratigraphic unit into 10°C increments based on the unit's burial history and geothermal gradient. To each 10° segment, a temperature factor is assigned which takes into account the exponential nature of reaction rates. This factor is then multiplied by the time in millions of years that the rock unit in question has remained within the 10° temperature segment. The sum of the values thus obtained for the total burial time of the bed is its TTI. Reflectances can be calculated from the TTI using the following equation, developed from the data in Table 4 of Waples (1980):

$$\text{Log } R_o = -0.4769 + 0.2801 (\log \text{TTI}) - 0.007472 (\log \text{TTI})^2$$

Models have been set up to calculate TTI values for two beds in the Mount Allan section, one at 57 m, termed Bed A, and another at 929.8 m, termed Bed B. The reflectance values and the gradient between these beds derived from the first-order regression line are 2.34 for Bed A and 1.27 for Bed B, with a reflectance gradient of 0.123/100 m (see Line 9 in Fig. 23). These values were used to make comparisons with theoretical rank values using Lopatin's method. Considerations and assumptions made about the post-Kootenay geologic history of the Mount Allan area in constructing these time-burial models are outlined below.

Maximum thickness of post-Kootenay strata

The youngest rocks presently exposed in the Cascade Basin are 250 m of Blairmore Group preserved in the core of the Mount Allan Syncline on Mount Allan. Estimates of post-Kootenay, pre-Laramide sedimentary thickness must therefore be based on extrapolation from areas which, when palinspastically restored to their pre-Laramide position, were some tens of kilometres east and south of Mount Allan. The following estimates are based on extrapolations from existing reports and on considered geologic opinion, and must therefore be viewed only as approximations with a wide tolerance for error. The total thickness of Blairmore Group strata is estimated to have been originally about 1000 m, based on a slight northward extension of the palinspastically derived Blairmore isopachs of Norris (1964). The thickness of the overlying Alberta Group is estimated to have been 640 m (Stott, pers. comm., 1981), and of the Belly River Formation 1220 m (Norris, pers. comm., 1981). Altogether, this represents a possible total thickness of 2860 m of post-Kootenay strata. A more doubtful possibility would be the presence in this area at one time of still younger beds belonging to the Bearpaw, St. Mary River, and Willow Creek formations. These may have totalled 1700 m in thickness.

A range for post-Kootenay sediment thickness of between 2500 m and 6500 m was used in different time-burial models because of the uncertain nature of these estimates.

Role of the Rundle Thrust Fault

There is little doubt that the Rundle plate overrode the study area, for its present outcrop lies immediately to the southwest. The effect of frictional heat generated along the thrust plane was probably quite local and of negligible importance. This has been demonstrated elsewhere in thrust fault regimes (Norris, 1971; Hacquebard and Donaldson, 1974; Stach et al., 1975). A potentially more important effect would be the loading of an additional thickness of rock, that is, the thickness of the plate itself, over the coal-bearing strata. This would result in deeper burial and correspondingly higher temperatures. Another possible effect associated with faults might have been the disruption of normal heat flow patterns. In some instances, rocks in the footwall might have been cooler than those in the hanging wall, particularly if hanging wall rocks were emplaced rapidly, and some time might have elapsed before a normal temperature profile was re-established. Also, significant differences may have existed between the thermal conductivity of the rocks in the thrust plate and that in the original cover over the coals. Finally, the movement of hydrothermal fluids or groundwater might have been facilitated or at least altered by faulting, which would result in changes in the temperature regime affecting the coals.

Thrust faults in the Rocky Mountains are inclined surfaces which tend to cut upsection in both hanging wall and footwall in the direction of hanging wall displacement (Bally et al., 1966). In order to assess the possible effects of an overthrust plate on the rocks at a particular locality it is therefore necessary to first estimate the original thickness of the fault plate and the position of the projected fault plane above the locality. From a consideration of the regional geology of the Mount Allan area, as discussed in an earlier section, a reasonable estimate of the position of the Rundle Fault above the top of the Kootenay Group in the section is about 1200 m, with a plate thickness of about 2500 m (Fig. 2; Sec. B-B'). This model implies that the Rundle Thrust displaced about 1650 m of the estimated 2850 m of post-Kootenay sediments, and replaced them with a 2500 m thick plate, resulting in a net increase in load of about 850 m.

A range in fault plate thickness of between 2000 m and 4000 m was used in different time-burial models, although the position of the projected fault plane, about 1200 m above the top of the Kootenay Group in the Mount Allan section, was considered constant for all models.

Timing of events

The timing of geologic events is critical in assessing the magnitude and duration of burial regimes. For this study, use was made of dates on geotectonic charts by Douglas et al. (1970), who in turn had incorporated dates from Harland et al. (1964). Significant geologic events and their approximate timing are assumed to be as follows:

1. Deposition of 964 m of strata between the lowermost coal seam (Bed A) and the top of the Kootenay Group -- 141 to 129 Ma.
2. Deposition of 1000 m of Blairmore Group -- 129 to 100 Ma.
3. Hiatus -- 100 to 94 Ma.
4. Deposition of 640 m of Alberta Group -- 94 to 81 Ma.
5. Deposition of 1220 m of Belly River Formation and younger strata -- 81 to 65 Ma.
6. Laramide deformation and emplacement of Rundle thrust sheet -- 65 to 55 Ma.
7. Erosion and uplift -- 55 Ma to present.

The above time frame for this sequence of events was held constant for all time-burial models, although the amount of sediment deposited within each period was varied.

Geothermal gradients

The present geothermal gradient in the Mount Allan area is estimated to be between 2 and 2.5°C/100 m, based on AAPG maps of heat flow distribution patterns in Alberta (AAPG and USGS, 1976). This would appear to be too low to bring about the coal ranks at Canmore and Mount Allan, even assuming great depths of burial in the past. For example, with a constant geothermal gradient of 2.25°C/100 m, Lopatin's model requires a burial depth of about 6000 m for a period of 85 million years to produce the reflectance of 2.49 measured in the lowest seam at Mount Allan. This seems unlikely according to what is known of the geological history of the area. In addition, the rank gradient under such conditions would be lower than the present gradient at Mount Allan. Therefore, we must assume that a higher geothermal gradient existed in the past, which decreased to the lower values present today.

Three geothermal gradient scenarios were considered in the time-burial models. In the first, high geothermal gradient values were assumed to persist from the time of deposition of the Kootenay Group to 60 Ma, midway through the Laramide Orogeny, and then decrease linearly to the present values. In the second, similar assumptions were made except that the higher geothermal gradient was assumed to drop to present values over the 10 million year period between 60 and 50 Ma. In the third, cooling was assumed to begin at 65 Ma, reaching present values at 50 Ma. A range in values from 2.25 to 5.5°C/100 m was used in the time-burial models for the maximum geothermal gradients.

Procedure

The procedure followed was to construct a series of time-burial models for beds A and B of the Mount Allan section, each model differing in terms of depth of burial and other details of deposition. On each of these models different temperature grids, corresponding to different geothermal gradients were superimposed. TTI values were determined for each model and corresponding reflectance values and gradients calculated. The burial history and geothermal gradients used for one such model are illustrated in Figure 26. Assumptions made in this example are the "best-estimates" of post-Kootenay sediment thickness, position and thickness of the Rundle plate, and timing of the events discussed above. In this model, a geothermal gradient which decreases over a 10 million year period from 3 to 2.25°C/100 m has been superimposed. TTI values calculated for each 10°C increment in this model appear in Table 3. Theoretical reflectances calculated from these TTI's, using the equation cited earlier, are 1.39 for Bed A and 0.88 for Bed B, with a reflectance gradient of 0.058/100 m. Geothermal gradients of 3.5, 4.0 and 4.5°C/100 m were also superimposed on this time-burial model and the theoretical reflectances and gradients calculated are given in Table 4. From these data, a curve of theoretical reflectance values versus geothermal gradient can be derived, for each bed, as well as a curve relating theoretical reflectance gradient to geothermal gradient, as shown in Figure 27. Utilizing these curves, the reflectance values and gradients determined from the first-order regression line on Mount Allan can then be related to the causative geothermal gradient. For example, in this particular time-burial model, the 2.34 reflectance of Bed A indicates a geothermal gradient of 3.97°C/100 m, the 1.27 reflectance of Bed B indicates a geothermal gradient of 3.81°C/100 m (Fig. 27A), and the 0.123/100 m reflectance gradient indicates a geothermal gradient of 4.09°C/100 m (Fig. 27B). The degree of correspondence between the three indicated geothermal gradients determined from the observed reflectance values is a measure of the relative validity of a particular time-burial model; in this example, variation between the indicated geothermal gradients has a range of only 0.28°C/100 m.

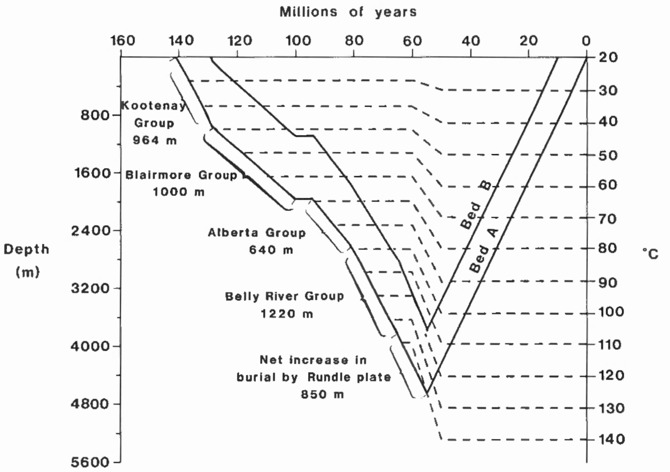


Figure 26. *Time-burial model for Mount Allan section, with iso-temperature lines illustrating method utilized to determine TTI (see text).*

A number of time-burial models were tested in this manner, each with a series of geothermal gradients superimposed. The range of variation in indicated geothermal gradients was calculated for each model and is plotted against the maximum depth of burial of Bed A in Figure 28. An interesting trend is revealed in this plot. The points plotted in Figure 28 appear to show three populations, which are identified as A, B and C. The time-burial models represented by the points in population A show the least amount of variation in their calculated geothermal gradients. They also show the lowest maximum depth of burial for Bed A, between 3800 and 4600 m. An average depth of burial for population A is 4200 m with an average geothermal gradient of 4.3°C/100 m over approximately the first half of the burial history, from 141 to 60 Ma. This compares to a maximum depth of burial of 4674 m, which is indicated if "best-estimate" values are used for the thickness and position of the Rundle fault plate and the thickness of the post-Kootenay sedimentary load. A maximum temperature calculated for this depth of burial and geothermal gradient, assuming a 20°C average surface temperature, would be in the order of 200°C. Populations B and C represent models with a greater maximum depth of burial and show greater variations in the calculated geothermal gradients.

One series of calculations was made for a maximum depth of burial of 3000 m using geothermal gradients of 5.5, 6.0, 6.5 and 7.0°C/100 m. A plot of the resulting data showed a maximum difference in calculated geothermal gradients of >1.05, that is, a number which would plot above the vertical axis range shown in Figure 28. This suggests that for depths of burial less than 3500 m the trend shown in Figure 28 would bend sharply upward, lending credence to the indicated best-fit averaged depth of burial of 4200 m and average geothermal gradient of 4.3°C/100 m. In addition, calculations were repeated for the model shown in Figure 26, with two changes in the model parameters. Movement on the thrust fault was postulated to have begun at 70 Ma instead of 65 Ma and emplacement to have been completed in 2 m.y. instead of 10 m.y. The calculated reflectances and R_o gradients for the adjusted model are shown in Table 4. The calculations showed surprisingly little difference from those obtained from the original model shown in Figure 26. One reason for this is that the maximum depth part of the burial lines for the two seams has not really changed but instead has been shifted relative to the position of the thrust fault, so that resulting calculations show little variance.

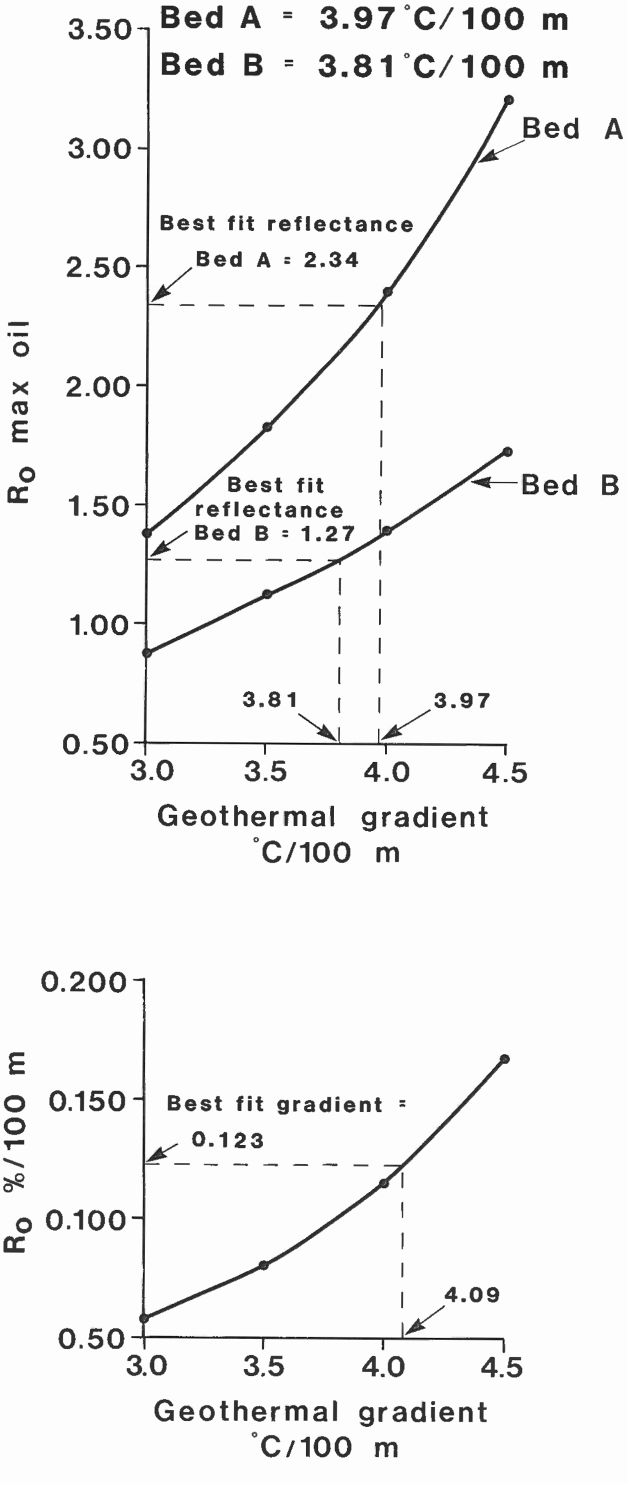


Figure 27. *A - Reflectance values calculated for time-burial model in Figure 26 [using Lopatin's (1971) technique] for several geothermal gradients, illustrating method of determining the geothermal gradient from the best-fit rank data. B - Relationship of reflectance gradient calculated for time-burial model in Figure 26 (using Lopatin's technique) to geothermal gradient, illustrating method of determining the geothermal gradient from the best-fit rank gradient.*

TABLE 3

Calculation of TTI values derived from Figure 26

BED A				BED B			
Temperature Interval °C	Temperature Factor	Δ Time M.y.[1]	Interval TTI[2]	Temperature Interval °C	Temperature Factor	Δ Time M.y.	Interval TTI
20-30	0.0039	9.73	0.04	20-30	0.0039	13.61	0.0
30-40	0.0078	9.74	0.08	30-40	0.0078	14.89	0.12
40-50	0.0156	10.93	0.17	40-50	0.0156	14.90	0.23
50-60	0.03125	14.43	0.45	50-60	0.03125	18.80	0.59
60-70	0.0625	14.44	0.91	60-70	0.0625	12.00	0.75
70-80	0.125	20.13	2.52	70-80	0.125	10.40	1.30
80-90	0.25	11.93	2.98	80-90	0.25	8.63	2.16
90-100	0.5	11.74	5.87	90-100	0.5	7.64	3.82
100-110	1	9.60	9.60	100-110	1	7.53	7.53
110-120	2	7.46	14.92	110-120	2	10.60	21.20
120-130	4	6.67	26.68				
130-140	8	7.80	62.40				
140-150	16	6.40	102.40				
TOTALS		141.00	229.02			119.00	37.75

[1] Time in millions of years.
[2] TTI = Temperature factor x Δ time.

TABLE 4

Calculated maximum reflectances for beds A and B at different geothermal gradients

	BED A		BED B		
Geothermal[1] Gradient	TTI	R_o	TTI	R_o	R_o[2] Gradient
3.0	229.02	1.39 (1.34)[3]	37.75	0.88 (0.88)[3]	0.058 (0.053)[3]
3.5	719.62	1.83 (1.84)	97.81	1.13 (1.12)	0.080 (0.083)
4.0	2259.95	2.39 (2.46)	226.70	1.39 (1.44)	0.115 (0.117)
4.5	8396.50	3.21	582.87	1.74	0.168

[1] °C /100 m

[2] % /100 m
[3] Values in parentheses obtained from adjusted model with plate movement initiated at 70 Ma and completed in 2 m.y.

It is tempting to suggest that the burial depth and geothermal gradient represented by the population A models in Figure 28 are close to the burial and thermal history of the Mount Allan area. The maximum suggested temperature of 200°C corresponds to that proposed by Hutcheon et al. (1980) as a result of their mineralogical studies of rocks from the Mount Allan area, although the geothermal gradient of 4.3°C/100 m is higher than the 3.3°C/100 m which they suggest from their studies. The required depths of burial for population A are not excessive, indeed they can be satisfied by the thickness of strata (3824 m) estimated for the interval from Bed A to the top of the Belly River Formation in the Mount Allan area, plus another 400 m which might be contributed by an increase in the thickness of any part of the Blairmore, Alberta, Belly River, or younger strata, or the Rundle plate. The geothermal gradient of 4.3°C/100 m is higher than normal and its proposed existence from the time of deposition to 60 Ma is probably not correct; however, this problem may not be as disturbing as it at first appears, as it is more important that the highest geothermal gradient more or less coincides with the time of deepest burial because of the exponential character of the coalification model. The effect of additional loading by the Rundle plate cannot be supported or disproved by this study of the Kootenay coal-bearing succession at a single site, although it is not inconsistent with results reported herein. More light might be cast on this question by the study of additional Kootenay sections in the vicinity of Mount Allan or elsewhere.

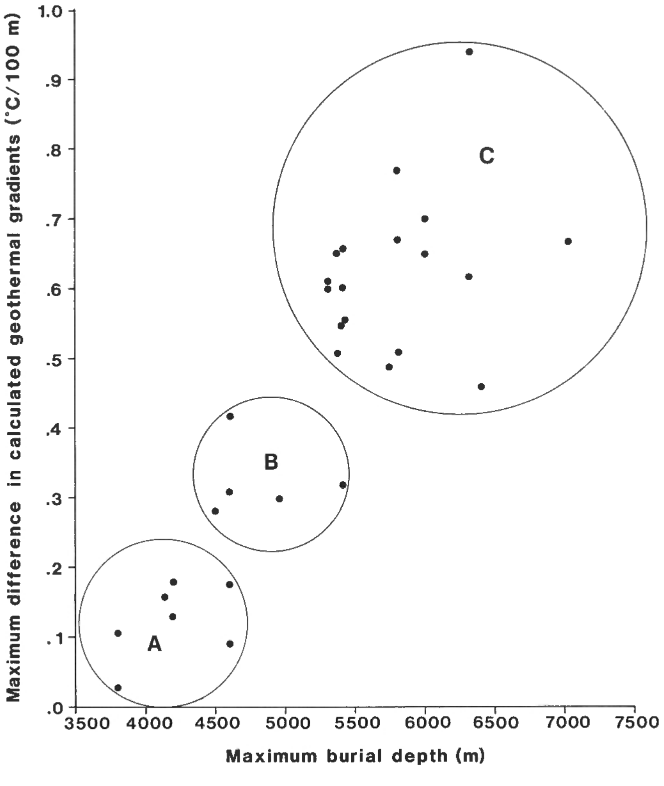


Figure 28. *Relationship of maximum burial depth in all time-burial models to maximum variation in calculated geothermal gradients (see text). A, B, C are apparent groupings of these models discussed in text.*

CONCLUSIONS

The Kootenay Group and adjacent strata within the Cascade Coal Basin form part of an eastward-thinning clastic wedge which has been segmented and deformed by faulting and folding during the Laramide Orogeny. Clastic sediments within the group were derived from source terrains located southwest of the basin which were undergoing deformation (Columbian Orogeny) during deposition of these strata. Systematic vertical variations within the group include an overall upward decrease in number, thickness and lateral continuity of coal seams; upward increases in the mean grain size of both fine and coarse deposits, in the ratio of coarse to fine deposits, in the lateral continuity of coarse deposits, and in the depositional energy level within individual grain size classes; and variations in clast composition, including a maxima for detrital carbonate in the middle of the group, and a marked change in pebble composition between the Elk-Pocaterra and Cadomin-equivalent conglomerates. These variations can be related to depositional setting and to the rocks exposed in the source areas for these sediments.

Coarsening-upward strata of the upper Fernie Formation are interpreted as prodelta and distal distributary mouth bar deposits laid down in front of north and northeasterly prograding, wave-dominated delta systems. Overlying laterally extensive sandstones of the Morrissey Formation represent distributary mouth bar sands which have been reworked and deposited within foreshore-beach-beach ridge-dune environments. Coarse grained, typically fining-upward units within the Mist Mountain Formation are interpreted as the deposits of meandering rivers, constrained to narrow meander belts, which flowed northeasterly across deltaic and alluvial plains. Intervening finer grained sediments, which include interbedded claystone, siltstone, fine grained sandstone and coal that comprise about ninety per cent of the formation, are interpreted as levee, crevasse splay, lacustrine and swamp-marsh deposits, which accumulated in interchannel floodplain areas by overbank sedimentation and in situ growth. The upward decrease in number and thickness of coal seams within the overlying Elk Formation, and the upward increase in lateral continuity of coarse deposits, reflect a change in channel morphology to high sinuosity meandering or braided with correspondingly higher rates of lateral migration, which may be related to an increase in paleoslope and deposition on more proximal parts of an alluvial plain. Floodplain deposits are generally coarser grained and comprise a smaller proportion of the Elk as compared to the Mist Mountain Formation, suggesting that floodplain areas were of smaller physical dimensions and more subject to overbank flooding and encroachment by laterally migrating channels. Accompanying these changes in depositional setting may have been a change to a more arid climate, which resulted in the absence of coal in the upper Elk and overlying lower Blairmore Group, and the presence of red weathering claystones in the Pocaterra Creek Member. Pebble and cobble conglomerates of the lower Blairmore Group and intervening finer grained strata represent deposition on mid- to distal-portions of alluvial fans. Unconformities of unknown magnitude are present beneath the basal Pocaterra Creek Member conglomerates and beneath the Cadomin-equivalent conglomerates.

Subsequent to deposition, Kootenay Group strata were buried by younger sediments estimated to be in the order of 2860 m thick, and deformed during the Laramide Orogeny, resulting in folding, faulting and the emplacement of the Rundle Thrust plate over the basin. A net increase in burial of about 850 m may have resulted. Based on vitrinite reflectance analysis, coal seams within the group appear to have been subjected to maximum temperatures in the order of 200°C during this burial process, resulting in the semi-anthracite to bituminous ranks observed in the basin. Geothermal gradients during the first part of the coal maturation process were in the order of 4.3°C/100 m, subsequently declining to the presently observed 2-2.5°C/100 m. Geothermal gradients at Mount Allan were probably similar to those at other widely separated localities in the southern Canadian Rocky Mountains, based on the similarity of rank-depth gradients at most locations. Uplift and erosion subsequent to Laramide deformation has exposed the basin at its present structural level.

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