Geology of the Princeton Basin

PAPER 1983 - 3

Province of British Columbia

Ministry of
Energy, Mines and
Petroleum Resources

GEOLOGICAL BRANCH
MINERAL RESOURCES DIVISION

Canadian Cataloguing in Publication Data

McMechan, Robert D. (Robert Douglas), 1953-
Geology of the Princeton Basin

(Paper, ISSN 0226-9430 ; 1983-3)

Bibliography: p.
ISBN 0-7718-8397-8

1. Geology - British Columbia - Princeton Region. I. British Columbia. Ministry of Energy, Mines and Petroleum Resources. II. Title. III. Series: Paper (British Columbia. Ministry of Energy, Mines and Petroleum Resources) ; 1983-3.

QE187.M32 1983 557.11'41 C84-092010-5

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Paper 1983-3

Province of British Columbia
Ministry of Energy, Mines and Petroleum Resources

Victoria, British Columbia
November 1983

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SUMMARY

The Princeton Basin, south-central British Columbia, is a half graben bounded on its eastern margin by a north-northeasterly trending, west-dipping extension fault that has a minimum stratigraphic separation in the order of 1 400 metres. The basin is filled with Paleogene strata of the Princeton Group. The basal strata consist of flows and related volcaniclastic rocks of the Lower Volcanic Formation that attain a maximum aggregate thickness of 1 370 metres. These are overlain by a minimum 1 700-metre thickness of coal-bearing, nonmarine terrigenous clastic and lesser volcaniclastic sedimentary rocks of the Middle Eocene Allenby Formation.

The Allenby Formation is informally subdivided into three members. Flows and tuffs that are intercalated predominantly with basal sedimentary strata of the Allenby Formation are designated as the 'volcanic member.' Sedimentary strata of the Allenby Formation that outcrop in the southern part of the basin can be subdivided on the basis of coal occurrence and proportion of volcaniclastic material into a lower clastic and an upper coal-bearing member. The four coal zones of historical economic importance (Princeton-Black-Blue Flame, Pleasant Valley-Jackson, Gem-Bromley Vale, Golden Glow) occur in the basal 530 metres of the 'coal-bearing member.' Other coal zones (Freeman, Allenby, Bethlehem) occur in the upper middle part of the preserved 'coal-bearing member.' Strata in the northern part of the basin appear to be a coarser and thicker lateral facies equivalent of the 'lower member' in the south, although precise correlation is uncertain.

Strata of the Allenby Formation have been deposited primarily in fluvial environments. The coarser northern facies probably represents a higher energy braided river depositional environment, whereas the finer southern facies probably represents a lower gradient, meandering river environment in which related backswamp, overbank/floodplain, and lacustrine environments were common. The coal probably accumulated as vegetative matter in peat (?) swamps in these latter environments. The distribution of facies, the variation in maximum clast size, the orientation of paleocurrent indicators, and the sediment provenance suggest that sedimentary strata of the Allenby Formation were derived largely from a terrane that lay to the north-northeast of the Princeton Basin, and that the Osprey Lake intrusive body supplied much of the arkosic detritus. Volcanic detritus was locally derived.

The Princeton Basin is shallower in the north than in the south. Strata of the Allenby Formation comprise a homoclinal, east-dipping panel in the northern part of the basin, whereas they outline a complex, deeper basin in the south that has been modified by faulting and folding. Gravity profiles across the basin outline variations in preserved thickness of Paleogene sediment fill, in places in excess of 1 200 metres, and clearly delineate anomalies associated with the known coal zones.

Historical coal production in the Princeton Basin is in the order of 1.8 million tonnes (2 million tons) of a subbituminous product. The coal seams exhibited marked lateral variability in thickness, character, and quality; the mining operations were often plagued with economic and geologic difficulties. Nevertheless, the Princeton Basin still contains a substantial coal resource that is probably two orders of magnitude greater than that previously mined. Stratigraphic and structural relationships within the Allenby Formation show that the southwestern part of the basin is the most promising for future coal exploration.

INTRODUCTION

The Princeton Basin covers an area of 170 square kilometres in south-central British Columbia (Fig. 1). Excellent access is provided by Highways 3 and 5, and the Jura road to the northeast, the Copper Mountain road to the southeast, the Tulameen road to the west, and numerous secondary roads (Fig. 2).

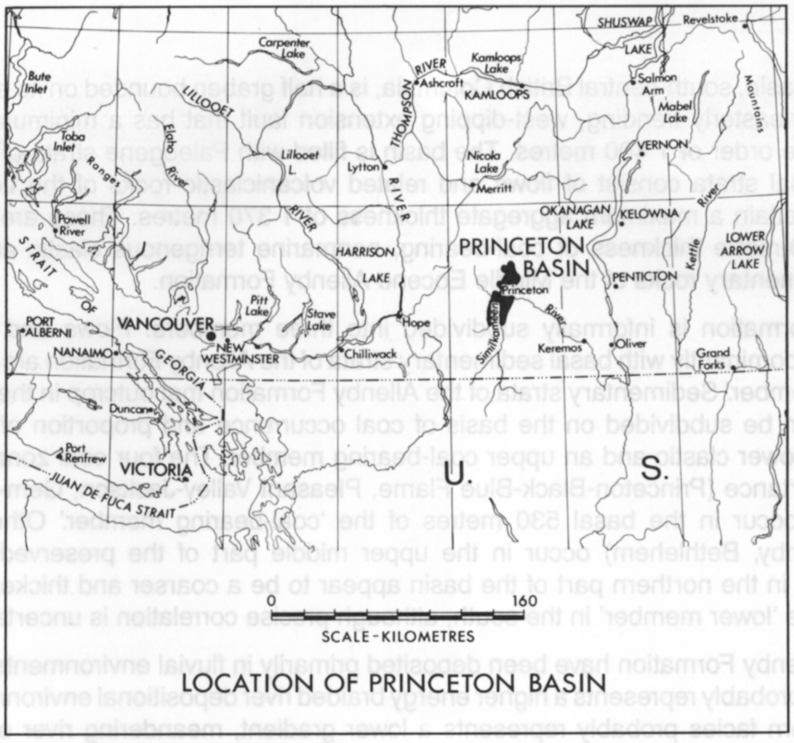


Figure 1. Location map of the Princeton Basin.

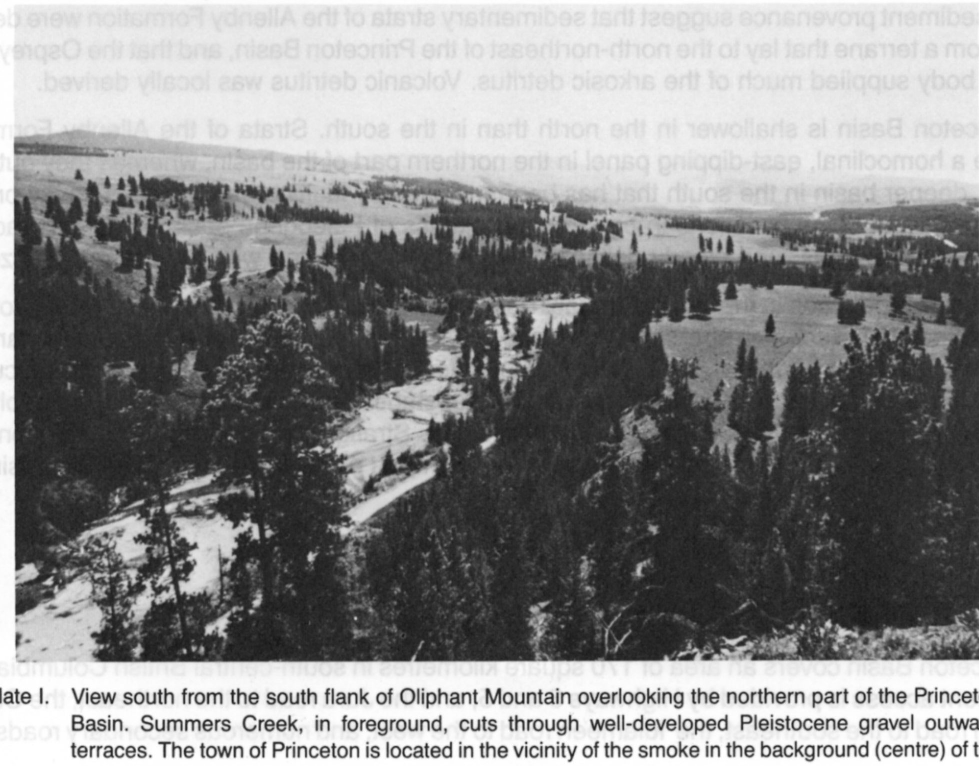


Plate I. View south from the south flank of Oliphant Mountain overlooking the northern part of the Princeton Basin. Summers Creek, in foreground, cuts through well-developed Pleistocene gravel outwash terraces. The town of Princeton is located in the vicinity of the smoke in the background (centre) of the photograph.

The Princeton Basin occupies an elongate, north-northeasterly trending topographic depression drained by the Similkameen and Tulameen Rivers and their tributaries. Much of the basin is open, grassy range land with relatively subdued, rolling topography (Plate I). Steeper, timber-covered slopes surround the basin on the north, west, south, and southeast margins.

Outcrops occupy significantly less than 1 per cent of the overall basin area and as many as one-third of them have slumped or are otherwise disturbed. The best exposures are immediately adjacent to the Tulameen and Similkameen Rivers and to Summers Creek; the others are dominantly in small creek gullies or in railroad and road cuts.

PHYSIOGRAPHY AND GLACIAL GEOLOGY

The Princeton Basin is located at the southern end of the Thompson Plateau (Holland, 1964) and is part of a transitional belt between the Interior Plateau to the northeast and the Cascade Mountains to the southwest. Maximum relief is about 770 metres: the highest point is at approximately 1 400 metres elevation on the southwestern margin of the basin and the lowest point at about 630 metres on the Similkameen River just east of Princeton.

The present drainage pattern has two distinct elements, one parallel to and the other perpendicular to the long axis of the basin. Summers Creek, Whipsaw Creek, the southern segment of the Similkameen River, and local portions of various tributary creeks have a north-northeasterly alignment, whereas the internal drainage network of the basin has a prominent southeasterly grain (Fig. 1). These elements reflect the structural control of the Princeton Basin, although both have probably been modified by glacial activity (*see* Hills, 1962).

During Pleistocene time the entire Princeton Basin became buried under ice. The maximum thickness of this sheet is uncertain, but it was evidently thick enough to erode the tops of mountains as high as 2 600 metres (Rice, 1947). All mountain tops in the Princeton area are well rounded and subdued, and the basin itself is covered by an extensive mantle of drift that is commonly 2 to 25 metres thick and ranges up to 53 metres (Anderson, 1972). The late glacial history of the basin has been described by Mathews (1944) and Hills (1962).

PREVIOUS GEOLOGICAL WORK AND PRESENT INVESTIGATION

Shaw (1952) summarized relevant previous geological work in the Princeton area by G. M. Dawson (1879), H. Bauerman (1885), C. Camsell (1907), and H.M.A. Rice (1947).

K. Fahrni reconnoitered the southern half of the Princeton Basin in search of coal while he was chief geologist at Copper Mountain. He reported on the coal possibilities of Lot 406 (in the Bromley Vale area) and on his sampling at the Black mine in 1945 and 1947 respectively in private reports to the Granby Consolidated Mining, Smelting and Power Co. Ltd.

W. S. Shaw began a detailed study of the sedimentation and stratigraphy of coal-bearing rocks of the Princeton Coalfield in 1951. He named these strata the Allenby Formation, developed tentative correlations of known coal occurrences, assigned many of these occurrences to one of four coal zones, and constructed a tentative structural contour map using the pavement of a certain seam in the lowest (Princeton-Black) zone (Shaw, 1952).

L. V. Hills (1962, 1965a) revised the stratigraphy of the basin and identified numerous microflora which he later used as a basis of palynological correlation among Early Tertiary basins in the interior of British Columbia (Hills, 1965b). Boneham (1968) questioned the significance of some of Hills' zones and offered additional information on the palynology of the Princeton, Tulameen, and Merritt coal basins. Paleontologic and radiometric age determinations reported in Hills (1965a) and Hills and Baadsgaard (1967) support earlier work of Russell (1935), Rouse and Mathews (1961), and Mathews (1963) in establishing a Middle Eocene age for coal-bearing strata of the Allenby Formation.

The purpose of the present investigation was threefold:

(1) to produce a geological map of the Princeton Basin and immediate area at a scale of 1:50 000,
(2) to determine the structural and stratigraphic setting of coal-bearing strata of the Allenby Formation, and
(3) to develop a geologic framework for further coal exploration.

Fieldwork commenced in mid-May and was completed by late September, 1975. The fieldwork and initial report were completed under contract with the British Columbia Ministry of Energy, Mines and Petroleum Resources.*

ACKNOWLEDGMENTS

John Nebocat gave excellent help in the field; he was responsible for mapping most of the pre-Tertiary rocks along the western margin of the Princeton Basin, in addition to reconnaissance mapping in various parts of the basin itself. I would like to thank Mr. and Mrs. Dick Trehearne and Messrs. Jerry Logan and 'Smudge' Rubis for their interest and assistance. The cooperation of Messrs. Don James of Granby Mining Corporation, T. Macauley of Newmont Mines Limited, and E. Anderson of Bethlehem Copper Corporation in granting access to their files was greatly appreciated. I am indebted to the Ministry of Energy, Mines and Petroleum Resources for logistical support, to geologists of the Mineral Resources Division, and to Professor P.McL.D. Duff of the University of Strathclyde for helpful discussions.

I also wish to thank my wife Margot for her assistance during the latter stages of the fieldwork, and for her enthusiastic encouragement during all phases of the study.

The manuscript has benefited significantly from review by Dr. N. C. Carter and M. E. McMechan.

GENERAL GEOLOGY

Numerous exposures of Tertiary rocks are found throughout the Interior Plateau region of southern British Columbia. They occur in isolated structural basins, fault troughs, and pre-existing topographic depressions surrounded by older and topographically higher rocks. A few erosional remnants cap hilltops adjacent to the basins (Taylor, *et al.*, 1964). The bulk of these Tertiary rocks are of volcanic origin and vary widely in composition. Relatively thick sequences of coal-bearing sedimentary rocks, mainly of fluviatile and lacustrine origin, are interbedded with these broadly lenticular flows and pyroclastic sheets in some basins.

This report on the geology of the Princeton Basin focuses on coal-bearing strata of the Allenby Formation. Pre-Tertiary rocks and intrusive rocks are also briefly discussed in order to relate the map units used around the periphery of the coalfield to those of previous workers, to aid in identification of the types of basement directly underlying the Allenby Formation, and to facilitate the determination of sediment provenance. The reader is referred to the work of Rice (1947) and Preto (1972, 1974, 1975, 1976, 1979) for more comprehensive information.

PRE-TERTIARY ROCKS

Pre-Tertiary stratified rocks have been divided into two map units, where possible (Fig. 2):

Unit 1: Nicola Group of Rice (1947); dark to light green and grey basaltic to andesitic (?) flows, tuffs, and breccias; augite and augite-plagioclase porphyry flows and breccias; the rocks are commonly chloritized and in many places bleached and silicified; minor amounts of limestone and limy mudstone occur; probably of Late Triassic age.

Unit 4: Kingsvale Group of Rice (1947); reddish brown to green rhyolitic to dacitic breccias and flows; lesser grey plagioclase porphyries of intermediate composition; probably of Early Cretaceous age.

* Initial report received January 15, 1976; revised manuscript received June 5, 1980.

INTRUSIVE ROCKS

Intrusive rocks have been mapped as follows (Fig. 2):

Unit 2: Other intrusions — mostly fine-grained intrusive rocks of variable composition that includes diorite and microdiorite of the Copper Mountain intrusions; Late Triassic or younger (Preto, 1972; Rice, 1947, unit 8).

Unit 3: Osprey Lake intrusion — dominantly pink and grey granite and quartz monzonite, commonly containing large pink phenocrysts of microcline within a medium to coarse-grained groundmass; some light-coloured granodiorite; Jurassic or younger (Rice, 1947, units 6 and 7).

Unit 5: Allison Creek stocks — pink to grey leucogranite, syenodiorite, monzonite, granodiorite, and quartz diorite; minor amounts of mafic microdiorite; post Lower Cretaceous (Preto, 1979, unit 12).

SUB-PRINCETON GROUP (EARLY PALEOGENE) UNCONFORMITY

Strata of the Princeton Group unconformably overlie volcanic rocks of the Upper Triassic Nicola Group, the Lower Cretaceous Kingsvale Group, and intrusive rocks of various ages. The eastern margin of the basin appears to be fault bounded and additional faults may offset the basement within the basin. The topographic paleorelief is difficult to ascertain, but was presumably low to moderate in absolute terms (Taylor, *et al.*, 1964). The unconformity is well exposed near the confluence of Summers and Allison Creeks (Plate II), where the present elevation difference between Oliphant Mountain and the lowest exposures of the Allenby Formation to the north and south suggests a minimum paleorelief of 300 metres. Relief on the floor of the developing Princeton Basin is inferred to have been of the same order of magnitude (Figs. 9 and 12).

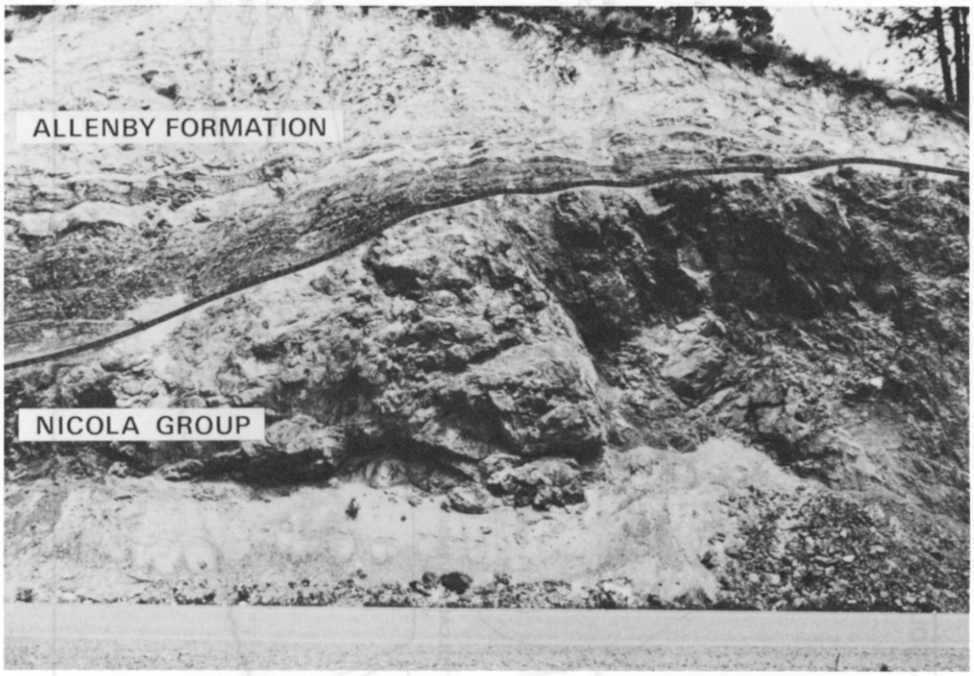


Plate II. Sub-Allenby Formation unconformity exposed on Highway 5 near confluence of Summers and Allison Creeks. Fine-grained tuffaceous (?) sediments of the Allenby Formation lap onto sheared and weathered (?) rocks of the Nicola Group. Unconformity has about 8 metres of topographic relief at this locality and has at least 300 metres in this part of the basin. For scale, entire exposure is about 11 metres high. View to east.

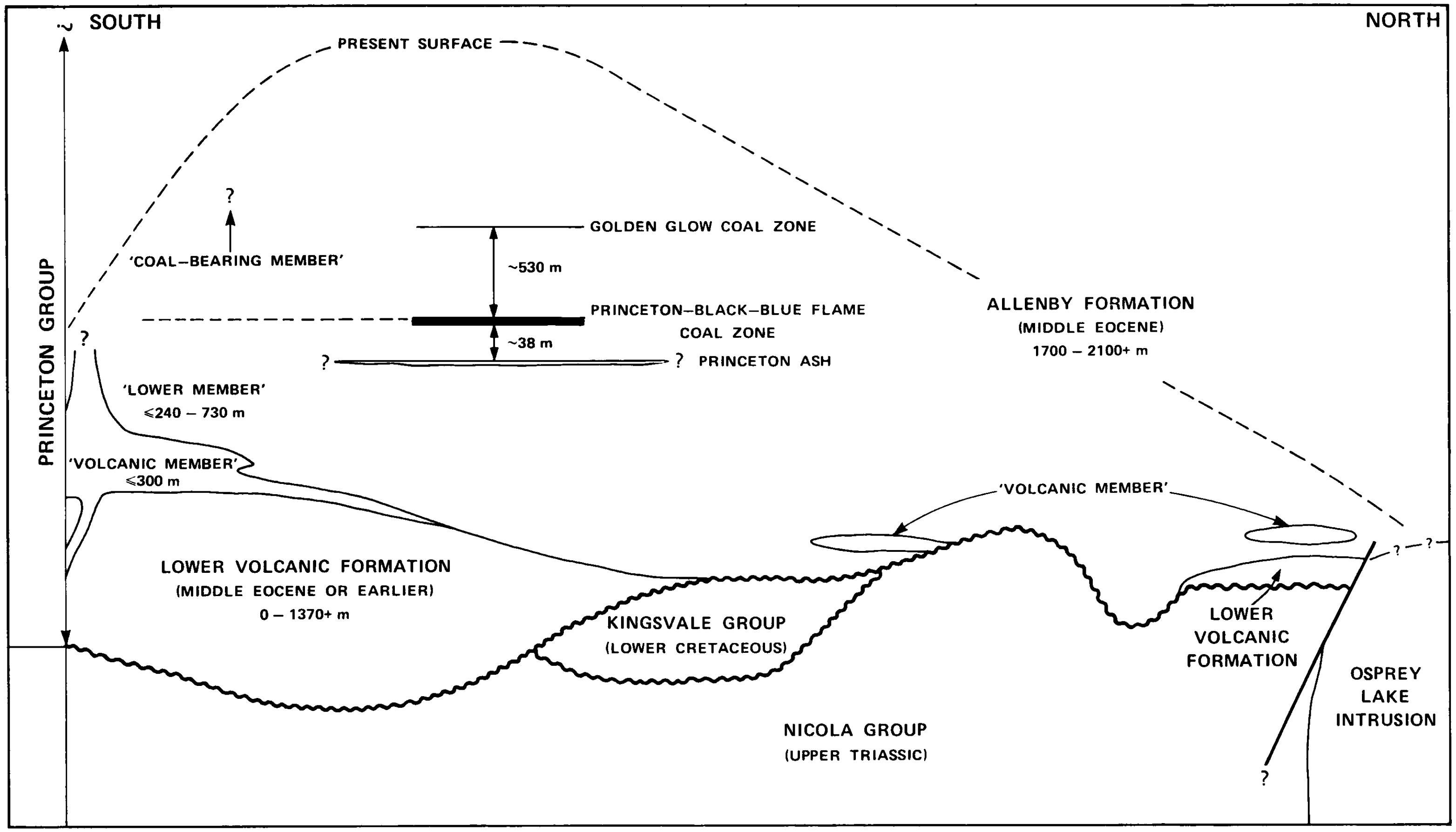


Figure 3. Schematic diagram showing stratigraphic relationships in the Princeton Basin. The Lower Volcanic and Allenby Formations comprise the Princeton Group.

TERTIARY ROCKS: PRINCETON GROUP

The paucity of good outcrop exposures in the Princeton Basin has frustrated detailed stratigraphic correlation of the Tertiary rocks, but gross stratigraphic units can be recognized (Figs. 3 and 12).

Camsell (1907), Rice (1947), and Shaw (1952) interpreted that the Tertiary stratigraphy of the Princeton map-area consists of an upper and lower volcanic sequence separated by sedimentary rocks of freshwater origin. Rice (1947, pp. 27, 28) introduced the name Princeton Group to encompass these Tertiary lavas and sediments. Shaw (1952) proposed a formal subdivision into Lower Volcanic, Allenby, and Upper Volcanic Formations. Hills (1962) found that the Upper Volcanic Formation was a laterally discontinuous unit interbedded with the lower strata of the Allenby Formation (Fig. 3), and concluded that these volcanic rocks should be included as part of the Allenby Formation (Hills, 1965a).

With the exception of the term 'Allenby Group,' Hills' (1965a) stratigraphic divisions and nomenclature have been used in this report. Rice's term 'Princeton Group' has priority and also has a broader geographic connotation. Princeton Group is thus used here to encompass the Lower Volcanic and Allenby Formations following the usage of Preto (1972). The volcanic unit within the lower part of the Allenby Formation is informally referred to as the 'volcanic member' of this formation.

LOWER VOLCANIC FORMATION

The oldest Tertiary strata of the Princeton Basin consist of 1 370 metres or more of intercalated flows, breccias, tuffs, and minor amounts of volcaniclastic sediment of the Lower Volcanic Formation. These volcanic rocks are well exposed along the ridge that forms the southwestern margin of the coalfield, and in particular along a deep ravine cut through this ridge by the north fork of Findlay Creek opposite the Taylor-Burson and Jackson mines. They crop out for a considerable distance south of the coalfield (Rice, 1947, Map 888A), but lens out rapidly to the north in the vicinity of the Tulameen River (Fig. 2) and thin to the east. Flows and pyroclastic rocks correlated with the Lower Volcanic Formation also occur over a limited area on Summers Creek in the northernmost part of the basin. There is no evidence for a regional structural discordance between the Lower Volcanic Formation and the overlying Allenby Formation (*see* Shaw, 1952), and local apparent discordance is readily explained in terms of topographic irregularity on the surface of individual flows.

Rocks of the Lower Volcanic Formation range in composition from rhyolitic breccias to dacite, andesite and basalt flows to porphyries (*see* Rice, 1947). The intermediate varieties appear to be most common.

The Lower Volcanic Formation may be distinguished in the field by its stratigraphic position and by criteria proposed by Hills (1962). This unit characteristically lacks coalified or petrified wood fragments, lacks phenocrysts of olivine, tends toward angular fragments on weathering with red and brown colours predominating, contains more amygdules than vesicles, and lacks columnar or flaggy joints. Breccias and tuffs are more common in the Lower Volcanic Formation, and in general they are much more altered than those of the 'volcanic member' of the Allenby Formation. In some cases, distinction between these volcanic units is difficult and can only be made on the basis of geomorphic relationships or an arbitrary cutoff.

The Lower Volcanic Formation was subdivided into two map units (Fig. 2):

Unit 6a: Red or brown lahars and pyroclastic (?) breccias with subordinate red flows, tuffaceous units, and interbedded volcaniclastic sedimentary rocks.

Unit 6b: Undifferentiated varicoloured flows of intermediate composition, commonly vesicular or amygdaloidal, with minor amounts of breccia.

ALLENBY FORMATION

Shaw (1952, p. 8) proposed the name Allenby Formation for Tertiary strata consisting 'predominantly of massive, cross-bedded granule and pebble conglomerate, sandstone and massive and thinly bedded shale, with intercalated beds of coal, carbonaceous siltstone and shale, and bentonite' that are well exposed along the banks of the Similkameen River near Allenby, with a maximum exposed thickness of 1 070 metres.

Hills (1962, 1965a) modified the definition to include flows and breccias assigned to Shaw's 'Upper Volcanic Formation,' arguing that they are actually interbedded with basal sedimentary strata of the Allenby Formation, and suggested that the formation could be as much as 1 830 metres thick. Present work indicates that the total preserved stratigraphic thickness of the Allenby Formation is at least 1 600 metres, and possibly up to 2 100 metres.

The Allenby Formation can be informally subdivided into two sedimentary 'members' and a third 'volcanic member,' based on gross stratigraphic relationships in the southern half of the Princeton Basin. The 'lower member' comprises a mixture of arkosic and volcaniclastic sedimentary rocks and contains very little coal. The basal sediments are in many places coarse, poorly sorted, angular sedimentary breccias composed entirely of rock debris of local origin (Hills, 1965a). This 'lower member' ranges in thickness from 240 to 470 metres, and locally attains a thickness of about 730 metres (for example, Asp Creek, *see* A–A', Fig. 9; Fig. 12). The Princeton Ash (an important horizon that has been radiometrically dated) occurs about 38 metres below the top of this member.

Lava and breccias of the 'volcanic member' intertongue with and locally crosscut basal sediments of the 'lower member.'

The upper division is predominantly arkosic and contains most of the known coal zones. It will be referred to as the 'coal-bearing member' of the Allenby Formation. The lower portion of this member encompasses the four coal zones having known economic importance (Princeton-Black-Blue Flame, Pleasant Valley-Jackson, Gem-Bromley Vale, and Golden Glow; *see* Stratigraphic Setting of Coal Seams for development of these correlations), and is approximately 530 metres thick. A further 320 metres, and probably up to 830 metres of sedimentary rocks, that lie on top of this lower portion, contain three other coal zones (Freeman, Allenby, and Bethlehem). The Bethlehem seam has potential economic importance (Anderson, 1972, 1976).

Subdivision of the Allenby Formation is difficult in the Princeton Basin north of the northwesterly trending 'Rainbow Lake' anticline (of Hills, 1962). Coal zones there are not well developed and other distinctive markers are apparently lacking. Most of the strata exposed in the north are thought to be a thicker and coarser lateral facies equivalent of the 'lower member' of the Allenby Formation, although they probably attain a thickness in the order of 1 500 metres and may be the equivalent of virtually the entire Allenby Formation section exposed in the south.

All size gradations between coarse breccia/boulder conglomerate and mudstone/shale are represented in the Allenby Formation. Pebble, cobble, and boulder conglomerates outcrop primarily in the northern extremity of the Princeton Basin, although they are also exposed in a few localities farther south (Figs. 2 and 5). They are only found in the 'lower member.' Granule conglomerates (or 'grits') outcrop throughout the map-area, but are less abundant in the south (Hills, 1962). Fine clastic sediments predominate in the coal-bearing member of the Allenby Formation that is exposed in the southern half of the basin. The ratio of fine (shale, mudstone, claystone, siltstone) to coarse (sandstone, conglomerate) clastic material is about 65 to 35 based on inspection of subsurface logs given in Rice (1947) and Anderson (1972, 1976).

SEDIMENTARY ROCK TYPES OF THE ALLENBY FORMATION

BRECCIAS: Both volcanic and sedimentary breccias are present within the Princeton Group, and the latter are common in the lowermost exposures of the Allenby Formation (Hills, 1962). These breccias are generally found near the margins of the basin and are composed almost entirely of clasts derived from the surrounding volcanic rocks indicating a local provenance (Hills, 1965a; present study). The fragments show little or no size sorting and range from sand size to blocks over a metre across. Stratification is crude and is commonly defined by subtle particle size variations or lenticular beds of finer material. Exposures on Highway 5 about 1.2 kilometres north of the junction of Summers and Allison Creeks, and on Summers Creek about 5.4 kilometres north of this same confluence, well illustrate these textural characteristics and local provenance (Plate III).

A distinctive unit consists of dominantly matrix-supported angular to subrounded clasts of Allenby arkosic sedimentary rocks, Nicola and Kingsvale volcanic rocks, white pyroclastic rocks, brick red volcanic breccias (*see* Lower Volcanic Formation), and some intrusive rocks. Clasts range up to 10 centimetres in size (average 1 to 2 centimetres). This debris flow-like mixture was observed interbedded with more mature Allenby Formation sedimentary rocks in the vicinity of Asp Creek about 1.3 kilometres upstream from the Tulameen road bridge. Its significance is discussed under General Stratigraphy and Depositional Environments.

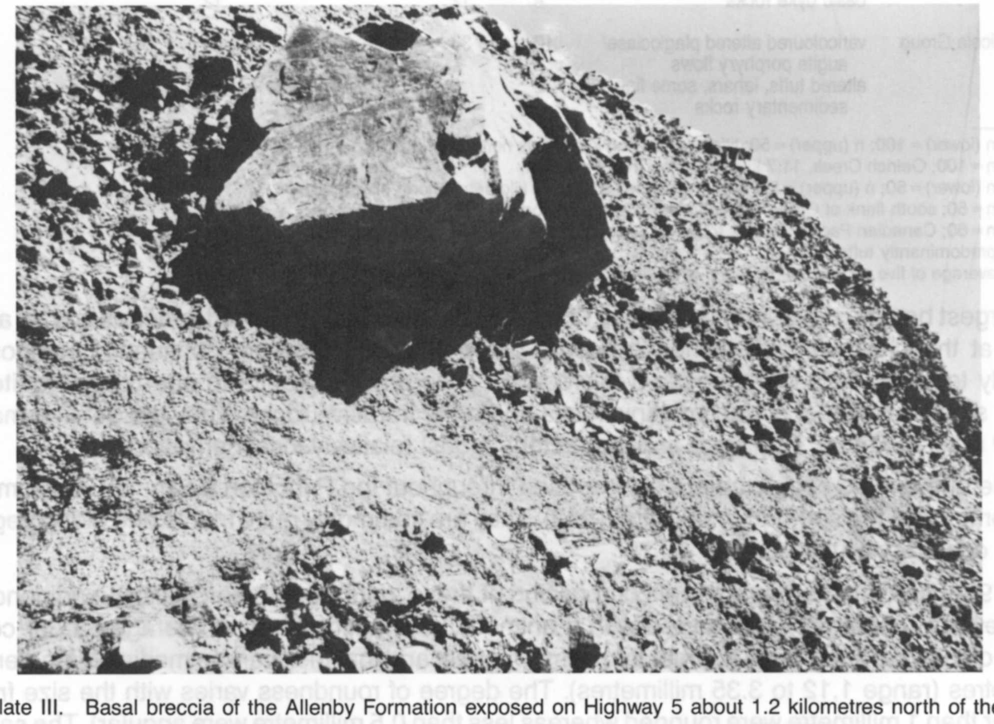


Plate III. Basal breccia of the Allenby Formation exposed on Highway 5 about 1.2 kilometres north of the junction of Summers and Allison Creeks. It probably represents a reworked (?) talus or debris flow deposit. For scale, large block is 1.2 metres across.

CONGLOMERATES: Cobble and boulder conglomerates are well exposed at Summers Creek Bluffs and adjacent areas, as well as on Highway 5 about 12 kilometres north of Princeton. Clasts observed at the former locality range in size from 5 to 30 centimetres, although Hills (1965a) reported rare boulders up to 90 centimetres. In general, cobbles and boulders comprise 50 per cent or more of the conglomerate by volume and there seems to be a continuous size gradation from the finest to the coarsest particles. The cobbles and boulders are usually subrounded to well rounded, with rare subangular ones. The clast lithotype makeup varies widely from place to place and within an individual section, although crystalline igneous rocks, particularly granite to quartz monzonite, are the dominant clast types (Table 1). These conglomerates are usually clast supported, and the matrix is generally arkosic in composition. Nicola (?) volcanic clasts locally comprise up to 25 per cent by volume (for example, at the Highway 5 locality described previously). Individual beds are a metre or more in thickness; interbedded sandstone lenses or alternation of granule-pebble and cobble-boulder beds delineate stratification. Conglomerates commonly fill shallow erosional scours in underlying beds and commonly exhibit imbrication.

TABLE 1. CLAST LITHOTYPES IN CONGLOMERATES FROM THE 'LOWER MEMBER' OF THE ALLENBY FORMATION, NORTHERN HALF OF PRINCETON BASIN

		BM-24[1]		BM-32[2]	BM-114[3]		BM-6[4]	BM-133[5]	Hills (1965a)[7]
	Clast Lithotype	**Lower**	**Upper**		**Lower**	**Upper**			
		percent	*percent*	*percent*	*percent*	*percent*	*percent*	*percent*	*percent*
Allenby Formation	buff arkosic or tuffaceous sandstone and siltstone		8	5	22			90[6]	1
Mainly Lower Volcanic Formation	light grey and reddish grey vesicular basalt/andesite				14	16			
Osprey Lake Intrusion	granite and quartz monzonite	60	38	} 70	64	64	86	10	} 97
Other Intrusions	other crystalline intrusive rocks	22	6				14		
	basic dyke rocks	4	12			12			
Mainly Nicola Group	varicoloured altered plagioclase/augite porphyry flows	12	30	} 25		4			} 2
	altered tuffs, lahars, some fine sedimentary rocks	2	6			4			

[1]— n (lower) = 100; n (upper) = 50; Highway 5, 11.8 kilometres north of Princeton.
[2]— n = 100; Oelrich Creek, 11.7 kilometres north of Princeton.
[3]— n (lower) = 50; n (upper) = 25; Summers Creek Bluffs, 12 kilometres north of Princeton.
[4]— n = 50; south flank of Oliphant Mountain, 9 kilometres north of Princeton.
[5]— n = 60; Canadian Pacific Railway tracks; 8.5 kilometres north-northeast of Princeton.
[6]— predominantly tuffaceous.
[7]— average of five pebble counts (various locations).

The largest boulders observed in Allenby Formation conglomerates exceed 3 metres across and are found at the previously mentioned exposure on Highway 5. They are dominantly composed of partially to completely disaggregated microcline (?) porphyritic granite to quartz monzonite, with lesser, smaller clasts of Nicola volcanic rocks and other intrusive rocks. They are set in a matrix of pebbly arkosic wacke. Their size and character suggest relatively local derivation.

Granule and pebble conglomerate are exposed throughout the Princeton Basin, but are somewhat less common in the southern half (Hills, 1962). They are commonly quite friable and disaggregate to yield a coarse granular 'sand.'

Hills (1962) studied the mechanical composition of these 'grits' from three localities and concluded that they are moderately well sorted with a unimodal distribution, that an average 50 per cent by weight of the total samples is coarser than 2 millimetres, and that the average median diameter is 2.1 millimetres (range 1.12 to 3.35 millimetres). The degree of roundness varies with the size fraction (greater than 1 millimetre were rounded whereas less than 0.5 millimetre were angular). The samples studied were arkosic throughout their entire size range, but there was considerable variation in the type of feldspar and feldspar-quartz ratio with change in size; microcline-microperthite being dominant in the coarser fraction and plagioclase important in the finer fraction (Hills, 1962). On the basis of visual estimates, the granule conglomerates are composed of 20 to 60 per cent feldspar; 15 to 30 per cent quartz (some of which is strained); 40 per cent granite, quartz monzonite, and granodiorite; and 25 per cent various volcanic materials, particularly white tuff (*cf.* Shaw, 1952). Common accessory minerals are biotite, sphene, apatite, and magnetite (Hills, 1965a). In many exposures the matrix is predominantly coarse sand to silt, with possibly minor amounts of clay (Hills, 1962), whereas up to 30 or 40 per cent mud to clay matrix is present in others (Shaw, 1952; present study). Granule conglomerates in the latter category are characteristically poorly exposed, particularly where the matrix contains an expandable clay, such as bentonite-montmorillonite.

SANDSTONES: Coarse, poorly sorted arkosic sandstones, similar to the granule-conglomerate, are very common. In the northeastern part of the basin near Summers Creek, every gradation between arkosic wacke (arkose) and tuff are found. The thick to very thick beds of coarser sandstone and conglomerate are generally massive, and commonly the only evidence of stratification is the orientation of carbonaceous material, pebble trains, or thin silty partings. These coarser sandstones sometimes grade upward into buff to grey, thin-bedded finer sandstones containing common carbonaceous impressions or wispy laminae. Load casts are locally developed in the bases of coarser beds.

Simple, planar and trough cross-stratification (McKee and Weir, 1953) are frequently found in the sediments of medium sand size and coarser. The amplitude of these cross-strata ranges from less than 25 centimetres in the finer sandstones to 4 metres or more in the granule-pebble conglomerate. Small-scale ripple-drift cross-laminae are developed locally in the finer sandstone.

The sandstones are generally very friable with a poorly sorted, predominantly clastic matrix. In some cases, the clasts seem to be held together by a clayey paste and kaolinite (Shaw, 1952) or bentonite-montmorillonite form a significant part of the matrix. The better indurated sandstones are generally cemented by calcium carbonate and are commonly concretionary. In the vicinity of Tertiary volcanic rocks, the sandstone grains have been well bonded by silica (Shaw, 1952). Iron staining is ubiquitous, but iron (hematite ?) cementation is observed only in some of the basal sandstones overlying the Nicola Group.

MUDROCKS: The fine-grained sedimentary rocks show more variation than the coarse-grained types. They range from massive sandy shale, siltstone, and soft mudstone-claystone to friable, carbonaceous 'paper' shale, and better indurated, very finely laminated shale. The rocks are multicoloured, with brownish red, buff, dark grey, and white dominant, and other shades of grey and red common. Thin section study reveals that the silt fraction commonly makes up as much as 50 per cent of the shales by volume. Quartz, microcline, and plagioclase are the dominant minerals in this fraction and suggest a provenance similar to that of the coarser clastic sediments. The clay-size fraction was not studied in detail.

Thick beds of fissile, in many places carbonaceous, shale are more common in the southern half of the basin than in the north, and are in places rich in fossils. Plants and, locally, insects are well preserved as carbonaceous impressions, but collection of specimens is hindered by the very friable nature of the rocks. Coalified materials are commonly associated with these black or grey shales.

The red shales and mudrocks contain less visible organic material than the darker ones. Plant or fish impressions are the only evidence of organic remains. Oxidized pyrite imparted the red colour in most cases (Hills, 1962). These red mudrocks and the white to grey claystones are massive and both generally exhibit a conchoidal fracture.

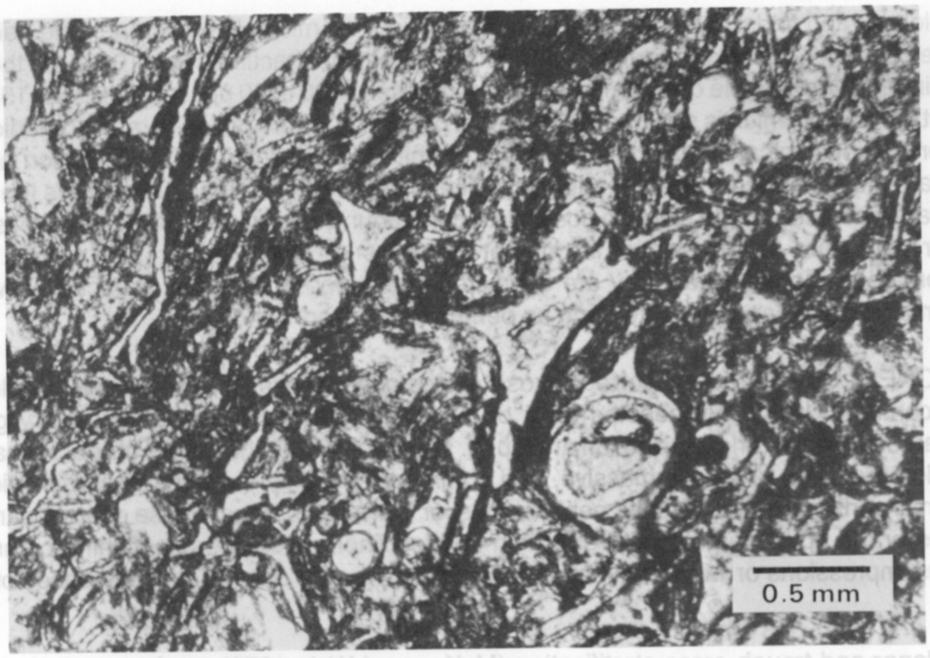


Plate IV. Devitrified (?) vitric tuff exposed on the Similkameen River about 4.6 kilometres south of Princeton. Note triangular outlines and undeformed character of individual glass shards, and concentrically zoned, filled bubble cavities. Framework contains scattered crystal (quartz, K-feldspar) and lithic (welded tuff) fragments. Matrix is predominantly fine-grained devitrified glassy material plus clay. Plane light.

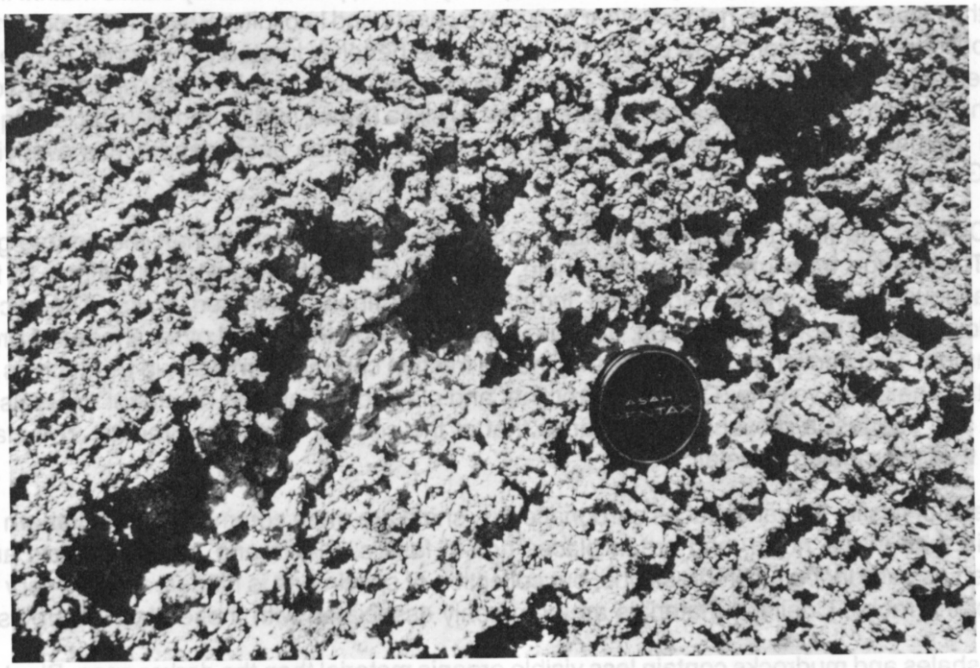


Plate V. Surface weathering character of bentonite exposed on Summers Creek about 1 kilometre upstream from the confluence with Allison Creek. Note characteristic 'popcorn-like' appearance resulting from desiccation shrinkage of bentonite that had previously swelled upon exposure to water. For scale, lens cap is about 5 centimetres across.

Moderately well-indurated, finely laminated shales outcrop in several places in the northern half of the coalfield. A notable example, located on the west bank of Allison Creek about 300 metres downstream from the confluence with Summers Creek, exhibits 20 to 30 laminae per centimetre and contains exquisitely preserved leaves (Shearer, 1973).

The fine-grained sedimentary rocks contain a variety of sedimentary structures. Hills (1962) reported mud cracks from several localities and well-preserved raindrop prints from another on Whipsaw Creek. Flame structures and convolute stratification are well developed in exposures on Asp Creek.

Local *in situ* burning of coal seams has melted some of the shales, producing either a 'frothy' glassy mass (*see* Church, *et al.*, 1979) or simply a local red colouration. Examples of these phenomena may be found at the Black coal mine (M8, Fig. 13A) and along the Similkameen River south of Allenby, respectively. Rice (1947) and Shaw (1952) suggested the possibility of local burning and induration of sedimentary strata by later volcanic flows.

SILICEOUS AND CALCAREOUS ROCKS: Silicified diatomite, limy chert, and siliceous and dolomitic limestone are exposed at Vermilion Bluffs, 3.2 kilometres southwest of Princeton on the Tulameen River (Fig. 2; *see* also Hills, 1962). Dark argillaceous limestones also occur at a few other localities in the basin (Hills, 1962). Very thinly interbedded coal and chert have been reported from an exposure on the Similkameen River, about 8.8 kilometres south of Princeton (Boneham, 1968; *see* section 2, Fig. 13B). Siliceous and calcareous rocks such as these make up only a small proportion of the preserved Allenby Formation, but are nevertheless important in reconstruction of depositional environments because of their common association with coal.

PYROCLASTIC ROCKS AND BENTONITE: Strata of the Allenby Formation contain a considerable amount of tuffaceous material. White tuffs and arkoses containing abundant light grey ash fragments are common in the northeastern portion of the basin. Silicified vitric tuffs are found along the Similkameen River, 4.6 kilometres south of Princeton (Plate IV), and are also intimately associated with coal at the Taylor-Burson mine (M10, Fig. 13A).

The Princeton Ash is a tuffaceous unit of considerable importance because it has been dated radiometrically (Rouse and Mathews, 1961; Mathews, 1963; *see* Age of the Allenby Formation). The ash forms conspicuous white to grey outcrops with blocky, slab-like or rhombohedral fractures. It is composed of potash-rich volcanic glass matrix containing crystal fragments of andesine, biotite, and minor amounts of quartz (Hills, 1962). It is a minimum of 6 metres thick and serves as a local marker bed about 38 metres stratigraphically below the Princeton-Black- Blue Flame coal zone. The Princeton Ash can easily be traced in the vicinity of Princeton along the Tulameen River, but has not been positively identified in other parts of the basin. The tuffs on Summers Creek and a silicified basal pyroclastic unit at Vermilion Bluffs are similar to it in many respects, but there are some textural differences, at least in the former case (Hills, 1962). Other broadly lenticular white tuffaceous siltstones and claystones occur at different levels within the stratigraphic column (for example, on Highway 3, about 5 kilometres southwest of Princeton) and detract from the value of the Princeton Ash as a regional marker.

Bentonites also occur throughout the Allenby Formation. Their degree of purity varies and they were probably formed by devitrification of volcanic ash. Most are acidic in composition (Table 2). They may be classified as 'nonswelling,' noncolloidal calcium bentonites based on limited testing (Cummings and McCammon, 1952), although they do swell sigificantly upon exposure to water, as observed in historic mine workings (Hughes, 1947) and in outcrop (Plate V).

These bentonites commonly occur as lenticular beds associated with shales or coaly shales, and generally range from a few centimetres to a few metres in thickness. Notably thicker beds also occur (for example, Spence, 1924) but are not well exposed because of their tendency to encourage slope failure. An approximately 9-metre-thick zone of sandy bentonite was encountered at shallow depth in

TABLE 2. CHEMICAL ANALYSES OF BENTONITES FROM THE ALLENBY FORMATION, PRINCETON BASIN

	Cummings and McCammon (1952[1]) *per cent*	BM-338[2] *per cent*
SiO_2	68.60	70.20
Al_2O_3	12.10	13.78
Fe_2O_3	2.00	3.59 (Fe_2O_3 + FeO)
FeO	0.32	
MgO	1.84	1.84
CaO	1.84	2.03
Na_2O	0.50	<0.30
K_2O	0.23	0.20
TiO_2	0.14	0.197
MnO	—[3]	0.017
P_2O_5	0.17	0.036
S	Nil	—[3]
H_2SO_4	0.61	—[3]
C	0.08	—[3]
CO_2	0.17	8.00 (CO_2 + H_2O)
H_2O (105°C)	7.71	10.00[4]
H_2O (>105°C)	3.24	

[1]—Representative samples of the Princeton bentonites.

[2]—Average of two samples collected from shallow boreholes located 7.2 kilometres south-southwest of Princeton, 0.4 kilometre east of the Similkameen River.

[3]—Not analysed.

[4]—Loss on ignition estimated from fused X.R.F. sample bead.

TABLE 3. CHEMICAL ANALYSES OF FLOWS FROM THE PRINCETON GROUP, PRINCETON BASIN

	BM-236[1] *per cent*	BM-236A[1] *per cent*	BM-254[2] *per cent*	BM-351[3] *per cent*	JN-28[4] *per cent*	JN-28A[4] *per cent*
SiO_2	60.60	57.90	59.05	60.30	66.10	67.60
Al_2O_3	14.70	15.50	16.45	16.40	15.75	15.50
Fe_2O_3 + FeO	5.10	5.22	5.79	5.52	3.22	2.80
MgO	4.03	5.50	3.69	3.00	1.70	1.25
CaO	5.90	6.10	5.74	5.60	3.58	3.65
Na_2O	3.98	3.72	4.45	3.85	3.90	2.55
K_2O	2.60	1.98	1.71	2.36	3.80	3.95
TiO_2	0.64	0.67	0.78	0.67	0.47	0.45
MnO	0.075	0.11	0.094	0.095	0.049	0.05
P_2O_5	0.40	0.44	0.302	0.305	0.20	0.165
CO_2	1.00[5]	1.00[5]	1.00[5]	1.00[5]	2.00[5] (CO_2 + H_2O)	2.00[5] (CO_2 + H_2O)
H_2O	2.00	2.00	2.00	2.00		

[1]— BM-236, BM-236A Lower Volcanic Formation (?); 'Castle Rock', 2.6 kilometres east of Princeton.
[2]— BM-254 Volcanic member, Allenby Formation; 2.3 kilometres east-southeast of Princeton.
[3]— BM-351, Volcanic member, Allenby Formation; 5.9 kilometres south of Princeton.
[4]— JN-28, JN-28A, Volcanic member, Allenby Formation; 5.0 kilometres northwest of Princeton.
[5]— Loss on ignition estimated from fused X.R.F. sample bead.

boreholes at a locality 7.2 kilometres south-southwest of Princeton (0.4 kilometre east of the Similkameen River). The two 4.6-metre-thick impure bentonitic beds reported by Shaw (1952) and the 4.3-metre-thick bentonite seam reported by Cummings and McCammon (1952) were not identified in the field.

'VOLCANIC MEMBER' OF THE ALLENBY FORMATION

Extrusive rocks belonging to the 'volcanic member' of the Allenby Formation may be distinguished from those of the Lower Volcanic Formation by: stratigraphic position; grey, greenish grey, or grey-black colour; common olivine phenocrysts; tendency toward spheroidal weathering; well-developed flaggy or columnar jointing; highly vesicular nature (with vesicles commonly stretched parallel to 'basal' flaggy fractures); and generally fresh appearance (Hills, 1962). They also contain coalified or petrified wood.

Chemical analyses of selected flows from the volcanic member (Table 3) indicate an andesitic to dacitic composition, although some of the rocks look like basalt in the field.

Rhyolitic to dacitic tuffs and breccias that are exposed near Ashnola along the southeastern margin of the Princeton Basin ('Princeton Biotite Rhyolite' (?) of Hills, 1965b; Hills and Baadsgaard, 1967) resemble parts of the Lower Volcanic Formation but have been assigned to the 'volcanic member' because they appear to cut across some of the lowest exposed sedimentary rocks of the Allenby Formation (*see* Fig. 3; Montgomery, 1967).

ALLENBY FORMATION MAP UNITS

The transition from the dominantly volcanic units of the Lower Volcanic Formation to the overlying, dominantly sedimentary beds of the Allenby Formation occurs over an interval of a few hundred metres in which flows and breccias are interbedded or intercalated with the sedimentary rocks. The contact is arbitrarily placed at the base of the sedimentary rocks, except where flows characteristic of the 'volcanic member' underlie them; in this latter case the contact is placed at the base of these flows (Fig. 2).

The distribution of outcrops and extent of the Allenby Formation within the Princeton Basin are shown on Figure 2. Margins of the basin are well defined in many places, either by visible contacts as in the extreme north or by topographic boundaries as in the southwest and the extreme southeast.

Modification from the previously mapped limits of the coalfield at Jura is the result of a test hole drilled by Kennco Explorations, (Western) Limited in 1960. This drill hole encountered several hundred metres of steeply dipping (55 to 65 degrees) Allenby Formation sediments (Hills, 1962). The extension of the east side of the basin, about 5 kilometres south of Princeton, is the result of a hole drilled on the Nob claim group by a former holder of the ground (Christopher and Macauley, 1973).

The 'volcanic member' of the Allenby Formation was mapped as:

Unit 7a: Undifferentiated flows of dacitic to basaltic composition that are generally fresh in appearance, may have olivine phenocrysts, are commonly vesicular, and have well-developed flaggy or columnar joints; subordinate tuff and breccia of rhyolitic to dacitic composition occur; interbedded primarily with basal sedimentary rocks of the Allenby Formation.

In a few cases, it is difficult to demonstrate that flows tentatively assigned to the volcanic member based on their physical characteristics actually occur in the lower portion of the Allenby Formation.

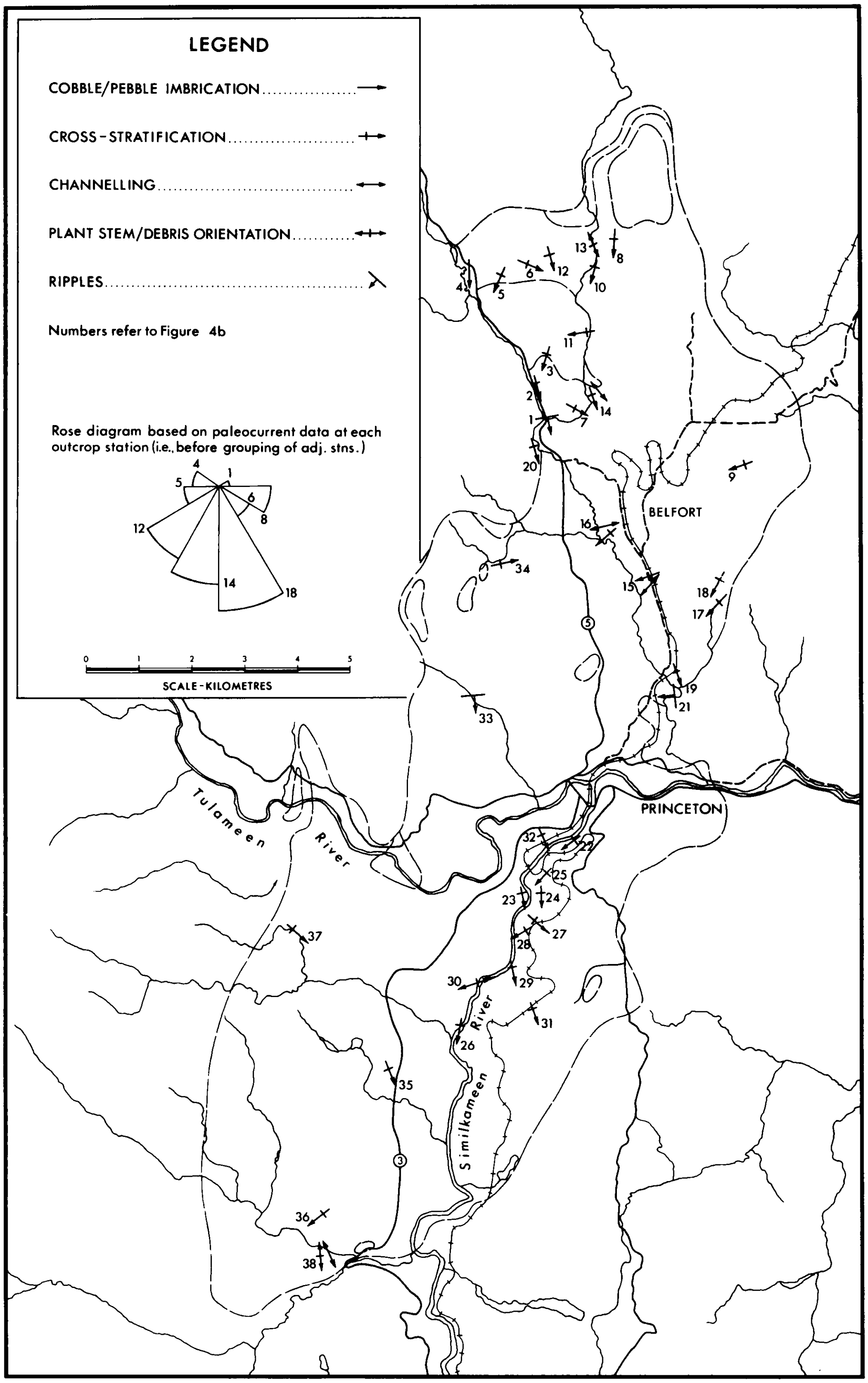
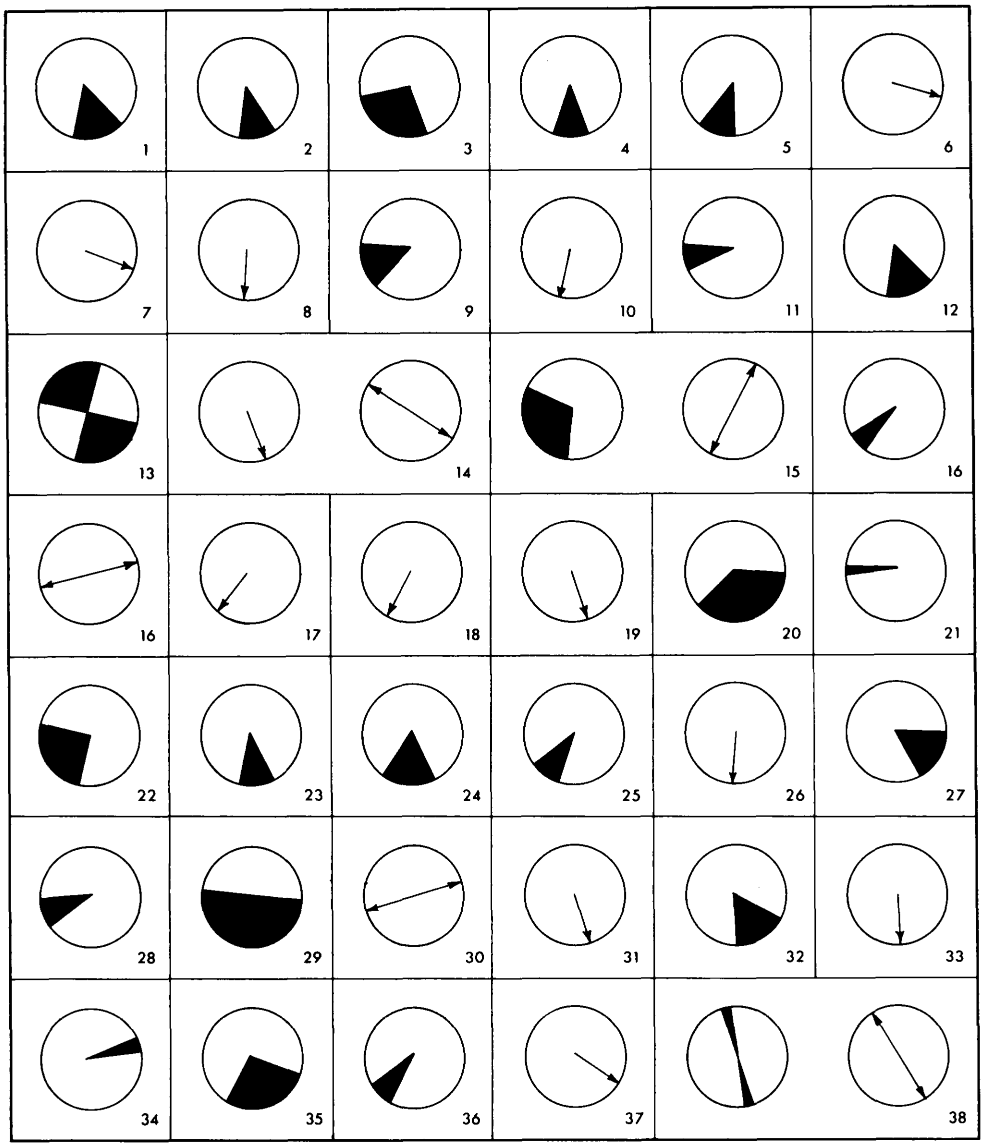


Figure 4a. Paleocurrent directions, Allenby Formation, Princeton Basin.



LEGEND

Variability of current direction as indicated by measurements of cross-stratification at one or more stations (large degree of variability, e.g., at 29, commonly reflects grouping of two or more adjacent stations)..

Variability of current direction as indicated by measurements of linear features (plant debris, channelling)at one or more stations ....

Average current direction indicated by cross-stratification ; measurement averaged at outcrop scale (in some places only one set visible, 3D commonly poor)........ ⟶

Average current direction indicated by linear feature ; only one linear feature visible (e.g., at 30 – a tree branch or trunk) .... ⟷

Figure 4b. Variability of current direction measurements (*see* Figure 4a for locations).

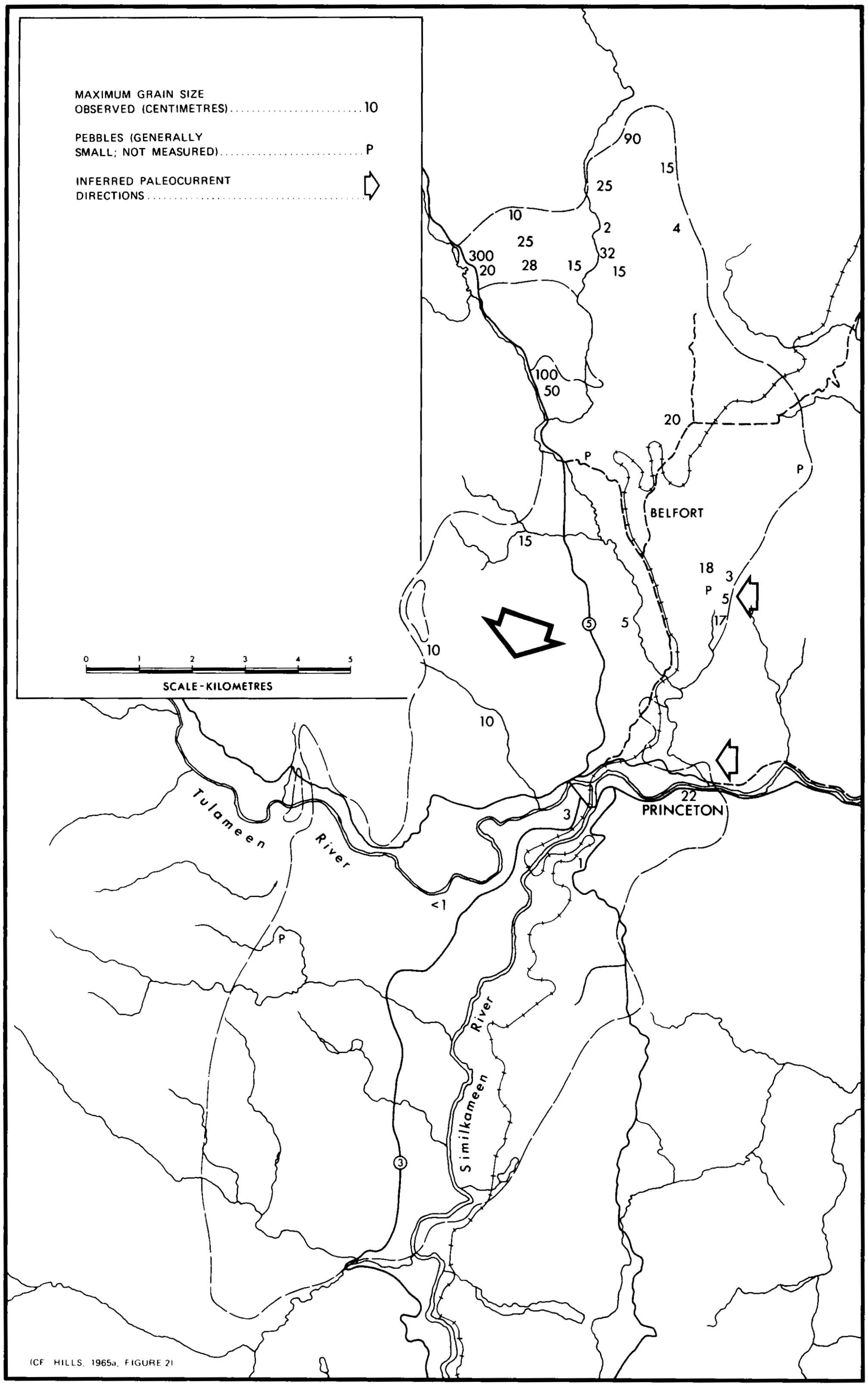


Figure 5. Clast size variation in the Allenby Formation, Princeton Basin (compare Hills, 1965a, Figure 2).

They are not directly overlain by a significant thickness of sedimentary rocks. The flows exposed on the top of the ridge along the southeast margin of the basin and in the upper bluffs on Summers Creek are examples. Further work, perhaps including radiometric dating, will be required to determine their real stratigraphic position, and to distinguish them from lithologically similar Miocene plateau lavas.

Allenby Formation sedimentary strata were mapped by visual estimation or, where practicable, by detailed measurement of the stratigraphic section at every exposure visited. Particular emphasis was given to the occurrence and thickness of coal or carbonaceous sedimentary rocks. The lack of distinctive, areally extensive marker beds and the paucity of prior stratigraphic information made it nearly impossible to ascertain the precise position of a given outcrop within the stratigraphic sequence. These sedimentary strata were therefore assigned to one of four map units based on the dominant lithologic characteristics (Fig. 2):

Unit 7b: Consists dominantly of bentonitic and other tuffaceous material, including white ash (for example, Princeton Ash); bentonite commonly silty or sandy.

Unit 7c: Consists dominantly of carbonaceous shale to mudstone; some siltstone and noncarbonaceous claystone; coal; mudrocks may contain tuffaceous material and are locally burnt due to spontaneous combustion of adjacent coal.

Unit 7d: Consists of very thinly to thickly interbedded fine to very coarse-grained, tuffaceous to arkosic wacke; siltstone; brown, commonly carbonaceous, shale; some claystones and coal.

Unit 7e: Consists dominantly of medium to very coarse-grained arkosic wacke, in many places containing tuffaceous material; includes granule-pebble-cobble-boulder conglomerate of similar composition.

PALEOCURRENTS AND PROVENANCE

The nature and extent of the Paleogene drainage system in the Princeton Basin exerted an important control on the distribution and thickness of coal-bearing facies within the Allenby Formation. Paleocurrent indicators and sediment provenance yield important information about this system.

PALEOCURRENTS: Orientation of cross-stratification and channelling, imbrication of pebbles and cobbles, and preferred orientation of plant and root fragments were recorded for use in paleocurrent determination. These raw data were corrected for tilt of the regional stratification using a method outlined by Potter and Pettijohn (1963). The average paleoflow directions were first estimated at each station using vector methods. Mean paleocurrent flow data from adjacent stations were then grouped together, and the resulting map and rose diagram are presented on Figure 4A. The variability associated with each of these summary data is shown on Figure 4B.

The paleocurrent data indicate a south to southwesterly directed drainage system, which received minor contributions from the sides of the basin (*cf.* Hills, 1965a, Fig. 2). This unimodal paleocurrent pattern is consistent with the inferred fluvial depositional environment (*see* General Stratigraphy and Depositional Environments).

Clast size variations provide additional paleocurrent information (Fig. 5). The gradation from coarse conglomerates in the northern part of the basin to granule conglomerates and sandstones farther south is accompanied by a marked decrease in the maximum clast size observed, from 90 centimetres (and locally up to 3 metres) in the north to less than 3 centimetres near Princeton and to generally less than 5 millimetres farther south, with the exception of a few anomalies near the edges of the basin (for example, at Allison; *see* Fig. 5). These grain size variations in the coarser clastic sedimentary rocks also suggest a northern source.

PROVENANCE: The provenance of the coarse basal deposits of the Allenby Formation is relatively local, as noted previously. In contrast, the dominantly arkosic sedimentary rocks overlying these basal deposits (Table 1) were derived from a predominantly granitic terrane that is located away from the immediate basin area, although the sediment suffered little abrasion in passing from the source to the site of deposition. The wide areas of exposure of the Coast Intrusions and Tertiary intrusive rocks are the obvious sources. The volcanic detritus in these arkosic sedimentary rocks was undoubtedly derived from both the dominantly volcanic Nicola and Kingsvale Groups and Tertiary extrusive rocks.

Hills (1962, 1965a) suggested that the Osprey Lake intrusion (Coast Intrusions, Unit 6 of Rice, 1947, Map 888A) was the main source of most of the nonvolcanic detritus in the Allenby Formation, based on study of the texture and mineralogy of both. The relative abundance of microcline-microperthite (*see* Hills, 1965a, p. 275), plagioclase (An_{35}), quartz, and accessory minerals in the sedimentary rocks is very similar to that of the Osprey Lake intrusion. The size distributions of individual minerals are also very nearly the same, and distinctive features such as myrmekitic texture, replacement (?) microperthite, undulatory extinction in quartz, and the definition of grain boundaries are also common to both (Hills, 1962).

As further support for his hypothesis, Hills (1962) reported that the Allenby Formation sedimentary rocks lap on to the Osprey Lake intrusion in the northeastern part of the basin. However, disturbed (?) bedding attitudes and the presence of numerous small faults suggest that their contact is now primarily fault controlled. Furthermore, these Allenby sedimentary rocks could not have been derived from this marginal part of the intrusive body as it has a different and more basic composition (granodiorite) than clasts in the sedimentary rocks. Nevertheless, these relationships do not detract from the compelling evidence favouring the main part of the Osprey Lake intrusion to the northeast as the major source of the arkosic detritus.

The provenance of the abundant tuffaceous material in the Allenby Formation is uncertain, but at least some was locally derived. The rhyolitic to dacitic tuffs exposed on the southeastern margin of the Princeton Basin are quite altered and appear to be very close to a volcanic vent that is a likely source for some of these tuffaceous horizons, including perhaps the Princeton Ash.

GENERAL STRATIGRAPHY AND DEPOSITIONAL ENVIRONMENTS

The Allenby Formation is not sufficiently well exposed to enable construction of a complete stratigraphic column, but incomplete partial sections may be constructed at various localities (for example, Figs. 6, 7, and 8). Comparison of these sections illustrates important lateral and vertical stratigraphic variations in the Allenby Formation, particularly in the ratio of fine to coarse clastic sedimentary rocks, the abundance of coal, and the proportion of volcaniclastic material. These relationships permit subdivision of the sedimentary strata of the Allenby Formation into a lower, predominantly clastic member and an upper, coal-bearing member. They also show that the 'volcanic member' is interbedded and/or intercalated with the 'lower member.' The following discussion of these gross stratigraphic patterns and of the depositional environments represented by the Allenby Formation sets a useful framework for discussion of the stratigraphic setting of coal-bearing rocks in the Princeton Basin.

A measured section at Summers Creek Bluffs shows the character of the 'lower member' of the Allenby Formation (Fig. 6; Plate VI). At this locality, the basal sedimentary rocks overlie flows and breccias of the Lower Volcanic Formation, whereas at others they directly overlie volcanic rocks of the Nicola or Kingsvale Groups or, locally, intrusive rocks. The basal detritus generally reflects a local provenance.

Poorly sorted muddy breccias containing subangular blocks up to 1.2 metres across are common in other exposures of the basal strata, and probably represent colluvial deposits, most likely of talus or debris flow type (Plate III). The occurrence of a matrix-supported, debris flow-like breccia containing clasts of Allenby sedimentary rocks, at a level well above the base of the formation (on Asp Creek), is

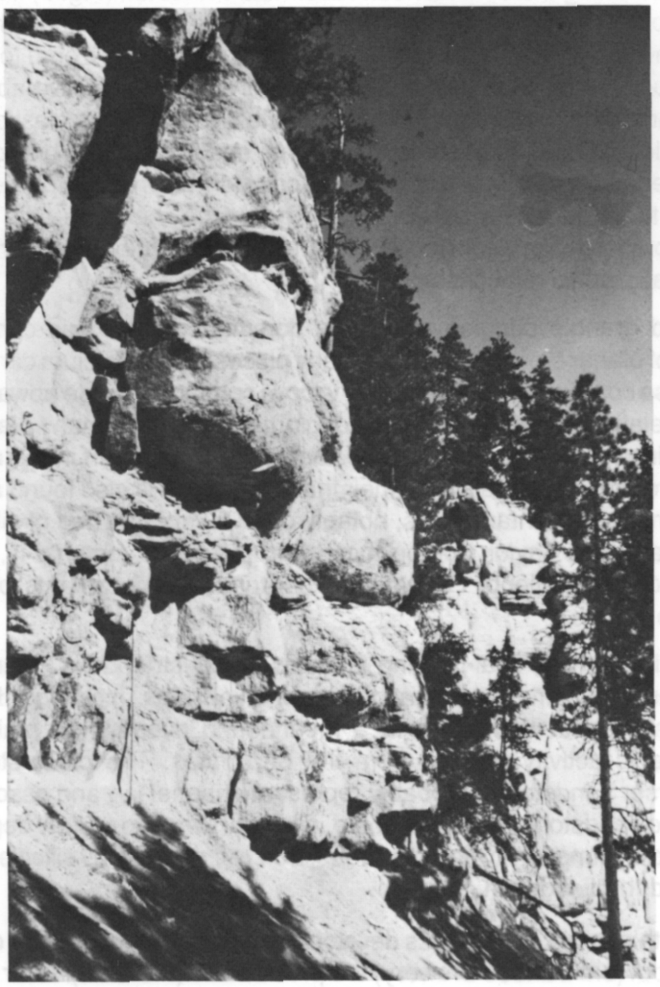


Plate VI. Upper bluffs on Summers Creek. These resistant thin-bedded to massive lithic tuffs, tuffaceous wackes, and granule conglomerates occur in the upper part of the measured section (Fig. 6) and form a distinctive local stratigraphic marker. For scale, Jacob's staff (lower left) is 1.5 metres long.

significant in that it suggests an active tectonic environment (extensional faulting) at the time of deposition of the lower member.

The overlying strata in the Summers Creek section consist mainly of granule to boulder conglomerates. These conglomerates occur as both massive and normally or inversely graded beds. They show broad scour-and-fill relationships, contain tabular sets of planar cross-strata, and contain scattered very thin coaly lenses and streaks. The stratigraphic character and sedimentary structures are consistent with deposition in a fluvial environment, probably either from sheet floods or migrating bars in a sediment-laden braided river system. The predominance of coarse clastic sediment suggests relative proximity to the source terrane. Angular tuffaceous and/or bentonitic material, occurring as (rip-up ?) clasts in the matrix and as individual beds, dilutes the arkosic detritus in this section. Its abundance attests to the continuing importance of volcanic activity during deposition of the lower member of the Allenby Formation. The presence of flows of the volcanic member (?) overlying most of the sedimentary rocks on Summers Creek is further evidence of this activity.

The composite section along the Similkameen River near Princeton (Fig. 7) illustrates the character of the lower portion of the 'coal-bearing member' of the Allenby Formation, which extends from the base of the Princeton-Black-Blue Flame coal zone (and equivalent horizons) to the top of the Golden Glow coal zone. Important features of this section are the greater relative abundance of coal, the apparent lack of coarse conglomerates (ratio of fine clastics to coarse clastics: 60 to 40), and the appearance of significant amounts of shale, mudstone, and claystone. This composite section was constructed from measured sections and subsurface information. Environmental interpretation is largely constrained to those strata observed at the surface, because little or no information is available from the borehole logs (reported *in* Rice, 1947) concerning sedimentary structures, clast provenance, and stratigraphic relationships.

The sandstones and granule conglomerates are dominantly of arkosic composition, commonly contain tabular sets of planar crossbeds, and in many places exhibit calcium carbonate concretionary layers or zones. These coarse clastic sedimentary rocks commonly grade upward into carbonaceous shale and/or coal. Relatively massive granule conglomerate beds in many places contain very thin interbeds of fine-grained sandstone or siltstone. Bentonite is common in the matrix of some of the sandstones and is probably responsible for their friable nature. It is also found as very thin interbeds within some of the finer sedimentary rocks, notably coal. A very thin bed of silicified (?) vitric tuff is interbedded with coal at the Taylor Burson mine, but tuffaceous material is, in general, not very abundant in this portion of the Allenby Formation. White tuffaceous fragments, of the type observed at Summers Creek, are scarce.

Typical detailed sections of the coal-bearing intervals are illustrated on Figures 13B and 14. The observed sedimentary structures and stratigraphic relationships, including the fining upward sequences, are consistent with deposition in a meandering river/alluvial plain environment, with intermittent (?) volcanic activity inferred from the bentonites. The cross-stratified granule conglomerates and coarser sandstones probably represent channel lag and associated large channel bars, whereas the fine sandstone, siltstone, shale, and coal were most likely deposited in upper point bar and overbank/backswamp environments. Trees, now represented by silicified, *in situ* tree stumps, periodically stabilized the floodplain.

The large amplitude, thin to thick crossbeds developed in exposures of granule conglomerate behind the Princeton bus depot (old Cariboo Brewery) are problematic (Plate VII). After rotating the overlying and underlying carbonaceous siltstone and shale beds back to horizontal, the residual dips of 20 to 25 degrees of the steepest beds necessitate a minimum local paleorelief of greater than 4 metres. The coarser grain size and moderately good sorting (Hills, 1962; Figs. 1, 2, and 3) rule out deposition as eolian dunes and the relief may be somewhat large for channel bars within a coarse sand-granule bed braided river. These strata probably represent lateral accretion/point bar channel deposits in a large, steep gradient meandering river setting. The convex upward basal terminations of similar large-scale crossbeds (*see* 'epsilon' cross-strata, Allen, 1963) in a similar stratigraphic interval (exposed along the Tulameen River 500 metres northwest of the Canadian Pacific Railway tunnel at Princeton) and the broad channelling relationships visible at other good exposures nearby support this interpretation.

Many of the scattered surface exposures in the southern portion of the Princeton Basin belong to the upper portion of the 'coal-bearing member' of the Allenby Formation. The section exposed along the shallow canyon of the Similkameen River west of Allenby was implicitly chosen by Shaw (1952) as the 'type section' for the Allenby Formation, and represents the lowest part of the above stratigraphic interval. This section (Fig. 8) is characterized by massive beds of medium to coarse-grained arkosic wacke that are relatively enriched in quartz compared to those of the lower sections discussed previously, and that fine upward into carbonaceous siltstone and shale. Fine clastic sedimentary rocks are more abundant than in the lower portion of the 'coal-bearing member' (ratio of fine clastics to

Plate VII. Large amplitude, thin to thick cross-beds in granule conglomerate exposed behind the Princeton bus depot. Probably represent lateral accretion/point bar plus channel deposits in a large, steep gradient meandering river environment. For scale, the exposure is about 11 metres high.

coarse clastics: 70 to 30). Interlensing sandstone, siltstone, and shale are common. Bentonite is also more abundant and is dominant at the top of the measured section (Fig. 8). Many of the intervals are covered with slumps or earth flows involving sandy or silty bentonite. The thin seams of coal and shaly coal at the base of the section probably correlate with the Golden Glow zone. Only traces of coal are present in the better exposed, lower middle part of this section (Fig. 8), and although other coal seams should occur in the overlying covered intervals, particularly those corresponding to the Freeman coal zone (Fig. 12), none were found at the surface.

These characteristics are consistent with deposition in a lower energy meandering river environment located farther away from the arkosic source terrane than the one represented by the previous column (Fig. 7). The apparent decrease in the abundance of coal in this part of the Allenby Formation may be related to the increase in the abundance of bentonitic and tuffaceous material, representing more frequent explosive volcanic activity.

A potentially important coal seam encountered in Bethlehem Copper Corporation's drill program in the southern half of the Princeton Basin (Anderson, 1972) occurs in the upper part of the 'coal-bearing member,' stratigraphically above the measured Allenby section (Fig. 8, *see* also Fig. 12). The presence of this coal zone high in the preserved column may indicate a transition back to an environment that was more suitable for growth, accumulation, and preservation of organic matter, perhaps with less volcanic activity. Fine clastic sedimentary rocks still dominate in these uppermost strata. Ratios of fine clastics to coarse clastics of 65 to 35 are estimated from borehole logs in Anderson (1972, 1976), and bentonitic material is common in surface exposures.

Various alluvial plain subenvironments, in addition to the fluvial ones discussed previously, are also represented in the Allenby Formation. Lacustrine, paludal (swamp), and overbank/floodplain subenvironments are particularly important in that they offered a favourable setting for the accumulation of fine clastic sediments and the abundant organic matter now represented by coal.

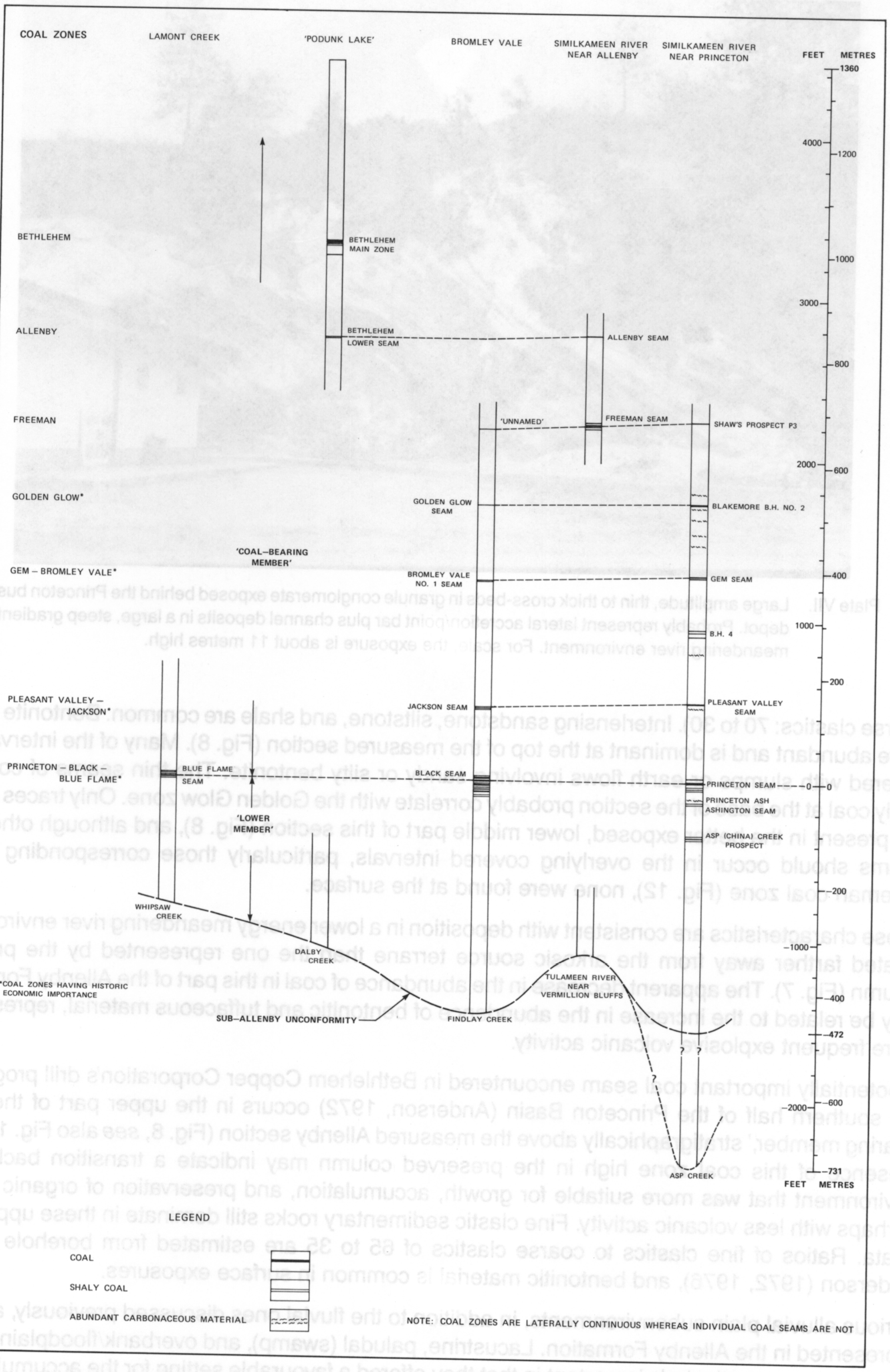


Figure 12. Correlation chart of coal zones in the Allenby Formation, Princeton Basin.

Finely laminated to massive shales, mudstones, and claystones occur in most parts of the Princeton Basin, and many contain very well-preserved fossil plants and some insects. Preservation of delicate organic remains (for example, *see* Shearer, 1973) requires very quiet water, redox potential (Eh) less than zero at or below the sediment water interface (Krumbein and Garrels, 1952), and little or no bioturbation. A stratified lake with stagnant bottom waters is indicated. The abundance of encrusting gypsum suggests that the lake waters were at times saline. Kuc (1974) described similar silty shales from near the base of the Allenby Formation at a locality on Summers Creek 5 kilometres north of Princeton, and also interpreted them to represent slow and undisturbed sedimentation of organic remains in the bottom of a lake. She attributed the alternation of white, tuffaceous coarse silt laminae poor in fossils with darker, less silty, organic rich ones to cycles in bioproduction, perhaps on an annual basis.

Hot (?) springs were locally associated with lacustrine and swamp environments, and their activity sometimes interrupted the accumulation of organic matter. The rhythmically interbedded coal and chert exposed on the Similkameen River 8.6 kilometres south of Princeton (section 2, Fig. 13B) were interpreted by Boneham (1968, p. 39) as being deposited in a 'peat bog which [was] periodically invaded by hot, silica-rich water from nearby hot springs. The existing vegetation was killed and the silica precipitated as the volcanic water mixed with the acidic waters of the bog and cooled. ... In the cooling waters the plants were able to establish themselves and so begin the formation of another peat layer.' Hills (1962; *see* also Dawson, 1879) interpreted the strata at Vermilion Bluffs to be an ancient spring deposit, and inferred that the spring was either intermittent or intermittently inundated by lake waters. The deposits alternated from siliceous to calcareous and back again over the life of the spring. The presence of these hot springs may be attributed to coeval geothermal/volcanic activity.

The coal deposits probably accumulated as vast quantities of organic debris in swamps, bogs, and lakes, and also perhaps in overbank or cutoff channel environments. Luxuriant plant growth in the former humid warm temperate to subtropical lowland climate supplied the debris (Hills, 1965b; Shearer, 1973). These accumulations of organic debris were preserved as coal where they were protected from oxidation by a water cover and were eventually buried safely out of reach of the erosive power of the shifting stream channel(s) (Shaw, 1952).

Thus the partial sections of the Allenby Formation (Figs. 6, 7, and 8) illustrate a transition from a higher energy braided river (± alluvial fan) depositional environment to a lower energy meandering river setting, both away from the inferred upland source terrane in the north and upward in the stratigraphic column. Lacustrine, swamp, and, locally, hot spring subenvironments are also represented.

The occurrence of thick lava flows conformably beneath the Allenby Formation suggests a cause-and-effect relationship, whereby lava flows dammed parts of the valley and initiated alluviation (Shaw, 1952). This relationship may have affected the early phases of the sedimentation, but it fails to account for the great preserved thickness of Allenby Formation strata, and backfilling of a gradually subsiding structural trough is the most reasonable explanation.

AGE OF THE ALLENBY FORMATION

The age of the Allenby Formation was for a long time a subject of controversy. Bell (*in* Rice, 1947) compared the Allenby flora to the Bridge Creek flora of the John Day Basin in Oregon, considered to be Upper Oligocene or Lower Miocene. Carpenter (*in* Rice, 1947) identified a collection of insects and assigned a tentative age of Oligocene or Miocene. A mammal tooth found in 1933 in the W. R. Wilson coal mine (probably Pleasant Valley No. 2 mine) was identified by Russell (1935) as *Trogosus minor* in the *Tillodontia* (a primitive order of mammals) and was assigned a Middle Eocene age. Fish and molluscs have provided no clear-cut evidence of age.

Rouse and Mathews (1961; *see* also Mathews and Rouse, 1963; Mathews, 1963) initiated a program of palynological and potassium-argon radiometric dating in an attempt to clarify the correlation and age of Tertiary strata in the interior of British Columbia. Their work indicated that these strata can be divided into two age groups; a Middle Eocene sequence of volcanic and sedimentary rocks, and a Mio-Pliocene sequence of similar rocks. They included the Allenby Formation with the Middle Eocene group on the basis of a 48 ± 2 Ma radiometric date from the Princeton Ash. Additional potassium-argon radiometric dating and palynological study have confirmed this Middle Eocene (*see* van Eysinga, 1975) assignment (Hills, 1965b; Hills and Baadsgaard, 1967).

The discrepancy in age assignment between absolute methods (and the mammal tooth age) and the macro/microfloral assemblages can be attributed to the inadequacies of criteria previously used in assignment of ages to the latter group (Evernden and James, 1964), and to the effect of climate, altitude, latitude, mountain barriers, and other factors on the composition of synchronous but geographically isolated Tertiary floras (Rouse and Mathews, 1961).

STRUCTURAL GEOLOGY

INTRODUCTION

The Princeton Basin is situated near the southern end of the Nicola Belt, a north-trending terrane underlain primarily by rocks of the Late Triassic Nicola Group. The belt is united by similar stratigraphy and tectonics, and is noted for its large number of copper mines and prospects (Preto, 1972; *see* also Rice, 1947; Carr, 1962; Preto, 1979). Older east and northwest-trending structures in the Nicola Belt are cut by later north and northwest-trending sets of intersecting and branching faults that control a system of grabens in the southern interior of British Columbia (Carr, 1962; Preto, 1972).

The Princeton Basin is a complex half graben superimposed on this terrane and is filled with Paleogene rocks of the Allenby Formation (Figs. 2, 9, and 10). Its internal configuration has been inferred from structural attitudes measured at numerous small, partly covered and often partially slumped exposures of weakly competent Allenby Formation strata, and is portrayed on the accompanying geological map (Fig. 2). Unreliable data were filtered out and the remainder averaged for clarity of presentation.

Projections of coal occurrences of historic economic importance (Fig. 9) delineate the inferred subsurface structure of the Princeton Basin. Although these coal zones occur at certain definite horizons within the Allenby Formation, their projections are solely intended to delineate the structure and do not imply the continuation of good (or poor) coal seams.

The structural contour map for the southern portion of the Princeton Basin (Fig. 10) has been modified after Shaw (1952, Fig. 1B) using additional surface and subsurface structural data (Fig. 2; Anderson, 1972, 1976), and the postulated correlation of the Princeton, Black, and Blue Flame coal zones (*see* Stratigraphic Setting of Coal Seams). Contours have been drawn on the pavement of the coal zone where it has been positively identified, and in other areas the contours indicate only the inferred position of approximately equivalent strata (Fig. 14). It is important to note that because of the paucity of subsurface control, the structural contour map can be, at best, a tentative guide to further exploration, and that positions of the inferred contours may have to be modified as more subsurface information becomes available.

The Princeton Basin may be separated into two parts for convenience in discussing the structural geology, using the gentle, northwest-trending 'Rainbow Lake' anticline (Hills, 1962) as the boundary.

NORTHERN AREA

The northern half of the basin is a large, gently folded, homoclinal panel that has been tilted to the east. The dips range from 15 to 25 degrees and flatten to the east; dip reversal is common at the extreme eastern margin of the basin. Most of the sedimentary rocks exposed in this area are thought to belong to the lower member of the Allenby Formation (below the Princeton-Black-Blue Flame coal zone). Higher strata may occur 2 to 3 kilometres south of Jura where as much as 1 500 metres of section may be present. In most other places in the northern part of the basin, the sediment cover is relatively thin; altered flows and tuffs of the Nicola Group are exposed at the surface approximately 2.5 kilometres north of Princeton [formerly identified by Shaw (1952) as Upper Volcanic Formation and by Hills (1962) as Lower Volcanic Formation]. Geophysical exploration (McAndrew, 1973; Gower and Anderson, 1961; Cochrane and Scott, 1971) has identified two other areas on the flanks of the 'Rainbow Lake' anticline, 2 and 7.5 kilometres north of Princeton, where rocks of the Nicola Group probably occur very close to the surface.

SOUTHERN AREA

The southern part of the basin is, in a broad sense, a structural depression having its greatest apparent depths west of the Similkameen River, beneath the Podunk Lake area 7 to 8 kilometres southwest of Princeton, and near Ashnola at the southeastern extremity of the basin (Fig. 10). On the southern flank of the 'Rainbow Lake' anticline, the sedimentary rocks dip gently (10 to 20 degrees) to the south through the village of Princeton, except between Asp Creek and the Tulameen River, where the strata dip gently to the east. Numerous undulations on the scale of a few tens of metres modify the otherwise uniform southerly dips observed along the Similkameen River in the vicinity of Princeton, and two major, east-trending, asymmetric anticlinal structures are present south of Princeton and southwest of Allenby ['Allenby Anticline' of Shaw (1952)]. Numerous smaller folds are superimposed on these larger structures, but they probably die out at depth. A gentle to moderate southerly dip continues to the south of these anticlines. On the western margin of the basin, sedimentary rocks dip approximately 50 degrees to the east; the easterly overturning of strata exposed in the Black mine (M8) may be ascribed to surface slumping, as a more reasonable 50-degree easterly dip prevails at depth (Fahrni, 1947). Volcanic rocks locally dip as steeply as 80 degrees to the east, although those on the Tulameen River may have been affected by a landslide (Fig. 2). In the extreme southern portion of the basin, structural attitudes fan off the broad north-plunging anticlinal nose upon which the Blue Flame mine (M14) was situated. Little information is available in the southwestern portion of the basin but the north-northeast-trending normal fault and north-plunging broad syncline to the west have been inferred from surface exposures and from the writer's interpretation of the Bethlehem Copper Corporation's drill hole logs (Anderson, 1972, 1976).

The existence of discrete outcrop zones with relatively consistent attitudes, the difficulty in reconciling subsurface information with projections based on surface attitudes (*see* Monger, 1968; Fig. 3), and the presence of small-scale normal faults in surface exposures suggest that many more moderate scale faults are likely to be present within the basin than are recognized at the surface, and that their effects will have been smoothed out in the structural contour map (Fig. 10).

BASIN MARGINS AND FAULT CONTROL

Topographic and geologic relationships along the eastern margin of the Princeton Basin suggest that it is fault controlled; the significant disturbance of structural attitudes along it suggests that at least some of the movement was post-depositional. This fault is probably a northward continuation of the Boundary normal fault of Preto (1972) and follows a marked north-northeast-trending lineament along the eastern margin of the basin. It may continue into the Hayes Creek Valley to the northeast. The fault is moderately to steeply west-dipping and probably flattens with depth to the west in order to account for the predominant eastward tilt of Allenby Formation strata, particularly evident in the northern part of the basin (*see* also discussion of gravity-depth sections). The stratigraphic separation across the normal fault is inferred to be in the order of 1 400 metres, with west side down (B-B', C-C', Fig. 9).

The northeastern margin of the basin, that is the contact with the Osprey Lake intrusion (Fig. 2), is now fault controlled, as shown by intense fracturing, the 'healing' of some of the fractures with magnetite, and the anomalously steep bedding attitudes in this area; it may originally have been a nonconformity (Hills, 1962, 1965a). Sheared zones in rocks of the Nicola Group exposed along Summers Creek suggest a continuation of Rice's (1947) and Preto's (1979) Summers Creek fault zone, but geologic relationships do not appear to support Tertiary movement; the same is true for the inferred fault zone along Allison Creek.

A north-trending fault having predominantly (west side down) normal displacement, with perhaps a small component of right lateral offset, is inferred to intersect the Tulameen River about 4 kilometres west of Princeton. This 'Asp Creek' fault is probably the continuation of a splay off the Allison fault (*see* Rice, 1947; Preto, 1979). Although drift cover prevents tracing this fault (zone) very far into the coalfield, a series of possibly related normal faults of small displacement was reported at the western extremity of the Pleasant Valley No. 2 mine (M7; Shaw, 1952).

In spite of the rather steep structural attitudes along the western margin of the basin, the apparent conformity of the Allenby Formation strata with the underlying Lower Volcanic Formation suggests that this contact is not fault controlled. Hence, the Princeton Basin is not a simple graben. The structural and topographic asymmetry of the basin is, in fact, quite marked (Figs. 2, 9, and 10).

SUMMARY AND TECTONIC MODEL

The Princeton Basin thus appears to be a half graben with a major listric normal fault zone bounding the eastern margin. The relatively common occurrence of easterly dips within the graben suggests that at least some of the fault movement postdated sedimentation. Nevertheless, the relatively thick pile of Allenby Formation strata must have been localized, at least initially, in a developing fault basin.

The broad, open, east to southeast-trending fold structures, such as the Rainbow Lake anticline (Fig. 2), may have resulted from differential movements within basement rocks during graben development. This northeast-southeast shortening may have formed from transfer of right lateral offset from the northerly trending 'Asp Creek' fault to the northeasterly trending Boundary fault in a zone where the two faults converge (Fig. 2, inset).

The structure and preserved stratigraphy in the Princeton Basin, and in numerous others in south-central British Columbia (Monger, 1968; Taylor, *et al.*, 1964), thus record a period of crustal extension with accompanying graben development and volcanism during the Eocene. These phenomena may be ascribed to intracontinental ductile crustal spreading linking the Fraser River and northern Rocky Mountain Trench right lateral transform fault zones (Price, 1979).

GRAVITY

INTRODUCTION

During the latter part of 1975, C. A. Ager and Associates Ltd. conducted a reconnaissance gravity survey of the Princeton Basin as a complementary study to the author's geologic investigations. Three east-southeast/west-southwest profiles were surveyed (Fig. 11) with the intent of investigating the gross basinal geometry and of testing for the presence of coal anomalies. The following discussion summarizes and reviews the results of Ager's (1975) report; the particulars of the gravity survey and the method of reduction of field measurements are summarized in Appendix A.

Sedimentary rocks of the Allenby Formation overlie a basement of denser Tertiary (Lower Volcanic Formation) and older volcanic rocks (Kingsvale, Nicola Groups), and their presence should give rise to a significant gravity low. The less dense coal zones within the Allenby Formation should similarly give rise to subtle gravity lows within the broader basin gravity low. The usefulness of this gravity survey lies not only in delimiting the subsurface configuration of the basin and in identifying near-surface occurrences of known coal zones, but also in testing for the presence of significant thicknesses of coal at depth, as have been discovered at Hat Creek (*see* Church, 1977).

BASIN GEOMETRY/THICKNESS OF SEDIMENT FILL

In order to determine the basin geometry, and hence to estimate the thickness of sediment fill, Ager used a simple slab model. This model assumes that the sedimentary accumulation forms a relatively simple geometrical shape — a rectangular slab — of uniform density and infinite longitudinal extent superimposed on a higher density basement. By assigning densities of 2.20 grams per cubic centimetre and 2.70 grams per cubic centimetre to the sedimentary rocks and basement, respectively, and using information regarding the position of the half width relative to the mapped contact, depth section estimates were then calculated for each of the profiles (Fig. 11, upper curve). Ager emphasized that the depth values given on the cross-sections are only approximate, noting that the simple slab model probably underestimates the basin depth by perhaps 5 to 10 per cent (Ager, 1975, personal communication). He suggested more sophisticated modelling and determination of actual rock densities as a means of improving the precision.

Following Ager's suggestion, the author performed (H_2O) saturated bulk density measurements on 31 samples from the Princeton Basin, and summarized additional published saturated bulk density determinations on similar lithologies of Early Tertiary age (Appendix B). By weighting the various lithologies by their relative abundance (as observed in measured sections and boreholes) and making reasonable assumptions concerning the expected increase in shale density with depth (Nettleton, 1962), average saturated bulk densities were estimated for the basement and overlying sedimentary column for each of the three gravity profile lines (Table 4). The resulting density contrasts were used in the simple slab model to calculate revised profiles for the Princeton Basin (Fig. 11, lower curves).

TABLE 4. AVERAGE SATURATED BULK DENSITIES, PRINCETON BASIN[1]

	Line	Basement (g/cm³)	Sediment (g/cm³)	Density Contrast (g/cm³)
Ager (1975)	All	2.70	2.20[4]	0.50
This study	675N	2.66[2]	2.28[4]	0.38
	300N	2.55[3] (2.66)	2.26[4]	0.29 (0.40)
	190N	2.55[3] (2.66)	2.25[4]	0.30 (0.41)

[1] — *See* Appendix B for calculations.
[2] — Nicola Group.
[3] — Lower Volcanic Formation.
[4] — Allenby Formation.

The most obvious features of the gravity profiles are that the basin is considerably shallower in the north than in the south, and that, of the lines surveyed, the preserved sedimentary fill is thickest (Ager, 1975, 721 metres; revised, this report, 1 243 metres; *see* Table 5) under line 300N. Another notable characteristic of the three gravity profiles (*see* Fig. 11) and corresponding depth sections is their marked asymmetry; the deepest part of the basin is on the east side. The relatively steep to near vertical character of the eastern basin margin inferred from the upper portions of the complete Bouguer gravity profiles (Fig. 11, note in particular line 675N) is consistent with the steeply west-dipping fault contact that has been inferred from surface geology. The concave upward character of the slope along the eastern portion of the complete Bouguer gravity profiles suggests that the basin boundaries slope inward at a moderate angle; this could, in part, reflect a flattening of the postulated bounding fault with depth. The gentle slope of the western portion of line 675N is consistent with the inferred relatively thin cover of Allenby Formation strata lying unconformably over Nicola Group rocks with a gentle, east-dipping contact. In contrast, the markedly steeper character of the western parts of lines 190N and 300N may be ascribed to the relatively steep (45 to 55 degree) east-dipping contact of the Allenby Formation sedimentary rocks with the underlying Lower Volcanic Formation; surface geologic relationships do not require a fault along this southwestern margin.

The gentle convex upward profiles near the centres of lines 190N and 675N indicate either that the sedimentary rocks are denser or the basin fill is thinner (reflecting a topographic 'high' in the basement) in the middle of the basin. This character could also be ascribed in part to basin edge effects due to faulting. The virtual lack of this feature on line 300N suggests that the profiles reflect the configuration of the basement surface, rather than the presence of anomalous densities, and that edge effects are small. Part of the depth section profile along line 190N may be ascribed to fault modification of the pre-existing surface topography on the Lower Volcanic Formation; a normal fault with west side down intersects the profile immediately west of centre (*see* Figs. 10 and 11). The depth section profile along line 675N, on the other hand, describes the surface topography of the underlying Nicola Group rocks, with little evidence for significant vertical fault modification.

TABLE 5. ESTIMATED VERTICAL THICKNESS OF SEDIMENTARY FILL IN PRINCETON BASIN AT SELECTED LOCATIONS ON GRAVITY PROFILE LINES

Line	Density Contrast *(g/cm³)*	Location	Thickness *metres (feet)*	Location	Thickness *metres (feet)*	Location	Thickness *metres (feet)*
675E	0.50[1]	E	282 (925)	F	201 (660)	G	463 (1,520)
(*see* Fig. 11d)	0.38[2]		371 (1,217)		265 (868)		610 (2,000)
300N	0.50[1]			D	721 (2,365)		
(*see* Fig. 11c)	0.40				901 (2,956)		
	0.29[2]				1 243 (4,078)		
190N	0.50[1]	A	597 (1,960)	B	511 (1,675)	C	607 (1,990)
(*see* Fig. 11b)	0.41		728 (2,390)		622 (2,042)		739 (2,426)
	0.30[2]		995 (3,266)		851 (2,792)		1 011 (3,317)

[1] — Density contrast used by Ager (1975).
[2] — Density contast favoured in this study (*see* Table 4).

COAL ANOMALIES

Coal is less dense than ordinary sedimentary rocks (about 1.2 to 1.3 grams per cubic centimetre for subbituminous coal, in contrast to 2.25 to 2.3 grams per cubic centimetre for the enclosing sedimentary rocks; *see* Appendix B). Its presence will be revealed by gravity low regions or by locally steep changes in the gravity gradient, or both. The known coal beds in the Princeton Basin are generally narrow with gentle to moderate dips (15 to 50 degrees), for which one may infer a narrow gravity response of small amplitude, probably less than 1 milligal (Ager, 1975).

Very definite density boundaries can be identified along each of the profiles (arrows on Fig. 11) that represent contacts or density change boundaries between adjoining interbasin sedimentary units, including coal (Ager, 1975). Several subtle, but distinct, gravity low features (open circles on Fig. 11) caused by less dense geological units within or on top of the basin rocks, have also been identified. These areas, marked by the open circles and arrows labelled 'C' on Figure 11, are therefore prime possibilities for coal locations; they are listed in Tables 6A, 6B, and 6C.

TABLE 6A. LINE 190N—GRAVITY ANOMALIES/DENSITY CHANGE CONTACTS, PRINCETON BASIN[1]

53E	subtle anomaly situated along projection of Princeton-Black-Blue Flame coal zone; consistent with the presence of a narrow coal zone with moderate to steep dip
68E	overburden anomalies related to glacial outwash terraces
80E	broad prominent anomaly mainly related to overburden (valley was a prominent glacial meltwater channel; *see* Hills, 1962); two smaller anomalies at 77E and 81E (within main anomaly) situated along projection of Bromley Vale and Golden Glow coal zones
96E	density change contact corresponding to lower coal zone identified by Bethlehem Copper Corporation (DDH 71-12; Anderson, 1972; *see* Allenby coal zone of Fahrni, 1945)
115E	prominent anomaly corresponding to main coal zone identified by Bethlehem Copper Corporation's drill program (upper zone DDH 71-12; Anderson, 1972)
131E	prominent anomaly reflecting presence of unknown, near-surface coal seam or other low density medium such as shale or bentonitic clay
148E	anomaly related either to abundant bentonitic clay at surface or to projection of possible coal zone from 131E
162E	possible fault contact
197E 211E	density change contacts of uncertain importance (may indicate contacts of small near-surface coal zones)
228E	deep anomaly adjacent to Similkameen River in part related to dirty coal seams exposed on the west bank, but mainly related to river alluvium
239E 255E 264E	density change contacts of uncertain importance; probably denote contacts of thick (?) shales or bentonitic clays

[1] — Refer to profile on Figure 11b.

TABLE 6B. LINE 300N—GRAVITY ANOMALIES/DENSITY CHANGE CONTACTS, PRINCETON BASIN[1]

24E	small anomaly caused by overburden or lighter tuffaceous sedimentary rocks interbedded with flows of the Lower Volcanic Formation
44E	basin contact anomaly; in part caused by tuffaceous sedimentary rocks intercalated with the uppermost flows and breccias of the Lower Volcanic Formation
56E	anomaly corresponds to Princeton-Black-Blue Flame coal zone, immediately north of the Black (Glover's) mine (M8 of Shaw)
66E	density change boundary possibly related to Jackson coal zone
72E	anomaly probably related to Bromley Vale coal zone [mined at Bromley Vale No. 1 mine (M13)]
84E	anomaly probably related to Golden Glow coal zone [mined at Bromley Vale No. 2 mine (M15) and Shaw's prospect P4]
97E	anomaly mainly caused by overburden (Findlay Creek was a prominent glacial meltwater channel; *see* Hills, 1962); could also be related to an uncertain projection of Fahrni's Freeman coal zone (*see* 137E)
137E	anomaly probably corresponds to coal zone projection from Fahrni's Freeman coal seam and Shaw's prospect P3
157E	overburden anomaly; immediately adjacent to major gravel pit
176E	density change contact possibly corresponding to projection of Fahrni's Allenby coal zone
205E	broad anomaly mainly caused by Similkameen River alluvial fill; smaller anomalies at 196E and 208E probably correspond to projection of Bethlehem Copper Corporation's main (upper) coal zone (DDH 71-12; Anderson, 1972), whereas the subtle anomaly at 214E probably corresponds to the Allenby coal zone
234E 256E	density change contacts probably related to bentonite beds or coal seams of only minor importance

[1] — Refer to profile on Figure 11c.

TABLE 6C. LINE 675N—GRAVITY ANOMALIES/DENSITY CHANGE CONTACTS, PRINCETON BASIN[1]

105E	overburden anomaly (underlain by rocks of Nicola Group)
139E	density change contact of uncertain importance; probably shale or bentonite overlying more dense conglomerate
163E	anomaly chiefly caused by overburden (situated on 'riser' between gravel-mantled outwash terraces); small coal zone, such as that already prospected on Summers Creek (Shaw's P9) may in part be responsible
181E	density change contact of uncertain importance
210E	most likely overburden anomaly
249E } 273E }	density change contacts of uncertain importance; only a few very thin, poor quality coal zones of restricted lateral extent have been identified at the surface in this area, and hence these contacts most likely represent the interfaces between denser conglomerates and less dense fine clastic sedimentary rocks, the latter being of tuffaceous or bentonitic character

[1] — Refer to profile on Figure 11d.

Several of these anomalies are in areas where changes in overburden thickness are suspect, for example, at the Similkameen River on lines 190N (228E) and 300N (205E), and under Allison Creek on line 675N (163E). Small anomalies on the western portion of line 300N (24E, 44E) demarcate the basin contact and zones of lighter tuffaceous sedimentary rocks intercalated with the uppermost flows of the Lower Volcanic Formation, whereas other anomalies probably reflect the presence of lower density fine clastic sedimentary rocks or bentonitic clay at the surface (for example, 239E on line 190N).

The chief value of the gravity method is not in monitoring subtle quality variations in minor coal zones, but rather in delineating known coal zones of significant historical important (for example, Princeton-Black-Blue Flame zone), and in identifying new ones (for example, Bethlehem zone). The reliability of this method is illustrated by the reasonably certain correlation of some of the anomalies on line 300N with projections of known coal zones. However, the interfering effects of small anomalies caused by overburden and other near-surface, low-density media, and variability of structural attitudes of the coal zones make it difficult to rank the coal anomalies (listed in Tables 6A, 6B, 6C and discussed following) in any definite order of economic importance (*see* Ager, 1975).

The Princeton-Black-Blue Flame and Bromley Vale coal zones have been positively identified on both lines 300N (56E, 72E) and 190N (53E, 77E); the gravity response suggests that the former deteriorates and/or thins significantly to the south. The Golden Glow coal zone was tentatively traced south from Bromley Vale to line 190N (81E), whereas the Jackson and other minor coal zones were not. The Freeman and Allenby coal zones of Fahrni (1945) were tentatively traced from the Similkameen River in the vicinity of Allenby across line 300N to the Bromley Vale area (137E, 176E); the latter was also tentatively correlated with the lower coal zone encountered in Bethlehem Copper Corporation's drill program (96E on line 190N). An anomaly corresponding to the main (upper) Bethlehem coal zone was identified on line 190N (115E) and tentatively on line 300N (196E, 208E). Most of the other anomalies and density change contacts listed in Tables 6A, 6B, and 6C may be ascribed to overburden, as noted previously, or to minor coal zones of little or no historical economic significance. Perhaps the most prominent exceptions are two anomalies on line 190N (131E, 148E) which are of similar magnitude to that attributed to the projection of the main Bethlehem coal zone. If these anomalies do indeed reflect a coal zone, then this zone could be a worthwhile exploration target due to its proximity to the surface.

The gravity method was also used to evaluate the possibility of thick coal deposits within the Princeton Basin, of similar magnitude to those of Hat Creek. Such deposits would be indicated by anomalies of 5 to 10 milligals within the gravity low trough regions of each profile (Ager, 1975; *see* Fig.

11). In this regard, the most obvious and unknown candidate is the 6-milligal gravity low trough anomaly centred at about 268E on line 675N. This possibility is rather unlikely, however, as no thick coal zones have been discovered at the surface (north of the United Empire-Red Triangle property; M17, M18) along the western edge of the homoclinal panel, nor were any encountered in a 150-metre drill hole in the vicinity of Jura station (H. R. Trehearne, personal communication, 1975). In the opinion of Ager (1975), the other trough regions hold some promise for thick coal zones, although the writer is less optimistic. In spite of poor surface geological control, the southwestern portion of the basin is perhaps the best candidate for thick coal deposits based on favourable geologic-stratigraphic setting and easier exploitation logistics (*see* Coal Geology).

COAL GEOLOGY

MINING HISTORY

Coal first gained economic significance in the Princeton Basin shortly after 1901, following exploratory drilling by the Vermilion Forks Mining and Development Co. Ltd. at Princeton and along the Similkameen River. Two promising seams were discovered; the lower (Princeton or No. 1) seam being more favourable than the upper (Gem) seam. The first coal to be produced on a commercial scale was extracted in 1909 from the No. 1 mine of the Princeton Coal and Land Co. Ltd. located immediately south of the junction of the Tulameen and Similkameen Rivers. The uppermost 2 to 3 metres of the 5 to 7-metre-thick lower seam was exploited. Detailed production statistics for this mine, and the others in the Princeton Basin, are summarized in Table 7.

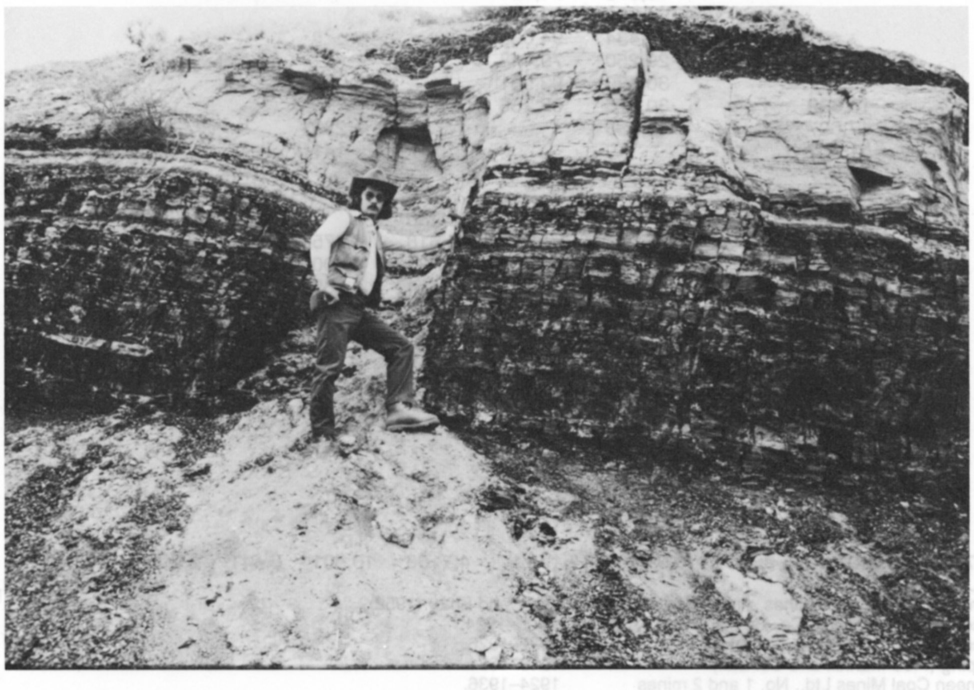


Plate VIII. Dirty coal seam in the upper part of the main Princeton coal zone exposed adjacent to the Princeton Coal and Land Co.'s No. 1 mine (M2, Fig. 13a). Note rectangular, blocky, subconchoidal fracture pattern. 'Cleat' is oriented nearly perpendicular to the exposure face and dips steeply to the left (northwest).

TABLE 7. PRODUCTION FROM PRINCETON COALFIELD (tons)[1]

Year	Princeton Coal and Land Co. Ltd.[2]	Tulameen Collieries Ltd.[3]	Pleasant Valley Mining Co. Ltd.[4]	Princeton Tulameen Coal Co. Ltd.	Granby Collieries	Black Coal Mine[5]	Jackson's Coal Mine	Taylor Burson Coal Company, Limited	United Empire Mining Company	Blue Flame Collieries	ANNUAL TOTALS
1909	150										150
1910	11,868										11,868
1911	23,396										23,396
1912	28,174								500		28,674
1913	27,206								1,752		28,958
1914	19,535										19,535
1915	15,548										15,548
1916	29,458										29,458
1917	48,926										48,926
1918	38,673										38,673
1919	24,702										24,702
1920	24,211										24,211
1921	16,865										16,865
1922	23,880										23,880
1923	20,264										20,264
1924	11,875	1,581									13,456
1925	7,725	7,350									15,075
1926	911	14,558									15,469
1927		15,800								3,343	19,143
1928		20,148								20,855	41,003
1929		41,773	5,874							5,530	53,177
1930		45,765	21,663							12,248	79,676
1931		64,671	14,112							13,037	91,820
1932		57,965	16,346		411					11,780	86,502
1933		54,061	9,479		1,062					10,373	74,975
1934		21,529	10,147		1,060					13,030	45,766
1935		9,601	5,799		786					26,603	42,789
1936		12,362	7,202	899	1,298					21,576	43,337
1937			5,255	16,477	22,480					6,730	50,942
1938				18,513	74,164						92,677
1939				21,856	93,742						115,598
1940				26,434	94,030						120,464
1941		4,152		29,250	79,448	30					112,880
1942		10,617		30,620	83,981						125,218
1943		15,699		30,375	62,255	2,254					110,583
1944		47,687		18,038			233				65,958
1945		51,802					141				51,943
1946		37,877						1,012			38,889
1947		41,634				25		2,380			44,039
1948		22,580				24,230		3,049			49,859
1949	437	29,776				15,618	4,075				49,906
1950	1,311	11,048				25	4,400				16,784
1951	367					4	1,652			1,690	3,713
1952										6,306	6,306
1953										7,047	7,047
1954										12,431	12,431
1955										11,971	11,971
1956										3,078	3,078
1957										1,601	1,601
1958										156	156
1959										1,161	1,161
1960										1,194	1,194
1961										346	346
New Totals	375,482	640,036	95,877	192,462	514,717	42,186	10,501	6,441	2,252	192,086	
										Grand Total	2,072,040
										Tonnes	1 879 723

[1] Figures from Minister of Mines, Annual Reports, Rice (1947), and Shaw (1952).

[2] Princeton Coal and Land Co. Ltd., No. 1 and 2 mines 1909–1924.
Princeton B.C. Colliery Co. Ltd., No. 3 mine 1925–1926.
Stripping (Fred Mannix and Co. Ltd.) 1949–1951.

[3] Tulameen Coal Mines Ltd., No. 1 and 2 mines 1924–1936.
Tulameen Collieries Ltd., No. 3 mine 1941–1945.
Pleasant Valley Mining Co. Ltd., No. 4 mine 1945–1950.

[4] Pleasant Valley Mining Co. Ltd., No. 1 and 2 mines. 1929–1937.

[5] Granby Collieries 1941–1943.
Stripping (Fred Mannix and Co. Ltd.) 1947–1951.

Rice (1947, pp. 123-127) outlined the history of most of the individual operations up to 1944. Their locations are illustrated on Figure 13A. More recent activity has been of a limited nature. Tulameen Collieries Ltd. opened their Pleasant Valley No. 4 mine, 500 metres northeast of the Pleasant Valley Mining Company Ltd. No. 2 mine, in 1945 and production continued until 1950. Following closure of The Granby Consolidated Mining, Smelting and Power Company Limited's collieries in the Bromley Vale area (approximately 7 kilometres southwest of Princeton) in 1943, Granby became interested in alternative sources of coal to fire their 17 500 kilowatt thermal power plant, which was located on the east bank of the Similkameen River 1.5 kilometres south of Princeton. Limited excavation was undertaken by Granby in 1947 at the site of the old Black mine to determine stripping possibilities. Fred Mannix and Co. Ltd. commenced stripping at this location in 1948 and commenced a similar project in 1949 at the site of the Princeton Coal and Land Co. Ltd.'s No. 1 mine (Plate VIII). Once the overburden was removed, the coal was produced at both locations up until 1951, largely by small groups using hand-picking methods. In order to continue supply of electric power to its Copper Mountain operations until closure in 1957 (Preto, 1972), Granby had evidently turned to other sources for its coal, probably from other mines in the Princeton area, as well as from Coalmont in the Tulameen Basin (*Minister of Mines, B.C.,* Ann. Rept., 1943, 1944).

Small-scale production was continued in 1945 in the Jackson mine, at which time it became temporarily inactive. James Taylor discovered another coal prospect 1 kilometre north of the Jackson mine and the Taylor Burson Coal Company, Limited was formed to develop it. Coal was produced from 1946 to 1948 from a seam which apparently lay just above the Jackson seam (Shaw, 1952), although the correlation was speculative. It was postulated that southward continuation of this Taylor Burson coal zone might better be exploited from the old Jackson mine, and so from 1949 to mid-1951, the latter was reopened with small production. The reclamation of several large, near-surface pillars in the Blue Flame mine by the Taylor Burson Coal Company, Limited was the only activity in the Princeton Basin between 1951 and 1961. Apart from scattered boreholes within the basin, which were drilled by various companies testing the extent of mineralization in underlying rocks of the Nicola Group, exploration was dormant up until 1971, when Bethlehem Copper Corporation drilled 12 holes on coal licences held in the southwestern part of the basin (Anderson, 1972). Three additional exploratory holes were drilled in late 1975-early 1976 (Anderson, 1976).

Thus short-lived, small-scale production has characterized coal mining activity in the Princeton Basin. The peak annual output for the area was 113 596 tonnes (125 218 tons), attained in 1942, and 'only rarely has any one mine exceeded a daily production of 500 tons [454 tonnes]' (Shaw, 1952). It is nevertheless notable that the total production of the Princeton Coalfield exceeded 1.9 million tonnes (2.1 million tons) (Table 7).

PHYSICAL CHARACTER AND CLASSIFICATION

Coal from the Princeton Basin ranges in rank from lignite to subbituminous 'A' (ASTM classification), with subbituminous varieties prevalent (Shaw, 1952). The calorific values range from 14.05 to 24.52 megajoules per kilogram (MJ/kg) (6 040 to 10 540 Btu per pound), probably on an 'as received basis' (*see* Tables 8A and 8B). Analyses performed to date (for example, Dickson, 1941) indicate that it is a noncoking variety of coal. When freshly exposed, it is shiny and black and breaks with a rectangular, blocky, subconchoidal fracture; a cleat is sometimes well developed. When exposed to the air, the coal slacks readily because of its high moisture content, which ranges up to 25 per cent. Its storage characteristics are generally poor, with a tendency to spontaneous combustion when stockpiled in large volumes (Hughes, 1947). The ash content of the mineable coal ranges from as low as 4 per cent upward to the allowable limit under the particular mining conditions. The sulphur content is generally low, the few available analyses showing less than 1 per cent (Shaw, 1952).

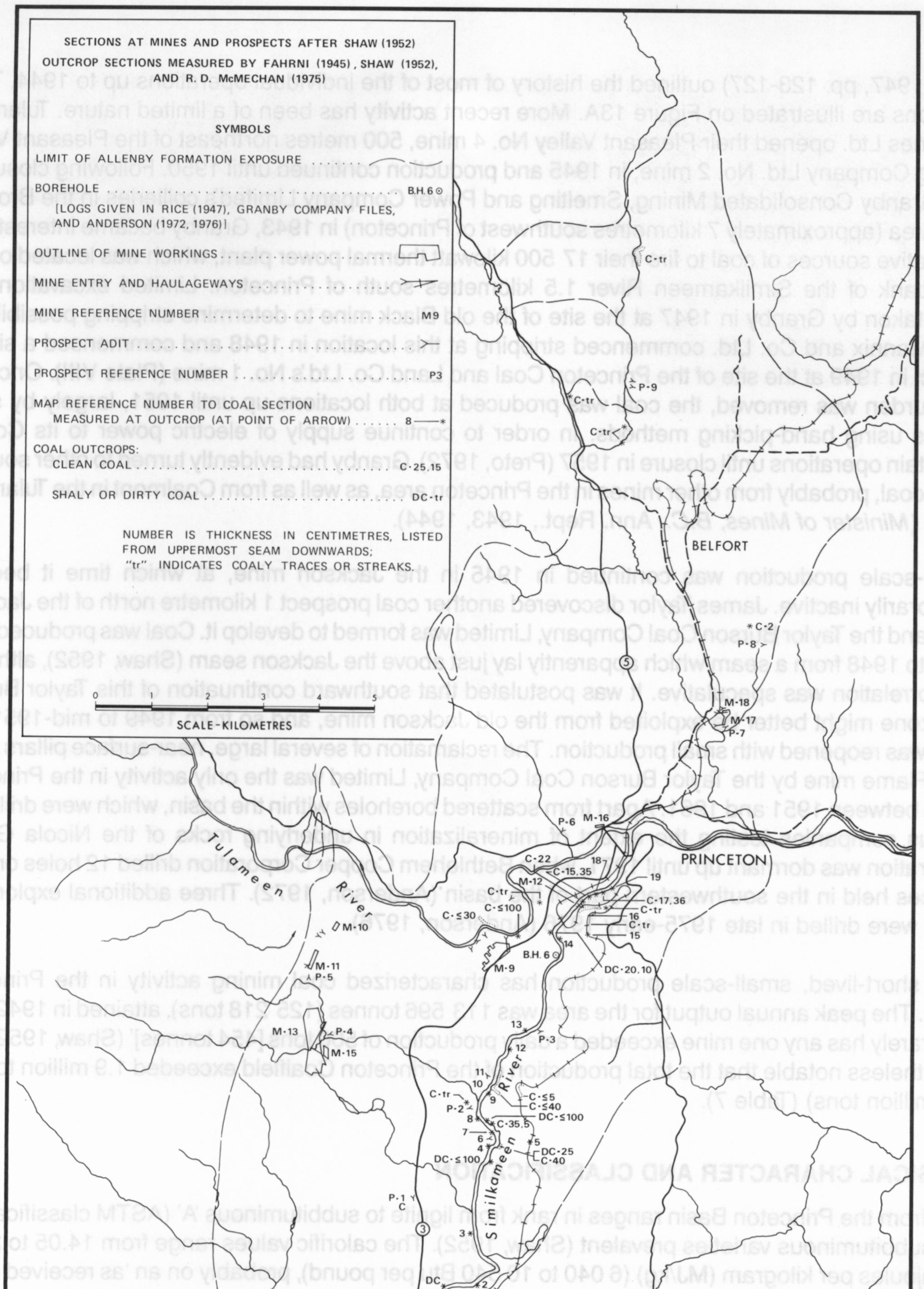


Figure 13a. Coal outcrops, mines, and prospects, Princeton Basin (excluding Princeton-Black-Blue Flame coal zone); for index, *see* Figure 13b.

TABLE 8A. COAL ANALYSES FROM MAIN PRINCETON SEAM, ALLENBY FORMATION, PRINCETON BASIN

	M5[5]	M4[4]	M3[3]	M2[2]	M1[1]
Moisture %	15.70	14.9	15.80	18.0	16.6
Volatile Combustible Matter %	30.25	29.5	28.50	32.7	33.0
Fixed Carbon %	49.45	47.6	48.40	42.8	43.0
Ash %	4.60	8.0	7.30	6.5	8.4
Sulphur %	0.32	0.20	0.55	0.6	0.6
Calorific Value (kJ/kg as received)	24.52	22.82	23.97	22.91	22.91

[1] Princeton Coal and Land Co. Ltd., No. 2 mine, Minister of Mines, B.C., Ann. Rept., 1923.
[2] Princeton Coal and Land Co. Ltd., No. 1 mine, Minister of Mines, B.C., Ann. Rept., 1923.
[3] Princeton B.C. Colliery Co. Ltd., probably No. 3 mine, Dickson (1941) (average of analyses from top and lower benches).
[4] Princeton-Tulameen No. 1 mine (mine run), Dickson (1941).
[5] Tulameen Valley Coal Co., No. 1 mine, Dickson (1941) (average of analyses from top and lower benches).

TABLE 8B. COAL ANALYSES FROM VARIOUS SEAMS, ALLENBY FORMATION, PRINCETON BASIN

	M8[4]	M8[3]	A[2]	B[2]	M13[1]
Moisture %	24.9	24.7	13.26	15.72	13.9
Volatile Combustible Matter %			28.50	28.76	28.3
Fixed Carbon %			45.02	42.64	44.1
Ash %	35.3	21.1	13.22	12.80	13.7
Sulphur %					0.63
Calorific Value (kJ/kg as received)	11.17	14.05	21.21	19.47	19.91

[1] Granby No. 1 mine (mine run), Dickson (1941).
[2] Mines 'A' and 'B', average of five samples from each of Pleasant Valley Mining Co. Ltd., No. 4 mine (M4) and Taylor Burson Coal Company, Limited, No. 1 mine (M10), range of calorific values 17.21 to 24.10 kJ/kg, Hughes (1947).
[3] Black mine, No. 2 cut, uppermost 18 metres of coal zone with 3 metres waste excluded (numerous partings not removed), Fahrni (1947).
[4] Black mine, No. 2 cut, uppermost 18 metres of coal zone with waste included, Fahrni (1947).

STRATIGRAPHIC SETTING OF COAL SEAMS

Outcrops of thin lensing coal beds and coaly shale are widely distributed over the Princeton Basin, but thicker workable coal seams are localized in the southern half. Most of the historical mining and exploratory activities have been confined to the Princeton and Bromley Vale areas (Figs. 13A and 13B). Very little development work has taken place in the north. For the purposes of discussion, it is convenient to separate the basin into the productive southern and nonproductive northern parts (Shaw, 1952; Hughes, 1947), using the northwesterly trending 'Rainbow Lake' anticline north of Princeton as the boundary.

SOUTHERN AREA

Early workers in the Princeton Basin were not able to develop a satisfactory correlation scheme because of lack of uniformity within seams and lack of other distinctive markers. Further geologic study by Fahrni (1945) and Shaw (1952), however, demonstrated that the thick workable coal seams, though highly variable in thickness, do occur within definable coal-bearing zones, and that broad-scale correlation of these zones was possible. Shaw (1952) discussed these zones in detail, and was careful to point out that in spite of reasonable zonal correlations, in no case could any one seam within a zone be definitely correlated over large areas unless actually connected by mine workings.

Most of the coal zones are confined to the upper coal-bearing member of the Allenby Formation, whose base is arbitrarily placed at the base of the Princeton-Black-Blue Flame coal zone. Only a few prospects of negligible economic importance occur stratigraphically near the top of the basal member (Fig. 12).

A columnar section constructed in the vicinity of Princeton (Figs. 7 and 12) illustrates the coal zones identified by Shaw (1952). Four zones, each containing coal seams of workable quality, lie within a stratigraphic interval of about 530 metres. The historically commercial seams within these zones are, in ascending order, the Princeton, Pleasant Valley (or Princeton No. 2), Gem, and an unnamed seam intersected in Blakemore's borehole No. 2.

Shaw (1952) constructed a similar section for the Bromley Vale area comprising four coal zones that were mined or prospected. The known coal seams within these zones are, again in ascending order, the Black, Jackson, Bromley Vale, and Golden Glow (or Bromley Vale No. 2).

The coal zones thus defined can be physically traced only part of the way from Princeton to Bromley Vale, although an acceptable correlation is indicated from comparison of the columnar sections (Fig. 12). Lacking knowledge of markers such as distinctive, areally extensive ash falls (*see* discussion of Pyroclastic Rocks in the Allenby Formation), the primary basis of the correlation is the close match of the stratigraphic intervals between the coal zones in the two areas.

The Blue Flame coal zone, developed at the southern extremity of the basin, has various characteristics in common with the Princeton and Black zones; it is not only the stratigraphically lowest coal zone of economic importance in its area, but it is also the thickest (*see Minister of Mines, B.C.,* Ann. Rept., 1928, p. C483). Fahrni (1945) suggested a correlation between the Blue Flame and Black coal zones on the basis of this parallelism, and, in spite of Shaw's (1952) reservations, the writer believes this tentative correlation to be consistent with the structural information available at present. This coal zone will subsequently be referred to as the Princeton-Black-Blue Flame coal zone to emphasize the geographically separate elements of this tentative correlation.

Two additional coal zones, the Freeman and Allenby, are exposed on the Similkameen River near Allenby (Fahrni, 1945) and occur at a stratigraphically higher position than the four previously discussed. They have not been exploited to any great extent and their economic importance is uncertain.

In contrast, a potentially important coal seam was discovered in the south-central Princeton Basin, in the vicinity of Podunk Lake, by Bethlehem Copper Corporation (Anderson, 1972, 1976). Although many of their drill holes penetrated only the upper (main) zone, drill hole 71-12 also intersected a minor coal zone which may be correlative to the Allenby zone on the basis of structural and geophysical (gravity) evidence. If this correlation is correct, then the main Bethlehem seam lies about 1 020 metres stratigraphically above the Princeton-Black-Blue Flame zone and is the stratigraphically highest coal zone identified in the Princeton Basin.

NORTHERN AREA

The detailed stratigraphic relationship of the rocks in the northern area to those of the south is uncertain due to the probable thickness and facies changes across the 'Rainbow Lake' anticline; individual stratigraphic units probably thicken and become coarser to the north. Although the structure of the northern area appears markedly simpler than that of the south, relatively few good stratigraphic sections are exposed and those measured give little indication of workable coal seams. Among the three known occurrences of coal (Summers Creek prospects, P9; Deer Valley prospect, P8; and United Empire-Red Triangle mines, M17-M18), only the latter was mined and even there the coal was poor in quality and restricted in distribution (Shaw, 1952). Based on stratigraphic characteristics, one may speculate that the United Empire-Red Triangle coal zone occurs in the upper part of the basal member of the Allenby Formation.

COAL OUTCROPS AND SEAM STRATIGRAPHY

Typical coal seam outcrop and borehole sections from various coal zones and other horizons in the Allenby Formation are illustrated on Figure 13. The sections are displayed in approximate ascending stratigraphic order from bottom right to upper left, with the probable stratigraphic position of groups of coal sections noted previously. The locations of these sections, and of additional coal outcrops of lesser importance, are shown on the accompanying map (Fig. 13A). The thicknesses of coal seams at each of the outcrop exposures are listed in ascending stratigraphic order.

The Princeton-Black-Blue Flame coal zone is the best known in the Princeton Basin, and should serve as a reasonable model for the stratigraphic variations to be expected in various other coal zones. Its internal stratigraphy is shown on Figure 14.

Perhaps the most striking feature evident from this correlation chart (Fig. 14) is the marked variability in thickness of the coal-bearing zone. Shaw (1952) could not determine whether the thinning of this zone from the Princeton No. 1 mine (M2) westward to the Tulameen No. 3 (M5) and Pleasant Valley No. 2 mine (M7) was due to actual thinning or to selection of a suitable part of the seam for mining; this writer favours a combination of both.

Another notable characteristic is that the coal sections bear little detailed resemblance to one another. Although thin partings or beds of carbonaceous shale, bone, grey or reddish shale, claystone, and bentonite are commonly in intimate association with the coal in this and other zones, they gradually change thickness and, in some cases, stratigraphic position laterally. It is doubtful if any partings or set of partings can be traced far. Their usefulness in terms of coal seam correlation is thus limited. The existence of numerous partings, many too small to show on the sections, poses a number of potential mining problems which are discussed in a following section.

The Princeton-Black-Blue Flame coal zone has been extensively exposed in only two mines, the Black-Granby Consolidated Mining, Smelting and Power Company Limited strip mine (M8) and the Princeton No. 1 colliery (M2). In the town area, the seams worked (indicated by bars to the left of each column on Fig. 14) comprise only part of the zone, and a thick section of dirty coal lies below the mineable portion (Shaw, 1952).

Significant lateral variability in seam thickness, character, and quality, as illustrated by the Princeton-Black-Blue Flame coal zone, can be expected even on a relatively local scale, as a consequence of the depositional environment of the Allenby Formation. The coal seams most likely represent backswamp/overbank deposits in the inferred alluvial floodplain setting. Thin, discontinuous coal seams that commonly contain numerous partings most likely reflect a combination of relatively slow basin subsidence, frequent floods, and recurring volcanic activity. Perhaps volcanism is responsible for the high ash content in the coal. Closer to the source area, as in the northern part of the Princeton Basin, extensive backswamps either would not develop or would not be environmentally stable in association with a braided stream/alluvial fan environment. Nevertheless, the occurrence in the southern part of the basin of apparently laterally extensive coal zones at discrete intervals within the stratigraphic column indicates that sedimentologic, volcanic, and tectonic factors periodically favoured the growth, accumulation, and preservation of organic matter.

Stratigraphic relationships thus suggest that the southern half of the Princeton Basin is the most promising for coal exploration. It not only encompasses the known outcrop distribution of the coal-bearing member of the Allenby Formation and was the site of most historical coal mining activity, but also is the locus of alluvial environments that were favourable for the accumulation and preservation of organic matter.

STRUCTURAL SETTING

The structural configuration of individual coal zones, particularly that of the main Princeton-Black-Blue Flame zone, has already been discussed in the context of the structural setting of the Princeton Basin as a whole. The structural behaviour and local configurations of the coal seams, however, merit further discussion. For the most part, strata of the Allenby Formation have been only mildly deformed and the coal seams reflect this. The soft coal beds have assumed a passive role, and it is only in areas of more intense deformation, such as in the core region of the Allenby anticline and a similar structure immediately north (Fig. 10) and immediately adjacent to faults, that seams exhibit significant tectonic thinning or thickening. Individual seams are probably offset by numerous small-scale (a few centimetres to tens of centimetres) normal and reverse faults throughout the basin, but these faults appear to be most common in spatial association with the major structures. Normal (?) faults with offsets more than a few metres have been identified only in three of the historically active workings: the Pleasant Valley No. 2 mine (M7), the Black-Granby Consolidated Mining, Smelting and Power Company Limited strip mine (M8) and the Princeton No. 1 colliery (M2; eastern margin). Many more are undoubtedly present in the basin.

Individual coal seams of the Princeton Basin thus exhibit only small-scale structural modification, particularly in association with the larger structures. Although this relatively minor modification should not hinder regional correlations, it may affect coal seam mining development.

COAL DEVELOPMENT PROBLEMS

Coal mining in the Princeton Basin has been characterized by short-lived operations that have been plagued with economic and geological problems (Hughes, 1947; Shaw, 1952). Any future coal exploration and development in the basin will have to resolve these problems, and to consider additional logistical and environmental difficulties.

ECONOMIC FACTORS

Economic factors primarily concern the availability of a market for the coal. The generally high ash content (particularly where partings are also mined), the noncoking quality, and the poor storage characteristics of this subbituminous coal severely limit the economics of long distance transportation to market. The poor washing characteristics preclude upgrading through wet washing methods. In addition, the poor storage characteristics and mining difficulties require advance planning of workings so the individual areas are exhausted in a relatively short time, which also necessitates maintenance of year-round production and consumption. A local thermal electric generation station is a possible candidate as such a market.

GEOLOGIC FACTORS

Geological factors relate to mine location and engineering. They include: the intimate association of bentonite with coal seams; the relatively weak strata enclosing the seams (underground) and their tendency for slope instability (surface); *in situ* characteristics of the coal seams; rapid lateral variations within the seams; structural configuration of the seams (including coal seam deformation); and intrazone and basinwide correlation of coal seams.

The first two of these factors are common to the entire basin and may be resolved by improved mining techniques. 'Bentonite is exceedingly troublesome when wet, so that well drained workings are essential. The low strength of the enclosing strata necessitates larger supporting pillars, particularly along the roadways. The difficulties engendered by the breaking and crumbling of the strata are multiplied by the increased quantity of water brought into contact with the bentonite beds' (Shaw, 1952, p. 3; *see* also Hughes, 1947). Roof and floor problems (particularly swelling and collapse) plagued the underground operations, whereas slope failure, common in present surface exposures (Fig. 2), would likely be a major problem in any surface operation.

The remaining two factors influence the selection of mineable areas. Knowledge of the variation in thickness and quality of the seams, including identification of weathered or burned-out areas, and of the structural features to be encountered, including identification of rolls, pinch-outs, major faults, and minor fracture offsets, is essential to long-range mine layout planning. It also provides a basis for computing the mineable reserves (Shaw, 1952).

LOGISTICAL/ENVIRONMENTAL FACTORS

These factors relate to the feasibility and impact of future coal mining development. These developments must be situated to expedite mine drainage and minimize cultural or environmental disturbance. For example, these factors, together with structural difficulties imposed by the location of now-collapsed historical workings, preclude further entry to the deeper areas in the vicinity of Princeton from slope approaches driven in coal, although economic factors would probably also rule it out.

RESOURCE POTENTIAL AND RECOMMENDATIONS FOR EXPLORATION

The resource potential of the Princeton Basin is uncertain in precise terms, but it is clear that the historical production of 1 879 723 tonnes (2 072 040 tons) of coal (Table 7) represents substantially less than 1 per cent of the total *in situ* resource (Hughes, 1947; Dolmage, Campbell and Associates Ltd., 1975).

There are numerous potential target areas within the Princeton Basin which have not been thoroughly prospected for coal. The northeastern portion of the basin is largely unexplored, although the stratigraphic setting is less favourable than in the southwestern area where coal zones are apparently better developed. The configuration of the coal zones in the immediate vicinity of Princeton is well known, but this area holds little promise because much of the near-surface coal has already been mined out.

An exploration program could proceed from the standpoint of extending known coal zones or of reconnaissance in new areas. In either case, a recommended approach, in general terms, would be as follows:

(1) cautious use of geologic maps and sections to identify promising target areas where known coal zones project to the surface;

(2) gravity profiles across the strike of these promising areas to identify potential coal-bearing strata;

(3) exploratory wildcat drilling to test the most promising of these coal anomalies;

(4) detailed follow-up drilling program to extend newly discovered and known coal zones (for example, Princeton-Black-Blue Flame zone along the western margin of the basin).

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APPENDIX A. GRAVITY SURVEY METHODOLOGY, PRINCETON BASIN

The gravity survey of the Princeton Basin was undertaken by C. A. Ager and Associates Ltd. in November and December, 1975; three cross-basin profiles were surveyed using a La Coste and Romberg gravity meter with a station spacing of 60.96 metres (200 feet). All gravity values were calculated relative to the National Gravity Base Station (9031-54), located beside the Canadian Pacific Railway station at Princeton (*see* Garland and Tanner, 1957); this station has the following parameters:

Latitude	49° 27.8′ North
Longitude	120° 30.2′ West
Elevation	639 metres (2,096 feet)
Grid Coordinates	235E + 444N
Observed Gravity	980778.38 mgal
C.B. Gravity	−129.83 mgal

The complete Bouguer gravity anomaly values ($\Delta\rho_B$) were determined for each station by solving equations (1) and (2) below using standard procedures (Ager, 1975):

$$\Delta\rho_B = \rho_O - \rho_E \qquad (1)$$

where

$$\rho_E = \rho_L + \rho_{FA} + \rho_{BS} + \rho_{TE} \qquad (2)$$

and where

ρ_O = observed gravity field at given station
ρ_E = gravity field effect resulting from earth itself
ρ_L = latitude effect
ρ_{FA} = free air effect (elevation above datum such as sea level-elevation geoid surface)
ρ_{BS} = Bouguer slab effect
ρ_{TE} = terrane effect (calculated to radius of 1 460 metres around station in this survey).

A listing of the complete Bouguer gravity anornaly data for all stations is given in the Appendix to Ager's (1975) report.

APPENDIX B. SATURATED BULK DENSITY DETERMINATIONS, PRINCETON BASIN

	Lithology	Source	No. of Determinations (this study)	Values (range)	Used
Allenby Formation	conglomerate (very coarse sandstone)	1	3	2.42 (2.38–2.44)	2.40
	conglomerate (Tertiary/Cretaceous)	2		2.37	
	sandstone	1	7	2.33 (2.10–2.44)	2.34
	sandstone (Tertiary)	2		2.35 (2.03–2.73)	
	sandy shale/siltstone	1	6	2.26 (2.05–2.41)	2.27
	sand/clay mix; siltstone	2		2.28 (1.81–2.54)	
	shale/claystone/mudstone	1	5	2.11 (1.91–2.38)	2.12
	shale (Tertiary)	2		2.13 (2.04–2.29)	
	carbonaceous shale	1	2	2.12 (2.03–2.20)	2.12
	dark shale (Early Tertiary)	2		2.28	
	lignitic to subbituminous coal	4, 5		1.30 (1.12–1.50)	1.30
Lower Volcanic Formation	massive to slightly vesicular flow	1	3	2.59 (2.51–2.64)	2.55
	vesicular/amygdaloidal flow	1	2	2.52 (2.47–2.55)	
	breccia (probably andesite ± basalt)	1	1	2.34	
	Kamloops volcanic rocks	3		2.60	
Nicola Group	andesite (slightly basaltic)	2		2.62 (2.67)	2.66
	basalt	2		2.90	
	dacite	2		2.59	
	silicified tuff	2		2.56	
	greywacke	4		2.69	
Osprey Lake Intrusion	granodiorite	1	2	2.66	2.68
	granodiorite	2		2.72	
	granite	2, 4		2.66	

1 — This study.
2 — Birch, *et al.* (1942).
3 — Ager, *et al.* (1972).
4 — Peele and Church (1941).
5 — Schlumberger Ltd. (1972).

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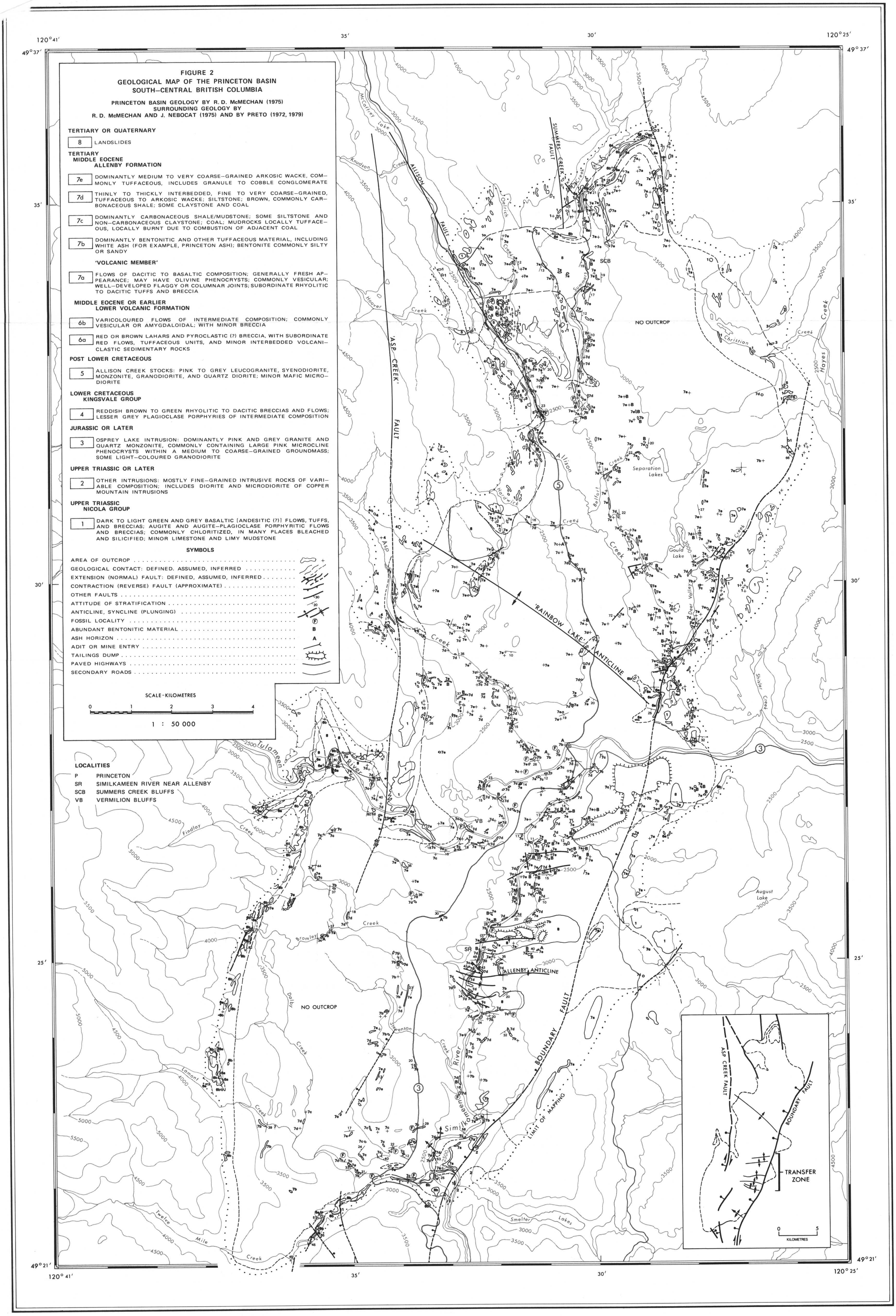
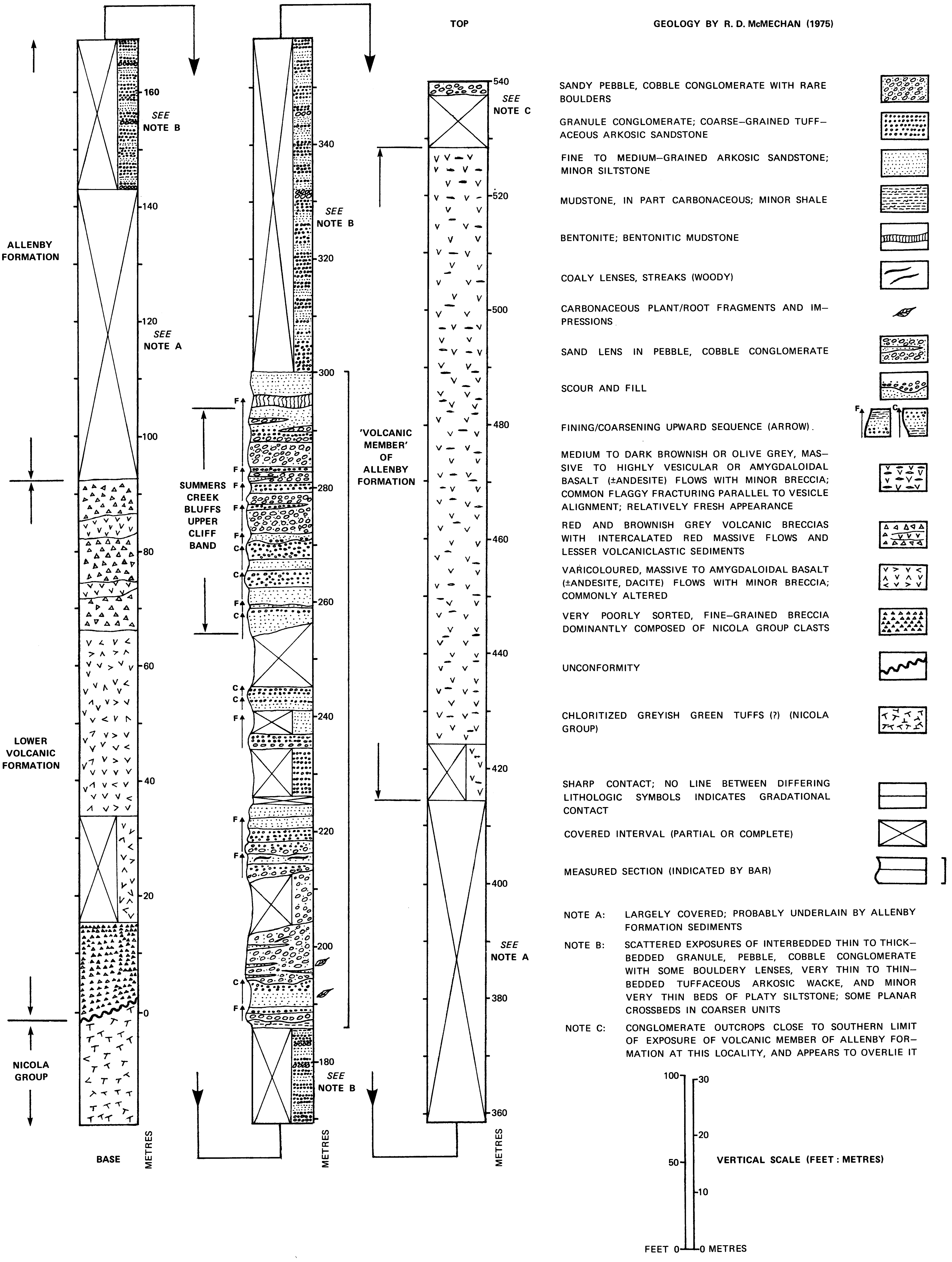


FIGURE 2
GEOLOGICAL MAP OF THE PRINCETON BASIN
SOUTH-CENTRAL BRITISH COLUMBIA
PRINCETON BASIN GEOLOGY BY R. D. McMECHAN (1975)
SURROUNDING GEOLOGY BY
R. D. McMECHAN AND J. NEBOCAT (1975) AND BY PRETO (1972, 1979)
TERTIARY OR QUATERNARY
8 LANDSLIDES
TERTIARY
MIDDLE EOCENE
ALLENBY FORMATION
7e DOMINANTLY MEDIUM TO VERY COARSE-GRAINED ARKOSIC WACKE, COMMONLY TUFFACEOUS, INCLUDES GRANULE TO COBBLE CONGLOMERATE
7d THINLY TO THICKLY INTERBEDDED, FINE TO VERY COARSE-GRAINED, TUFFACEOUS TO ARKOSIC WACKE; SILTSTONE; BROWN, COMMONLY CARBONACEOUS SHALE; SOME CLAYSTONE AND COAL
7c DOMINANTLY CARBONACEOUS SHALE/MUDSTONE; SOME SILTSTONE AND NON-CARBONACEOUS CLAYSTONE; COAL; MUDROCKS LOCALLY TUFFACEOUS, LOCALLY BURNT DUE TO COMBUSTION OF ADJACENT COAL
7b DOMINANTLY BENTONITIC AND OTHER TUFFACEOUS MATERIAL, INCLUDING WHITE ASH (FOR EXAMPLE, PRINCETON ASH); BENTONITE COMMONLY SILTY OR SANDY
'VOLCANIC MEMBER'
7a FLOWS OF DACITIC TO BASALTIC COMPOSITION; GENERALLY FRESH APPEARANCE; MAY HAVE OLIVINE PHENOCRYSTS; COMMONLY VESICULAR; WELL-DEVELOPED FLAGGY OR COLUMNAR JOINTS; SUBORDINATE RHYOLITIC TO DACITIC TUFFS AND BRECCIA
MIDDLE EOCENE OR EARLIER
LOWER VOLCANIC FORMATION
6b VARICOLOURED FLOWS OF INTERMEDIATE COMPOSITION; COMMONLY VESICULAR OR AMYGDALOIDAL; WITH MINOR BRECCIA
6a RED OR BROWN LAHARS AND PYROCLASTIC (?) BRECCIA, WITH SUBORDINATE RED FLOWS, TUFFACEOUS UNITS, AND MINOR INTERBEDDED VOLCANICLASTIC SEDIMENTARY ROCKS
POST LOWER CRETACEOUS
5 ALLISON CREEK STOCKS: PINK TO GREY LEUCOGRANITE, SYENODIORITE, MONZONITE, GRANODIORITE, AND QUARTZ DIORITE; MINOR MAFIC MICRODIORITE
LOWER CRETACEOUS
KINGSVALE GROUP
4 REDDISH BROWN TO GREEN RHYOLITIC TO DACITIC BRECCIAS AND FLOWS; LESSER GREY PLAGIOCLASE PORPHYRIES OF INTERMEDIATE COMPOSITION
JURASSIC OR LATER
3 OSPREY LAKE INTRUSION: DOMINANTLY PINK AND GREY GRANITE AND QUARTZ MONZONITE, COMMONLY CONTAINING LARGE PINK MICROCLINE PHENOCRYSTS WITHIN A MEDIUM TO COARSE-GRAINED GROUNDMASS; SOME LIGHT-COLOURED GRANODIORITE
UPPER TRIASSIC OR LATER
2 OTHER INTRUSIONS: MOSTLY FINE-GRAINED INTRUSIVE ROCKS OF VARIABLE COMPOSITION; INCLUDES DIORITE AND MICRODIORITE OF COPPER MOUNTAIN INTRUSIONS
UPPER TRIASSIC
NICOLA GROUP
1 DARK TO LIGHT GREEN AND GREY BASALTIC (ANDESITIC (?)) FLOWS, TUFFS, AND BRECCIAS; AUGITE AND AUGITE-PLAGIOCLASE PORPHYRITIC FLOWS AND BRECCIAS; COMMONLY CHLORITIZED, IN MANY PLACES BLEACHED AND SILICIFIED; MINOR LIMESTONE AND LIMY MUDSTONE
SYMBOLS
AREA OF OUTCROP
GEOLOGICAL CONTACT: DEFINED, ASSUMED, INFERRED
EXTENSION (NORMAL) FAULT: DEFINED, ASSUMED, INFERRED
CONTRACTION (REVERSE) FAULT (APPROXIMATE)
OTHER FAULTS
ATTITUDE OF STRATIFICATION
ANTICLINE, SYNCLINE (PLUNGING)
FOSSIL LOCALITY
ABUNDANT BENTONITIC MATERIAL
ASH HORIZON
ADIT OR MINE ENTRY
TAILINGS DUMP
PAVED HIGHWAYS
SECONDARY ROADS
SCALE-KILOMETRES
1 : 50 000
LOCALITIES
P PRINCETON
SR SIMILKAMEEN RIVER NEAR ALLENBY
SCB SUMMERS CREEK BLUFFS
VB VERMILION BLUFFS
120°41′
35′
30′
120°25′
49°37′
49°21′
25′
NO OUTCROP
'ASP CREEK' FAULT
ALLISON FAULT
SUMMERS CREEK FAULT
'RAINBOW LAKE' ANTICLINE
ALLENBY ANTICLINE
BOUNDARY FAULT
LIMIT OF MAPPING
Tulameen River
Similkameen River
Allison Creek
Summers Creek
Separation Lakes
Gould Lake
August Lake
Smelter Lakes
Twelve Mile Creek
Bromley Creek
Dalby Creek
Findlay Creek
Lamont Creek
Hoover Creek
Knudson Creek
McCaffrey Lake
Christian Creek
Hayes Creek
Shisler Creek
Deer Valley
Belfort Creek
Hardwick Creek
Oelrich Creek
Stevenson Creek
ASP CREEK FAULT
BOUNDARY FAULT
TRANSFER ZONE
KILOMETRES

FIGURE 6

COLUMNAR SECTION OF THE PRINCETON GROUP (LOWER VOLCANIC FORMATION AND LOWER PORTION OF ALLENBY FORMATION) EXPOSED IN SUMMERS CREEK BLUFFS, NORTH OF PRINCETON*

GEOLOGY BY R. D. McMECHAN (1975)



*SEE FIGURE 2 FOR PRECISE LOCATION (SCB).

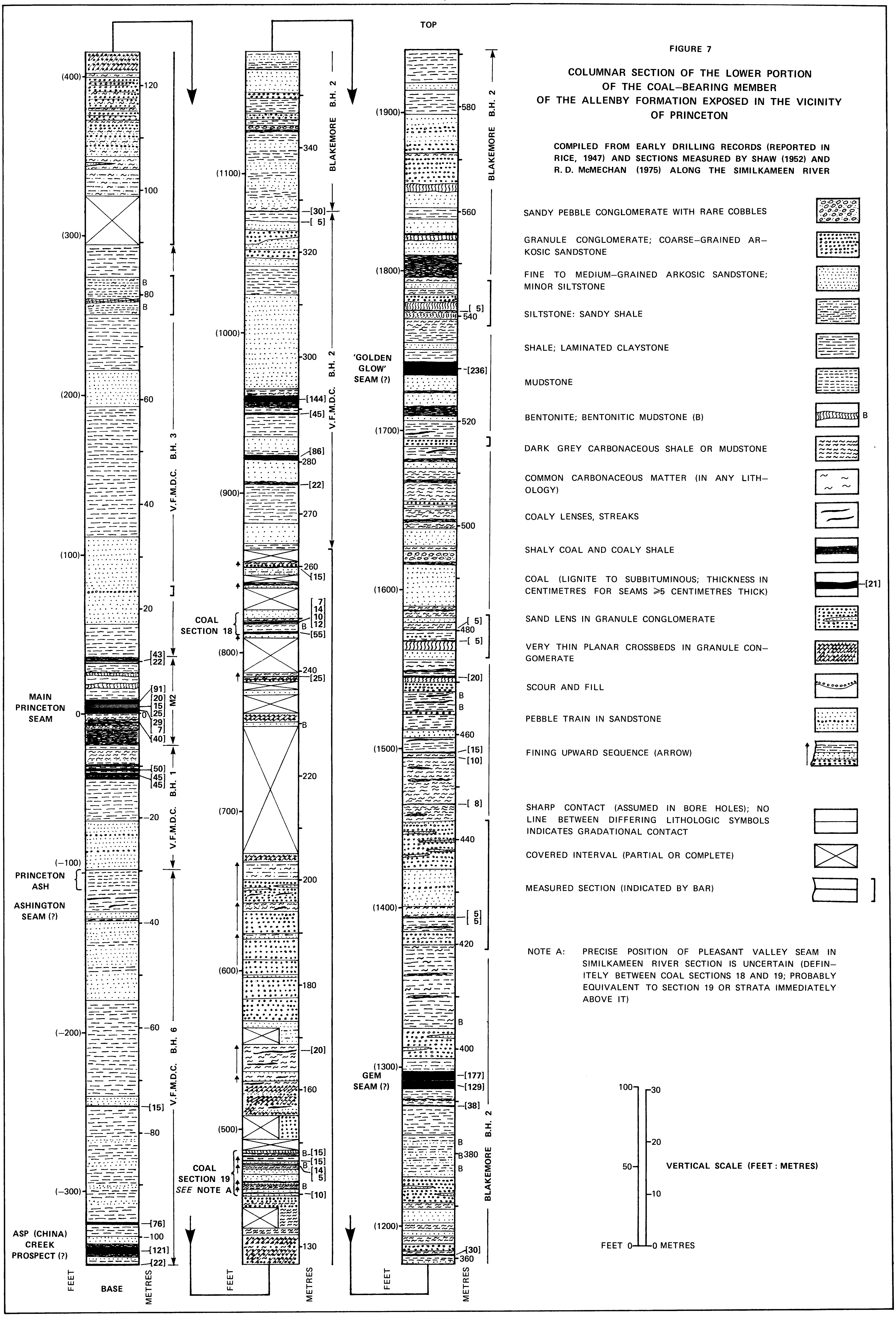


FIGURE 7

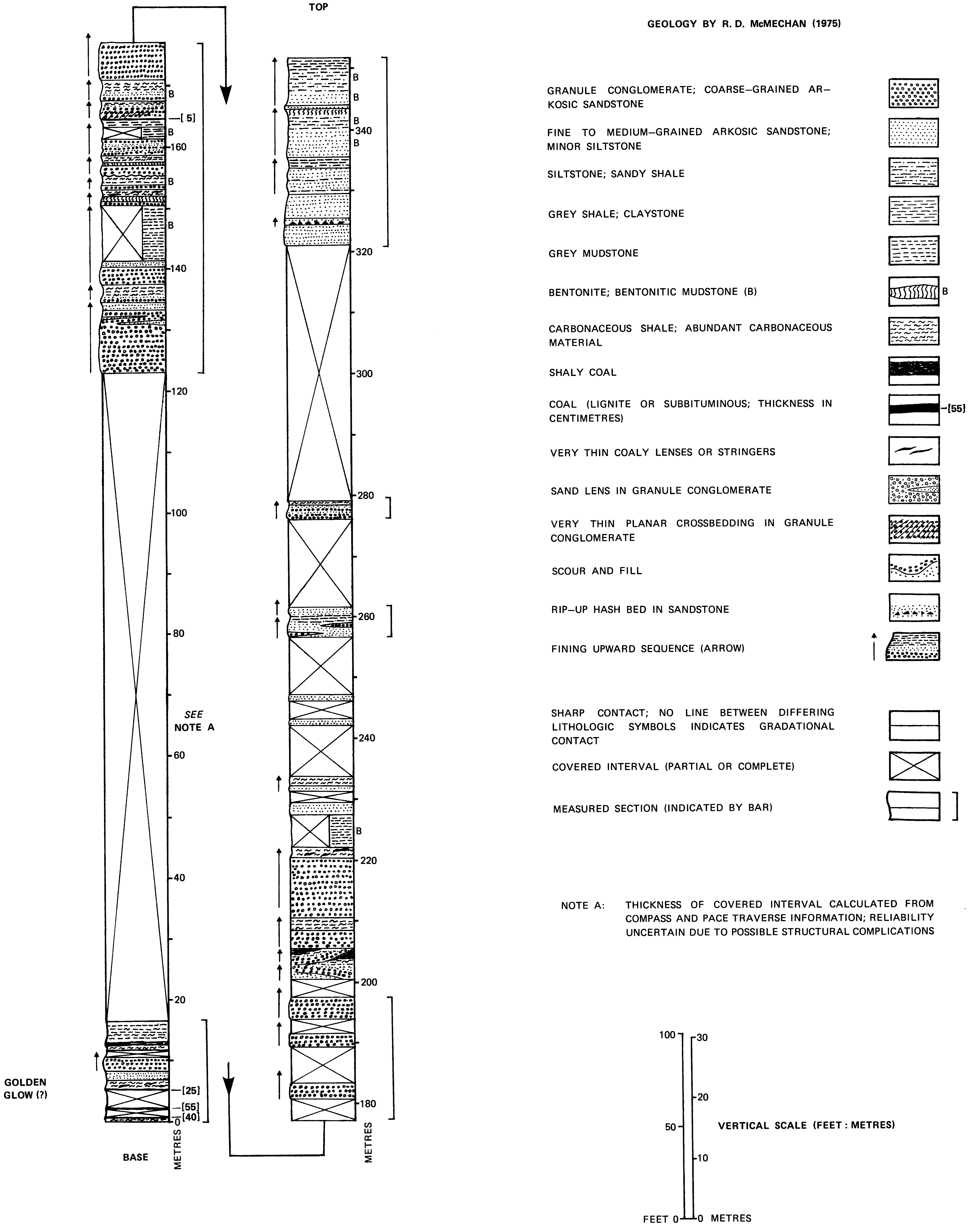
COLUMNAR SECTION OF THE LOWER PORTION OF THE COAL–BEARING MEMBER OF THE ALLENBY FORMATION EXPOSED IN THE VICINITY OF PRINCETON

COMPILED FROM EARLY DRILLING RECORDS (REPORTED IN RICE, 1947) AND SECTIONS MEASURED BY SHAW (1952) AND R. D. McMECHAN (1975) ALONG THE SIMILKAMEEN RIVER

FIGURE 8

COLUMNAR SECTION OF THE MIDDLE PORTION OF THE COAL–BEARING MEMBER OF THE ALLENBY FORMATION EXPOSED ALONG THE SIMILKAMEEN RIVER NEAR ALLENBY*

GEOLOGY BY R. D. McMECHAN (1975)



**SEE* FIGURE 2 FOR PRECISE LOCATION (SR)

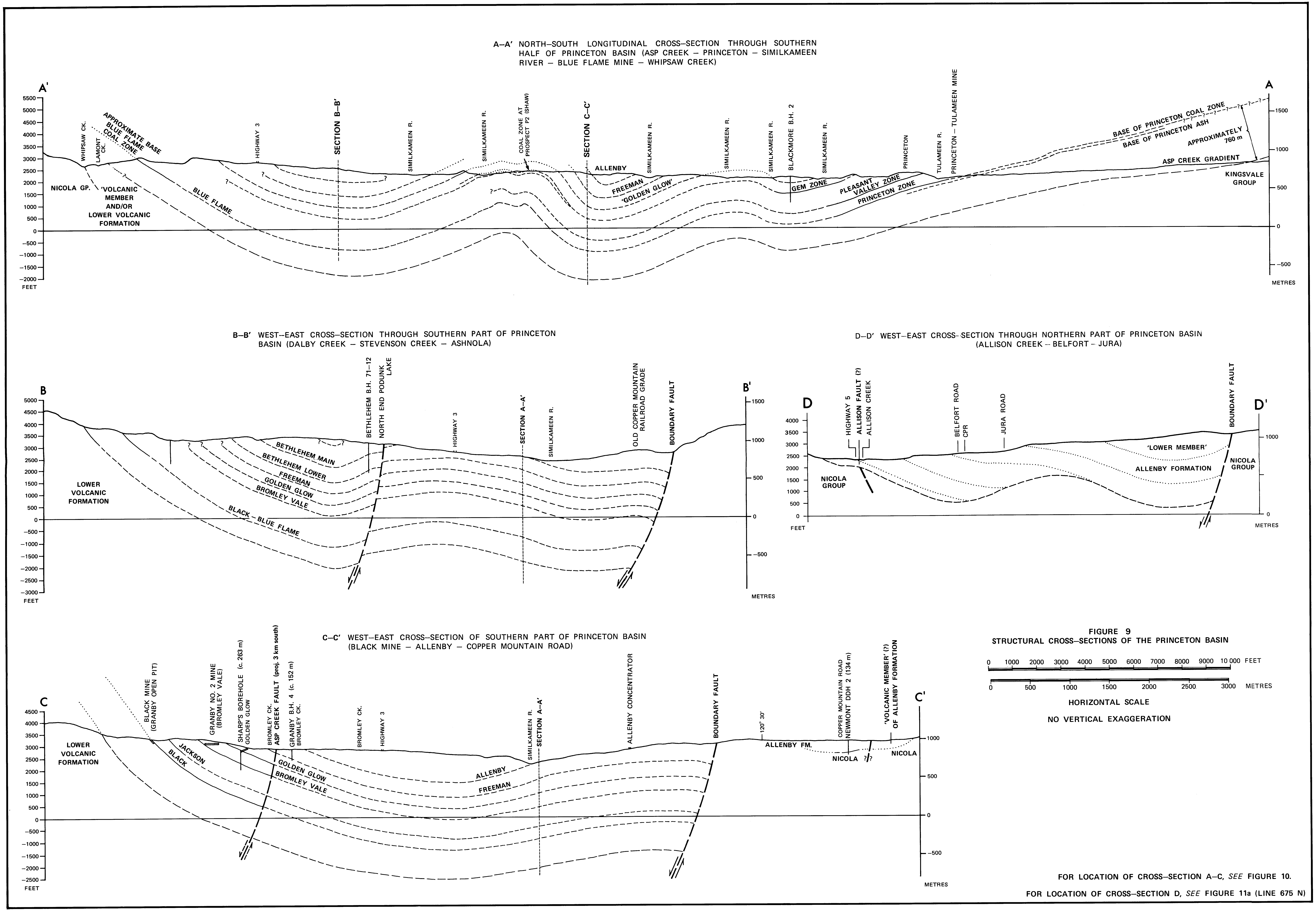


FIGURE 9
STRUCTURAL CROSS–SECTIONS OF THE PRINCETON BASIN

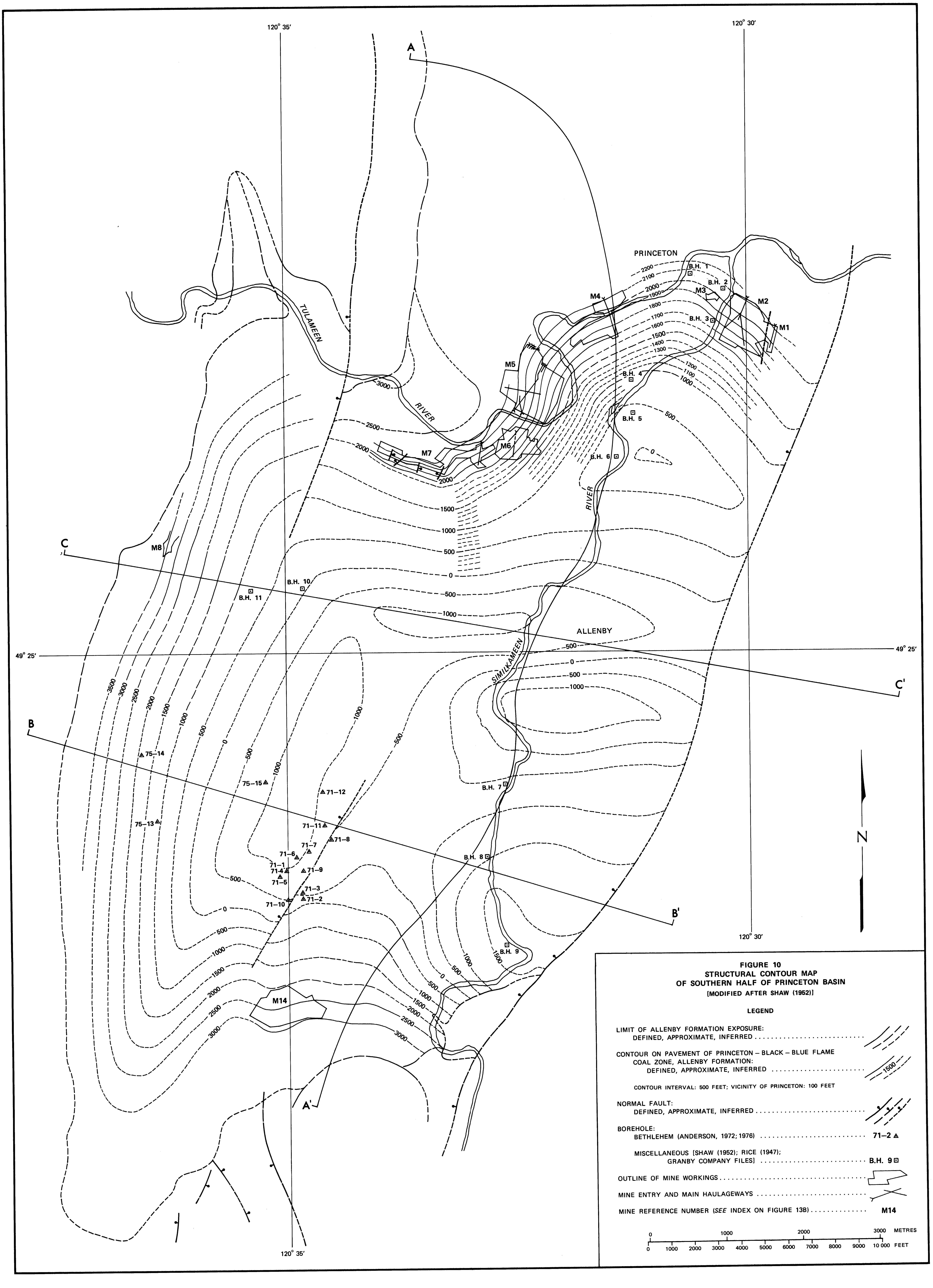


FIGURE 10
STRUCTURAL CONTOUR MAP OF SOUTHERN HALF OF PRINCETON BASIN
[MODIFIED AFTER SHAW (1952)]

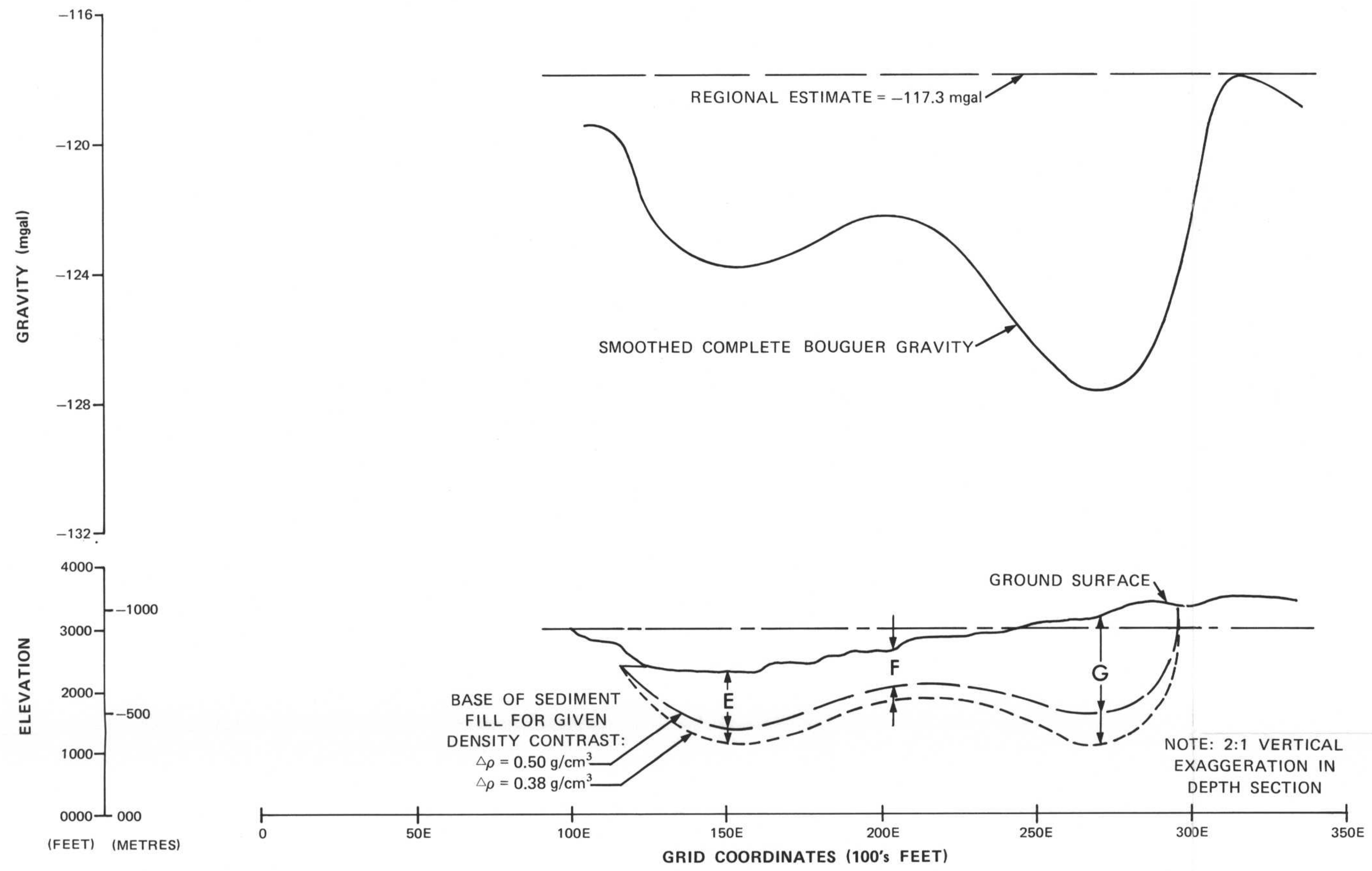


FIGURE 11d. LINE 675N GRAVITY/DEPTH SECTION
(*SEE* TABLE 5 FOR ESTIMATES OF THICKNESS OF SEDIMENT FILL AT LOCATIONS INDICATED)

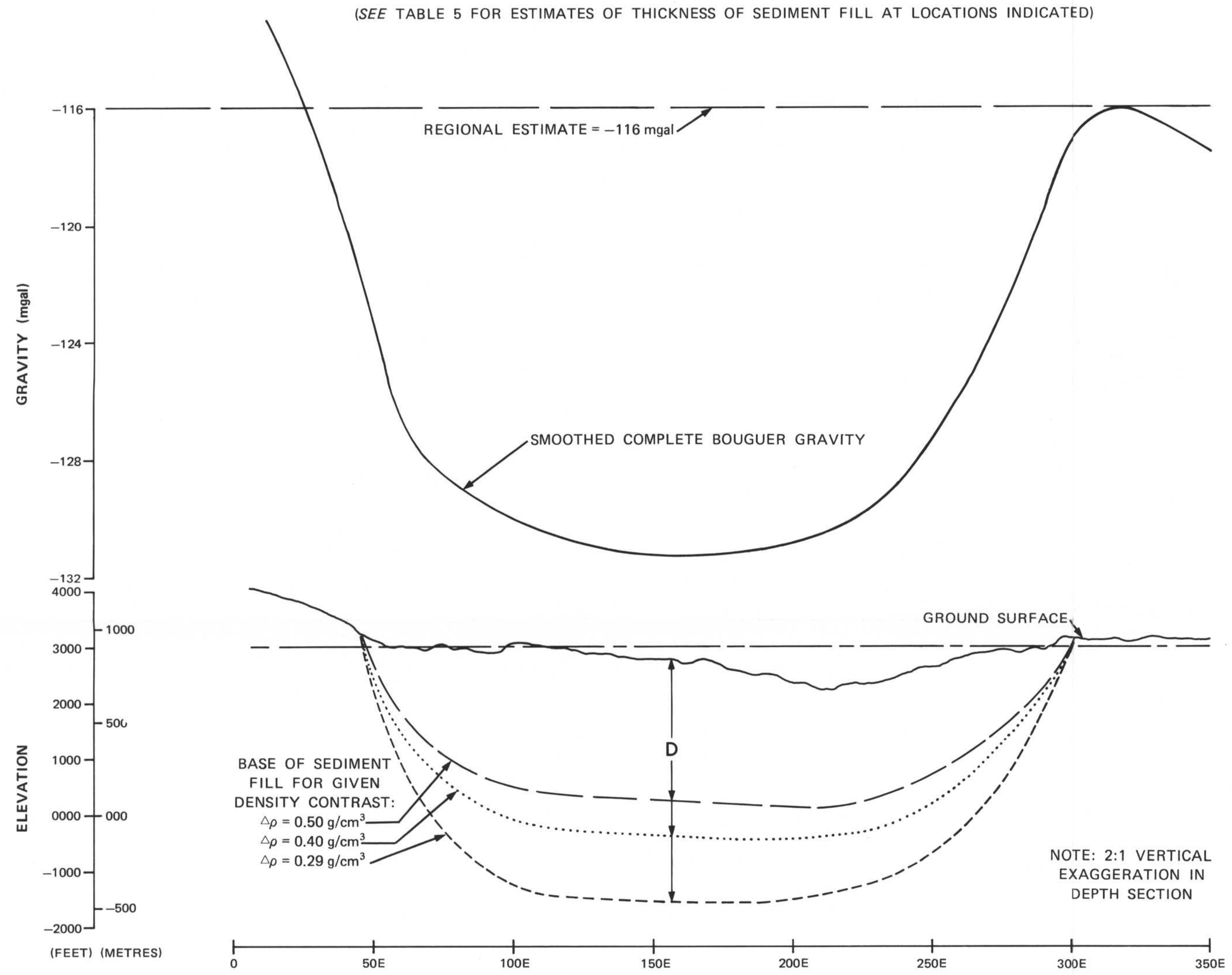


FIGURE 11c. LINE 300N GRAVITY/DEPTH SECTION
(*SEE* TABLE 5 FOR ESTIMATES OF THICKNESS OF SEDIMENT FILL AT LOCATION INDICATED)

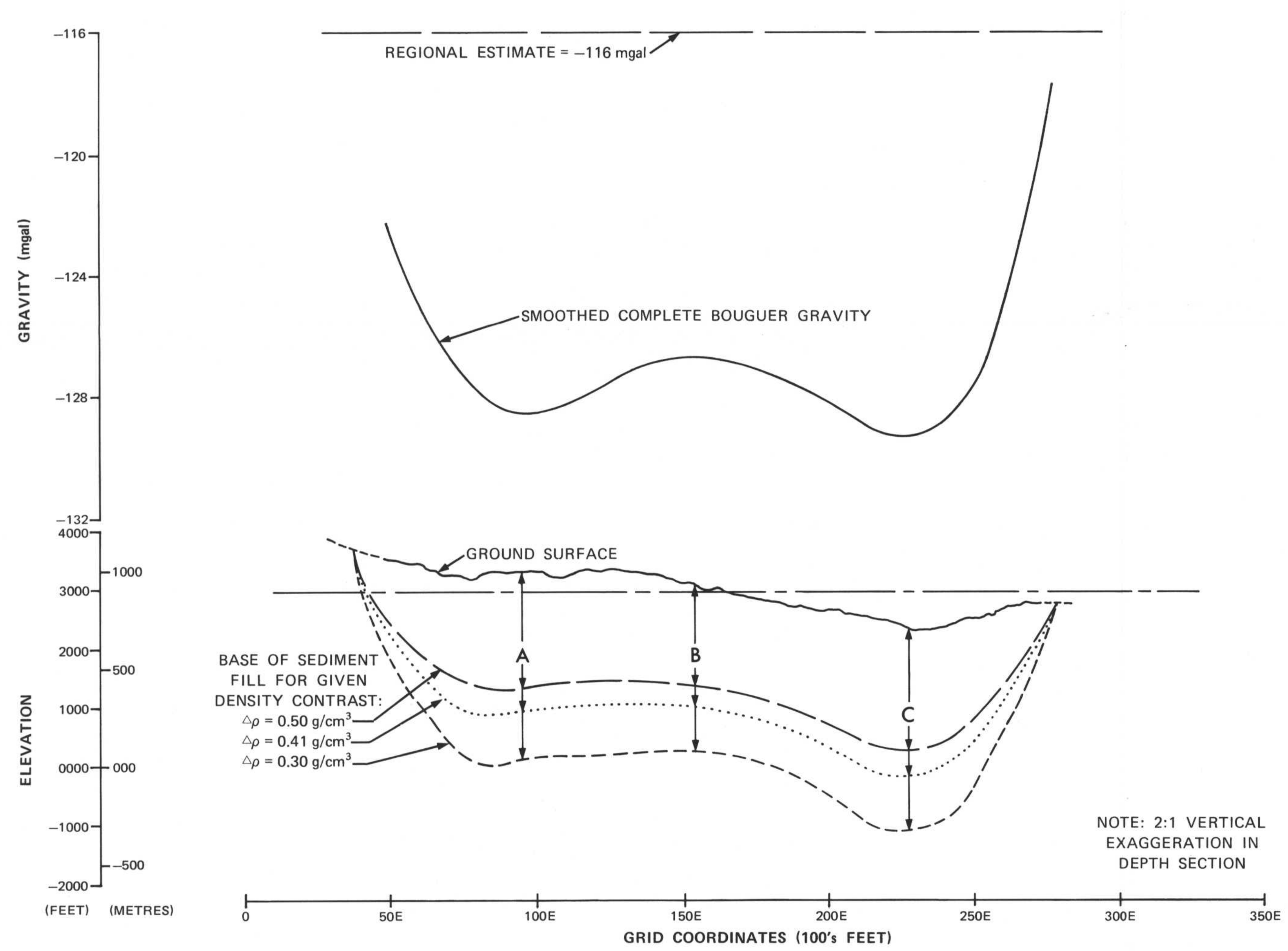


FIGURE 11b. LINE 190N GRAVITY/DEPTH SECTION
(*SEE* TABLE 5 FOR ESTIMATES OF THICKNESS OF SEDIMENT FILL AT LOCATION INDICATED)

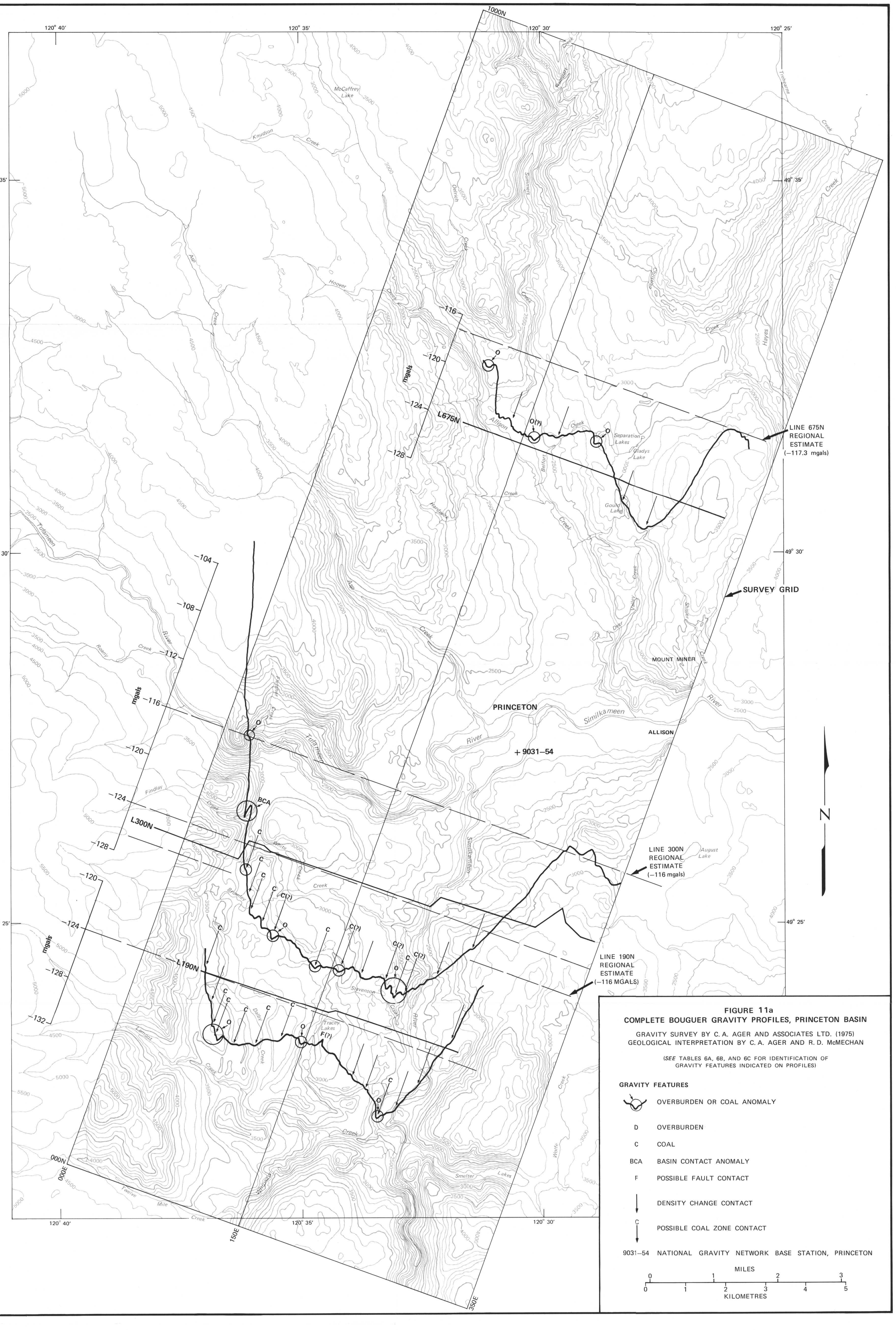


FIGURE 11a
COMPLETE BOUGUER GRAVITY PROFILES, PRINCETON BASIN
GRAVITY SURVEY BY C. A. AGER AND ASSOCIATES LTD. (1975)
GEOLOGICAL INTERPRETATION BY C. A. AGER AND R. D. McMECHAN
(*SEE* TABLES 6A, 6B, AND 6C FOR IDENTIFICATION OF GRAVITY FEATURES INDICATED ON PROFILES)

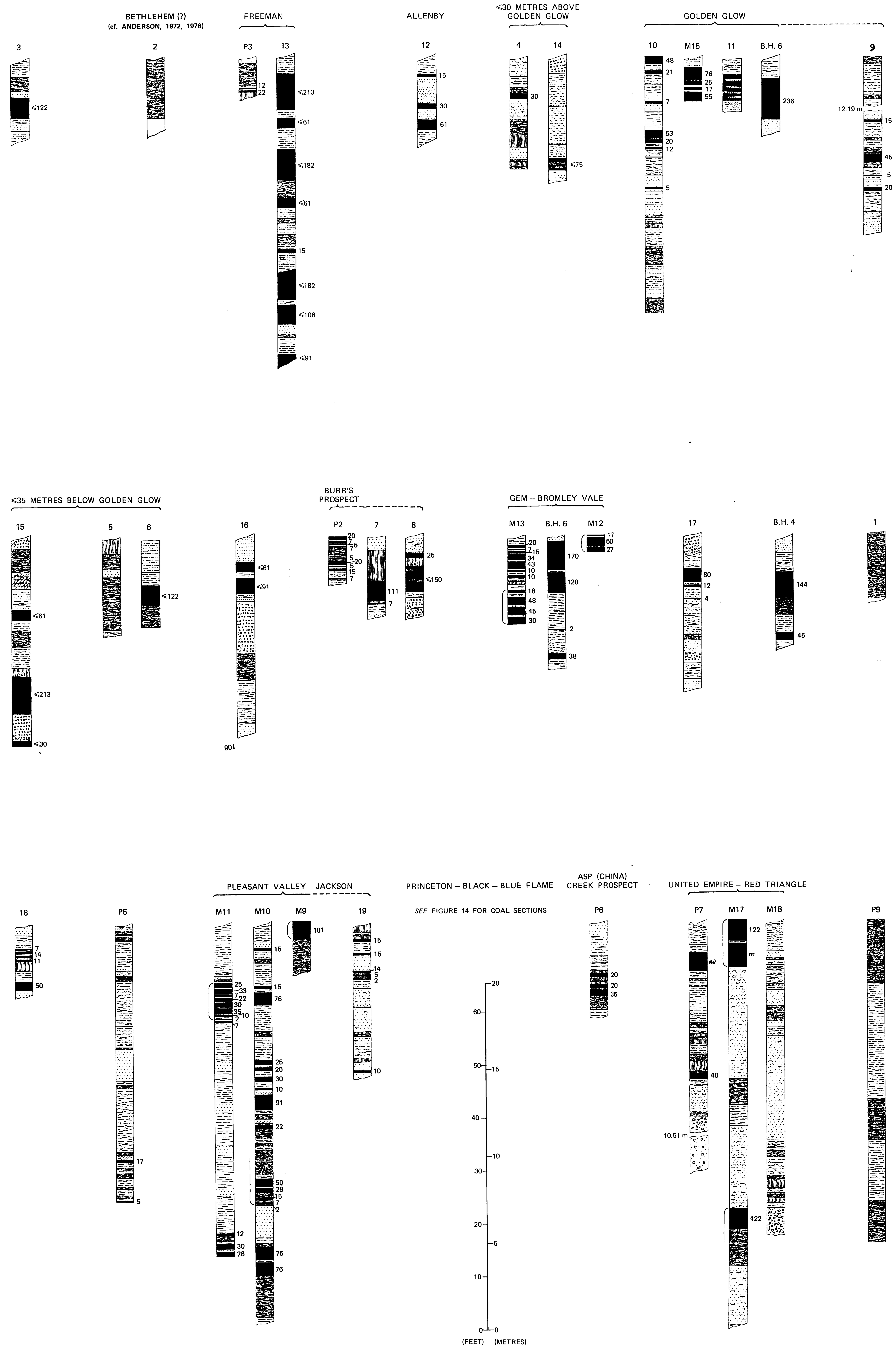


FIGURE 13B. COAL SECTIONS, ALLENBY FORMATION, PRINCETON BASIN

LEGEND RELATING TO SECTIONS

- COAL, SUB–BITUMINOUS (THICKNESS OF CLEAN COAL IN CENTIMETRES SHOWN AT RIGHT)
- SHALY COAL (MAY BE INTERCALATED WITH CLEAN COAL)
- VERY THIN COALY LENSES OR STREAKS
- CARBONACEOUS SHALE
- BENTONITE
- CLAYSTONE/SHALE
- SANDY SHALE
- SANDSTONE
- PEBBLE, GRANULE CONGLOMERATE
- VERY THIN PLANAR CROSSBEDDING IN GRANULE CONGLOMERATE
- PART OF COAL SEAM MINED

INDEX TO MINES, PROSPECTS, AND BOREHOLES

M 1	PRINCETON COAL AND LAND CO. NO. 2 MINE
M 2	PRINCETON COAL AND LAND CO. NO. 1 MINE
M 3	PRINCETON B.C. COLLIERY CO. LTD. NO. 3 MINE
M 4	PRINCETON–TULAMEEN MINE
M 5	TULAMEEN COLLIERIES LTD. NOS. 1, 2, AND 3 MINES
M 6	PLEASANT VALLEY NO. 4 MINE
M 7	PLEASANT VALLEY NO. 2 MINE
M 8	GRANBY COMPANY STRIP MINE (BLACK MINE)
M 9	PLEASANT VALLEY NO. 1 MINE
M10	TAYLOR–BURSON MINE
M11	JACKSON MINE
M12	GEM MINE
M13	BROMLEY VALE NO. 1 MINE
M14	BLUE FLAME MINE
M15	BROMLEY VALE NO. 2 MINE
M16	ASHINGTON MINE
M17	UNITED EMPIRE MINE
M18	RED TRIANGLE MINE
P1	TAYLOR–BURSON COAL COMPANY PROSPECT
P2	TAYLOR–BURSON COAL COMPANY (BURR'S) PROSPECT
P3	FREEMAN PROSPECT
P4	GOLDEN GLOW (HAIG) PROSPECT
P5	UNNAMED PROSPECT
P6	ASP (CHINA) CREEK PROSPECT
P7	PROSPECT OR, POSSIBLY ENTRY INTO UNITED EMPIRE MINE
P8	DEER VALLEY PROSPECT
P9	SUMMERS CREEK PROSPECT
B.H. 1	VERMILION FORKS MINING AND DEVELOPMENT CO. B.H. NO. 6
B.H. 2	VERMILION FORKS MINING AND DEVELOPMENT CO. B.H. NO. 1
B.H. 3	VERMILION FORKS MINING AND DEVELOPMENT CO. B.H. NO. 3
B.H. 4	VERMILION FORKS MINING AND DEVELOPMENT CO. B.H. NO. 2
B.H. 5	GRANBY COMPANY POWER PLANT BOREHOLE (GRANBY'S FILES)
B.H. 6	BLAKEMORE B.H. NO. 2
B.H. 7	VERMILION FORKS MINING AND DEVELOPMENT CO. B.H. NO. 5
B.H. 8	VERMILION FORKS MINING AND DEVELOPMENT CO. B.H. NO. 4
B.H. 9	BLAKEMORE B.H. NO. 1
B.H. 10	GRANBY COMPANY B.H. NO. 4 (GRANBY'S FILES)
B.H. 11	SHARP'S BOREHOLE
71– 1	TO 71–12 BETHLEHEM (ANDERSON, 1972)
75–13	TO 75–15 BETHLEHEM (ANDERSON, 1976)
1–19	OUTCROP SECTIONS MEASURED BY R. D. McMECHAN (1975)

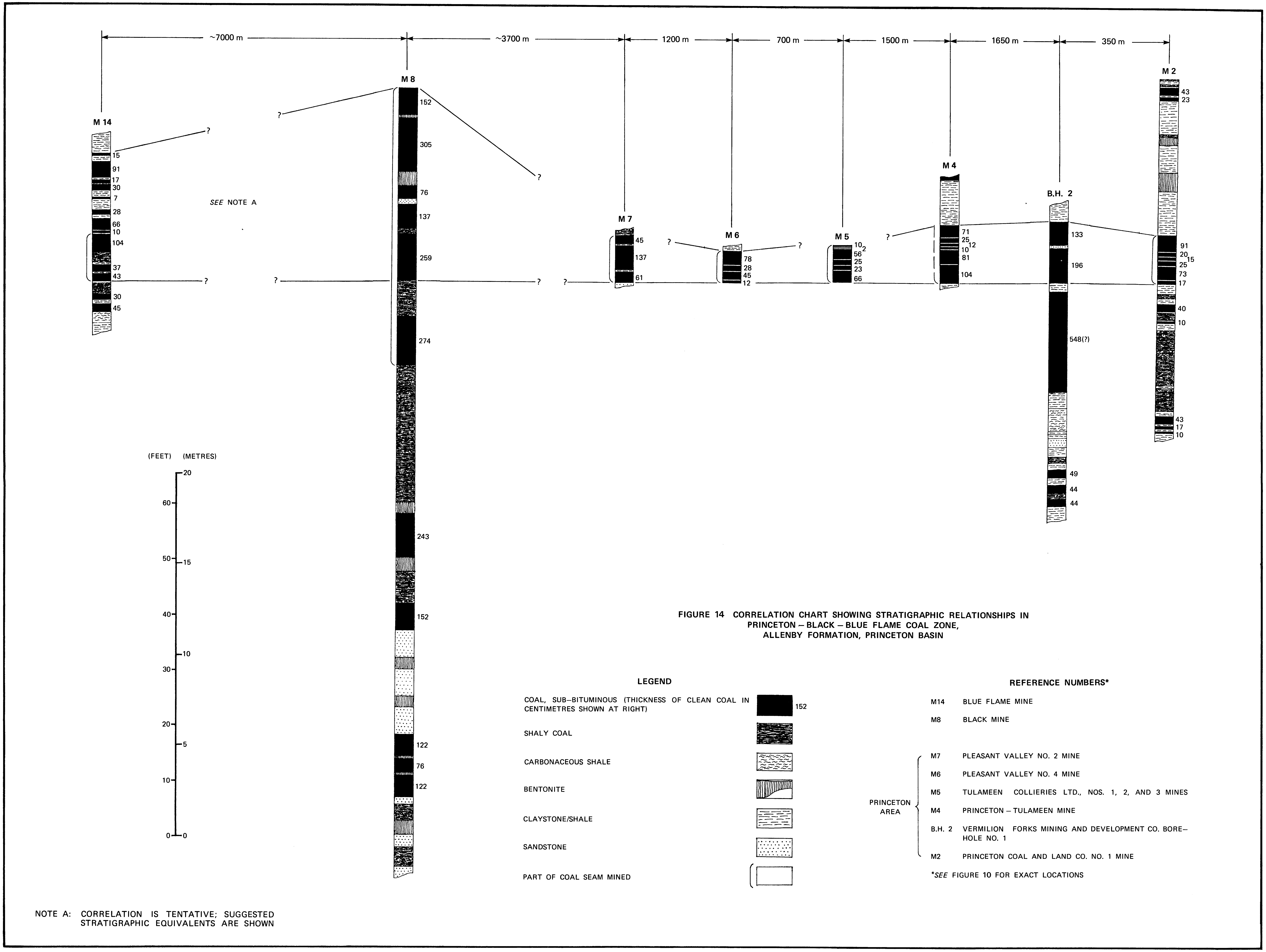


FIGURE 14 CORRELATION CHART SHOWING STRATIGRAPHIC RELATIONSHIPS IN PRINCETON – BLACK – BLUE FLAME COAL ZONE, ALLENBY FORMATION, PRINCETON BASIN

LEGEND

- COAL, SUB–BITUMINOUS (THICKNESS OF CLEAN COAL IN CENTIMETRES SHOWN AT RIGHT) — 152
- SHALY COAL
- CARBONACEOUS SHALE
- BENTONITE
- CLAYSTONE/SHALE
- SANDSTONE
- PART OF COAL SEAM MINED

REFERENCE NUMBERS*

M14	BLUE FLAME MINE
M8	BLACK MINE

PRINCETON AREA:

M7	PLEASANT VALLEY NO. 2 MINE
M6	PLEASANT VALLEY NO. 4 MINE
M5	TULAMEEN COLLIERIES LTD., NOS. 1, 2, AND 3 MINES
M4	PRINCETON – TULAMEEN MINE
B.H. 2	VERMILION FORKS MINING AND DEVELOPMENT CO. BORE-HOLE NO. 1
M2	PRINCETON COAL AND LAND CO. NO. 1 MINE

*SEE FIGURE 10 FOR EXACT LOCATIONS

NOTE A: CORRELATION IS TENTATIVE; SUGGESTED STRATIGRAPHIC EQUIVALENTS ARE SHOWN

Province of British Columbia

Ministry of
Energy, Mines and
Petroleum Resources