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HEAVY MINERAL ANALYSIS OF UPPER CRETACEOUS AND PALEOCENE SANDSTONES IN ALBERTA AND ADJACENT AREAS OF SASKATCHEWAN

by

© RIYADH ABDULRAHIM RAHMANI

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research, for acceptance, a thesis entitled, Heavy Mineral Analysis of Upper Cretaceous and Paleocene Sandstones in Alberta and Adjacent Areas of Saskatchewan, submitted by Riyadh Abdulrahim Rahmani, B.Sc. (U. Baghdad), M.Sc. (U.B.C., Vancouver), in partial fulfilment of the requirements for the degree of Doctor of Philosophy.

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Supervisor

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External Examiner

April, 1973

To my father and Dr. Robert E. Garrison

ABSTRACT

The uppermost Cretaceous and Paleocene sequence in Alberta and adjacent areas of Saskatchewan is a molasse clastic wedge thickening from east to west from zero to about 13,000 feet in the Rocky Mountain Foothills area. To analyse the provenance and dispersal of the heavy mineral content of the sandstones of this sequence, the lithostratigraphic units were grouped into three lithostratigraphic "slices": Belly River "slice", Edmonton "slice" and Paskapoo "slice".

Application of Q-mode factor analysis to the heavy mineral data of the three "slices" generated ten heavy mineral associations on the basis of which ten heavy mineral provinces were delineated and mapped. These associations are composed of assemblages of apatite, epidote-clinozoisite, garnet, hornblende, sphene and zircon. The heavy mineral provinces are generally elongate and parallel or subparallel to the tectonic elements of the source area to the west (Omineca Geanticline and later the Laramide Uplift). The distribution of the heavy mineral provinces suggests a dominant southeastward-flowing fluvial system, with a more subordinate easterly and northeasterly system or systems in the extreme south. In lower Belly River time (Foremost equivalent) dispersal of the heavy minerals in the eastern part of the study area (Hornblende Province) may have been largely by longshore currents, since the enclosing rocks are of shoreline to shallow marine environments.

K-Ar ages of detrital hornblende from the easternmost provinces indicate

sources in the Mesozoic crystalline rocks of the northern parts of the Omineca Geanticline. Light and heavy mineral data show major contributions of clastic detritus from pre-existing sedimentary sources of the Carboniferous-Permian (Cache Creek and equivalents) eugeosynclinal cherts, carbonates, argillites and greywackes and Proterozoic and Lower Cambrian quartzites of the Omineca Geanticline. A contribution of sedimentary components from closer older Mesozoic and Paleozoic source rocks of the ancestral Rocky Mountains (Laramide Uplift) increased toward the close of the Cretaceous Period and became dominant during the Paleocene Epoch, especially to the southwestern parts of the study area. This suggests that the Laramide Uplift was higher in its southern parts than in the north. The heavy and light mineral evidence indicates significant and almost equal contribution from metamorphic and volcanic sources. The suspected metamorphic sources were the Amphibolite, Greenschist, Metagreywacke and Zeolite Facies underlying the Omineca Geanticline. Contemporaneous volcanism in central and western British Columbia and Western Montana contributed the bulk of the volcanic detritus of the sequence with lesser contribution from older Mesozoic volcanics of central and eastern British Columbia along and nearby the Omineca Geanticline. Plutonic contribution is difficult to assess on the basis of the available data.

Vertical changes in the composition of the heavy mineral suites and areal patterns of the heavy mineral provinces with time reflect the effect of the latest major pulses of the Columbian (Nevadan) Orogeny and the early pulses

of the Laramide Orogeny. These changes are preferably explained by lateral shifting of drainage basins due to tectonism within a source area of complex geology, rather than by compositional changes due to uplift and gradual unroofing of an areally static drainage basin.

A subsidiary petrographic and scanning electron microscope examination of etch features of hornblende, garnet, sphene, staurolite and epidote has suggested a sequence of intrastratal solution events whereby unstable heavy mineral populations may partially dissolve.

The study also demonstrates the usefulness of heavy mineral in helping to solve regional stratigraphic problems. The sudden appearance of floods of epidote-clinozoisite at or slightly above the base of the Paskapoo Formation of the central Foothills and slightly above the Kneehills Tuff of the Plains suggests that the Paskapoo-Brazeau contact of the central Foothills is approximately time-equivalent with the Kneehills Tuff of the Plains, and that the Cretaceous-Paleocene boundary in the central Foothills occurs within Paskapoo beds.

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Samples from the CPOG-Strathmore core were made available by the Alberta Oil and Gas Conservation Board; those from the Swan Hills and the Northwestern Plains were supplied by the Research Council of Alberta; and P. Gunther generously provided samples from the Blackstone River.

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Finally, I thank my wife, Geraldine, for her unfailing support and help in so many ways that only a wife can give. Her assistance in the field and her patient typing of the first draft of the thesis are particularly appreciated.

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INTRODUCTION

A. General Setting and Scope

The uppermost Cretaceous to Paleocene of Alberta and the adjacent part of Saskatchewan is a clastic wedge sequence thickening from east to west from 0 to 13,000 feet. The sandy units of this sequence are predominantly continental and were deposited along the margins of a retreating epicontinental sea that once covered most of the Western Interior of North America and that at times was connected with the Arctic Ocean.

Much work has been done on the stratigraphy and paleontology of the uppermost Cretaceous and Paleocene rocks of the Western Interior Plains and Rocky Mountain Foothills of Canada. Knowledge gained from these studies has helped to reconstruct a rough paleogeographic picture including a general indication of the position of source areas supplying the terrigenous clastic detritus.

To gain more realistic and accurate knowledge of the position in space and time, and the composition of these sources, a regional study of the detailed petrographic and paleocurrent aspects of these rocks is required. However, there have been very few published studies along these lines, especially on the older parts of the sequence. Such studies have been sporadic in time and are confined to the southern and eastern parts of the study area; hence, interpretations reached regarding provenance and dispersal are rather

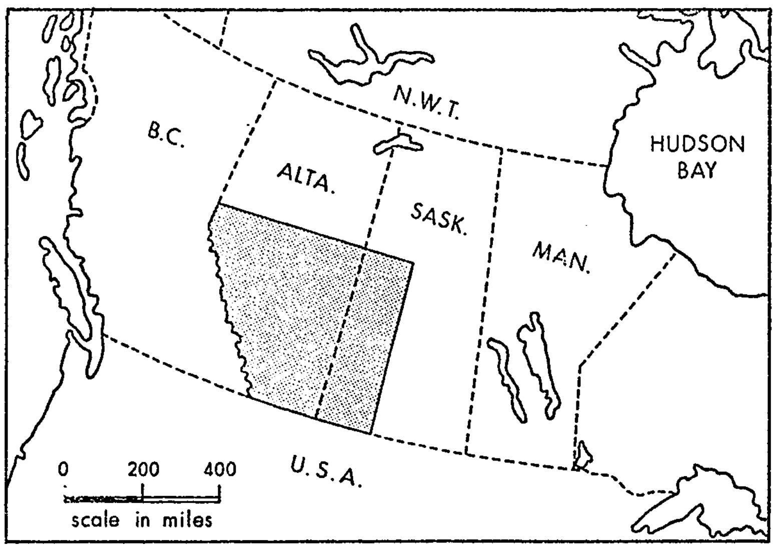


Fig. 1. Location of Study Area

incomplete and uncoordinated. The writer has, therefore, undertaken the task of studying the heavy mineral content of the entire sequence on a regional scale with the following objectives in mind:

1. To study the heavy mineral distribution and to attempt to delineate heavy mineral provinces.
2. To identify the rock types and to locate in space and time the position of the distributive provinces that shed clastic detritus to the depositional basin.
3. To evaluate, in general terms, the potential use of heavy minerals in the regional correlation of the lithostratigraphic units of the study area.

B. Study Area and Material Used

The area of study covers all of the Province of Alberta south of the 55th parallel (just south of the city of Grande Prairie) and adjacent parts of Saskatchewan (Fig. 1). Sandstone samples were collected from surface exposures and borehole cores from the Rocky Mountain Foothills and the Plains to the east. Detailed locations are given in Appendix A. The nature and source of material used in this study are as follows:

1. Heavy minerals:
   (a) Surface and subsurface core samples collected and studied by the writer.

(b) Surface samples collected by Dr. J.F. Lerbekmo and some of his former graduate students.

(c) Surface and core samples collected and studied by J.F. Lerbekmo (1963 and 1964), B. Chi (1966), Carrigy (1971) and McLean (1971).

2. Light minerals:

Published and unpublished light mineral data of other workers were used to supplement conclusions reached on the basis of heavy minerals.

3. Paleocurrent data:

Data available in literature (Carrigy, 1971 and Shepheard and Hills, 1970).

A total of 217 samples were quantitatively studied for their heavy mineral content, and the data treated statistically. Semi-quantitative data on an additional 55 heavy mineral samples (McLean, 1971) were also utilized.

C. Late Mesozoic and Early Tertiary Geologic History of Western Canada

The following summary of the geologic history of Western Canada during the Late Mesozoic and Early Tertiary is drawn mainly from recent treatments by Douglas (1970, p. 438-481) and Nelson (1970). This discussion is intended to give a broad picture of the tectono-depositional events that led to the formation of the thick clastic wedges under study. The geologic history

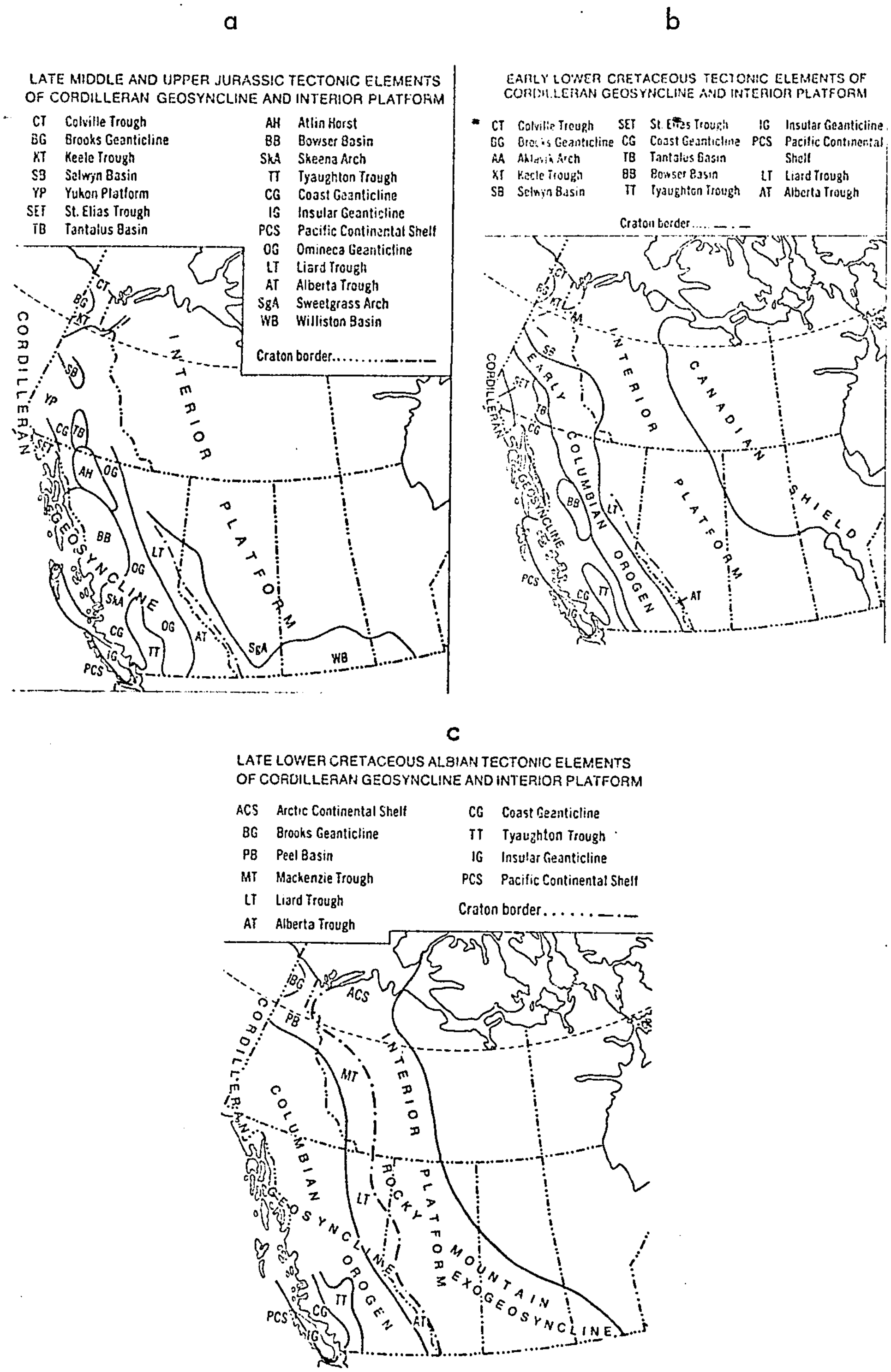


Fig. 2. Tectonic Elements of the Cordilleran Geosyncline and Interior Platform (after Douglas, 1970, p. 439-465) a. Late Middle and Upper Jurassic, b. Early Lower Cretaceous, c. Lower Cretaceous (Albian)

d e

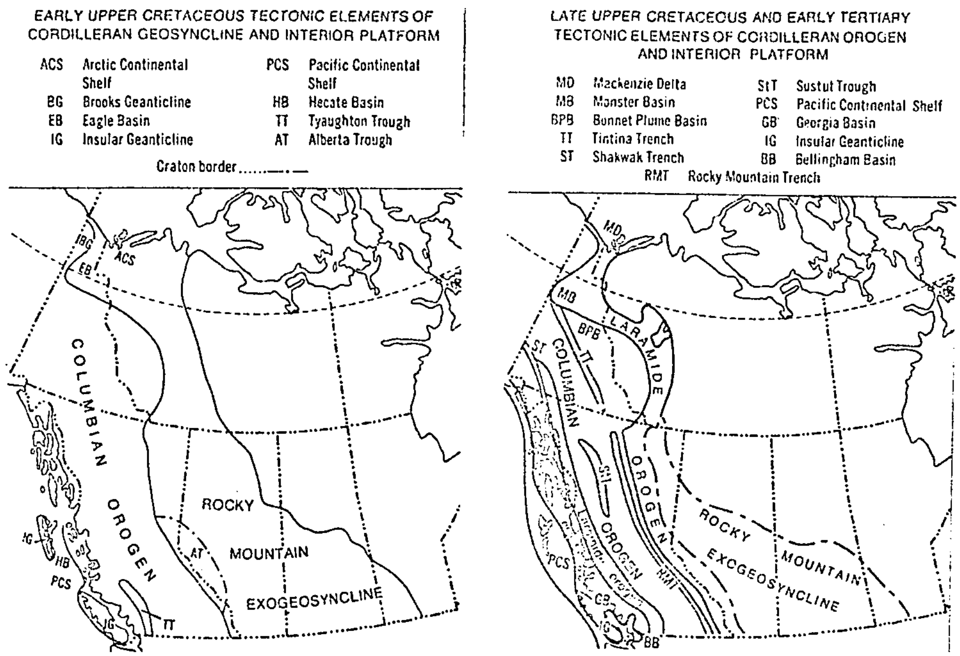


Fig. 2. (cont'd) d. Early Upper Cretaceous, e. Late Upper Cretaceous and Early Tertiary

of rocks older than those studied in this thesis is also included for the sake of completeness.

Deposition of thick wedges of clastic sediments in deeply subsiding troughs in western Alberta and northeastern British Columbia began late in the Jurassic Period (Kootenay Formation) (Fig. 2a), although some relatively thick detrital units were laid down as early as the Triassic (Spray River Group). It was not until the deformation of the Cordilleran Geosyncline that voluminous amounts of clastic detritus began moving from newly formed highlands (Columbian Orogen) eastward to fill a contemporaneously subsiding trough parallel to the orogen. This trough, called the Rocky Mountain Exogeosyncline, represents the subsiding western cratonic margin. The westernmost part of the exogeosyncline received the bulk of the derived detritus and subsided most strongly and deeply, forming what is called the Liard-Alberta Trough (Figs. 2b, 2c and 2d). A smaller portion of these clastics was carried further eastward onto the cratonic part of the exogeosyncline.

This episode of deformation, one of the latest undergone by the Cordilleran Geosyncline, started late in the Jurassic and came to be known as the Columbian Orogeny (synonymously, the Nevadan and the Coast Range Orogenies). It affected mainly the central and western parts of the geosyncline and lasted until early Late Cretaceous. Price and Mountjoy (1970) have suggested the extension of the influence to the eastern part of the geosyncline to form the earliest Rocky Mountains in the Late Jurassic. During this orogeny the Cordilleran Geosyncline underwent major deformation, regional metamorphism,

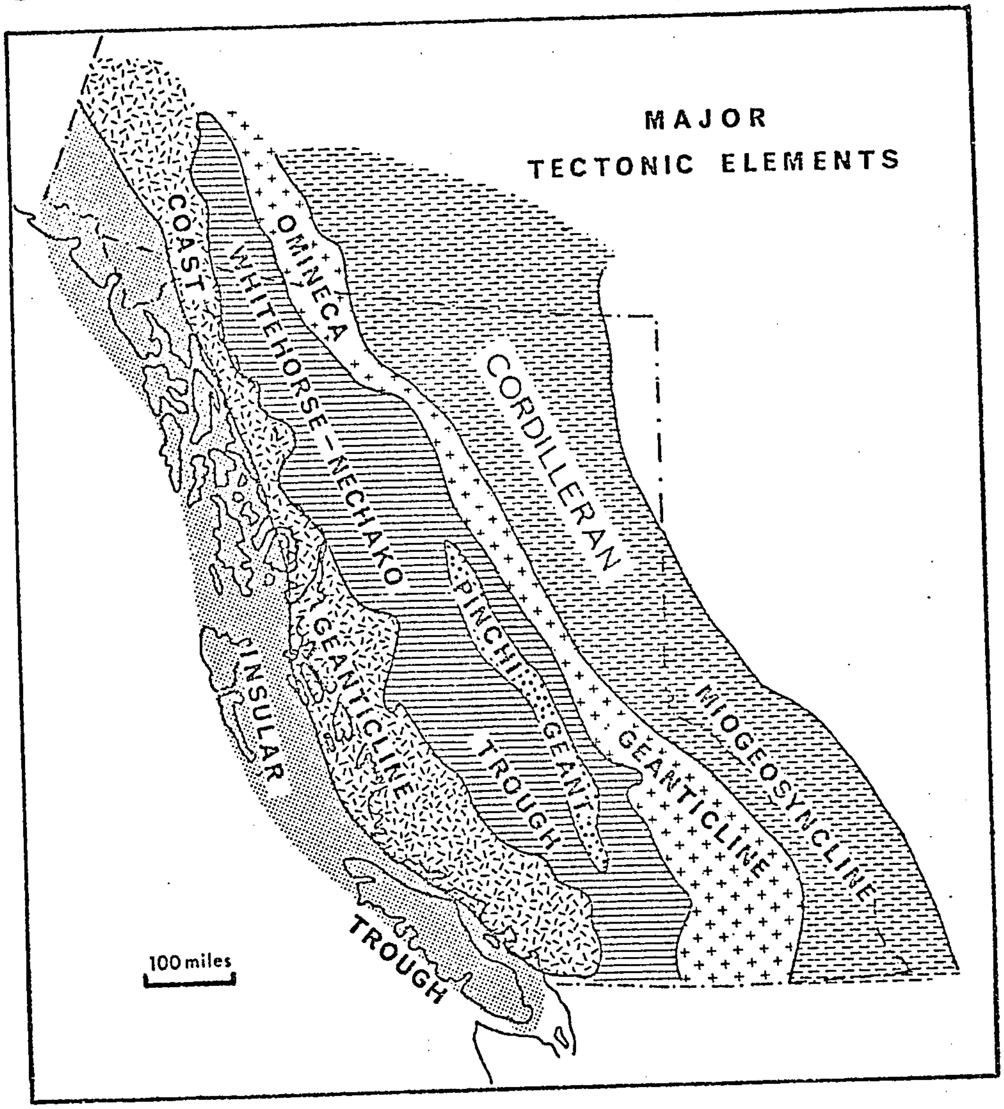


Fig. 3. Major tectonic elements of the Cordillera of western Canada (modified slightly after Souther, 1970).

granitic intrusion and uplift, resulting in the formation of the following structural provinces (Fig. 3):

1. Eastern Columbides (Omineca Geanticline), the southern part of which is formed by a northeasterly trending alpine-type orogen whose plutonic core zone forms most of the Omineca Geanticline. In the north, the Eastern Columbides include the arcuate Selwyn Fold Belt and the eastern termination of the Brooks Geanticline.
2. Columbian Zwischengebirge (Whitehorse-Nechako Trough) which is characterized by a northwesterly trending mosaic of elongated and uplifted blocks with intervening troughs and successor basins.
3. Western Columbides (Coast Geanticline or Insular Belt) which embrace the Insular, Coast, Cascade and St. Elias segments of predominantly plutonic rocks and steeply dipping, southwesterly directed structures.

The Columbian Orogeny consisted of fairly distinct phases. The early phase took place in latest Jurassic time. This phase of intense activity was restricted mainly to the Omineca Geanticline. The middle phase, of Aptian to Albian time, was more widespread. The latest phase, in early Late Cretaceous, was manifested by widespread plutonic activity during which the earliest phases of the Coast Range, Cassiar, Itsi and Nelson batholiths developed.

To the east of the mountainous Cordillera lies a flat land underlain by nearly horizontal Paleozoic and Mesozoic sediments. Along the mountain front, rivers deposited conglomerate, sandstone, siltstone and shale in the

Rocky Mountain Exogeosyncline to form the Lower Cretaceous Kootenay Formation which is presently restricted to the Rocky Mountains and the southern Foothills. Extensive coal seams in the formation indicate low swampy depositional areas.

Throughout the early Cretaceous the Western Cordillera continued to emerge episodically with some marine incursions in central and northwestern British Columbia. During this time the mountains supplied a great volume of sediment that formed thick detrital wedges, particularly to the east in the Rocky Mountain Exogeosyncline. Early in the epoch, an epicontinental sea (Clearwater Sea) began advancing southward across northern Alberta and British Columbia. At the edge of this sea, sand and clay sediments derived from the western mountains and, to a lesser extent, from the Canadian Shield were deposited by rivers and in lakes and swamps to form the Mannville Group. To the west of Mannville deposition a thicker sequence of contemporaneous sediments was laid down in the deeply subsiding parts of the exogeosyncline to form the continental Blairmore Group. During deposition of the Mannville-Blairmore sediments another epicontinental sea was spreading intermittently northward through the United States and across the Prairie Provinces, joining with the northern sea for short periods of time. This resulted in complex facies relationships within the Mannville Group.

The two seas finally coalesced near the close of the Early Cretaceous

Epoch and covered almost all of the Western Interior Plains for a period of 35 million years, from the Early Cretaceous through much of the Late Cretaceous Epoch. Sediments deposited in this seaway, which is generally known as the Colorado Sea, are mainly shales of wide extent. The Early Cretaceous sequence is called the Lower Colorado Group in Canada.

In early Late Cretaceous, shales of the Upper Colorado Group were deposited. The highlands of the Columbian Orogen to the west shed some sandy detritus to the western shores of the Colorado Sea to form a minor accumulation of sand that graded eastward into marine clay. This sand accumulation formed what is now called the Dunvegan Cardium Formations. During the late Late Cretaceous the sea retreated southward intermittently punctuated by two minor advances before its final withdrawal. These transgressions and regressions resulted in a complex interfingering of marine and non-marine rocks in the Upper Cretaceous Series. The three principal regressive phases are represented by the extensive sand deposits of the Milk River Formation and the Belly River and Edmonton Groups.

Just before the close of the Cretaceous Period, deformation of the Cordilleran Geosyncline assumed another form which continued into the Tertiary. Western Canada was essentially all land by the beginning of the Tertiary, and the mountain belts generated by the Columbian Orogeny were rejuvenated during the Laramide Orogeny (Fig. 2e). The early phase of the Laramide Orogeny began in late Late Cretaceous and the late phase probably ended early in the Oligocene. The Laramide Orogeny had its principal effects on the easternmost and northernmost parts of the Cordilleran region, during which the following structural elements were formed: the linear Rocky Mountain Thrust Belt, the arcuate MacKenzie Fold Belt and the Northern Yukon Fold Complex. Structures of the Columbian and older orogens were slightly modified during the Laramide Orogeny and some movement took place along previously formed faults. Discordant bodies of quartz monzonite, granite, syenite and quartz diorite intruded the Cordillera. These intrusions, as in earlier phases, were confined to the Omineca and the Coast Range Geanticlines.

Deposition in the Rocky Mountain Exogeosyncline continued during the late Cretaceous and early Tertiary. The newly forming Rocky Mountains began to supply a large part of the clastic detritus, and at times shut off any significant flow of detritus from the older and more westward Columbian Orogen (specifically the Omineca Geanticline). Depocenters migrated eastward in front of the advancing thrusts of the Rocky Mountains. These sediments were carried mainly by rivers and deposited over a broad flat coastal plain that covered much of Alberta, Saskatchewan and adjacent areas to the east and south. The resulting deposits of sandstone, siltstone, shale and conglomerate contain low-grade coals of lignite rank, testifying to the swampy nature of parts of this plain at times. Only two moderately large erosional remnants are left today of the widespread blanket of Tertiary sediments. The largest remnant occupies the central portion of the Alberta Syncline and extends from just south of the 55th parallel south to the International Border. This remnant is comprised of the Paskapoo, Willow Creek and Porcupine Hills Formations. The other remnant covers part of southern Saskatchewan, adjacent southeastern Alberta, southwestern Manitoba and Montana. The Ravenscrag Formation of the Cypress Hills and Saskatchewan and the Turtle Mountain Formation of Manitoba make up this remnant.

D. Regional Stratigraphy

The uppermost Cretaceous and Paleocene succession in the study area is an essentially continuous depositional record with only minor local breaks. Beginning with the onset of the regression following the marine transgression represented by the Wapiabi (Niobrara) Santonian marine shale, the sequence became progressively more continental, and by the end of Paleocene time, practically all of the Canadian Western Interior and Cordillera were above sea level.

The lithostratigraphic units studied here are those of the Post-Colorado Supergroup (Williams and Burk, 1964) and Paleocene that contain large proportions of sandstone, in this case largely non-marine. Table 1 shows the correlation of these units in the Plains and Foothills of Alberta, using the geographic subdivision of Williams and Burk (1964), and incorporating the revised correlations and terminology of Carrigy (1970, 1971) and Irish (1970) and the suggestion of the present paper that the Cretaceous-Paleocene boundary occurs within the Paskapoo Formation of the central Foothills. The correlations are also shown in the cross-sections of Figure 4 which have been modified slightly from Stott (in Douglas, 1970, p. 456-458) to correspond with Table 1.

For the purpose of more wieldy treatment of the heavy mineral data, the lithostratigraphic units of the Post-Colorado Supergroup and Paleocene were grouped into three lithostratigraphic "slices" which are internally approximately synchronous. It will be seen that the heavy mineral data support the selection of the boundaries between these units. The groupings into the three "slices" are as follows (Fig. 4):

1. Belly River "Slice"

This includes the Belly River Group of the southern Plains, the lower part of the Wapiti Formation of the northwestern Plains, the Belly River Formation of the southern Foothills and the lower part of the Brazeau Formation of the central and northern Foothills.

2. Edmonton "Slice"

This includes the Edmonton Group, St. Mary River, Eastend, Whitemud and Battle Formations of the southern Plains, the upper part of the Wapiti Formation of the northwestern Plains, the St. Mary River Formation of the southern Foothills and the upper part of the Brazeau Formation of the central and northern Foothills.

3. Paskapoo "Slice"

This includes the Paskapoo (after Carrigy, 1970, 1971; Irish, 1970)

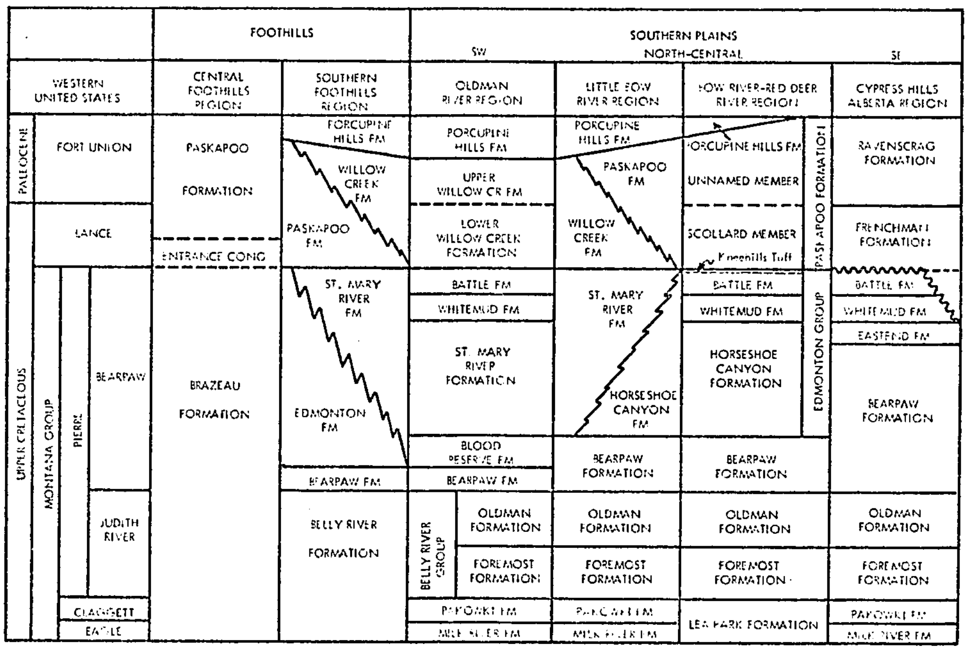


Table 1. Correlation of the uppermost Cretaceous and Paleocene formations of the southern Alberta Plains and the Foothills (modified after Irish, 1970 and Carrigy, 1970, 1971).

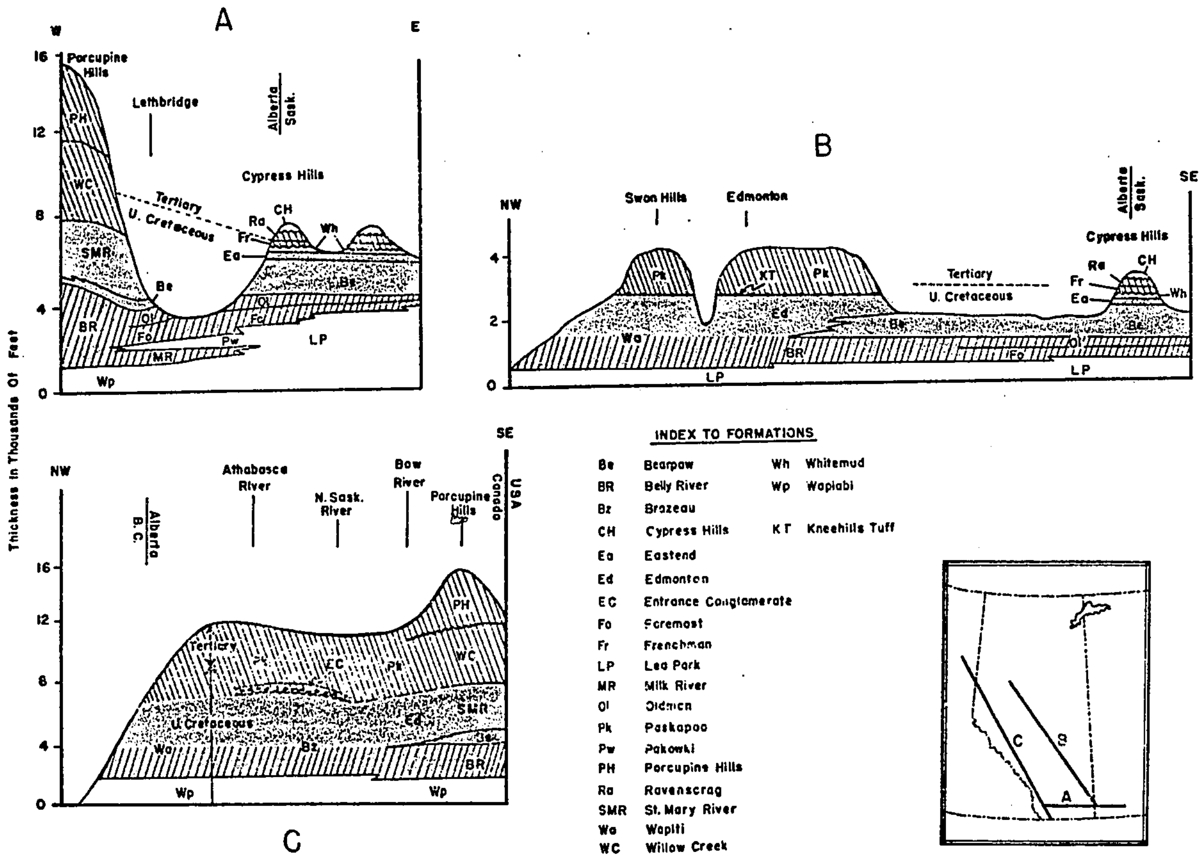


Fig. 4. Stratigraphic sections of Upper Cretaceous and Tertiary rocks, Alberta and adjacent areas of British Columbia and Saskatchewan (modified after Stott, in Douglas, 1970, p. 456-458). Lithostratigraphic "slices" referred to in text are colored.

Willow Creek, Porcupine Hills, Frenchman and Ravenscrag Formations of the southern Plains, the Paskapoo Formation of the northwestern Plains, the Porcupine Hills, Willow Creek and Paskapoo Formations of the southern Foothills and the Paskapoo Formation of the central and northern Foothills.

A more detailed description of the lithostratigraphic units studied and a discussion of the more recent revisions in the stratigraphic terminology are given in Appendix C for the reader's convenience.

E. Methodology

1. Sampling Plan

The ideal sampling scheme for this type of study is a uniform areal and stratigraphic coverage of all the lithostratigraphic units under investigation. In the Foothills, sandstone samples were obtained when measuring surface stratigraphic sections, and in the Plains spot sampling was carried out since there are very few places where any significant thickness of section is exposed. Consequently, in the Plains area, exact stratigraphic positions of some samples are uncertain. It was hoped to obtain sandstone samples at 100 to 200 feet intervals (stratigraphically) and to have sections spaced by not more than 50 miles. However, several unfavorable conditions resulted in a considerable departure from such a uniform sampling plan. These conditions and limitations are as follows:

(a) Sampling was restricted to sandstones that are neither very coarse nor very fine-grained.

(b) In many of the measured sections there are large intervals composed mainly of mudstone and/or shale.

(c) Exposures of any significant thickness are restricted to the narrow belt of the Rocky Mountain Foothills. Here, some of the sections are faulted and the stratigraphy is uncertain; such sections were not measured. In the Plains area, which constitutes the bulk of the study area, good exposures are scarce and small, and subsurface cores of the continental sandstones are rare. Oil well cuttings were not considered to be sufficiently reliable.

(d) After preliminary examination of the heavy mineral suites of some of the Foothills sections, it was found that these suites are stratigraphically of uniform composition throughout large thicknesses. This observation resulted in widening the vertical sample spacing in these sections. This was done with caution in order not to overlook any significant and sudden compositional changes. Figure 5 shows the sample and section locations.

2. Preparation of Samples

Poorly consolidated samples were disaggregated either by crushing with the fingers or by rolling under a wooden rolling pin on a plexiglass sheet. Moderately and well consolidated samples were first coarsely crushed in a jaw crusher. Chips were further disaggregated by light crushing (not grinding) with

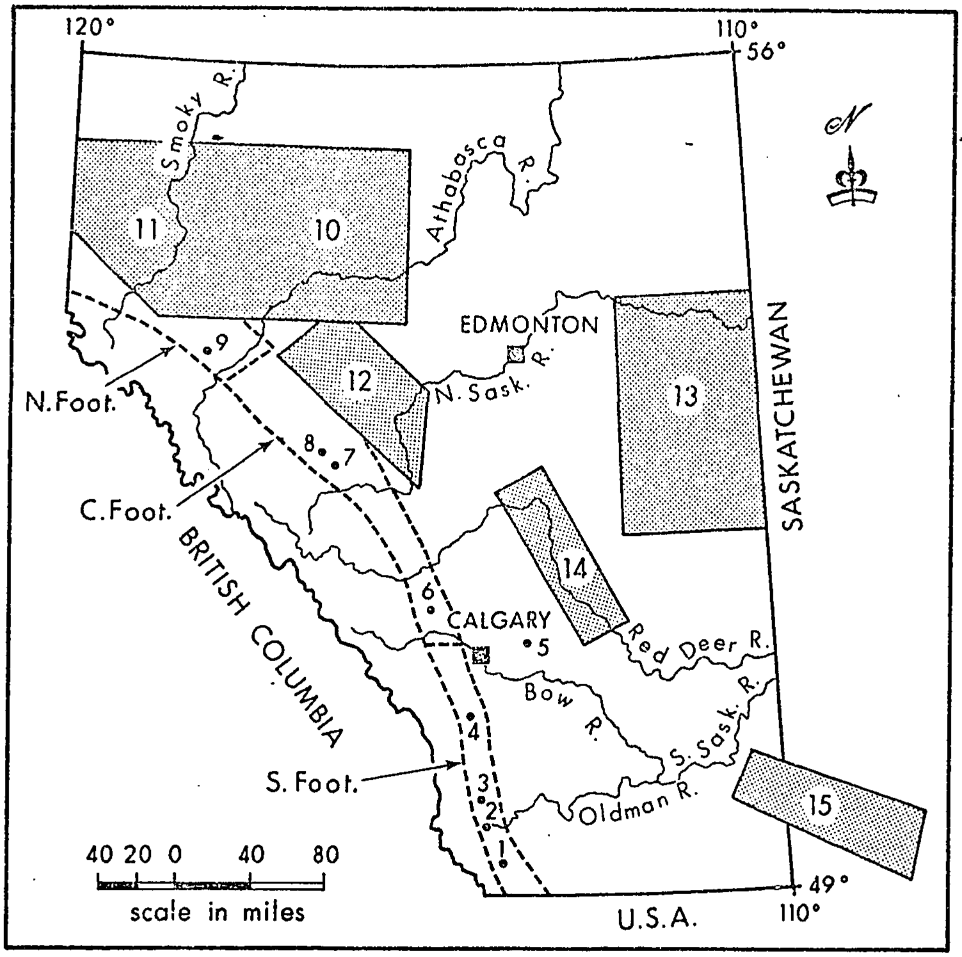


Fig. 5. Sample locations. 1. Drywood River; 2. Porcupine Hills; 3. Oldman River; 4. Highwood River; 5. CPOG-Strathmore well; 6. Little Red Deer River; 7. Colt Creek; 8. Blackstone River; 9. Wildhay River; 10. Swan Hills; 11. Northwestern Plains; 12. Western Plains; 13. East-Central Alberta; 14. Red Deer River Valley; 15. Cypress Hills

a hammer and anvil, or mortar and pestle, to very small aggregates and then rolled with the wooden rolling pin on a plexiglass sheet.

The sample was then sieved to obtain an average of 40 gm. of -80+230 mesh sand for the heavy mineral separation; large samples were split with a standard mechanical splitter. Heavy minerals were separated using tetrabromoethane (S.G. = 2.95) and standard separatory funnels. A small sample of the heavy mineral fraction was taken using an Otto-type microsplitter. This sample was then mounted permanently in aroclor (R.I. = 1.66) on a millimeter grid slide.

3. Heavy Mineral Counting

The mounted heavy mineral grains were identified under the petrographic microscope. Relative abundance determinations were made by counting 200 non-opaque heavy mineral grains (except biotite). Biotite and opaque grains accompanying the 200 non-opaque heavy minerals were counted simultaneously.

The point count method used here is similar to the Area Method described by Galehouse (1971, p. 391-392) whereby all mineral grains contained in the one millimeter square are counted. The squares are chosen to be systematically distributed over the entire slide in order to obtain a random sample. The resulting grain count by this method is a number per cent which can be treated statistically (Galehouse, 1971, p. 394). Inspection of confidence intervals charts of point counting of mineral grains shows that a count of 200 to 300 grains per sample is sufficient for the purpose of the present study. Increasing the count does not decrease the confidence interval enough to justify the extra time spent in the counting (Hubert, 1971, p. 457).

Other study methods used in this thesis, the details of which can be found in their respective sections, are as follows:

(a) K-Ar Radiometric Dating

(b) Electron Microprobe Chemical Analysis

(c) Scanning Electron Microscopy

RESULTS

A. Description of Heavy Minerals

This description includes the petrographic properties, abundance, general distribution, possible source rock-types and potential source areas of the major heavy mineral constituents of the sandstones under study. The non-opaque heavy minerals except biotite (NOHM-B) are dealt with first, alphabetically.

Allanite: Allanite of the study area is reddish-brown, brown and deep red; not uncommonly it is strongly pleochroic from dark red to brown. It was frequently found to occur as isotropic grains of very deep red color. This variety was identified on the basis of grain shape, fracture, relief and lustre. This isotropic form of allanite is considered by Milner (1962) to be the product of alteration. Angular to subangular grains are dominant with occasional occurrences of tabular, euhedral or rounded grains. It is optically biaxial negative, but only a few grains were found suitable for determining this property.

Allanite occurs throughout most of the study area, although it is more abundant in the Foothills and immediately adjacent Plains. It averaged 3.5% of the NOHM-B. In the Foothills, allanite occasionally makes up as much as 35%, but more commonly 10 to 15%, of the suite, especially in rocks of the Belly River Group and the lower part of the Edmonton Group and their equivalents. It rarely exceeds 10% in the upper part of the Edmonton Group and the lower part of the Paskapoo Formation of the Foothills. In the Plains, the only important occurrences of allanite are in the Belly River Group and the lower part of the Edmonton Group of the CPOG-Strathmore core 25 miles east of Calgary, and in the upper part of the Edmonton Group and the lower part of the Paskapoo Formation in a section along the Smoky River about 50 miles east of the Foothills disturbed belt and 20 miles south of the town of Grande Prairie. Notably, these latter occurrences are close to the Foothills area. Throughout the Plains, allanite is a minor constituent that rarely exceeds 5%. This distribution strongly suggest dispersal from the northwest, west or southwest. Possible source rocks for allanite are acid igneous and metamorphic rocks and certain ores (Milner, 1962, p. 33). The suspected source area (eastern Cordillera) is of complex geology of plutonic, metamorphic, volcanic and sedimentary rocks. Tracing the specific source terrain of any detrital heavy mineral into these suspected source areas where published work on the petrography of their accessory minerals is scarce, is a very difficult task. However, published work indicates that allanite is a common accessory in the major phases of the Idaho Batholith (up to 0.05% in the tonalites) (Larsen and Schmidt, 1958 in Lerbekmo, 1963). The quartz-monzonite phase of the Idaho Batholith yields minor allanite. It is not reported among the accessory minerals of the Nelson Batholith in southeastern British Columbia. It commonly occurs as an accessory in the gneissic rocks of the Valhalla Gneissic complex of southeastern British Columbia and, to a lesser extent, in the granodiorite of the same complex (Reesor, 1965). The Valhalla Gneissic complex is partially contemporaneous with the Nelson Batholith (Late Jurassic to Early Tertiary). There is no mention of allanite in the accessory

	AV.	MIN. VAL.	MAX. VAL.
Hornblende	10.57	0.00	91.84
Garnet	20.84	0.00	79.30
Epidote-Clinozoisite	17.35	0.00	72.58
Apatite	13.99	0.00	69.55
Rutile	2.51	0.00	17.39
Sphene	6.12	0.00	45.85
Tourmaline	3.12	0.00	24.25
Tremolite-Actinolite	0.48	0.00	6.00
Allanite	3.77	0.00	34.65
Chlorite	2.14	0.00	21.38
Zircon	17.38	0.00	79.70
Staurolite	0.24	0.00	2.28
Chloritoid	0.46	0.00	14.78
Glaucophane	0.01	0.00	0.50
Kyanite	0.05	0.00	2.50
Andalusite	0.36	0.00	4.04
Others	0.68	0.00	5.50

Table 2. General statistics of non-opaque, non-micaceous heavy minerals (percentages).

minerals listed in the Omineca Intrusions of central British Columbia (Roots, 1954). To the north, just south of the Yukon-B.C. boundary, in the Jennings River Map-Area, Gabrielse (1969) reported allanite in the hornblende-quartz-diorite and hornblende-granite in the Cassiar Intrusions (Early Jurassic to Late Cretaceous). To the west of this area, Aitken (1959) reported a rare occurrence of allanite in Alaskite.

From the above information, one cannot specify the source of the allanite. The Idaho Batholith and the Valhalla Gneissic complex may have been the main sources of allanite, especially to the southern and southwestern parts of the study area. However, crystalline rocks of the rest of the Omineca Geanticline to the north could equally well have contributed allanite to the depositional basin.

Apatite: Apatite is one of the five most common heavy minerals of the study area; it ranges in abundance from 0 to 69% and averages about 14% (Table 2). Apatite of the study area shows no diagnostic stratigraphic significance since it occurs throughout, vertically and areally. However, it is less common in the Belly River Group of east-central Alberta, certain horizons of the Brazeau Formation and the Paleocene part of the Paskapoo Formation of the Plains and the Foothills north of the Bow River. This low occurrence is more an overshadowing effect of floods of either epidote or hornblende rather than a decrease in the absolute amount of apatite.

Angular to subangular apatite is by far the most abundant shape variety. It ranges from 47 to 70% of the total apatite and averages about 60%. The

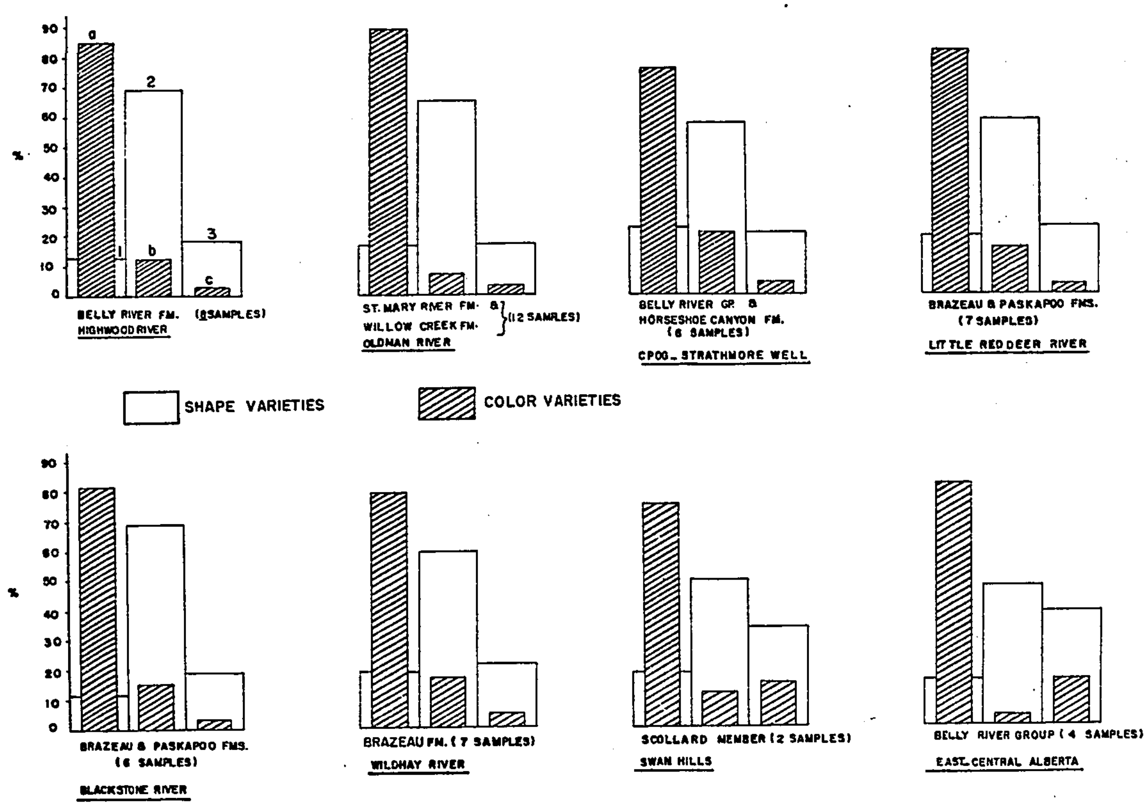


Fig. 6. Color and shape varieties of apatite. a. colorless; b. colored; c. colorless with abundant black inclusions. 1. euhedral-subhedral; 2. angular-subangular; 3. rounded-subrounded.

rounded to subrounded variety ranges from 17 to 38% and the euhedral to subhedral variety ranges from 11 to 22% (Fig.6). The rounded to subrounded grains are relatively more abundant in the Plains sandstones. This is probably due to the fact that the Plains are farther from the source area than the Foothills, and in this relatively soft mineral, rounding has taken place with the longer transport.

Three major color varieties were recognized: (1) colorless apatite, 74 to 90%; (2) colored apatite, including bright brown (2.5 YR 5/8), red to red orange (10R 4-5/8) and red to dark red (7.5 R 3/4 & 4/8) colors (3.5 to 21%), and (3) colorless apatite with black inclusions arranged in straight lines parallel to the crystallographic c-axis of apatite (3 to 16%) (Fig. 6). The colored variety also commonly contains black inclusions arranged in lines parallel to the c-axis. The coloring usually occurs either as a core (nucleus) surrounded by colorless apatite, or as irregular color patches in a colorless base or, less commonly, evenly throughout the whole grain. The colored varieties are not uncommonly pleochroic from lighter to darker shades of the color. Along the Foothills, colored varieties are more abundant north of the Bow River than to its south, but decrease eastward towards the Plains (Swan Hills and east-central Alberta, Fig. 6). The colorless variety with the black inclusions is more abundant to the north in the Swan Hills area and to the east in east-central Alberta. All apatite varieties in the study area were found to be generally fresh, showing no evidence of solution.

Possible source rocks for apatite are igneous rocks, especially granites and syenites (Milner, 1962, p. 48) and their volcanic equivalents. In the study area the colored varieties and those with the black inclusions may prove very helpful in tracing specific source areas. However, the writer knows of only one reference to colored apatites in the suspected source area of the Cordillera. This occurrence is reported by Aitken (1959) who found apatite prisms with prominent smoky cores which are pleochroic from brown to dark grey, in granodiorites and quartz-monzonites of the 4th July Batholith of the Coast Range intrusive complex of northwestern British Columbia. The age of this batholith is Triassic to Cretaceous. However, there is no reason not to suspect the occurrence of similar apatite in other intrusive rocks that occur throughout the length of the Cordillera. Until further work is done on detailed description of accessory minerals of crystalline rocks in the Cordillera, this occurrence in northwestern B.C. is considered a possible source for these apatites. This suggestion is further supported by the fact that colored apatite increases in relative abundance northwestwards along the Foothills. Chi (1966, p. 81) suggested that part of the colored apatite in the Frenchman Formation of south-eastern Alberta could have been derived from the Canadian Shield of northeastern Alberta. The present writer believes that if there has been any contribution of sediments from the Canadian Shield to the study area during the Late Cretaceous and Paleocene, it must have been very small. A later discussion of the heavy mineral provinces and paleocurrents will elaborate on the above statement.

Colored apatite with cores containing inclusions were found to be common in several stratigraphic horizons in Britain (Fleet and Smithson, 1928). It was also found to be a widespread accessory mineral in several bodies of granitic rocks in Britain (Groves and Mourant, 1929).

Chlorite: Chlorite is a widespread but sporadically occurring mineral in the study area. It ranges from 0 to 21%, averages about 2% (Table 2) and occurs more abundantly in the Foothills, where sections are thicker and sediments are deeply buried. This higher occurrence in the Foothills could be the result of secondary alteration of pre-existing mafic minerals, or due to the nearness of the Foothills to a western source for the chlorite.

The chlorite grains are rounded to subrounded, deep green to yellowish-green and slightly pleochroic. Inclusions of opaque and non-opaque minerals are not uncommon. The varieties penninite and clinochlore were recognized; possible chamosite occurrences were counted as separate components. Several instances of biotite altering to chlorite were observed, but rarely do amphiboles show any suggestion of alteration to "chloritic matter". Chlorites are common metamorphic minerals, especially in low grade schists and contact-altered magnesium limestones (Milner, 1962, p. 85 and 159). Chlorite occurrence and distribution in the study area is not suggestive of any specific source area.

Chloritoid: Chloritoid is important in the Foothills and immediately neighbouring Plains. It ranges from 0 to 15% but averages less than 0.5%. It generally occurs, in the study area, in two varieties: (1) pale grey, greyish-green, or pale green with abundant acicular and tabular opaque and non-opaque inclusions, and (2) grey to green, devoid of inclusions. Both varieties are commonly pleochroic. Grains are generally equant to somewhat tabular, and show no visible evidence of solution.

Crystalline schists, phyllites, quartzites and reconstituted argillaceous sediments are possible source rocks for chloritoid (Milner, 1962, p. 80). Chloritoid of the study area has no apparent stratigraphic significance, except for the fact that it is almost absent in rocks of the Edmonton Group and its equivalents. Its distribution does not point to any specific source area.

Epidote-Clinozoisite: Because of similar distribution, provenance and general mineralogy, epidote and clinozoisite are treated together in this study. However, epidote is far more abundant than clinozoisite which makes up only a small fraction of this mineral pair. Epidote-clinozoisite occur commonly to abundantly in all the formations under study except in the Foothills area south of the Bow River where they are almost absent. Throughout the rest of the study area, epidote-clinozoisite appear in flood proportions at several stratigraphic levels. Most of these epidote-clinozoisite rich zones are not persistent and correlative through the study area within the limit of sample control for this study. An exception is the epidote-clinozoisite flood that appears in early Lance time (basal Paskapoo) which is areally persistent from the central Foothills to the Plains area as far east as the eastern erosional limit of the Paskapoo Formation.

Proportions of epidote-clinozoisite range from 0 to about 73% and averages 17 %. Epidote is rounded to angular, irregular and rarely euhedral or subhedral. It is pleochroic from almost colorless to pale yellow, yellow or yellowish-green, and commonly shows hacksaw terminations as evidence for solution etching. Black inclusions are commonly present. Clinozoisite also shows hacksaw terminations but differs from epidote in being paler with lower birefringence.

Possible source rocks for epidote are low-grade schists, crystalline metamorphic rocks, especially altered impure limestone, and also highly altered igneous rocks originally rich in ferro-magnesian minerals. Source rocks of clinozoisite are crystalline schists and metamorphosed basic igneous rocks (Milner, 1962, p. 103 and 86).

Several areas in the U.S. or Canadian Cordillera could have contributed epidote and clinozoisite. Certain limitations as to the specific source can be exercised when examining the areal distribution of the epidote-clinozoisite. The near absence of epidote-clinozoisite in the southern Foothills and the lack of suitable sources to the south and southeast of the study area suggest the source to have been to the west and northwest.

Garnet: Garnet is the most abundant non-opaque heavy mineral throughout the study area (Table 2). It ranges from 0 to almost 80% and averages about 21%. Five major color varieties were recognized. Most abundant are the colorless, yellow to orange (shades of 2.5Y, 5Y, 7.5Y and 10YR) and pink (5R 6-8/4) varieties. Red to red-orange (10R 5-6/8) and red (5R 4-6/6 and 5/4-5) varieties are less abundant (Fig. 7). Inclusions are common, including bubbles, opaques, dusty specks and acicular crystals of

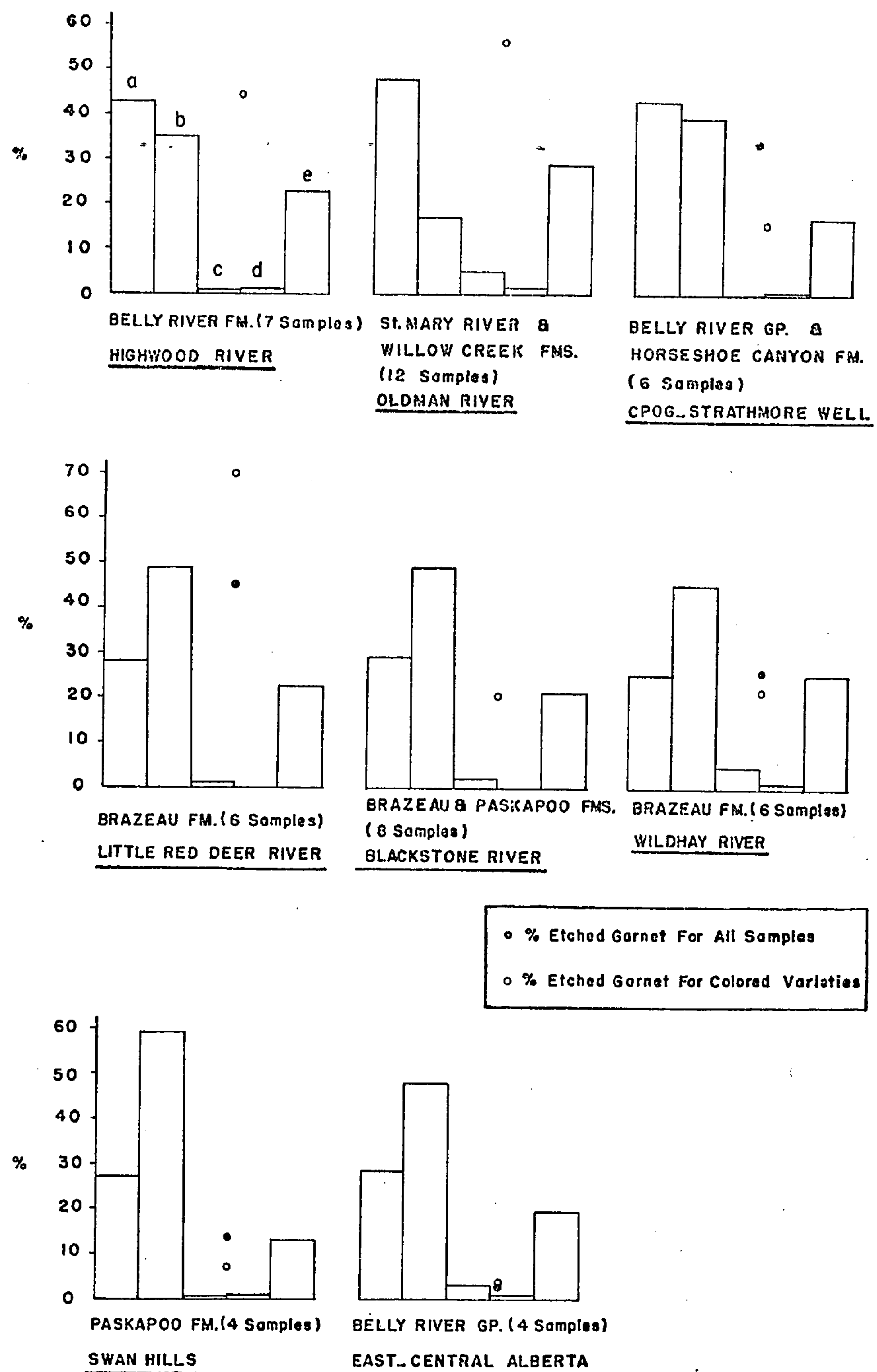


Fig. 7. Color varieties of garnet. a. colorless; b. orange-yellow; c. red-reddish orange; d. red; e. pink.

unidentified species. Colorless varieties with abundant black inclusions described by Lerbekmo (1963, p. 72) were recognized sporadically throughout but were not quantitatively treated. On the basis of X-ray diffraction data, Lerbekmo found both colorless and red garnet to be of approximately the same composition, dominantly composed of almandine, with pyrope and spessartite the next two most important "molecules". He found the orange variety (and possibly the yellowish-orange and pink varieties of the present study) to be nearly pure spessartite or a mixture dominated by either almandine or pyrope. Angular to subangular garnet is the most common type with minor proportions of euhedral to subhedral and rounded to subrounded grains. Solution etching of garnet is very common (Figs. 7 ,29 and 30) resulting in grains having imbricate wedge markings. Figure 7 shows clearly how the colorless variety exceeds the yellow-orange variety south of the Bow River and how this relationship is reversed north of the Bow River along the Foothills. This may suggest at least two sources of garnet, one from the south or southwest dominated by the colorless variety, and the second from the northwest dominated by the yellow-orange variety.

Ultimate possible sources of the garnet are metamorphic rocks, particularly crystalline gneisses and schists in the case of almandine, ultrabasic igneous rocks in the case of pyrope, and acid igneous rocks and low-grade metamorphic rocks in the case of spessartite (Milner, 1962). As to the specific source area, at present one can only say that the garnets were derived from crystalline rocks of the Omineca Geanticline of the eastern Cordillera.

Hornblende: Hornblende is a very abundant heavy mineral in the sandstones of the eastern parts of the study area, particularly in the Frenchman Formation of southeastern Alberta (Chi, 1966, p. 48), the lower part of the Belly River Group of east-central Alberta and adjacent areas of Saskatchewan, and the Paskapoo Formation of the Plains. It ranges from 0 to 92% and averages about 11% over the entire study area (Table 2).

Hornblende of the study area occurs as elongate, lath-like cleavage fragments which frequently have a skeletal and fragile appearance, and commonly show hacksaw terminations indicating solution etching. Three color varieties, green to olive, brown to reddish-brown and red (oxyhornblende) were recognized. Green to olive hornblende is most abundant and exceeds 80% of the hornblende population. Second in abundance is the brown to reddish-brown type which averages about 15% of the total. All color varieties are pleochroic. Bubble, crystal (apatite?) and opaque inclusions are common either parallel to the crystallographic features or randomly oriented.

Possible ultimate sources of hornblende are igneous and metamorphic rocks, especially granite, syenite, diorite and equivalent volcanic rocks, hornblende schist and amphibolite (Milner, 1962, p. 124). Hornblende occurs as an essential mafic and as an accessory mineral in most of the crystalline rocks of the Omineca and the Coast Geanticlines of the Cordillera, and the crystalline rocks of the Canadian Shield of northeastern Alberta. Radiometric dating, however, of some of these detrital hornblendes has discounted the possibility of the Canadian Shield as a significant source. Therefore the hornblende must have come from Cordilleran sources. The specific source is elaborated on in other sections of this thesis.

Rutile: Rutile is a widespread heavy mineral, but common only in the Foothills and the immediately adjacent Plains, especially south of the Bow River. Abundance of rutile ranges from 0 to 17% and averages 2.5%. Grains are usually irregular, stumpy and anhedral and locally entirely rounded, but commonly subangular to subrounded. The euhedral form is met with not uncommonly, some having elbow twins. Obliquely striated grains are very few. Three color varieties of almost equal abundance were recognized: red (7.5R 4/8 and 3/6), red-orange (10R 5-6/8) and orange. No evidence of solution was observed in rutile. Possible ultimate sources of rutile are acid igneous and crystalline metamorphic rocks. It can also originate in situ from the decomposition of ilmenite (Milner, 1962, p. 175). Rutiles of suspected authigenic origin were not counted in this study. Rutile is an extremely stable mineral and rounded grains may have undergone several cycles of erosion and deposition. It is very likely that a large part of the rutile of the study area, especially in the southern Foothills (and particularly of the Porcupine Hills Formation) is multicyclic.

Sphene: Sphene is a very common mineral in many of the rocks studied. It is rare to absent only in the southern Foothills. It is a major constituent of the heavy mineral yield of the Horseshoe Canyon Formation of the Red Deer River Valley and the CPOG-Strathmore core and the Scollard Member of the Red Deer River Valley. It assumes only minor importance in the Brazeau Group of the Little Red Deer River and the Belly River Group of the CPOG-Strathmore core. Abundance ranges from 0 to about 46% and averages about 6%.

Sphene was found to occur as colorless, pale yellow, orange and light brown grains; the latter two color varieties are usually pleochroic. Euhedral and broken euhedral grains are not uncommon, but sphene usually occurs as subangular to subrounded and occasionally rounded fragments. As in garnet, sphene grains commonly show the imbricate wedge markings and occasionally exhibit the hacksaw terminations indicating solution etching. Opaque, bubble and apatite inclusions were observed frequently. As in the case of rutile, suspected authigenic sphene grains were disregarded.

Granites, intermediate igneous and crystalline metamorphic rocks are some of the possible sources of sphene (Milner, 1962, p. 192). Specific sources are discussed in a later section.

Tourmaline: Tourmaline is a common and very widespread heavy mineral. It is particularly common in the Foothills sections, especially south of the Bow River, and in the Ravenscrag Formation of the Cypress Hills area. It ranges in abundance from 0 to about 24% and averages over 3%.

Several color varieties were recognized; of these, the dusky green, dark yellowish green, olive brown and light brown varieties are the most frequently encountered. Other colors are pink, black, blue and red. All these color varieties are distinctively pleochroic. Three shape varieties are exhibited by tourmaline: euhedral to subhedral, angular to subangular and subrounded to rounded. There is no sharp distinction between the subangular and subrounded grains. Locally, the subrounded to rounded tourmaline is very common and likely it has been recycled. Authigenic overgrowths on well rounded grains were observed occasionally. Some grains have abundant black inclusions; other inclusions are bubbles and zircon crystals.

Possible sources of derivation of tourmaline are pneumatolytic rocks, acid igneous rocks, pegmatites, schists, gneisses and phyllites (Milner, 1962, p. 196). Krynine (1946) comprehensively discussed the provenance of the different tourmaline color varieties; no such interpretations are attempted here.

Zircon: Zircon is one of the major heavy mineral constituents and is abundant in most of the samples. Quantities range from 0 to 80% and average about 17% (Table 2). It is relatively more abundant in the Foothills sections, especially in the St. Mary River, Willow Creek and Porcupine Hills Formations of the southern Foothills.

On the basis of color zircon was subdivided into two varieties: (a) colorless and yellow grains, the latter being uncommon, and (b) hyacinth zircon which includes pink, red and purple grains. Hyacinth zircon was found to be commonly rounded. Coloring in hyacinth is caused by the breakdown of the atomic structure due to disintegration of radioactive elements in the mineral. Hyacinth is generally considered to be of Precambrian age and may very well have been recycled many times. It is significantly more abundant in the southern Foothills (Fig. 8). In the Plains, hyacinth is more abundant in the Cypress Hills area and decreases towards the northwest, except for anomalous single-

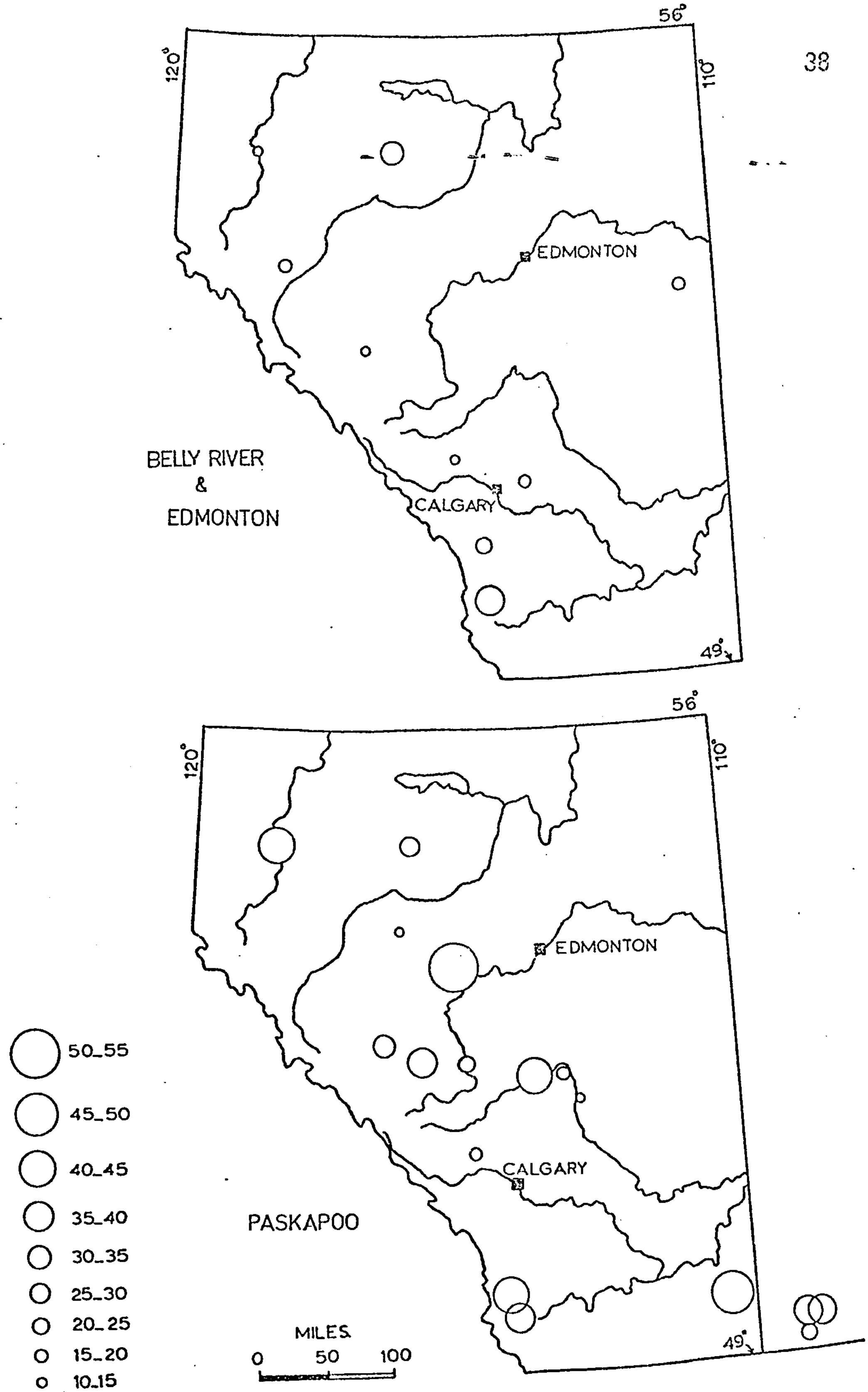


Fig. 8. Areal variation of hyacinth zircon. Numerals refer to % of hyacinth in total zircon.

sample localities that may have very high hyacinth contents. Hyacinth relative abundance increases stratigraphically. This trend is particularly noticeable in the southern Foothills, where there is a relative increase upward from the Belly River through the St. Mary River, Willow Creek and Porcupine Hills Formations (Figs. 8 and 9). In the latter formations, hyacinth makes up about 40% of the zircon population. According to shape, zircon was subdivided into three varieties: (a) euhedral and broken euhedral grains (by far the most abundant variety), (b) angular to subangular grains with no recognizable crystal faces (generally colorless) and (c) rounded to subrounded and broken rounded grains (second in abundance and mainly hyacinth). The breakage of the euhedral and rounded grains is taken here to be the result of transportation and sedimentation processes rather than due to crushing of the samples during preparation.

Zoning was observed occasionally, most commonly among the hyacinth varieties. The zoning is usually confined to the peripheral part of the crystal.

Contact twinning was observed in several crystals. Chi (1966) described such twinning in conjunction with knee-shaped twinning along the (101) face in the zircons of the Scollard Member, the Frenchman and the Ravenscrag Formations. Overgrowths on zircon were found only occasionally.

Inclusions are very common in all types of zircon, especially the colorless variety. Inclusions consist of (a) elongate euhedral apatite or rutile crystals randomly oriented or preferentially oriented parallel to the zircon (c-axis) length: (b) regular- to irregular-shaped gas or liquid inclusions of brown to reddish-brown color; and (c) opaque inclusions.

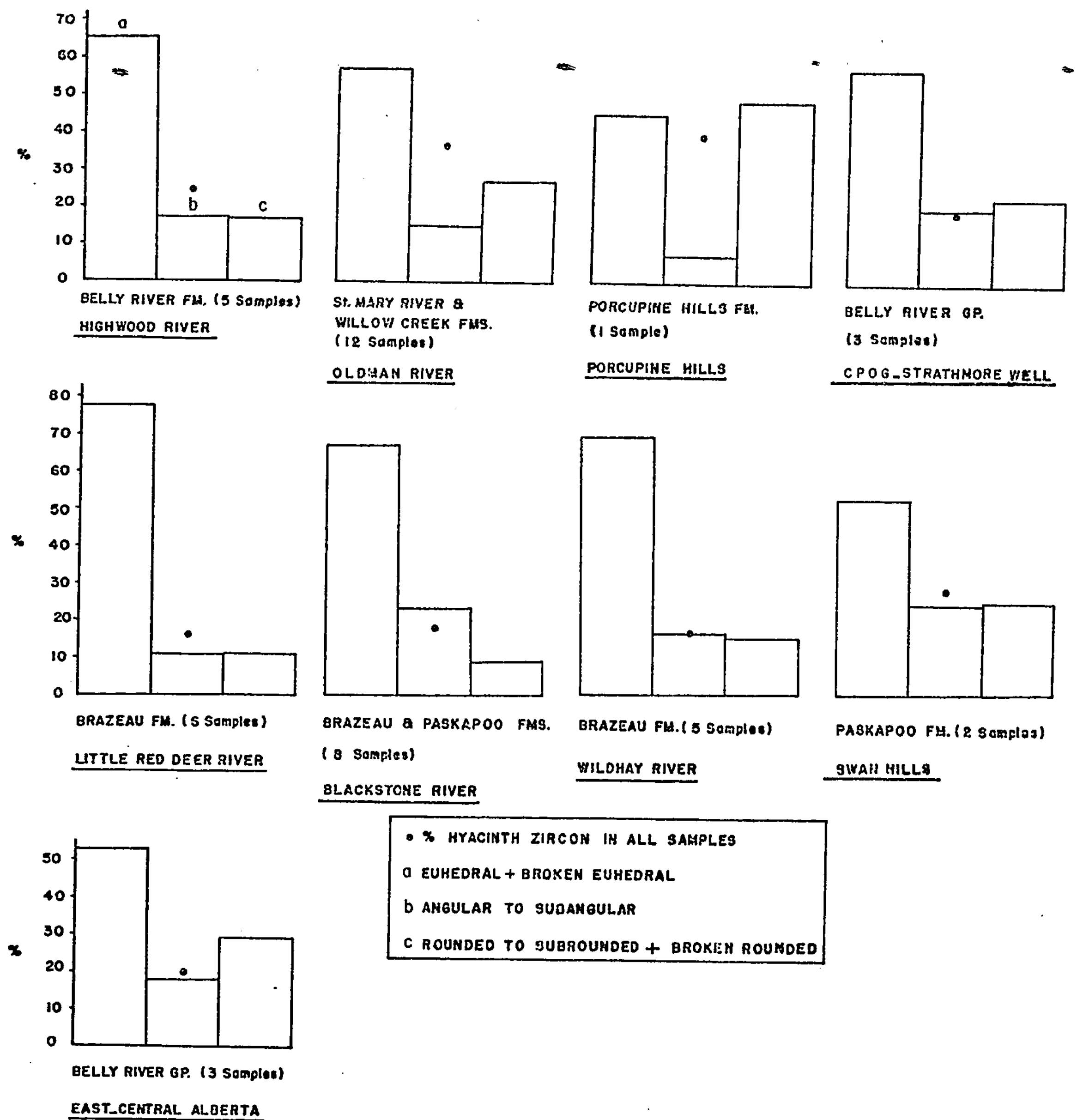


Fig. 9. Shape varieties of zircon and relative abundance of hyacinth.

Poldervaart made an extensive study of detrital zircon in the United States and South Africa and noted that "zircons of sediments are predominantly grains with rounded terminations, or angular fragments, but sharply pointed, euhedral crystals are generally subordinate" (1955, p. 441). Results of the present study suggest the contrary since sharp, euhedral zircon crystals are very common. Poldervaart noted that the excellent resistance of zircon is due more to chemical stability than to resistance to abrasion. Freise (1931, in Poldervaart, 1955, p. 437) found that zircon has less abrasive resistance than epidote, garnet, staurolite, rutile and tourmaline, and is of the same order of resistance as quartz and apatite. Therefore, well-rounded zircon may not necessarily have undergone "several" cycles of transportation and sedimentation although it is still likely. However, as soon as a zircon crystal or angular grain becomes rounded (possibly through one or two cycles) it becomes more resistant to chemical etching.

Rounded zircon predominates in late differentiates and extrusive calc-alkalic rocks, while bipyramidal euhedral zircon is common in more extreme alkaline rocks (Poldervaart, 1956, p. 550). The hyacinth zircon of this study could have its ultimate source in the Precambrian crystalline rocks of British Columbia-Montana-Idaho-Alberta, to the south and southwest of the study area. The immediate source of some of the hyacinth could have been in the Upper Paleozoic sediments flanking the Omineca Geanticline and/or the older Mesozoic rocks of the ancestral Rocky Mountains.

Other Non-Opaque Non-Micaceous Heavy Minerals: Non-opaque heavy minerals observed as minor and sporadic occurrences, but some with important provenance value are tremolite-actinolite, andalusite, staurolite, kyanite, zoisite, brookite, anatase, glaucophane pyroxene, monazite, spinel and xenotime. Some identifications of the latter three heavy minerals are considered questionable.

Biotite: Biotite is more abundant in southwestern Alberta than elsewhere in the study area (Fig. 10). Its abundance from one sample to another is haphazard, and depends to a large extent on the hydrodynamic conditions during deposition. Values range from 0 to about 43 grains associated with 100 grains of other non-opaque heavy minerals.

Biotite occurs as irregular, flaky grains but six-sided crystals are not uncommon. Four color varieties were recognized: brown, reddish-brown, red, and, rarely, olive to green, in that order of abundance. There is no recognizable trend in the distribution of these color varieties (Fig. 11) throughout the study area except for the decrease in the relative percentage of the red biotite northward along the Foothills. A few grains were observed to be partially altered to chlorite.

Lerbekmo (1963, p. 68) noted that, in the Belly River Formation of the southern Foothills, the reddish-brown variety outnumbered the brown variety by a ratio of 3:2. Lerbekmo did not report any red biotite. Chi (1966, p. 57) recognized brown and red varieties in the Scollard Member, the Frenchman and the Ravenscrag Formations. He noted that brown biotite is the more

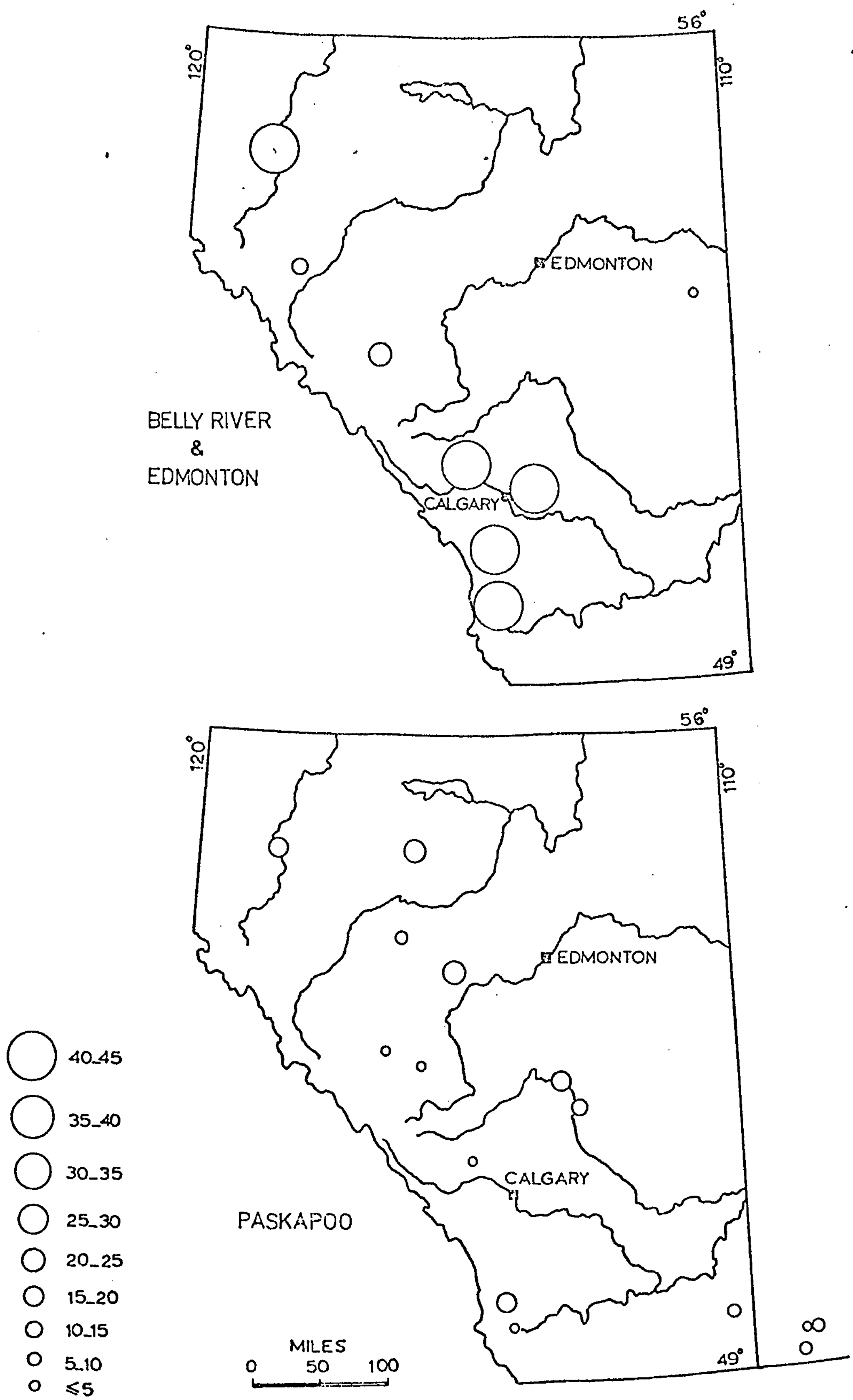


Fig. 10. Areal variation of biotite. Numerals refer to number of biotite grains associated with 100 non-opaque heavy mineral grains.

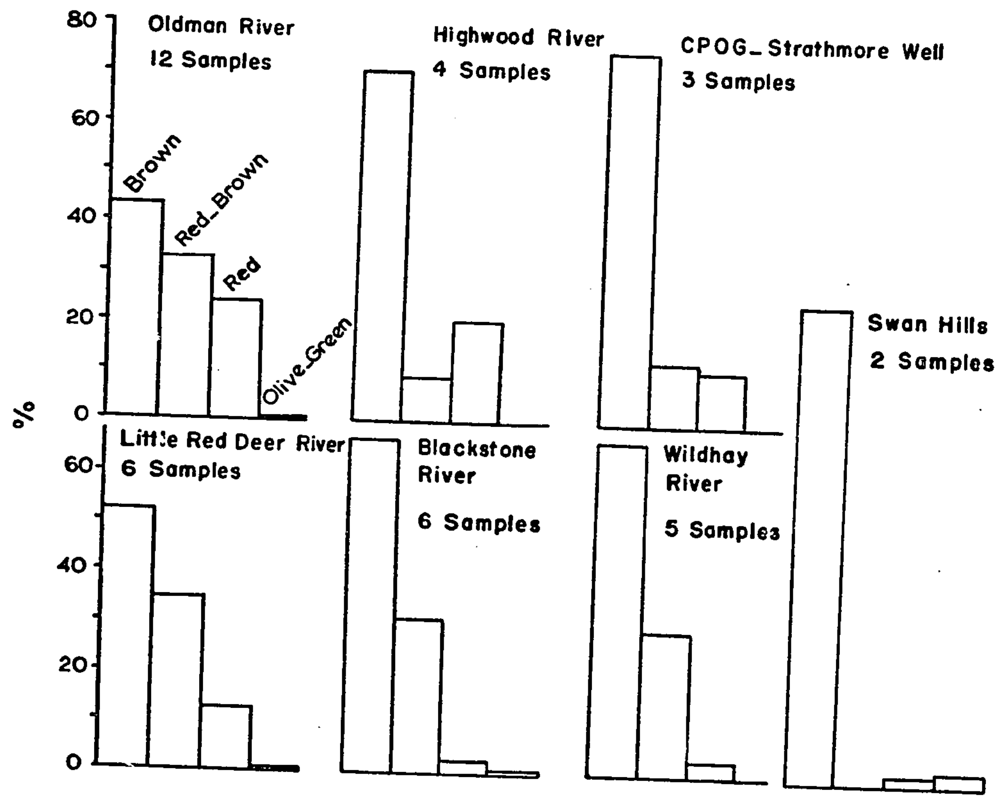


Fig. 11. Color varieties of biotite.

abundant variety. McLean (1969, p. 259) recognized brown to olive-brown, reddish-brown to orange and brownish-green to greenish-brown biotite color varieties in the Belly River Group of the Plains. Since color grouping by the previous workers does not coincide with that of the present work, quantitative treatment of the color varieties is not possible.

Biotite commonly occurs in acidic to intermediate igneous rocks and is an important constituent of such metamorphic rocks as schist, gneiss and hornfels (Berry and Mason, 1959, p. 514). Lerbekmo (1963, p. 68) attributed the reddish-brown variety to regionally metamorphosed rocks and the brown variety to both plutonic and volcanic rocks.

Opaque Heavy Minerals: Opaque heavy minerals are most abundant in the southern Foothills and in the Plains west of the Swan Hills (Fig. 12). In abundance they range from 47 to 320 grains associated with 100 grains of non-opaque heavy minerals (except biotite). Distribution of the opaques from one sample to another is variable, probably due to the diagenetic nature of some opaque materials.

They were subdivided into four varieties on the basis of color: blacks (the most abundant variety), made up of ilmenite, magnetite and chromite; whitish (second in abundance), made up mostly of leucoxene; reds, mainly hematite and some hematized hornblende; and pyrite, the least common variety.

Blatt (1967) and Blatt *et al.*,(1972, p. 289) draws attention to the potential use of opaque minerals in provenance determination. He points out that sedimentary petrologists have neglected detailed study of opaque heavy

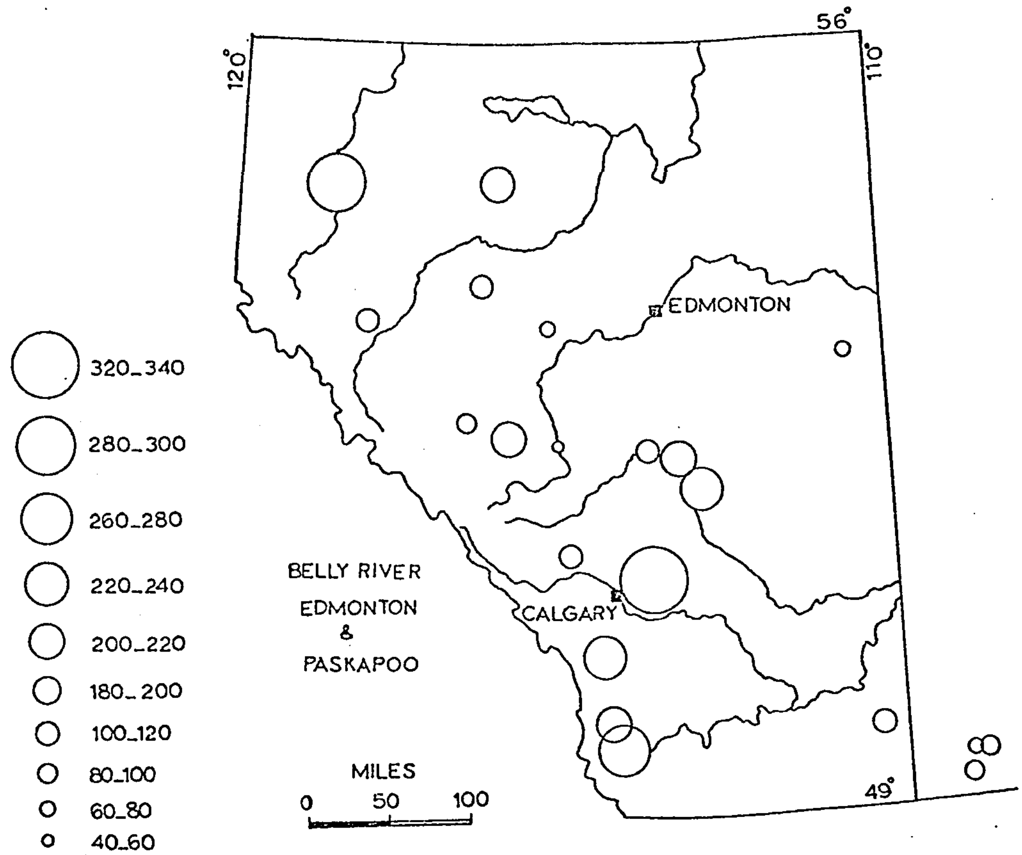


Fig. 12. Areal variation of opaque heavy minerals. Numerals refer to number of opaque grains associated with 100 non-opaque, non-micaceous heavy mineral grains.

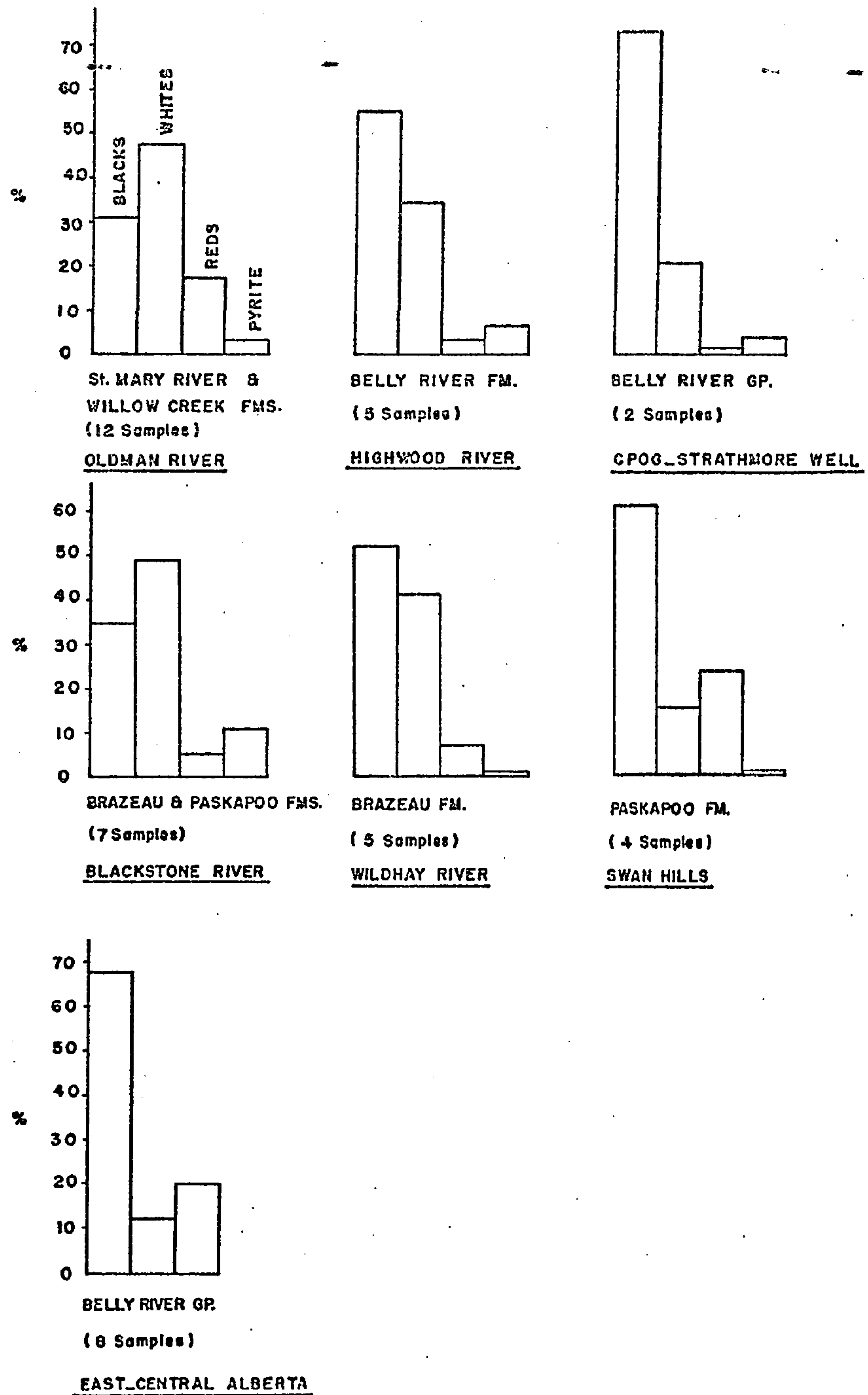


Fig. 13. Color varieties of opaque minerals.

minerals because of the time consuming preparatory techniques and the fact that few sedimentary petrologists have had training in ore microscopy. Studies of opaque minerals of suspected source areas are lacking, therefore a dual study is required before much information can be gained by study of the opaques in the detrital rocks.

Ilmenite and magnetite come from igneous rocks, especially basic and ultrabasic types (Milner, 1962, p. 129). The percentage of titanium in magnetite coexisting with ilmenite was used by Abdullah (1965, in Blatt et al., 1972, p. 290) "... as a criterion of the igneous or metamorphic parentage of the grain and also as an indicator of the metamorphic temperature at which the grain was formed". Leucoxene is usually a decomposition product of ilmenite (Milner, 1962, p. 137) and forms largely in situ. Hematite and most of the pyrite of the present study are of secondary origin(diagenetic).

B. Distribution of Heavy Minerals

1. Areal Distribution

In the previous section, distribution of the heavy minerals was discussed in general terms. The present discussion deals with the composition and areal distribution of the heavy minerals of the lithostratigraphic units of the study area. All correlative lithostratigraphic units are dealt with under one heading resulting in four such groups. From older to younger, they are as follows:

(a) Belly River Group/Formation and Equivalents: This grouping includes the Belly River Group and the lower part of the Wapiti Formation of the Plains, the Belly River Formation of the southern Foothills and the lower part of the Brazeau Formation of the central and northern Foothills.

(b) Edmonton Group/Formation and Equivalents: These include the Edmonton Group of the central Plains, the middle part of the Wapiti Formation (Allan and Carr's, 1946 members B, C & D) of the northwestern Plains, the St. Mary River, Whitemud and Battle Formations of southwestern Alberta and the upper part of the Brazeau Formation of the central and northern Foothills.

(c) Scollard Member and Equivalents: Lithostratigraphic units included here are the Scollard Member of the Paskapoo Formation of the central Plains, the upper part of the Wapiti Formation (member E) of the northwestern Plains, the Frenchman Formation of the Cypress Hills, the lower part of the Willow Creek Formation of southwestern Alberta and the basal 600 feet of the Paskapoo Formation of the central Foothills.

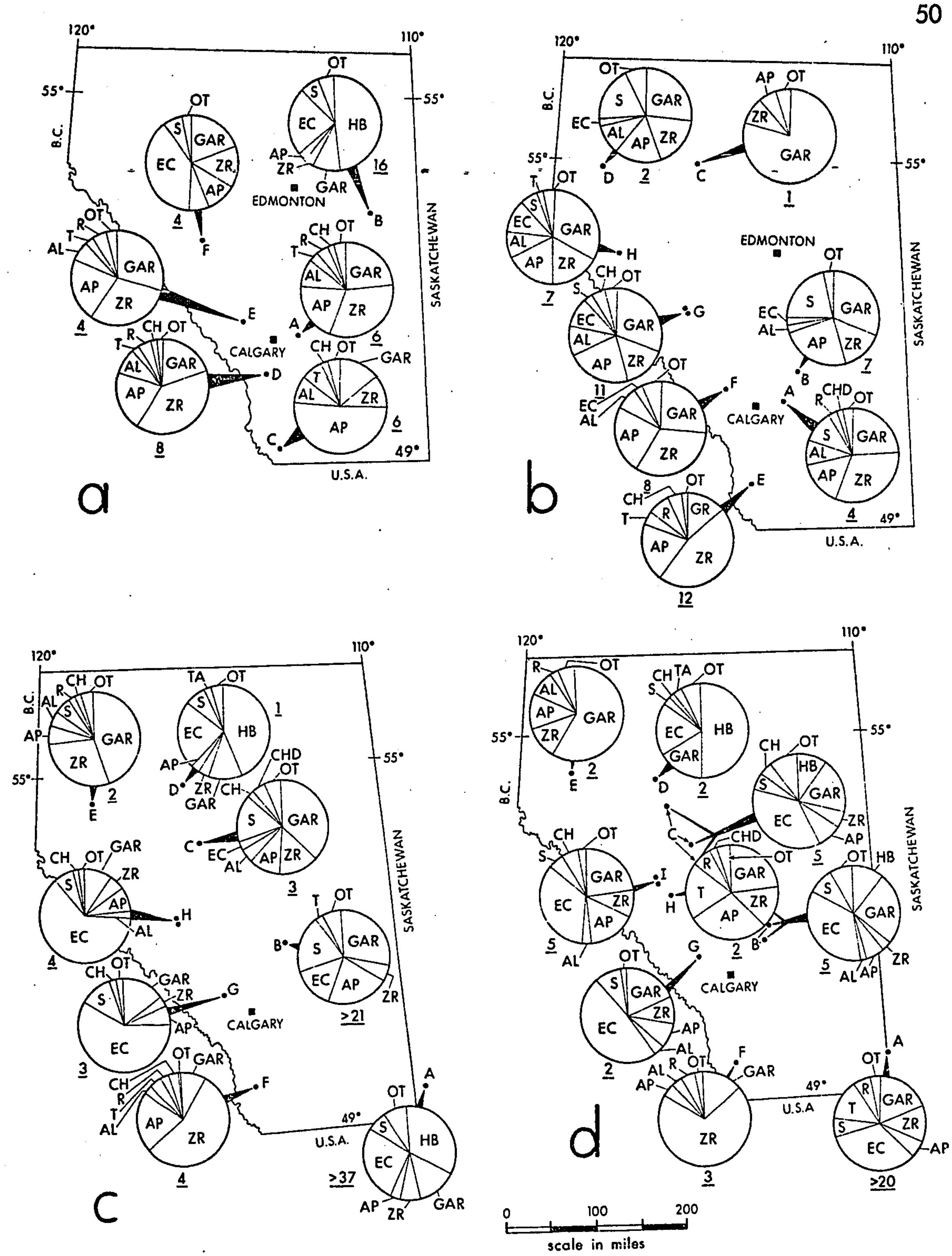


Fig. 14. Areal distribution of non-opaque, non-micaceous heavy minerals. a. Belly River Gp.; b. Edmonton Gp.; c. Scollard Mbr.; d. Paleocene. HB: Hornblende; GAR: Garnet; ZR: Zircon; AP: Apatite; AL: Allanite; EC: Epidote-Clinozoisite; S: Sphene; T: Tourmaline; R: Rutile; CH: Chlorite; CHD: Chloritoid; TA: Tremolite-Actinolite; OT: Others. Underlined numerals refer to number of samples.

(d) Paleocene lithostratigraphic units: These include the "old"-Paskapoo of the northwestern and central Plains, the Ravenscrag Formation of the Cypress Hills, the upper part of the Willow Creek Formation, the Porcupine Hills Formation of southwestern Alberta and all the Paleocene strata within the Paskapoo Formation of the central Foothills.

Ideally, discussion of areal variation of heavy minerals is optimal when dealing with synchronous sediments of short time span (i.e. geologically instantaneous), such as the case of Recent sediments. As we are here dealing with large thicknesses of sediment representing considerable geologic time, even when subdivided as above, areal trends of heavy mineral variation may very likely be affected by stratigraphic trends. Discussion of areal trends is confined to heavy minerals making up proportions of at least two per cent of the total suite. For brevity the symbol NOHM-B is here used to mean non-opaque heavy minerals excluding biotite. The reader is referred to Figure 14 and Table 3.

Belly River Group/Formation and Equivalents: The Belly River Group at the CPOG-Strathmore well in the southwestern Plains is about 850 feet thick. It is divided into the Oldman and the underlying Foremost Formations of approximately equal thicknesses. Slightly over 75% of the NOHM-B assemblage consists of zircon, garnet and apatite (Fig. 14a-A). Of less frequency are allanite, rutile, tourmaline (significantly more abundant in the Oldman Formation) and chlorite (decreases upward). Others that are found in lesser amounts are sphene (confined to the Foremost Formation), chloritoid, anatase,

Table 3. Areal distribution of non-opaque, non-micaceous heavy minerals. Ac. Actinolite; Ag. Augite; Al. Allanite; An. Anatase; And. Andalusite; Ap. Apatite; Br. Brookite; Cd. Corundum; Ch. Chlorite; Chd. Chloritoid; Dm. Dumortierite; Dp. Diopside; EC. Epidote-Clinozoisite; En. Enstatite, Ep. Epidote; Gar. Garnet; Gp. Glaucophane; Hb. Hornblende; Hy. Hypersthene; Id. Idocrase; Ky. Kyanite; M. Monazite; Py. Pyroxene; R. Rutile; S. Sphene; Sp. Spinel; St. Staurolite; T. Tourmaline; T-A. Tremolite-Actinolite; Tm. Tremolite; Tz. Topaz; Xe. Xenotime; Zo. Zoisite; Zr. Zircon.

	LOCATION	LITHOSTRAT. UNIT	THICKNESS EXAMINED (FEET)	MAJOR NON-OPAQUE HEAVY MINERALS(%)	MINOR NON-OPAQUE HEAVY MINERALS	REFERENCE FIGURE
PALEOCENE	Cypress Hills	Ravenscrag Fm.	225	EC=33,Gar=19,T=14,Zr=13, S=6,R=5,Ap=5.	Al, Ch, And, Zo, T-A, St, Chd, Br, Py.	14d- A
	Red Deer River Valley	Paskapoo Fm. (Paleocene)	Approx. 200	EC=36,Gar=25,Hb=11,S=9, Ap=7,Zr=3,Al=2.	T, R, T-A, Ch, Sp, And, Py, An, Ky, Br.	14d- B
	Western Plains	" "	?	EC=38,Gar=19,Hb=10,Ap=9, S=6,Zr=5,Ch=4.	Al, Chd, R, T, Zo, T-A, Sp, St.	14d- C
	Swan Hills	" "	?	Hb=50,EC=18,Gar=17,T-A=3, S=2,Ch=2.	T, Ap, Zr, Chd, Zo, Al, Tz, St, Dp.	14d- D
	Northwestern Plains	" "	?	Gar=60,Ap=12,Zr=11,Al=9, R=3.	Ep, T, Ch, S, St, Hb.	14d- E
	Porcupine Hills (west)	Porcupine Hills Fm.	240	Zr=70,Gar=13,R=5,Ap=4, Al=4.	S, T, And, Chd, Ch.	14d- F
	Little Red Deer River	Paskapoo Fm. (Paleocene)	350	EC=49,Gar=18,Zr=10,Ap=9, S=8,Al=4.	T, R.	14d- G
	N. Sask. River.	" "	4000 two samples	Ap=29,Gar=23,T=20,Zr=14, R=7,Chd=2.	Ch, Sp, An, Al, Ep.	14d- H
	Blackstone River & Colt Creek	" "	500 + 650	EC=35,Gar=22,Ap=17,Zr=9, Ch=6,S=5,Al=3	R, T, Chd, And, St, Sp.	14d- I
SCOLLARD MEMBER	Cypress Hills	Frenchman Fm.	375	Hb=34,EC=27,Gar=14,Zr=7, S=6,Ap=4.	T, R, T-A, Ch, And, St, Chd, Gp, Py, Br.	14c- A
	Red Deer River Valley	Scollard Member	Approx.250	Gar=29,Ap=23,S=19,EC=14 Zr=5,T=2.	Al, R, Ch, And, St, Chd, Sp, Py, Br, Hb.	14c- B
	Drayton Valley to Whitecourt	Scollard Member	?	Gar=37,S=16,Zr=14,Ap=11, Chd=5,Al=5,EC=3,Ch=2.	R, Ch, St, Ky, Hb, Tz, And, An, Ep, Ac, Xe.	14c- C
	Swan Hills	" "	one sample	Hb=44,EC=24,Gar=12,S=7, Ap=4,Zr=3,T-A=2.	Al, R, T, St, Ch, Gp.	14c- D
	Northwestern Plains	" "	?	Gar=45,Zr=29,Ap=6,S=6, Al=5, R=2.	T, Chd, Ep, And, Id.	14c- E
	Oldman River	lower Willow Creek Fm.	Approx. 700	Zr=56,Ap=21,Gar=8,T=5, Ch=4,Al=3,R=2.	Ep, An.	14c- F
	Little Red Deer River	lower part of Paskapoo Fm.	600	EC=59,Gar=15,S=11,Ap=6 Zr=3,Ch=2.	Al, T, R, Hb, Sp, Ch, An.	14c- G
	Blackstone River & Colt Creek	" " "	600 + 600	EC=64,Gar=10,Ap=8,S=7, Zr=5,Al=2,Ch=2.	R, T, Chd, St, Ky, Sp.	14c- H
EDMONTON GROUP	CPOG Strathmore Well	Horseshoe Canyon Fm.	900	Zr=33,Gar=23,Ap=16,S=11, Al=9,R=3,Chd=2.	T, Tz, St, Ch, Cz, Ep, An, Ant, Dm.	14b- A
	Red Deer River Valley	Edmonton Gp.	800	Gar=31,Ap=25,S=21,Zr=14, Al=3,EC=3.	T, Ch, Chd, St, R, And, Sp, Tm, An.	14b- B
	Swan Hills	upper part of Wapiti Fm.	one sample	Gar=79,Zr=9,Ap=6.	Al, R, Chd, T, Dm.	14b- C
	Northwestern Plains	upper part of Wapiti Fm.	two samples	Gar=26,S=19,Zr=18,Ap=17, Al=10,EC=2.	T, St, Chd, R, Sp.	14b- D
	Oldman River	St. Mary River Fm.	2900	Zr=47,Ap=20,Gar=13,R=7, Ch=5,T=4.	Al, Chd, An, Tz, M, Sp, S, Ep.	14b- E
	Little Red Deer River	Edmonton Fm.	2500	Zr=33,Gar=26,Ap=24,Al=8, EC=3.	Ch, S, T, R, And, An, Ky, M.	14b- F
	Blackstone River & Colt Creek.	upper Brazeau Fm.	3200	Gar=30,Ap=22,Zr=16,Al=11, EC=10,Ch=5,S=3.	R, T, Chd, Zo, St, An, M, Dp, Sp.	14b- G
	Wildhay River	" "	3000	Gar=35,Zr=18,Ap=15,EC=11, Al=9.	R, Ch, Zo, Chd, St, An, Ag, And, Tz, Xe, Tm, Cd, Hy, Sp.	14b- H
BELLY RIVER GROUP	CPOG Strathmore Well	Foremost & Oldman Fms.	750	Zr=33,Gar=23,Ap=20,Al=10, R=4,T=3,Ch=2.	S, Chd, An, Br, En, Xe, St, Hb, Ep.	14a- A
	East-Central Alberta	Belly River Gp.	Approx.700	Hb=48,EC=23,Gar=10,S=7, Ap=3,Zr=3.	Al, R, Ch, T, St, Zo, T-A, Hy, En, Chd, Ky, And, Cd.	14a- B
	Drywood River	Belly River Fm.	1900	Ap=52,Gar=14,Zr=11,Al=9, T=7,Ch=2.	R, And, Zo, Sp, Chd, Ep, An, Py, Cd.	14a- C
	Highwood River	" " "	1800	Zr=40,Ap=20,Gar=20,Al=9, R=5,Ch=3,T=2.	Chd, Ep, M, Cd, S, An, Sp, Tz, St, Br.	14a- D
	Little Red Deer River	" " "	1100	Zr=30,Gar=30,Ap=22,Al=6, R=5,T=3.	Ch, Chd, And, Ep, An, Tz, Xe, S.	14a- E
	Blackstone River	lower Brazeau Fm.	1000	EC=40,Gar=19,Zr=14,Ap=11, Al=7,S=7.	Ch, T, R, An, Chd, Zo, St, Xe.	14a- F

brookite (?), enstatite, xenotime (?), staurolite, hornblende and epidote.

In east-central Alberta the Belly River Group consists of a lower deltaic to shallow marine Foremost Formation (made up of several tongues of sandstone and shale) and an upper fluvial Oldman Formation. Hornblende is generally absent in the Oldman Formation, but makes up about 75% of the NOHM-B assemblage of the underlying Foremost Formation (Fig. 14a-B). Epidote-clinozoisite make up 25% of the NOHM-B of the entire group, being more abundant in the Oldman Formation. Garnet averages 10%, sphene 7%, and zircon and apatite each average 3%. All of the latter four minerals are more abundant in the Oldman Formation. Other heavy minerals, of minor importance, are allanite (more abundant in the Oldman Formation), rutile, chlorite, tourmaline, staurolite, zoisite, tremolite-actinolite, hypersthene, enstatite, chloritoid, kyanite, andalusite and corundum. There is an indication that hornblende of the Foremost Formation is more abundant in sandstone that is stratigraphically close to either underlying or overlying marine shale. This may indicate that the hornblende is marine transported, at least in the area where the samples were collected.

In the southern Foothills, along the Drywood River, the Belly River Formation measures about 2,250 feet (Lerbekmo, 1963). Here apatite makes up 52% of the NOHM-B assemblage (Fig. 14a-C). Garnet accounts for 14%, zircon 11%, allanite 9%, tourmaline 7% and chlorite 2%. Other minerals of minor importance are rutile, andalusite, zoisite, spinel, chloritoid, epidote, anatase, pyroxene and corundum.

Farther north along the southern Foothills at the Highwood River, the Belly River Formation has a minimum thickness of about 1,900 feet. Here zircon constitutes about 40% of the NOHM-B assemblage, apatite 20%, garnet 20%, allanite 9%, rutile 5%, chlorite 3% and tourmaline 2% (Fig. 14a-D). Other NOHM-B of minor occurrence are chloritoid, epidote, monazite (?), corundum, sphene, anatase (?), spinel (?), topaz, staurolite and brookite.

The Belly River Formation on the Little Red Deer River in the central Foothills is about 1,100 feet thick. Here zircon and garnet, of equal abundance, make up about 60% of the NOHM-B assemblage (Fig. 14a-E). Apatite makes up 22%, allanite 6%, rutile 5% and tourmaline 3%. Other NOHM-B are chlorite, chloritoid, andalusite, epidote, anatase, topaz, xenotime (?) and sphene.

Farther north in the central Foothills, along the Blackstone River, beds equivalent to the Belly River Formation make the lower 1,000 feet of the Brazeau Formation. Here epidote-clinozoisite constitute 40% of the NOHM-B assemblage (Fig. 14a-F), while garnet constitutes 19%, zircon 14%, apatite 11%, allanite 7%, and sphene 7% of the assemblage. Other NOHM-B are chlorite, tourmaline, rutile, anatase, chloritoid, zoisite, staurolite and xenotime(?).

With the above data (Fig. 14a) and some semiquantitative data from McLean (1971), general areal trends in variation of the NOHM-B across the study area during Belly River time can be outlined as follows:

(1) Hornblende of important proportions is confined to east-central Alberta and the adjacent areas of Saskatchewan. It is rare to absent in the rest of the Plains and the Foothills.

(2) Epidote-clinozoisite is confined to the northern, eastern and southeastern parts of the study area.

(3) Sphene seems to follow fairly closely the trend shown by epidote-clinozoisite.

(4) Apatite shows a relative decrease northward along the Foothills and northeastward towards east-central Alberta. This trend is strongly affected by the diluting effect of epidote-clinozoisite and/or hornblende.

(5) Zircon shows a significant relative decrease from west to east and northeast, from the Foothills to the Plains. As for apatite, this trend is also affected by the dilution by epidote-clinozoisite and/or hornblende.

(6) There is a slight but definite decrease in allanite northwestwards along the Foothills. From west to east allanite also decreases in relative abundance to become very minor to absent in southern, southeastern, and east-central Alberta and adjacent areas of Saskatchewan.

(7) Tourmaline decreases northwestward along the Foothills and northeastward towards east-central Alberta. McLean's data (1971, Fig. 28, p. 62) confirm this trend.

(8) Rutile of significant quantity is confined to the Highwood River, Little Red Deer River and the CPOG-Strathmore area, all within a 30-mile radius from the city of Calgary (Fig. 14a, A, C, D and E).

<u>Edmonton Group/Formation and Equivalents:</u> At the CPOG-Strathmore well, the core begins in the Horseshoe Canyon Formation and a total of 1,041

feet of this formation were recovered. Here zircon comprises 33% of the NOHM-B assemblage, garnet 23%, apatite 16%, sphene 11%, allanite 9%, rutile 3% and chloritoid 2% (Fig. 14b-A). Other NOHM-B are tourmaline, topaz, staurolite, chlorite, clinozoisite, epidote, anatase, anthophyllite and dumortierite (?).

Along the Red Deer River Valley of the Plains, a composite section of the Edmonton Group in the Drumheller area measures about 800 feet (Irish, 1970). Here garnet constitutes 31% of the NOHM-B assemblage, apatite 25%, sphene 21%, zircon 14%, allanite 3% and epidote-clinozoisite 3% (Fig. 14b-B). Other NOHM-B are tourmaline, chlorite, chloritoid, staurolite, rutile, andalusite, spinel, tremolite (?) and anatase.

Farther north, in the Swan Hills area, only one sample was available for study. The NOHM-B assemblage here is composed of 79% garnet, 9% zircon and 6% apatite (Fig. 14b-C). Other NOHM-B are allanite, rutile, chloritoid, tourmaline and dumortierite (?).

To the west of the Swan Hills area, in the northwestern Plains south of the city of Grande Prairie, only two samples were available for study. Garnet forms 26% of the NOHM-B assemblage, sphene 19%, zircon 18%, apatite 17%, allanite 10%, epidote-clinozoisite 2% (Fig. 14b-D). Other NOHM-B are tourmaline, staurolite, chloritoid, chlorite, rutile and spinel.

In the southern Foothills, the St. Mary River Formation measures approximately 3,200 feet. Along the Oldman River of this area 2,900 feet of this formation were measured. Zircon makes up 47% of the NOHM-B of this section. Apatite makes up about 20%, garnet 13%, rutile 7%, chlorite 5% and tourmaline 4% (Fig. 14b-E). Others are allanite, chloritoid, anatase, topaz, monazite (?), spinel, sphene and epidote.

To the northwest, along the Little Red Deer River, beds correlative with the Edmonton Group of the Plains measure about 2,500 feet. Here zircon makes up 33% of the NOHM-B assemblage, garnet 26%, apatite 24%, allanite 8%, epidote-clinozoisite 3% (Fig. 14b-F). Other NOHM-B are chlorite, sphene, tourmaline, rutile, andalusite, anatase, kyanite, monazite (?) and chamosite (?).

In the Blackstone River and Colt Creek area (Fig. 14b-G), the beds equivalent to the Edmonton Group and the Bearpaw Formation of the Plains measure about 3,200 feet. Here garnet forms 30% of the NOHM-B assemblage, apatite 22%, zircon 16%, allanite 11%, epidote-clinozoisite 10%, chlorite 5% and sphene 3% (Fig. 14b-G). Others include rutile, tourmaline, chloritoid, zoisite, staurolite, anatase, monazite (?), diopside and spinel.

At the Wildhay River, in the southern part of the northern Foothills (Fig. 14b-H), the 3,000 feet measured are probably all equivalent to the Bearpaw Formation plus the Edmonton Group of the Plains. At this locality, garnet constitute 35% of the NOHM-B, zircon 18%, apatite 15%, epidote-clinozoisite 11%, allanite 9%, sphene 6% and tourmaline 2%. Others include rutile, chlorite, zoisite, chloritoid, staurolite, anatase, aegirine, andalusite, topaz, xenotime, tremolite, corundum, hypersthene and spinel.

In the Cypress Hills, in the southeastern part of the study area, the upper part of the Edmonton Group is represented by the Battle, Whitemud and Eastend Formations. Here Fraser et al (1935, in McLean, 1971, Table 13, p. 67) found hornblende "common". Epidote was found to be "common" in the Eastend Formation, but "minor" in the Whitemud Formation.

The areal trends in the heavy mineral distribution of the Edmonton Group and its equivalents can be summarized as follows:

(1) Zircon decreases northwestwards along the Foothills. It also decreases from west to east and northeast, from the Foothills towards the Plains.

(2) Garnet increases northwestwards along the Foothills, being more abundant in the northern and central Foothills than the southern Foothills. In southern Alberta, garnet increases from west to east.

(3) Apatite in the central localities is more abundant than in either the northern or southern localities.

(4) Epidote-clinozoisite increases northwestwards along the Foothills. They are minor to absent in the southern localities; and decrease eastwards from the Foothills to the Plains.

(5) Rutile in important quantities is confined to the southern localities.

(6) Tourmaline is significantly more abundant in the Foothills, especially in the southern part.

(7) Allanite appears to be significantly more abundant in the Foothills and the immediately adjacent Plains than in the Plains farther east. Along the Foothills, allanite increases northwestward.

(8) Sphene of importance seems to be confined to a belt that runs northwestward including localities A, B, G, H and D of Figure 14b.

(9) According to data in McLean (1971), hornblende is confined to southeastern Alberta, but it is not quantitatively clear in what abundance this hornblende occurs.

Scollard Member and Equivalents (Lance): In the Cypress Hills of southeastern Alberta Lance age is represented by the 375 feet thick Frenchman Formation (Chi, 1966, p. 7). Chi's heavy mineral data show that the NOHM-B assemblage consists of 34% hornblende, 27% epidote-clinozoisite-zoisite, 14% garnet, 7% zircon, 6% sphene and 4% apatite (Fig. 14c-A). Others are tourmaline, rutile, tremolite-actinolite, chlorite, andalusite, staurolite, chloritoid, glaucophane, pyroxene and brookite.

In the Red Deer River Valley, east of the city of Red Deer, the NOHM-B assemblage of the Scollard Member consists of 29% garnet, 23% apatite, 19% sphene, 14% epidote-clinozoisite-zoisite, 5% zircon and 2% tourmaline (Fig. 14c-B). Other NOHM-B are allanite, rutile, chlorite, andalusite, staurolite, chloritoid, spinel, pyroxene, brookite and hornblende.

In the Plains to the west of the city of Edmonton, from Drayton Valley north to the town of Whitecourt at the southern edge of the Swan Hills, the NOHM-B assemblage of Scollard Member correlative beds consists of 37% garnet, 16% sphene, 14% zircon, 11% apatite, 5% chloritoid, 5% allanite, 3% epidote-clinozoisite and over 2% chlorite (Fig. 14c-C). Others are rutile, chlorite, staurolite, kyanite, hornblende, topaz, andalusite, anatase, enstatite (?), actinolite and xenotime (?).

On the north side of the Swan Hills only one sample was available from the Scollard Member (Fig.14c-D). The NOHM-B assemblage of this sample is constituted by 44% hornblende, 24% epidote-clinozoisite, 12% garnet, 7% sphene, 4% apatite, 3% zircon and 2% tremolite-actinolite. Others are allanite, rutile, tourmaline, staurolite, chlorite and glaucophane.

In the northwestern Plains, west of the Swan Hills, hornblende is almost non-existent and the NOHM-B assemblage of correlative beds consists of 45% garnet, 29% zircon, 6% apatite, 6% sphene, 5% allanite, over 2% rutile and 2% chlorite (Fig. 14c-E). Other NOHM-B are tourmaline, chloritoid, epidote, andalusite, chamosite and idocrase (?).

In the southern Foothills, along the Oldman River (Fig. 19F), the Scollard Member correlative is the lower Willow Creek Formation. Here the NOHM-B assemblage consists of 56% zircon, 21% apatite, 8% garnet, 5% tourmaline, 4% chlorite, 3% allanite and over 2% rutile. Other NOHM-B are epidote and anatase.

At the Little Red Deer River in the central Foothills (Fig. 14c-G). The Scollard Member correlative beds are probably represented by approximately the basal 600 feet of the Paskapoo Formation. Here epidote-clinozoisite makes up 59% of the NOHM-B assemblage, garnet 15%, sphene 11%, apatite over 6%, zircon over 3% and chlorite 2%. Other NOHM-B are allanite, tourmaline, rutile, hornblende, spinel, chlorite and anatase.

In the northern part of the central Foothills, along the Blackstone River and Colt Creek (Fig. 14c-H), the Scollard Member correlative beds are also apparently represented by the basal 600 feet of the Paskapoo Formation. The NOHM-B assemblage of the beds consists of 64% epidote-clinozoisite, 10% garnet, over 8% apatite, 7% sphene, 5% zircon, over 2% allanite and 2% chlorite. Other NOHM-B are rutile, tourmaline, chloritoid, staurolite, kyanite and spinel.

When discussing the areal trends in the distribution of the NOHM-B below, the diluting effect of floods of epidote-clinozoisite and hornblende should be born in mind, and therefore these trends are only relative:

(1) Hornblende seems to be confined to the southeastern part of Alberta and to the northern part of the Swan Hills.

(2) Garnet is relatively more abundant in the Plains than in the Foothills. In the Plains (excluding sample of Fig. 14c-D) garnet increases northward and northwestward.

(3) Apatite is more abundant in the southern and central than in the northern parts of the study area.

(4) Sphene is absent only in the southern Foothills.

(5) Tourmaline is of important occurrence only in the Red Deer River Valley and the Oldman River of the southern Foothills (Fig. 14c, B and F).

(6) Allanite, rutile and chlorite are important only in the western

parts of the study area.

(7) Zircon does not show any clear trend. However, it is more abundant in the southwestern and western parts of the study area.

Paleocene: In the Cypress Hills of southeastern Alberta the Paleocene is represented by the 225 feet thick Ravenscrag Formation (Fig. 14d-A). The NOHM-B assemblage consists of 33% epidote-clinozoisite-zoisite, 19% garnet, 14% tourmaline, 13% zircon, 6% sphene, over 5% rutile and 5% apatite. Other NOHM-B are allanite, chlorite, andalusite, tremolite-actinolite, staurolite, chloritoid, brookite and pyroxene (Chi, 1966, p. 60).

Along the Red Deer River Valley (Fig. 14d-B) the NOHM-B assemblage of the Paleocene Paskapoo consists of 36% epidote-clinozoisite, 25% garnet, 11% hornblende, 9% sphene, 7% apatite, 3% zircon and 2% allanite. Other NOHM-B are tourmaline, rutile, tremolite-actinolite, chlorite, spinel, andalusite, pyroxene, anatase, kyanite (?) and brookite (?). In this area, just east of the city of Red Deer, two of the Paleocene samples contin no hornblende and consist mainly of epidote-clinozoisite garnet.

West and northwest of the Red Deer River Valley, in the Rocky Mountain House-Drayton Valley-Mcleod River area (Fig. 14d-C) the NOHM-B assemblage consists of 38% epidote-clinozoisite, 19% garnet, 10% hornblende, 9% apatite, 6% sphene, 5% zircon and 4% chlorite. Other NOHM-B are allanite, chloritoid, rutile, tourmaline, zoisite, tremolite-actinolite, spinel, staurolite and kyanite.

In the Swan Hills area (Fig. 14d-D) the NOHM-B assemblage is made up of 50% hornblende, 18% epidote-clinozoisite, 17% garnet, 3% tremolite-actinolite, over 2% sphene and 2% chlorite. Other NOHM-B are tourmaline, apatite, zircon, chloritoid, zoisite, allanite, topaz, staurolite and diopside.

In the Plains west of the Swan Hills (Fig. 14d-E) the NOHM-B assemblage of the Paleocene rocks consists of 60% garnet, 12% apatite, 11% zircon, 9% allanite and 3% rutile. Other NOHM-B are epidote, tourmaline, chlorite, sphene, staurolite and hornblende.

Along the Oldman River of the southern Foothills (Fig. 14d-F) a 240 foot section in the Porcupine Hills Formation about 1,100 feet above its base, probably represented younger Paleocene than in those sections discussed above. The NOHM-B assemblage of sandstones from this section is composed of 70% zircon, 13% garnet, 5% rutile, over 4% apatite and 4% allanite. Other NOHM-B are sphene, tourmaline, andalusite, chloritoid and chlorite.

Along the Little Red Deer River of the southern part of the central Foothills (Fig. 14d-G) the upper 350 feet of the section are basal Paleocene. The NOHM-B assemblage of these Paleocene sandstones consist of 49% epidote-clinozoisite, 18% garnet, 10% zircon, 9% apatite, 8% sphene and 4% allanite. Other NOHM-B are tourmaline and rutile.

On the eastern edge of the central Foothills about 4,000 feet of Paleocene beds outcrop along the North Saskatchewan River (Fig. 14d-H). The base of this section is marked by the Saunders (Foothills) coal zone which lies

800 to 1,200 feet above the base of the Foothills Paskapoo Formation. As in the Porcupine Hills Formation, this section may represent younger Paleocene. Only two samples were counted from this 4,000 foot thick section because of the uniformity of composition. The NOHM-B assemblage of these samples consists of 29% apatite, 23% garnet, 20% tourmaline, 14% zircon, 7% rutile, and over 2% chloritoid. Other NOHM-B are chlorite, spinel, anatase, allanite, epidote (?) and xenotime (?). There is an abundance of dahllite and collophane in these samples.

A short distance to the northwest of the North Saskatchewan River section are the Blackstone River and Colt Creek sections (Fig.14d-l). Here the basal 500 and 650 feet (respectively) of the Paleocene were studied. Epidote-clinozoisite decreases markedly and almost disappears at about 800 feet above the base of the Paskapoo Formation.

General areal trends of the non-opaque heavy minerals are as follows:

(1) Hornblende is restricted to a belt encompassing north-central and central Alberta (Fig.14d).

(2) Excluding the younger Paleocene, epidote-clinozoisite occurs mainly in western, central and southeastern Alberta.

(3) Apatite increases towards the western and northwestern parts of the study area. It is more abundant in the Foothills and the immediately neighbouring Plains than farther east.

(4) Sphene has a similar distribution to epidote-clinozoisite.

(5) Zircon decreases from west to east and from south to north.

(6) Along the Foothills, garnet increases northwestwards. It shows no definite trend in the Plains.

(7) Tourmaline is restricted to southeastern Alberta and to the younger Paleocene beds of the North Saskatchewan River section. Both these areas are of younger Paleocene.

(8) Rutile shows no recognizable trend except it is more abundant in the younger Paleocene.

(9) Allanite shows a general decrease from west to east and from northwest to southeast.

(10) Chlorite is restricted to the west-central Plains and the northern part of the central Foothills.

2. Vertical Distribution:

This section deals with the major stratigraphic trends in the non-opaque heavy minerals of the studied lithostratigraphic units. The approach will be such that these trends are considered region by region rather than section by section. Reference should be made to Figure 15 for location and to Table 4 and Figures 16 to 24 for trends.

(a) <u>Southern Foothills:</u> (Fig. 15A) In the southern Foothills of Alberta the non-opaque heavy minerals of the Belly River to Porcupine Hills sequence are dominated by apatite, zircon and garnet. Others are allanite,

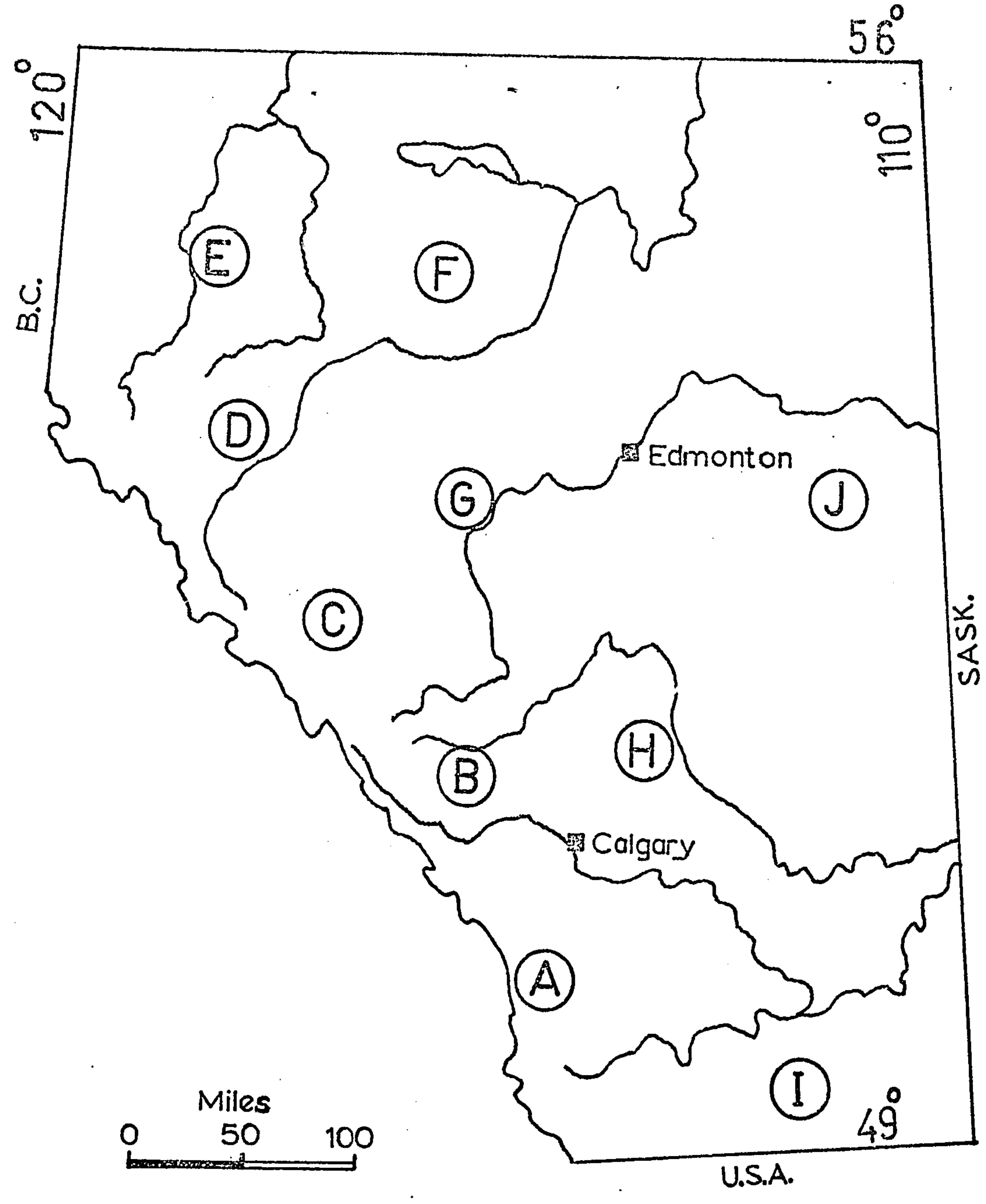


Fig. 15. Generalized areas of sample locations.

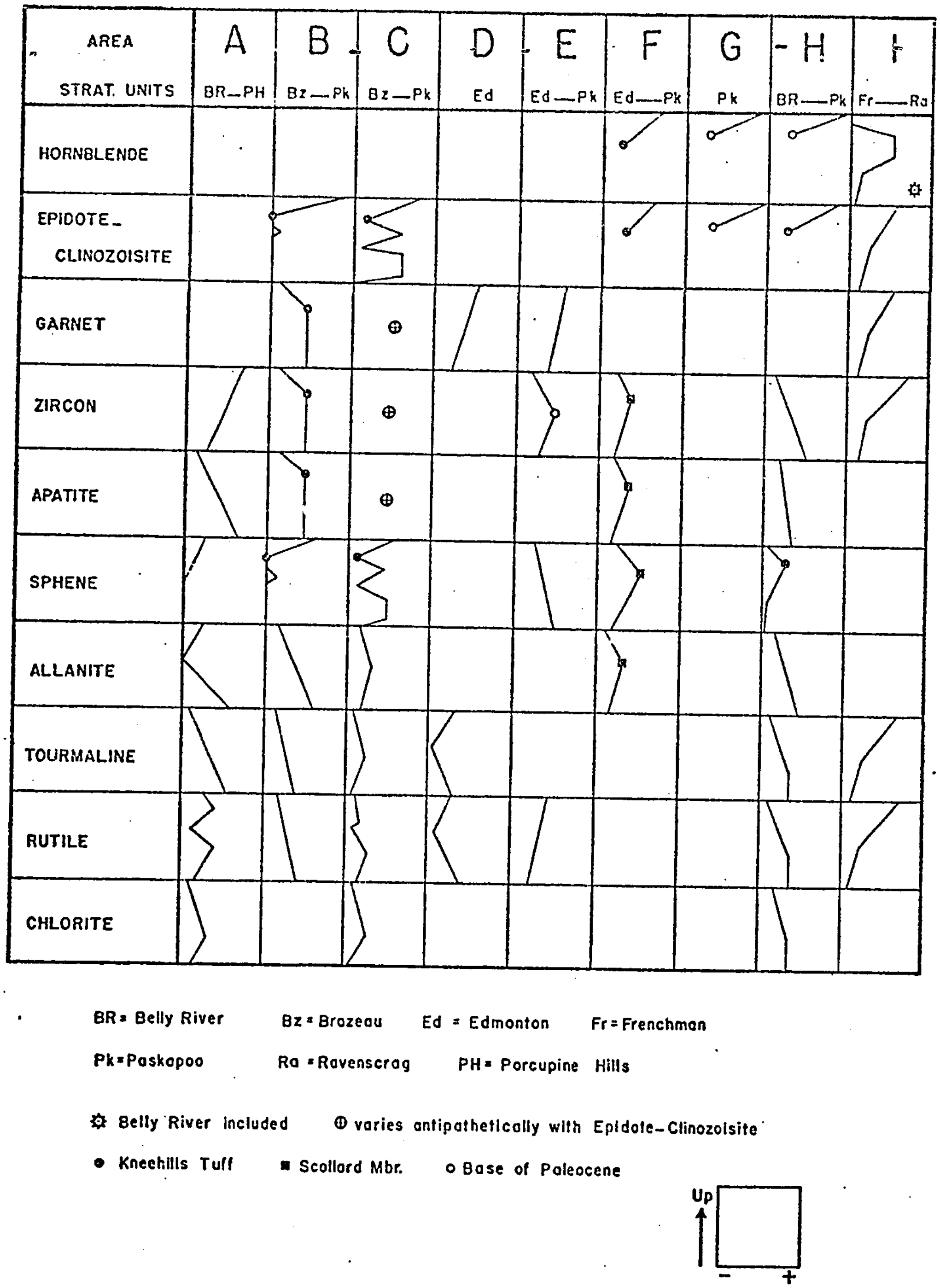


Table 4. Generalized vertical trend of non-opaque, non-micaceous heavy minerals.

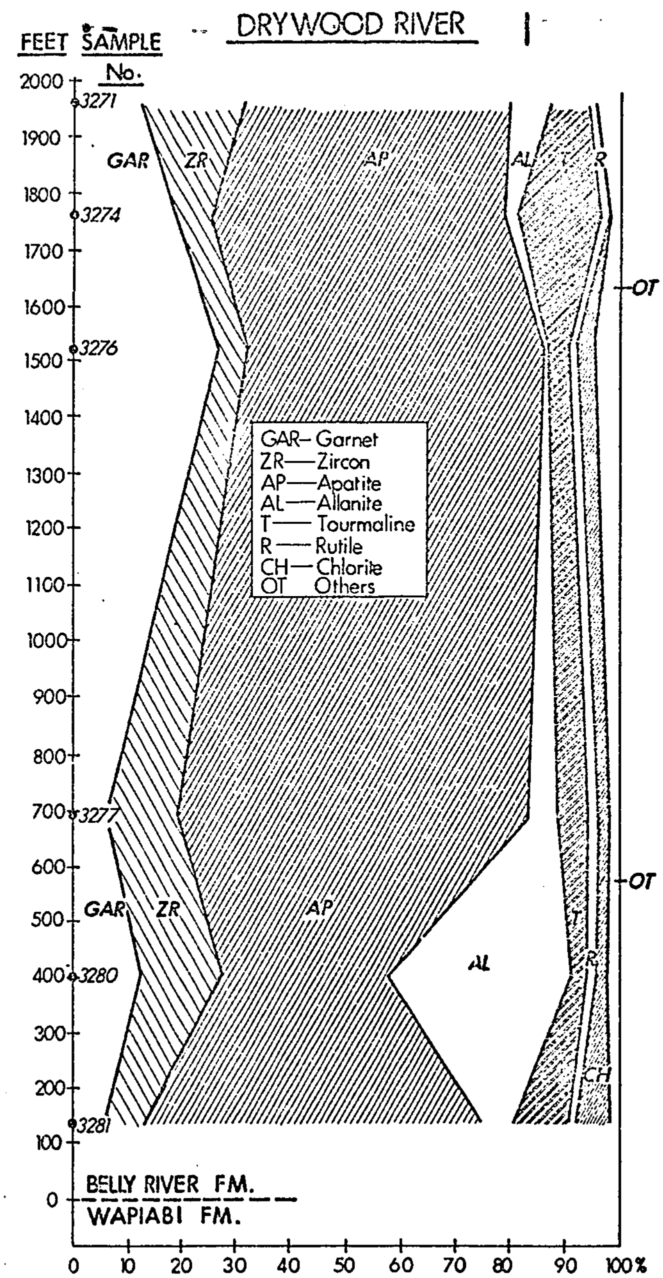


Fig. 16. Vertical distribution of non-opaque, non-micaceous heavy minerals (modified after Lerbekmo, 1963). For location see Fig. 5.

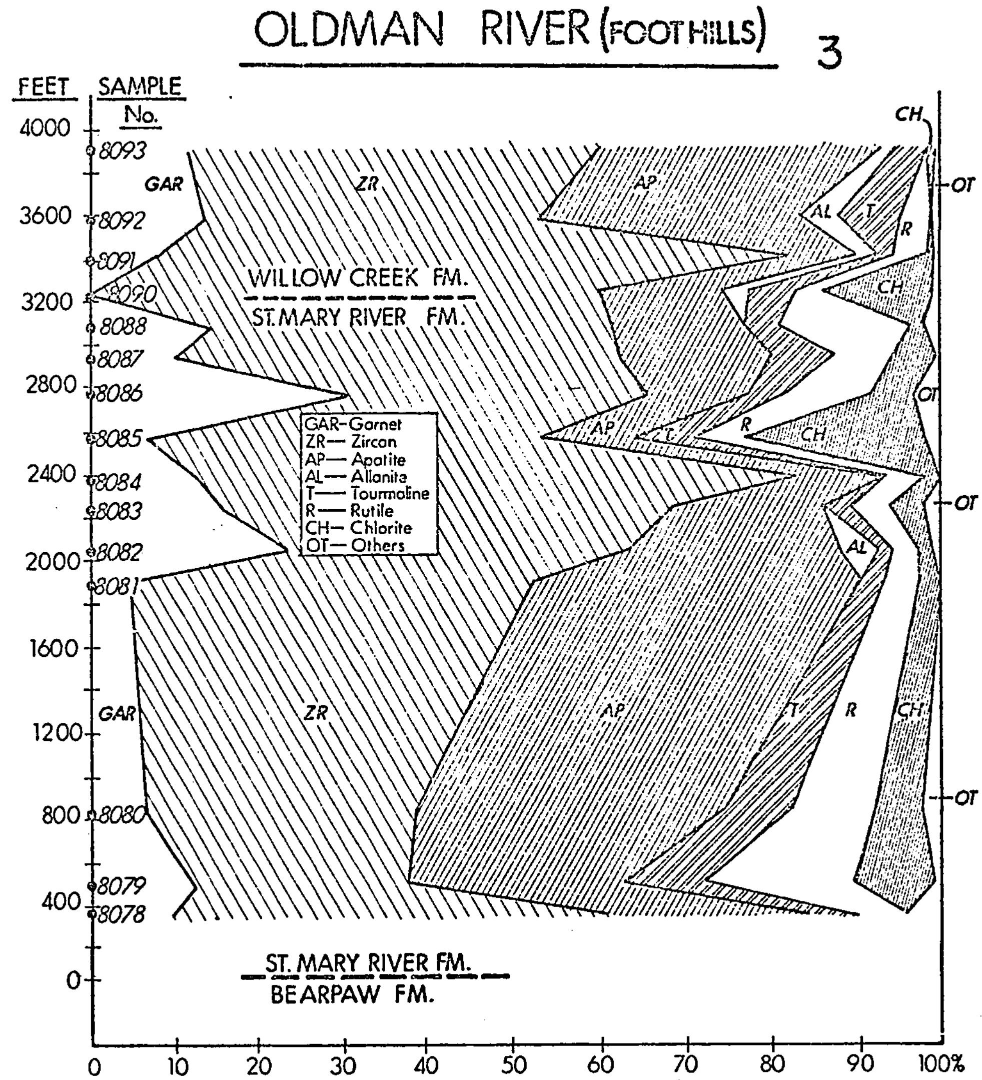


Fig. 17. Vertical distribution of non-opaque, non-micaceous heavy minerals. For location see Fig. 5.

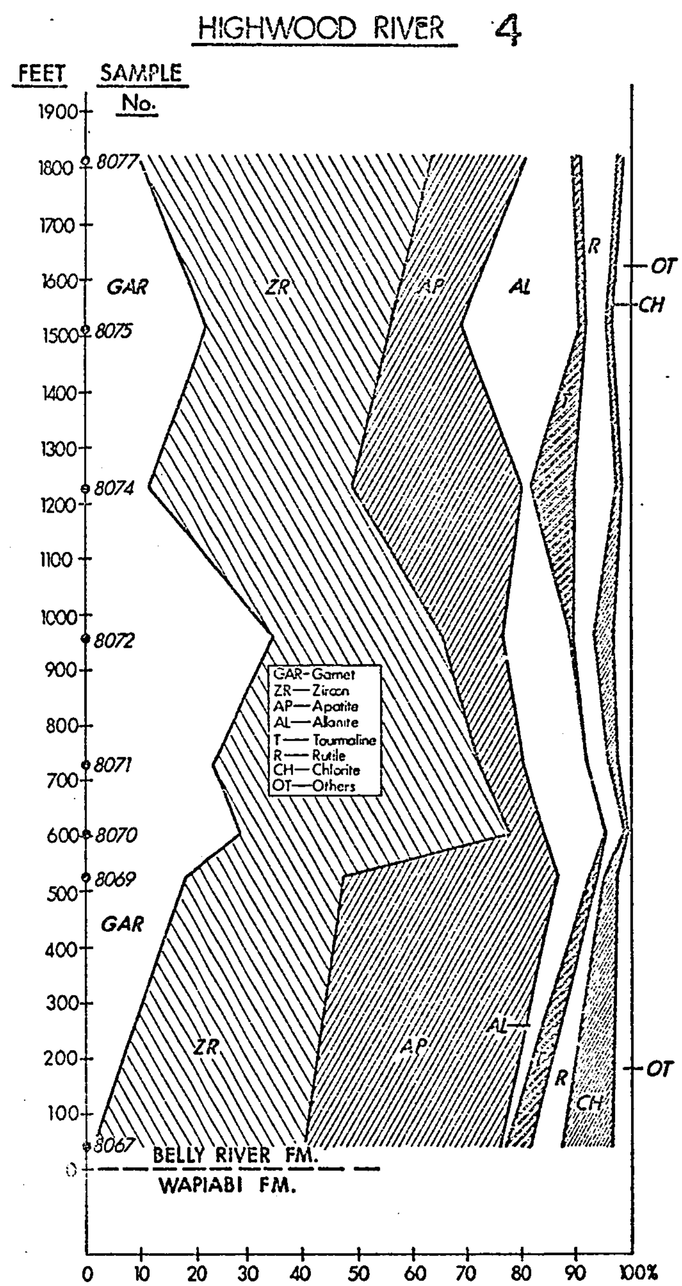


Fig. 18. Vertical distribution of non-opaque, non-micaceous heavy minerals. For location see Fig. 5.

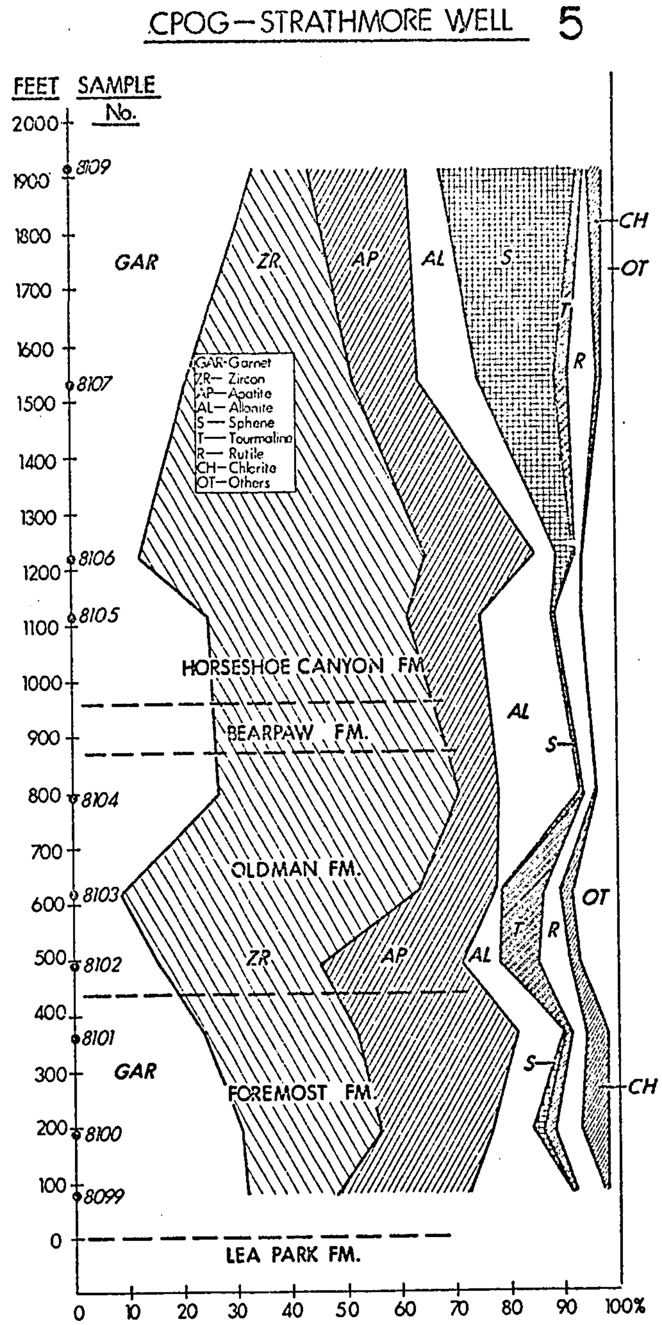


Fig. 19. Vertical distribution of non-opaque, non-micaceous heavy minerals. For location see Fig. 5.

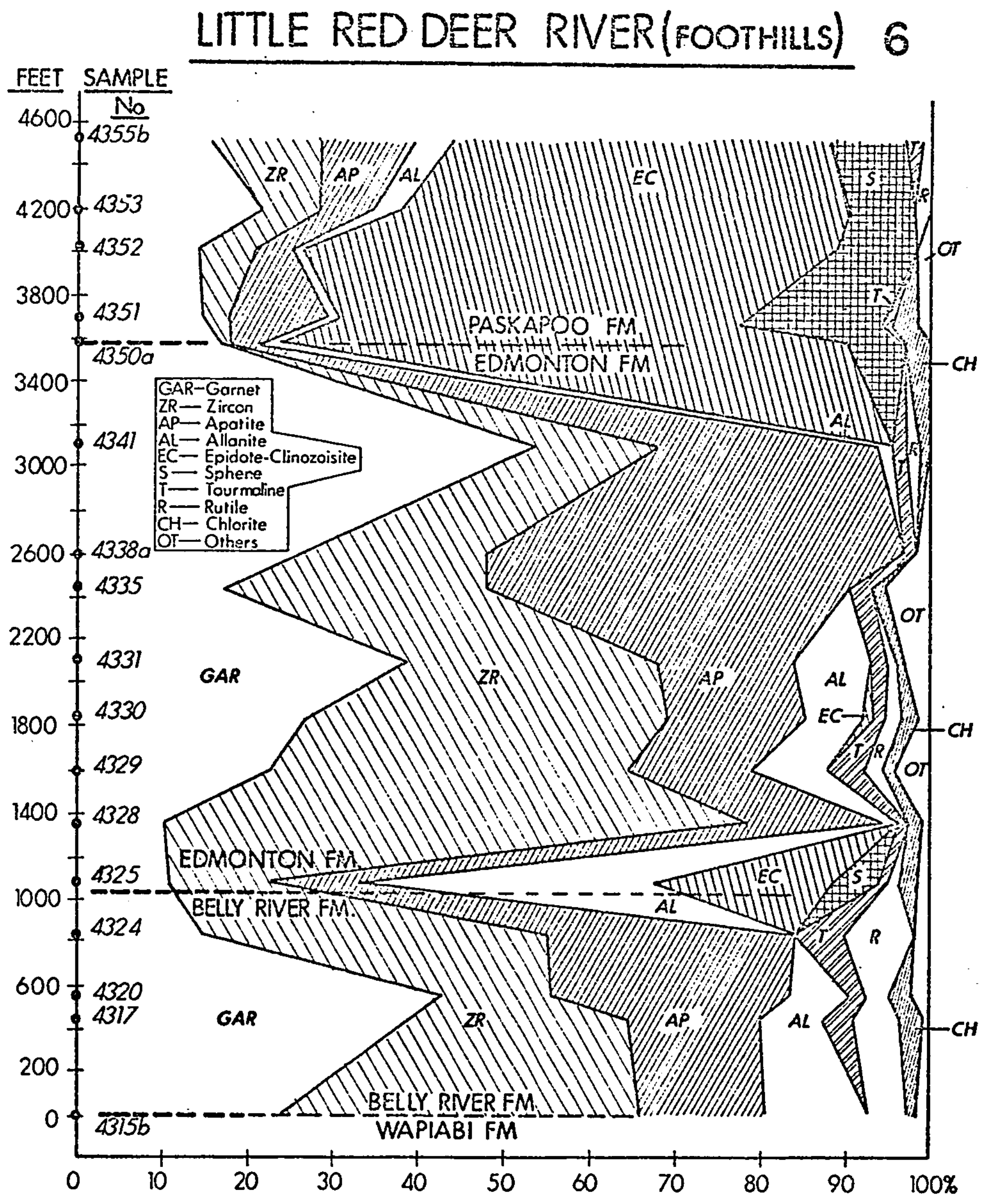


Fig. 20. Vertical distribution of non-opaque, non-micaceous heavy minerals. For location see Fig. 5.

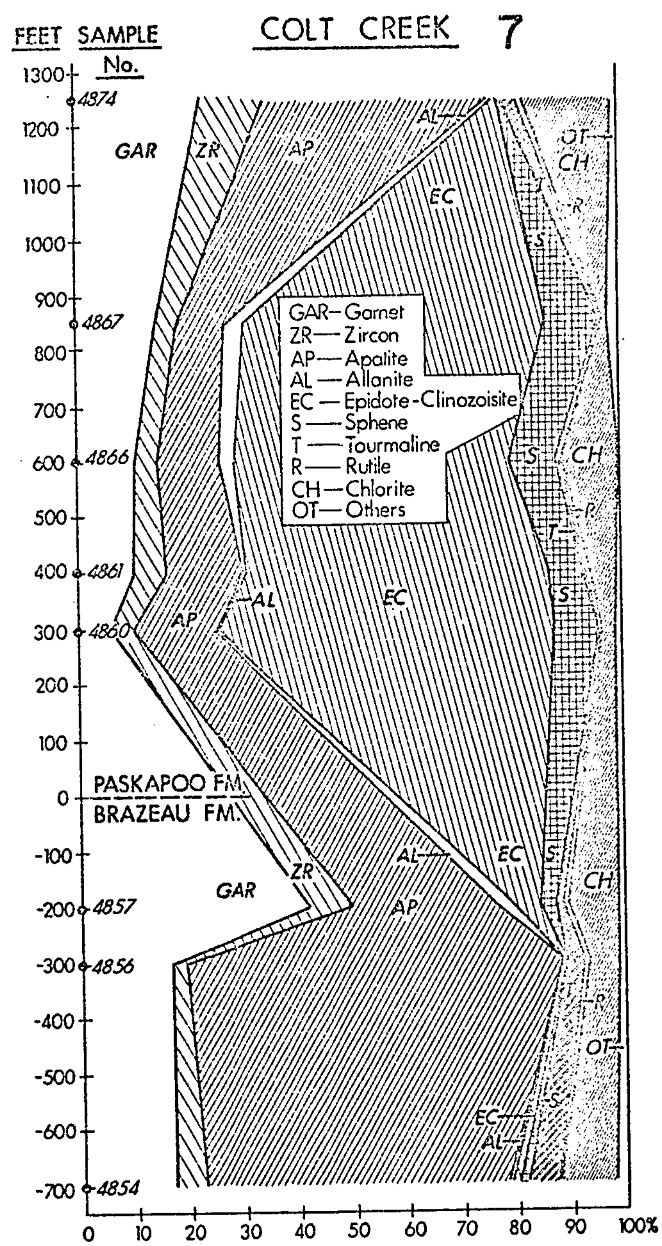


Fig. 21. Vertical distribution of non-opaque, non-micaceous heavy minerals. For location see Fig. 5.

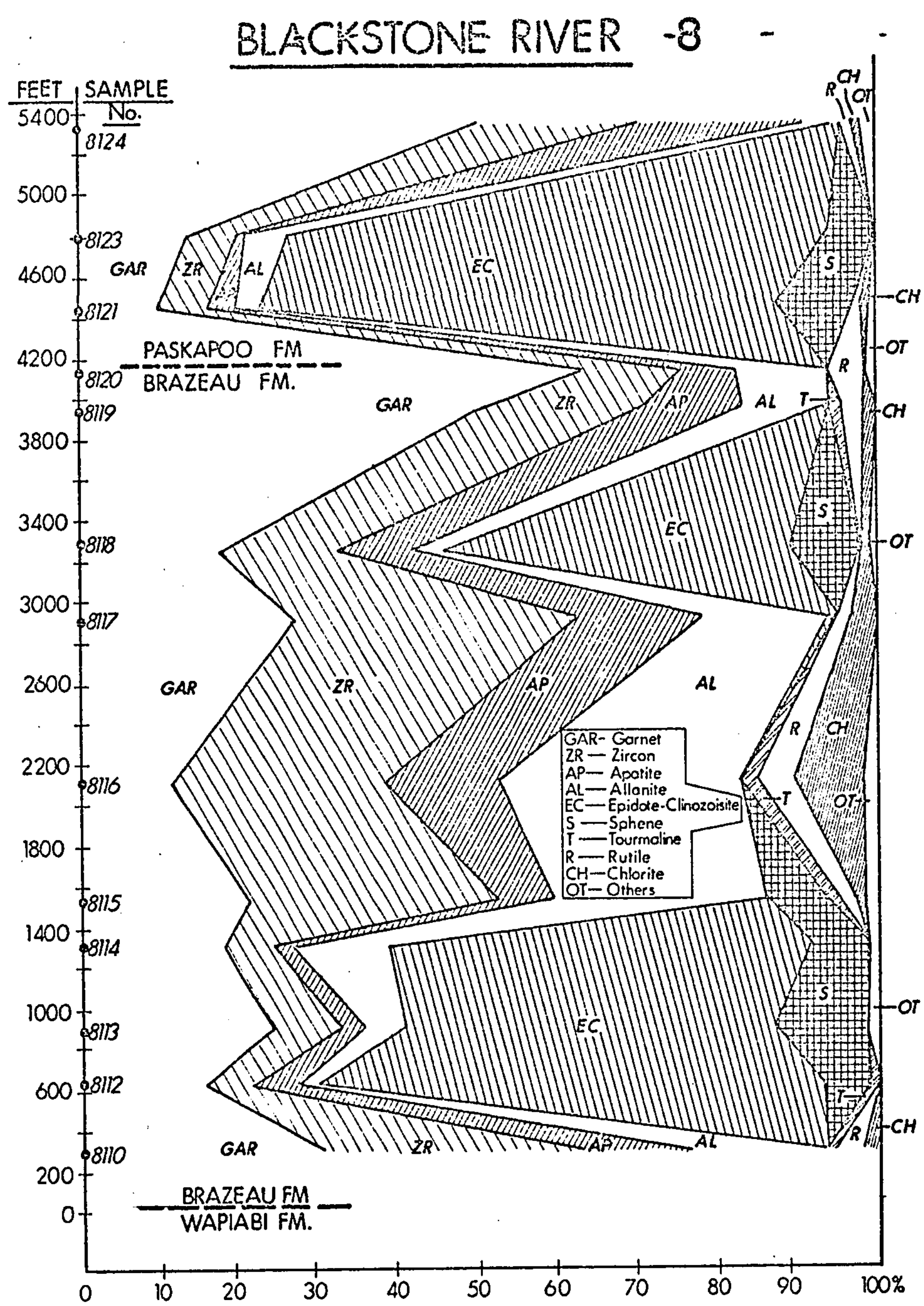


Fig. 22. Vertical distribution of non-opaque, non-micaceous heavy minerals. For location see Fig. 5.

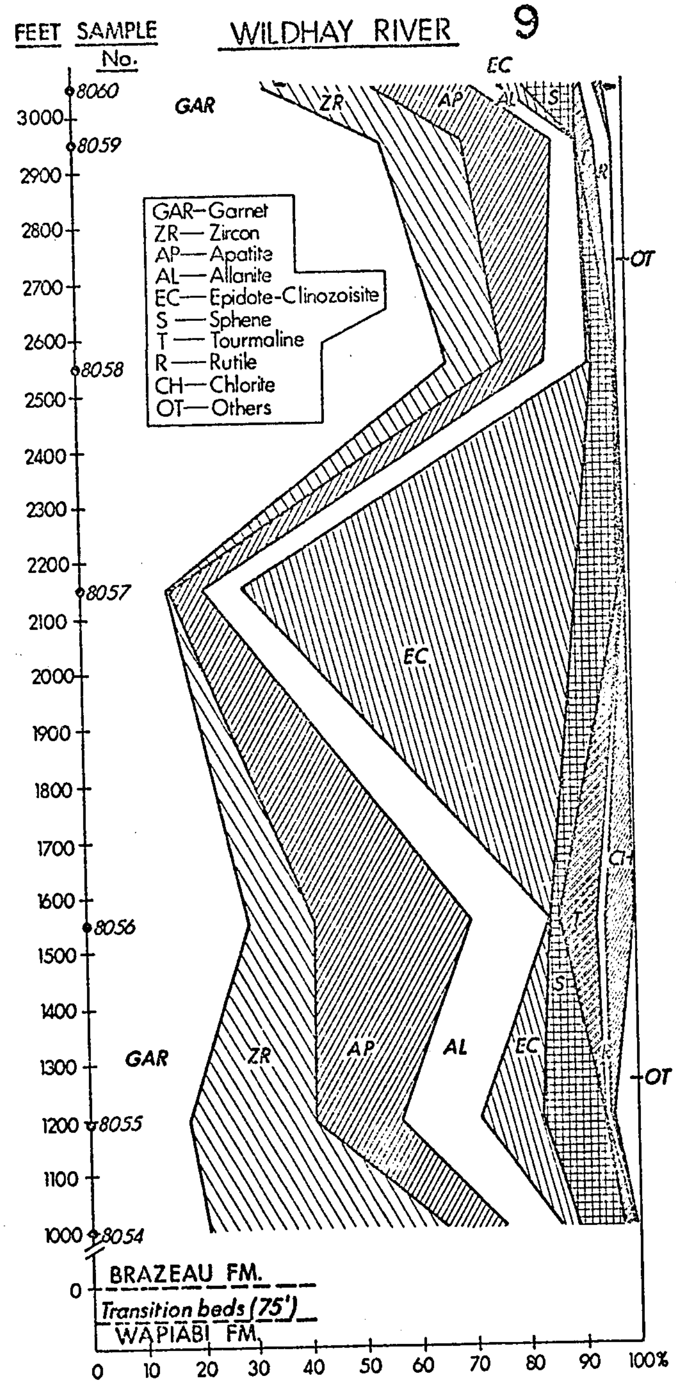


Fig. 23. Vertical distribution of non-opaque, non-micaceous heavy minerals. For location see Fig. 5.

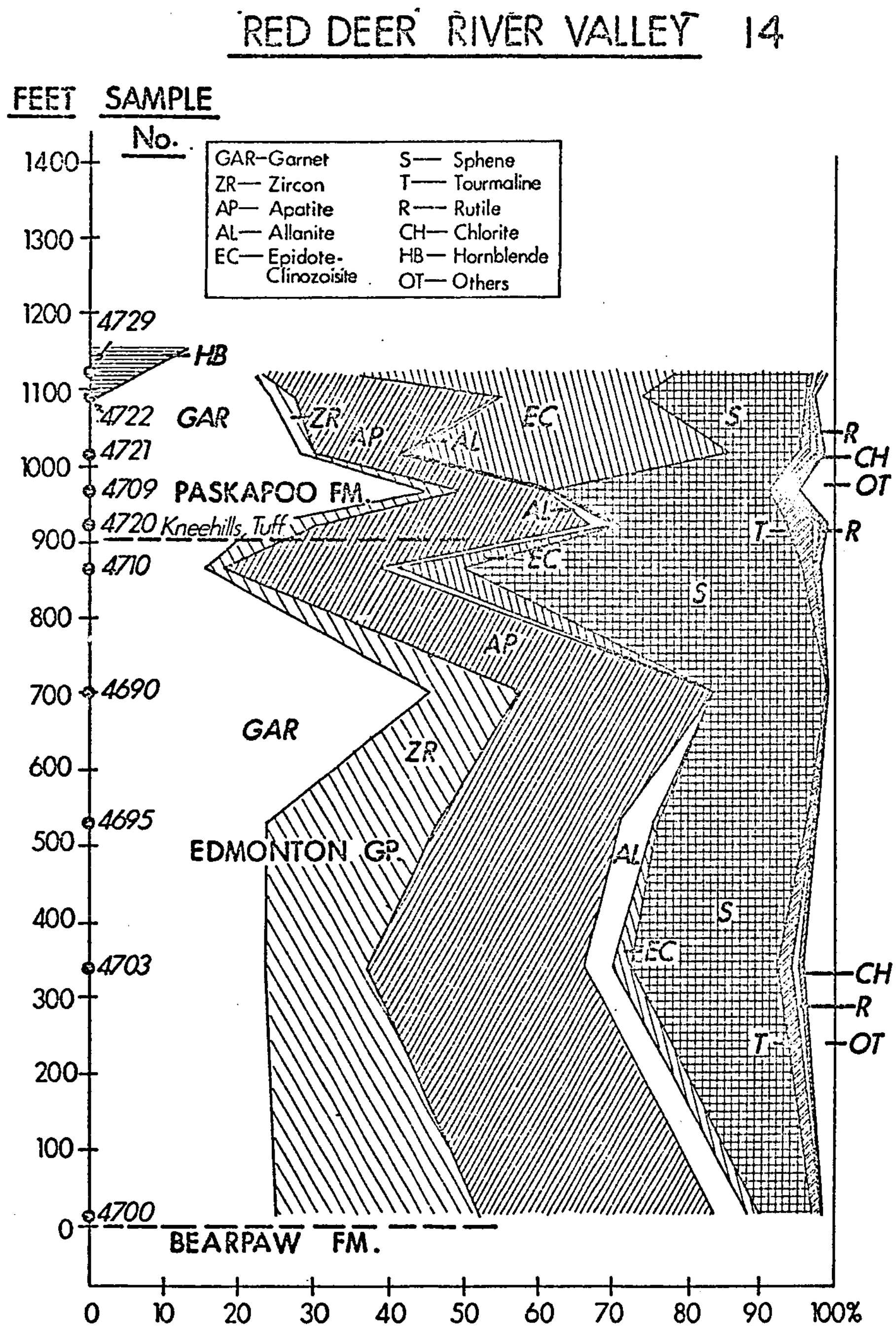


Fig. 24. Vertical distribution of non-opaque, non-micaceous heavy minerals. For location see Fig. 5.

tourmaline, rutile, sphene and chlorite. The major vertical trends are:

(1) Zircon increases gradually to become the dominant component in the Porcupine Hills Formation (Table 4A). With this increase there is an increase in the relative abundance of the hyacinth zircon which in turn is accompanied by an increase in the relative abundance of rounded zircon. The latter observation is confirmed by the work of Carrigy (1971, Table 6, p. 43).

(2) Apatite decreases gradually from being dominant in the Belly River Formation to a minor component in the Porcupine Hills. However, Carrigy's (1971, p. 41) data show that apatite is only slightly less abundant than zircon in the Porcupine Hills Formation. It should be noted that Carrigy made a more extensive areal coverage than that reported in the present thesis.

(3) Tourmaline shows a general decrease upward until it assumes a minor role in the Porcupine Hills Formation. Again, Carrigy's data show tourmaline as a major non-opaque heavy mineral component of the Porcupine Hills Formation.

(4) Allanite exhibits a general upward decrease. It declines in abundance and almost disappears in the St. Mary River Formation but appears again in the lower part of the Willow Creek and the Porcupine Hills Formations, although never in such high percentages as in the Belly River Formation.

(5) Rutile shows two maxima. It increases to a maximum in the St. Mary River Formation, declines in the lower part of the Willow Creek

Formation, then reaches a second maximum in the lower Porcupine Hills Formation and declines thereafter.

(6) Sphene is absent throughout the Belly River, St. Mary River and the lower part of the Willow Creek Formations. It probably first appears in the upper part of the Willow Creek Formation (Carrigy, 1971, p. 42) to persist as a minor component throughout the overlying Porcupine Hills Formation.

(7) Chlorite increases upwards to form a maximum in the St. Mary River Formation, but declines to become minor to absent in the Porcupine Hills Formation. Possible diagenetic formation may have obliterated the original trend.

(b) South-Central Foothills: (Fig. 15B) This region is represented by a section along the Little Red Deer River which exposes the Brazeau and Paskapoo Formations. The dominant non-opaque heavy minerals are garnet, zircon, apatite and epidote-clinozoisite. Others are allanite, rutile, sphene, tourmaline and chlorite. The major vertical trends are:

(1) Epidote-clinozoisite appears in flood proportions first in the basal beds of the Paskapoo Formation. Below this level it is only found in moderate amounts in one sample from the upper part of the Brazeau Formation. This sudden influx of epidote-clinozoisite in the basal Paskapoo, as will be seen later, occurs widely in the central Foothills, central Plains and the Swan Hills.

(2) Garnet, zircon and apatite are of equal abundance in the Brazeau Formation, but decrease in importance in the Paskapoo Formation mainly due to dilution by influx of epidote-clinozoisite.

(3) Allanite is more abundant in the lower and middle parts of the Brazeau Formations, and declines through the upper Brazeau and the Paskapoo Formations.

(4) Sphene follows a similar trend to that of epidote-clinozoisite.

(5) Tourmaline shows a general upward decrease, becoming very minor to absent in the Paskapoo Formation.

(6) Rutile shows a definite upward decrease.

(c) North-Central Foothills: (Fig. 15C) This region is represented by the Blackstone River, Colt Creek and North Saskatchewan (Saunders) sections. Here, all the Brazeau and a large portion of the Paskapoo Formations are exposed. The major vertical trends are:

(1) Epidote-clinozoisite is a major component of the lower part of the Brazeau Formation, but occurs only in one sample in the upper Brazeau. As in the Little Red Deer section, a sudden influx of epidote-clinozoisite comes in the basal beds of the Paskapoo Formation. In this area there is an indication that the epidote-clinozoisite abundance declines suddenly 800 to 900 feet above the base of the Paskapoo Formation to disappear entirely in the younger Paskapoo beds of the North Saskatchewan River (Saunders section).

(2) Allanite is more abundant in the middle part of the Brazeau Formation than below or above this level.

(3) Sphene follows a trend similar to that of epidote-clinozoisite.

(4) Rutile shows two maxima. It is minor to absent in the lower part of the Brazeau, reaches a maximum in the middle part, and a smaller second maximum about 70 feet below the Paskapoo Formation.

(5) Tourmaline and chlorite show a peak in the lower-middle Brazeau Formation.

(d) Northern Foothills: (Fig. 15D) This region is represented by the upper part of the Brazeau Formation (Edmonton equivalent) of the Wildhay River section. Garnet shows a general tendency to increase upward, while chlorite is confined to the lower part of the section. Rutile and tourmaline decrease upward to near disappearance at the middle of the section, but increase again toward the top of the section.

(e) Northwestern Plains: (Fig. 15E) A composite section along the Smoky River exposes the upper part of the Wapiti (equivalent to the upper part of the Edmonton Group) and the lower part of the Paskapoo Formations. Here garnet, zircon, apatite, sphene and allanite are the dominant non-opaque heavy minerals, with lesser proportions of rutile, chlorite, epidote-clinozoisite and tourmaline. The major vertical trends are:

(1) Garnet shows a general upward increase.

(2) Zircon increases upward to the Cretaceous-Paleocene

transition, then decreases in the Paleocene.

(3) Rutile shows a gradual upward increase.

(4) Sphene decreases upward gradually.

(f) Swan Hills: (Fig. 15F) The section of this area is a close correlative of that in the Northwestern Plains. Hornblende, garnet, sphene, epidote-clinozoisite, zircon and apatite make up the bulk of the non-opaque heavy minerals with lesser amounts of allanite, tourmaline, chlorite and rutile. The major vertical trends are:

(1) Hornblende appears only above the Kneehills Tuff level and increases upward.

(2) Epidote-clinozoisite appear suddenly above the Kneehills Tuff level. Although they almost disappear within the Lance strata they increase upward through the Paleocene.

(3) Sphene, zircon, apatite and allanite are significant only in the Scollard Member (Lance), decreasing above and below.

(g) West-Central Plains: (Fig.15G) Data samples here are scattered and fragmentary and no stratigraphic relations are established. Epidote-clinozoisite and hornblende appear in significant amounts at the base of the Paleocene Paskapoo beds.

(h) South-Central Plains: (Fig.15H) This region includes the Red Deer River Valley sections and the CPOG-Strathmore core. Here garnet, apatite, sphene, zircon, allanite and epidote-clinozoisite make up the bulk of the non-opaque heavy minerals. Others are hornblende, tourmaline, rutile, and chlorite. The major vertical trends are:

(1) Zircon and apatite show a gradual upward decrease.

(2) Sphene is minor in the Belly River Group. It first appears in significant proportions in the Horseshoe Canyon Formation, forms a maximum at the Kneehills tuff level and declines thereafter, probably due to the diluting effect of epidote-clinozoisite and hornblende.

(3) Epidote-clinozoisite first appears in significant amounts just above the Kneehills Tuff level, to increase upward.

(4) Hornblende first appears in the basal Paleocene beds to become a major non-opaque heavy mineral in this part of the Paskapoo Formation.

(5) Allanite exhibits a general upward increase.

(6) Tourmaline, rutile and chlorite are more abundant in the Belly River Group than in the overlying rocks.

(i) Southern Plains: (Fig. 151) Data on this region come from Chi (1966) and McLean (1971) and include the area south of the Oldman and South Saskatchewan Rivers representing the Belly River Group, Frenchman and Ravenscrag Formations. Little data exist on the Edmonton Group equivalents. The major vertical trends are:

(1) Hornblende is rare to absent in the Belly River Group (synonym: Judith River Formation) but increases slowly until it becomes a major constituent of the non-opaque heavy minerals of the Frenchman Formation to decline thereafter and to disappear at the base of the Ravenscrag Formation.

Due to lack of data, the following trends deal only with the Ravenscrag and Frenchman Formations:

(2) Zircon, tourmaline and rutile are significantly more abundant in the Ravenscrag than in the underlying Frenchman Formation.

(3) Epidote-clinozoisite and garnet are also somewhat more abundant in the Ravenscrag Formation.

These apparent trends are probably the result of the flood of hornblende in the Frenchman Formation.

(j) East-Central Plains: (Fig. 15J) Only the Belly River Group is present in this area. As mentioned previously, outcrops in this region are scarce and small and only the very general stratigraphic trends in the heavy minerals can be outlined. The major event here is the stoppage of hornblende supply at the end of Foremost time. This event is associated with the increase in the relative abundance of the other heavy minerals. Coinciding with this event is the increase in the sphene/epidote-clinozoisite ratio in the Oldman Formation.

C. Radiometric Age Dating

1. General Statement

We have seen from previous sections that hornblende is the major non-opaque heavy mineral constituent of sandstones of the Belly River Group and the Paskapoo and Frenchman Formations of the southeastern, eastern, northeastern and northern parts of the study area (Figs. 14a, c, and d), and that it is scarce or absent in the western, southwestern and southern parts of the study area. Previous workers (Chi, 1966 and Lerbekmo, pers. comm.), whose work was confined to the southern half of the present area of study, suggested that this hornblende distribution could be explained by derivation from an eastern to northeastern source in the Canadian Shield. The K-Ar radiometric study was undertaken by the present writer to prove or disprove the above assumption that the hornblende had formed in Precambrian time.

Five of the six samples used for radiometric dating are from the lower part of the Belly River Group (Foremost equivalent) of east-central Alberta and one sample (a composite of two samples) is from the Frenchman Formation of the Cypress Hills of southeastern Alberta. The available size of the sandstone samples from the rest of the Paskapoo Formation and equivalents did not yield sufficient amounts of hornblende for the purpose. However, the areal pattern and relation to source area of the hornblende provinces of Belly River and Paskapoo times are similar enough that it is reasonable to assume that results of the radiometric age-dating of the Belly River and Frenchman hornblende can be applied to the rest of the Paskapoo hornblende.

2. Analytical Techniques

Heavy minerals from lower Belly River sandstones of east-central Alberta and the Frenchman sandstones of southeastern Alberta, which are composed mainly of hornblende, were separated according to the method discussed earlier. The hornblende separation was done by conventional magnetic (Franz isodynamic separator) and heavy liquid techniques (tetrabromoethane and methylene iodide). The mineral concentrates analysed were greater than 90% pure. The impurities (mainly epidote, some clinozoisite, sphene) have negligible potassium contents and act only as dilutants of the K-Ar system, not affecting the Ar-K ratio. Dilute methylene iodide was used to remove biotite (and any K-feldspar) from the final concentrate.

Potassium determination and argon extraction and analysis were carried out according to standard techniques, that have been in use for a number of years, in the University of Alberta Geochronology Laboratory (see O'Nions, 1969, pp. 33-40). About 0.1 gm. of the hornblende concentrate was used for the potassium determination and approximately 1.5 gm. for the argon extraction.

3. Results

The K-Ar dates obtained (Table 5) range between 114 and 155 m.y., that is, from the Late Jurassic to the earliest part of the Late Cretaceous Epochs

AK No.	Sample No.	Location	% K_2O	% Rad. Ar	Ar/K	Age (m.y.)
1008	8034	Sec. 6,51,8,W4	0.68	100*	0.00709	117(± 6.5)
1009	8035	Sec. 18,50,8,W4	0.75	100*	0.00771	127(± 15.5)
1010	8037	Sec. 7,55,7,W4	0.61	86	0.00945	155(± 10.0)
1011	8038	Sec. 4,47,6,W4	0.65	100*	0.00680	114(± 14.5)
1012	8041	Sec. 33,49,8,W4	0.62	100*	0.00827	136(± 15.0)
1029	5044 & 5045	Sec. 14,8,3,W4	0.77	20	0.00795	131(± 10.0)

*Low sensitivity on argon run, maximum date is calculated. True date is likely less than this by 5-20%.

Table 5. K-Ar age dates of detrital hornblende from the Belly River Group of east-central Alberta (8034 to 8041) and the Frenchman Formation of southeastern Alberta (5044 and 5045).

(Kulp's Geologic Time Scale, 1961). The precision of the dates obtained is also shown in the last column of Table 5.

For the purposes of this study, the precision of the dates is not critical. The results show beyond doubt that these hornblendes come from a Mesozoic rather than a Precambrian source area.

4. Discussion

In order to better appreciate the K-Ar dates obtained in this study, one should consider the following factors that could have influenced the quality of the material dated:

(a) Accuracy of the Geological Age of the Sedimentary Deposit: It is very important to establish the time of deposition of the sediments containing the dated detrital hornblende as it will help in narrowing down the number of sources that might have contributed these hornblendes.

The Frenchman Formation of southeastern Alberta is of Late Maestrichtian age (Lance) (Williams and Burk, 1964). It includes 375 feet (Chi, 1966, p. 7) of strata that lie between the underlying Kneehills Tuff (beginning Lance) and the overlying Ravenscrag Formation, the base of which marks the Cretaceous-Tertiary boundary. According to K-Ar radiometric data of Shafiqullah et al (1964) the age of the Kneehills Tuff is 66 m.y. and the Cretaceous-Tertiary boundary is 63 $\pm$ 1 m.y. Since the dated detrital hornblende composite sample comes from near the middle of the Frenchman Formation, it is reasonable to state that the hornblende and host sediments were deposited in southeastern Alberta about 64 m.y. ago.

The age of the Belly River Group in east-central Alberta is middle Campanian (Williams and Burk, 1964). The dated sandstone samples were taken from a 250 foot interval whose base is 300 feet above the base of the 900 foot thick Belly River Group. In the southern Foothills, the Belly River Formation is approximately 2500 feet thick at the Drywood River. Here a 2.5 foot thick bentonite bed, 45 feet below the top of the formation, yielded two K-Ar dates of 77 m.y. and 74 m.y. from biotite and sanidine respectively (Lerbekmo, 1963 and University of Alberta K-Ar File: AK 42 and AK 43). Taking the average as 75 m.y., this date, according to Kulp's (1961) geologic-time scale, puts the time of deposition of the bentonite bed in the upper middle of the Campanian Epoch. It follows that the deposition of the Belly River Formation of the southern Foothills was nearly completed 75 m.y. ago. Utilizing a sedimentation rate of 350 ft/m.y., extrapolated from calculations by Shafiqullah et al (1964) for sedimentation in the Foothills region, it would have taken 7 m.y. to deposit the 2500 feet of the Belly River Formation of the southern Foothills. That is, the deposition of the Belly River Formation started approximately 82 m.y. ago. Assuming synchronism in the deposition of the southern Foothills and east-central Alberta Belly River sediments (although upper and lower contacts are very likely diachronous) and that these dated samples were taken from the middle of the Belly River Group, it is probably reasonably accurate to state that the dated detrital hornblende and host sediments were deposited in east-central Alberta about 80 m.y. ago.

(b) Hornblende Varieties and their Relationship to Sources: Petrographically the dated hornblende occurs in several color varieties dominated by green to olive and brown to reddish-brown types, the green to olive hornblende being three times as abundant as the brown to reddish-brown variety. Red (oxyhornblende) and bluish varieties are present in only trace amounts. Therefore, the obtained K-Ar dates are those of green to olive and brown to reddish-brown hornblende. Microprobe chemical analysis of the green to olive hornblende (discussed in more detail elsewhere) show them to be mainly Magnesio-Hornblende according to Leake's Classification (1968). There are two extreme possibilities as to the sources of these hornblendes that might explain the spread in the dates obtained:

(i) The difference in dates obtained may be accounted for by assuming that each dated sample contains hornblende derived from a different source area and these sources are of different ages.

(ii) The hornblende in each sample may represent a combination of hornblendes from a number of sources of various ages, and the different K-Ar dates obtained are caused by the different degrees of mixing (i.e. different ratios) of these hornblendes in each sample.

With respect to the first possibility, it seems highly unlikely that the source supplying the hornblende would vary in this manner in a short period of time and within the confines of a relatively small depositional area. The second possibility seems more likely to have been the situation that produced the differences in the obtained dates.

(c) Adequacy of Sampling: It is clear that six samples are not adequate to treat the results statistically; however, the purpose of the age dating was to decide between two sources of significantly different geologic ages, namely, the Mesozoic crystalline rocks to the west and the Precambrian crystalline rocks to the east and northeast of the study area. Therefore, the six samples are adequate for this purpose, especially since the spread of the obtained dates is well within the limits of the range of dates obtained from the Mesozoic Cordilleran crystalline rocks.

(d) Possible Extent of Argon Loss Due to Exogenic Processes: The climate and topography of the suspected source, which in turn determines the intensity of chemical weathering, can only be inferred from the study of the geometry, texture and mineral stability of the resulting sediments. Geometry and detrial textures of the Belly River Group and Frenchman Formation indicate that the source area must have an actively rising mountainous terrain (i.e. the Omineca Geanticline). The abundance of hornblende, a chemically unstable heavy mineral in these rocks, is witness to the limitations on chemical weathering in the source area.

The dated hornblende, as viewed with the petrographic and scanning electron microscopes, shows no indication of chemical alteration that might have resulted in preferential loss of argon which would lower K-Ar dates. Krylov (1961, p. 328-329) noted no significant changes in the Ar:K ratio between granitic rocks and their decomposition products when these decomposition products do not show distinct traces of chemical weathering. Therefore, it is safe to assume that the Ar:K ratio of the dated hornblende did not change significantly at the source area.

Chemical alteration in the transporting (rivers) and depositing (continental-marine transition) environments is not suspected. Krylov (1961, p. 337) indicated that the Ar:K ratios of fluvioglacial deposits remain unchanged when compared with the Ar:K ratio of "the mother granite".

The only diagenetic change that the hornblende is suspected to have undergone is chemical solution (not alteration) that resulted in the formation of hacksaw terminations and other grain-surface features discussed elsewhere. The writer believes that this chemical solution affected the hornblende only volumetrically by removing parts of the grains, rather than affecting the elemental balance which would be observed in the form of alteration, easily detectable with the petrographic microscope.

5. Source of the Hornblende

Figures 31 and 33 show the areal distribution of the hornblende provinces during Belly River and Paskapoo time. The approximate western boundary of this province runs northwest-southeast. This areal pattern seems to exclude a hornblende source directly west, southwest or south. To the northeast and east lies the Precambrian Canadian Shield, proved to be an unlikely source on the basis of the K-Ar dating. Therefore, we are left with only two possibilities, a source to the northwest, in central and northern British Columbia and the southern Yukon, and/or to the southeast in eastern Montana and states to the east. The latter area is an unlikely source for hornblende due to the absence of any known Mesozoic crystalline rocks. Therefore central and northern British Columbia and the southern Yukon seem to be the likely source for this hornblende. As mentioned before, the most abundant color variety of hornblende is the green to olive type, with lesser amounts of brown to reddish-brown hornblende. The suspected source area of the northern Omineca Geanticline (Fig. 3) is made up mainly of Mesozoic plutonic and metamorphic rocks. The age of the Mesozoic metamorphism in this area was determined, on the basis of stratigraphic and radiometric dating evidence, to be Triassic, that is, older than 180 m.y. (Monger and Hutchison, 1971) and therefore older than the dates obtained from the detrital hornblende. However, radiometric dating of the plutons of this area, indicate emplacement during the Columbian Orogeny (late Late Jurassic to latest Early Cretaceous), which is compatible with the dates obtained from the Belly River Group and Frenchman Formation hornblende. This may suggest that this hornblende was derived largely from these plutons with less contribution from the metamorphic rocks. Presence of hornblende in the Belly River Group (Campanian) indicates that the crystalline rocks of the northern Omineca Geanticline were unroofed and became available to erosion by Campanian time and possibly earlier.

D. Microprobe Chemical Analysis

1. General Statement

This procedure was undertaken to supplement the radiometric age dating results in the search for source areas that supplied the detrital hornblende to the depositional basin.

To reach such a goal, one should chemically analyze as many hornblende samples as possible from the suspected crystalline sources and the sandstones in order to make a meaningful comparison. One would hope that there would be significant chemical differences between samples taken from the different suspected crystalline source rocks that can be detected and matched with similar chemical differences in detrital hornblendes of the sandstones. However, due to the scarcity of available crystalline hornblende samples (five), the above objective of matching detrital with crystalline hornblendes could not be statistically justified if obtained. Therefore, the writer has had to depend mainly on the chemical analyses of the detrital hornblende in reaching any conclusions.

2. Analytical Procedure

Hornblende grains were handpicked from the heavy accessory mineral concentrates from the sandstones and igneous rocks. As almost all of the hornblende of the igneous rocks is dark green or olive-green in color, only hornblende of these colors was handpicked from the heavy minerals of the sandstone. The five igneous specimens came from four areally widely spaced intrusive bodies along the Omineca Geanticline. The 58 detrital hornblende samples came from twelve sandstone specimens of the Upper Cretaceous of east-central Alberta and the Cypress Hills and the Paleocene of the Red Deer River Valley and the Swan Hills (Fig. 25).

The handpicked hornblende grains were mounted in an epoxy resin and polished for electron microprobe analysis. An ARL-EMX microprobe, housed in the Department of Geology of the University of Alberta, was used for the Si, Ti, Al, Fe, Mn, Mg, Ca, Na and K. Peaks and backgrounds were counted for 50 second periods. Grains were traversed randomly but evenly. For each of the igneous hornblende samples five grains were analysed and the results were averaged. However, due to the possible mixed origin of the detrital hornblende each analysed grain was considered as an independent analysis. Four to five grains were analysed in each detrital hornblende sample. The samples were counted against a Mn-Cummingtonite standard (E Mn Cummingtonite 4 of Klein, 1964 in Rucklidge et al, 1971) for the analysis of Mn and a Kaersutite standard (Kakanui Kaersutite of Mason, 1968) for the analysis of Si, Ti, Al, Fe, Mg, Ca, Na and K. The atomic number, absorption and fluorescence corrections were applied employing an

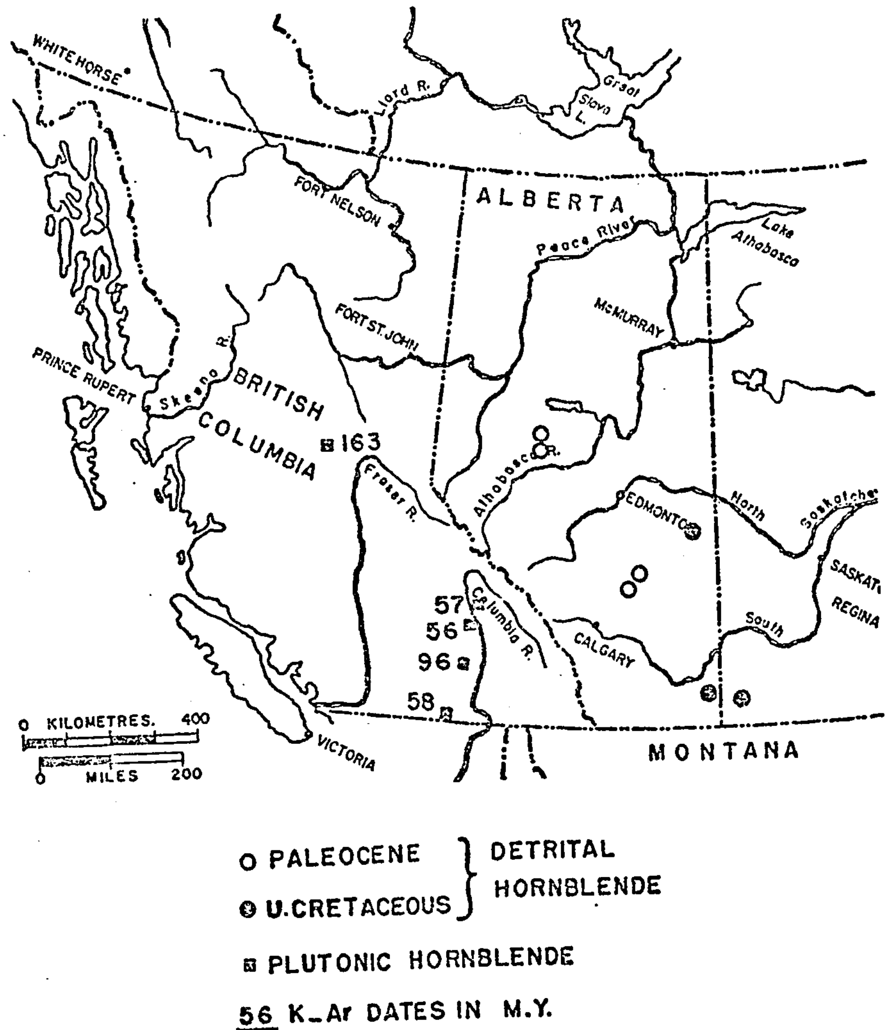


Fig. 25. Location of hornblende samples analysed with the electron microprobe.

APL-360 program written by Smith and Tomlinson (1970).

3. Results and Discussion

The analyses of the hornblendes are presented in Table 6 . The majority of them fall in the category of magnesiohornblende of Leake's (1968, Fig. 2, p. 8) amphibole classification. The few remaining hornblendes were tschermakitic-hornblende, ferroan-pargasite, magnesian-hastingsitic hornblende, ferroan-pargasitic hornblende, etc.

A Q-mode factor analysis program developed by Klovan and Imbrie (1971) (details of program to be found elsewhere in the thesis) was applied to the per cent oxides data in an attempt to search for a more specific and meaningful grouping of the analyzed samples and hopefully to relate these groupings to recognized origins and sources. Since only five oxides make the bulk of the composition, and the other four occur in minor amounts, the concentrations of all the oxides were transformed to percentage of their ranges in order to give equal chance to the minor oxides to appear in the resulting factors. Three-factor varimax solution with 94.8% cumulative variance was chosen mainly on the basis of high values of cumulative variance, communalities and eigenvalues and also because of the fact that a significant grouping resulted. The choice of a four-factor solution does not add more important information, and a choice of a two-factor solution results in a few samples with very low communalities and no significant trend. Factor 1 represents

Sample	2989	2927	2340	2915	2913	5000 1	5000 2	5000 3	5000 4	5000 5	4729 1	4729 2	4729 3	4729 4	4729 5
SiO_2	46.60	48.10	42.66	41.34	41.35	42.04	39.95	40.63	42.12	41.20	41.96	44.61	43.20	41.68	43.22
TiO_2	0.82	0.87	0.89	1.03	0.77	0.39	2.12	2.48	1.34	1.91	1.44	0.96	0.45	1.19	1.47
Al_2O_3	6.74	4.51	9.42	10.79	11.76	14.20	13.71	11.73	10.76	12.58	13.53	10.77	15.03	13.35	11.63
FeO	16.06	18.04	20.72	19.83	20.99	18.91	17.26	16.47	17.31	14.15	13.68	15.34	15.66	16.20	16.53
MnO	0.65	0.78	1.30	1.17	0.51	0.15	0.29	0.19	0.41	0.19	0.15	0.28	0.16	0.28	0.28
MgO	13.13	12.18	8.83	8.94	8.38	7.92	9.69	10.59	11.00	12.45	12.13	11.86	9.54	10.72	11.02
CaO	11.64	11.16	11.44	11.37	11.52	10.79	11.42	11.73	11.93	11.57	11.24	11.49	10.74	11.02	11.22
Na_2O	1.35	1.62	1.32	1.32	1.33	2.01	1.93	1.63	1.30	1.95	2.21	1.30	1.73	2.12	1.23
K_2O	0.81	0.64	1.27	1.52	1.06	0.51	1.20	1.88	1.30	1.23	0.44	0.64	0.43	0.28	0.64
Total	97.80	97.90	97.84	97.31	97.66	96.92	97.56	97.32	97.47	97.22	96.76	97.26	96.94	96.83	97.23
	Structural formula on the basis of 23 oxygens														
Si	6.943	7.208	6.565	6.388	6.355	6.381	6.066	6.191	6.393	6.183	6.257	6.636	6.423	6.277	6.477
Al	1.057	0.792	1.435	1.612	1.645	1.619	1.934	1.809	1.607	1.817	1.743	1.364	1.577	1.723	1.528
Total Tetrahedral	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000
Al	0.127	0.004	0.274	0.354	0.485	0.921	0.520	0.297	0.317	0.408	0.635	0.525	1.056	0.647	0.530
Ti	0.092	0.098	0.102	0.120	0.089	0.045	0.242	0.284	0.153	0.215	0.161	0.108	0.050	0.134	0.166
Fe^{+2}	1.994	2.253	2.657	2.553	2.688	2.392	2.184	2.091	2.189	1.769	1.700	1.902	1.940	2.033	2.063
Mn	0.083	0.099	0.169	0.154	0.067	0.020	0.038	0.025	0.053	0.024	0.019	0.036	0.020	0.036	0.035
Mg	2.917	2.720	2.026	2.059	1.921	1.791	2.192	2.404	2.489	2.784	2.695	2.631	2.113	2.407	2.461
Total Octahedral	5.213	5.174	5.228	5.290	5.250	5.169	5.176	5.101	5.201	5.200	5.310	5.202	5.179	5.257	5.255
Ca	1.858	1.792	1.887	1.882	1.898	1.754	1.857	1.914	1.939	1.860	1.795	1.832	1.710	1.778	1.802
Na	0.389	0.471	0.395	0.397	0.396	0.591	0.567	0.481	0.383	0.568	0.638	0.375	0.499	0.618	0.357
K	0.154	0.123	0.249	0.299	0.208	0.099	0.231	0.364	0.251	0.236	0.084	0.121	0.082	0.054	0.123
Total large	2.401	2.386	2.531	2.578	2.502	2.444	2.655	2.759	2.573	2.664	2.517	2.328	2.291	2.450	2.282

Table 6. Electron microprobe analyses of hornblendes and mineral structural formulas on the basis of 23 Oxygens.

Sample	4723 1	4723 2	4723 3	4723 4	8130 1	8130 2	8130 3	8130 4	8142 1	8142 2	8142 3	8142 4	8142 5	5030 1	5030 2	5030 3	5030 4	5030 5
SiO_2	43.18	45.30	45.66	46.90	49.29	49.10	48.54	45.26	41.85	43.37	41.35	47.35	46.05	43.46	46.84	49.73	49.42	48.00
TiO_2	1.67	1.23	1.42	0.51	1.12	1.10	1.13	1.43	1.19	1.35	0.98	1.34	1.22	2.37	0.48	0.32	0.37	0.93
Al_2O_3	8.99	8.01	9.22	8.79	6.01	6.21	6.38	7.70	10.38	9.31	12.08	6.73	8.34	10.99	10.94	5.76	7.19	7.06
FeO	19.06	16.82	13.13	10.71	11.56	11.97	12.40	19.22	19.72	18.30	19.55	14.81	14.68	12.74	13.73	12.88	9.18	13.25
MnO	0.41	0.65	0.23	0.16	0.33	0.33	0.38	0.43	0.53	0.46	0.37	0.44	0.47	0.18	0.23	0.18	0.20	0.32
MgO	10.11	12.05	13.10	15.55	16.99	16.82	16.27	11.03	9.32	10.53	8.74	10.06	13.82	13.66	12.67	15.14	17.11	15.92
CaO	11.65	11.50	12.24	12.17	10.67	10.87	10.72	10.52	11.36	11.79	11.40	11.17	10.78	11.46	10.37	12.55	12.14	10.75
Na_2O	1.20	1.22	1.25	1.26	1.22	1.30	1.23	1.19	1.21	1.18	1.26	1.12	1.48	2.00	1.31	0.84	1.12	1.40
K_2O	1.10	0.98	0.84	0.53	0.28	0.34	0.29	0.58	1.52	1.21	1.06	0.52	0.42	0.81	0.25	0.51	0.27	0.35
Total	97.38	97.76	97.09	96.58	97.48	98.03	97.33	97.35	97.05	97.51	96.78	93.54	97.26	97.67	96.81	97.90	96.99	97.97
	Structural formula on the basis of 23 oxygens																	
Si	6.592	6.789	6.756	6.867	7.126	7.084	7.067	6.842	6.453	6.590	6.361	7.266	6.818	6.409	6.864	7.225	7.113	6.979
Al	1.408	1.211	1.244	1.133	0.874	0.916	0.933	1.158	1.547	1.410	1.639	0.734	1.182	1.391	1.136	0.775	0.887	1.021
Total Tetrahedral	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000
Al	0.209	0.203	0.364	0.384	0.151	0.140	0.161	0.215	0.339	0.258	0.550	0.482	0.274	0.519	0.753	0.211	0.333	0.188
Ti	0.192	0.138	0.158	0.056	0.121	0.119	0.124	0.163	0.137	0.155	0.113	0.155	0.136	0.263	0.053	0.035	0.040	0.101
Fe^{+2}	2.424	2.100	1.619	1.307	1.392	1.439	1.504	2.420	2.533	2.317	2.505	1.894	1.811	1.566	1.677	1.559	1.100	1.605
Mn	0.054	0.082	0.028	0.020	0.040	0.041	0.047	0.055	0.069	0.059	0.049	0.057	0.059	0.023	0.029	0.022	0.025	0.040
Mg	2.300	2.691	2.890	3.394	3.662	3.617	3.531	2.485	2.141	2.385	2.005	2.300	3.050	3.003	2.766	3.277	3.670	3.450
Total Octahedral	5.179	5.214	5.459	5.161	5.366	5.356	5.367	5.338	5.219	5.147	5.222	4.888	5.330	5.374	5.278	5.104	5.168	5.384
Ca	1.906	1.847	1.940	1.909	1.654	1.679	1.672	1.703	1.877	1.920	1.879	1.836	1.710	1.811	1.627	1.953	1.873	1.675
Na	0.355	0.355	0.358	0.356	0.343	0.364	0.348	0.350	0.360	0.347	0.374	0.333	0.425	0.572	0.372	0.236	0.312	0.395
K	0.214	0.188	0.159	0.100	0.052	0.062	0.053	0.112	0.298	0.234	0.207	0.102	0.079	0.152	0.046	0.094	0.049	0.064
Total large	2.475	2.390	2.457	2.365	2.049	2.105	2.073	2.165	2.535	2.501	2.460	2.271	2.214	2.535	2.045	2.263	2.234	2.134

Table 6. (cont'd)

Sample	5044 1	5044 2	5044 3	5044 4	5044 5	5045 1	5045 2	5045 3	5045 4	5045 5	8035 1	8035 2	8035 3	8035 4	8035 5
SiO_2	48.50	42.18	43.43	48.52	46.79	48.55	43.96	43.63	47.71	47.93	44.81	45.97	44.49	44.33	45.90
TiO_2	1.05	1.07	2.07	1.27	1.28	1.05	2.05	1.87	1.09	1.28	1.95	1.89	2.26	1.80	1.26
Al_2O_3	6.63	13.00	10.43	6.23	6.63	6.54	10.51	10.85	7.23	6.80	9.75	9.58	8.96	11.33	8.94
FeO	13.06	12.71	12.99	12.80	15.19	12.97	13.61	12.33	14.06	12.56	10.31	9.53	14.45	10.49	15.14
MnO	0.36	0.12	0.23	0.35	0.62	0.38	0.39	0.20	0.42	0.28	0.18	0.12	0.46	0.10	0.39
MgO	15.64	13.23	14.23	15.80	13.34	15.78	13.84	14.39	14.78	16.24	16.24	16.77	13.56	15.67	13.50
CaO	11.15	11.89	11.28	11.21	11.80	10.81	11.24	11.18	10.90	10.75	11.37	11.01	11.31	11.11	10.99
Na_2O	1.25	2.19	2.01	1.22	1.41	1.26	1.82	1.83	1.37	1.37	1.85	1.92	1.62	2.15	1.54
K_2O	0.32	0.57	0.74	0.37	0.83	0.29	0.71	0.56	0.41	0.33	0.51	0.59	0.96	0.35	0.61
Total	97.96	96.96	97.42	97.77	97.87	97.63	98.13	96.83	97.96	97.54	96.96	97.38	98.06	97.33	98.26
	Structural formula on the basis of 23 Oxygens														
Si	7.046	6.269	6.432	7.060	6.943	7.066	6.468	6.457	6.973	6.980	6.558	6.654	6.588	6.456	6.750
Al	0.954	1.731	1.568	0.940	1.057	0.934	1.532	1.543	1.027	1.020	1.442	1.346	1.412	1.544	1.250
Total Tetrahedral	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000
Al	0.181	0.546	0.252	0.129	0.102	0.188	0.291	0.349	0.219	0.148	0.239	0.288	0.151	0.401	0.299
Ti	0.114	0.120	0.231	0.139	0.143	0.115	0.226	0.208	0.119	0.140	0.214	0.205	0.251	0.197	0.139
Fe^{+2}	1.580	1.574	1.602	1.552	1.877	1.572	1.669	1.520	1.712	1.524	1.257	1.150	1.782	1.273	1.855
Mn	0.044	0.016	0.029	0.044	0.078	0.047	0.049	0.026	0.052	0.035	0.023	0.014	0.057	0.012	0.049
Mg	3.387	2.930	3.140	3.426	2.950	3.422	3.036	3.174	3.220	3.524	3.542	3.618	2.993	3.401	2.958
Total Octahedral	5.306	5.186	5.254	5.290	5.150	5.354	5.271	5.277	5.322	5.371	5.275	5.275	5.234	5.284	5.300
Ca	1.735	1.893	1.790	1.748	1.875	1.685	1.771	1.772	1.706	1.678	1.783	1.708	1.795	1.734	1.731
Na	0.353	0.630	0.578	0.343	0.405	0.356	0.519	0.524	0.387	0.386	0.524	0.539	0.464	0.606	0.440
K	0.060	0.108	0.140	0.069	0.157	0.054	0.134	0.107	0.077	0.062	0.095	0.109	0.181	0.064	0.115
Total Large	2.148	2.631	2.508	2.160	2.437	2.095	2.424	2.403	2.170	2.146	2.402	2.356	2.440	2.404	2.286

Table 6. (cont'd)

Sample	8041 1	8041 2	8041 3	8041 4	8041 5	8038 1	8038 2	8038 3	8038 4	8038 5	8034 1	8034 2	8034 3	8034 4	8034 5
SiO_2	41.79	47.01	45.23	40.85	44.40	46.44	44.33	47.67	46.53	43.21	38.88	44.28	42.92	45.13	45.63
TiO_2	1.86	1.47	2.03	2.61	2.06	1.31	1.71	1.11	1.11	2.05	3.13	1.61	1.94	1.67	1.22
Al_2O_3	12.36	7.59	9.15	12.11	10.44	8.75	9.45	7.39	7.17	11.28	13.37	9.99	8.98	8.04	8.70
FeO	12.33	13.92	13.78	13.94	12.51	13.52	13.88	13.54	14.48	10.99	14.31	15.74	20.93	15.99	15.35
MnO	0.15	0.36	0.37	0.16	0.18	0.48	0.37	0.45	0.54	0.12	0.23	0.40	0.58	0.79	0.35
MgO	14.39	15.19	14.21	13.31	14.72	14.65	14.26	15.06	13.82	15.28	11.89	12.59	9.13	12.55	13.28
CaO	11.14	10.86	10.94	11.40	11.19	10.41	10.83	10.96	11.59	11.03	11.79	10.75	11.42	11.11	11.06
Na_2O	2.08	1.37	1.71	2.36	2.01	1.41	1.78	1.17	1.22	2.12	2.09	1.71	1.44	1.55	1.59
K_2O	0.86	0.44	0.62	0.76	0.29	0.41	0.57	0.37	0.54	0.27	1.62	0.72	1.27	0.85	0.59
Total	96.95	98.21	98.03	97.48	97.80	97.38	97.17	97.73	96.96	96.35	97.29	97.78	98.62	97.69	97.77
	Structural formula on the basis of 23 Oxygens														
Si	6.211	6.860	6.643	6.110	6.498	6.813	6.581	6.962	6.920	6.385	5.891	6.583	6.542	6.747	6.757
Al	1.789	1.140	1.357	1.890	1.502	1.187	1.419	1.038	1.080	1.615	2.109	1.417	1.458	1.253	1.243
Total Tetrahedral	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000
Al	0.376	0.166	0.227	0.244	0.299	0.326	0.235	0.235	0.177	0.349	0.278	0.333	0.155	0.163	0.276
Ti	0.208	0.161	0.225	0.293	0.277	0.145	0.190	0.122	0.124	0.227	0.356	0.180	0.222	0.188	0.136
Fe^{+2}	1.527	1.693	1.686	1.737	1.526	1.652	1.716	1.648	1.794	1.353	1.806	1.950	2.628	1.992	1.894
Mn	0.019	0.045	0.046	0.020	0.023	0.059	0.047	0.056	0.068	0.015	0.030	0.051	0.075	0.101	0.044
Mg	3.188	3.303	3.110	2.967	3.212	3.204	3.155	3.279	3.063	3.365	2.684	2.790	2.075	2.797	2.930
Total Octahedral	5.318	5.368	5.294	5.261	5.337	5.386	5.343	5.340	5.226	5.309	5.054	5.304	5.155	5.241	5.280
Ca	1.774	1.698	1.719	1.826	1.754	1.636	1.722	1.715	1.846	1.747	1.913	1.713	1.864	1.779	1.755
Na	0.599	0.387	0.487	0.684	0.569	0.402	0.511	0.331	0.351	0.606	0.614	0.491	0.426	0.450	0.456
K	0.162	0.082	0.116	0.145	0.053	0.076	0.109	0.069	0.102	0.051	0.312	0.137	0.248	0.163	0.111
Total Large	2.535	2.167	2.322	2.655	2.376	2.114	2.342	2.115	2.299	2.404	2.839	2.341	2.538	2.392	2.322

Table 6. (cont'd)

SCALED VARIMAX FACTOR SCORES

Variables	Factor 1	Factor 2	Factor 3
SiO_2	2.174	0.149	0.395
TiO_2	0.173	0.293	-1.141
Al_2O_3	-0.310	0.776	-1.602
FeO	0.258	2.014	0.325
MnO	0.520	1.014	0.687
MgO	1.884	-0.656	-0.810
CaO	0.440	0.941	-0.202
Na_2O	0.001	0.045	-1.923
K_2O	-0.251	1.374	-0.064

Table 7. Scaled varimax factor scores. Q- mode factor analysis of hornblende microprobe data.

NORMALIZED VARIMAX FACTOR COMPONENTS

		COMM.	FACTOR 1	FACTOR 2	FACTOR 3
1	2989	0.9729	0.5550	0.3885	-0.0565
2	2927	0.8999	0.5961	0.3773	-0.0265
3	2340	0.9218	0.1079	0.8749	-0.0172
4	2915	0.9297	0.0627	0.8903	-0.0471
5	2913	0.9687	0.0442	0.8537	-0.1027
6	5000 1	0.7681	0.0253	0.5367	-0.4379
7	5000 2	0.9967	0.0216	0.5099	-0.4685
8	5000 3	0.8890	0.0413	0.5891	-0.3697
9	5000 4	0.9512	0.1363	0.6788	-0.1850
10	5000 5	0.9707	0.0982	0.3407	-0.5611
11	4729 1	0.9665	0.1192	0.1809	-0.6999
12	4729 2	0.9525	0.3550	0.4124	-0.2326
13	4729 3	0.7639	0.0953	0.3837	-0.5209
14	4729 4	0.8974	0.0960	0.2998	-0.6042
15	4729 5	0.9449	0.2182	0.4998	-0.2820
16	4723 1	0.9683	0.1672	0.7201	-0.1127
17	4723 2	0.9912	0.3941	0.5330	-0.0729
18	4723 3	0.8678	0.4439	0.3194	-0.2367
19	4723 4	0.8218	0.7210	0.0936	-0.1853
20	8130 1	0.9872	0.9029	0.0108	-0.0863
21	8130 2	0.9951	0.8732	0.0243	-0.1025
22	8130 3	0.9879	0.8748	0.0316	-0.0937
23	8130 4	0.8628	0.3985	0.5243	-0.0773
24	8142 1	0.9774	0.0683	0.8436	-0.0881
25	8142 2	0.9733	0.1849	0.7149	-0.1001
26	8142 3	0.9675	0.0468	0.8023	-0.1509
27	8142 4	0.9207	0.5714	0.3819	-0.0467
28	8142 5	0.9701	0.6052	0.1909	-0.2039
29	5030 1	0.9743	0.2334	0.1799	-0.5867
30	5030 2	0.7943	0.6301	0.1310	-0.2389
31	5030 3	0.7982	0.8610	0.1266	-0.0124
32	5030 4	0.8487	0.9009	0.0154	-0.0837
33	5030 5	0.9813	0.8081	0.0540	-0.1379
34	5044 1	0.9985	0.8369	0.0689	-0.0942
35	5044 2	0.9169	0.1693	0.1815	-0.6492
36	5044 3	0.9866	0.2754	0.1624	-0.5622
37	5044 4	0.9948	0.8381	0.0668	-0.0951
38	5044 5	0.9600	0.5590	0.3492	-0.0918
39	5045 1	0.9919	0.8581	0.0493	-0.0925
40	5045 2	0.9860	0.3178	0.2187	-0.4635
41	5045 3	0.9965	0.3198	0.1226	-0.5577
42	5045 4	0.9907	0.7528	0.1215	-0.1257
43	5045 5	0.9874	0.8063	0.0348	-0.1569
44	8035 1	0.9791	0.4439	0.0460	-0.5101
45	8035 2	0.9815	0.4788	0.0203	-0.5009
46	8035 3	0.9510	0.3591	0.3109	-0.3300
47	8035 4	0.9975	0.3284	0.0313	-0.6403
48	8035 5	0.9906	0.5066	0.2529	-0.2386
49	8041 1	0.9666	0.1714	0.1470	-0.6816
50	8041 2	0.9852	0.7044	0.1128	-0.1828
51	8041 3	0.9728	0.4432	0.1723	-0.3846
52	8041 4	0.9760	0.1047	0.1846	-0.7108
53	8041 5	0.9860	0.3531	0.0777	-0.5692
54	8038 1	0.9278	0.6676	0.1136	-0.2189
55	8038 2	0.9771	0.4096	0.1671	-0.4233
56	8038 3	0.9917	0.7954	0.1092	-0.0954
57	8038 4	0.9792	0.6550	0.2579	-0.0371
58	8038 5	0.9929	0.2806	0.0357	-0.6837
59	8034 1	0.9145	0.0288	0.3710	-0.6002
60	8034 2	0.9649	0.3202	0.3214	-0.3584
61	8034 3	0.9674	0.1048	0.7826	-0.1126
62	8034 4	0.9455	0.4102	0.4301	-0.1597
63	8034 5	0.9890	0.4883	0.2610	-0.2506

Table 8. Normalized varimax factor components. Q-mode factor analysis of hornblende microprobe data.

mainly the influence of the oxides SiO_2-MgO; Factor 2, the oxides FeO-K_2O-MnO; and Factor 3, the oxides Na_2O-Al_2O_3-TiO_2. Tables 7 and 8 show the relationship between the oxides and the factors and the loadings of the samples on the three factors.

Three cross-plots of the three factors result in interesting relationships (Figs. 26,27 and 28). In all three plots the Upper Cretaceous detrital hornblende samples (with the exception of two samples) fall on one side of an arbitrary compositional line drawn on these plots, while the Paleocene detrital hornblende samples plot on both sides of the line. All the Upper Cretaceous and less than half of the Paleocene samples contain less FeO-K_2O-MnO (Factor 2) and more SiO_2-MgO (Factor 1) than the rest of the Paleocene samples. The igneous hornblende samples fall on both sides of the line, with those of radiometric dates (K-Ar) 56, 57 and 96 m.y. on the Paleocene detrital hornblende side and those of radiometric dates 58 and 163 m.y. on the Upper Cretaceous and Paleocene detrital hornblende side.

The following provenance model is suggested, assuming that the above chemical differences reflect two populations of hornblende derived from two sources: in Late Cretaceous time source area A furnished hornblende type A to the depositional basin (Figs. 26, 27 and 28). Some of this hornblende yielded K-Ar dates ranging from 114 to 155 m.y. In Paleocene time another source area B (areal separation from source area A is unknown) became available to supply hornblende type B along with the continuous supply of type A

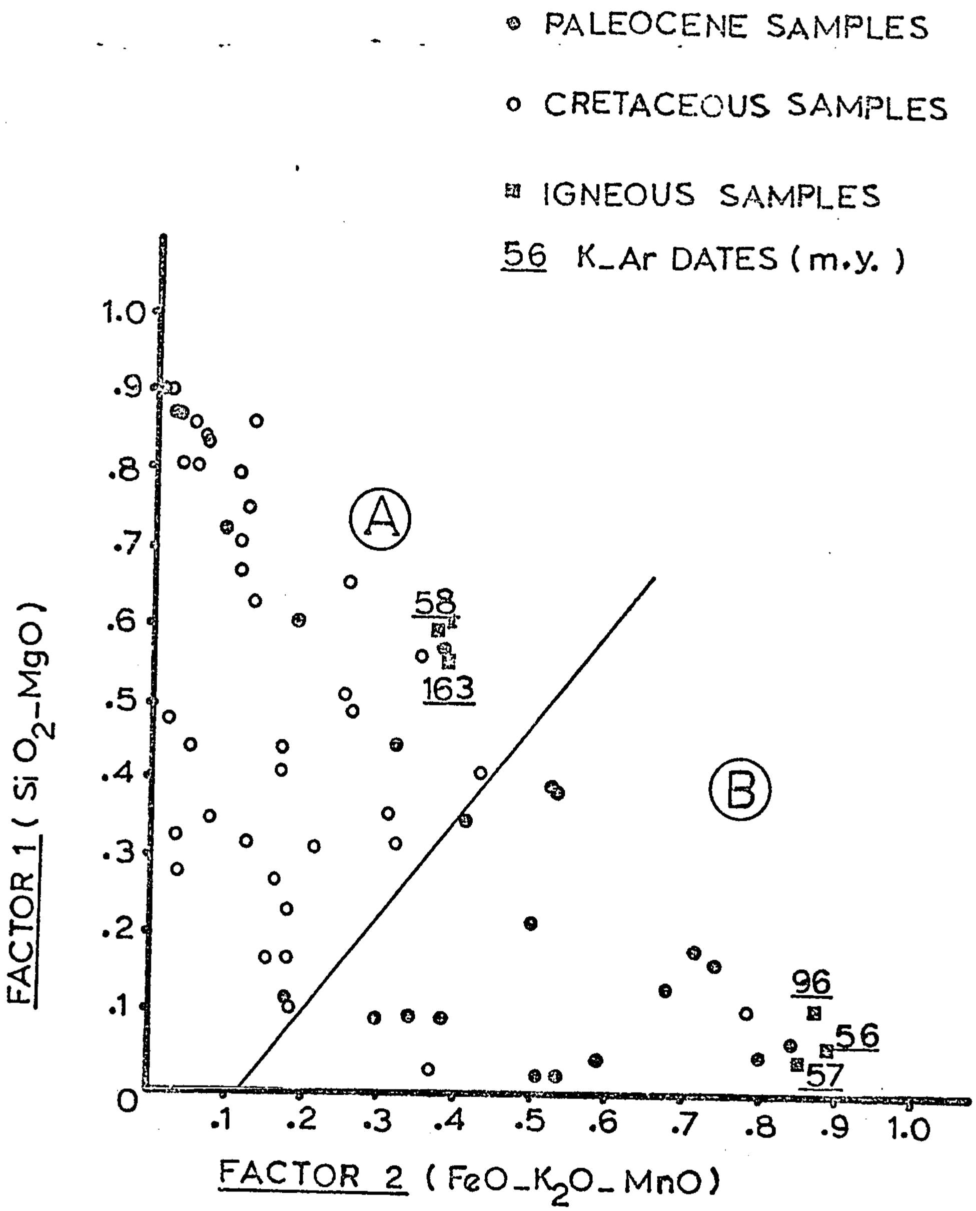


Fig. 26. Scatter plot of Factor 1 versus Factor 2 of normalized varimax factor components for Q-mode factor analysis of hornblende microprobe data. 3-factor varimax solution.

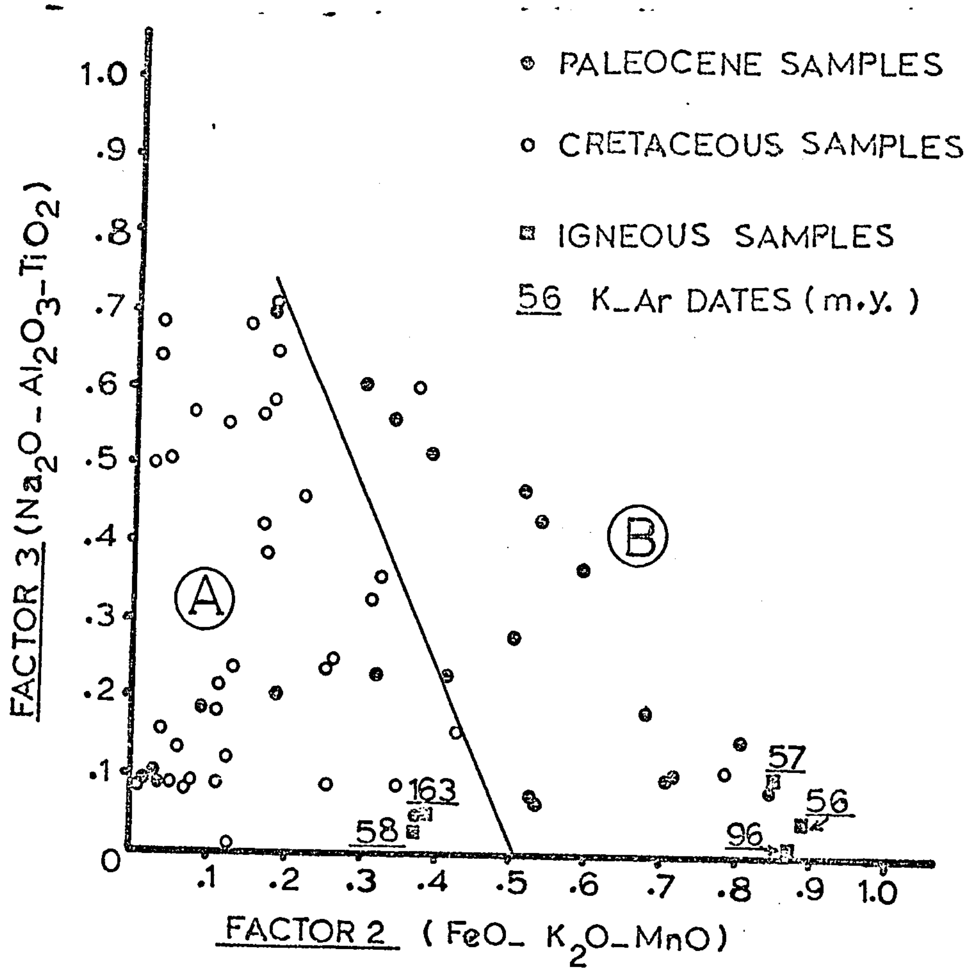


Fig. 27. Scatter plot of Factor 3 versus Factor 2 of normalized varimax factor components for Q-mode factor analysis of hornblende microprobe data. 3-factor varimax solution.

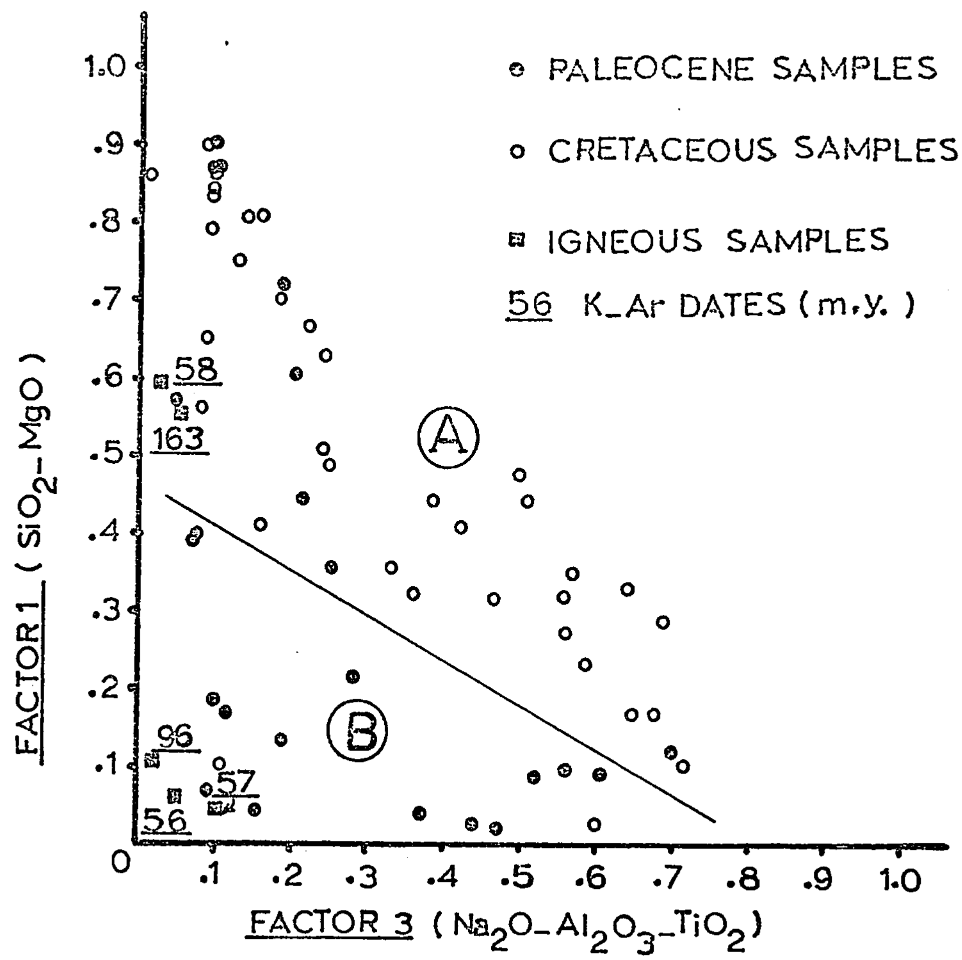


Fig. 28. Scatter plot of Factor 1 versus Factor 3 of normalized varimax factor components for Q-mode factor analysis of hornblende microprobe data. 3-factor varimax solution.

hornblende from the still existing source area A. Source area B was made available either by unroofing of a crystalline complex in the same drainage area of A-source during the Paleocene, or by change in the drainage system and tapping of an already existing source area B.

E. Grain-Surface Etching Features: Scanning Electron Microscopy

1. General Statement

Much has been written on the chemical stability and removal of certain heavy minerals by intrastratal solution in arenaceous deposits (for comprehensive reviews and references, see Boswell 1933 and 1941, Bramlette 1929 and 1941, Pettijohn 1941 and 1957, Smithson 1941 and van Andel 1959). Inferences regarding the chemical stability of heavy minerals were drawn mainly from grain-surface textural studies (e.g. Smithson, 1941) and stratigraphic distribution (e.g. Pettijohn, 1941). Pettijohn (1941 and 1957) argued that chemical stability and the removal of certain heavy minerals by intrastratal solution accounts for the apparent increase in complexity of the heavy mineral suite upward in the stratigraphic column, chemically unstable heavy minerals being gradually removed by intrastratal solutions in the older rocks. Krynine (1942) challenged Pettijohn's interpretation and attributed this phenomenon to provenance.

Certain heavy minerals in sandstones show grain-surface features that are attributed by many sedimentary petrologists to diagenetic etching by intrastratal solutions. Examples are the hacksaw terminations (notched borders) of the amphiboles, pyroxenes, staurolite, epidote and clinozoisite, and imbricate wedge markings (IWM) on garnet, sphene, staurolite, etc. However, some workers (Hubert, 1971, p. 459) cautioned the interpretation of "...all raggedly angular, hacksaw grains of garnet, staurolite, augite and hornblende as having been produced by intrastratal solution." Hubert believes that such features could possibly have developed during initial breakage of grains at the source area or during transportation.

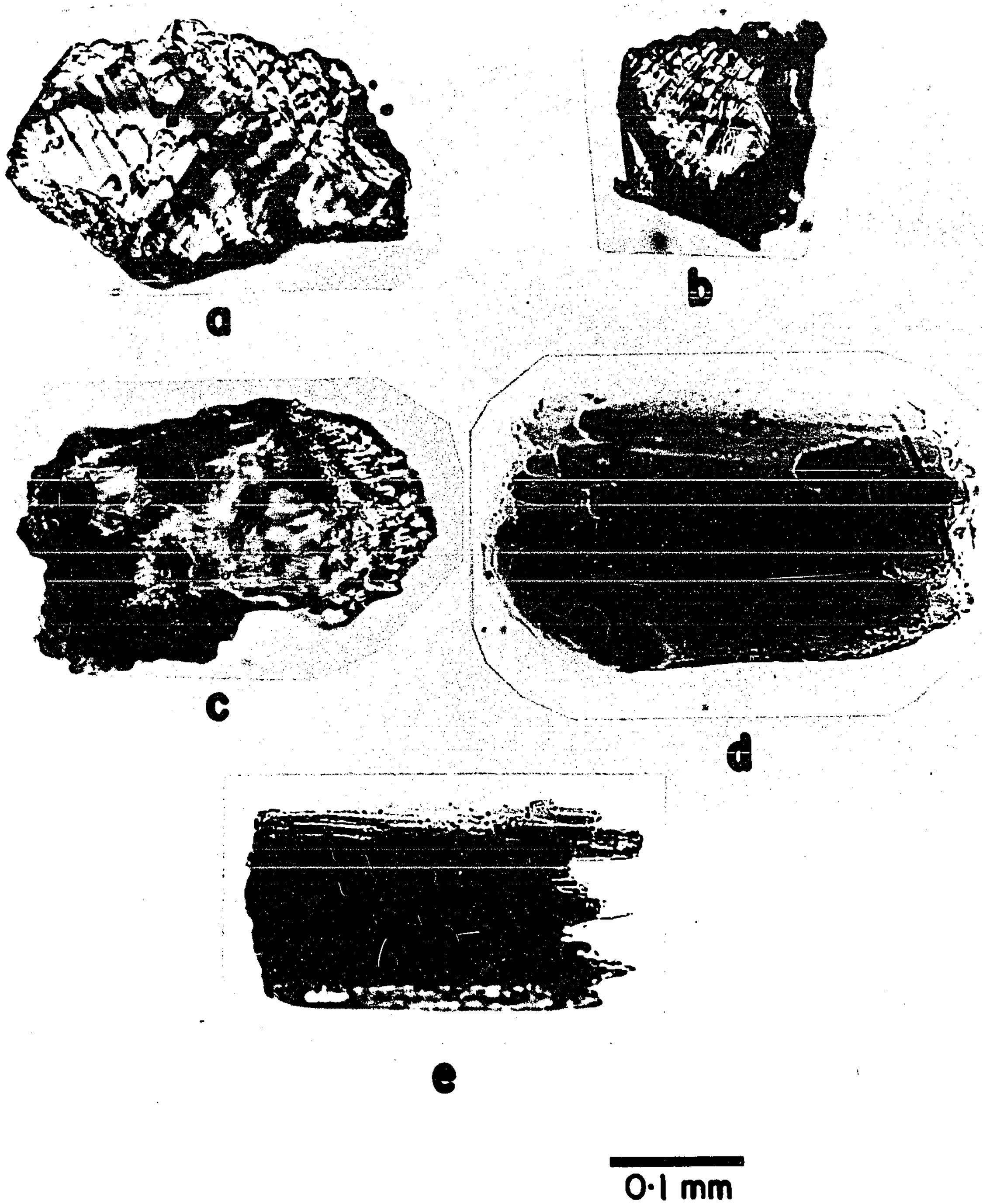
Some of the above-mentioned features have been successfully duplicated in the laboratory by etching the heavy mineral grains with corrosive solutions (Bramlette, 1929; McMullen, 1959). This section describes a petrographic and scanning electron microscopic study of diagenetic etch features on grains of selected heavy minerals.

2. Etch Features Viewed with the Petrographic Microscope

Garnet: Garnet has been reported by several heavy-mineral workers to show imbricate wedge markings (IWM) (Fig. 29a). Bramlette (1929) showed two photomicrographs of such a feature on garnet and attributed it to diagenetic chemical etching. Bramlette was successful in reproducing an identical feature in the laboratory by placing crushed garnet grains in hydrofluoric acid. McMullen (1959) encountered a similar feature in spessartite from the Upper Cretaceous Cardium Formation of Western Canada. He also successfully

Fig. 29. Photomicrographs illustrating grain-surface textures of naturally etched heavy minerals from Upper Cretaceous-Paleocene sandstones of Alberta.

(a) Orange garnet showing imbricate wedge markings.
(b) Sphene showing imbricate wedge markings.
(c) Staurolite showing imbricate wedge markings and hacksaw termination.
(d) Hornblende showing cleavage-bounded segments in various stages of "retreat".
(e) Hornblende with hacksaw termination.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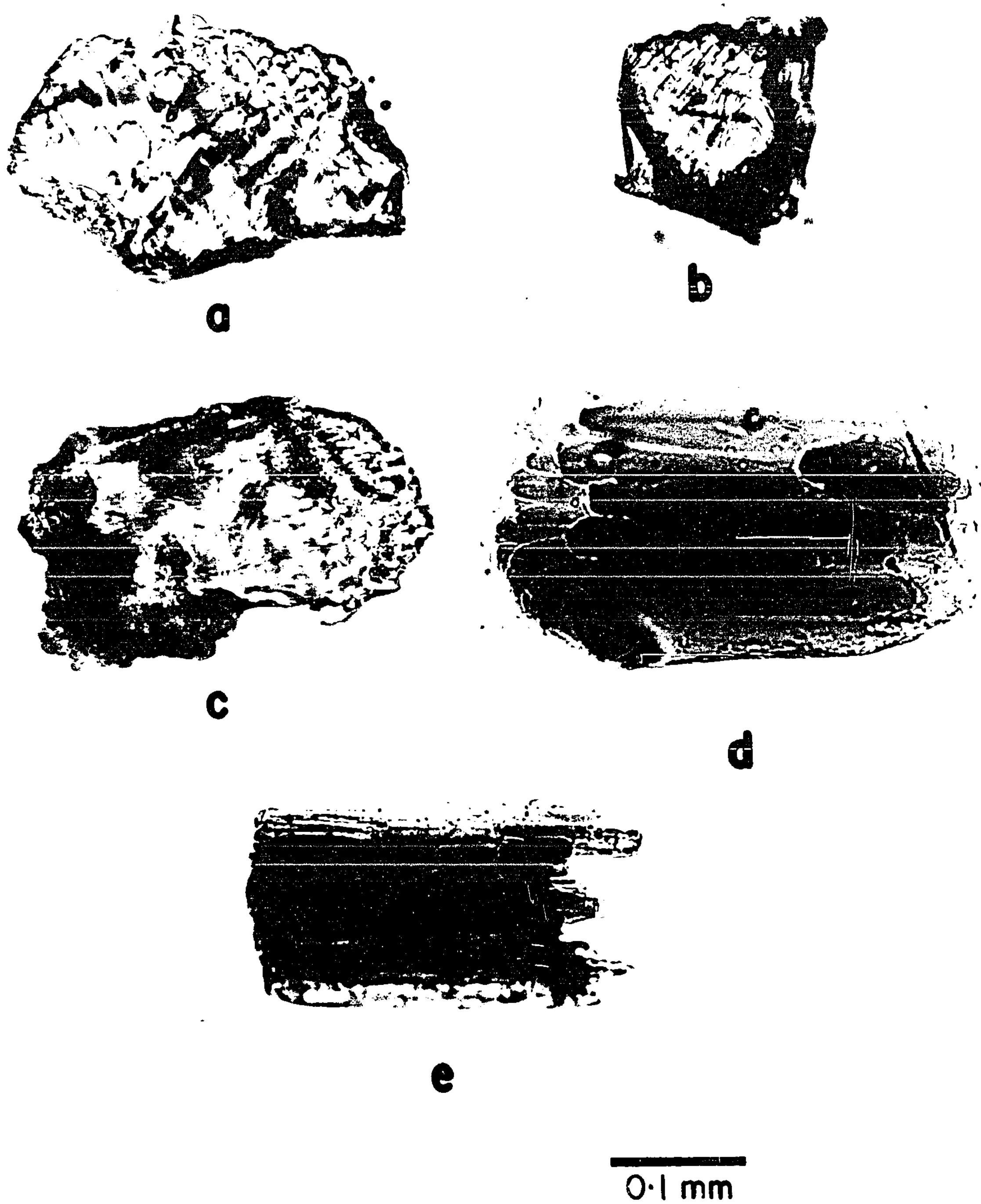
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reproduced this feature by placing crushed spessartite in a 1N solution of NaOH for "several days". The presence of fresh apatite, which is soluble in even weak acids, with the naturally etched garnet led McMullen to conclude that the natural solutions that etched the garnets of the Cardium Formation "...were more likely to have been basic than acidic." McMullen regarded these IWM to be parallel to the dodecahedral crystal boundaries of garnet. Another less commonly observed feature that has been attributed to chemical etching is "pitting" (McMullen, 1959; Beveridge, 1960). Beveridge studied many samples from Tertiary formations in the Santa Cruz Mountains of California, and noted that "...surface etching is a common feature of these garnets." This etching feature took the shape of numerous elliptical pits that covered grain surfaces and imparted a "microscaly" appearance to the garnet. McMullen (1959) thought that pitting on garnet is the result of differential solution caused by variations in the composition of garnet.

In the Upper Cretaceous and Paleocene sandstones of Alberta studied by the writer, garnet shows the typical IWM (Fig. 29a). Data at hand suggest that etching of garnet is more common in deeply buried sandstones. This is probably a result of higher temperature and/or pressure which promotes chemical etching. It was found that within a single heavy mineral sample, some garnet grains of a given color variety would be etched, while other grains of the same color appear fresh. All color varieties appear to exhibit this variation in etching to some extent.

Replacement of garnet by calcite was observed to be very common in the Upper Cretaceous and Paleocene sandstones of Alberta. Clay-sized minerals are less commonly observed to replace garnet. The replacement is generally partial. However, in a few instances complete replacement by calcite was observed, but garnet identification could be made on the still preserved (in calcite) shape of the grain and the IWM. Calcite replacement is more readily detected under crossed-nicols; under polarized light such replacement can easily be overlooked. In some grains the calcite-garnet replacement "front" has a hacksaw outline suggesting that replacement proceeds along crystallographic planes. However, the majority of replacements are irregular and probably take place along fractures and chemical composition irregularities, and proceed inward. Clay-sized replacement material is easily recognized under plane-polarized light because it gives the grain a turbid appearance. Volumetrically significant replacement of garnet by calcite and clay-sized minerals has been reported by Potter (1968, p. 1343). He relates garnet chemical stability to rock permeability and lithology.

Sphene: Sphene has been reported by some workers to exhibit etch features, IWM and hacksaw terminations (Boswell, 1941; Beveridge, 1960). These features were also observed in sphene from Upper Cretaceous and Paleocene sandstones of Alberta. In fact, they are locally so characteristic of sphene that they were used occasionally for quick distinction from zircon (Fig. 29b). As with garnet, some sphene grains in the same sample appear to be fresh. The writer believes that the hacksaw terminations and IWM are a single feature; hacksaw appearance develops when the IWM occur on the grain's terminations. Replacement of sphene by calcite is rare.

Staurolite: Smithson (1941) noticed that much of the staurolite of the Jurassic and Triassic of Yorkshire shows etching which is "...somewhat similar to that of garnet", that is, with the imbricate wedge markings. These etched grains have ragged outlines "...the direction of the sharper spikes being usually along the c-axis as shown by the pleochroism."

In the Upper Cretaceous and Paleocene sandstones of Alberta staurolite was encountered occasionally. These that are etched show identical features to those described by Smithson (1941), and similar to those shown by garnet (Fig. 29c). Partial replacement of staurolite by calcite was also observed occasionally. One grain was seen to have well-developed hacksaw terminations and was surrounded with sparry calcite. Under crossed-nicols, calcite is seen to go beyond the hacksaw terminations towards the center of the grain. This could be interpreted as calcite replacing staurolite. Alternatively, this calcite could be merely overlapping the staurolite grain rather than replacing it.

Hornblende: Hacksaw terminations, fragility and skeletal appearance shown by many detrital hornblendes have been reported frequently in literature dealing with heavy minerals. Photomicrographs of altered, relic and etched hornblende are shown by Chi (1966) and Walker (1967).

In the Upper Cretaceous and Paleocene sandstones of Alberta, hornblende grains locally comprise the bulk of the non-opaque heavy mineral yield (excluding biotite). Generally these grains are prismatic, fragile and skeletal-looking and commonly show hacksaw terminations (Figs. 29d and 29e), as compared to more stubby-looking, fresh hornblende of crystalline rocks.

Epidote and clinozoisite from the Upper Cretaceous and Paleocene sandstones of Alberta are less commonly observed to have hacksaw terminations. This observation confirms the published accounts of the stability of epidote, where epidote is believed to be more resistant to chemical action than sphene and hornblende, and probably equal to or more resistant than the iron-rich garnet (Pettijohn et al., 1972, p. 305).

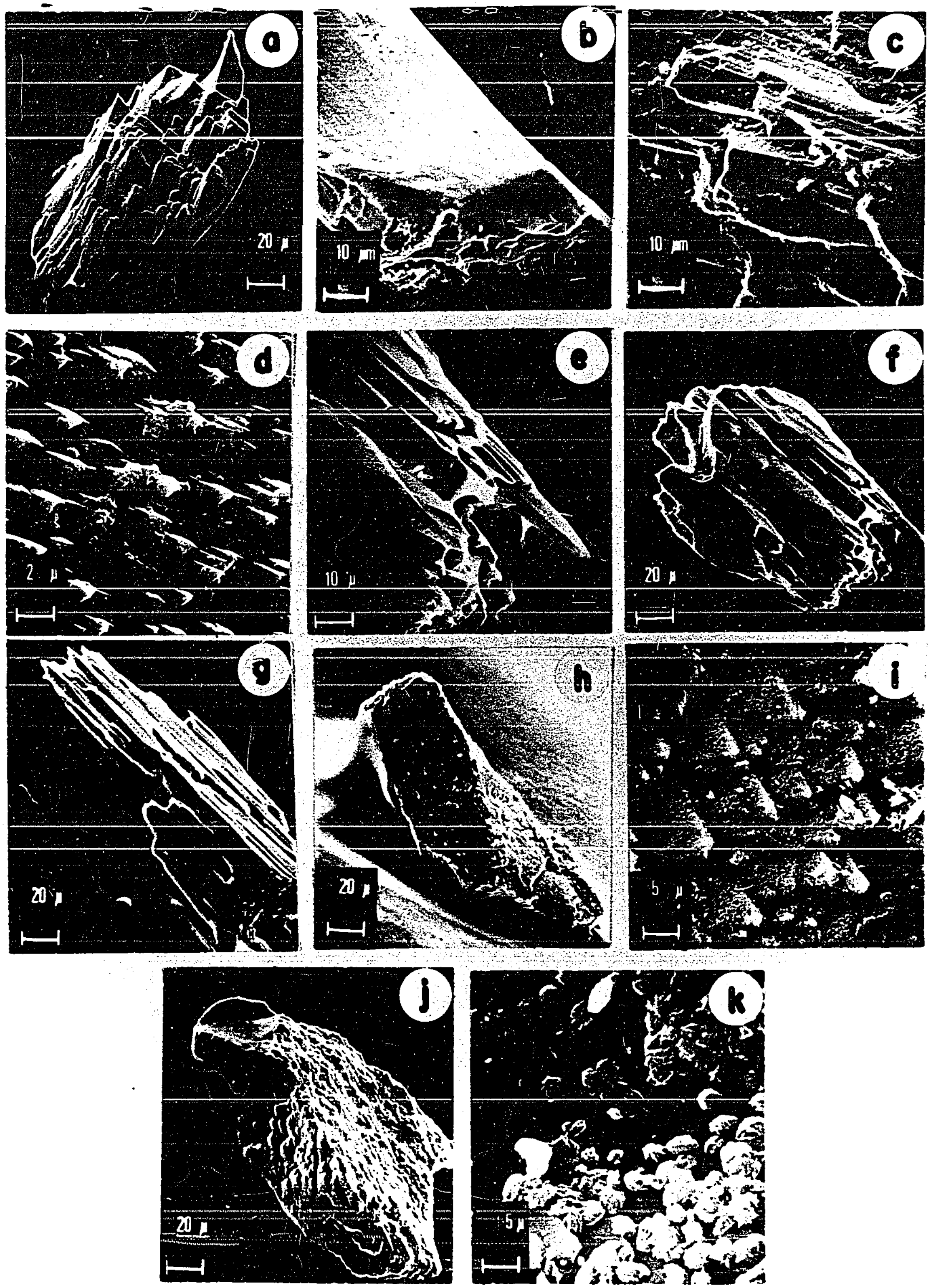
3. Scanning Electron Microscopy

To determine the manner by which etching features described above have developed, one has to resort to higher magnification than the ordinary petrographic microscope. Hornblende and garnet from Upper Cretaceous and Paleocene sandstones of Alberta were handpicked and prepared according to a standard technique (Krinsley, 1971), and viewed with a Cambridge Stereoscan Model S4 scanning electron microscope.

Hornblende: The outstanding feature of naturally etched hornblende viewed under the SEM is the smoothness of the cleavage plates (Figs. 30a and 30b) as contrasted with freshly broken cleavage fragments from crystalline

Fig. 30. Scanning electron photomicrographs of naturally etched hornblende and garnet from Upper Cretaceous-Paleocene sandstones of Alberta (a, b and d-k) and fresh hornblende from syenite (c).

(a) Naturally etched hornblende grain showing smooth cleavage surfaces and hacksaw appearance.
(b) Hornblende with smooth prism surface showing "swollen" termination with irregular etch pattern of rounded ridges and depressions.
(c) Fresh hornblende from syenite. Note rough, unetched prism face.
(d) Detail of the termination of a naturally etched hornblende. Note the regular geometric pattern reflecting the hornblende cleavage, possibly produced by slow etching.
(e) Hacksaw termination of a naturally etched hornblende. Note the non-uniform length of the "teeth" produced by slow etching.
(f) Same grain as in 2e illustrating an intermediate stage of slow etching. Note the "retreating" cleavage plates along the length of the grain, resulting from etching.
(g) An advanced stage of etching. Note fragility and appearance of "etch-holes".
(h) Naturally etched garnet with one surface entirely covered by imbricate wedge markings.
(i) Same grain as in 2h. Note the many sizes of the IWM which are covered with fine, rosette-shaped "particles".
(j) Naturally etched garnet partially covered with IWM. Note the smooth upper tip of the grain.
(k) Rosette-shaped clay mineral (?) particles covering a naturally etched garnet grain.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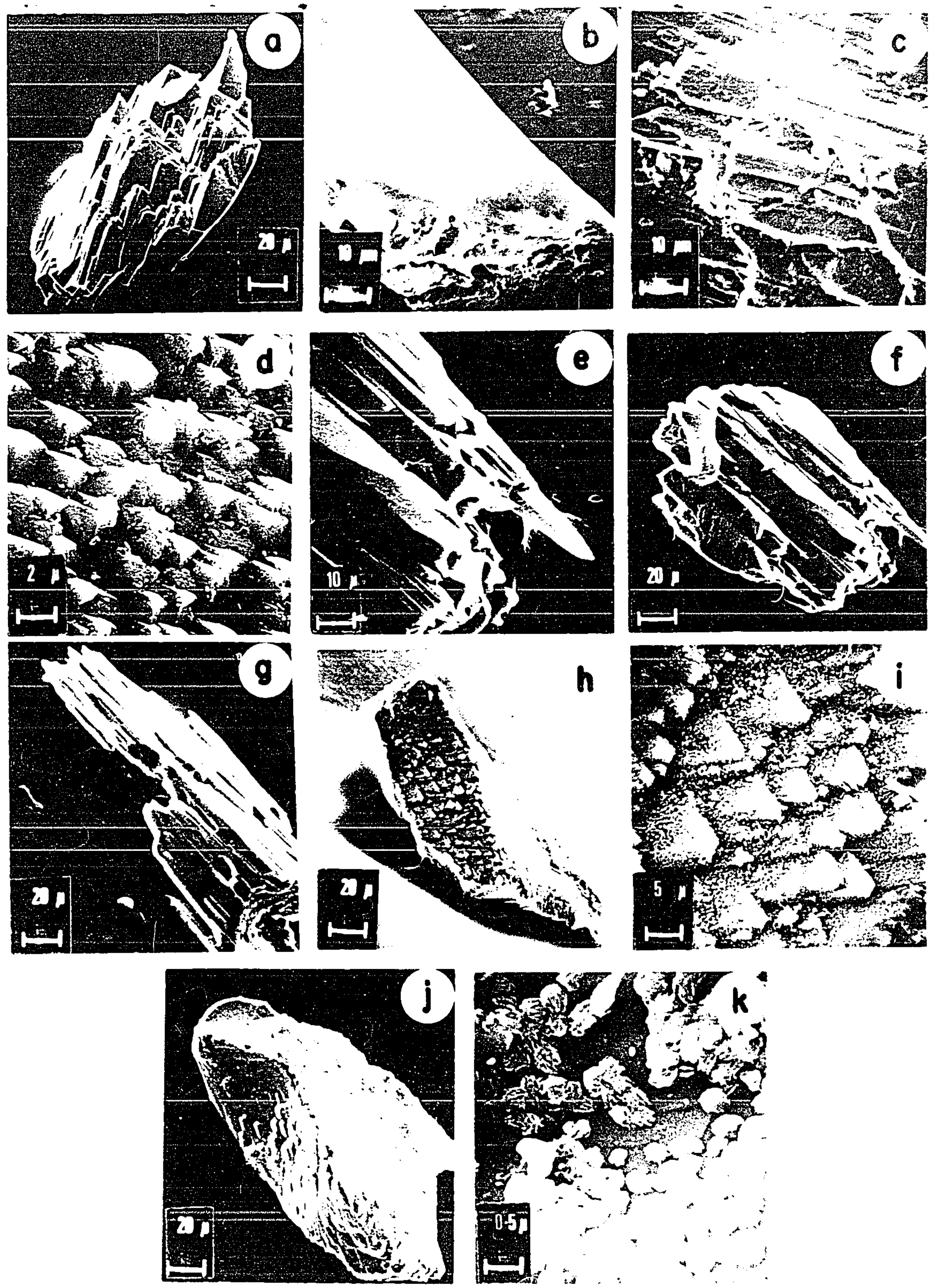
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rocks (Fig. 30c). Terminations of the detrital grains where two sets of cleavage meet the surface are ragged and assume on of the following forms: (1) Terminations that do not follow the pattern of intersection of the two sets of cleavage (Fig. 30b). The ragged surfaces here consist of irregular, rounded ridges and depressions. (2) Regular, geometric terminations controlled by intersection of the two sets of cleavage. The ridges are either small and of uniform size (Fig. 30d) or large and not uniform in size, resulting in the formation of hacksaw terminations (Figs. 30a, 30e and 30f). The first type of grain termination probably develops when the etching process is strong and fast and gives insufficient time for the etching solution to differentially etch along the two cleavage sets. In this case, the etching proceeds simultaneously along cleavages and the area in between, forming an irregular pattern. Slow etching probably proceeds along the cleavages and a regular pattern of the second type develops.

It is pertinent at this stage to speculate on the stages of the development of the hacksaw feature and the skeletal and fragile nature and eventual disappearance of many hornblende grains. Natural etching solutions (intrastratal solutions) are more likely to work preferentially on those parts of the grain that show more relief and surface area. Terminations of the freshly deposited hornblende, where cleavage intersections give them raggedness, are probably optimum sites for etching. Etching proceeds from these terminations, working inwards. Simultaneously, cleavage faces on the prisms will be etched smooth of any irregularities inherited from breakage at the source or imparted to them during transportation (Figs. 30a and 30b). Etching will eventually strip the cleavage plates one by one in a manner exemplified by Figure 30f; terminations of the cleavage prism retreat before the etching solution until the prism completely dissolves away. Figures 30f and 30g show this process in its different stages of development. If this process is carried to completion, the entire grain disappears. If it terminates before completion, the process leaves behind fragile, skeletal-looking grains which commonly, though not necessarily, display hacksaw terminations (Fig. 30g). Etching may localize along cleavage traces resulting in removal of parts of cleavage faces, leaving holes (Fig. 30g).

Garnet: Only naturally etched grains that showed IWM were hand-picked for SEM viewing. In the five grains examined, this feature entirely covered some grain surfaces (Fig. 30h) and only partially covered others (Fig. 30j).

These IWM have equilateral outlines (Fig. 30i) with apical angles that range between 70 and 75 degrees. There are two general size groups (Fig. 30i). The larger has an average length of seven microns on a side, whereas the smaller group has an average length of four microns. Even smaller IWM, having an average length of one micron, were observed on one grain. In detail these IWM have relatively smooth surfaces: however, in two grains they are uniformly covered with an abundance of particles that have a rosette form and an average size of slightly less than half a micron (Figs. 30i and 30k). The uniform distribution of these particles over the IWM surfaces (Fig. 30i) rules out the possibility that they may have resulted from contamination during preparation. They are possibly clay minerals formed as a result of the natural etching and alteration of the garnet. With further etching this layer of rosette particles would be removed with the existing "layer" of IWM in the sculpturing of another set deeper in the grain (Fig. 30j, see upper left smooth tip of the grain). The smooth grain surface of Figure 30j is lower than the adjacent part of the grain which carries the IWM. This smooth surface possibly bore a set of IWM which have since been etched, and the process arrested before the removal of the rest of the IWM. The fact that only certain surfaces of a given garnet grain show these IWM may indicate that the surfaces carrying the IWM are those that made the walls of pores in the sandstone, while the unetched surfaces were bordering a chemically inert matrix, cement or framework material. Alternatively it may have been caused by compositional variation within the garnet. The writer favors the former explanation, since compositional variation in garnet is usually of a zoned nature. One grain surface that does not carry the IWM shows very small, subcircular pits, about one half a micron in diameter, randomly and widely spaced within a hummocky surface. It is thought that all these variations in surface texture observed on garnet may represent several stages of the process that leads to the eventual elimination and disappearance of garnet. The observations and the conclusions and speculations based upon them support Smithson's (1941) hypothesis of the stages of etching and disappearance of garnet which states that "The first stage appears to be the development of a slightly mammillated surface, then of minute rhomb-pattern, and as corrosion proceeds the grain becomes etched to form a skeletal crystal with a rhombic dodecahedral structure...; while the final stage seems to be the total disappearance of the mineral." The mammillated surface mentioned by Smithson probably represents grain surfaces with very slender elongate IWM.

4. Summary and Conclusions

(a) Etching usually appears to be related to a mineral's crystallographic features (e.g. cleavage, parting and crystal faces).

(b) Imbricate wedge markings seem to be characteristic of many naturally etched minerals (e.g. garnet, sphene and staurolite).

(c) Some etch features, such as "pits", do not appear to be controlled by mineral crystallography. Chemical inhomogeneity may be the controlling factor.

(d) Fragility, skeletal appearance and, commonly, hacksaw terminations are characteristic of chemically etched hornblende, probably under both pedogenic and diagenetic conditions.

(e) Etching and eventual removal of hornblende may proceed in the following manner: (1) Etching begins on the grain's terminations and simultaneously on the grain's cleavage surfaces, which are smoothed by the etching solution; (2) differential removal of cleavage plates at the grain's terminations will result in the development of the hacksaw feature. Solution proceeds inward, during which cleavage plates retreat away from the terminations and are eventually completely removed exposing deeper cleavage plates. If solution differentially etches more severely at localized spots along cleavage traces, large volumes between cleavage traces may be removed leaving holes (Fig. 30g). If the etching process continues the grain will eventually disappear.

(f) Etching and eventual removal of garnet grains (and probably sphene and staurolite) may proceed in the following manner: (1) Initial etching sculptures imbricate wedge markings; (2) with further etching the grain is reduced to a skeletal form and eventually disappears.

(g) Not all grains of a chemically unstable heavy mineral necessarily become etched in any given sample. Some remarkably fresh grains of garnet, sphene and staurolite are found along with etched ones in the same sample. This is probably due to the distribution of the factors that control chemical etching, e.g. permeability, cement, sorting, etc. It is possible that only the grains and grain surfaces that outline pore spaces undergo chemical etching.

(h) In calcite-cemented sandstones, calcite replacement seems to be an important factor in the removal of many heavy minerals, especially garnet.

(i) It is possible that some mineral grains may have been completely dissolved away by intrastratal solution; however, it is doubtful that intrastratal solution would completely eliminate the entire population of a given heavy mineral from a sand bed on a regional scale. Irregularities in porosity and permeability of the enclosing sandstones would render this unlikely. It is also doubtful that intrastratal solutions have regional compositions uniform enough to act upon and dissolve away an entire heavy mineral population.

(j) Since the naturally etched minerals studied here coexist with an abundance of remarkably fresh apatite, and apatite is very soluble in acidic solutions, the nature of the etching solution must have been basic.

(k) The hornblende of this study was derived from a suspected source area more than 500 miles from where the samples were collected. It is unlikely that their present fragile, skeletal nature with hacksaw terminations could have originated during weathering (pedogenesis) of the source area, and survived transportation which must have been in large part as bed load. The writer believes that they are the result of solution etching after deposition.

F. Heavy Mineral Provinces

Heavy mineral provinces established in this study were generated by a Q-mode factor analysis program that was developed to handle a large number of samples by Klovan and Imbrie (1971). The field of application of factor analysis in the study of heavy minerals was pioneered by Imbrie and van Andel (1964). This section will centre on the discussion of the application of Q-mode factor analysis and the heavy mineral provinces.

1. Q-Mode Factor Analysis

"Factor analysis is a statistical technique designed to explain complex relations among many variables in terms of a few factors, which themselves represent simpler relations among fewer variables. Factor analysis only demonstrates the relations; it does not explain them. The explanation of the factors must be in the context of known information about the variables. There are several types of factor analysis. Q-mode factor analysis consists of a comparison of the samples in terms of the variables. This technique essentially evaluates the homogeneity of the sample or population being studied" (Klovan, in Hitchon et al, 1971, p. 570).

Theoretical discussion and geological applications of the factor analysis technique is to be found in Imbrie and Purdy (1962), Imbrie and van Andel (1964), Klovan (1966) and Harbaugh and Merriam (1968).

The data matrix used in this study consists of heavy mineral percentages (variables) and sample numbers (items). An Algorithm and Fortran IV program for large scale Q-mode factor analysis developed by Klovan and Imbrie (1971) and briefly called CABFAC (Calgary and Brown Factor Analysis) is here used with the IBM 360/67 computer of the University of Alberta.

Initial inspection and prior experience with the heavy mineral assemblages led the writer to divide the heavy mineral samples of the entire sequence into three, internally homogenous groups, each representing a litho-stratigraphic unit. These three groups of samples were factored separately. When the resulting factors within a single group were mapped a geographically coherent pattern resulted. However, when the three groups were factored together, the mapped factors resulted in a patchy and "unrealistic" pattern. The reason for this is that the heavy mineral assemblages of the three groups are internally more homogeneous and are the result of three different tectono-depositional regimes.

The rotated factors obtained in this study are thought to represent heavy mineral associations which in turn can be used to map heavy mineral provinces. Some of the factors obtained essentially represent a single heavy mineral. The heavy mineral associations are the result of heavy mineral mixing in the depositional realm.

The choice of number of rotated factors used in mapping the heavy mineral provinces is based on prior knowledge of the nature and type of heavy mineral associations, on whether or not a particular number of factors will result in a "reasonable" areal pattern of heavy mineral provinces, and on considerations of the cumulative variances and communalities.

Table 9 (a, b and c) gives the matrix of factor loadings for the 217 samples of the entire sequence on the first four factor axes (Belly River Group), first two factor axes (Edmonton Group) and first four factor axes (Paskapoo Formation), respectively, which have been rotated according to the varimax procedure. Relatively few samples have communalities lower than 0.5 (poor). High communalities mean that a good description of the samples has been obtained by the use of the respective number of rotated factors. Table 9 also

NORMALIZED VARIMAX FACTOR COMPONENTS

SAMPLE	COMM.	FACTOR 1	FACTOR 2	FACTOR 3	FACTOR 4
8034	0.9978	-0.0002	0.9973	0.0024	-0.0000
8037	0.9990	0.0000	0.9997	0.0002	0.0000
8036	0.9986	-0.0001	0.9997	0.0001	-0.0001
8046	0.9981	0.0000	0.7973	0.2026	0.0001
8033	0.9891	0.0008	0.2325	0.7569	0.0098
8048	0.9884	-0.0025	0.8373	0.1599	0.0003
8044	0.9368	0.1529	0.2261	0.6140	0.0070
8045	0.9981	-0.0000	0.9964	0.0035	-0.0000
8032	0.9892	0.0004	0.4209	0.5717	0.0070
8047	0.8391	0.1032	0.7639	0.1294	0.0035
8052	0.9903	0.0003	0.2969	0.7009	0.0018
8035	0.9986	-0.0001	0.9965	0.0034	0.0000
8039	0.9984	0.0000	1.0000	0.0000	0.0000
8042	0.9903	0.0129	0.0022	0.9848	0.0000
8053	0.9690	0.1045	0.0017	0.8514	0.0424
8050	0.8642	0.1867	0.0035	0.8045	0.0054
3271	0.9918	0.2474	0.0002	0.0095	0.7430
3274	0.9619	0.1139	0.0003	0.0121	0.8737
3276	0.9301	0.1360	0.0005	0.0247	0.8388
3277	0.9845	0.0951	0.0001	0.0023	0.9026
3280	0.6922	0.4740	0.0000	0.0213	0.5047
3281	0.9909	0.0561	0.0001	0.0031	0.9407
8067	0.8014	0.5536	0.0000	0.0008	0.4455
8069	0.9839	0.5012	0.0002	0.0158	0.4828
8070	0.9943	0.9801	0.0001	0.0191	0.0006
8071	0.9839	0.9817	0.0001	0.0148	0.0034
8072	0.9437	0.9176	0.0004	0.0495	0.0325
8074	0.9141	0.6705	0.0001	0.0055	0.3239
8075	0.9451	0.9207	0.0001	0.0309	0.0483
8077	0.8886	0.9462	0.0000	0.0040	0.0498
8099	0.8369	0.6688	0.0004	0.0609	0.2699
8100	0.9452	0.7763	0.0005	0.0592	0.1639
8101	0.9916	0.6762	0.0003	0.0281	0.2954
8102A	0.9735	0.6919	0.0002	0.0156	0.2922
8103	0.8009	0.9667	0.0000	0.0034	0.0298
8104	0.9933	0.9685	0.0004	0.0280	0.0031
8110	0.9621	0.9071	0.0002	0.0416	0.0511
8111	0.9333	0.0174	0.0020	0.8674	0.1132
8112	0.9570	0.0041	0.0025	0.9899	0.0034
8113	0.9948	0.0584	0.0023	0.9388	0.0005
4315B	0.9940	0.9394	0.0001	0.0185	0.0420
4317	0.8778	0.8557	0.0007	0.0578	0.0858
4320	0.7665	0.5716	0.0010	0.0820	0.3455
4324	0.9069	0.7428	0.0002	0.0068	0.2503
	VARIANCE	35.584	21.400	20.012	17.288
	CUM. VAR.	35.584	56.984	76.996	94.285

Table 9a. Q-mode factor analysis of non-opaque, non-micaceous heavy minerals. Belly River Group.

NORMALIZED VARIMAX FACTOR COMPONENTS

SAMPLE	COMM.	FACTOR 1	FACTOR 2
8125	0.7772	0.0220	0.9780
8131	0.7690	0.2980	0.7020
8132	0.9168	0.2695	0.7305
8054	0.9310	0.7832	0.2168
8055	0.8583	0.4878	0.5122
8056	0.8680	0.2485	0.7515
8057	0.2166	-0.0049	0.9951
8058	0.8386	0.0368	0.9632
8059	0.8796	0.1202	0.8798
8060	0.9909	0.2703	0.7297
4857A	0.9600	0.0378	0.9622
4857	0.7859	0.1879	0.8121
4856	0.3972	0.2667	0.7333
4854	0.4792	0.2972	0.7028
8078	0.9806	0.9548	0.0452
8079	0.7697	0.8048	0.1952
8080	0.8025	0.8831	0.1169
8081	0.8940	0.9454	0.0546
8082	0.9854	0.7498	0.2502
8083	0.9795	0.9327	0.0673
8084	0.9382	0.9868	0.0132
8085	0.8618	0.9873	0.0127
8086	0.8729	0.5921	0.4079
8087	0.9822	0.9594	0.0406
8088	0.9404	0.9313	0.0687
8089	0.9649	0.9823	0.0177
8105	0.9313	0.7109	0.2891
8106	0.9791	0.9325	0.0675
8107	0.9077	0.6329	0.3671
8109	0.8889	0.4541	0.5459
4700	0.9431	0.5208	0.4792
4703	0.8430	0.2516	0.7484
4695	0.8925	0.4160	0.5840
4690	0.9491	0.1143	0.8857
4710	0.4242	0.0308	0.9692
4697	0.9467	0.0232	0.9768
4999	0.9232	0.2106	0.7894
8114	0.2551	0.0119	0.9881
8115	0.7479	0.6684	0.3316
8116	0.6481	0.7876	0.2124
8117	0.9332	0.6582	0.3418
8118	0.3629	0.1835	0.8165
8119	0.8766	0.1982	0.8018
8120	0.8083	0.0594	0.9406
4325	0.3498	0.3243	0.6757
4328	0.9635	0.9854	0.0146
4329	0.9639	0.8055	0.1945
4330	0.9669	0.7466	0.2534
4331	0.9385	0.4339	0.5661
4335	0.8135	0.6986	0.3014
4338A	0.7527	0.4354	0.5646
4341	0.9129	0.1336	0.8664
	VARIANCE	43.046	38.805
	CUM. VAR.	43.046	81.851

Table 9b. Q-mode factor analysis of non-opaque, non-micaceous heavy minerals. Edmonton Group.

NORMALIZED VARIMAX FACTOR COMPONENTS

SAMPLE	COMM.	FACTOR 1	FACTOR 2	FACTOR 3	FACTOR 4
5050A	0.6968	0.8002	-0.0017	-0.0348	0.1633
5057	0.7944	0.8310	-0.0017	-0.0217	0.1456
8094	0.9551	0.0390	-0.0004	-0.0040	0.9566
8097	0.9650	0.1406	-0.0011	-0.0077	0.8506
8098	0.9382	0.1105	-0.0012	-0.0078	0.8806
4777	0.9655	0.1730	-0.0163	-0.7962	0.0144
6004B	0.9549	0.0124	-0.5720	-0.4123	0.0033
6017B	0.9312	0.2366	-0.0257	-0.7377	0.0000
6019A	0.9836	0.0057	-0.2090	-0.7849	-0.0005
6027	0.9710	0.2432	-0.0216	-0.7337	0.0015
4874	0.6995	0.9031	-0.0015	-0.0154	0.0799
4867	0.9837	0.0243	-0.0160	-0.9597	0.0000
4866	0.9211	0.0151	-0.0149	-0.9680	0.0029
4729	0.9505	0.1005	-0.0660	-0.8305	-0.0030
5000	0.9619	0.1032	-0.2978	-0.5979	0.0012
4723	0.9664	0.1265	-0.5498	-0.3190	-0.0046
5200	0.9820	0.0287	-0.0197	-0.9472	-0.0044
5198	0.8397	0.6551	-0.0166	-0.3269	0.0013
8129	0.9753	0.0677	-0.8246	-0.1074	-0.0003
8130	0.9987	0.0079	-0.9519	-0.0400	-0.0001
8135	0.7908	0.9342	-0.0111	-0.0541	0.0007
8136	0.8614	0.9486	-0.0076	-0.0347	0.0091
8123	0.9859	0.0007	-0.0158	-0.9823	0.0011
8124	0.9049	0.8956	-0.0062	-0.0316	0.0666
4353	0.9878	0.0538	-0.0177	-0.9271	0.0014
4355B	0.9806	0.0717	-0.0156	-0.8769	0.0358
5438	0.9669	0.3414	-0.0110	-0.4690	0.1786
5430	0.8861	0.0989	-0.0108	-0.7530	0.1374
5431	0.9722	0.2132	-0.0143	-0.7235	0.0490
5432	0.9490	0.2263	-0.0161	-0.7393	0.0182
5433	0.8260	0.0710	-0.0159	-0.8847	0.0283
5434	0.8166	0.0830	-0.0159	-0.8596	0.0414
5435	0.9145	0.1028	-0.0164	-0.7492	0.1317
5436	0.9290	0.0400	-0.0125	-0.6898	0.2577
5437	0.9157	0.0653	-0.0070	-0.3410	0.5867
5033	0.9829	0.3768	-0.0092	-0.2930	0.3210
5034	0.8885	0.2900	-0.0104	-0.5865	0.1132
5035	0.8934	0.2655	-0.0129	-0.6019	0.1197
5037	0.9775	0.1569	-0.0080	-0.4255	0.4096
5021A	0.9120	0.3189	-0.0185	-0.6609	0.0017
5023	0.8279	0.0994	-0.0142	-0.8853	0.0011
5025	0.9277	0.1389	-0.0141	-0.8467	0.0002
5026	0.9411	0.3273	-0.0156	-0.6220	0.0351
5028	0.9491	0.1820	-0.0155	-0.7832	0.0193
5029	0.9412	0.0470	-0.0157	-0.9373	-0.0000
6001B	0.7698	0.8911	-0.0099	-0.0818	0.0172
4861	0.9504	0.0175	-0.0145	-0.9637	0.0043
4860	0.9382	0.0037	-0.0135	-0.9818	0.0010
4720	0.7731	0.9537	-0.0020	-0.0296	0.0146
4709	0.8762	0.9384	-0.0067	-0.0476	-0.0072
4721	0.9892	0.1816	-0.0178	-0.7977	-0.0029
4722	0.8648	0.6576	-0.0119	-0.3289	-0.0015
4728	0.8003	0.8436	-0.0052	-0.1500	-0.0012
8126	0.9962	0.0193	-0.8265	-0.1540	0.0002
8127	0.8997	0.8122	-0.0092	-0.0801	0.0984

Table 9c. Q-mode factor analysis of non-opaque, non-micaceous heavy minerals. Paskapoo Formation.

NORMALIZED VARIMAX FACTOR COMPONENTS

SAMPLE	COMM.	FACTOR 1	FACTOR 2	FACTOR 3	FACTOR 4
8128	0.8903	0.9384	-0.0058	-0.0466	0.0092
8133	0.8245	0.9245	-0.0091	-0.0523	0.0141
8134	0.8913	0.4774	-0.0044	-0.0240	0.4942
8121	0.9876	0.0005	-0.0149	-0.9829	0.0017
8122	0.9812	0.0000	-0.0157	-0.9842	-0.0001
4350A	0.9897	0.0058	-0.0162	-0.9759	-0.0021
4351	0.9551	0.0769	-0.0179	-0.9106	-0.0005
4352	0.9914	0.0063	-0.0159	-0.9763	0.0015
8090	0.9556	0.0574	-0.0001	-0.0029	0.9395
8091	0.9775	0.0563	-0.0005	-0.0050	0.9382
8092	0.9041	0.3642	-0.0006	-0.0090	0.6262
8093	0.8993	0.2788	-0.0005	-0.0074	0.7132
5426	0.9681	0.0829	-0.0163	-0.8141	0.0863
5427	0.9840	0.1168	-0.0183	-0.8525	0.0124
5428	0.9871	0.1019	-0.0202	-0.8605	0.0174
5429	0.9579	0.2723	-0.0190	-0.6999	0.0088
5424	0.9975	0.0065	-0.9137	-0.0797	0.0000
5425	0.9946	0.0029	-0.9224	-0.0678	0.0058
5039	0.9760	0.1697	-0.1142	-0.6286	0.0875
5040	0.9746	0.0047	-0.1720	-0.8128	0.0105
5041	0.9757	0.1240	-0.0327	-0.7806	0.0627
5042	0.9834	0.1195	-0.0637	-0.8102	0.0065
5043	0.9908	0.0008	-0.5601	-0.4362	0.0030
5044	0.9963	-0.0006	-0.9969	0.0022	0.0003
5045	0.9970	-0.0012	-0.9947	0.0039	0.0003
5046	0.9233	0.4312	-0.3138	-0.2543	-0.0007
5415	0.9275	0.4770	-0.0177	-0.4060	0.0993
5416	0.9616	0.6168	-0.0208	-0.3592	0.0032
5417	0.9731	0.0907	-0.3428	-0.4606	0.1059
5418	0.9922	0.1849	-0.3441	-0.4623	0.0087
5419	0.9833	0.2519	-0.0971	-0.6509	-0.0001
5420	0.9714	0.2503	-0.3972	-0.2999	0.0527
5421	0.9753	0.2126	-0.3358	-0.3503	0.1014
5422	0.9679	0.1885	-0.2049	-0.4057	0.2009
5423	0.9786	0.0854	-0.7820	-0.1281	0.0044
5030	0.9971	0.0069	-0.9310	-0.0613	0.0009
5031	0.9968	0.0113	-0.9871	-0.0014	0.0003
5032	0.9955	0.0095	-0.6714	-0.3082	0.0109
5409	0.9929	0.0294	-0.3312	-0.6376	0.0018
5411	0.9969	0.0081	-0.3927	-0.5913	0.0080
5412	0.9928	0.0510	-0.7069	-0.2416	0.0004
5414	0.9933	-0.0000	-0.9998	-0.0002	-0.0000
5041	0.9959	-0.0000	-0.9996	-0.0000	0.0003
5402	0.9960	-0.0027	-0.9923	-0.0049	0.0001
5403	0.9965	-0.0003	-0.9988	-0.0001	0.0008
5404	0.9971	0.0000	-0.9969	-0.0030	0.0001
5405	0.9970	0.0000	-0.9736	-0.0211	0.0053
5406	0.9896	0.0062	-0.0888	-0.8798	0.0252
5408	0.9964	0.0026	-0.9767	-0.0201	0.0006
5019	0.9654	-0.0002	-0.0135	-0.9862	0.0001
5070	0.9878	0.9146	-0.0057	-0.0600	0.0198
5071	0.9788	0.6876	-0.0047	-0.0496	0.2581
5072	0.9020	0.5546	-0.0081	-0.2907	0.1465
5073	0.9845	0.6388	-0.0122	-0.2852	0.0639
5074	0.8244	0.8762	-0.0018	-0.0240	0.0980
5076	0.9321	0.9362	-0.0038	-0.0268	0.0332
5077	0.9785	0.8396	-0.0077	-0.1382	0.0144
5063	0.8903	0.7835	-0.0034	-0.0492	0.1639
5064	0.8186	0.9314	-0.0022	-0.0256	0.0408
5068	0.9698	0.1870	-0.0165	-0.7965	-0.0001
5069	0.9470	0.8491	-0.0047	-0.0712	0.0749
4716	0.9680	0.5552	-0.0061	-0.1034	0.3353
4717	0.9831	0.4278	-0.0118	-0.4452	0.1152
4720	0.9877	0.7221	-0.0052	-0.0923	0.1804
4721	0.9690	0.1592	-0.0190	-0.8107	0.0010
4722	0.9743	0.5570	-0.0127	-0.4303	-0.0000
	VARIANCE	25.141	19.459	40.227	9.307
	CUM. VAR.	25.141	44.599	84.826	94.133

Table 9c. (cont'd)

	BELLY RIVER GROUP				EDMONTON GROUP		PASKAPOO FORMATION			
VARIABLES	FAC 1	FAC 2	FAC 3	FAC 4	FAC 1	FAC 2	FAC 1	FAC 2	FAC 3	FAC 4
Hornblende	-0.018	4.115	-0.194	-0.035	-	-	-0.195	-4.078	0.051	0.018
Garnet	1.992	0.133	1.173	0.081	-0.011	3.454	3.286	-0.347	-0.645	-0.561
Epidote-Clinozoisite	-0.598	0.183	3.791	-0.095	-0.295	0.717	-0.750	-0.450	-3.992	-0.079
Apatite	0.306	0.031	0.091	4.049	1.170	1.414	1.959	0.042	-0.022	0.245
Rutile	0.367	0.007	-0.013	0.054	0.422	-0.066	0.281	0.027	-0.129	0.262
Sphene	-0.079	-0.043	1.074	-0.104	-0.195	1.043	1.106	-0.064	-0.475	-0.505
Tourmaline	0.035	0.022	-0.057	0.564	0.257	0.023	0.209	0.056	-0.337	0.511
Tremolite-Actinolite	-0.001	0.082	0.012	-0.003	-0.001	0.006	-0.002	-0.167	-0.027	0.024
Allanite	0.917	-0.071	0.187	0.042	0.279	0.573	0.292	-0.002	-0.040	0.067
Chlorite	0.114	-0.003	-0.018	0.190	0.279	0.041	0.383	0.008	-0.041	0.046
Zircon	3.402	-0.011	-0.054	-0.462	3.755	-0.361	0.413	-0.058	-0.177	4.003
Staurolite	0.009	0.004	0.050	-0.014	-0.007	0.043	0.054	-0.007	-0.004	-0.023
Chloritoid	0.069	0.018	0.026	0.020	0.036	0.021	0.091	-0.009	-0.003	-0.038
Glaucophane	-0.000	-0.000	-0.000	-0.000	-0.000	0.000	-0.001	-0.002	-0.003	-0.001
Kyanite	-0.003	-0.003	0.027	0.001	0.002	0.001	0.018	0.001	0.002	-0.014
Andalusite	-0.005	0.007	0.001	0.027	0.015	0.005	0.038	-0.037	-0.042	0.002
Others	0.054	0.054	0.075	0.073	0.077	0.037	0.053	-0.033	-0.015	-0.022

Table 10. Scaled varimax factor scores. Q-mode factor analysis of non-opaque, non-micaceous heavy minerals.

	Factor 1	Factor 2	Factor 3	Factor 4
Belly River Group	Zircon	Hornblende	Epidote-Clinozoisite	Apatite
	Garnet		Garnet	
Edmonton Group	Zircon	Garnet		
	Apatite	Apatite		
		Sphene		
Paskapoo Formation	Garnet	Hornblende	Epidote-Clinozoisite	Zircon
	Apatite			
	Sphene			

Table 11. Heavy mineral associations generated by Q-mode factor analysis.

shows the cumulative variances of the three groups of samples. For the Belly River Group, the four factors accounted for 94.3%, the two factors of the Edmonton Group accounted for 81.9% and the four factors of the Paskapoo Formation accounted for 94.1% of the total amount of information available from the distributions.

Table 10 gives the scaled varimax factor score matrices of the Belly River, Edmonton and Paskapoo samples respectively and shows the relationships between the variables and the obtained factors. From Table 10 the writer chose loadings equal to or higher than 1.0 to obtain the heavy mineral associations that represent the factors; these are presented in Table 11. The resulting heavy mineral associations (factors) were used to map the heavy mineral provinces presented in Figures 31, 32 and 33.

2. Heavy Mineral Associations

(a) Belly River Group and Equivalents: Forty-four samples were factored and the normalized 4-factor varimax solution was found to generate the most reasonable heavy mineral associations, resulting in a satisfactory mapping of the heavy mineral provinces (Fig. 31). This solution accounted for 94.3% of the total amount of information available in this group of samples (Table 9a).

Figure 31 shows the four pure-association heavy mineral provinces and one mixed-association heavy mineral province. The latter is located in

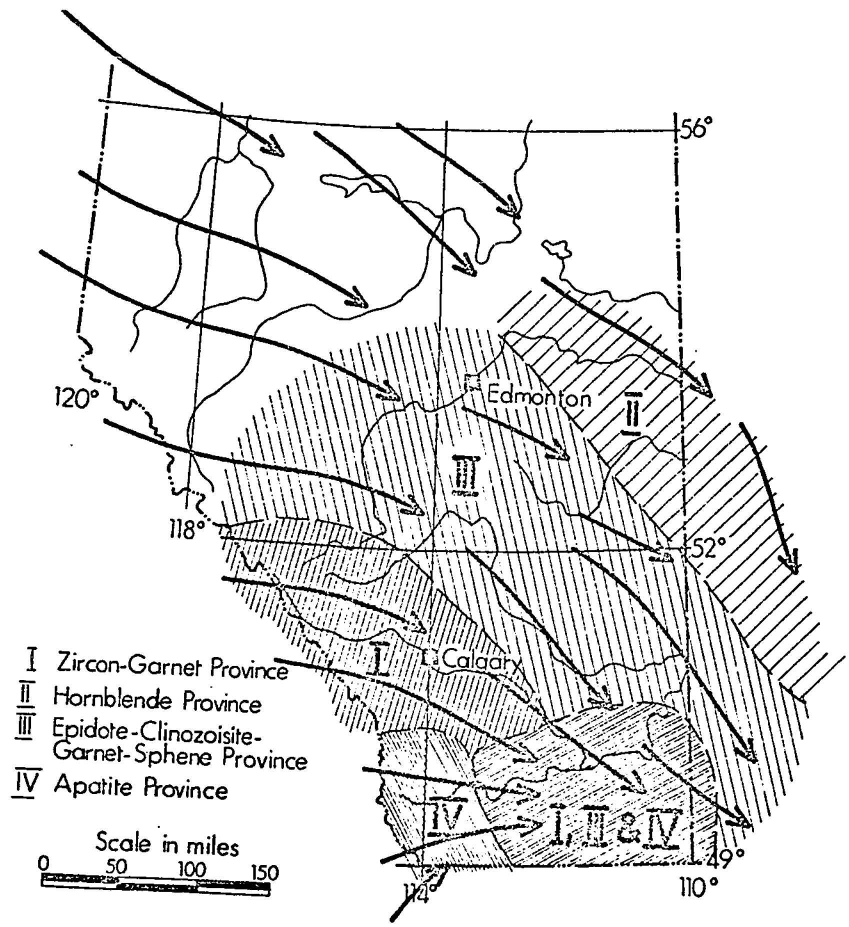

Fig. 31. Heavy mineral provinces and dispersal. Belly River time.

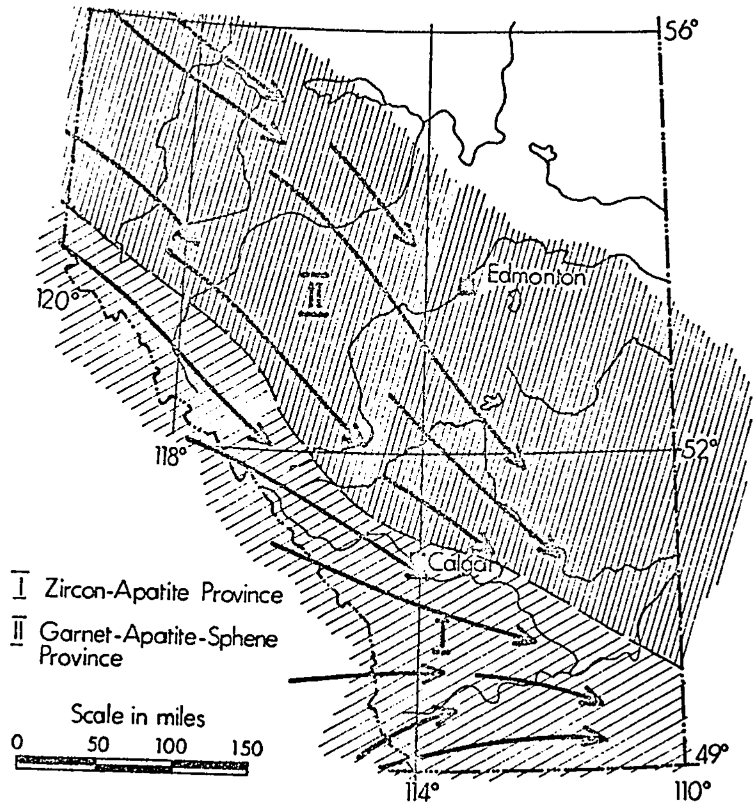

Fig. 32. Heavy mineral provinces and dispersal. Edmonton time.

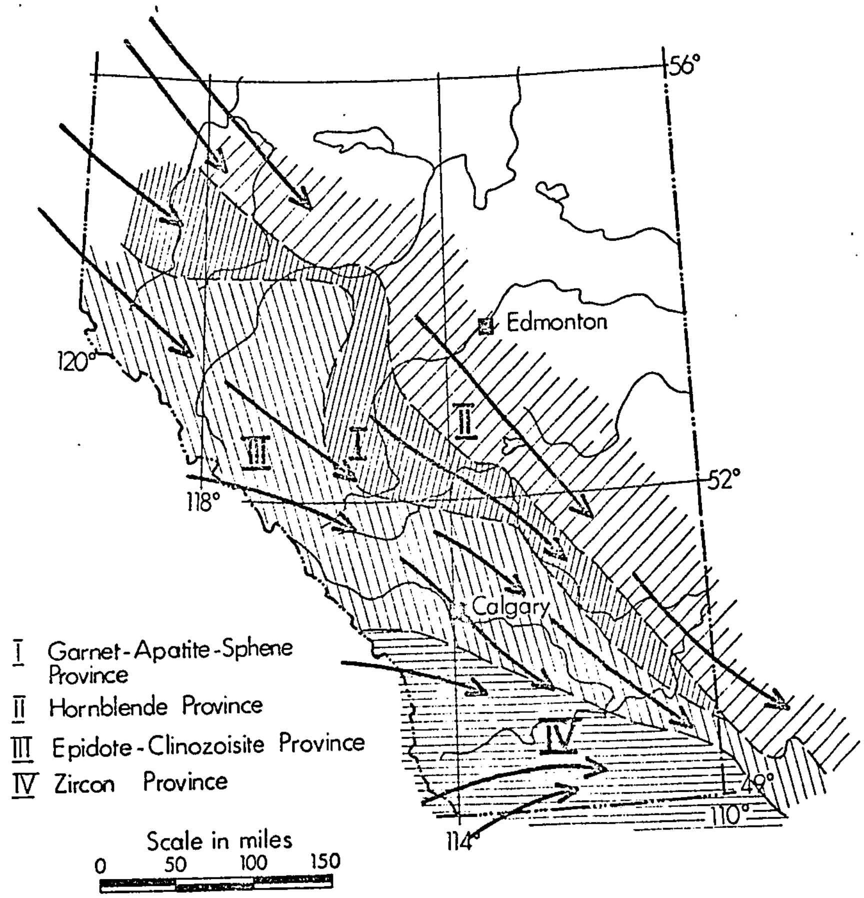

Fig. 33. Heavy mineral provinces and dispersal. Paskapoo time.

southern and southeastern Alberta. Along most of their length, the heavy mineral provincial boundaries represent their average position throughout the section under examination. The heavy mineral provinces are as follows: (1) Apatite Province (A-P) occupying southwestern Alberta represented by the Drywood River section; (2) Zircon-Garnet Province (ZG-P), to the north and northwest of A-P, represented by the Highwood River, CPOG-Strathmore and the Little Red Deer River sections: (3) Epidote-Clinozoisite-Garnet-Sphene Province (ECGS-P), stretching from the central and northern Foothills through the central and eastern Plains of Alberta to southwestern Saskatchewan; (4) Hornblende Province (H-P) restricted to east-central Alberta and adjacent areas of Saskatchewan. In east-central Alberta and adjacent areas of Saskatchewan, the ECGS Province coincides with the Oldman Formation and the H-Province with the underlying Foremost Formation. Hence the ECGS-Province easternmost limit (Fig. 31) represents only the easternmost Oldman Formation erosional limit. However, to the south both the Oldman and the Foremost Formations belong to the ECGS-Province. Most of the data used to map the latter two provinces are quantitative, obtained by the writer, but some are semi-quantitative to qualitative, reported by McLean (1971); (5) Mixed-association Province resulting from the mixing of the associations of the A, ZG and the ECGS Provinces. Data on this Province is of a qualitative nature obtained from McLean (1971).

(b) Edmonton Group and Equivalents: Fifty-two samples were factored and the normalized 2-factor varimax solution was found to result in the best mappable heavy mineral provinces, although it accounted for only 82% of the total information (Table 9b).

Figure 32 shows the areal distribution of the heavy mineral provinces of Edmonton Group time which are as follows: (1) Zircon-Apatite Province almost restricted to the disturbed belt of the western part of the study area; (2) Garnet-Apatite-Sphene Province extending from the Smoky River in the northwest, to the Red Deer River Valley to the southeast and including the eastern parts of the disturbed belt. The eastern limits of the latter province are uncertain because of erosion.

(c) Paskapoo Formation and Equivalents: A total of 121 samples were factored and the normalized 4-factor varimax solution was chosen to map the heavy mineral provinces (Fig. 33). This solution accounted for 94.1% of the total information available in these samples (Table 9c).

The distribution of the heavy mineral provinces is shown in Figure 33. It should be noted that the positions of the heavy mineral provincial boundaries are gradational and approximate. The peculiar pattern shown by the Epidote-Clinozoisite Province was probably only temporary and may have been slightly different during the time of deposition of the Paskapoo Formation. The heavy mineral provinces are as follows: (1) Zircon Province restricted to the southern part of the study area and including the disturbed belt and the Plains; (2)

Epidote-Clinozoisite Province that trends northwest to southeast; (3) Garnet-Apatite-Sphene Province trending northwest-southeast and traversing only Plains areas, and (4) Hornblende Province trending northwest-southeast, whose eastern limit is erosional.

INTERPRETATIONS

A. Provenance and Dispersal

1. General Statement

This discussion of the provenance and dispersal of Upper Cretaceous and Paleocene sandstones of Alberta relies primarily on the composition and areal pattern of the heavy mineral provinces.

The concept of a sedimentary petrographic province was originally defined by Baturin (1931) during his work in the Caucasus. Baturin (quoted in Doeglas, 1940) defined a sedimentary petrographic province as "... a complex of sediments which by their geographical distribution, age and origin forms a natural unit." This concept is equally applicable to the heavy minerals as well as the light minerals of clastic sediments. However the difference is one of magnitude. It is possible to have more than one heavy mineral province within one light mineral petrographic province. A theoretical example is that a feldspathic petrographic province which has feldspar (the major component of the sandstone, i.e. an arkose) derived from both an igneous source (granite) and a metamorphic source (gneiss), may contain a zircon-apatite province and a staurolite-garnet province derived from the granite and the gneissic sources respectively. Sedimentary petrographic provinces are primarily dependent on provenance.

On the other hand, a distinction must be made between sedimentary petrographic provinces and lithologic associations, for the former is primarily determined by provenance and the latter by tectonism. Radulescu (1964, p. 287) presented his views on this subject and the following is a quotation from his paper: "The sedimentary petrographic province is not a tectostructural concept and it should not be confused with rock associations in tectostructural units of the earth's crust...The sedimentary petrographic province is not a lithologic or facies unit. The surface distribution of a rock type or of similar or kindred types does not constitute a province. It is not a time unit, and consequently, the presentation of the rocks of the same age as a petrographic province is erroneous. The sedimentary petrographic province is a genetic concept for the definition of which the decisive element is the provenance, but not the sedimentary conditions which determine, for instance, the facies...In various cases, its content may exceed or be less than the content of a lithologic unit; it details the tectostructural, facies or time notion content, but it is also possible to exceed the content of the last two." The present writer agrees, in a general way, with Radulescu's ideas. However, it is not always the case that a petrographic province "... is not a time unit ..." as he claims. A petrographic province in a particular area may have synchronous upper and lower boundaries, therefore representing a time unit. In fluvial-deltaic-shallow marine complexes, lithofacies are usually diachronous due to hydrodynamic conditions that prevailed at the time of deposition. However, mineralogical boundaries tend to be more synchronous and transcend lithologic boundaries. Figure 34 shows a typical regressive sequence with two diachronous lithofacies resulting in two lithostratigraphic units, LU 1 and LU2. Lines 1 to 5 represent time lines from oldest to youngest respectively. LU 1 is silt and was deposited in deeper water than LU 2 which is composed of fine sand. At any given time, mineralogically homogeneous detrital clastics brought to this retreating shoreline will be sorted into two lithofacies of qualitatively the same mineralogy (excepting clay minerals), although size and density sorting may cause proportional abundance of minerals to be different. If at any time tectonism in the source area results in exposure to erosion of different source rocks, the mineralogy of the supplied detrital clastics will change, and the composition of the two lithofacies, though they are of the same lithologic association character as of the previous time, will be different. Therefore sediments deposited during the time period between lines 1 and 3 (Fig. 34) may represent a particular heavy mineral province which is different than the heavy mineral province deposited during the time period between lines 3 and 4 or 4 and 5. The point is that heavy mineral provinces may represent time units.

In summary, a lithologic association may be composed of more than one light-mineral petrographic province, and the latter in turn may be composed of more than one heavy mineral province.

2. Regional Sedimentary Dispersal

In general, published data on these Cretaceous-Paleocene sediments

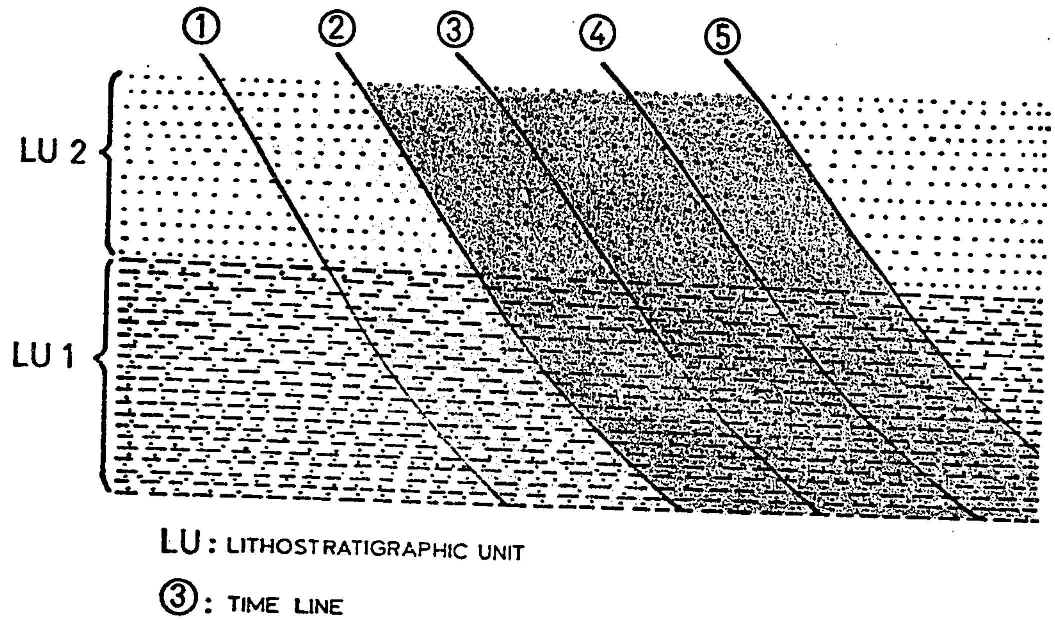

Fig. 34. Generalized relationships between lithostratigraphic units, time lines and heavy mineral associations (colored). See text.

suggest a west-to-east dispersal system. Isopach maps (Williams and Burk, 1964) show thickening of the Upper Cretaceous sediments to the west and less so to the northwest, and facies maps show a lateral gradation from predominantly marine shale in the eastern Plains to mixed marine and continental sediments in the western Plains and Foothills. Existing remnants of Paleocene rocks also show thickening to the west. This evidence on its own tends to suggest major sediment dispersal from west to east. Southwest to northeast dispersal directions were suggested by petrographic and sedimentologic studies on the Belly River Group by Lerbekmo (1963) in the southern Foothills and by McLean (1971) in the Plains. However, a glance at the paleogeographic maps of the Late Cretaceous in Williams and Burk (1964) quickly forces the reader to consider major dispersal from northwest to southeast due to availability of highlands to the northwest and the presence of a sea to the southeast towards which rivers are expected to flow. Some paleocurrent data by Carrigy (1971) also suggest northwest-southeast transport.

A strong dispersal system from northwest to southeast is suggested by the results of the present study (Figs. 31, 32 and 33). An alternative interpretation of principal dispersal from west to east across heavy mineral provincial boundaries was discarded by the writer since it implies that from west to east the heavy mineral associations were formed as a result of regional west to east selective sorting. There is negligible west to east decrease in grain size in the sandstone units within the area of study. Moreover, sandstone samples used in this study were limited to a relatively narrow range of modal grain size (near

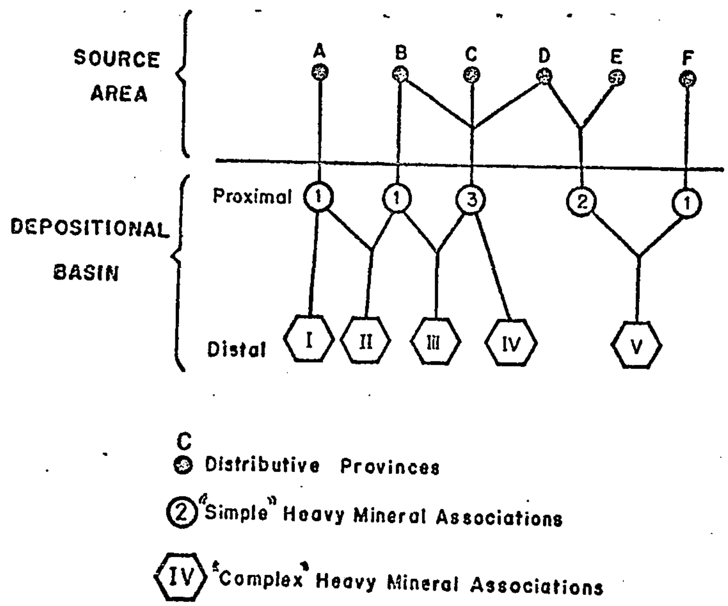

Fig. 35. Diagrammatic representation of relationships between provenance and heavy mineral associations as they may have existed during Late Cretaceous and Paleocene. (modified after Imbrie and van Andel, 1964)

the fine to medium sand boundary), a sampling procedure that minimizes the effect of selective sorting. Most convincing, however, is the fact that the west to east order of appearance of the heavy mineral associations does not coincide with the theoretical order of deposition of heavy minerals as controlled by their hydraulic size and hydrodynamic behavior (Griffiths, 1967, Fig. 10.5, p. 217).

3. Detailed Provenance and Dispersal

It was previously indicated that the obtained factors (made up of one or more heavy minerals) represent the states of heavy mineral mixing just as the sediments entered the depositional basin; that heavy mineral assemblages of some samples are represented mainly by one factor, whether this factor is a single-mineral or multi-mineral, and others are represented by more than one factor. The following discussion is an attempt to sort out the relationships between the heavy mineral associations (factors) and provenance that resulted in the formation of the heavy mineral assemblages of the Upper Cretaceous and Paleocene sandstones. This method is outlined in the work of Imbrie and van Andel (1964, p. 1152-1153, Fig. 12) on the Gulf of California and the Orinoco-Guayana Shelf heavy minerals: Figure 35 illustrates in a general way the possible relationships as might have existed between distributive provinces and heavy mineral associations of the depositional basin at any given time during the Late Cretaceous and Paleocene in Western Canada. Distributive provinces (A to F, Fig. 35) may contribute heavy mineral suites, each dominated either by a single or by several heavy minerals. The degree of mixing of these heavy mineral suites prior to their introduction to the proximal parts of the depositional realm will determine the nature and composition of the heavy mineral associations (Fig. 35, numbered circles; numerals refer to number of dominant heavy minerals in each association). In Figure 35 it is assumed that heavy mineral suites released by distributive provinces A to F are each dominated by a single heavy mineral. Further downcurrent transportation of the proximal heavy mineral associations may result in further mixing and formation of "complex" heavy mineral associations in the distal parts (Fig. 35). On the other hand, complete downcurrent mixing may result in a single or a few homogenized heavy mineral associations. At I (Fig. 35) the heavy mineral "association" is dominated by a single mineral, an example of almost complete lack of mixing since their release from the distributive province A. At V, showing the other extreme, there has been a prior mixing of suites in the source area and in the proximal part of the depositional area.

In the following sections the provenance and dispersal of the individual heavy mineral associations will be dealt with in some detail. An attempt is here made to coordinate heavy mineral data with those of published and unpublished light mineral and paleocurrent data to reach the outlined conclusions.

(a) Belly River Time: During Belly River time (mid-Campanian) the eastern Cordillera stood fairly high (Omineca Geanticline, Fig. 3), supplying large volumes of coarse clastics eastward to be deposited in the Rocky Mountain Exogeosyncline and its deeply subsiding Alberta Trough. This uplift of the Omineca Geanticline, representing one of the last pulses of the Columbian Orogeny, had forced the shoreline of the epicontinental sea of the Interior Platform to withdraw to the south and southeast into southern Saskatchewan. During this time rivers carried sediment from the highlands of the west and deposited them in alluvial fans, floodplains and deltas to the east along the northwestern and western margins of the sea. During early Belly River (Foremost) time, sediments came from the northwest, west and southwest, while in later Belly River (Oldman) time, sediment dispersal was mainly from the northwest (Williams and Burk, 1964, Figs. 12-13 and 12-20, p. 187). During this time, earlier Mesozoic and Paleozoic sediments of the Cordilleran Miogeosyncline were undergoing earliest stages of deformation (very early Laramide). However, this deformation, east of the Omineca Geanticline, was topographically too low to act as a barrier against flow of clastics from the west, or to supply any of its own.

Four "pure" heavy mineral associations and one mixed heavy mineral association are recognized in Belly River time, producing five heavy mineral provinces as follows:

Apatite Province: This province occupies southwestern Alberta (Fig. 31) including the disturbed belt and the adjacent Plains, and it is represented by the Drywood River section. The distributive province probably covered an area situated to the west and southwest and the sediment dispersal was towards the east and northeast.

Sandstones of the Belly River Formation of this region are lithic (mainly sedimentary) composed of quartz, rock fragments and feldspar in that order of abundance (Lerbekmo, 1963, p. 62-63). Major heavy minerals (greater than 2%) of these sandstones are apatite, garnet, zircon, allanite, tourmaline and chlorite.

The apatite, a major constituent, may have been contributed by both an igneous source (angular and euhedral grains) and a sedimentary source (rounded to subrounded grains). Evidence from light minerals indicated major contributions from sedimentary sources that "... included cherty carbonates, shales and sandstones, probably in that order of abundance" (Lerbekmo, 1963, p. 79). However, Lerbekmo did not specify a source area that contained such sediments. Such a sedimentary source may have been the Carboniferous sequence of central British Columbia (Cache Creek Group and equivalents). The subrounded to rounded apatite, tourmaline, rutile and zircon were probably derived from these rocks. A metamorphic contribution, second in volumetric abundance to the sedimentary, was propounded by Lerbekmo, (ibid, p. 79). These metamorphic source rocks were thought to vary from argillites, slates and phyllites (evidenced by rock fragments), through low-grade schists (evidenced by quartz, mica, chlorite, chloritoid) to medium-grade schists (evidenced by garnet, mica, quartz). Lerbekmo put the source for this metamorphic detritus in the "Metamorphosed phases of the Late Precambrian Belt Series in contact with Mesozoic intrusives..." in southeastern British Columbia, Idaho and Montana (Shuswap Complex of the southern Omineca Geanticline). The present writer concurs with Lerbekmo in this assignment. Detritus of volcanic origin is very common in the Belly River Formation of the Apatite Province. It is, however, uncertain what proportion of the volcanic material in the sandstone is from the erosion of pre-existing volcanic rocks (Lerbekmo, 1963, p. 79). Contemporaneous volcanism was common in the Late Cretaceous as evidenced by the presence of bentonites throughout the Belly River Formation of this region. This volcanism must have contributed some detritus to the sandstones of the Belly River. Of the heavy minerals, some of the euhedral and angular to subangular apatite, euhedral and angular zircon and the moderate brown biotite (especially the euhedral grains) were probably derived from the contemporaneous volcanism. Lerbekmo (1963, p. 79) suggested that the Cretaceous volcanics of southern and southwestern Montana were an unlikely source for the Belly River volcanic detritus for the reason that the "... regional grain-size distribution indicates that the water-moved material came from a general westerly direction." From consideration of the coarsest size mode of the bentonite, terminal velocity and wind velocity, Lerbekmo said that "... it appears unlikely that the contributing volcano was more than 100 miles away and possibly only half this distance. Possible positions are almost certainly restricted to the western half of the compass, and this would place the volcano within the overthrust belt of the present Rocky Mountains. As these mountains were not yet formed in Upper Cretaceous time, no evidence of such volcanic centers would today be present, the extrusive piles having been removed by erosion during the earliest Laramide movements in the late Cretaceous or early Tertiary, and the rocks buried by over-thrusting of Paleozoic rocks toward the east." However, there are "... enormous volumes of rhyolite, rhyodacite and dacite ash-flows and ignimbrites" that were extruded during Late Cretaceous in the western Cordillera of British Columbia (Souther, 1972, p. 56) that could very well have contributed the bulk of the volcanic material to the Upper Cretaceous sandstones to the east.

A plutonic contributor to the Apatite Province is not clearly evident on the basis of the mineralogical evidence. Mesozoic intrusives cover large areas in British Columbia, Washington, Idaho and Montana, and were very likely exposed to erosion at the time of deposition of the Belly River Formation. Since plutonic rock fragments are probably no longer recognizable in sandstones of mean grain size less than very coarse-grained sand (Boggs, 1968), the likelihood of recognizing such material in the Belly River fine- to medium-grained sandstone is very low. None of the heavy minerals of the Belly River Formation of the region is necessarily exclusively of plutonic origin. Lerbekmo (1963) suggested that the Nelson batholith (or other Mesozoic intrusives) could have contributed some detritus, based upon the matching K-Ar radiometric dates from detrital Belly River feldspars with those of Nelson batholith feldspars. The age dates obtained are 107 and 110 m.y. respectively. Comparison of these dates with dates of 77 and 74 m.y. obtained from a bentonite bed from the Belly River Formation clearly indicated that the Belly River detrital feldspar was not the result of contemporaneous volcanism. Contribution from the Idaho batholith was also suggested by Lerbekmo (ibid.) based on similarity of the optical properties of the Belly River and Idaho batholith allanites.

Briefly, therefore, sandstones of the Belly River Formation of the Apatite Province was probably derived in the main part from Carboniferous to Permian sedimentary rocks of central and southern British Columbia (Cache Creek Group and equivalents) and, to a lesser extent, from low to medium-grade metamorphic rocks of the Late Precambrian Belt Series equivalents in contact with Mesozoic intrusives in southern British Columbia, Idaho and Montana.

A contribution from volcanic sources is also suggested, and could have been mainly from contemporaneous volcanism that took place in the Cordilleran of British Columbia. The mineral evidence suggests minor contributions from Mesozoic intrusives in British Columbia and the northwestern states.

Zircon-Garnet Province: This province extends from the mid-southern Foothills north to mid-central Foothills and over some of the adjacent Plains (Fig. 31). It is represented by three sections: Highwood River, Little Red River and the CPOG-Strathmore core.

The distributive province for the Zircon-Garnet Province may have been located in the metamorphic belt of the southern part of the Omineca Geanticline, probably just north to northwest of the Apatite distributive province. Major heavy minerals found in this province are zircon, garnet, apatite, allanite, rutile, tourmaline and chlorite.

There is no data on the petrography of the light minerals in this province, therefore inference regarding provenance has to be drawn mainly from the heavy minerals. It should be pointed out here that inferences on provenance obtained from heavy minerals are only qualitative, and without the help of light mineral data there is no way of evaluating the volumetric contribution of the different source rock-types.

A secondary source terrain, a major contributor to the Apatite Province to the south, is only evidenced by the presence of some grains of well-rounded zircon (especially hyacinth of ultimate Precambrian source), rutile, tourmaline and probably apatite. Most of the zircon, however, a major component of this province, is euhedral and angular (Fig. 9) and could have been derived from contemporaneous Late Cretaceous volcanism. Other heavy minerals of possible contemporaneous volcanic derivation present in the Zircon-Garnet Province are euhedral and angular apatite and brown, euhedral biotite. A probably very important high-grade metamorphic source terrain is positively evidenced by the presence of considerable amounts of garnet and some grains of staurolite and andalusite. Red and reddish-brown biotite and some of the zircon may have been derived from this metamorphic source. Indications of some contribution from a low-grade metamorphic source terrain are given by the presence of chloritoid, chlorite and some brown tourmaline. This metamorphic detritus could have been derived from the northern parts of the Shuswap metamorphic complex of the southern Omineca Geanticline and/or from the Wolverine metamorphic complex of the central parts of the Omineca Geanticline. Positive evidence for a contribution from sialic plutonic rocks is the presence of angular to subangular and euhedral rutile. Other heavy minerals that might have been derived from plutonic rocks are apatite, zircon, some tourmaline and brown biotite. This plutonic detritus could have been contributed by any of the several Mesozoic intrusives scattered along the central and southern parts of the Omineca Geanticline.

Epidote-Clinozoisite-Garnet-Sphene Province: This heavy mineral province occupies the northern part of the central Foothills, central and east-central Plains of Alberta and adjacent areas of Saskatchewan (Fig. 31). This province is outlined on the basis of data from the Blackstone River section in the central Foothills, samples from east-central Alberta and data from McLean (1971) on adjacent areas of Saskatchewan and southern Alberta.

The distributive province may have been situated along the Omineca Geanticline just north of the Zircon-Garnet distributive province which it may have partially overlapped. Therefore dispersal of sediments must have been from the west and northwest to the east and southeast. The distributive province was not placed to the south or southeast in central or eastern Montana for lack of a high source area and suitable source rocks in that direction. The major heavy minerals in this province are epidote-clinozoisite, garnet, sphene, zircon, apatite and allanite.

Light mineral dataare available only in the Plains. McLean(1971, Fig. 24, p. 55) classified the sandstones of the Plains as mainly lithic and feldspathic sandstones (rock fragments, 10-50% (volcanic, metamorphic and sedimentary); feldspars, 35-65% (plagioclase dominant, k-feldspars common, microcline rare)).

On the basis of the heavy minerals alone one would suspect that the distributive province was mainly metamorphic. Dominance of epidote-clinozoisite, garnet and probably sphene, and the uncommon occurrence of staurolite, andalusite and kyanite (especially in the Plains) would support the above conclusion. However, study of the light mineral fraction made by

McLean (1971) in the eastern and southern parts of the ECGS Province indicated that contemporaneous volcanism as well as older volcanic rocks was a major source of clastic detritus. McLean, who emphasized only contemporaneous volcanism, based his conclusion on the dominance of volcanic rock-fragments over the other types of rock fragments, presence of fresh sanidine, bi-pyramidal quartz crystals, bentonite and tuff beds. Furthermore, the sandstone of the Oldman Formation of east-central Alberta is very bentonitic, attesting to the significance of contemporaneous volcanicity. In the Foothills, bentonite and tuff beds are present in strata of Belly River age, but light mineral data are lacking.

The possible source of the metamorphic components of this province could have been from the rocks of the Amphibolite Facies (garnet, staurolite, kyanite, andalusite and some of the epidote), Greenschist Facies (epidote) and the Metagreywacke and Zeolite Facies (epidote, sphene and clinozoisite) of the northern part of the Shuswap metamorphic complex and the Wolverine metamorphic complex of the southern and central parts of the Omineca Geanticline (Metamorphic Map of the Canadian Cordillera, Monger and Hutchison, 1971). There is, however, a general northwestward increase in the ratio of orange and yellow to colorless garnet, which may be the result of addition of colored garnet from metamorphic sources further to the northwest.

A plutonic contribution of volumetric importance is not evident in the heavy mineral suite, but the presence of zircon, apatite, allanite and sphene may represent such a source. McLean (1971, Table 15, p. 69) indicated some definite plutonic contribution on the basis of the presence of "... interlocking polycrystalline grains..." and evidence from other authors' studies in coarser clastic sediments." Such a plutonic source may be the intrusives associated with the metamorphic complex of the Omineca Geanticline.

A sedimentary source of some importance is suggested in McLean's data by the presence of chert, microcrystalline carbonate fragments and detrital dolomite rhombs. Heavy minerals of possible sedimentary source are rounded hyacinth and some colorless zircon, rounded apatite and the rare occurrences of rounded rutile and tourmaline. Specific source rocks are probably the upper Paleozoic (Carboniferous to Permian) eugeosynclinal rocks of central and southern British Columbia discussed earlier. The lower 750 feet of the Brazeau Formation (Belly River equivalent) in the northern Foothills of this province contain abundant conglomeratic horizons, wherein the pebbles are composed mainly of dark grey chert and white quartzite. The most likely source for the white quartzite pebbles is the Proterozoic and lower Cambrian clastic sedimentary rocks (e.g. Atan Group), and for the cherty pebbles the Upper Paleozoic eugeosynclinal rocks (e.g. Cache Creek Group), both in the Omineca Geanticline.

Hornblende Province: The Hornblende Province (Fig. 31) lies to the east and northeast of the area of study in Alberta and Saskatchewan. Data used to outline this province are those of the present writer and some qualitative to semi-quantitative data from McLean (1971). As was pointed out earlier, the boundary between the Hornblende and the ECGS Provinces partly represents the eastern erosional limit of the latter province. Generally, the eastern boundary of the ECGS Province of east-central Alberta and adjacent areas of Saskatchewan approximately coincides with the outcrop pattern of the Oldman Formation, while the Hornblende Province coincides with that of the underlying Foremost Formation. This relationship does not hold in southern Alberta and adjacent areas of Saskatchewan where neither the Oldman nor the Foremost Formations are hornblende bearing. The Hornblende Province of east-central Alberta, partially hidden below the younger ECGS Province, may not extend much farther west beyond its mapped boundary (Fig. 31). However, there are no data available from Foremost rocks in the subsurface to the west except for the basal 10 to 60 feet of the Belly River Formation of the Pembina Oil Field about 60 miles southwest of Edmonton. Here the heavy mineral suite contains neither hornblende nor epidote-clinozoisite (Khamesra, 1963).

The hornblende distributive province is envisaged to have been the plutonic and metamorphic complex in the general area of the present day Cassiar Mountains in the northern part of the Omineca Geanticline. Major heavy minerals of this province are hornblende, epidote-clinozoisite and apatite; minor heavy minerals are sphene, garnet and zircon. Staurolite, chloritoid, kyanite and andalusite occur in very minor to rare amounts.

In the previous discussion of the radiometric age dating of the Belly River hornblende, the writer concluded that these hornblendes were derived largely from the intrusives of the Cassiar Mountains area. Heavy mineral evidence suggests that metamorphic rocks, of the same general area, were probably second in importance to plutonics in clastic detritus contribution. Epidote-clinozoisite, sphene, chloritoid, garnet, staurolite, kyanite and andalusite attest to metamorphic sources of both low and high grades. As in the case of the ECGS Province, contemporaneous volcanicity could have contributed significantly to this province. The light mineral fraction shows an abundance of volcanic rock fragments (McLean, 1971), but this evidence could equally suggest an older volcanic source, certainly widespread in central and northern British Columbia.

It is interesting to note that the western outline of the Hornblende Province closely approximates the shape of the western shoreline of the contemporaneous "Lower Belly River Sea" shown in Williams and Burk (1964, Fig. 12-19, p. 187) paleogeographic maps. The position of this shoreline was determined on the basis of litho- and bio-facies evidence. It is possible that rivers draining the northern Omineca Geanticline in Middle Campanian time, carried hornblende (and other detritus) through northeastern British Columbia and northwestern Alberta and deposited them in deltaic and littoral environments around the Lower Belly River Sea. The hornblende and associated sediments may then have been carried farther south and southeastward by marine longshore currents.

Mixed-Association Province of Southern Alberta: This heavy mineral province represents the mixing of the associations of the Apatite, Zircon-Garnet and the Epidote-Clinozoisite-Garnet-Sphene Provinces. This province, qualitatively outlined on the basis of data from McLean (1971), covers a large area in southern Alberta and adjacent Saskatchewan (Fig. 31). Provenance and dispersal of the sediments of this province is the same as that of the constituent provinces.

(b) Edmonton Time: During late Middle Campanian or early Late Campanian, subsidence in the depositional area caused a major transgression of the Bearpaw Sea extending as far north as the Athabasca River (Williams and Burk, 1964, Fig. 12-21, p. 187). In this sea, marine muds and minor sands were deposited to form the Bearpaw Formation. During and after the maximum extension of the Bearpaw Sea coarser clastics deposited on its western and northwestern margins form the lower beds of the Edmonton Group of that area. During this time sediment dispersal seems to have been mainly from the northwest, bringing sediments from a moderately to strongly positive area of northern British Columbia and probably southern Yukon (Williams and Burk, 1964, Fig. 12-21, p. 187). Increasing tectonic activity in the eastern Cordillera resulted in an increase in the supply of detrital clastics, and southerly to easterly migration of the continental and deltaic sedimentary environments. This sedimentary shift followed the withdrawal of the Bearpaw Sea to the east and southeast. During this time, the remainder of the Edmonton Group was deposited. Dispersal was from the northwest, west and southwest (Shepheard and Hills, 1970, Fig. 2c, p. 169).

Two heavy mineral associations were recognized in Edmonton time, by which two heavy mineral provinces were mapped (Fig. 32). It is evident, from comparing the composition and areal pattern of the heavy mineral provinces of Belly River and Edmonton times (Figs. 31 and 32) that considerable changes took place in the relative positioning and composition of the distributive provinces. These changes are preferably explained by shifting of drainage basins due to tectonism rather than by compositional changes of static distributive provinces due to deeper erosion and unroofing. The major compositional changes that took place from Belly River to Edmonton time are the apparent cut in supply of hornblende and epidote-clinozoisite, and the reconstitution of the other provinces. The distribution of hornblende and epidote-clinozoisite could have shifted farther to the northeast where the Edmonton Group is presently eroded.

Zircon-Apatite Province: This province seems to be restricted to the central and southern Foothills and the southwestern Plains. However, on the basis of qualitative heavy mineral data of Byers (1969, p. 321), whereby zircon is a major heavy mineral of the Eastend and the overlying Whitemud Formations, this province might be extended to southeastern Alberta and adjacent areas of Saskatchewan to include the Cypress Hills area (Fig. 32). Sections that helped to delineate this province are those of the Oldman River, CPOG-

Strathmore core, Little Red Deer River and the Blackstone River.

The distributive province probably covered most of the crystalline complex of the southern part of the Omineca Geanticline of the Canadian Cordillera and equivalent rocks to the south in Idaho and Montana. Sediment dispersal was from northwest to southeast and west to east. Major heavy minerals to be found in this province are zircon, apatite, garnet, allanite, rutile, chlorite, tourmaline and chloritoid. Light mineral data are lacking in this province except for those of Byers (1969) on the Eastend and the Whitemud Formations of the Cypress Hills. Byers' petrographic work indicates that sandstones of the Eastend Formation are "volcanic lithic sandstones whereas those of the Whitemud Formation are metamorphic lithic sandstones" (Byers, 1969, p. 322). Binda's (1970) data also indicates that the Whitemud Formation sandstones of the Cypress Hills are metamorphic lithic.

As is the case with most of the Upper Cretaceous sections, bentonites and bentonitic sandstone and shale are common in the Edmonton Group of the Zircon-Apatite Province. This points to an important contribution from contemporaneous volcanism. Specific sources (volcanic vents) for such volcanic detritus was discussed previously in the section on the Belly River Group. However, Ritchie (1957) concluded that the volcanic material of the Kneehills Tuff, a widespread stratigraphic marker at the top of the Edmonton Group, had its source in volcanic vents of Late Cretaceous age in the general area of the Boulder Batholith near Butte, Montana. Ritchie based his conclusion on the similarity of the elemental chemistry and heavy accessory minerals of the Kneehills Tuff and the rhyolitic effusive phases of the Boulder Batholith. On the basis of a regional northward decrease in the grain size of the coarse fraction of the Kneehills Tuff, Binda (1970, pp. 23-28, Fig. 4) suggested a southern provenance for this tuff and agreed with Ritchie in placing the source volcanic vent(s) in the general area of Butte, Montana.

Heavy minerals of suspected contemporaneous volcanic source, present in this province, are euhedral zircon, brown biotite and euhedral and angular apatite. Evidence from light minerals comes from a study by Byers (1969) on the Eastend and Whitemud Formations of southeastern Alberta and southwestern Saskatchewan. In the Eastend Formation, lithic grains constitute 40 to 75 per cent of the sandstone framework of which the volcanic lithic grains are dominant. These volcanic grains were probably derived from a mixture of contemporaneous and older volcanics in south-central British Columbia, northern Idaho or western Montana.

Well-rounded zircon (mainly hyacinth), tourmaline and rutile point to a relatively important contribution from an older sedimentary source. This conclusion is borne out by the presence of chert grains forming 5 to 10 per cent of the sandstone framework of the Eastend and Whitemud Formations (Byers, 1969, p. 322). This sedimentary detritus could have been partly derived from the Upper Paleozoic rocks of interior British Columbia and Idaho-Montana (in the latter states the Upper Paleozoic rocks are at present covered by younger rocks) and partly from the older Mesozoic rocks of the ancestral Rocky Mountains, which were, according to Bally et al., (1966, p. 366, Fig. 11) involved in the folding and thrusting of the Cordilleran Miogeosyncline.

The presence of significant proportions of garnet (almandine), some andalusite and a few grains of kyanite and staurolite points to an important contribution from a high-grade metamorphic terrain. Some of the zircon and apatite may have been derived from the same source. A low-grade metamorphic source is suggested by the presence of moderate proportions of chloritoid and chlorite. Metamorphic rock fragments (quartzite, schist and gneiss) were found to be very abundant in the sandstones of the Whitemud Formation and to occur to a lesser extent in the underlying Eastend Formation (Byers, 1969). The specific source areas for these metamorphic components may have been in the Shuswap and/or the Wolverine metamorphic complexes of the southern part of the Omineca Geanticline and similar rocks in Idaho and Montana (the highly metamorphosed phases of the Precambrian Belt Supergroup).

Convincing evidence of a significant plutonic contribution to this province is lacking. However, some of the zircon and probably most of the apatite, rutile and some tourmaline may have been derived from the Mesozoic intrusives of British Columbia, Idaho and Montana.

Garnet-Sphene-Apatite Province: This province occupies the easternmost parts of the central Foothills and the Plains from the Red Deer River Valley to west of the Swan Hills (Fig. 32). Data on this province comes from the Red

Deer River Valley, GPOG-Strathmore core, Little Red Deer River section, Blackstone River section, Wildhay River Section, the Swan Hills and the northwestern Plains.

The distributive province may have been that part of the Omineca Geanticline to the immediate north and partially overlapping the distributive province of the Zircon-Apatite Province (i.e. central part of the Omineca Geanticline). Sediment dispersal was mainly from northwest to southeast. Major heavy minerals in this province are garnet, apatite, sphene, zircon, allanite and epidote-clinozoisite (the latter is especially abundant in the Wildhay River section of the northern Foothills). Other heavy minerals that exist in lesser amounts are rutile, chloritoid, staurolite, andalusite and kyanite. Sandstones of this heavy mineral province, in the Red Deer River Valley area, are mainly lithic with sedimentary fragments exceeding volcanic fragments in abundance, and with very minor occurrences of metamorphic rock fragments (Binda, 1970 and Shepheard and Hills, 1970).

Evidence for contribution from contemporaneous volcanism, as suggested by the presence of bentonites and tuffs, was discussed previously. However, sandstones of the lower part of the Edmonton Group of the Red Deer River Valley contain minor amounts of volcanic rock fragments (Shepheard and Hills, 1970, p. 186). Volcanic rock fragments became more abundant in the upper parts of the Edmonton Group (Binda, 1970) probably due to increasing volcanism that produced the Kneehills Tuff and a number of bentonites.

Except for some rounded zircon grains (including hyacinth), heavy mineral fractions show little evidence of contribution from a pre-existing sedimentary source. However, the lithic sandstones of the Red Deer River Valley are rich in chert and other sedimentary rock fragments (Binda, 1970 and Shepheard and Hills, 1970). Specific source areas and rocks for this sedimentary detritus may have been the Upper Paleozoic of central and southern British Columbia which contains abundant chert, along with a possible contribution from the older Mesozoic of the ancestral Rocky Mountains. It is likely that pre-existing sedimentary rocks have contributed most of the detrital clastics to the sedimentary basin of this heavy mineral province.

As with the previously discussed heavy mineral provinces, high-grade metamorphic sources have left undisputed evidence of their contribution to the sediments under study. Abundance of garnet, the persistence of staurolite and the occasional occurrence of andalusite and kyanite support this contention. The source area for these metamorphic components may have been the Amphibolite Facies of the central Omineca Geanticline of British Columbia. Epidote-clinozoisite and chloritoid could have been derived from the Greenschist Facies, and sphene from the Metagreywacke and Zeolite Facies of the same general area (G.S.C. Map 1322A, Monger and Hutchison, 1971). There are very few metamorphic rock fragments in the lithic sandstones of the Edmonton Group of the Red Deer River Valley (Binda, 1970; Shepheard and Hills, 1970) and it is not known how much of the light minerals (e.g. quartz and feldspar) were contributed by a metamorphic source. Volumetrically, metamorphic sources may have contributed nearly as much detritus as volcanic sources (both older and contemporaneous volcanics) and probably more than the contribution from only the older volcanics.

Again, definite evidence for a significant contribution from a plutonic source is not available from either the heavy or light mineral fractions. However, some or most of the apatite and zircon could have been derived from a plutonic source; allanite and rutile may also have come from a plutonic source. Evidence from conglomerates and finer clastics of the Upper Cretaceous to Paleocene Sustut Group of north-central British Columbia suggests that Omineca Intrusions were unroofed at that time (Gabrielse, in Douglas, 1970, p. 460). Therefore, these intrusions may have contributed abundant clastic detritus to this province. However, as mentioned previously plutonic rock fragments, the best evidence for plutonic contribution, are rarely recognizable as such in sandstones of mean grain size less than very coarse-grained sand.

(c) Paskapoo Time: Rocks of Paskapoo time are all those of post-Kneehills Tuff, Lance and Paleocene age. Four heavy mineral associations were recognized, from which four heavy mineral provinces were mapped (Fig. 33), namely: Zircon Province, Epidote-Clinozoisite Province, Garnet-Apatite-Sphene Province and Hornblende Province. The observed changes in provinces, compositions, and areal positions from Edmonton to Paskapoo time are (Figs. 32 and 33):

(1) The Zircon-Apatite Province of Edmonton time gave way to a Zircon Province in Paskapoo time. The latter province is restricted to the southern and southwestern parts of the study area.

(2) The Garnet-Apatite-Sphene Province persisted throughout, but with lesser areal extent.

(3) An Epidote-Clinozoisite Province appeared between the above-mentioned provinces.

(4) A Hornblende Province came into existence on the east and north-eastern side of the Garnet-Apatite-Sphene Province.

It is quite clear that a considerable change took place, near the time of the deposition of the Kneehills Tuff, in the composition and areal positions of the distributive provinces of the source area in the Eastern Cordillera. These changes were brought about by the increasing intensity and migration of the locale of tectonism in the source area. It was probably at this time that the earliest major pulse of the Laramide Orogeny occurred.

Zircon Province: This province covers most of the southern Foothills and the southern Plains of Alberta south of the Bow-South Saskatchewan Rivers (Fig. 33). Two sections on the Oldman River (Foothills) and several others in the Cypress Hills area were used to establish this province.

The distributive province was probably situated in the extreme south part of the Omineca Geanticline and extended southward into Idaho and western Montana. Dispersal appears to have been mainly from west to east along with dispersal components from southwest to northeast and from northwest to southeast. Paleocurrent data (dip-azimuth direction of cross-stratification) of the Porcupine Hills Formation in southwestern Alberta show a vector mean pointing northeast (Carrigy, 1971, Fig. 5, p. 22).

Major heavy minerals to be found in this province are zircon, garnet, apatite, allanite, rutile, tourmaline and chlorite. Only two grains of andalusite and one grain of chloritoid were found in this area. Light mineral petrography shows that sandstones of this province are lithic and most of the rock fragments are of sedimentary origin (Carrigy, 1971, Chi, 1966, and Nelson, 1968).

The relatively abundant light mineral data on the Willow Creek and Porcupine Hills Formations (Carrigy, 1971, Table 12, p. 124 and Nelson, 1968, Table 1, p. 427 and Fig. 2, p. 429) and the Frenchman Formation (Chi, 1966, Table 5-1, p. 40) show beyond doubt that the distributive province was composed mainly of sedimentary rocks. Carrigy (Fig. 12, 1971) presented a plot of the percentage distribution of chert grains in post-Kneehills sandstones. It clearly shows a general north and northwestward decrease in relative chert abundance away from southwestern Alberta. This trend also coincides, in general terms, with a north to northwestward decrease in detrital carbonate grains (Carrigy, 1971, Fig. 18). These trends suggest that the sedimentary sources were located to the west and southwest of southwestern Alberta, and coincide with the Zircon Distributive Province.

Heavy minerals that reflect a sedimentary source are rounded zircon (largely hyacinth) and rutile which occur in abundance, and less abundant rounded tourmaline and apatite. A relatively less volumetrically important sediment contribution are high-grade metamorphic source rocks indicated by garnet, and low-grade metamorphic rocks represented by chlorite. Contributions from volcanic sources, contemporary or older, are not significant, judged on the basis of heavy minerals. Carrigy (1971, p. 38) proposed, on the basis of rock fragment composition, the following relative abundance of sedimentary, metamorphic and volcanic contributions:

Willow Creek Formation: sedimentary > volcanic > metamorphic

Porcupine Hills Formation: sedimentary > metamorphic > volcanic

Plutonic sources are not particularly evident from the heavy mineral composition unless apatite, allanite and rutile were derived from such sources. A decrease in the relative abundance of feldspar from the Willow Creek to the overlying Porcupine Hills Formation (Carrigy, 1971, p. 36) indicates the diminishing contribution of crystalline sources and the increasing influx of material from sedimentary sources.

Source rocks that supplied the sedimentary grains were probably the Paleozoic cherty carbonates and older Mesozoic detrital rocks brought into the erosional realm during the thrusting and uplifting of the Rocky Mountains (Laramide Uplift). The metamorphic components may have been derived from the metamorphic terrain of the Omineca Geanticline further west which was not completely cut off by the newly rising Rocky Mountains.

Nelson (1968, p. 428-429), however, thought that the source for this sedimentary detritus might have been in the Paleozoic sediments of the Purcell and Selkirk Mountains (i.e. the Omineca Geanticline) west of the present day Rocky Mountains. Since this area is presently underlain by large expanses of metamorphic and plutonic rocks (which may exceed sedimentary rocks in areal abundance), one would have to assume that these metamorphic and plutonic rocks were mostly covered during very Late Cretaceous and Paleocene time in order to accept Nelson's assumption; otherwise, the metamorphic contribution would be dominant over the sedimentary contribution, while facts attest to the contrary. It is also not likely that the Omineca Geanticline would shed an increasing volume of detritus from sedimentary sources with time. The then newly rising Rocky Mountains with their huge piles of Paleozoic carbonates and cherts and older Mesozoic detrital rocks are more appealing to the writer as sources for the Zircon Province. However, other sedimentary sources of less importance (those suggested by Nelson) which were probably of clastic nature may have also contributed some of the abundant, multicycled rounded zircon and rutile. Carrigy (1971, p. 75) suggested that the sources were mainly sedimentary rocks composed of Paleozoic carbonates and chert in the southern extension of the Rocky Mountains (southern Laramide Uplift).

Epidote-Clinozoisite Province: This heavy mineral province occupies all the central and northern Foothills and forms a narrow belt that runs northwest-southeast through the southern Plains of Alberta (Fig. 33). The northeastern end of the Epidote-Clinozoisite Province protrudes northeastward displacing the adjacent province in that direction.

The distributive province may have occupied a large portion of the central Omineca Geanticline to the west and northwest of the Epidote-Clinozoisite Province, sediment dispersal being from west and northwest to east and southeast with localized southwest to northeast dispersal components (Fig. 33).

The major heavy minerals of this province are epidote-clinozoisite, garnet, apatite, sphene, tourmaline, zircon and chlorite. Chloritoid is of minor importance but occasionally exceeds 2 per cent. Minor to rare are andalusite, staurolite and kyanite. The sandstones of this province are also largely lithic. Rocks of this province fall in the Volcanic Petrologic Province of Carrigy (1971, pp. 61 and 75) with dispersal direction from northwest to southeast. However, Carrigy's petrologic provinces are broader and less well defined than the presently defined heavy mineral provinces. Carrigy's (1971, p. 38) data shows the following relative contribution of sources on the basis of rock fragment composition:

Paskapoo Formation: metamorphic $>$ volcanic $>$ sedimentary

Ravenscrag Formation (i.e. Ravenscrag and Frenchman):

volcanic $>$ sedimentary $>$ metamorphic

Chi's (1966) rock fragment data shows the following order of contribution to the Scollard Member and Frenchman Formation: sedimentary $>$ volcanic $>$

metamorphic. Therefore on the basis of the light mineral data (mainly rock fragments), volcanic and sedimentary sources may have been about equally important in contributing clastic detritus to this province, with metamorphic sources being a close third. Again, plutonic contribution would be underestimated using the rock fragment evidence alone.

Heavy minerals of the Epidote-Clinozoisite Province suggest the following sources (metamorphic terminology and geology of Monger and Hutchinson, 1971, G.S.C. Map 1322 A):

(1) Epidote-clinozoisite and chlorite (?): source in the Greenschist Facies of the central Omineca Geanticline north of the city of Prince George, British Columbia.

(2) Garnet and the minor occurrences of staurolite, chloritoid, andalusite and kyanite: source in the Amphibolite Facies of the same general area.

(3) Sphene (probably mostly metamorphic due to its association with other metamorphic minerals): source in the Metagreywacke and Zeolite Facies of the same area.

(4) Glaucophane (recognized only in the Frenchman Formation of the Cypress Hills): source in the Glaucophane-Lawsonite Schist Facies in the central Omineca Geanticline (Unit 3 of the G.S.C. Map 1322A).

(5) Euhedral zircon and minor euhedral apatite: possibly from

contemporaneous volcanism in central and western British Columbia prevalent during and after deposition of the Kneehills Tuff.

(6) Some of the zircon, apatite (including colored varieties) and tourmaline: sources in the acidic plutonic rocks of the central Omineca Geanticline (e.g. Topley batholith).

Contribution from crystalline sources to this province may have exceeded that of sedimentary sources, contrary to the situation we have in the Zircon Province to the south. This suggests that the newly forming Rocky Mountains to the immediate west of this area did not significantly shut off the flow of clastic detritus coming from the crystalline rocks of the Omineca Geanticline further to the west. This in turn may suggest that the ancestral Rocky Mountains were higher in southwestern than in western Alberta (rejuvenated Montania of southwestern Alberta and neighboring United States).

Garnet-Apatite-Sphene Province: This province occupies a narrow belt, to the east and northeast of the previous province, trending northwest to southeast across the Plains area (Fig. 33). It is a continuation of the Garnet-Apatite-Sphene Province of Edmonton Group time, but since then it had shifted slightly to the east and northeast, and became restricted on the east and northeast by the appearance of the Hornblende Province (Fig. 33).

The distributive province was located in the central and/or northern parts of the Omineca Geanticline just north of the Epidote-Clinozoisite Distributive Province, and west and northwest of the Garnet-Apatite-Sphene

Province. Sediment dispersal was from northwest to southeast as evidenced by the areal pattern of the heavy mineral province and by paleocurrent data of Carrigy (1971).

The major heavy minerals found in this province are garnet, apatite, sphene, zircon, allanite, chloritoid, rutile, and epidote-clinozoisite. There are minor occurrences of staurolite and andalusite and rare occurrences of kyanite and glaucophane. The sandstones are lithic and their light mineral content is similar to that of the previous province, indicating a similar provenance.

The heavy minerals point to a major high-grade metamorphic source with low-grade metamorphic, volcanic and acidic plutonic sources of lesser importance. Rounded zircon and rutile indicate a contribution from sedimentary sources. However, light mineral evidence shows that sedimentary sources were far more important than suggested by heavy minerals.

Composition of the source areas is generally similar to that discussed in the Epidote-Clinozoisite Province. The difference that resulted in the formation of two distinct heavy mineral provinces was probably that of proportions of low-grade (Greenschist, Greywacke and Zeolite Facies) and high-grade (Amphibolite Facies) metamorphic rocks contribution.

<u>Hornblende Province:</u> The Hornblende Province is the easternmost heavy mineral province of Paskapoo time. Its eastern and northeastern limits are not known since the Paskapoo Formation and equivalent rocks are eroded

in eastern Alberta (Fig. 33). The areal pattern of this province points to a distributive province situated in the northern part of the Omineca Geanticline with sediment dispersal from northwest to southeast (Fig. 33). Major heavy minerals are hornblende, garnet, epidote-clinozoisite, sphene, zircon, tremolite-actinolite and apatite. Of minor to rare occurrences are staurolite, andalusite, kyanite and glaucophane.

The sandstone is lithic in this province with composition and inferences on provenance based on light minerals similar to those discussed in the two previous heavy mineral provinces. The provenance discussion here will centre around the use of heavy minerals. In the province, hornblende makes up from one-third to one-half of the non-opaque heavy mineral suite. Most of this hornblende is green and olive, with lesser amounts of brown and red-brown hornblendes and very rare occurrences of bright red hornblende (oxyhornblende). The latter two color varieties may have been derived partially from basic volcanic rocks. Blue to blue-green hornblende of distinctive metamorphic origin is extremely rare. Therefore most of the hornblende was probably derived from an acidic to intermediate plutonic source. However, a metamorphic origin for some of these olive and green varieties cannot be ruled out. Other heavy minerals of probable plutonic source are zircon, apatite and likely some of the sphene. Epidote-clinozoisite, garnet, tremolite-actinolite, some of the sphene, kyanite, andalusite and glaucophane all attest to the presence in the source area of considerably high- and low-grade metamorphic terrain. Sedimentary source rocks are evidenced only slightly by the occurrence of rounded zircon and apatite. However, rock fragments of sedimentary nature suggest a relatively significant contribution from a sedimentary cover. This material was discussed previously for the Epidote-Clinozoisite Province. Evidence from rock fragments for volcanic contribution was also discussed previously and was suggested to have been fairly significant. The euhedral zircon and apatite may have been derived from contemporaneous volcanicity. In summary, heavy mineral data point to the following order of source rock contribution to the Hornblende Province:

$$\text{Metamorphic and plutonic} \gg \text{Volcanic} > \text{Sedimentary}$$

On the other hand, based on rock fragment composition, the following order of contribution is suggested:

$$\text{Volcanic} \geq \text{Sedimentary} > \text{Metamorphic} > \text{Plutonic}$$

The metamorphic (low and high-grade), plutonic and stratified cover rocks of the Cassiar Mountains (northern Omineca Geanticline) are the most appealing as source rocks.

SUMMARY AND CONCLUSIONS

This study was undertaken to determine the provenance and dispersal of the sandstones of the Upper Cretaceous and Paleocene molasse sequence of Alberta and adjacent areas of Saskatchewan. The sequence ranges in thickness from zero feet in the east to 13000 feet in the west, and consists, from bottom to top, of the Belly River Group, the Edmonton Group, the Paskapoo Formation, and their equivalents. The approach was to study the heavy minerals of sandstone samples collected from the Rocky Mountain Foothills and from the Plains to the east. The common non-opaque, non-micaceous heavy minerals encountered were, in alphabetical order, allanite, apatite, epidote-clinozoisite, garnet, hornblende, rutile, sphene, tourmaline and zircon.

Scanning electron microscopy of detrital garnet and hornblende revealed grain-surface etch features that show the manner of diagenetic solution of these minerals. K-Ar ages of detrital hornblende from Upper Cretaceous sandstones in the eastern and southeasternmost parts of the study area range from 114 to 155 m.y. and indicate sources in Mesozoic crystalline rocks of the northern Omineca Geanticline.

To analyse the provenance and dispersal of the heavy mineral content of the sandstones of this sequence, the lithostratigraphic units of this sequence were grouped into three lithostratigraphic "slices" as follows: the Belly River "slice", Edmonton "slice" and Paskapoo "slice". Application of Q-mode factor analysis to the heavy mineral data of the three "slices" generated ten heavy mineral associations on the basis of which ten heavy mineral provinces were delineated and mapped. The heavy mineral provinces are generally elongate and parallel or subparallel to the tectonic elements of the source area to the west (Omineca Geanticline and later the Laramide Uplift) occupying vast coastal plains bounded to east and southeast by a widely shifting epeiric sea.

During Belly River time (Early Campanian) five heavy mineral provinces are recognized: Apatite Province, Zircon-Garnet Province, Epidote-Clinozoisite-Garnet-Sphene Province, Hornblende Province and a fifth province made up of a mixture of heavy minerals of the first three provinces (Fig. 31). Sediment dispersal at this time was largely fluvial from northwest to southeast, with a more easterly direction in the southern part of the study area. Dispersal of mineral grains in the Hornblende Province during lower Belly River time (Foremost) is believed to have occurred in shallow marine environments by longshore currents flowing to the southeast, since the enclosing rocks are of shoreline to shallow marine environments. Heavy and light mineral evidence shows a major detrital contribution to the Belly River sandstones from sedimentary sources, probably Upper Paleozoic cherts, carbonates and detrital clastics of central and southern interior of British Columbia (Cache Creek Group and equivalents). A lesser contribution came from low- and high-grade metamorphic terrain (Amphibolite, Greenschist and Zeolite Facies) of the Omineca Geanticline and its southern extension in the northwestern United States.

Contemporaneous volcanism in British Columbia and western Montana as well as older volcanics of the British Columbia interior made an appreciable contribution to the clastic detritus of the Belly River Group. The available evidence suggests a very minor contribution from plutonic sources.

In early Edmonton time (late Middle or early Late Campanian) a major transgression of the epicontinental sea (Bearpaw Sea) took place. During this time interval, sediment dispersal seems to have been mainly from the northwest, bringing sediments from a moderately to strongly positive area of northern British Columbia, and probably the southern Yukon. Later, increasing tectonic activity in the eastern Cordillera resulted in an increase in the supply of detrital clastics, and southerly to easterly migration of the continental and deltaic sedimentary environments. This sedimentary shift accompanied the withdrawal of the Bearpaw Sea to the east and southeast, and provided the major deposits of the Edmonton Group. As for the Belly River, dispersal was mainly toward the southeast but assumed a more easterly direction toward the southern part of the study area. Two heavy mineral provinces were recognized in Edmonton time: a Zircon-Apatite Province and a Garnet-Apatite-Sphene Province. It is evident from comparing the composition and areal patterns of the heavy mineral provinces of Belly River and Edmonton times (Figs. 31 and 32) that considerable changes took place in the positions and compositions of the distributive provinces. These changes are believed to be better explained by shifting of drainage basins due to tectonism rather than by compositional changes of static distributive provinces due to deeper erosion and unroofing. The heavy minerals of the study sequence do not show any consistent upward order of heavy mineral zones that should reflect the progressive "unroofing" of a source areas as erosion proceeds down to deeper levels, namely, from sedimentary through low-grade metamorphic, high-grade metamorphic and finally to plutonic rocks (van Andel, 1959, p. 160). The major compositional changes that took place from Belly River to Edmonton time are an apparent cut-off of supply of hornblende and epidote-clinozoisite, and the reconstitution of the other provinces. Light mineral, and to a lesser extent heavy mineral, evidence points to a major contribution from pre-existing sedimentary sources, probably from the Upper Paleozoic of the central and southern interior of British Columbia, and some closer sources in the older Mesozoic of the ancestral Rocky Mountains (rejuvenated Montania?), which were, according to Bally et al., (1966), involved in the early stages of folding and thrusting of the Cordilleran Miogeosyncline (early Laramide). There is abundant light mineral and some heavy mineral evidence for a significant contribution from volcanic sources, both contemporaneous and older. On the basis of rock fragment composition, contributions from volcanic sources appears to have increased in Edmonton time, possibly partially due to the increasing volcanism in British Columbia and Montana. Contributions from older volcanic rocks probably came from Mesozoic volcanics in the interior of British Columbia. Metamorphic contributions, of both high- and low-grade, seem to have been very important throughout Edmonton Group time, and were probably as volumetrically important as volcanic sources. However, light mineral evidence (rock fragments) suggests only a minor contribution from metamorphic sources throughout deposition of most of the lower part of the Edmonton Group (Horseshoe Canyon and Eastend Formations), but increasing later (Whitemud Formation). The source of these metamorphic components may have been the Amphibolite, Greenschist and Zeolite Facies of the Omineca Geanticline. As in the case of the Belly River Group, convincing light or heavy mineral evidence for any significant plutonic contribution is lacking. Evidence from conglomerates of Upper Cretaceous and Paleocene successor basins sediments in northern British Columbia indicates that the Omineca Intrusions were unroofed at that time (Gabrielse, in Douglas, 1970, p. 460). Therefore, these intrusions may have shed significant amounts of clastics to the Edmonton Group. But because plutonic rock fragments, probably the best evidence for a plutonic contribution, are generally not recognizable as such in the finer sandstones, such rock fragments were not found in any significant amounts in the medium- to fine-grained sandstones of the study area.

Continental sedimentation of Edmonton Group type continued during Paskapoo time. In the Paskapoo Formation and its equivalents, which include all post-Kneehills Tuff Lance and Paleocene rocks, four heavy mineral provinces were recognized (Fig. 33), namely: Zircon Province, Epidote-Clinozoisite Province, Garnet-Apatite-Sphene Province and Hornblende Province. The observed changes in the composition and areal pattern of heavy mineral provinces from Edmonton to Paskapoo time are (Figs. 32 and 33): (1) The Zircon-Apatite Province of Edmonton time gave way to a Zircon Province in Paskapoo time. The latter province is restricted to the southern and southwestern parts of the study area. (2) The Garnet-Apatite-Sphene Province persisted throughout, but with less areal extent. (3) An Epidote-Clinozoisite Province appeared between the above-mentioned provinces. (4) A Hornblende Province came into existence on the eastern and northeastern side of the Garnet-Apatite-Sphene Province. This suggests that a considerable change took place in the composition and positions of the distributive provinces of the eastern Cordillera near the time of deposition of the Kneehills Tuff. These changes were probably brought about by the increasing intensity and migration of the locale of tectonism in the source area. It was probably at this time (early Lance) that the earliest major pulse of the Laramide Orogeny occurred. Sediment dispersal was mainly to the southeast and east with northeast dispersal confined to the southern part of the study area. Heavy and light mineral evidence points to an near equal contribution from sedimentary and volcanic sources over most of the study area with a metamorphic contribution being a close third. As was previously mentioned, a plutonic contribution cannot be accurately assessed, but probably was not significant during Paskapoo time except that a considerable part of the sediments of the Hornblende Province may have been contributed by plutonic rocks of the Cassiar Mountains of northern British Columbia. Suspected sources for the sedimentary components of the Paskapoo Formation and its equivalents were the Upper Paleozoic sediments of the central and southern interior of British Columbia and the Mesozoic and Paleozoic clastics and cherty carbonates of the newly rising ancestral Rocky Mountains. Petrographic (heavy and light mineral) evidence indicates that crystalline sources of the Omineca

Geanticline contributed more to the central and northern than to the southern Foothills area, and that the southern Foothills received increasing amounts of sedimentary components from the ancestral Rocky Mountains. This in turn may suggest that the ancestral Rocky Mountains were higher in southwestern than in western Alberta (rejuvenated Montania of southwestern Alberta and the neighboring United States). Metamorphic and volcanic source areas were probably the same that contributed to the Edmonton Group.

The above discussed variations in the heavy mineral provinces with time probably reflect major pulses of tectonism in the Cordillera that resulted in the deposition of the three clastic lithostratigraphic units under study. Deposition of the Belly River Group may be correlated with the latest tectonic pulse of the Columbian Orogeny (Nevadan) and that of the Edmonton Group and the Paskapoo Formation with the earliest tectonic pulses of the Laramide Orogeny.

It appears from this study that only metamorphic source rocks leave definite and reliable heavy mineral evidence of their contribution. Volcanic source rocks, especially explosive contemporaneous, may leave heavy mineral evidence in the form of rare euhedral grains, but most of the more stable of such minerals may also come from plutonic rocks. Definite heavy mineral evidence for a contribution from pre-existing sedimentary rocks comes as well-rounded stable heavy minerals, but this evidence will almost always underestimate the volumetric contribution. Except for certain rarely occurring heavy minerals, evidence for a contribution from plutonic source rocks is very difficult to establish, especially volumetrically. Reasonable estimation of volumetric contribution from the different types of source rocks is only possible by a combination of light and heavy mineral studies, and knowledge of chemical stability and mechanical resistance.

Heavy mineral analysis as a stratigraphic tool in petroleum geology has been largely discarded in favor of micropaleontology. Selective sorting and intrastratal solution were factors suggested to possibly cause wide fluctuations in the proportions of heavy minerals, "...and while correlation of broad stratigraphic zones over large areas was quite feasible, local variations tended to be haphazard and the effectiveness of the tool in detailed studies was questionable" (Griffiths, 1967, p. 203).

However, heavy mineral studies have continued as an aid in regional paleogeographic reconstruction and in correlation studies in continental sediments. More recently, they have been increasingly used in local detailed studies of the hydrodynamics of sand deposition, and the literature is growing rapidly. This trend reflects perhaps a re-awakening of sedimentologists and stratigraphers to an awareness of the potential of heavy minerals as a powerful tool in interpreting the regional provenance, dispersal, transport, depositional and post-depositional conditions of terrigenous clastics. Doeglas, as early as 1940, recommended such an approach for better use of heavy mineral assemblages.

This study clearly shows the usefulness of heavy minerals in helping to solve regional stratigraphic problems. The sudden appearance of floods of epidote-clinozoisite at or slightly above the base of the Paskapoo Formation of the central Foothills (Figs. 20, 21 and 22) and slightly above the Kneehills Tuff of the Plains (Fig. 24) suggests that the Paskapoo-Brazeau Formation contact of the central Foothills is approximately time-equivalent with the Kneehills Tuff of the Plains, and that the Cretaceous-Paleocene boundary in the central Foothills occurs within Paskapoo beds. The fact that the heavy mineral suites of the samples of the entire sequence under study were divisible into three, internally rather homogenous, groups of samples coinciding with the regional lithostratigraphic subdivisions supports the usefulness of heavy minerals in stratigraphic analysis.

The effects of local selective sorting and intrastratal solution on the relative proportions of heavy minerals can be satisfactorily assessed in regional studies. Hence, as soon as the regional heavy mineral distribution is adequately understood, local and detailed studies can be safely undertaken. In the present work a few of the heavy mineral provinces contain some samples with anomalous heavy mineral suites that show the same heavy mineral species but in different proportions and orders of abundance. These anomalous heavy mineral suites are obviously of the same provenance as the host heavy mineral provinces, but differences may have been caused by selective sorting and/or intrastratal solution. Such information may not be gained if the worker restricts himself to localized studies without having a conception of the regional distribution. It also appears that the role of intrastratal solutions has been overestimated by some workers.

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APPENDIX A

SAMPLE LOCATION

Legend

* Exact stratigraphic position uncertain

** Exact stratigraphic position uncertain, but samples are arranged in stratigraphic order

APPENDIX A

Section/Area	Sample	Position	Lithost. Unit
Drywood River (Tp.4-29-W.4)	3271	1960' above top of Wapiabi Fm	Belly River Fm
	3274	1760' " " " " "	
	3276	1520' " " " " "	
	3277	690' " " " " "	
	3280	400' " " " " "	
	3281	135' " " " " "	
Porcupine Hills (Sec.35-7-1-W.5)	8098	1340' " " " Willow Creek Fm	Porcupine Hills Fm
	8097	1240' " " " " " "	
	8094	1100' " " " " " "	
Oldman River (Secs.1 & 12-10-2-W.5 and Secs.5 & 6-10-1-W.5)	8093	3905' " " " Bearpaw Fm	Willow Creek Fm
	8092	3575' " " " " "	
	8091	3410' " " " " "	
	8090	3240' " " " " "	
	8089	3100' " " " " "	St. Mary River Fm
	8088	3070' " " " " "	
	8087	2940' " " " " "	
	8086	2750' " " " " "	
	8085	2550' " " " " "	
	8084	2380' " " " " "	
	8083	2235' " " " " "	
	8082	2030' " " " " "	
	8081	1915' " " " " "	
	8080	850' " " " " "	
	8079	495' " " " " "	
	8078	360' " " " " "	
Highwood River (Secs.19 & 30-18-2-W.5)	8077	1815' " " " Wapiabi Fm	Belly River Fm
	8075	1515' " " " " "	
	8074	1225' " " " " "	
	8072	955' " " " " "	
	8071	725' " " " " "	
	8070	605' " " " " "	
	8069	525' " " " " "	
	8067	40' " " " " "	

Section/Area	Sample	Position	Lithst. Unit
CPOG-Strathmore Well (Lsd.7,Sec.12-25-25-W.4)	8109	1915' above top of Lea Park Fm	Horseshoe Canyon Fm
	8107	1535' " " " " " "	
	8106	1220' " " " " " "	
	8105	1115' " " " " " "	
	8104	790' " " " " " "	Belly River Gp
	8103	620' " " " " " "	
	8102a	490' " " " " " "	
	8101	360' " " " " " "	
	8100	190' " " " " " "	
	8099	80' " " " " " "	
Little Red Deer River (Sec.28-28-6-W.5)	4355b	4525' " " " Wapiabi Fm	Paskapoo Fm
	4353	4200' " " " " "	
	4352	4025' " " " " "	
	4351	3700' " " " " "	
	4350a	3585' " " " " "	
	4341	3100' " " " " "	Edmonton Fm
	4338a	2600' " " " " "	
	4335	2450' " " " " "	
	4331	2100' " " " " "	
	4330	1850' " " " " "	
	4329	1600' " " " " "	
	4328	1350' " " " " "	
	4325	1085' " " " " "	
	4324	850' " " " " "	Belly River Fm
	4320	550' " " " " "	
	4317	450' " " " " "	
	4315b	10' " " " " "	
Colt Creek (Secs.13 & 24-42-15-W.5)	4874	1250' above base of Paskapoo Fm	Paskapoo Fm
	4867	850' " " " " "	
	4866	600' " " " " "	
	4861	400' " " " " "	
	4860	300' " " " " "	
	4857a	200' below " " " "	Brazeau Fm
	4857	200' " " " " "	
	4856	300' " " " " "	
	4854	700' " " " " "	

Section/Area	Sample	Position	Lithost. Unit
Blackston River (Secs.18 to 28-43-16-W.5)	8124	5320' above top of Wapiabi Fm	Paskapoo Fm
	8123	4800' " " " " "	
	8122	4670' " " " " "	
	8121	4430' " " " " "	
	8120	4130' " " " " "	Edmonton Fm
	8119	3950' " " " " "	
	8118	3250' " " " " "	
	8117	2910' " " " " "	
	8116	2090' " " " " "	
	8115	1520' " " " " "	
	8114	1290' " " " " "	
	8113	900' " " " " "	Belly River Fm
	8112	620' " " " " "	
	8111	360' " " " " "	
	8110	285' " " " " "	
Wildhay River (Secs.19,29,30 & 32-52-27-W.5)	8060	3050' above top of Wapiabi Fm	upper Brazeau Fm (Edmonton Fm equivalent)
	8059	2950' " " " " "	
	8058	2550' " " " " "	
	8057	2150' " " " " "	
	8056	1550' " " " " "	
	8055	1195' " " " " "	
	8054	1000' " " " " "	

Section/Area	Sample	Position**	Lithost. Unit
Northwestern Plains			
NW¼ Tp.60-4-W.6	8136		Paskapoo Fm
NW¼ Tp.61-3-W.6	8135		
SW¼ Tp.63-2-W.6	8134		
SW¼ Tp.64-2-W.6	8133		
SE¼ Tp.67-4-W.6	8132		Edmonton Gp
NW¼ Tp.69-4-W.6	8131		
Swan Hills			
Sec.16-64-14-W.5	8130		Paskapoo Fm.
Sec.31-62-14-W.5	8129		
Sec.19-60-12-W.5	8128		
Sec.12-60-12-W.5	8127		
SW¼ Tp.68-14-W.5	8126		
NW¼ Tp.68-14-W.5	8125		Edmonton Gp.

Area	Sample	Position**	Lithost. Unit
Western Plains			
Sec.7-53-7-W.5	6001b		
Sec.12-49-7-W.5	6004b		
Sec.4-57-13-W.5	6019a		
Sec.20-53-16-W.5	6027		Paskapoo Fm
Sec.21-39-8-W.5 (Rocky Mountain House)	4777		
Sec.21-40-12-W.5 (Near Saunders)	5050a	about 2000' above base of Paskapoo Fm	
Sec.21-40-12-W.5 (Near Saunders)	5057	about 4500' " " " " "	
East-Central Alberta			
SE$\frac{1}{4}$ Sec.6-41-2-W.4	8050		
NW$\frac{1}{4}$ Sec.10-45-8-W.4	8053		
N.Sec.2 & 3-49-9-W.4	8042		Oldman Fm
NE$\frac{1}{4}$ Sec.8-47-7-W.4	8039		
SW$\frac{1}{4}$ Sec.18-50-8-W.4	8035		
NE$\frac{1}{4}$ Sec.19-45-7-W.4	8052		
Sec.26-51-11-W.4	8047		
SE$\frac{1}{4}$ Sec.7-50-4-W.4	8032		Foremost Fm
NE$\frac{1}{4}$ Sec.32-51-4-W.4	8045		
E$\frac{1}{4}$ Sec.32-51-4-W.4	8044		
NE$\frac{1}{4}$ Sec.31-44-1-W.4	8048		
NW$\frac{1}{4}$ Sec.28-49-4-W.4	8033		
SE$\frac{1}{4}$ Sec.15-51-9-W.4	8046		
Sec.21-54-7-W.4	8036		
N Sec.7 & 8-55-7-W.4	8037		
SW$\frac{1}{4}$ Sec.6-51-8-W.4	8034		

Section/Area	Sample	Position	Lithost. Unit
Red Deer River Valley			
SE$\frac{1}{4}$ Sec.13-30-23-W.4	5000	5' above Kneehills Tuff	Paskapoo-type sandstone
SE$\frac{1}{4}$ Sec.13-30-23-W.4	4999	10' below " "	" " "
Tp.28-21-W.4	4697	40' " " "	Edmonton-type sandstone
SE$\frac{1}{4}$ Sec.18-25-38-W.4	5198	150'-200' above base of Paskapoo Fm	Paskapoo-type "

Section/Area	Sample	Position	Lithost. Unit
NE¼ Sec.4-25-38-W.4	5200	50'-100' above base of Paskapoo Fm	Paskapoo-type sandstone
SW¼ Sec.17-38-23-W.4	4723	100' above U.Ardley Seam	" " "
Red Deer River Valley (composite section)			
NE¼ Sec.13-34-22-W.4	4729	1120' above top of Bearpaw Fm	Paskapoo Fm
NE¼ Sec.13-34-22-W.4	4728	1100' " " " " "	
SE¼ Sec.18-34-21-W.4	4722	1090' " " " " "	
SE¼ Sec.18-34-21-W.4	4721	1015' " " " " "	
SW¼ Sec.27-35-21-W.4	4709	965' " " " " "	
SE¼ Sec.18-34-21-W.4	4720	920' " " " " "	Edmonton Gp
SW¼ Sec.27-35-21-W.4	4710	865' " " " " "	
SW¼ Sec.16-31-21-W.4	4690	700' " " " " "	
SW¼ Sec.16-31-21-W.4	4695	530' " " " " "	
Sec. 15-29-20-W.4	4703	340' " " " " "	
SW¼ Sec.7-28-18-W.4	4700	10' " " " " "	

APPENDIX B

HEAVY MINERAL DATA

Heavy mineral data of the Cypress Hills samples are to be found in Chi (1966, pp. 100-111).

<u>Legend</u>

T: Less than 1%

**: Number of biotite and opaque grains accompanying the 100 non-opaque mineral grains

*: Only black opaques

++: Not available

+: Heavy minerals weight % in the -80 + 230 mesh size-fraction

*+: Magnetite removed by horseshoe magnet

NC: Not counted

APPENDIX B

Heavy Mineral Percentage Data

LOCATION	DRYWOOD RIVER						PORCUPINE HILLS			OLDMAN RIVER							
Lithost. Unit	Belly River Fm.						Porcupine Hills Fm.			St. Mary River Fm.							
SAMPLE NUMBER	3281	3280	3277	3276	3274	3271	8094	8097	8098	8078	8079	8080	8081	8082	8083	8084	8085
Hornblende	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Garnet	5.6	12.2	6.1	27.0	18.9	12.9	6.3	17.7	16.5	9.9	12.1	6.4	5.0	23.9	15.6	12.5	6.8
Epidote-Clinozoisite	T	T	-	T	-	T	-	-	-	-	T	-	-	-	-	-	-
Apatite	61.7	30.5	64.0	54.5	53.4	48.6	2.4	8.6	2.4	23.1	25.1	36.1	38.3	24.3	17.7	10.0	10.7
Rutile	1.2	1.8	1.8	1.6	1.6	1.2	3.4	6.2	5.3	6.4	17.4	9.4	4.5	3.2	4.9	4.0	5.8
Sphene	-	-	-	-	-	-	2.9	-	1.0	-	-	T	-	-	-	-	-
Tourmaline	9.9	2.4	5.5	3.7	15.2	7.0	T	1.0	1.0	5.4	9.7	7.9	2.5	1.4	2.9	-	6.8
Tremolite-Actinolite	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Allanite	6.2	33.5	5.5	T	2.6	7.6	3.4	1.0	7.3	-	-	-	-	4.6	-	1.0	-
Chlorite	6.2	1.8	1.8	3.2	-	-	T	-	-	T	9.2	5.5	2.5	1.8	3.9	2.0	21.4
Zircon	7.4	15.2	13.4	5.3	6.8	18.7	79.7	65.5	66.0	50.8	25.6	32.2	47.3	39.9	53.0	70.5	46.6
Staurolite	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Chloritoid	-	-	-	2.1	-	T	-	-	T	T	-	-	-	-	-	-	-
Glaucophane	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Kyanite	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Andalusite	-	-	1.2	-	-	1.2	1.0	-	-	-	-	-	-	-	-	-	-
Others	1.2	1.8	T	1.6	1.6	1.7	T	-	-	3.5	T	2.0	-	T	2.0	-	1.0
Biotite**	114	29	212	13	5	3	2	-	-	6	82	140	46	11	40	4	134
Opaques**	++	308	92	168	112	204	435	235	138	84	176	147	55	118	717	57	442
Heavy Minerals Weight% +	←—— <0.1 ——→						0.02	0.11	0.14	0.05	0.07	0.02	0.02	0.11	0.25	0.07	0.03

APPENDIX B

Heavy Mineral Percentage Data

LOCATION	OLDMAN RIVER								HIGHWOOD RIVER							
Lithost. Unit	St. Mary River Fm.				Lower Willow Creek Fm.				Belly River Fm.							
SAMPLE NUMBER	8086	8087	8088	8089	8090	8091	8092	8093	8067	8069	8070	8071	8072	8074	8075	8077
Hornblende	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Garnet	33.2	11.1	14.6	11.0	-	7.9	13.5	11.5	1.6	18.5	28.4	23.4	34.8	12.1	22.8	11.9
Epidote-Clinozoisite	-	-	-	-	-	T	-	T	T	T	-	-	T	-	1.0	-
Apatite	10.9	18.1	15.6	16.0	14.6	7.3	30.5	33.0	36.2	39.5	6.4	8.1	11.3	31.1	13.4	17.5
Rutile	9.8	7.0	15.6	2.0	3.1	3.7	3.5	-	5.5	1.5	3.4	3.8	3.9	7.7	4.0	6.7
Sphene	-	-	-	-	-	-	-	-	-	T	-	-	-	-	-	-
Tourmaline	5.2	7.0	3.9	1.5	5.4	2.1	7.5	4.0	4.7	1.5	-	-	T	7.7	1.0	1.6
Tremolite-Actinolite	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Allanite	-	-	-	1.0	3.1	2.6	4.5	1.5	T	5.4	11.3	12.0	12.3	2.0	21.3	8.3
Chlorite	5.2	5.0	1.5	T	13.1	1.1	-	1.0	9.5	2.4	T	1.4	3.4	T	1.0	1.0
Zircon	32.6	51.2	46.8	67.5	60.0	74.9	39.5	48.5	38.6	28.8	49.5	48.8	30.9	37.1	33.7	52.1
Staurolite	-	-	-	-	-	-	-	-	-	-	-	-	-	T	-	-
Chloritoid	T	T	T	-	-	-	-	-	T	1.5	-	-	1.0	-	1.0	1.0
Glaucophane	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Kyanite	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Andalusite	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Others	2.6	-	1.5	T	T	-	1.0	-	1.6	-	T	2.4	1.5	1.2	1.0	-
Biotite**	24	28	12	5	61	4	3	6	190	33	-	5	35	1	37	24
Opaques**	202	188	78	96	792	162	209	234	421	121	115	56	99	56	164	754
Heavy Minerals Weight%+	0.14	0.06	0.02	0.04	0.36	0.07	0.11	0.11	0.02	0.01	0.14	0.05	0.04	++	0.01	1.00

APPENDIX B

Heavy Mineral Percentage Data

LOCATION	CPOG-STRATHMORE WELL										LITTLE RED DEER RIVER						
Lithost. Unit	Belly River Gp.						Horseshoe Canyon Fm.				Belly River Fm.				Edmonton Fm.		
SAMPLE NUMBER	8099	8100	8101	8102a	8103	8104	8105	8106	8107	8109	4315b	4317	4320	4324	4325	4328	4329
Hornblende	-	-	-	-	-	T	-	-	-	-	-	-	-	-	-	-	-
Garnet	32.0	31.0	24.2	16.1	9.0	27.1	25.4	13.0	21.4	34.1	23.8	38.8	42.5	14.5	10.7	9.9	22.6
Epidote-Clinozoisite	T	1.5	T	T	1.0	1.0	T	-	T	-	-	-	T	-	20.9	T	-
Apatite	23.8	20.2	28.9	25.8	14.0	7.4	13.0	19.7	11.9	18.3	14.9	15.4	28.0	29.1	10.2	16.0	14.5
Rutile	5.3	4.9	2.8	5.4	3.0	2.0	4.9	1.4	5.5	1.0	4.7	5.5	2.6	7.9	1.3	T	2.1
Sphene	-	1.5	T	-	-	1.0	T	3.1	14.4	25.5	-	-	T	-	5.8	-	-
Tourmaline	1.0	2.5	1.0	7.3	8.0	T	-	T	2.0	1.0	T	3.5	1.8	5.9	T	1.0	4.3
Tremolite-Actinolite	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Allanite	18.9	7.4	8.5	6.8	1.0	14.8	13.5	4.0	11.0	5.8	11.9	7.5	6.6	-	34.7	1.9	9.0
Chlorite	T	4.9	3.8	2.0	2.0	-	T	-	T	2.4	T	3.0	2.6	T	2.2	1.4	1.3
Zircon	16.5	25.6	28.4	29.8	55.0	44.3	36.8	52.5	30.8	34.1	42.1	25.9	13.1	40.6	12.0	68.4	42.1
Staurolite	-	-	-	-	1.0	T	-	T	T	T	-	-	-	-	-	-	-
Chloritoid	T	T	1.0	3.4	4.5	T	2.7	3.6	1.0	T	T	-	T	-	-	T	T
Glaucophane	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Kyanite	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	T
Andalusite	-	-	-	-	-	-	-	-	-	-	T	-	T	-	-	-	2.1
Others	1.0	-	T	2.9	1.5	T	2.2	1.8	T	1.0	T	T	T	1.7	T	-	1.3
Biotite**	25	118	31	21	14	5	23	152	9	25	7	11	8	3	100	191	17
Opaques**	112	173	314	179	570	616	277	308	450	219	62	117	181	11	217	61	114
Heavy Minerals Weight%+	0.05	0.14	0.12	0.14	0.15	0.10	0.15	0.05	0.10	0.18	0.05	0.04	0.02	0.31	0.13	0.19	++

APPENDIX B

Heavy Mineral Percentage Data

LOCATION	LITTLE RED DEER RIVER										COLT CREEK								
Lithost. Unit	Edmonton Fm.					Paskapoo Fm.					Edmonton Fm.				Paskapoo Fm.				
SAMPLE NUMBER	4330	4331	4335	5338a	4341	4350a	4351	4352	4353	4355b	4854	4856	4857	4857a	4860	4861	4866	4867	4874
Hornblende	-	-	-	-	-	-	T	-	-	-	-	-	-	-	-	-	-	-	-
Garnet	26.8	38.4	17.2	27.0	53.5	16.7	14.5	14.3	21.6	15.3	16.8	16.5	34.8	49.5	6.1	10.2	10.7	14.7	22.9
Epidote-Clinozoisite	1.5	2.0	T	-	T	66.7	47.0	63.0	53.1	44.5	1.5	T	1.5	8.5	61.7	55.6	51.0	55.5	T
Apatite	16.2	16.3	42.0	48.5	26.0	3.5	12.0	4.3	6.0	11.0	55.6	69.6	35.8	16.5	15.3	14.3	11.2	8.6	41.1
Rutile	2.0	1.0	-	T	1.5	-	-	T	1.4	1.0	T	T	T	T	-	1.0	T	-	1.0
Sphene	T	-	T	T	T	7.1	17.0	9.0	7.7	9.1	1.5	-	T	5.5	8.2	6.1	8.7	10.1	1.0
Tourmaline	1.0	2.0	2.5	1.5	1.5	-	1.0	T	T	1.9	5.6	3.6	T	1.5	T	T	T	T	2.5
Tremolite-Actinolite	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Allanite	6.6	8.9	T	-	1.5	2.0	1.0	1.0	2.9	4.3	T	-	-	6.0	T	T	2.6	3.5	1.1
Chlorite	2.0	1.0	1.5	T	T	3.0	3.0	T	-	-	10.2	5.7	15.2	4.0	2.6	4.6	10.7	1.0	16.8
Zircon	42.4	30.0	30.8	21.0	14.5	1.0	3.0	6.6	6.7	13.0	5.6	2.6	9.6	6.0	4.1	6.1	4.1	4.0	12.8
Staurolite	-	-	-	-	-	-	-	-	-	-	-	-	-	1.0	T	-	-	-	-
Chloritoid	T	-	T	T	-	-	-	T	-	-	1.5	T	-	-	-	T	-	-	T
Glaucophane	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Kyanite	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Andalusite	T	T	2.5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	2.0	-
Others	-	T	1.5	-	-	-	1.0	-	-	-	T	T	T	1.0	-	T	-	-	T
Biotite**	51	13	NC	NC	NC	NC	NC	-	3	T	104	30	33	30	48	15	88	3	166
Opaques**	137	214	NC	NC	NC	NC	NC	31	81	44	31	25*	26*	110	59*	125	29*	29*	12*
Heavy Minerals Weight% +	0.04	++	++	++	++	++	++	++	++	++	0.24	0.05	0.16	0.26	1.11	1.60	0.74	0.57	0.14

APPENDIX B

Heavy Mineral Percentage Data

LOCATION	BLACKSTONE RIVER														
Lithost. Unit	Belly River Fm.				Edmonton Fm.							Paskapoo Fm.			
SAMPLE NUMBER	8110	8111	8112	8113	8114	8115	8116	8117	8118	8119	8120	8121	8122	8123	8124
Hornblende	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Garnet	30.4	7.3	15.4	24.1	18.1	21.1	11.4	27.1	17.5	50.5	63.6	9.9	14.6	13.8	49.3
Epidote-Clinozoisite	T	48.2	63.4	46.2	52.7	-	-	1.0	43.7	T	T	64.5	72.6	67.1	1.0
Apatite	13.7	20.2	5.7	3.0	2.4	7.2	14.3	15.4	9.7	12.4	6.4	3.5	T	1.0	21.5
Rutile	2.9	T	-	-	-	1.9	4.8	1.4	T	3.0	3.9	1.0	-	T	1.5
Sphene	T	8.3	5.7	11.6	7.8	7.7	-	T	8.7	-	-	9.9	2.7	5.7	-
Tourmaline	1.0	T	T	-	-	1.4	1.9	T	-	1.0	T	-	-	-	-
Tremolite-Actinolite	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Allanite	16.7	2.8	2.2	5.0	11.7	26.3	30.5	15.9	3.4	10.9	11.3	3.0	5.3	5.2	3.9
Chlorite	2.0	1.4	-	-	-	1.4	8.6	2.8	1.0	1.5	T	1.0	T	T	1.0
Zircon	31.9	10.1	6.2	8.5	6.3	31.6	26.7	35.5	14.6	20.3	12.3	6.4	3.1	6.2	20.0
Staurolite	-	-	-	1.0	-	T	-	-	-	-	-	T	-	-	1.0
Chloritoid	-	T	-	-	-	1.0	-	-	T	-	-	-	T	-	1.0
Galucophane	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Kyanite	-	-	-	-	-	-	-	-	-	-	-	T	-	-	-
Andalusite	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Others	-	T	T	T	1.0	-	1.9	-	T	-	-	-	-	-	-
Biotite**	51	17	2	1	9	17	98	17	10	23	14	3	1	-	15
Opaques**	145	36	26	41	81	112	220	82	119	92	94	74	80	44	127
Heavy Minerals Weight% +	0.13	0.28	0.21	0.38	0.18	0.02	0.06	0.04	0.22	0.08	0.05	0.10	0.76	0.28	0.08

APPENDIX B

Heavy Mineral Percentage Data

LOCATION	WILDHAY RIVER							WESTERN PLAINS							
Lithost. Unit	Brazeau Formation							Paskapoo Formation							
SAMPLE NUMBER	8054	8055	8056	8057	8058	8059	8060	6001b	6004b	6017b	6019a	6027	4777	5050a	5057
Hornblende	-	-	-	-	-	-	-	-	31.0	1.0	18.4	T	-	-	-
Garnet	21.6	18.2	29.5	15.7	67.3	55.9	34.8	43.4	7.5	29.5	10.6	28.7	20.3	21.9	24.4
Epidote-Clinozoisite	3.5	11.1	-	60.9	T	-	4.4	4.4	32.5	35.5	48.9	36.1	38.2	T	-
Apatite	11.1	15.7	28.6	6.1	7.4	16.1	18.1	7.4	9.5	6.0	6.9	6.9	14.6	24.6	32.5
Rutile	T	1.0	1.9	-	-	3.3	2.5	2.0	-	1.5	1.0	1.0	1.4	7.5	6.4
Sphene	8.0	11.6	1.9	8.1	4.0	-	9.8	2.0	4.0	4.5	6.0	10.4	5.7	-	-
Tourmaline	2.0	-	6.7	T	T	3.3	1.0	2.5	1.0	T	T	-	T	23.7	15.4
Tremolite-Actinolite	-	T	-	-	-	-	-	-	4.0	-	1.8	-	-	-	-
Allanite	10.1	14.6	14.3	7.1	8.4	4.3	4.9	2.5	-	3.0	T	2.0	1.4	3.1	T
Chlorite	-	T	5.2	T	-	-	1.0	5.4	5.5	5.0	1.8	2.5	4.7	1.3	1.7
Zircon	42.7	22.7	11.9	T	10.4	15.2	19.6	11.3	4.0	5.0	1.4	7.4	9.0	13.2	15.4
Staurolite	-	T	-	-	T	T	1.0	2.0	-	-	-	T	-	-	-
Chloritoid	-	-	-	-	1.0	T	1.0	14.8	T	7.5	1.8	3.5	2.4	1.7	3.0
Glaucophane	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Kyanite	-	T	-	-	-	-	-	2.0	-	-	-	T	-	-	-
Andalusite	-	-	-	-	-	-	T	-	-	-	-	-	-	-	-
Others	T	3.1	-	T	-	1.0	1.5	T	T	1.0	T	-	1.9	2.6	T
Biotite**	7	8	50	5	6	12	1	3	40	5	7	14	9	-	9
Opaques**	61	219	101	55	247	82	98	107	25	114	44	155	48	260	150
Heavy Minerals Weight%+	0.06	0.65	++	1.03	1.13	0.09	0.10	++	++	++	++	++	++	++	++

APPENDIX B

Heavy Mineral Percentage Data

LOCATION	NORTHWESTERN PLAINS						SWAN HILLS					
Lithost. Unit	Edmonton Gp.		Paskapoo Fm.				Ed. Gp.	Paskapoo Fm.				
SAMPLE NUMBER	8131	8132	8133	8134	8135	8136	8125	8126	8127	8128	8129	8130
Hornblende	-	-	-	-	T	-	-	44.1	T	-	43.5	57.3
Garnet	17.8	35.2	53.6	36.4	60.2	59.3	79.3	11.8	33.3	34.9	21.5	11.8
Epidote-Clinozoisite	1.0	3.6	1.5	T	3.0	T	-	23.6	4.0	T	19.0	17.4
Apatite	22.8	10.7	5.4	6.9	9.5	14.8	6.2	3.6	12.0	15.1	2.0	1.4
Rutile	1.5	1.0	1.5	3.2	2.5	2.9	T	T	1.5	-	-	-
Sphene	20.8	16.8	11.2	-	T	1.9	-	7.3	20.6	25.3	1.5	3.3
Tourmaline	3.0	1.0	1.0	2.3	1.0	1.4	T	T	-	1.6	2.5	T
Tremolite-Actinolite	-	-	-	-	-	-	-	2.3	-	T	4.5	2.4
Allanite	12.7	7.7	8.8	1.8	12.5	4.8	-	1.8	5.5	6.5	-	T
Chlorite	2.0	T	1.0	3.2	1.0	1.4	T	T	1.0	1.1	2.0	1.9
Zircon	13.2	21.9	14.6	43.3	9.0	12.9	9.3	3.2	20.6	11.3	2.0	1.4
Staurolite	1.5	1.5	-	-	T	T	-	T	-	T	-	T
Chloritoid	3.0	-	-	2.3	-	-	T	-	-	-	-	1.4
Glaucophane	-	-	-	-	-	-	-	T	-	-	-	-
Kyanite	-	-	-	-	-	-	-	-	-	-	-	-
Andalusite	-	-	T	-	-	-	-	-	-	T	-	-
Others	T	-	1.0	-	-	-	T	-	1.0	1.6	1.5	T
Biotite**	77	8	27	11	12	23	28	2	30	71	2	1
Opaques**	295	534	361	265	63	178	121	103	581	334	48	28
Heavy Minerals Weight% +	0.02	0.48	0.85	0.11	0.13	0.04	0.49	1.23	0.18	0.61	3.05	0.99

APPENDIX B

Heavy Mineral Percentage Data

LOCATION	EAST-CENTRAL ALBERTA															
Lithost. Unit	Belly River Group															
SAMPLE NUMBER	8034	8037	8036	8046	8033	8048	8044	8045	8032	8047	8052	8035	8039	8042	8053	8050
Hornblende	87.0	87.6	91.8	53.4	22.8	58.2	18.3	81.8	30.0	41.5	25.6	84.7	91.2	-	-	1.0
Garnet	T	1.5	T	8.1	12.6	2.4	26.7	1.5	9.0	31.5	10.1	1.5	T	16.1	16.0	18.5
Epidote-Clinozoisite	8.5	5.5	5.5	28.3	44.2	29.1	27.2	8.8	36.5	9.9	41.1	8.9	4.6	54.6	33.0	25.9
Apatite	T	1.0	-	1.8	6.5	2.4	5.0	T	5.5	3.2	3.4	1.5	1.4	2.4	11.0	4.9
Rutile	-	-	-	-	1.9	-	T	-	T	-	1.5	-	-	T	1.0	1.5
Sphene	1.5	-	-	6.7	7.4	4.7	6.4	T	8.5	5.4	11.1	1.0	-	14.2	16.5	22.4
Tourmaline	-	-	-	-	-	-	T	T	-	1.0	1.9	-	-	-	-	-
Tremolite-Actinolite	T	2.0	1.0	-	-	2.4	-	2.5	1.5	2.3	1.5	1.5	1.0	-	-	T
Allanite	-	-	-	T	1.0	-	T	T	T	T	1.5	-	-	2.0	5.5	11.2
Chlorite	-	-	-	-	-	-	-	-	-	-	-	-	-	T	T	-
Zircon	-	1.0	-	1.0	1.4	-	8.9	T	2.0	2.3	1.9	-	1.0	7.8	11.0	11.2
Staurolite	-	-	-	-	-	-	T	-	2.0	T	-	T	-	T	T	1.5
Chloritoid	-	T	-	-	1.0	-	3.5	-	T	1.0	-	-	-	-	T	-
Glaucophane	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Kyanite	-	-	T	-	-	-	-	T	-	-	-	-	-	-	2.5	-
Andalusite	-	T	-	-	-	T	-	-	-	-	T	-	-	-	-	-
Others	1.5	T	1.0	T	1.4	T	2.0	2.5	3.5	1.4	-	T	T	1.5	1.5	1.5
Biotite**	1	1	2	NC	NC	NC	-	-	8	NC	NC	1	NC	NC	2	3
Opaques**	8*+	16	3	NC	NC	NC	62*+	73*+	58*+	NC	NC	25	NC	NC	186*+	240*+
Heavy Minerals Weight % +	1.87	2.25	1.04	1.84	0.46	0.21	0.40	0.73	0.24	0.95	0.30	1.34	0.45	0.24	0.24	0.39

APPENDIX B

Heavy Mineral Percentage Data

LOCATION	RED DEER RIVER VALLEY																
Lithost. Unit	Edmonton Group							Paskapoo Formation									
SAMPLE NUMBER	4700	4703	4695	4690	4710	4697	4999	4720	4709	4721	4722	4728	4729	5000	4723	5200	5198
Hornblende	-	-	-	-	-	-	-	-	-	-	T	-	6.6	18.5	30.3	T	-
Garnet	25.2	23.7	24.0	45.5	15.5	42.0	37.7	22.2	45.2	28.4	24.6	23.9	15.7	16.0	25.2	23.1	42.9
Epidote-Clinozoisite	1.5	2.5	T	-	8.9	4.0	1.0	T	T	43.8	19.0	9.6	41.9	33.0	26.8	60.0	17.8
Apatite	31.6	29.3	24.5	26.0	21.1	23.0	17.1	36.9	11.7	11.4	27.2	31.5	12.1	12.5	4.0	3.1	1.4
Rutile	-	1.0	-	-	T	1.0	-	1.0	T	1.0	T	-	T	-	-	T	2.3
Sphene	7.0	19.7	19.9	15.5	45.8	22.5	20.1	22.7	28.9	9.0	22.1	24.9	17.7	5.0	3.0	5.8	14.6
Tourmaline	1.5	2.0	1.0	-	1.4	-	1.0	3.5	1.0	1.5	T	5.1	1.0	1.0	1.5	T	T
Tremolite-Actinolite	-	-	T	-	-	T	-	-	-	-	-	-	-	3.5	2.5	-	-
Allanite	4.5	3.5	4.6	-	1.9	3.0	2.0	3.0	T	1.0	T	T	1.0	2.0	1.5	2.2	4.1
Chlorite	T	T	T	-	T	-	-	1.0	2.5	1.0	-	-	1.5	-	T	T	1.0
Zircon	27.1	13.6	23.0	12.5	2.7	2.5	19.1	8.6	4.6	2.0	3.1	2.5	1.5	4.0	T	T	9.6
Staurolite	-	T	1.0	-	-	1.0	1.0	-	1.5	-	T	T	-	-	-	-	2.3
Chloritoid	-	T	-	-	-	-	-	-	T	-	-	-	-	-	-	-	-
Glaucophane	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Kyanite	-	-	-	-	-	-	-	-	2.0	-	-	-	-	-	-	-	-
Andalusite	-	1.0	-	-	-	-	-	-	-	-	-	-	-	3.5	4.0	-	-
Others	1.0	2.0	T	T	1.6	T	1.0	T	T	T	1.5	1.5	T	1.0	-	3.1	3.2
Biotite**	NC	NC	NC	NC	6	NC	NC	NC	T	NC	NC	NC	NC	NC	NC	-	2
Opaques**	NC	NC	NC	NC	200*	NC	NC	NC	54*	NC	NC	NC	NC	NC	NC	201	407
Heavy Minerals Weight% +	0.43	0.62	1.44	0.27	0.70	0.51	0.41	0.78	++	1.94	++	++	++	0.70	++	1.37	0.32

APPENDIX C

DETAILED REGIONAL STRATIGRAPHY AND RECENT REVISIONS OF TERMINOLOGY

A. Regional Stratigraphy

The stratigraphy of the lithostratigraphic units of the present study area has been under examination since the second half of the nineteenth century. Consequently, as is the case with many geologic areas of the world, the terminology applied to these units has evolved and changed as more detailed studies were undertaken. It is beyond the scope of this thesis to trace the terminological evolution. The terminology adopted here in the discussion of the regional stratigraphy encompasses the recent revisions made by Carrigy (1970, 1971) and Irish (1970) mainly on the Plains. In addition, the present writer has made a revision in the central and northern Foothills by placing the Cretaceous-Paleocene boundary within the Paskapoo Formation contrary to the widely held opinion that the base of the Paskapoo Formation of the Foothills represents the Cretaceous-Paleocene boundary (Table 1). Evidence to support these revisions is presented in a subsequent section. Table 1 shows the post-1970 stratigraphic terminology and correlation that will be used throughout this thesis. Tables 12 and 13 show the revisions made by Irish (1970) and Carrigy (1970), respectively.

For purposes of regional analysis the study area is subdivided into three main subareas: Southern Plains, Northwestern Plains and the Foothills.

after Allan and Sanderson (1945)		after Ower (1960)		after Srivastava (1968)		Irish (1969)	
Paskapoo Formation		Paskapoo Formation		Paskapoo Formation		Paskapoo Formation	Scollard Member
Edmonton Formation	Upper Edmonton	Edmonton Formation	member E	Edmonton Formation	Nevis member		
					Mammal-bearing member		
	Kneehills tuff zone		member D		Blackmud member	Edmonton Group	Battle Formation
					Whitemud member		Whitemud Formation
	Middle Edmonton		member C		Coaly member		Horseshoe Canyon Formation
			member B		Tolman member		
	Drumheller marine tongue				Drumheller member		
	Lower Edmonton				Non-coaly member		
			member A		Coaly member		
					Transition member		

Table 12. Subdivisions of the Edmonton Group, Red Deer River region, Alberta (after Irish, 1970).

AGE	SOUTHEAST		SOUTHWEST		SOUTH-CENTRAL	
	(Furnival, 1946)	(Russell, 1950)	(Tozer, 1956)	(Carrigy, 1970)	(Carrigy, 1970)	(Ower, 1960)
TERTIARY			PORCUPINE HILLS	PORCUPINE HILLS	PORCUPINE HILLS	PASKAPOO
TERTIARY	RAVENSCRAG	RAVENSCRAG	WILLOW CREEK	WILLOW CREEK	PASKAPOO	PASKAPOO
CRETACEOUS	---?--- FRENCHMAN	RAVENSCRAG	WILLOW CREEK	WILLOW CREEK	PASKAPOO: Scollard Member (Irish, 1970)	EDMONTON: Member E
CRETACEOUS	BATTLE	BATTLE	KNEEHILLS (Battle equivalent)	BATTLE	EDMONTON GROUP: BATTLE (Irish, 1970)	EDMONTON: Member D (Kneehills)

Table 13. Correlation of the revised Paskapoo Formation in the southern and southwestern Alberta Plains (after Carrigy, 1970, 1971).

This subdivision is adapted from Williams and Burk (1964). Stratigraphic discussions of these subareas are supplemented by relevant stratigraphic sections and correlation tables to which the reader should refer.

1. The Southern Plains

The southern Plains include southern Saskatchewan and Alberta east of the Foothills and south of the North Saskatchewan-Athabasca River area. It should be kept in mind that the sandy lithostratigraphic units thin from west to east, while the marine shaly units thin in the opposite direction.

The sandstone and shale of the Belly River Group, which is 900 ft. thick in east-central Alberta and thins to zero in eastern Saskatchewan, conformably overlies and intertongues with the marine shale of the Lea Park Formation. In this area the Belly River Group is broadly divisible into two units. The upper unit, mainly bentonitic sandstone and shale, is correlative with the Oldman Formation of southern Alberta; the lower unit, composed of intertonguing continental to shallow marine sandstone and marine shale, is broadly correlative with the Foremost Formation of southern Alberta. These two units become increasingly thicker, less distinguishable and more continental towards the west. The lower unit appears to split into several sandstone tongues that thin eastward in Saskatchewan and intertongue with several marine shale tongues of the underlying and partly equivalent Lea Park Formation. In this lower unit terminology and correlation is still controversial and difficult.

The difficulties arise from the complex facies relationships, poor outcrops and general similarities in the lithology of several sandstone and shale tongues. Table 14 shows the several strikingly different schemes of nomenclature proposed by five authors for east-central Alberta. The most recent work on the Belly River Group of east-central Alberta is by McLean (1971) who chose to use the American term "Judith River Formation" for its historical precedence and lesser ambiguity.

Westward, the Belly River Group becomes thicker; it is approximately 1100 feet thick in the Pembina oilfield area. The basal few tens of feet in the Plains west of Edmonton consist of a massive marine sandstone commonly called the "Basal Belly River Sandstone" or, farther south, the Verdigris Member (Slipper and Hunter, 1931, in Williams and Burk, 1964).

In southern Alberta, the Belly River Group is divided into two formations, the Foremost below and the Oldman above (Fig. 4). These two formations can be distinguished in the subsurface on mechanical logs over most of south-central Alberta (Williams and Burk, 1964). The Foremost Formation has lower and upper gradational contacts with the Pakowki and Oldman Formations, respectively. The Foremost Formation underlies large areas of southern Alberta, thinning to the east and north. It contains marine, brackish-water and fresh water faunas (Irish, 1971, G.S.C. Map 1286A). The overlying Oldman Formation has more sandstone and is more continental in nature than the underlying Foremost Formation; both formations carry commercial coal

TYRRELL 1887	SLIPPER 1919	ALLAN 1919	NAUSS 1945	SHAW & HARDING 1949
PIERRE SHALE	BULWARK SST / PIERRE SHALE	BEARPAW FORMATION	BEARPAW FORMATION	BEARPAW FORMATION
BELLY RIVER SERIES	BELLY RIVER SERIES: PALE BEDS	BELLY RIVER SERIES: MYRTLE CREEK FORMATION	BELLY RIVER GROUP: OLDMAN FORMATION	BELLY RIVER FORMATION: OLDMAN MEMBER
			PAKAN MEMBER	
	VARIEGATED BEDS	PAKAN FORMATION	UPPER BIRCH LAKE SANDSTONE	UPPER BIRCH LAKE SANDSTONE
			MULGA TONGUE (LEA PARK SHALE)	MULGA TONGUE
	BIRCH LAKE SANDSTONE	VICTORIA SANDSTONE	LOWER BIRCH LAKE SANDSTONE	LOWER BIRCH LAKE SANDSTONE
	GRIZZLY BEAR FORMATION	SHANDRO SHALES	GRIZZLY BEAR TONGUE (LEA PARK SHALE)	GRIZZLY BEAR MEMBER
	RIBSTONE CREEK FORMATION	BROSSEAU FORMATION	UPPER RIBSTONE CREEK SANDSTONE	RIBSTONE CREEK MEMBER
			VANESTI TONGUE (LEA PARK SHALE)	VANESTI MEMBER
?	LEA PARK FORMATION		LOWER RIBSTONE CREEK SANDSTONE	VICTORIA MEMBER
		LEA PARK FORMATION		SHANDRO MEMBER
			LEA PARK SHALE	BROSSEAU MEMBER
				LEA PARK FORMATION

Table 14. Lithostratigraphic nomenclature proposed by five authors in east-central Alberta (after McLean, 1971).

deposits.

The Bearpaw Formation (Table 1), composed of dark grey marine shale with a few thin sandstone and bentonite beds, conformably overlies the Belly River Group in the Southern Plains and reaches 1200 feet in thickness (Williams and Burk, 1964). This unit thins to the west and northwest; it is 650 feet thick in the southwestern plains just east of the Foothills, 350 feet thick east of Calgary, and 100 feet or less in the Pembina oilfield to the west of Edmonton (Williams and Burk, 1964, p. 175). The Bearpaw is equivalent to the upper Riding Mountain and Pierre shales of southeastern Saskatchewan, Manitoba and North Dakota.

The upper contact of the Bearpaw is transitional, passing vertically into a predominantly non-marine sequence which marks the last major regression of the epicontinental sea (Fig. 4). This sequence is known as the Edmonton Group (Irish, 1970) in central Alberta (Edmonton Formation of Allan and Sanderson, 1945) (Table 12); equivalent beds in southwestern Alberta and northwestern Montana are included in the St. Mary River, Whitemud and Battle Formations (Table 1). The Edmonton Group is subdivided into three formations (Irish, 1970) which include, from bottom to top: the Horseshoe Canyon Formation, consisting mainly of interlensed bentonite, argillaceous sandstones, bentonitic shales and coal seams; the Whitemud Formation, composed of white-weathering, green-grey argillaceous sandstone and light grey clay; and the Battle Formation, composed of mauve grey-weathering, purplish black bentonitic shale. The Kneehills Tuff occurs within the upper part of the Battle Formation. It is a widespread key horizon and normally occurs "... as a single bed between 6 and 10 inches thick but, locally, may occur as two or three thin beds between 2 and 3 inches thick separated by Battle Shale." (Irish, 1970, p. 140). Shafiqullah (1963) dated the Kneehills Tuff at 66 m.y. by the K-Ar method. "Surface exposures of the Edmonton Group extend in an arcuate band along the eastern margin of the Alberta Syncline ... These beds are bounded on the east by the underlying Bearpaw Formation and on the west by the overlying Paskapoo Formation." (Irish, 1970, p. 133). The Edmonton strata below the Whitemud Formation interfingers with beds of the St. Mary River Formation just north of the 50th parallel. Subsurface evidence allows beds of the Edmonton Group to be traced westward to the folded and faulted region of the Foothills. The term "Edmonton Group" cannot be satisfactorily used for correlative beds westward in the Foothills where the underlying Bearpaw shale is not present, because Edmonton beds are not readily distinguished from the underlying Belly River Formation (Irish, 1970, p. 133). A composite section of the Horseshoe Canyon Formation in the Red Deer River Valley measured by Irish amounts to 748 feet, but the thickness of this formation changes from east to west. The Whitemud Formation measures from 6 to 20 feet in the western parts of the Southern Plains and about 25 feet in the southeast. The Battle Formation has a maximum thickness of 25 to 30 feet, but has been thinned by erosion in the southeast (Irish, 1970, p. 140).

The St. Mary River Formation of the southwestern Plains, equivalent to the Horseshoe Canyon Formation, has a thickness in the order of 1500 to 1600 feet. The lower boundary of the formation is transitional with the underlying Bearpaw Shale; in the extreme southwestern Plains the Bearpaw grades upwards into a massive sandstone unit known as the Blood Reserve Member of the St. Mary River Formation. The member is generally not developed north of about latitude 50°North, and thickens southwards into northern Montana where Stebinger (1914) reported a thickness of 360 feet for the correlative Horsethief sandstone (Williams and Burk, 1964, p. 178) (Table 1, "Oldman River region" and Fig. 4). The St. Mary River Formation alternation of hard, lenticular sandstone and soft shale, together with the light color of the sandstone beds, gives the formation a characteristic appearance (Irish, 1971). In the Oldman River region of the southwestern Plains, the St. Mary River Formation is overlain by the Whitemud and Battle Formations. Here the Whitemud Formation consists of eight feet of white-weathering, greenish-grey bentonitic sandstone. This is overlain by the Battle Formation which is composed of twelve feet of mauve grey-weathering, purplish black bentonitic shale. Near the top, a six-inch thick silicified tuff bed is recognized and has been correlated with the Kneehills Tuff (Irish, ibid). Elsewhere in the southwestern Plains, St. Mary River Formation beds are conformably overlain by the Willow Creek Formation, the lower part of which is of latest Late Cretaceous age and the upper part of Paleocene age (Table 1 and Fig. 4).

In southeastern Alberta (Cypress Hills Region), the Bearpaw Formation is unconformably overlain by the predominantly non-marine Eastend Formation (Table 1; Fig. 4). The Eastend is confined to a semicircular band at the foot of the main escarpment of the Cypress Hills. It is about 330 feet thick at this locality and is composed of alternating soft, light grey-buff sandstone and friable, dark grey shale (Russell and Landes, 1940). It contains marine fossils in its lower portion, pointing to a gradational contact with the underlying marine shale of the Bearpaw Formation (Irish, 1971). The Eastend Formation is equivalent to the upper part of the Horseshoe Canyon Formation of Irish (1970) (Table 1). In the Cypress Hills, the uppermost beds of the Eastend Formation grade into the overlying Whitemud Formation. Conformably, but abruptly, the Battle Formation (Blackmud member of Srivastava, 1968) overlies the Whitemud Formation. The Battle Formation, 33 feet thick, is composed of mauve-weathering, purplish black, bentonitic rubbly shale. Occurring in the upper part of the Battle Formation is an eight-inch thick grey-weathering, grey-brown siliceous tuff bed, the Kneehills Tuff. The Battle Formation is disconformably overlain by the Frenchman Formation of Lance age.

The recently revised Paskapoo Formation (Carrigy, 1970 and 1971 and Irish, 1970) now encompasses Upper Cretaceous (Lance) strata above the Battle Formation (Tables 1,12 and 13). The Paskapoo Formation outcrops extensively in the area adjacent to the Rocky Mountain Foothills and forms the surface bedrock over a large area of the western Plains north of the city of Red Deer.

"The thickness varies from zero at the erosional edge in the Plains to 3,000 feet adjacent to the Foothills belt. The upper boundary of the formation is an erosion surface" (Carrigy, 1971, p. 15). "The Paskapoo Formation consists of fluvial and lacustrine deposits of massive, in part crossbedded, medium to coarse-grained, buff-weathering sandstone; hard to soft, fine-grained sandstone; and green and grey, friable, normally silty shales" (Irish, 1970, p. 143). The Scollard Member (Lance), with a maximum thickness of about 300 feet, consists of interbedded and interlensed grey and brown sandstone, green to grey shale and coal seams. The lower part of this member is mammal and dinosaur bearing, while the upper part is coal-bearing, the Ardley seam being commercially important. In places, there is extensive channelling in these Lance beds. These channels are filled with "... buff- to brown-weathering, medium- to coarse-grained sandstone similar to sandstones occurring higher in the formation" (Irish, 1970, p. 143). However, it is uncertain at present whether all of these sand-filled channels are of Scollard age or whether some may represent post-Scollard Paskapoo time (Lerbekmo, pers. comm.).

In the southwestern Plains of Alberta, the Paskapoo Formation is represented in time by the Willow Creek Formation and probably part of the lower Porcupine Hills Formation (Table 1). Carrigy (1970), however, believes that the Porcupine Hills Formation is younger than the Paskapoo Formation. On the Oldman River, the Willow Creek Formation conformably overlies the St. Mary River Formation. Its thickness is estimated to be between 1,000 and

1,300 feet. This formation is distinguished from the rather similar Oldman Formation beds by the presence of red and maroon-weathering shales and an abundance, in most shale units, of small irregularly-shaped calcareous concretions. Crossbedded, buff-weathering, grey sandstone beds occur towards the top of the Willow Creek Formation and become progressively more numerous upward, forming a transition zone with the overlying Porcupine Hills Formation. Faunal evidence indicates that the lower part of the Willow Creek Formation is of Late Cretaceous (Lance) age and the upper part is of Paleocene age.

The Porcupine Hills Formation occupies a large part of the Porcupine Hills, a prominent topographic feature in southwestern Alberta (Fig. 4). This formation outcrops extensively in these hills and is composed of "... a series of crossbedded sandstones and calcareous bentonitic shales ... The maximum preserved thickness of the formation is probably in the order of 3,000 feet, but because the upper boundary is an erosion surface, the original thickness cannot be determined" (Carrigy, 1971, p. 12). Carrigy has extended the northern limit of the Porcupine Hills Formation to the Bow River west of Calgary, and possibly further north, where it has traditionally been considered to be part of the Paskapoo Formation.

In the Cypress Hills area of southeastern Alberta and southwestern Saskatchewan, the Frenchman (Lance) and the overlying Ravenscrag (Paleocene) Formations are approximate time-equivalents to the Paskapoo Formation and probably the lower part of the Porcupine Hills Formation (Table 1; Fig. 4). The Frenchman Formation disconformably overlies the Battle Formation. Irish (1971) notes that "... although considerable erosion took place prior to deposition of the Frenchman, the beds are considered to be of Upper Cretaceous (Lance) age because of their Triceratops fauna." The lower part of the Frenchman Formation is medium-grained, cross-bedded, reddish brown-weathering sandstone with intercolated green and grey siltstone and silty shale. The upper part is composed of softer beds that consist of argillaceous sandstone, siltstone and shale that grade upward into strata of the Paleocene Ravenscrag Formation. The thickness of the Frenchman is reported to be between 225 and 250 feet by Crockford (1951) and 375 feet by Chi (1966, p. 7). The Ravenscrag Formation gradationally overlies the Frenchman Formation. Carrigy (1971, p. 12-13) suggested that the name Frenchman should be dropped and the name Ravenscrag Formation applied to the entire Lance and Paleocene sequence in southeastern Alberta for there is "... no lithologic distinction between Frenchman and Ravenscrag" Formations. However, the present writer retains the earlier usage for the reason that the two formations are distinguishable by their heavy mineral suites and other petrographic components (Chi, 1966). The Ravenscrag Formation is confined to a narrow rim around the higher parts of the Cypress Hills. It is composed of 225 feet of soft, grey and brown, fine-grained sandstone and brown and grey shale with some lignitic coal seams and bentonitic layers (Irish, 1971). The Ravenscrag Formation is disconformably overlain by the lower Oligocene

Cypress Hills Formation.

2. The Northwestern Plains

The Northwestern Plains include the region north of the Athabasca – North Saskatchewan River area and east of the Foothills. The stratigraphic terminology of the post-Kneehills Tuff sequence here is essentially the same as in central Alberta (see "Swan Hills" of Fig. 4). The Bearpaw shale does not extend as far north as this area; therefore, the Belly River and the Edmonton Group equivalents are not separable but lumped into one unit called the Wapiti Formation (Fig. 4). The Wapiti conformably overlies marine shales of the Smoky Group (equivalent to the Lea Park – Wapiabi shale) and attains a thickness of 3,800 feet west and northwest of Edmonton, while still further west, marginal to the Foothills, a maximum thickness of about 5,000 feet is recorded (these measurements include the Lance part of the Wapiti). Allan and Carr (1946) recognized five members in the Wapiti Formation. The uppermost member, E, is probably equivalent to the Scollard Member and Frenchman Formation to the south. This member should probably be included in the overlying Paskapoo Formation to be consistent with the latest revisions by Carrigy (1970, 1971) and Irish (1970). The lowest member, A, is equivalent to most or all of the Belly River Group; members B, C and D are approximately equivalent to the Bearpaw Formation and the Edmonton Group. The Kneehills Tuff zone probably occurs either near the top of the D or the base of E member.

However, this tuff has not yet been identified in outcrop in the Swan Hills area and plains to the west. The overlying Paskapoo Formation (revised terminology) has the general characteristics of this formation in the plains to the east and south of this area. Its upper boundary is erosional and the remaining thickness probably does not exceed 2,000 feet (excluding the Scollard Member which is probably as thick or slightly thicker than its equivalent in the Red Deer River Valley) (Williams and Burk, 1964, p. 182).

3. The Foothills

"The Foothills of the Rocky Mountains are that geographic and structural province of the western Canada sedimentary basin in which elevation and relief are considerably greater than in the Plains to the east, and in which structural deformation by folding and faulting is significant. On the west, the Foothills are bounded by the first continuous range of Paleozoic strata" (Williams and Burk, 1964, p. 182).

It is convenient to subdivide the Foothills area into the southern Foothills, which are situated between the International Border to the south and the Bow River to the north; the central Foothills between Bow and Athabasca Rivers; and the northern Foothills, north of the Athabasca River. For stratigraphic reasons the southern Foothills will be discussed separately, and the central and northern Foothills together.

In the southern Foothills, the Belly River Formation is the lowermost unit treated in this study (Table 1). It conformably overlies the marine Wapiabi (Shale) Formation of the Alberta Group. It is "... 2,000 - 2,500 feet thick composed mainly of mudstones interbedded with lenticular, fine- to medium-grained sandstones in units 5 - 100 feet thick. Thin intraformational mudstone-pebble conglomerates, nodular limestones, coal seams, bentonites, magnetite-sandstone, and pelecypod beds make up the remaining, minor part of the lithology" (Lerbekmo, 1963, p. 54). The thickness of the formation in the Foothills varies considerably from west to east and from south to north. The unit thins from west to east and sections measured by the writer and by J.F. Lerbekmo in the Foothills indicate that the Belly River Formation also decreases in thickness from southeast to northwest, parallel to the trend of the Foothills structures.

Gradationally and conformably overlying the Belly River Formation is the marine shale of the Bearpaw Formation which has a thickness of about 500 feet (Douglas, 1950) in the southern part of the southern Foothills and decreases in thickness northwestwards along the Foothills until it pinches out in the Bow River area.

"Continental sandstones, shales, carbonaceous shales and coals of the St. Mary River Formation conformably overlie the Bearpaw" (Williams and Burk, 1964, p. 182). The thickness of the formation is about 3,200 feet on the Oldman River. The overlying non-marine Willow Creek Formation is distinguished from the St. Mary River lithology by being softer and by the lighter color of the sandstone. Tozer (1956) measured 4,135 feet of Willow Creek Formation in this area, the lower part of which is considered to be of Lance age (Scollard Member correlative) and the upper part of Paleocene age. To the extreme south of the southern Foothills, the Willow Creek Formation is gradually and conformably overlain by the Porcupine Hills Formation. However, the Willow Creek Formation becomes progressively thinner northwestward as the result of removal by erosion. Hence the basal beds of the Porcupine Hills Formation overlie (progressively northward) older beds of the Willow Creek Formation (Douglas, 1950). Lithology of the Porcupine Hills Formation is discussed under "Southern Plains". At some point in the central southern Foothills, the St. Mary River and the Willow Creek Formations grade laterally (northwestward) into the Edmonton and the Paskapoo Formations (Fig. 36).

North of the Bow River, in the central and northern Foothills, the Bearpaw shale is not present and the Belly River and Edmonton beds are no longer easily recognized; therefore, they were lumped into one lithostratigraphic unit called the Brazeau Formation (Table 1). The lower beds of the Edmonton Formation (formational status is given to the Edmonton beds in the Foothills since the Battle and Whitemud Formations are not recognized) in the central Foothills are probably time equivalent to the Bearpaw shale. MacKay (1943) reported a thickness of about 4,700 feet for the Brazeau in the Wawa Creek map-area; Lang (1947) estimated that about 6,000 feet are present in the vicinity of the Athabasca River; and Irish (1965) estimated that about 7,000 feet

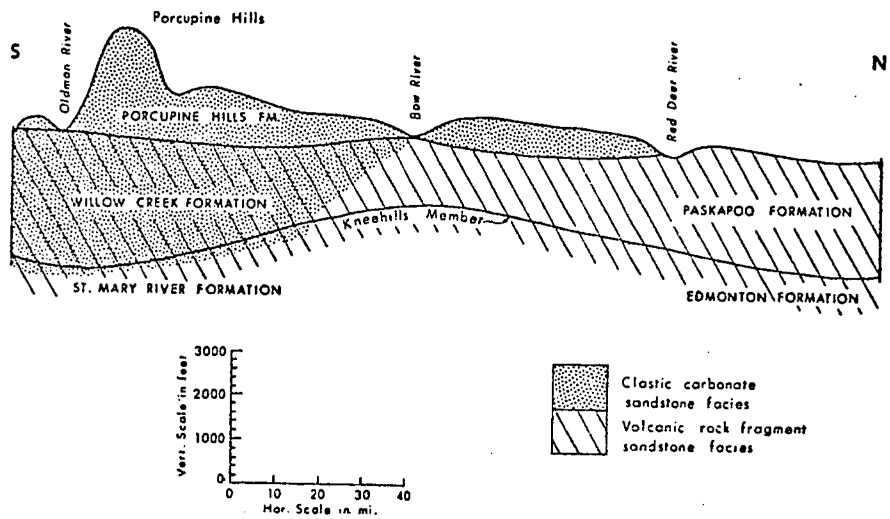

Fig. 36. Schematic cross-section showing the correlation of rock units and facies in post-Kneehills Tuff of central and southwestern Alberta (after Carrigy, 1971).

of Brazeau beds are present north of Entrance at the Wildhay River. The latter estimate is graphical and based on a structural cross-section and may therefore be exaggerated due to faulting. Farther to the northwest near the 54th parallel, Irish (1951) reported about 6,000 feet of Brazeau beds. These thicknesses are in close agreement with the maximum subsurface thickness of 5,000 to 5,500 feet along the western margin of the Plains. The Brazeau Formation thickens rapidly as the Foothills are approached, the thickening seeming to take place in the upper part of the Edmonton equivalent beds.

The Paskapoo Formation "conformably" overlies the Brazeau Formation. Its base is marked at the first appearance of a thick, brown-weathering, coarse-grained sandstone or, locally, a conglomerate bed (the Entrance Conglomerate) that has an average thickness of 20 feet. In the central Foothills the Paskapoo attains a thickness of over 5,000 feet and contains a major coal zone (Saunders Coal Seam) about 800 to 1,200 feet above its base. In the Entrance area, the Paskapoo Formation consists of "a thick succession of relatively soft interbedded sandstone and shale beds, with minor conglomerates, bentonitic beds, and coal seams. The sandstone is generally coarse and much of it is crossbedded. It is grey and weathers grey, brown and green. The shale is generally greenish grey and clayey. The conglomerate consists of pebbles and cobbles of waxy-lustred quartzite up to 12 inches in diameter ... carbonized remains of wood fragments are also common" (Irish, 1965). In the Entrance area, Irish estimated the Paskapoo to be at least 4,000 feet thick. Previous workers had considered the base of the Paskapoo of the Foothills to represent approximately the Cretaceous-Paleocene boundary and the entire Paskapoo Formation to be of Paleocene age. The present writer considers that part of the lower Paskapoo is of Lance age and is correlative with the recently revised Paskapoo Formation of the Plains. Evidence for this conclusion is given in a later section.

B. Recent Stratigraphic Revisions and the Nature of the Cretaceous-Tertiary Boundary

1. The Revisions

Recently, Irish (1970) and Carrigy (1970 and 1971) suggested some revisions in the terminology and boundaries of the uppermost Cretaceous and Paleocene lithostratigraphic units of the Plains of Alberta. Briefly, these revisions consisted of lowering the base of the Paskapoo Formation to include the Upper Edmonton Member of Allan and Sanderson (1945) and calling the latter the Scollard Member since it is best exposed in the Scollard Canyon of the Red Deer River Valley (Tables 12 and 13). Thus the "new" Paskapoo now contains Upper Cretaceous (Lance) strata at its base. The remaining part of the "old" Edmonton Formation was divided into three formations: the lowest and thickest unit was called by Irish the Horseshoe Canyon Formation, after Horseshoe Canyon west of the city of Drumheller where these strata are best exposed; the upper part was divided by Irish into the Whitemud and the overlying Battle Formations, thus raising the Edmonton beds to group status (Tables

12 and 13). This revision made the Edmonton Group and the Paskapoo Formation of central Alberta equivalent to the St. Mary River and the Willow Creek Formations, respectively, of southwestern Alberta (Table 1). Carrigy (1970, 1971) concurred with Irish's revision and concluded that the Porcupine Hills Formation of southwestern Alberta, usually thought of as equivalent to the Paskapoo Formation, is actually younger and overlies the Paskapoo Formation over a large area of the Plains and the Foothills of southwestern Alberta (Tables 1 and 12). The present writer, on the basis of evidence discussed later, concludes that the base of the Paskapoo Formation of the Foothills area does not represent the Cretaceous-Paleocene boundary but is rather of early Lance age, probably about Kneehills Tuff age; therefore, the Plains and the Foothills sections of the Paskapoo Formation are broadly time-equivalent and of Lance and Paleocene age.

Irish (1970, p. 140-141) stated his argument for redefining the Paskapoo Formation as follows: "... in order to have a well-defined marker for mapping in south-central Alberta, and because the Cretaceous beds above the Battle Formation resemble, lithologically, beds above the Ardley coal zone (Allan and Sanderson, 1945; Ower, 1960) rather than those of the Horseshoe Canyon Formation, it is proposed that those beds (Lance) be included in the Paskapoo Formation." Carrigy (1970) concurred with Irish's revision and concluded that the placement, by previous workers, of the base of the Paskapoo at the base of the first thick sandstone above the Ardley coal zone is not workable where the coal zone is absent, unexposed or unrecognizable as is the case in the Bow River area. Carrigy stated that in this thick non-marine sequence of Upper Cretaceous and Tertiary strata, only one marker bed, the Kneehills Tuff and one structural disconformity, the Willow Creek-Porcupine Hills disconformity, have been recognized to date; in his opinion these two features should form "...the natural boundaries for a rational rock unit subdivision of the nonmarine Upper Cretaceous and Tertiary strata in the Alberta Plains." Carrigy also concluded "...that the Porcupine Hills Formation is much more extensive than formerly mapped and that it overlies the Paskapoo Formation in the vicinity of Calgary." Carrigy's evidence for extending and placing the Porcupine Hills Formation overlying the Paskapoo Formation is mainly petrographic. Heavy mineral data obtained in the present study appear to support Carrigy's suggestions.

2. Nature of the Cretaceous-Tertiary Boundary

The discussion below centers on evidence for and against the presence of a regional stratigraphic break at the Cretaceous-Tertiary boundary in Alberta.

The Cretaceous-Tertiary boundary in Alberta occurs in a thick sequence of non-marine fluviatile and deltaic sediments which form clastic wedges that thicken westward. These sediments exhibit complex facies relationships of lenticular and often diachronous rock units. Marker beds are very few and paleontologic evidence is scanty where needed, close to this boundary. It is therefore clear that the task of establishing such a major time-stratigraphic boundary is not an easy one in this situation. However, the available evidence is sufficient to place the Cretaceous-Tertiary boundary in the Red Deer River Valley about 200 feet above the Kneehills Tuff. Lance dinosaurian fauna occur up to about 175 feet above the Kneehills Tuff (Sternberg, 1947 in Lerbekmo, 1964).

Bentonite from the Ardley (U. Ardley) coal seam, about 200 feet above the Kneehills Tuff, was dated at 63.4 $\pm$1.0 m.y. which was taken to be the best age for the Cretaceous-Tertiary boundary (Shafiqullah et al.,1964). The lowest known mammalian fauna found within the post-Scollard Member Paskapoo Formation along the Red Deer River Valley occur 200 to 300 feet above the base and has been dated as Upper Paleocene (Simpson, 1927 in Lerbekmo, 1964, p. 139). The controversy among geologists has been on the nature of the boundary at the top of the Scollard Member (top of the old Edmonton Formation). Allan and Sanderson (1945 in Irish, 1970, p. 141) observed brown-weathering channel-fill sandstones in beds of post-Battle age. They assigned these beds to the stratigraphically higher Paskapoo sandstone on the basis of lithological similarity and postulated the presence of an unconformable contact between the uppermost Cretaceous beds and those of the Paleocene Paskapoo Formation. Ower (1958, 1960) did not find evidence for such an unconformity although he believes that local disconformities do exist due to river channeling. He observed that "...some of the buff-weathering channel-fill sandstone bodies resting on the Kneehills Tuff zone (Battle Formation) contain dinosaur bones and are of Lance age. Thus, they are also of late Upper

Cretaceous age" (Ower, 1960 in Irish, 1970, p. 141). Local unconformable conditions were also suggested by Campbell and Almadi (1964, in Irish, 1970) but they did not see any evidence for an extensive unconformity at or near the top of the Upper Cretaceous section. They pointed out that it is doubtful that the buff-weathering sandstones are of Paleocene Paskapoo age. Lerbekmo (1964) suggested the presence of a disconformity where hornblende-bearing Paskapoo-type sandstone is found to rest directly on the Kneehills Tuff. Since the only other hornblende-bearing sandstone samples found were of Paleocene Paskapoo type and were taken at least 200 feet above the Kneehills Tuff, Lerbekmo came to the conclusion that this disconformity has differentially removed at least 200 feet of Lance (Scollard Member) strata. However, Lerbekmo's conclusion was based mainly on evidence from the Red Deer Valley where the Scollard Member sandstones do not usually carry hornblende. Data from the present study and from that of Chi (1966) indicate that hornblende does exist in Lance beds northwest (Swan Hills) and southeast (Cypress Hills) of the Red Deer River Valley. Therefore, it is possible that these hornblende-bearing channel-fill sandstones resting on the Kneehills Tuff are of Lance age. There is as yet no unequivocal fossil evidence for or against either interpretation. Tozer (1956, p. 30 in Irish, 1970) considered the Edmonton Group to be unconformably overlain by the Paleocene Paskapoo on the Bow River. He stated that "... over 200 feet of beds that overlie the Battle equivalent in the Red Deer Valley and which carry vertebrate fossils of Lance age (Sternberg, 1947) are absent on the

Bow River. The Paskapoo is, therefore, unconformable on the Edmonton." However, Irish (1970) remarks that the lower 300 feet of beds assigned to the Paleocene Paskapoo by Tozer at the Bow River have yielded no fossils and such beds may be of Late Cretaceous (Lance) age. Irish uses the same argument to suggest the possibility that the lowermost 200 to 300 feet of Paleocene Paskapoo beds of the Red Deer River and south as far as the Oldman River, being unfossiliferous, are of Late Cretaceous age, and that the Cretaceous-Paleocene boundary is gradational. In the Cypress Hills area, the Frenchman Formation of Late Cretaceous (Lance) age lies unconformably above the Battle Formation but has a gradational upper contact with the Paleocene Ravenscrag Formation (Fraser et al, 1935, pp. 39-40, in Irish, 1970). Irish describes the nature of the Cretaceous-Paleocene boundary in the central and southern Plains and states "Field mapping by the writer showed that the Cretaceous succession overlying the Battle Formation becomes progressively thinner southward from the Red Deer River region. In the Red Deer Valley, a maximum of about 290 feet of beds overlies the Battle Formation; on the north side of Bow River valley in Sec. 13, Tp. 22, Rge. 24, W4, Paskapoo-type sandstone overlies the Battle Formation, whereas, on the south side of the valley, both Battle and Whitemud Formations have been removed by erosion. Southward, those formations are not seen again in outcrop until the valley of Oldman River is reached. There, both the Whitemud and Battle Formations are exposed in Sec. 25, Tp. 10, Rge. 25, W4, where they separate the St. Mary River and the Willow Creek Formations.

Between Bow and Oldman Rivers, Paskapoo-type strata, at the surface, appear to rest on Edmonton (Horseshoe Canyon Formation) beds older than the Whitemud and Battle Formations although, farther west, those formations are present in the subsurface (Havard, in Irish and Havard, 1968). There is, therefore, the possibility of a progressive bevelling of the uppermost Cretaceous strata both from west to east and from north to south. The amount of this southward bevelling probably reaches a maximum just south of Bow River, and then decreases southward to Oldman River where there is no indication of erosion of equivalent beds (lower part of Willow Creek Formation)." It seems from the above discussion that Irish (1970) contradicted himself (compare the first and second paragraphs of p. 142 concerning the Bow River area) in using one kind of evidence to support two opposing ideas, namely, on the question of the age of the lower few hundred feet of Paskapoo-type sandstone in the Bow River valley.

In the southern Foothills the Cretaceous-Paleocene boundary occur within an apparently gradational succession of the Willow Creek Formation. No diagnostic fossils have been found in the Willow Creek Formation of the southern Foothills. However, eastward toward the Plains, Williams and Dyer (1930, in Douglas, 1950) reported a non-marine invertebrate fauna from the upper part of the formation dated as Upper Paleocene. Douglas (1950) suggested that many species of this fauna may be of Early or Middle Paleocene age: "The age of the remainder, or lower part, from which no fossils have been collected, may be Upper Cretaceous in age, as suggested by the transitional contact with the underlying St. Mary River Formation, and the absence of definite later Upper Cretaceous (Lance) fossils from the uppermost beds of the St. Mary River Formation". This conclusion is supported by Tozer (1953, p. 26) as he considered the lower Willow Creek Formation to be of Lance age. Tozer's work on the paleontology of the Cretaceous-Paleocene sequence of the northern part of the southern Foothills, south of the Bow River, indicates that "...the Cretaceous-Tertiary transition is represented by continuous non-marine sedimentation." He also cited evidence to suggest that the lower Willow Creek (Lance) fauna was found, in this area, to occur well within beds mapped as Paskapoo (Paleocene) Formation.

In conclusion, it seems that the evidence is stronger for a stratigraphic break at the Kneehills Tuff level than at the Cretaceous-Tertiary boundary. It will be seen later that the heavy mineral evidence also supports such a thesis.

The Cretaceous-Tertiary boundary and the age of the Brazeau-Paskapoo contact in the central Foothills area is treated separately in the following section.

3. Cretaceous-Tertiary Boundary in Central Foothills

In the central Foothills the problem of the Cretaceous-Tertiary boundary is quite different than in the Plains. In the former, the sequence is much thicker, and the Kneehills Tuff has not yet been recognized. As in the Plains, diagnostic micro-fossils have not been found in the vicinity of the Cretaceous-Tertiary boundary. Geologists have generally placed the base of the Paskapoo Formation at the first buff-weathering, resistant sandstone bed above the upper part of the

Brazeau Formation (i.e. Edmonton equivalent). This contact is marked by the presence of a 20-foot (average thickness) conglomerate of quartz and chert pebbles, called the Entrance Conglomerate Member by Lang (1945) in the region of Athabasca River. The conglomerate thins southward, but continues to occur in most sections south to the area of the Little Red Deer River (Lang, 1945 and Lerbekmo, pers. comm.). Lang considered this Brazeau-Paskapoo contact to mark the Cretaceous-Tertiary boundary (on the advice of Bell who worked on the paleobotany of these rocks). MacKay (1943) divided the post-Wapiabi sequence of this area into the Brazeau and Edmonton Formations of Cretaceous age overlain by the Paskapoo Formation of Paleocene age. Later Douglas (1958), working in the same area, grouped MacKay's Edmonton with the Paskapoo Formation and considered the base of his new Paskapoo Formation to mark approximately the Cretaceous-Tertiary boundary (essentially like Lang). Douglas correlated the base of the Paskapoo Formation with the Entrance Conglomerate of the Entrance area. Recently, however, there has been growing evidence, especially palynologic (Eliuk, 1969; Gunther, 1970) to suggest that the Brazeau-Paskapoo contact (marked by the Entrance Conglomerate) does not coincide with the Cretaceous-Tertiary boundary, but instead occurs well within the Upper Cretaceous, probably near the level of the Kneehills Tuff of the Plains. This revision would make the central Foothills Paskapoo time correlative with the newly defined Paskapoo Formation of the Plains (Table 1). Evidence from Tozer's (1953) work, given in the previous section, also suggests that the base of the Paskapoo Formation in the northern part of the southern Foothills may be well within Late Cretaceous time. The following discussion centers around evidence in support of the proposition that the base of the Paskapoo Formation (base of Entrance Conglomerate) of the central Foothills is probably correlative with the Kneehills Tuff and not the Cretaceous-Tertiary boundary.

Paleontologic evidence (molluscs and vertebrates, Russell, 1932, p. 147) indicates that large parts of the Paleocene rocks in the central Foothills are Early and Middle Paleocene. These were called pre-Paskapoo (Russell, 1932, p. 147) strata since they are not represented in the Plains Paskapoo (old terminology) as far as the available fossil evidence suggests. Russell (1932, p. 147) pointed out that these pre-Paskapoo Paleocene beds of the central Foothills might represent the time span of the Cretaceous-Tertiary unconformity of the Plains. Russell also suggested that part of these beds (which are above the Entrance Conglomerate) may represent a portion of the Lance stage of Late Cretaceous time. Elliot (1960) noted that the upper Brazeau Formation is marked by an increasing number of volcanic ash beds which he thought might be related to the widespread ash deposits that resulted in the Kneehills Tuff zone. The Entrance Conglomerate was thought by Elliot to have been deposited "...as a result of the same violent diastrophic events which provided the air-borne material for the earlier ash deposits. Thus, it is thought probable that the top of the Brazeau Formation may be the time equivalent of the top of the Middle Edmonton, that is, equivalent to the Kneehills Tuff zone. A similar interpretation to that of Elliot was advanced by Ower (1960). Ower states on p. 318 "However, a tuff bed and dark shale have been reported immediately below the Entrance Conglomerate. It is possible that the Entrance Conglomerate may be equivalent to the base of Member E" (see Table 12), i.e. the level of the Kneehills Tuff.

Eliuk (1969) made a palynologic study of the rocks associated with the Entrance Conglomerate in the Entrance area. Seven of the ten microfloral species recovered from rocks 75 feet above and below the Entrance Conglomerate are equivalent to species restricted to Snead's (1968) microfloral Zone A of the Cretaceous-Tertiary rocks of the Plains. The upper limit of Zone A is the lower Ardley coal seam of the Lance Scollard Member, which is about 60 feet above the Kneehills Tuff; the lower limit is near the middle of the Middle Edmonton Member (equivalent to the upper part of the Horseshoe Canyon Formation) (Table 12). The remaining three species have a common and wider range extending up into the Paleocene. On the basis of this evidence Eliuk suggested that the Entrance Conglomerate and the rocks immediately above and below are "...equivalent to part of Ower's Member D of the Edmonton Formation in the Alberta Plains and to basal (?) Lance Formation equivalents", that is, equivalent to the Kneehills Tuff zone. More recently, Gunther and Hills (in press and pers. comm. with senior author) made a palynologic study of the Brazeau and the lower part of the Paskapoo Formations along the Blackstone River of the central Foothills. They too compared the ranges of the flora obtained in the central Foothills with those of Snead's (1968) of the Plains. Their results show that the base of the Paskapoo Formation on the Blackstone River (not marked with conglomerate) is palynologically equivalent to the Entrance Conglomerate and to the Kneehills Tuff of the Plains. They also suggest the existence of "... one major unconformity or hiatus" in the Blackstone River section "... at the top of the Scollard Member equivalent" on the basis of a "...significant general extinction of species" at this level. They suggest that "... this marked change in assemblage probably correlates with the known unconformity or hiatus found in the Plains between the Scollard Member and the upper Paskapoo Formation (Snead, 1969)."