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SOURCE-ROCK POTENTIAL AND RESERVOIR CHARACTERISTICS OF THE LOWER (ALBIAN - TURONIAN) COLORADO GROUP, WESTERN CANADA SEDIMENTARY BASIN

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EXECUTIVE SUMMARY

This report synthesizes geochemical and isotopic data to evaluate the source-rock and reservoir potential of a portion of the Cretaceous Colorado Group shales of the Western Canada Sedimentary Basin. This work is part of a multidisciplinary study undertaken with Office of Energy and Resource Development (OERD) funding (Project # 6.1.1.14) by the Geological Survey of Canada to 1) identify distinct shale units in the studied interval 2) to provide quantitative mineralogy and bulk chemical properties that may be used for wireline calibration, and 3) to evaluate the depositional and facies controls on shale composition.

With regard to #3 above, this report includes geochemical contour maps and other data that characterize source-rock quality and maturity and evaluate depositional and diagenetic controls on source-rock characteristics. In addition, isotopic and chemical data are utilized to constrain the mechanisms and timing of authigenic carbonate and fracture formation. The regional scale of this study provides a framework for subsequent, detailed analyses of specific source-rock intervals that may be of economic interest.

ACKNOWLEDGMENTS

The author would like to thank Al Heinrich, Jenny Wong, Ron Fanjoy, Ross Stewart, Bob Davidson and Brad Gorham for performing much of the analytical work. Bill Sharman and Brian Rutley are thanked for their production of the photographs. Angus Leech assisted with sample preparation and processing. Fred Longstaffe and the Basal Reflections Society, particularly Paul Middlestead, at the University of Western Ontario, London, are thanked for providing isotopic data. The Dudes of Diagenesis provided ongoing intellectual stimulation and support and the late Stevie Ray Vaughn has been a frequent inspirational influence. Finally, I would like to thank Roger Macqueen and Dale Leckie for their continued support of this research.

INTRODUCTION

The evaluation of sedimentary source rocks has become an integral component of hydrocarbon exploration and basin analysis. Clastic source-rocks are commonly fine-grained (> 50% silt- or clay-sized material) and can be defined on the basis of their organic matter content with a minimum value of about 0.5 wt% (Tissot and Welte, 1984). In the context of basinal petroleum systems, source rocks may be further subdivided into three types: *possible source rock,* that is, a sedimentary rock that may have generated hydrocarbons but is not yet evaluated; *effective source rock*, one that has generated and expelled hydrocarbons; and *potential source rocks*, an immature sedimentary rock that is capable of generating hydrocarbons (Waples, 1984).

Source rocks may also be considered reservoirs when hydrocarbons are extracted from them directly. Biogenic gas is commonly extracted from potential source rocks. With advances in completion and extraction technology, some effective source rocks may also be economic liquid and gaseous hydrocarbon reservoirs (Mallory, 1977). Therefore, the study of source-rock reservoir characteristics, analogous to traditional reservoir rock (sandstone and carbonates) studies, should also be included in basin analysis, petroleum system and hydrocarbon exploration studies.

The Western Canada Sedimentary Basin (WCSB) is a classic foreland petroleum province and the clastic source-rocks within the WCSB have been studied for over 70 years (see Creaney and Allan, 1992, for a review). A major component of the Mesozoic basin fill is the Cretaceous Colorado Group and a large number of clastic, hydrocarbon-producing intervals in the WCSB are found within, or in units equivalent to, the Colorado Group. Despite the economic importance of this interval, relatively little was known about the source rock potential of Colorado Group shales until recently (Macauley, 1984; Allan and Creaney, 1991). Regional maturation patterns have been defined (Bustin, 1991; Creaney and Allan, 1992) and the thermal maturity of individual units or stratal successions have been examined in some detail (Macauley et al, 1985; Jones et al., 1986; Stasiuk and Goodarzi, 1988; Stasiuk et al., 1993). However, local variations in source-rock quality and maturity patterns are common (Bustin, 1991) and can only be evaluated by a detailed study of individual shale units that provides a greater degree of spatial resolution. This study examines source rock characteristics and maturation patterns within a newly defined stratigraphic architecture (Bloch et al., 1993) that provides a higher degree of resolution than previous studies.

A second objective of this study is to evaluate the reservoir characteristics of potential shale reservoirs. There is virtually no published data that addresses this aspect of source-rock evolution. Economic shale reservoirs require fracture porosity that may be developed by tectonic and burial stresses, or induced during reservoir development. Whatever the mechanism of fracture development, the fracture system must be maintained to accumulate and produce hydrocarbons. Brittle behaviour is necessary for fracture maintenance and the mineralogy, to a large degree, will determine whether or not a shale can maintain a fracture system. It is beyond the scope of this study to evaluate all the elements of reservoir property development: therefore, this report will focus on the mineralogy of the shale units studied herein and discuss the potential for fracture development and maintenance within those units in a compositional context.

GEOLOGICAL BACKGROUND

Recent work has described and redefined the stratigraphy of the Albian to Turonian portion of the Colorado Group and this background synopsis is taken largely from Bloch et al. (1993). The Cretaceous Colorado Group and equivalent strata form an extensive eastward-tapering wedge of predominantly marine shales extending for more than 1300 km from the Rocky Mountains to the Manitoba Escarpment (Fig. 1). Intercalated within the marine shales are numerous hydrocarbon-bearing sandstone bodies, including the St. Walburg, Barons, Doe Creek, Pouce Coupe, Howard Creek, Phillips, Jumping Pound and Medicine Hat sandstones, and the Dunvegan, Cardium, and Badheart formations (see Bloch, 1993, Fig 2). The deposition and distribution of sandstones within the Colorado Group have been characterized in numerous studies (see Stott, 1984; Leckie, 1989; Leckie and Smith, 1992, for summaries). The enveloping shales represent deposition in epicratonic seas during a global sea level rise that began in the Aptian and continued throughout the Cretaceous (Larson, 1991). The Albian to Turonian portion of the Colorado Group was deposited during the major pulse of eustatic sea level rise that peaked in the latest early Turonian (Schlanger and Jenkyns, 1976; Scholle and Arthur, 1980) and represents the time period from about 100 to 92 Ma (Obradovich, 1991). The interval includes the Late Albian *Miliammina manitobensis*, the Cenomanian *Verneuilinoides perplexus* and the Early Turonian *Hedbergella loetterlei* foraminiferal zones of Caldwell *et al.* (1978) and comprises four formations throughout much of the basin. In ascending order, they are the Westgate (late Albian), Fish Scales (earliest Cenomanian), Belle Fourche (early? to latest Cenomanian) and Second White Specks (Early to middle? Turonian) formations (Fig. 2).

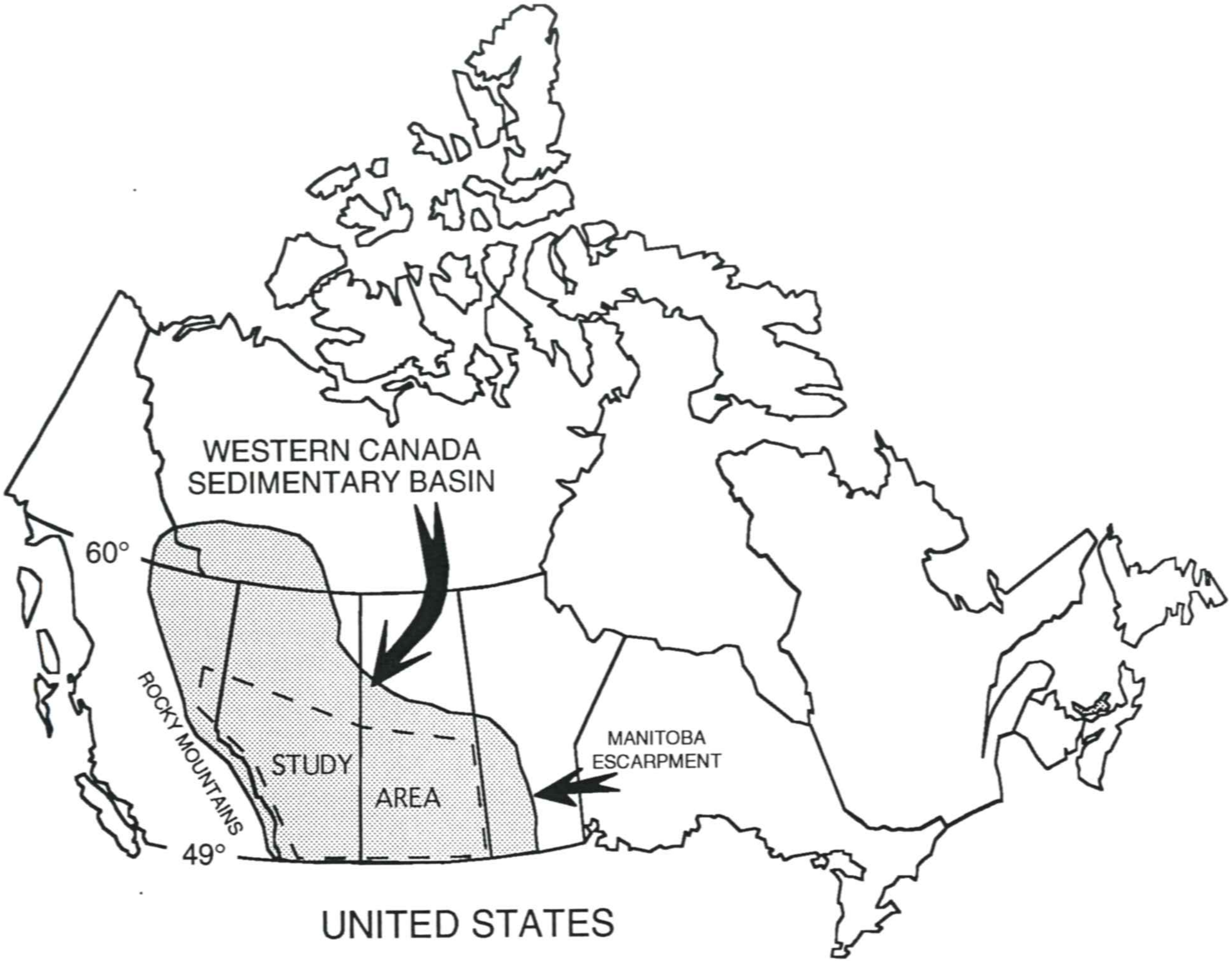


Figure 1. Study area and regional physiographic features.

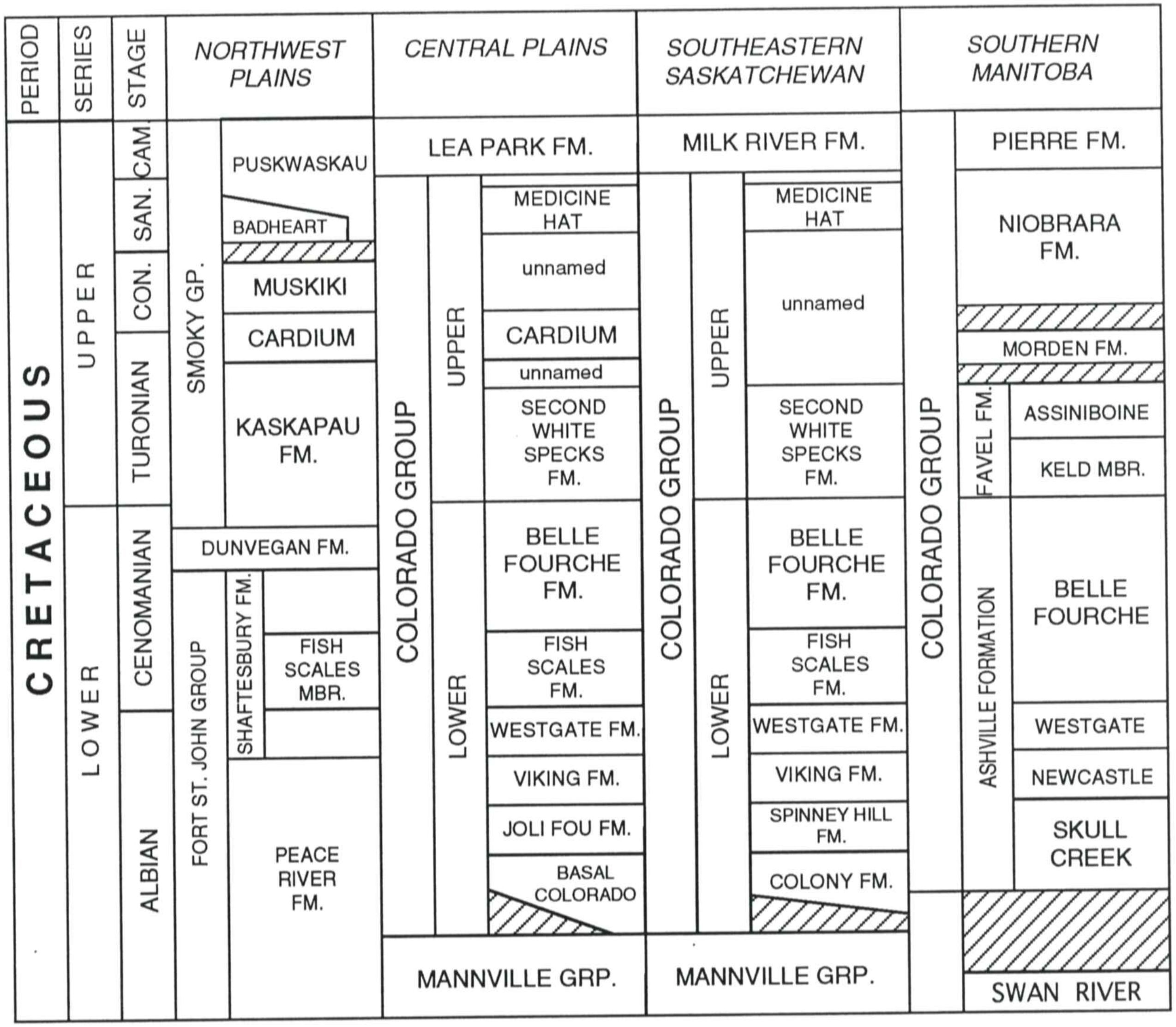


Figure 2. Stratigraphic nomenclature for the study area (after Bloch et al., 1993)

METHODS

Samples were selected from core and outcrop at intervals from 0.1 to 5m. A complete description of sampling procedures and preparation is given in Bloch (1994). Core and outcrop locations are listed in Table 1 and shown in Figure 3. Table 1 also includes Geological Survey of Canada curation numbers. Remaining samples are stored at the Institute of Sedimentary and Petroleum Geology, Calgary, and may be accessed utilizing these numbers.

Rock-Eval pyrolysis (Espitalié et al., 1977) was performed in duplicate on pulverized shale samples, using standard procedures on a DELSI Rock-Eval II/TOC apparatus. Information thus obtained includes the type of organic matter (oxygen and hydrogen indices), its maturity (T_{max}), and the amount of total organic carbon (TOC) contained in the sample. T_{max} is the temperature at which maximum hydrocarbon generation occurs during pyrolysis, and is an indication of the maturity of the organic matter contained in the sample. The Production Index (PI) is a measure of the amount of volatile hyrdocarbon components in the sample and therefore is also a maturity indicator. PI and T_{max} can also indicate the presence of contaminants or migrated petroleum. For a full discussion of the pyrolysis procedure, see Espitalié et al. (1977) and Peters (1986) .

Maps of three Rock-Eval parameters (TOC, HI and Tmax) for each formation were generated by averaging formation values for each well. The averaged values were gridded and contoured using Surface III (Kansas Geological Survey, 1992). Because of the small number of wells used as control points, the information on the maps should be regarded as general in nature and detailed studies in a particular area should be conducted. However, the relative differences between formations are interpreted to reflect controlling

TABLE 1 - CORE AND OUTCROP LOCATIONS WITH GEOLOGICAL SURVEY OF CANADA CURATION NUMBERS

CORE

LOCATION	NAME	GSC #
05-09-72-08 W6	IMPERIAL WEMBLEY	C167134
16-01-66-22 W5	AMOCO BIGSTONE	C167143
05-01-77-20 W5	IMPERIAL KATHLEEN #1	C167135
10-25-65-20 W5	SABINE ET AL IOSEGUN	C167144
10-05-53-20 W5	H.B. GALLOWAY	C167145
09-09-56-19 W5	HCS ET AL BEAVER CREEK	C167147
04-13-54-18 W5	TEXEX EDSON	C167146
14-29-13-29W4	BRASCAN ET AL OXLEY	C205701
10-36-11-29W4	AMTROG GULF CLARESHOLM	C205702
06-07-12-28W4	CANADIAN SUPERIOR OXLEY	C190616
14-29-11-28W4	DOME ET AL CLARESHOLM	C205706
06-30-13-27W4	MLC DEKALB CLARESHOLM	C179967
06-29-13-27W4	CAN HUNTER ET AL CLARESHOLM	C179966
04-08-13-27W4	SINCLAIR E. MATHEWS	C205704
06-32-13-27W4	CAN HUNTER ET AL CLARESHOLM	C205708
06-21-55-25 W4	AJAX MORINVILLE	C167142
08-25-12-24W4	PENN WEST ET AL BARONS	C205707
11-21-12-23 W4	MELAAR BARONS	C167150
16-10-12-23W4	BARONS SUPERIOR #1	C205703
10-34-42-22 W4	LCD ET AL BASHAW	C167138
06-16-11-22W4	CAN HUNTER KEHO	C179965
06-34-10-22W4	CAN HUNTER KIPP	C205705
06-16-06-22 W4	GULF MOHAWK BLOOD	C167149
07-12-42-21 W4	LCM ET AL BUFF LAKE NORTH	C167139
11-12-06-16 W4	AMOCO CONRAD	C167148
06-22-11-06 W4	G. BASIN BUX MEDICINE HAT	C179954
06-34-30-08 W4	AMOCO B-1 YOUNGSTOWN	C167141
07-14-01-05 W4	PACIFIC AMOCO SAPPHIRE	C179953
10-35-45-02 W4	ANDERSON HUSKY ROROS	C167136
06-18-45-01 W4	ANDERSON ET AL RIBSTONE	C167137
10-25-01-27W3	SASKOIL WILLOW CREEK	C179958
11-16-35-08W3	C.M.S. VANSCOY	C179956
05-22-34-01W3	U.S. BORAX & CHEMICAL	C179955
11-36-22-01W2	S.W.P BREDENBURY	C179957

OUTCROP

ELK CREEK 83B/4 UTM-735855	CRIPPLE CREEK	C190522 to C190614
KANANASKIS LAKES 82J UTM-68885663	HIGHWOOD RIVER	C170001 to C170050 and C190451 to C190456
LANGFORD CREEK 82J/1 UTM-850434	BRUIN CREEK	C190477 to C190521
FERNIE 82/G UTM-70755475	MILL CREEK	C190457 to C190471

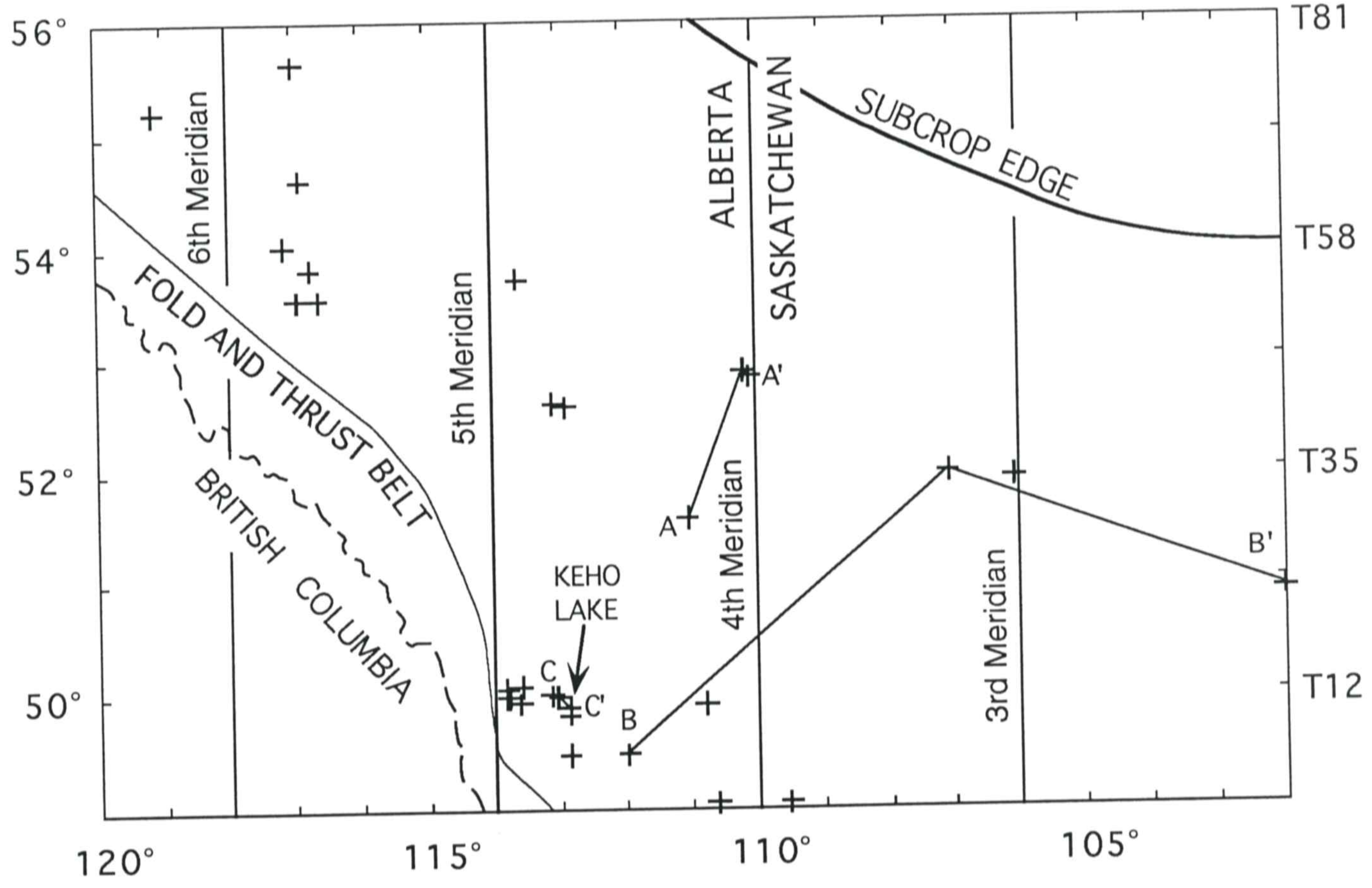


Figure 3. Core and cross-section locations (see Table 1).

processes on the deposition and maturation of the organic matter as all maps were generated using the same gridding and contouring criteria.

X-ray diffraction (XRD) was carried out on disaggregated and gently ground bulk rock shale and bentonite samples, and on their clay fractions (<2.0 and <0.2 μm e.s.d.) obtained by ultrasonic dispersion in distilled water and centrifugation. XRD results were obtained using a Philips PW1700 automated powder diffraction system with Fe-filtered Co $K\alpha$ radiation generated at 40 kV and 30 mA. Bulk, unoriented samples were scanned from 4 °2θ to 64 °2θ and clay fraction samples were scanned from either 2 or 4 °2θ to 40 °2θ with an increment of 0.05 °2θ at a recording speed of 1 °2θ/cm/50 sec. Clay fraction diffractograms were obtained under conditions of relative humidity (45 %), low humidity (~0 %), ethylene glycol saturation, and after heat treatment (550 °C). Some clay separates were run from 4 °2θ to 64 °2θ to evaluate 00ℓ peak positions and Bragg behaviour of clay minerals in mixtures (see Moore and Reynolds, 1989).

Bulk rock chemistry was determined by X-ray fluorescence (XRF) for ten major oxides on crushed shale and bentonite samples prepared by standard techniques (Baedecker, 1987). Analytical precision on replicate analyses of 1 g samples is less than 0.9 wt% for SiO_2, 0.5 wt% for Na_2O, 0.2 wt% for Al_2O_3 and 0.1 wt% for the other elements. Loss on ignition (LOI) was determined by combustion and thermogravimetric analysis, with a precision better than 0.7 wt%. XRF analysis of <0.2 μm and <0.1 μm clay fractions, previously characterized by XRD, was undertaken for a subset of samples in order to constrain clay mineral compositions. Because of the small amount of sample available, 100 mg aliquots were used and duplicate samples generally could not be made. Analytical error from replicate analyses of the primary standard (GSP-1) , as determined by comparison with published values (see Abbey,

1980) are within 0.4 wt% for all oxides. However, analytical precision for unknowns is significantly higher, especially for Na, because of the reduced sample size. Based on the analysis of one set of duplicate beads (see Table 3; #063419), relative errors for SiO_2, Al_2O_3, Fe_2O_3 and Na_2O are 5, 13, 17 and 79 %, respectively.

Total carbon was determined using a LECO WR-12 apparatus and total sulphur was analyzed on a LECO-32 Sulfur Determinator using standard techniques (see Baedecker, 1987). Carbon and sulphur analyses were run in duplicate and analytical precision is 0.2 wt% and 0.05 wt%, respectively, for carbon and sulphur abundance's up to about 8 wt%.

Concretion and fracture-fill carbonate cement samples for carbon and oxygen isotopic analyses were collected using a dental drill and analyzed by XRD for sample purity. All samples were reacted with anhydrous phosphoric acid using standard techniques (Friedman and O'Neil, 1977; Rosenbaum and Sheppard, 1986). Evolved CO_2 gas was analyzed on a VG-Optima mass spectrometer at the University of Western Ontario and the analytical results for carbon and oxygen are presented in standard δ notation (Craig, 1957) relative to Pee Dee Belemnite (PDB) and Standard Mean Ocean Water (SMOW), respectively. Analytical precision for both carbon and oxygen is less than 0.2 ‰ (per mil).

Polished sections were prepared from epoxy-impregnated core samples. Back-scattered electron microscopy (BSEM), using a Cambridge Stereoscan 150 electron microscope equipped with an 8 kV threshold annular back scatter detector, provided petrographic information. This was supplemented by energy-dispersive X-ray (EDX) analysis for qualitative mineral identification.

A linear programming method was used to determine the mineralogy of the shales from their bulk chemical composition, and to estimate clay mineral compositions from the <0.2 μm XRF analysis results. Linear programming distributes the analyzed oxides according to a set of (linear) equations, which are solved simultaneously using the mathematical method known as linear optimization. The development and use of this method is fully described in Bloch and Hutcheon (1992) and Caritat et al., (in press).

Detailed analytical results are given elsewhere in tabulated and graphic form (Bloch and Leckie, 1993; Bloch, 1994) and complete formation descriptions are given in Bloch et al. (1993). Data pertinent to the source-rock and reservoir characterization of the studied formations are presented below.

FORMATION CHARACTERISTICS

Westgate Formation

The Westgate Formation is characterized by the occurrence of dominantly Type III organic matter (OM) and TOC values generally less than 2 wt% (Fig. 4a). However, some samples have TOC values up to ~10 wt% that are atypical (Bloch et al., 1993). These samples are from west of Keho Lake in southwestern Alberta (Fig. 3) and are discussed in detail below. T_{max} values range from about 410 to 475 °C and generally increase with depth (Fig. 5a).

The lithology (Table 2) of the Westgate varies from mudstone to siltstone. Detrital minerals include quartz (15 - 52 wt%) and K-feldspar (0 - 6 wt%) with minor to trace amounts of plagioclase, micas (dominantly muscovite) and a suite of heavy minerals (anatase, apatite and zircon). Clay minerals are detrital and authigenic in origin and include mixed-layer illite/smectite (I/S; 12 - 51 wt%), kaolinite (9 - 25 wt%) and trace amounts of chlorite. Detrital illite and/or I/S is also present but has not been differentiated quantitatively from I/S. Authigenic minerals include pyrite (1 - 5.5 wt%) and siderite (0 - 6.5 wt%) with

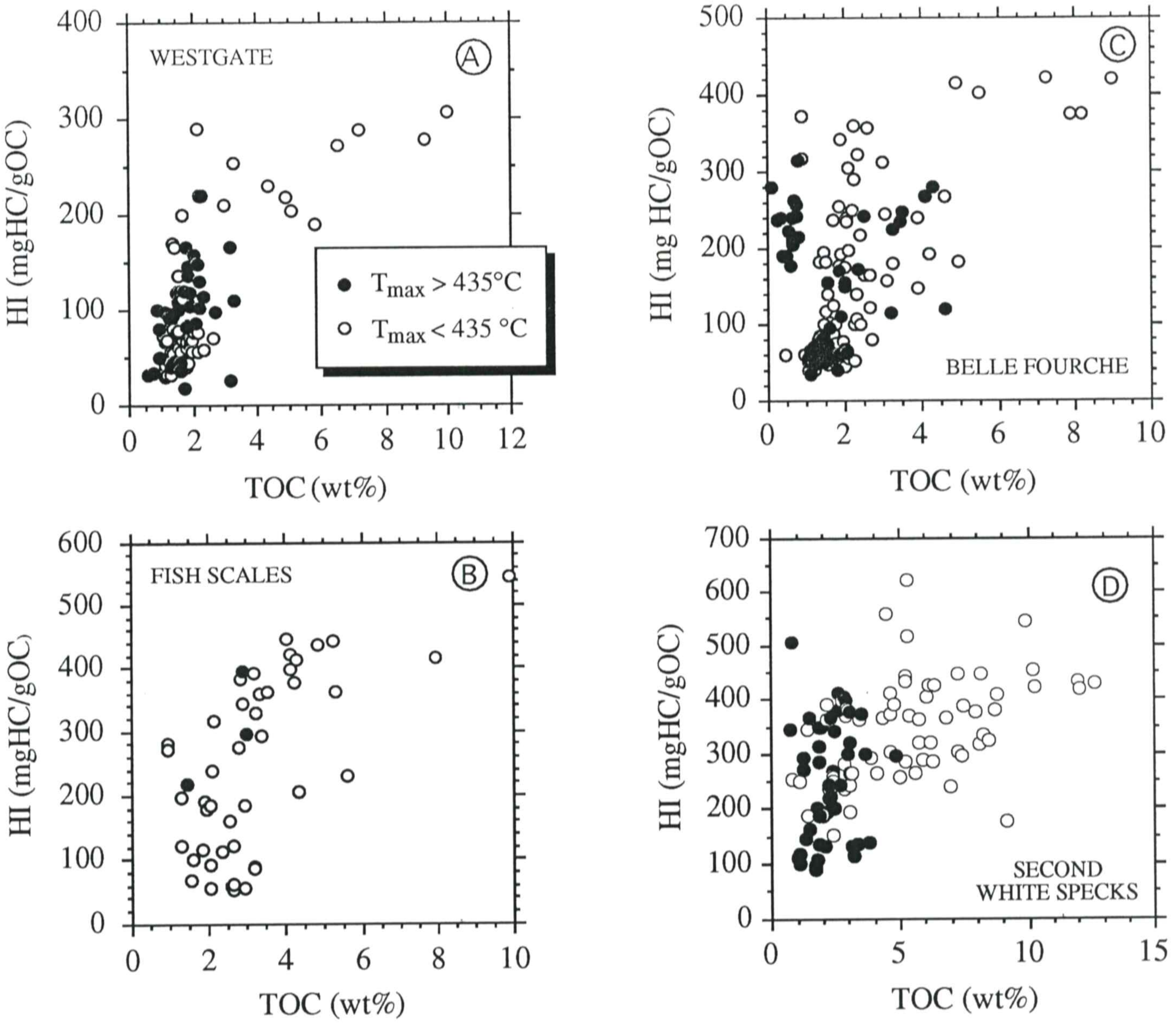


Figure 4. TOC versus HI values for the four indicated formations.

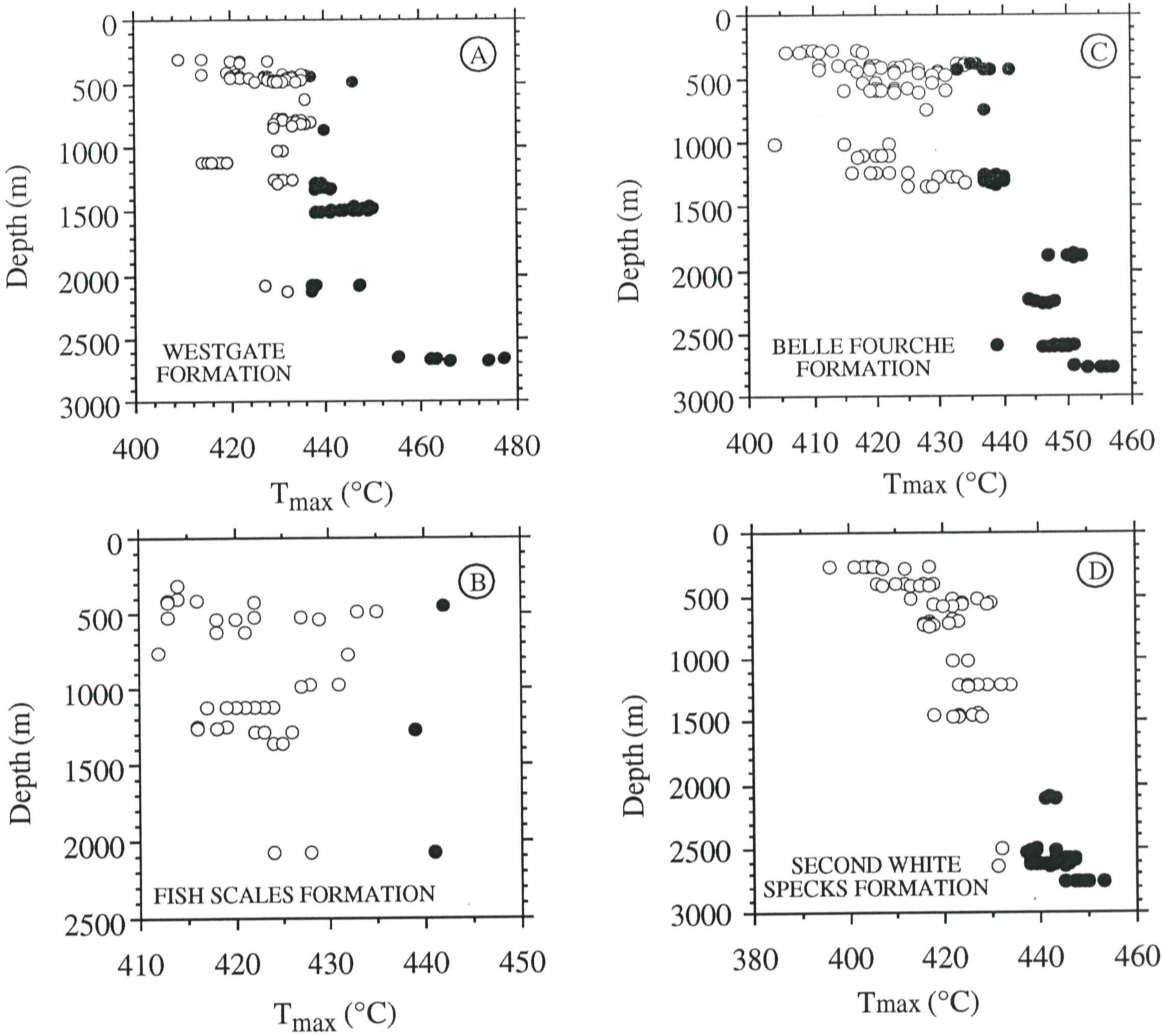


Figure 5. T_{max} versus depth for the four indicated formations.

TABLE 2 - average mineral modes for Colorado Group formations.

Formation	Qtz	I/S	Kao	Ksp	Plg	Pyr	Sid	Cal	Dol
Westgate	32	37	19	4	5	1.8	2.1	0	0
Fish Scales	40	29	14	3	0	3.2	0.5	0	1.8
Belle Fourche	36	29	21	5	0	2.2	2.3	0	0
Second White Specks	31	21	13	3	0	4.2	0	15.8	4.4

localized occurrences of jarosite, alunite, and rare dolomite. Silt-sized detrital grains are dominantly matrix supported but may be framework supported in silt-rich or sandy laminations. In some siltstones, detrital quartz grains have sutured contacts, primarily parallel to bedding (see Plate 4 in Bloch, 1994).

Fish Scales Formation

The Fish Scales Formation contains both Types II and III OM with TOC values up to about 8 wt% (Fig 4b). Similar to the Westgate Formation, samples with high TOC values occur west of Keho Lake. T_{max} values show no meaningful correlation with depth (Fig. 5b). This is due, in part, to sampling bias where there are few deeply buried samples.

The mineralogy of the Fish Scales Formation is similar to the Westgate Formation. Quartz (24 - 63 wt%) and K-feldspar (0-6 wt%) are the dominant detrital framework components with I/S (23 - 40 wt%), kaolinite (10 - 22 wt%) and trace amounts of chlorite. Authigenic pyrite (1 - 6.3 wt%) and minor siderite are present and dolomite (0 - 5 wt%) is more common than in the Westgate. The Fish Scales is generally fine-grained ranging from claystone to mudstone. However, a coarse, bioclastic conglomerate up to a few centimeters thick comprises the base of the formation and sandstones are locally present at the top.

Belle Fourche Formation

The Belle Fourche Formation contains a mixture of Types II and III OM with HI values from about 40 to over 400 mg HC/gOC (Fig. 4c). TOC values are less than 2 wt% in most of the lower Belle Fourche and are highest (~6 wt%) in the upper part of the formation that is transitional to the overlying Second White Specks Formation. As in the Westgate and Fish Scales formations, anomalously high TOC and HI values are found in core from the Keho Lake area. Mature (T_{max} > 435 °C) Belle Fourche samples show a good correlation between depth and T_{max} but immature samples show a wide range of T_{max} values (Fig 5c).

The Belle Fourche Formation is a non-calcareous to slightly calcareous mudstone to siltstone. Quartz ranges from 19 to 36 wt% and K-feldspar from 0 to 9 wt% with minor to trace amounts of mica. Plagioclase is rare and occurs only in samples from Saskatchewan. Clay minerals include I/S (16 - 45 wt%), kaolinite (8 - 43 wt%) and trace amounts of chlorite. Pyrite (0.1 to 6 wt%) is ubiquitous and authigenic siderite (0 - 4.4 wt%) is the dominant carbonate mineral and occurs primarily as concretions. Dolomite and calcite occur locally in the upper Belle Fourche.

Silt-sized grains, primarily quartz, are heterogeneously distributed. Framework supported silt laminations are common, particularly in the upper part of the formation however, similar to the other units, quartz and K-feldspar also commonly occur as matrix supported grains in clay- and mudstone.

Second White Specks

The mineralogy and the OM content of the Second White Specks (SWS) Formation are distinct. The SWS is a bioclastic calcareous mudstone to limestone with abundant Type II OM (Fig. 4d) up to about 13 wt % TOC. T_{max} and depth show a reasonable correlation and, similar to the other formations, immature samples show a range of T_{max} values (Fig. 5d). At an equivalent depth, SWS T_{max} values are about 5 to 15 °C lower than those of the Belle Fourche or Westgate formations.

Abundant calcite, up to 88 wt% occurring primarily as bioclasts, is a distinguishing characteristic of the SWS. Other detrital minerals are quartz (2 -

52 wt%), K-feldspar (0 - 5 wt%) and trace amounts of plagioclase, muscovite, anatase and apatite. Authigenic minerals include dolomite (0 - 6.3 wt%), pyrite (0 - 6.7 wt%), gypsum (0 - 13 wt%), and minor jarosite. Minerals of mixed detrital and authigenic origin include I/S (5 - 48 wt%) and kaolinite (0 - 25 wt%). Minor to trace amounts of chlorite, probably detrital in origin, also are present.

ORGANIC CARBON (TOC) DISTRIBUTION

The distribution of organic matter (OM) within Colorado Group is controlled by depositional facies and diagenetic processes including maturation and migration. The distribution of OM is shown for each formation on a basinal scale in Figures 6 through 9. The Type of OM is also useful in evaluating the distribution and maturation of OM and the HI values for each formation are shown in Figures 10 to 13. In addition, vertical profiles for TOC and HI are shown in Figures 14 to 16. The cross-section locations are shown in Figure 3.

The Westgate and Belle Fourche formations show broad areas of constant TOC content of between 1.5 to 2.0 wt%. In the Westgate, there is a slight increase in TOC in southern Alberta (Fig. 6). This increase is concomitant with an increase in HI (Fig. 10) and reflects the anomalously high TOC and HI values within the Westgate that occur in the area just east of the disturbed belt in the Keho Lake area (Figs. 4a and 16). A similar pattern is seen in the Fish Scales Formation (Figs. 7 and 11). The Belle Fourche Formation shows an increase in HI values in the same area but no discernible increase in TOC (Figs. 8 and 12). All three formations show a southwest to northeast decrease in HI values away from the disturbed belt.

In contrast, the SWS shows an increase in both TOC and HI to the northeast. Where the sediments are immature, these values are interpreted to

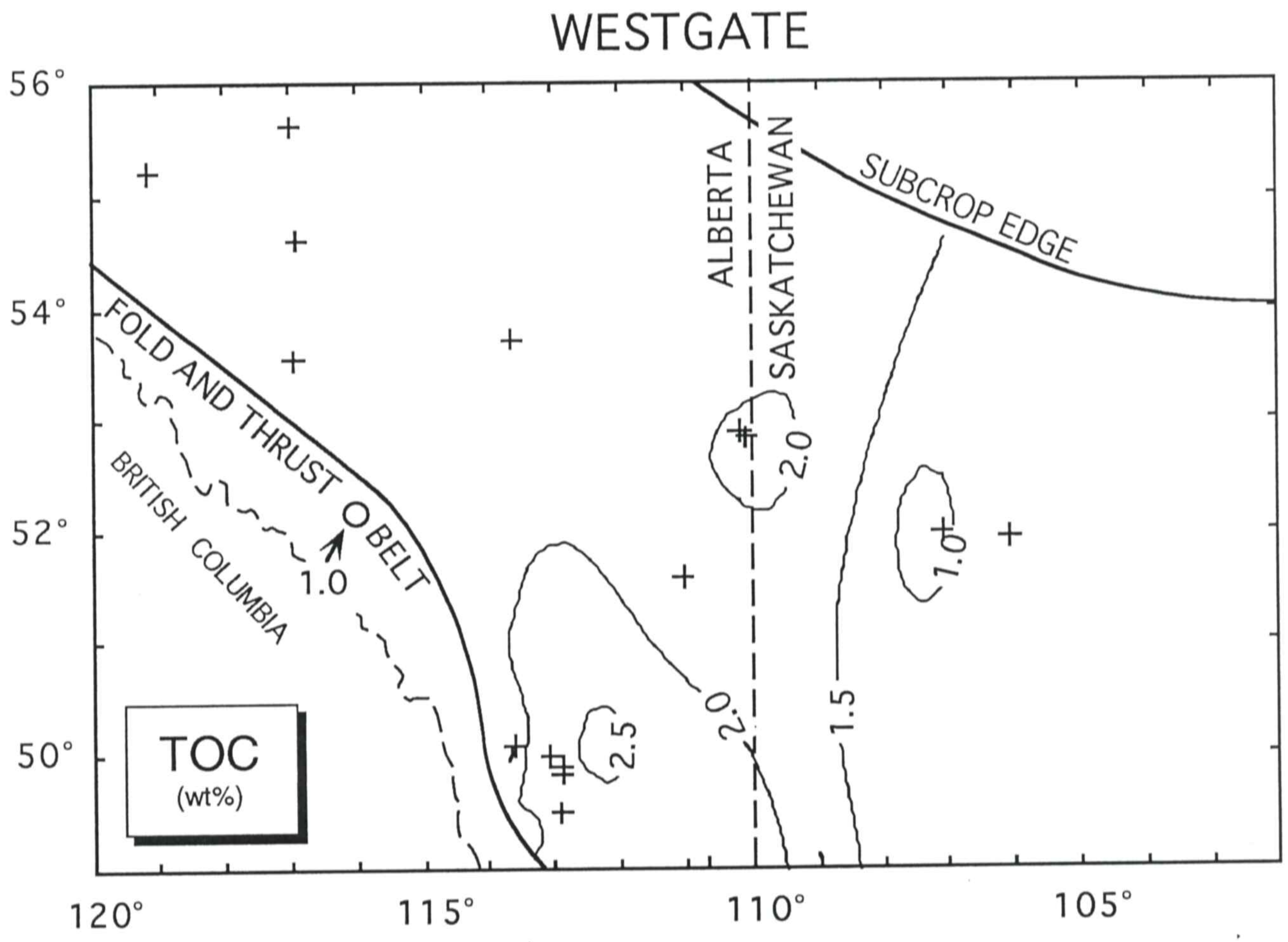


Figure 6. TOC contour map of the Westgate Formation. Contour interval = 0.5 wt%.

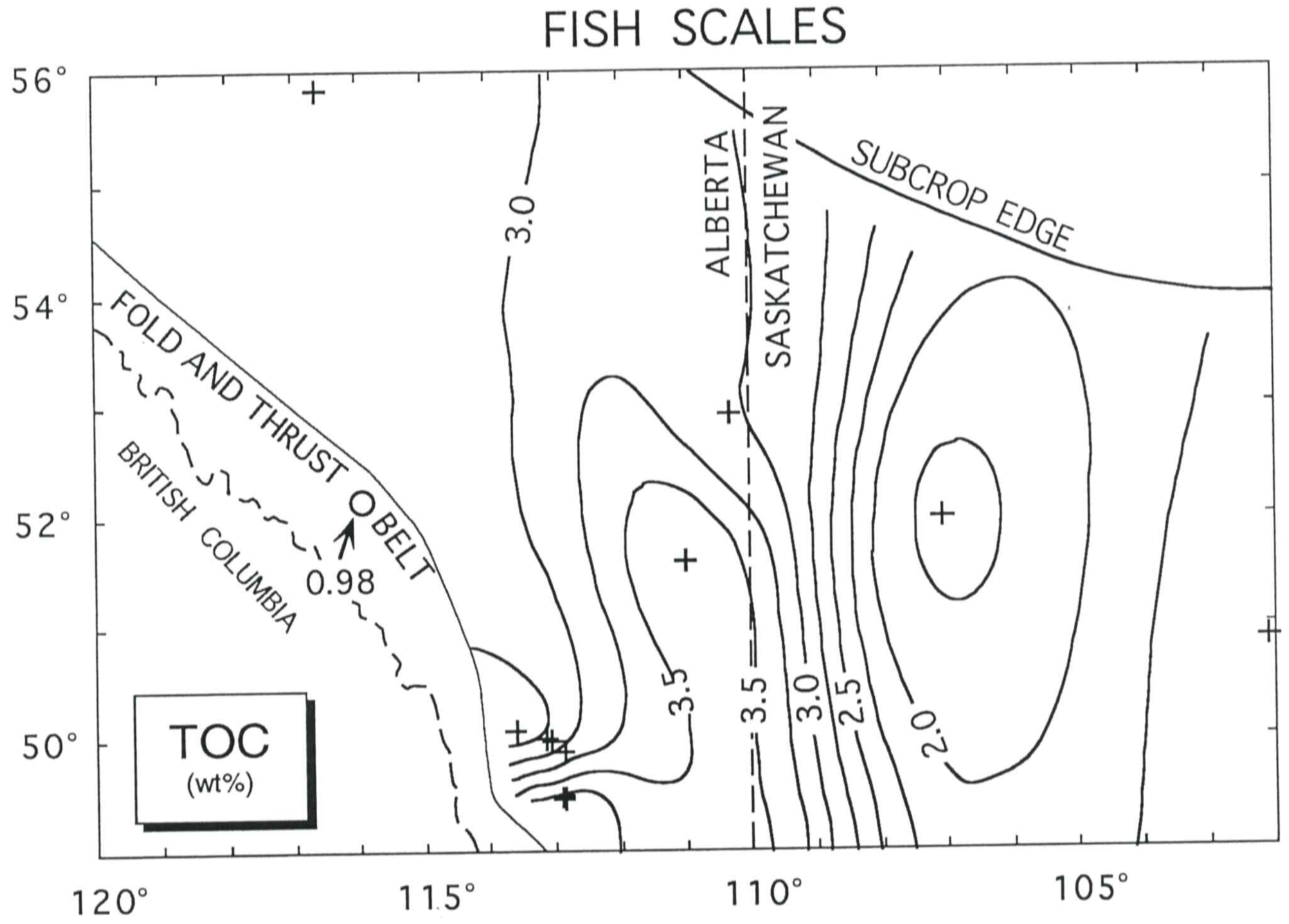


Figure 7. TOC contour map of the Fish Scales Formation. Contour interval = 0.25 wt%.

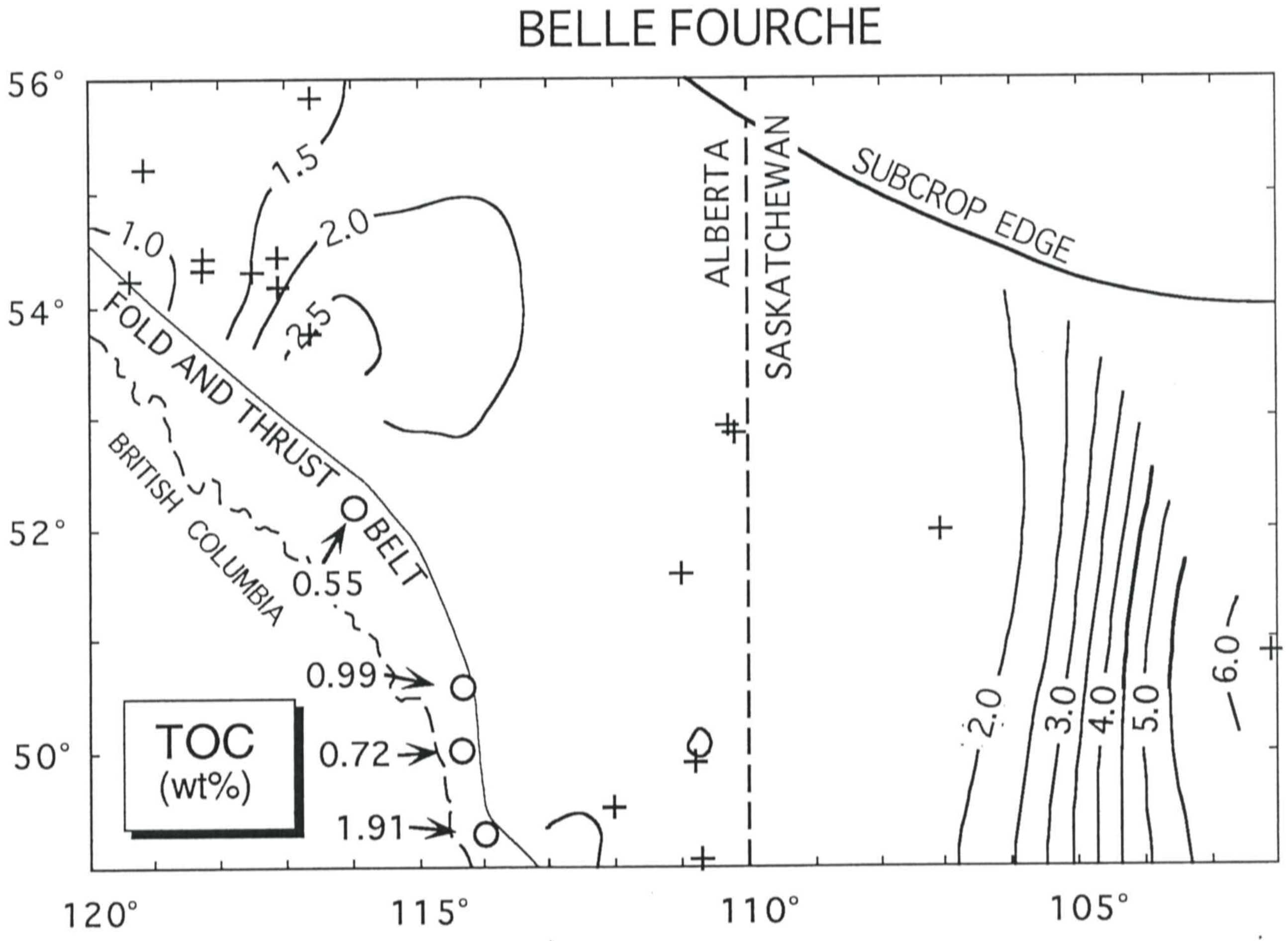


Figure 8. TOC contour map of the Belle Fourche Formation. Contour interval = 0.5 wt%.

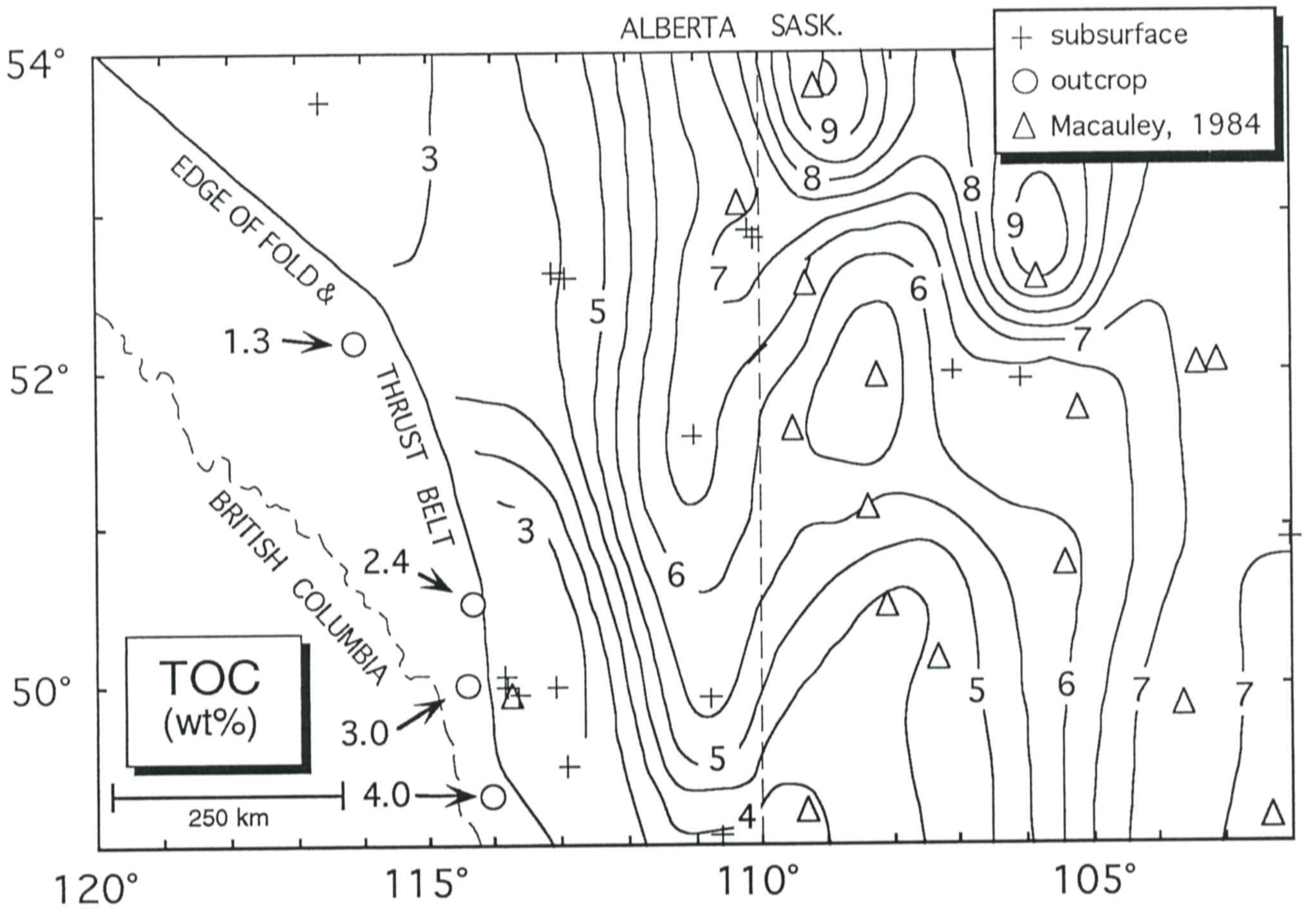


Figure 9. TOC contour map of the Second White Specks Formation. Contour interval = 0.5 wt%. Δ = data from Macauley (1984). O = outcrop locations.

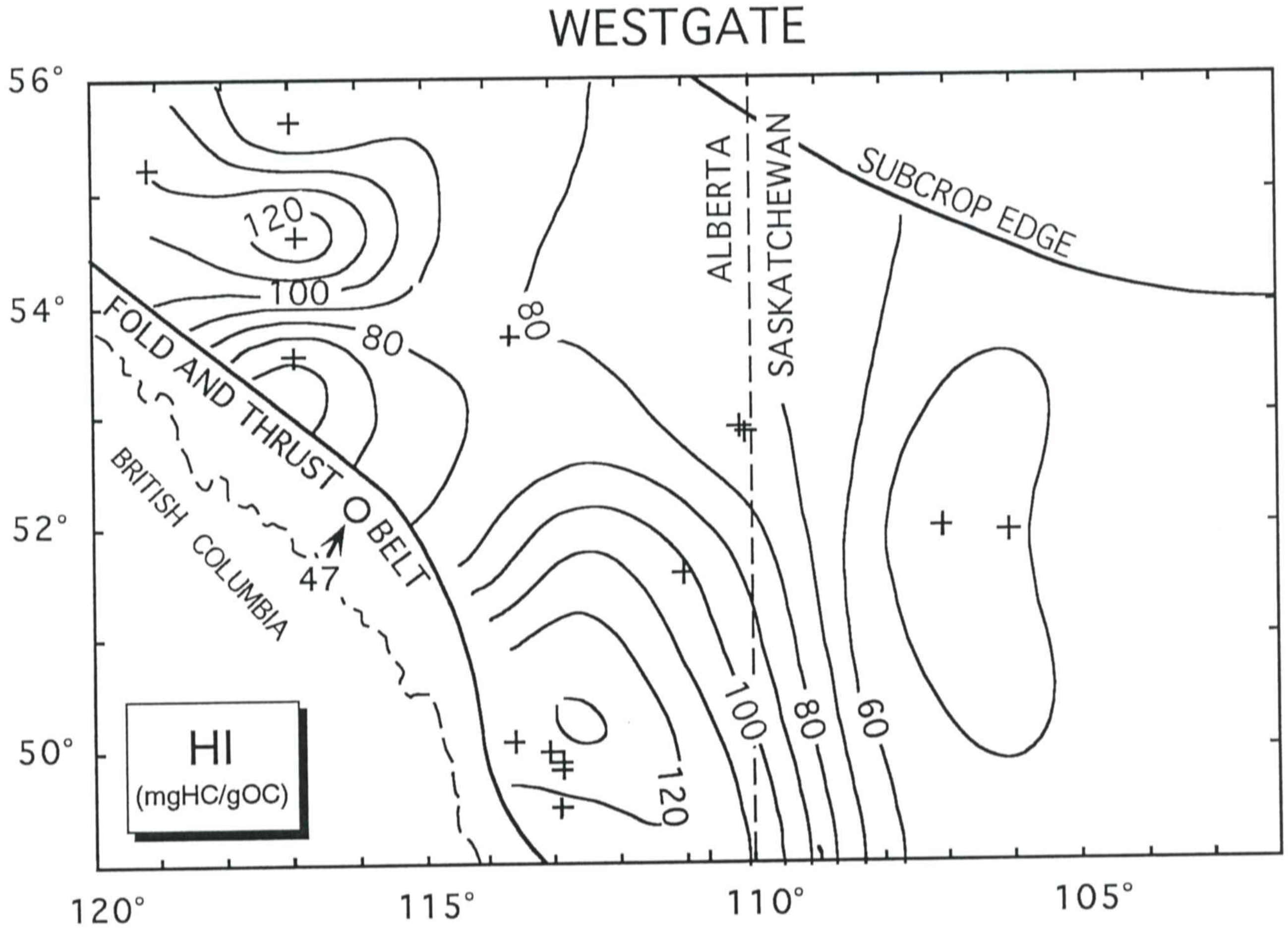


Figure 10. HI contour map of the Westgate Formation. Contour interval = 10 mgHC/gOC.

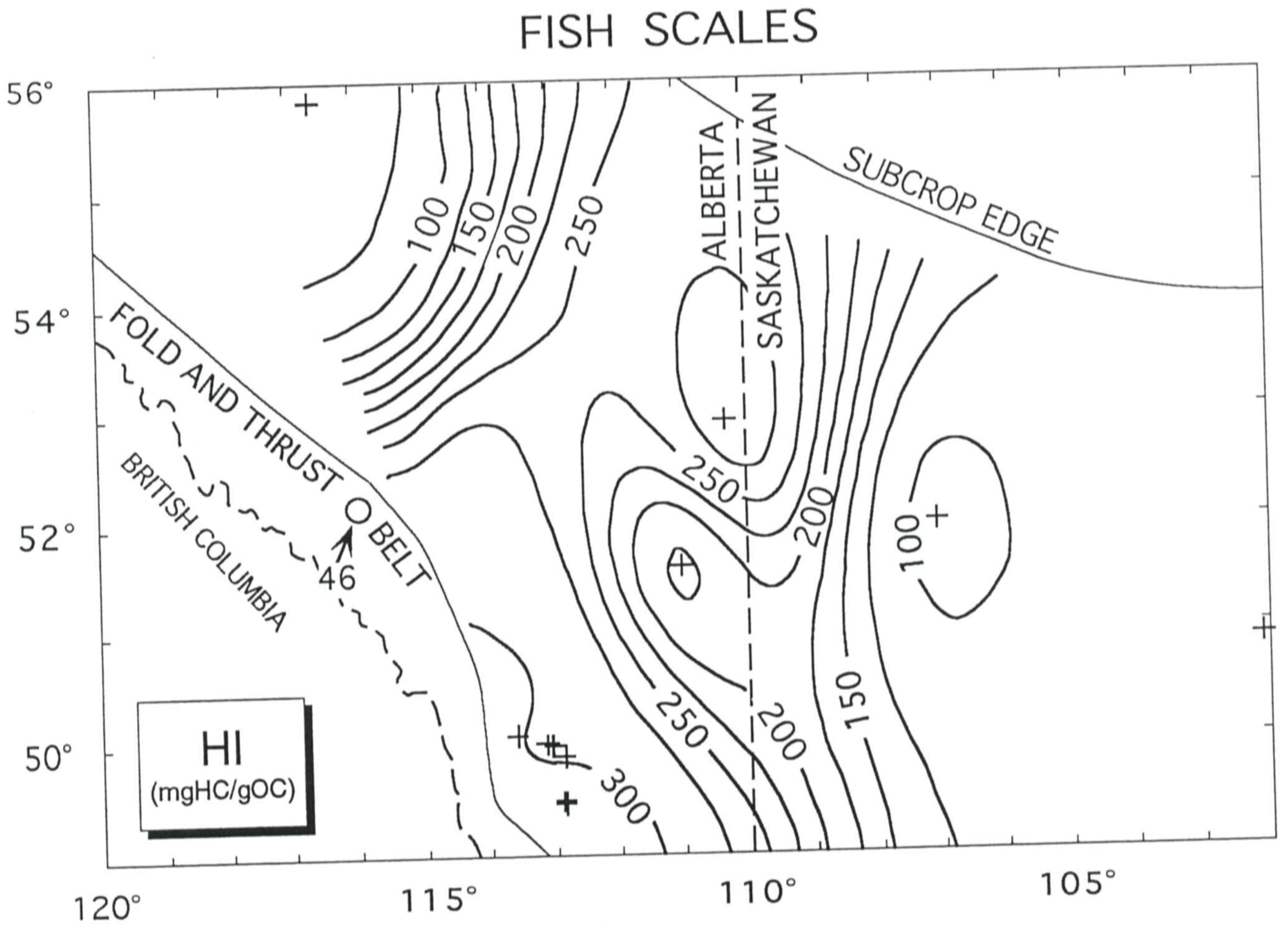


Figure 11. HI contour map of the Fish Scales Formation. Contour interval = 25 mg HC/gOC.

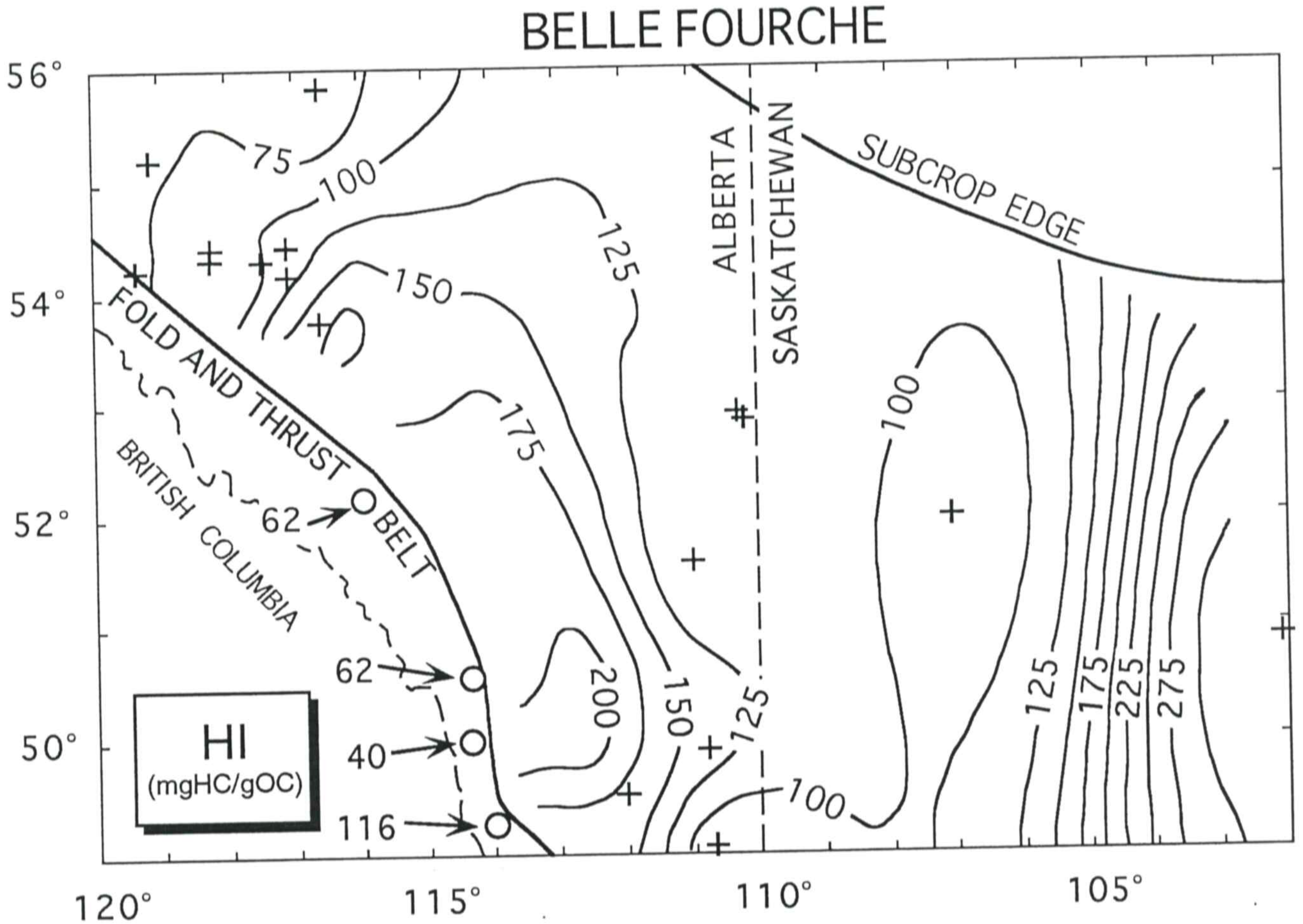


Figure 12. HI contour map of the Belle Fourche Formation. Contour interval = 25 mg HC/gOC.

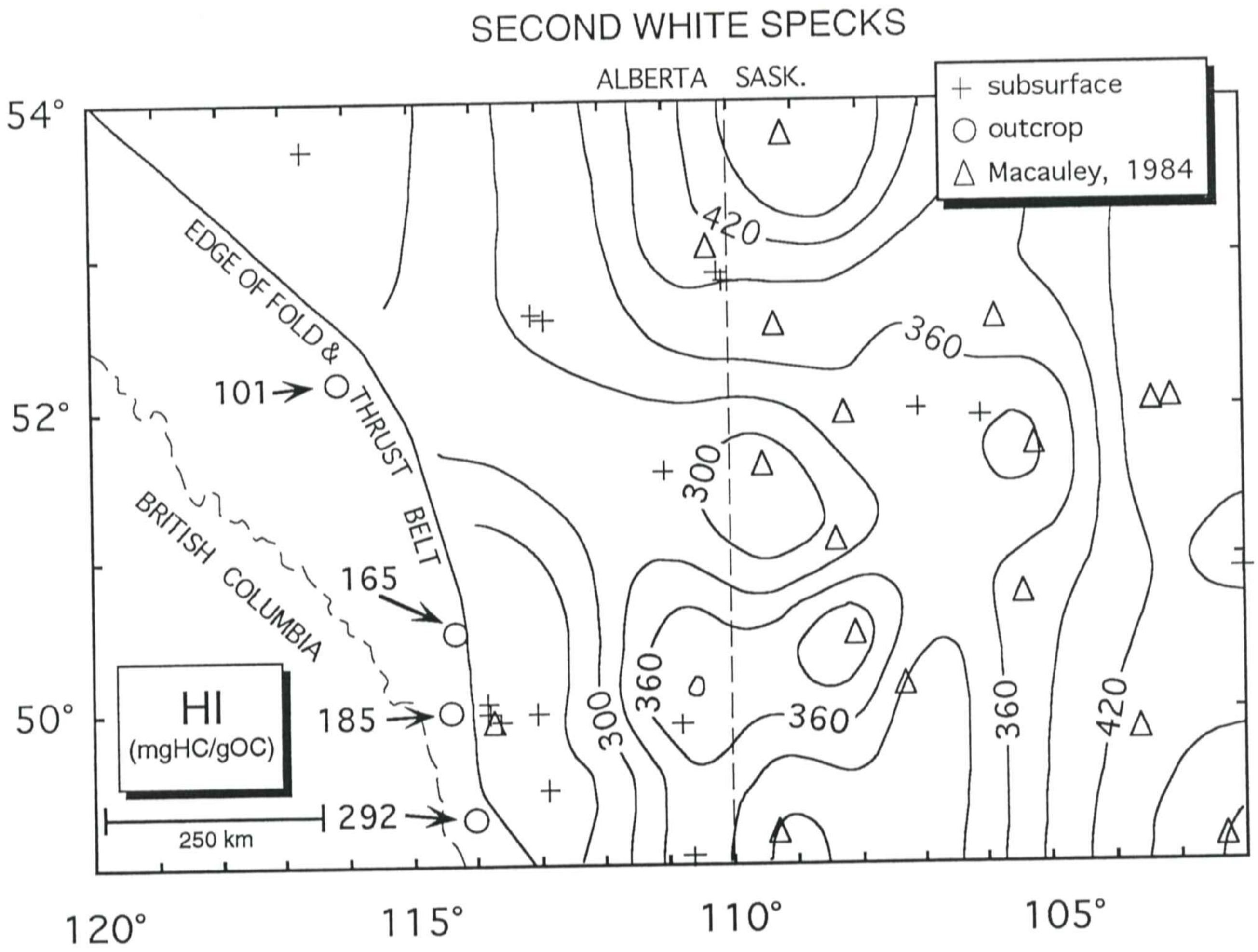


Figure 13. HI contour map of the Second White Specks Formation. Contour interval = 30 mg HC/gOC.

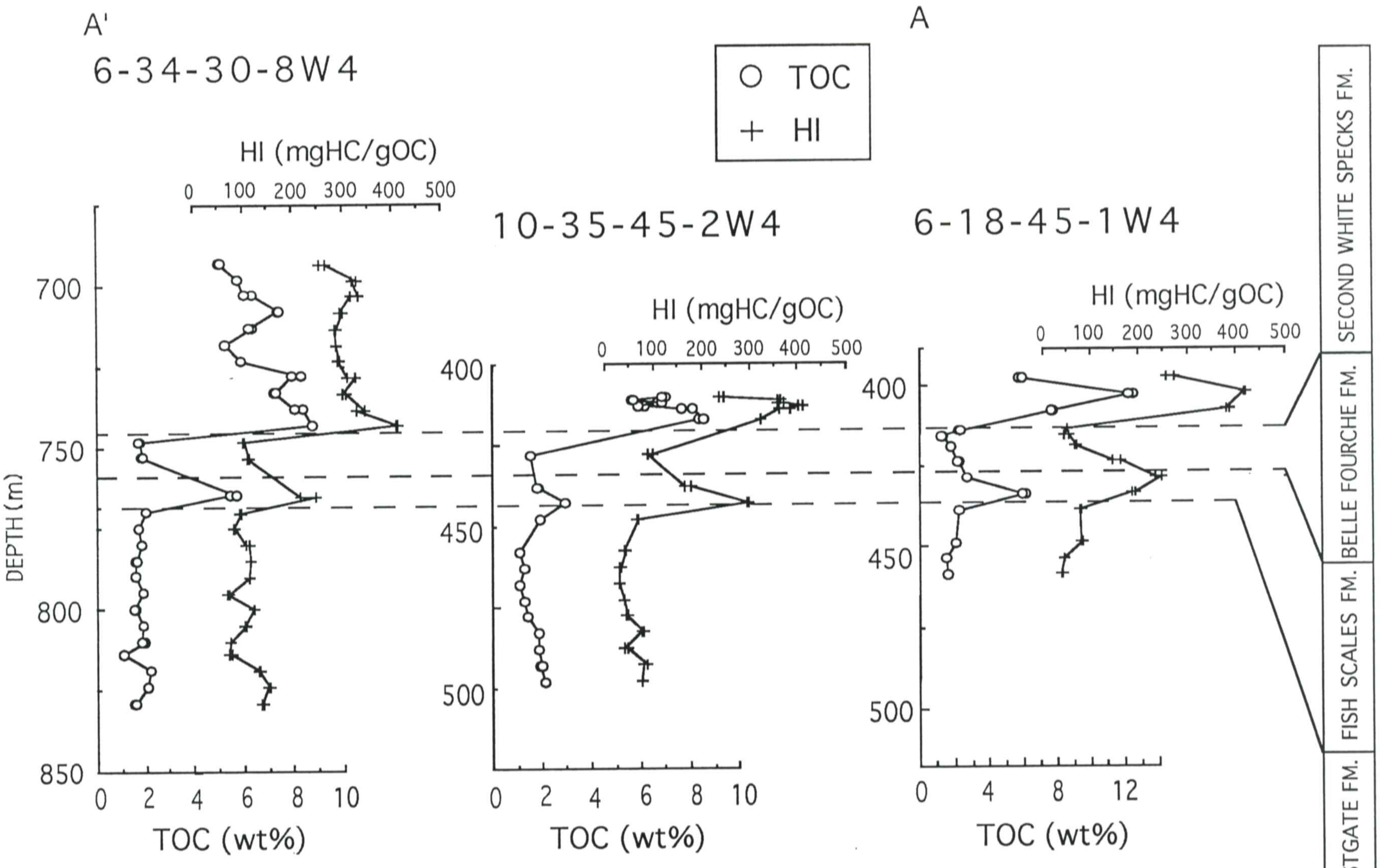


Figure 14. TOC and HI profiles along section A-A' (see Fig. 3 for location).

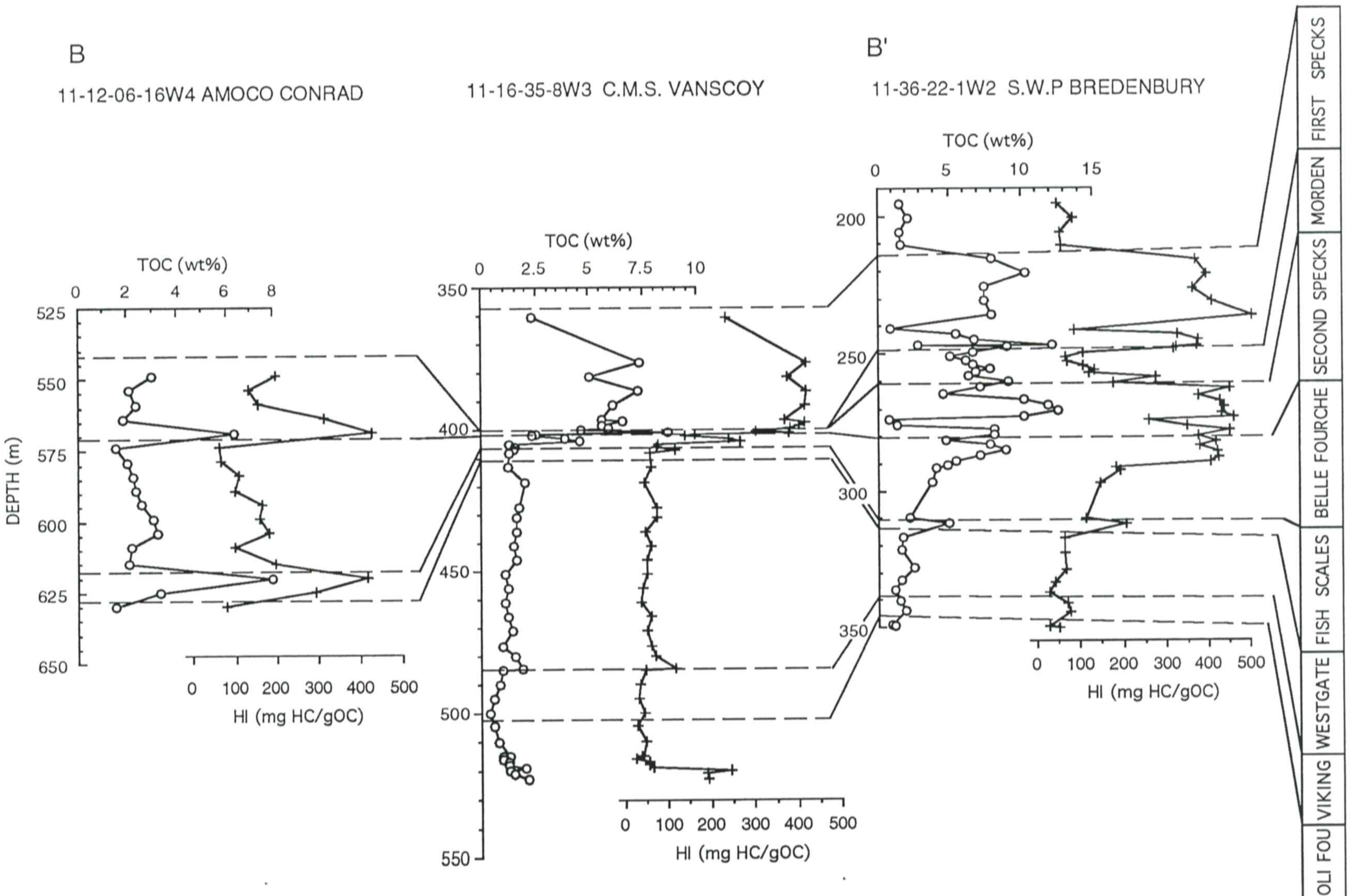


Figure 15. TOC and HI profiles along section B-B' (see Fig. 3 for location).

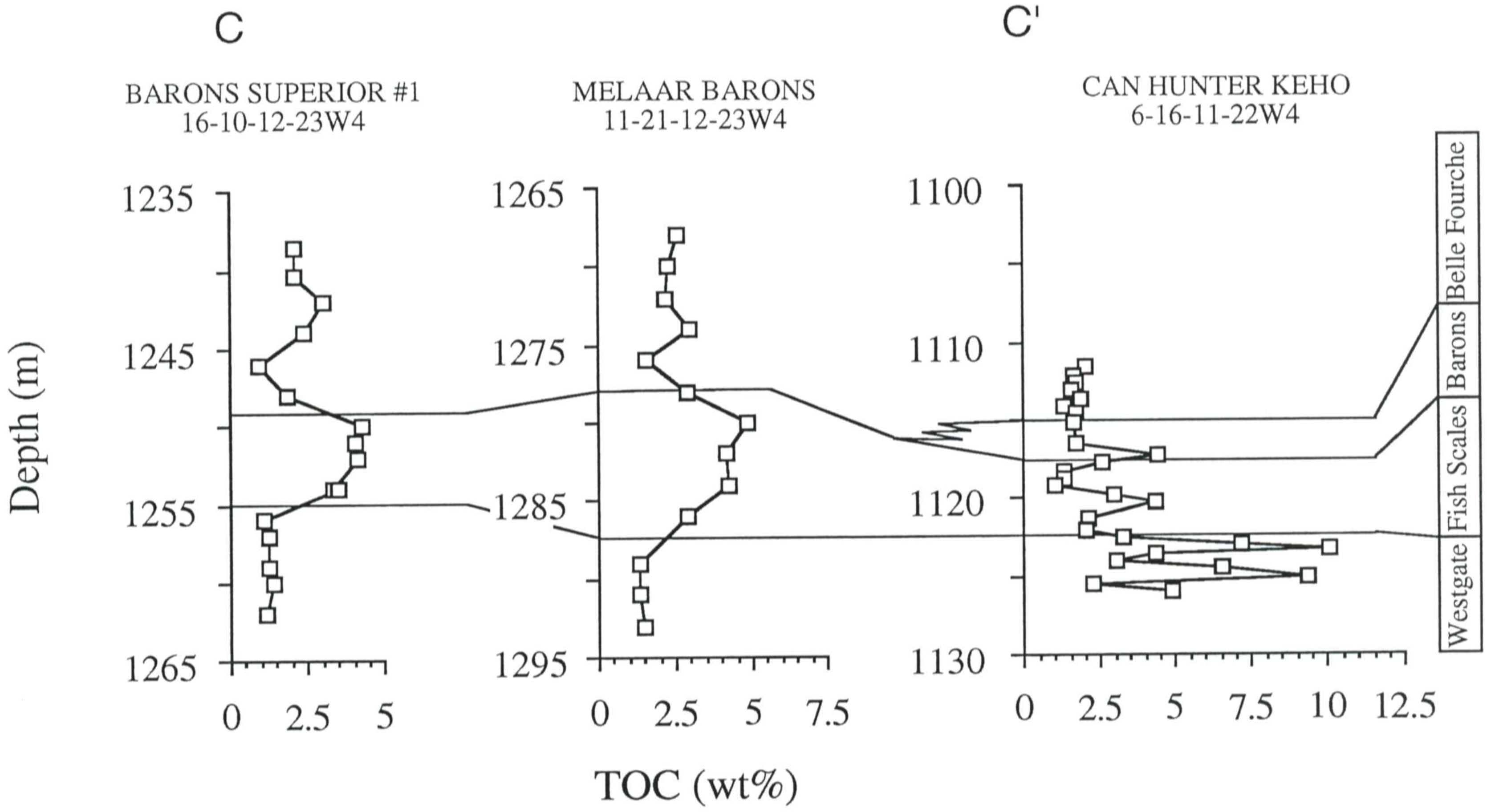


Figure 16. TOC and HI profiles along section C-C' (see Fig. 3 for location).

reflect increased marine organic productivity in the well-developed marine environment that existed in the basin during SWS deposition (Cadrin, 1992; Bloch et al, 1993). SWS organic matter was deposited primarily under anoxic bottom waters (Bloch et al, 1991; Cadrin, 1992). Lower TOC and HI values in the other formations reflect more proximal marine sediments deposited under more shallow-water conditions. These environments were less productive and bottom waters were dominantly dysaerobic.

MATURATION PATTERNS

Maturation, as indicated by the pyrolysis temperature of maximum hydrocarbon generation (T_{max}), generally increases with depth (Fig. 5). Scatter in the data results from differential erosion during Tertiary uplift and variable mixtures of OM types. On a basinal scale, this translates into an east to west increase in maturation (Figs. 17-20). The onset of oil generation is generally considered to begin when T_{max} values reach 435 °C (Tissot and Welte, 1984). This isotherm occurs at approximately 114° Longitude in the Westgate and Belle Fourche formations and further to the west, at about 115 ° Longitude, for the SWS. The data for the Fish Scales is too scattered to draw meaningful conclusions on a basinal scale, but in general, Fish Scales data is compatible with the other formations.

The occurrence of lower T_{max} values at equivalent depth in the SWS (Fig. 5d) suggests that oil generation may begin before the 435 °C "threshold" is reached. Snowdon (pers. comm.) suggested that this "suppression" (lower T_{max} values at equivalent depth) may be related to a high sulphur content of the SWS organic matter, similar to that documented in the Monterey Formation (Orr,

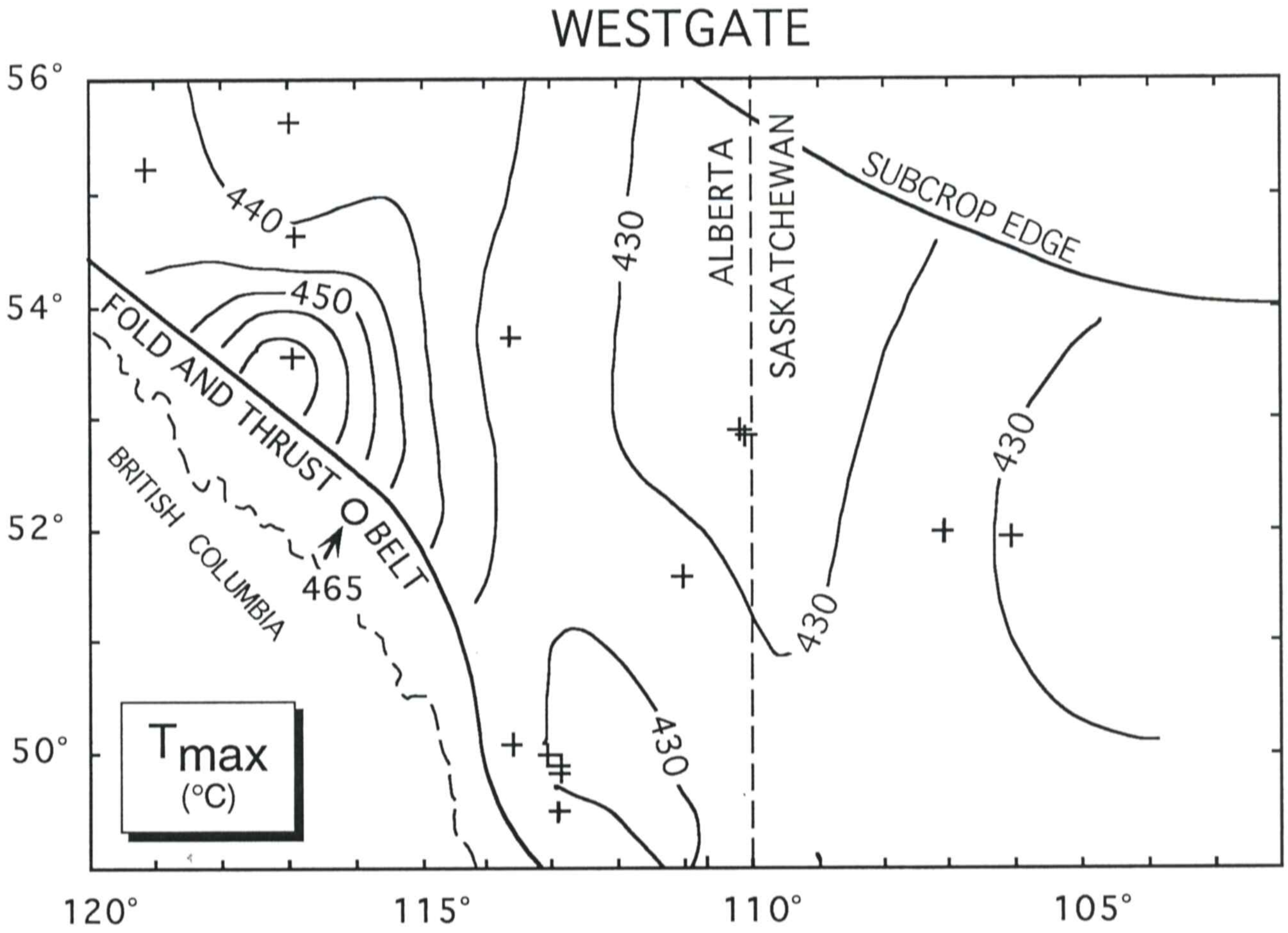


Figure 17. T_{max} contour map of the Westgate Formation. Contour interval = 10 °C.

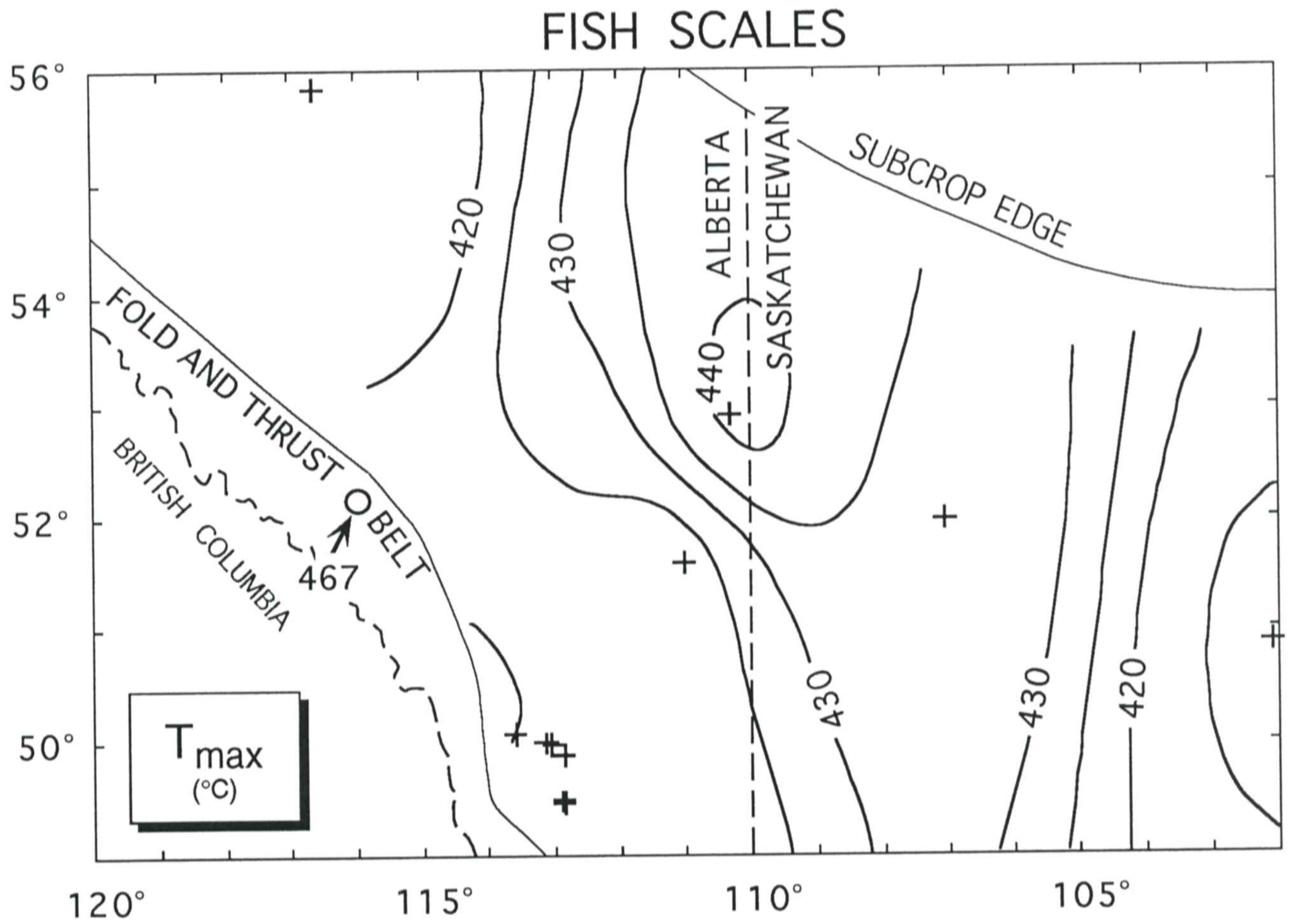


Figure 18. T_{max} contour map of the Fish Scales Formation. Contour interval = 5 °C.

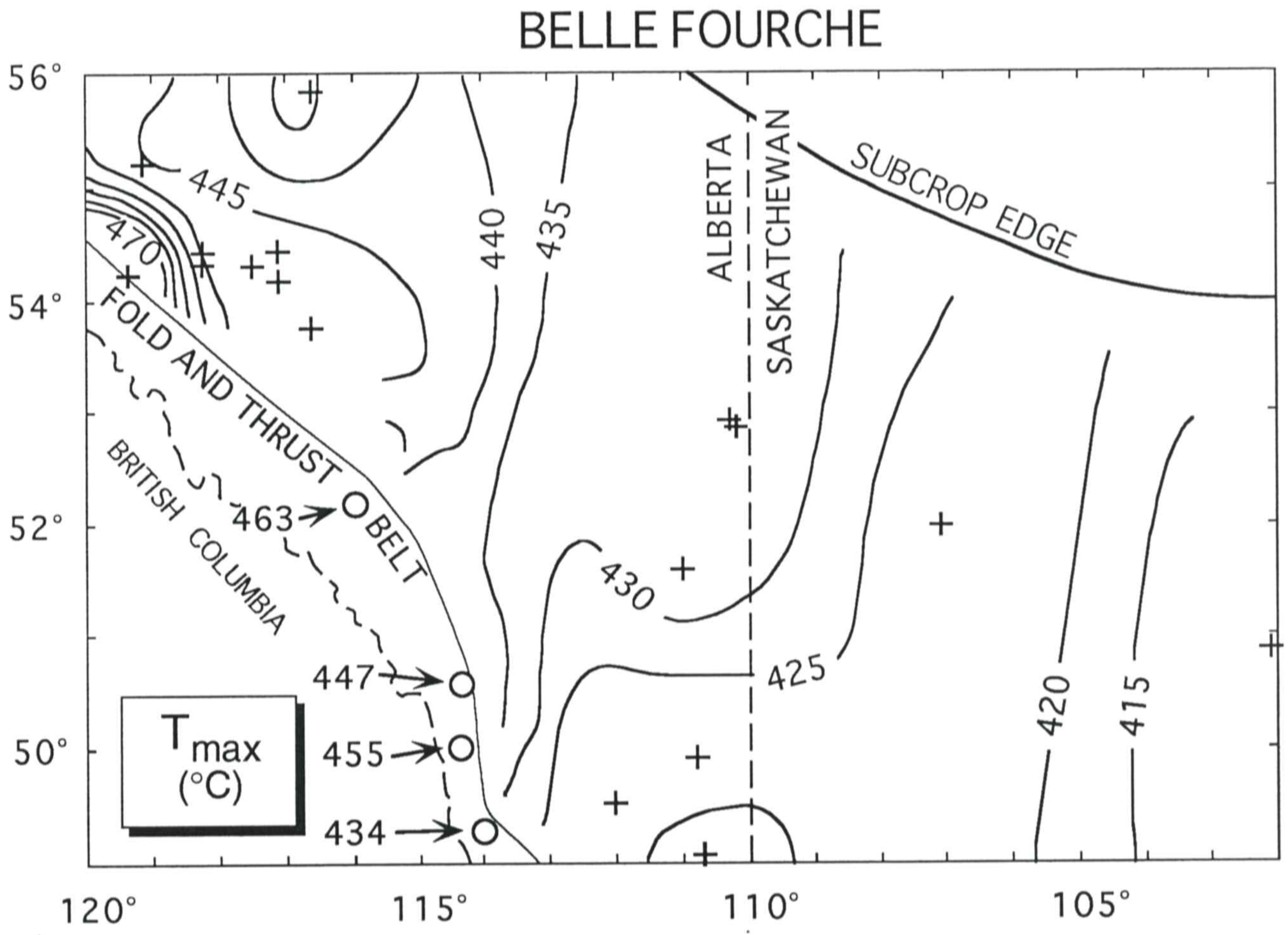


Figure 19. T_{max} contour map of the Belle Fourche Formation. Contour interval = 5 °C.

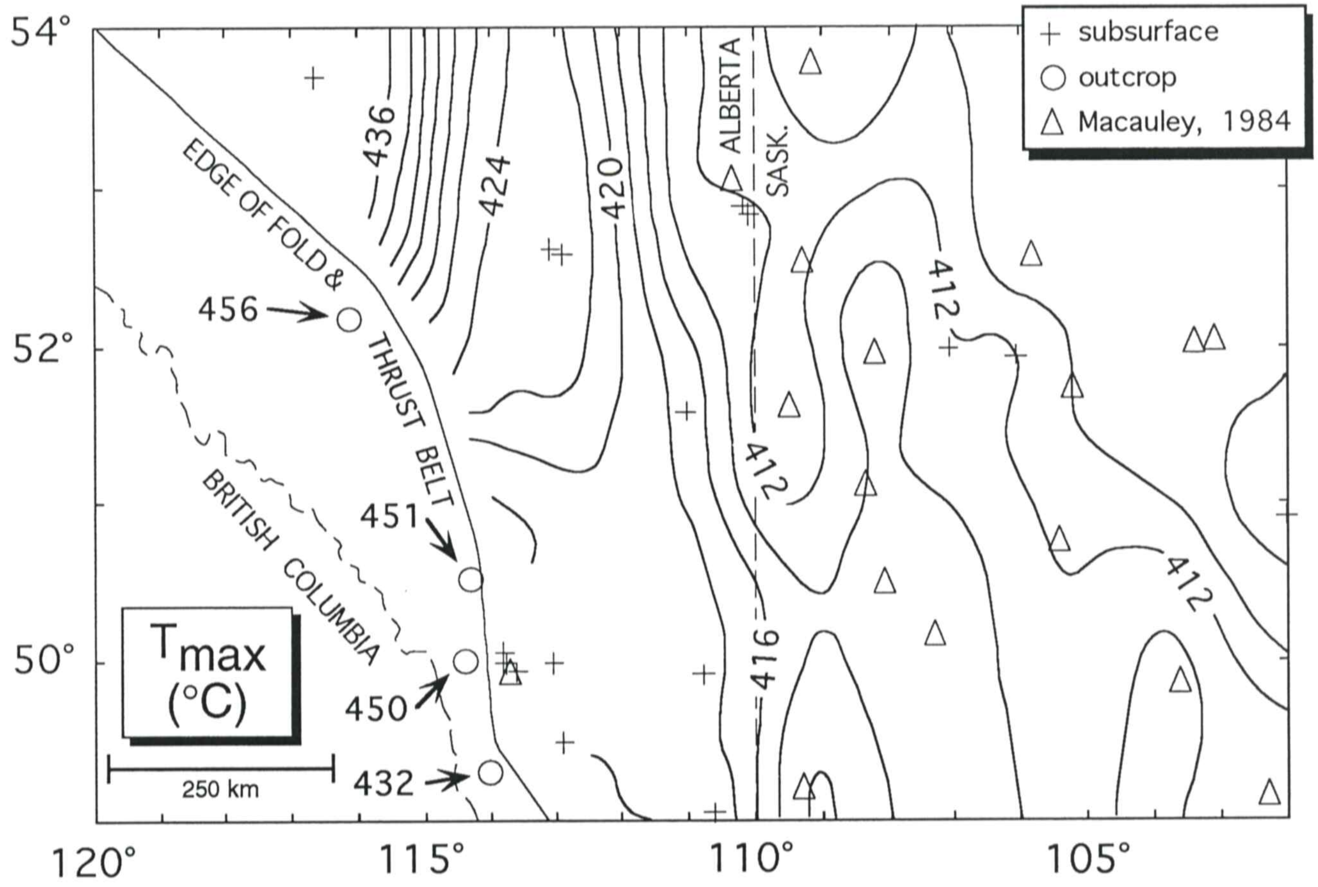


Figure 20. T_{max} contour map of the Second White Specks Formation. Contour interval = 2 °C. Outcrop values are not contoured.

1986; Baskin and Peters, 1992; Zaback and Pratt, 1992). However, high sulphur in organic matter has not been documented in the SWS. Further, sulphur incorporation into organic matter during early diagenesis occurs in iron-limited sediments (Singinghe Damste and de Leeuw, 1989) and the SWS is generally not iron-limited (Bloch et al, 1993). Alternatively, T_{max} suppression in the SWS may result from the absence of refractory Type III or IV organic matter, which has higher T_{max} values (Peters, 1986). This "suppression" appears to be about 10 °C (Fig. 5) and, if oil generation is occurring at lower temperatures, then a much larger volume of SWS sediment is in the oil window (Fig. 20).

The basinal scale data do not show the rapid increase in maturation just to the east of the fold and thrust belt in southwestern Alberta. Here, T_{max} values may increase by 15 to 20 °C over five Townships (Fig. 21), a lateral distance of approximately 50 km. Steep maturation gradients are present in this hinge zone because of the increased burial depth that results from loading by the Rocky Mountains directly to the west. Tectonically induced plunge in this zone also increases the potential for fracturing (Mallory, 1977).

DISCUSSION

Depositional Controls on Hydrocarbon Distribution

Where Colorado Group sediments are immature ($T_{max} < 435$ °C), the distribution of OM is controlled by paleoenvironmental conditions and depositional processes. The entire Albian to Turonian interval east of approximately 114 ° Longitude may be classified as a potential source rock with significant internal variability. Isopleths generally trend north -south. This is, in part, an artifact of the location of the sample control points that trend east - west. However, the north - south trends shown by the data are consistent with facies

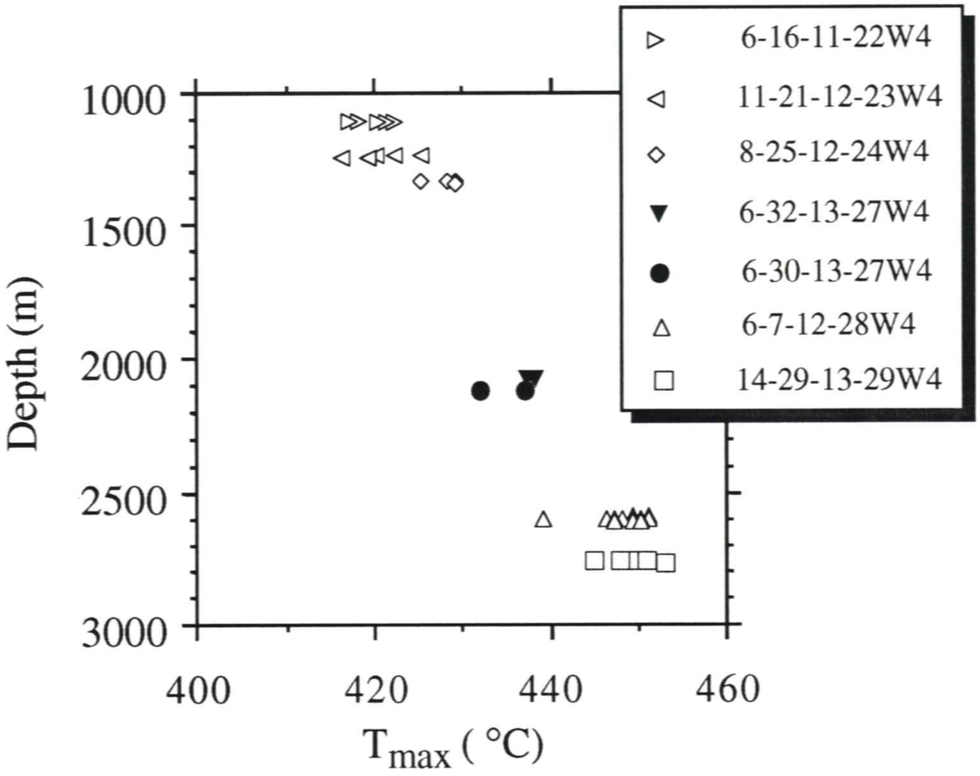


Figure 21. T_{max} versus depth trend of Belle Fourche (open symbols) and Westgate (filled symbols) formations just west of the Keho Lake area (see Fig. 3 for location).

models of the Interior Seaway (Kauffman, 1977) that indicate a north - south strike for basinal facies that, to a large degree, parallel paleoshorelines.

The persistence of low HI values in central Saskatchewan is suggestive of a paleohigh in that area. However, the increased thickness of the Westgate Formation in the C.M.S. Vanscoy well (Fig. 15) indicates a depocentre from which this formation thins to the east (rapidly) and the west. The thinning of the overlying units (Fish Scales, Belle Fourche, and SWS) in this well suggest localized uplift in this area sometime in the late Albian. The Morden Formation is not present in this area, and the Santonian First White Speckled Shale lies unconformably upon the SWS, resulting in the single Speckled Shale of central Saskatchewan (Caldwell et al, 1978). This stratigraphic package, in contrast to those to the east and west, suggest the development of a localized topographic high in central Saskatchewan that developed over perhaps 2 my in the late Albian. The cause of this basin-floor uplift remains elusive, but recent work (Leckie and Kjarsgaard, pers comm.) has documented the occurrence of kimberlites in central Saskatchewan that were emplaced approximately 95 Ma. The complex internal geometry and compositional variability of this marine shale sequence indicate that the Cretaceous foreland basin was a dynamic depositional system and that source-rocks may be much more heterogeneous than previously recognized.

The SWS east of 114° Longitude is a potential source-rock and is the source of biogenic gas produced in some parts of southern Saskatchewan (Stasiuk and Goodarzi, 1988). The Westgate, Belle Fourche and Fish Scales formations are also potential source rocks, but of a lesser quality. The greater abundance of Type III OM indicates that these formations are more gas prone.

Maturation Effects

Primary (depositional) heterogeneous OM distribution is affected by maturation and diagenetic overprinting west of 114 ° Longitude. The ratio of volatile hydrocarbons to the total hydrocarbons (S1/(S1+S2)) generated during pyrolysis, commonly called the production index (PI), provides information about the source of hydrocarbons within a sample and can discriminate between locally generated and migrated hydrocarbons or contamination.

Figures 22 to 25 show the PI (S1/(S1+S2)) plotted against T_{max} and depth for the four formations. PI values between 0.1 and 0.4 generally define the zone of oil generation (Tissot and Welte, 1984; Peters, 1986). On a plot of PI versus T_{max}, immature samples will plot in an area confined to values of < 0.1 and 435 °C, respectively, and mature samples will plot at greater values. The Belle Fourche (Fig. 24) and SWS (Fig. 25) formations show this relationship fairly well. However, in the Westgate Formation, a large number of immature samples plot at PI values greater than 0.1 (Fig. 22A). These samples either contain migrated hydrocarbons or are contaminated with drilling lubricants.

There are a large number of samples from the Amoco Youngstown B-1 well (Table 1) at approximately 700 m depth in both the Westgate and SWS formations that are contaminated with drilling lubricant. This is confirmed by GC-GCMS data (Paul Brooks, per comm.). Within the Westgate Formation, the remainder of samples with T_{max} less than 435 °C and PI greater than 0.1 primarily are from 2 cores; the Anderson Husky Roros and Imperial Kathleen #1. In the case of the former, there is no evidence to suggest contamination and the high PI values are attributed to small amounts of migrated hydrocarbons. Many of these sample are from the basal Westgate and the hydrocarbons may have migrated up from the underlying Viking Formation. TOC and HI values are

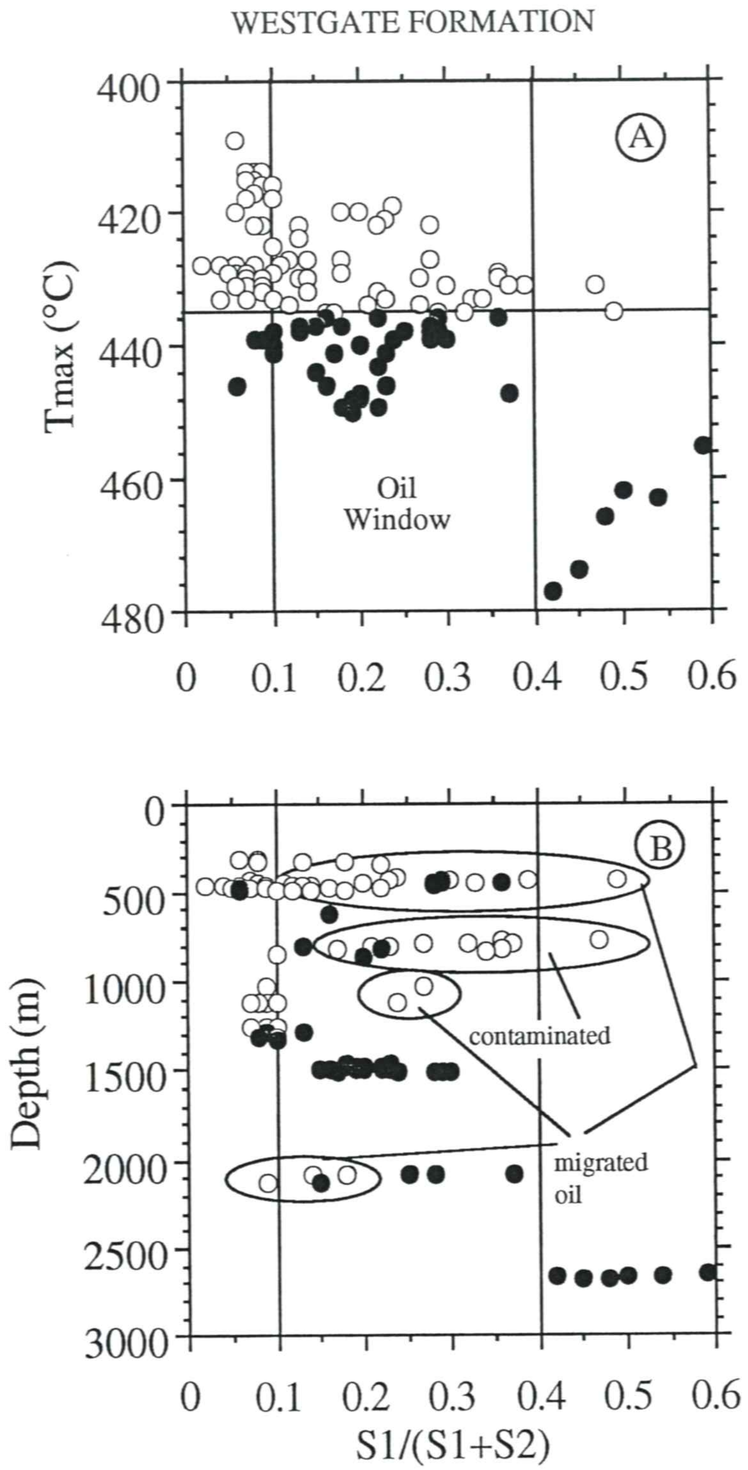


Figure 22. Production index (S1/(S1+S2) versus T_{max} (A) and depth (B) for the Westgate Formation.See text for discussion. Open and filled circles as in Figure 4.

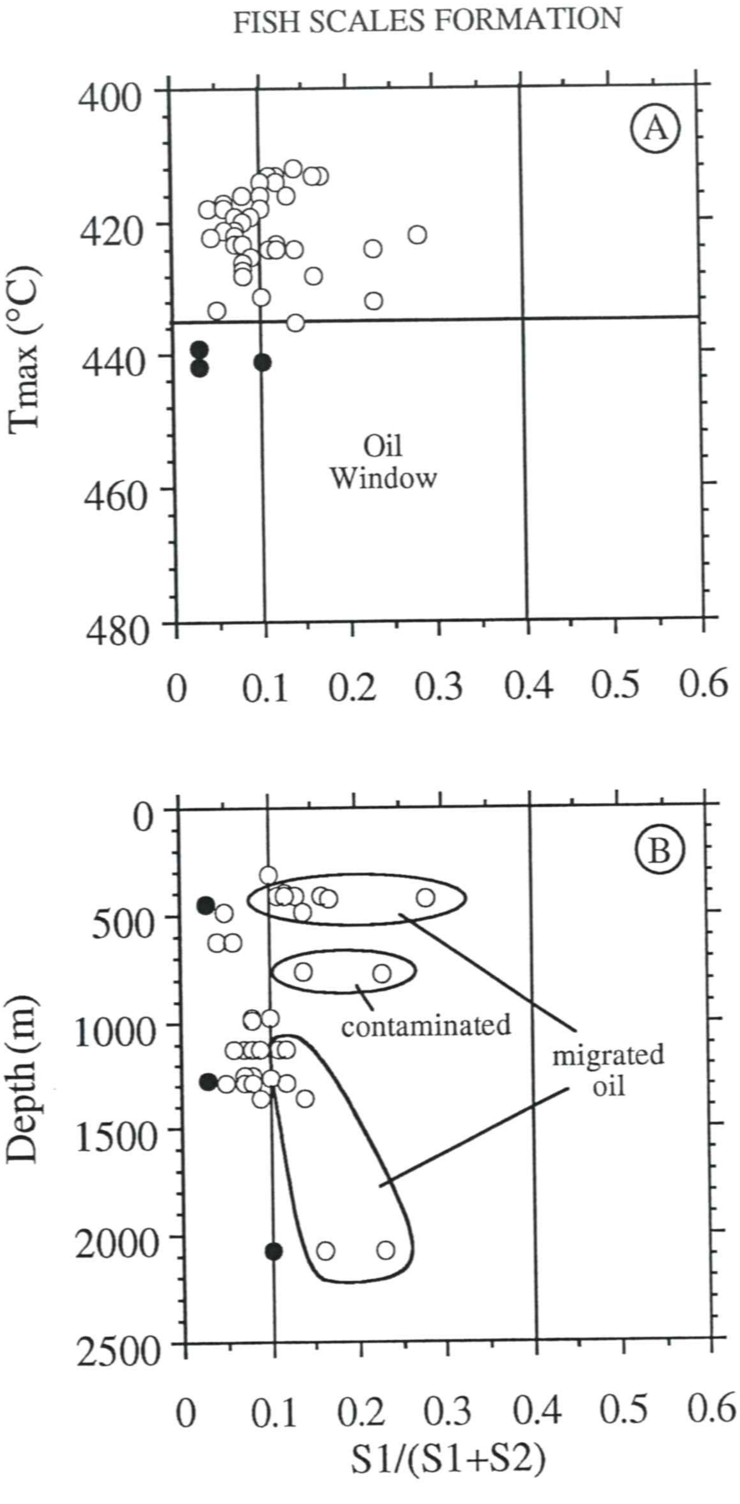


Figure 23. Production index (S1/(S1+S2) versus T_{max} (A) and depth (B) for the Fish Scales Formation.See text for discussion. Open and filled circles as in Figure 4.

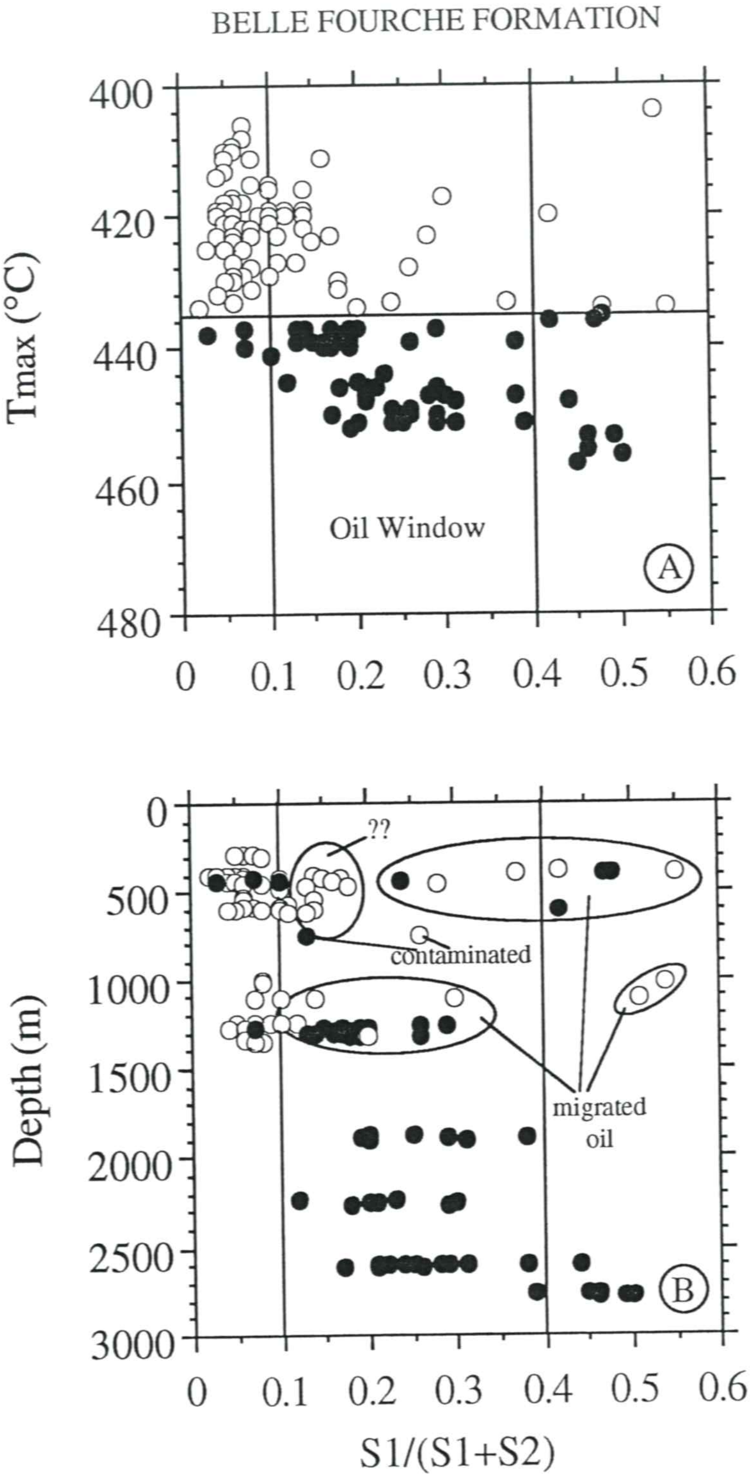


Figure 24. Production index (S1/(S1+S2) versus T_{max} (A) and depth (B) for the Belle Fourche Formation.See text for discussion. Open and filled circles as in Figure 4.

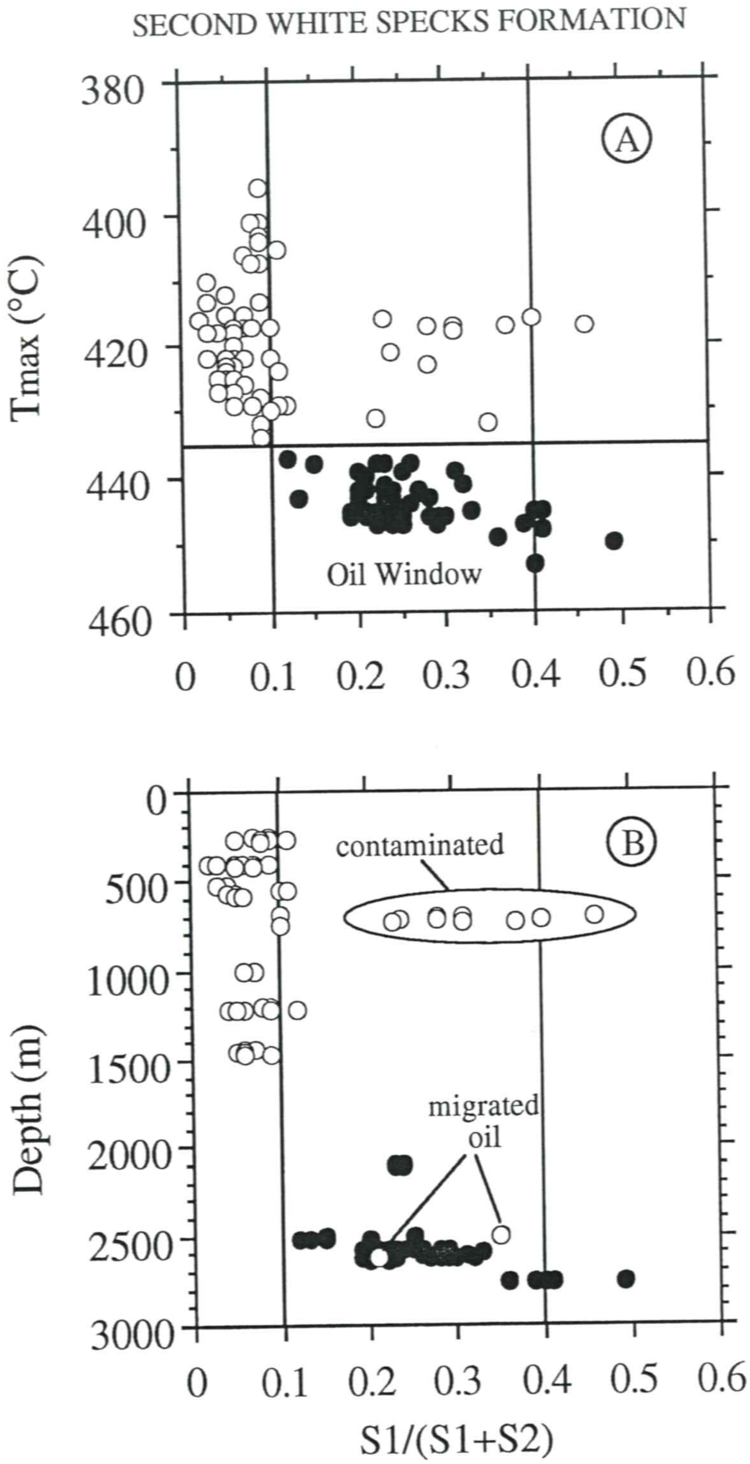


Figure 25. Production index (S1/(S1+S2) versus T_{max} (A) and depth (B) for the Second White Specks Formation.See text for discussion. Open and filled circles as in Figure 4.

slightly elevated in the basal Westgate (Fig. 14), consistent with this interpretation.

The samples from the Imperial Kathleen #1 well, spudded in 1951, are taken from 1 inch diamond drill core. Water-based drilling fluids were used and therefore the possibility of contamination by hydrocarbons is small, but cannot be completely ruled out. However, a nearby well (Imperial Wembley; see Table 1) contains OM that is marginally mature (Tmax to 440 °C) with PI values to about 0.2. Together, these wells form a local trend that is distinct from other wells (Fig. 26) and suggests the presence of migrated hydrocarbons. The amount of migrated oil is small because the TOC (Fig. 8) and HI (Fig. 12) values show no significant increase from average formation values.

Immature samples at depths greater than 1000 m with PI values greater than 0.1 are also anomalous (Fig. 22). The presence of migrated hydrocarbons in mature samples lowers the T_{max} value (Peters, 1986). These samples are from wells located just west of Keho Lake. In these cores, visible oil-staining has been documented, particularly in the Fish Scales Formation. Samples from the same cores characterized as immature occur at depth in the Fish Scales (Fig. 23), Belle Fourche (Fig. 24) and SWS (Fig. 25). These data are interpreted to represent the presence of pervasive migrated oil through the section. Anomalously high TOC and HI values in the Westgate (Figs. 4A and 16) further support this interpretation.

The presence of migrated hydrocarbons in the Keho Lake area, and perhaps in the extreme northwest of the study area, affects regional patterns of hydrocarbon distribution, as shown in the HI and, to a lesser extent, the TOC contour maps. The Westgate (Fig. 6) and Fish Scales (Fig. 7) TOC maps show somewhat higher values and the HI values show a marked increase towards the fold and thrust belt that centers on the Keho Lake area. This is opposite to

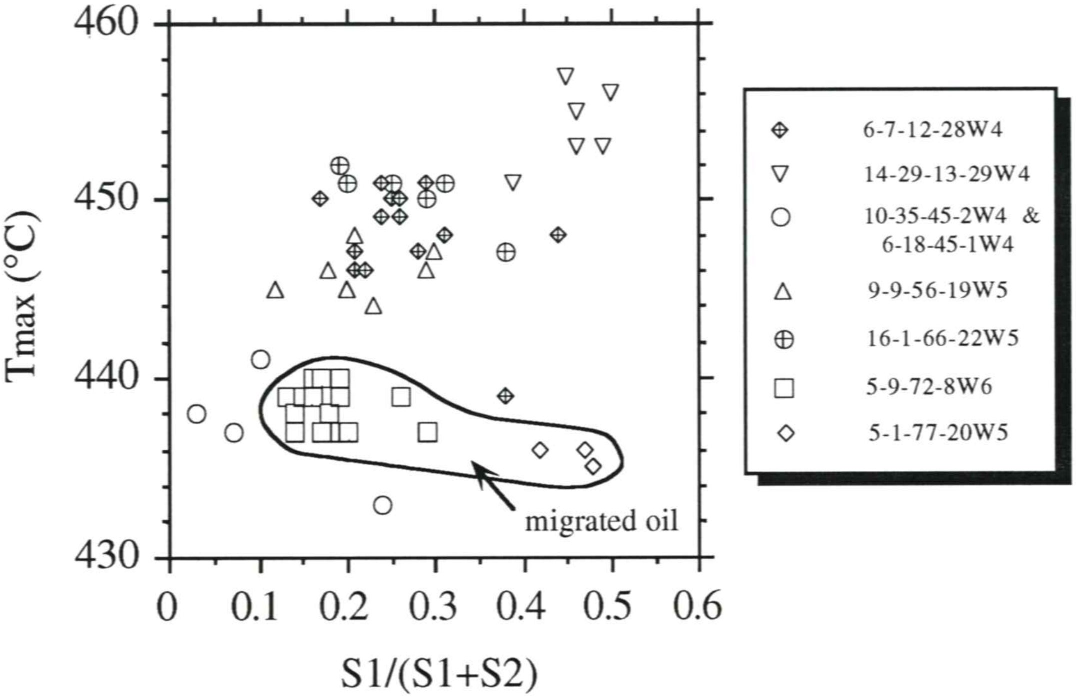


Figure 26. Production Index (S1/(S1+S2)) versus T_{max} for Westgate Formation samples from selected wells. See text for discussion.

"normal" source-rock trends that show a depletion in TOC and HI values with increasing maturity (Burtner and Warner, 1984). This characteristic trend is seen to the west of the fold and thrust belt where there is a distinct south to north increase in maturity (Figs. 19 and 20). The SWS shows a "normal"" source-rock trend, in contrast to the other formations (Figs. 9 and 13), where areas of higher maturity show a loss in hydrocarbon abundance and quality.

The SWS has been identified as an effective source rock(Macauley, 1984; Brooks et al., 1991; Creaney and Allan, 1992) and the regional trends shown herein are consistent with this interpretation. The enhanced stratigraphic resolution employed in this study indicates that migrated hydrocarbons, perhaps sourced from the SWS, have infiltrated other shale units of the Colorado Group. This infiltration is localized areally and stratigraphically, occurring primarily along contacts with more permeable, intercalated sandstones (Barons, Viking Formation) or in siltstone-rich horizons within the shales. The regional patterns of hydrocarbon distribution indicate that migration has occurred, or is occurring, in the area west of Keho Lake and in northwestern Alberta on the southern flank of the Peace River Arch. Both of these areas are adjacent to the fold and thrust belt where maturation indices rapidly increase and most of the studied interval is within the oil window. The updip and cross formation movement of evolved hydrocarbons within the Colorado Group is similar to other source-rock studies that indicate source-rock loss and accumulation of hydrocarbons in more porous and permeable units of basin-fill sediments (Burtner and Warner, 1984; Hagen and Surdam, 1984). The localization of hydrocarbon migration argues against widespread fluid movement through thick sections of generally low porosity and poorly permeable fine-grained sediment. Rather, localized areas of apparent hydrocarbon migration suggest fracture control on migration. The areas identified as containing migrated hydrocarbons are within or adjacent to tectonically disturbed belts where rapid changes in plunge or areas of overthrusting are common. Current production from Colorado Group shales occurs in areas adjacent to the Fold and Thrust Belt where changes are observed in the structural deformation of the basin-fill sediments (Portigal et al., 1989).

MINERALOGY AND RESERVOIR CHARACTERISTICS

The low porosity and permeability of shales result from the high proportion of clay minerals and a dominantly matrix-supported fabric that compacts significantly resulting in very poor reservoir properties. Therefore, economic production generally requires the occurrence of significant fracture porosity and permeability. To develop and sustain a fracture system, shales must behave in a brittle manner. Economic fractured shale reservoirs include the Mancos, Niobrara and Mowry (Mallory, 1977), Monterey (Graham and Williams, 1985), Bakken (Meissner, 1978) and Austin Chalk formations (Fritz et al., 1991). These units contain a high proportion of calcareous or siliceous material that imparts brittle characteristics to the rock. The only unit within the Colorado Group succession that contains considerable amounts of carbonate is the Second White Specks Formation (Table 2) and this unit is a proven producer (Portigal et al., 1989). Within the newly proposed stratigraphic nomenclature for the Colorado Group, considerable production identified to come from the "Second White Specks" actually comes from the siltstone interval in the uppermost Belle Fourche Formation. The relative importance of fracture porosity in production from calcareous and silt-rich intervals is not well understood but the variable and localized nature of "Second White Specks" production suggests that fracture porosity is a significant component. The distinct lithological (high proportion of quartz silt in the Belle Fourche) and mineralogical (calcareous nature of the Second White Specks) characteristics of the production interval within the Colorado Group suggest that mineralogy must be a factor in economic production from these units.

The relative effects of depositional and diagenetic controls on mineralogy and resulting rheological properties of Colorado Group shales are difficult to discern. Caritat et al (in press) demonstrated that diagenetic trends in mineralogy mimic depositional signals in the Belle Fourche Formation and this is probably applicable to other Colorado Group shale units. In the Belle Fourche, the illite content of I/S increases from east to west concomitant with an increase in maturity. However, the western portion of the basin is also the most proximal to the deltaic sediments of the equivalent Dunvegan Formation. These sediments are expected to contain a higher proportion of detrital illite as well as coarser grained quartz and feldspars. Therefore, depositional as well as diagenetic controls on mineralogy must be considered.

It is recognized from simple mass balance considerations that the formation of illite or illitic I/S from smectite or smectitic I/S results in the production of excess silica:

$$\begin{gathered}\mathrm{Na_{.28}K_{.18}Ca_{.04}[Al_{1.36}Fe^{3+}{}_{.34}Mg_{.33}]Si_{3.69}Al_{.31}O_{10}(OH)_2 + 0.4K^+ + 0.37Al^{3+}} \longrightarrow \\ \mathrm{Na_{.28}K_{.58}Ca_{.04}[Al_{1.42}Fe^{3+}{}_{.20}Mg_{.33}]Si_{3.38}Al_{.62}O_{10}(OH)_2 + 0.31Si^{4+} + 0.14\,Fe^{3+}} \qquad (1)\end{gathered}$$

as shown by these mixed-layer clay compositions from the Belle Fourche Formation (Caritat et al, in press). This silica commonly precipitates as fine-grained quartz within the matrix (see Caritat et al, in press; Fig. 10) or may contribute to quartz overgrowths that occur within the shale (Bloch and

Hutcheon, 1992). Other studies have suggested that this silica is exported to adjacent sandstones where it may contribute to quartz cementation (Sibley and Blatt, 1976). The precipitation of authigenic quartz or quartz cement within the shale, however, will contribute to lithification and may enhance the brittle characteristics of the rock. This could be a factor in fracture formation within shales.

Natural fractures are observed in core and outcrop, primarily in the Second White Specks Formation. Significant natural fracturing was found in only one core (Dome et al Claresholm; Table 1). Rubble zones with common slickensides were noted in other cores but the origin of the slickensides and resulting rubble are unclear in many cases. Coring induced fractures are also present (Fig. 27).

Calcite filled fractures are seen in concretionary horizons and are pervasive in some outcrops (Figs. 28-30). The orientation and spacing of the fractures observed in outcrop indicate that they formed as a result of compressive (thrusting) tectonic stress and that the Second White Specks Formation behaved as a cohesive, brittle body with predictable fracture characteristics (Figs.28-30). In contrast, fractures observed in core indicate both brittle and ductile behaviour in response to compressive tectonic stress (Fig. 31). Despite significant annealing in cataclastic zones, some good fracture porosity is preserved (Figs. 31b and c).

Some outcrop (Fig. 29b) and core fracture surfaces show oil-staining. In outcrop, it is not clear whether the oil is locally sourced or migrated from downdip. In the subsurface, however, it is likely that fracture porosity is a critical component of liquid hydrocarbon migration and production in the Second White Specks Formation. It is also important to note that fracturing is observed only in areas where Colorado Group shales are considered mature and therefore have

Figure 27. A) coring induced petal-centerline fractures (Kulander et al., 1990) in Second White Specks Formation. B) induced fracture surface showing slickensides (arrow).

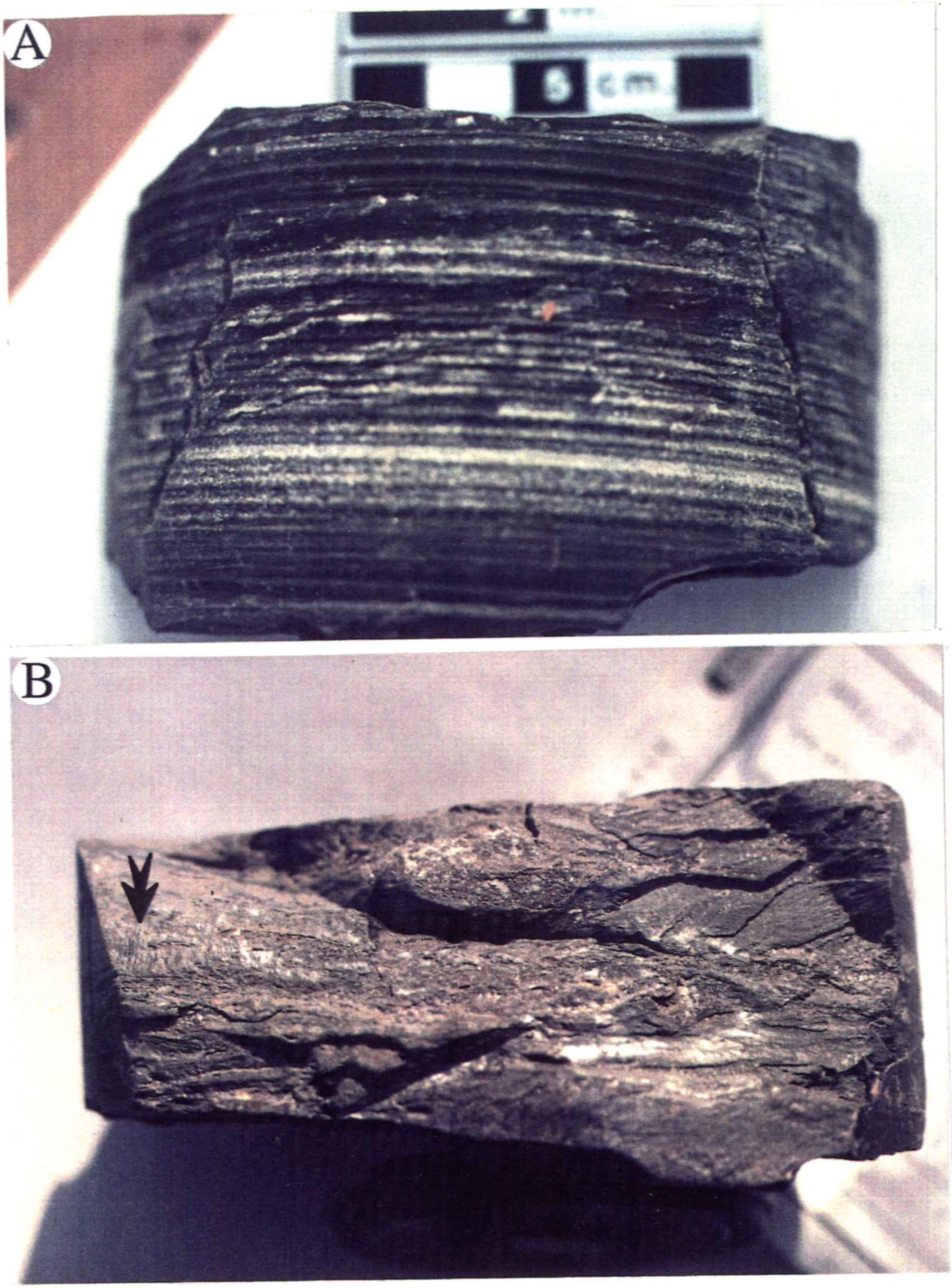
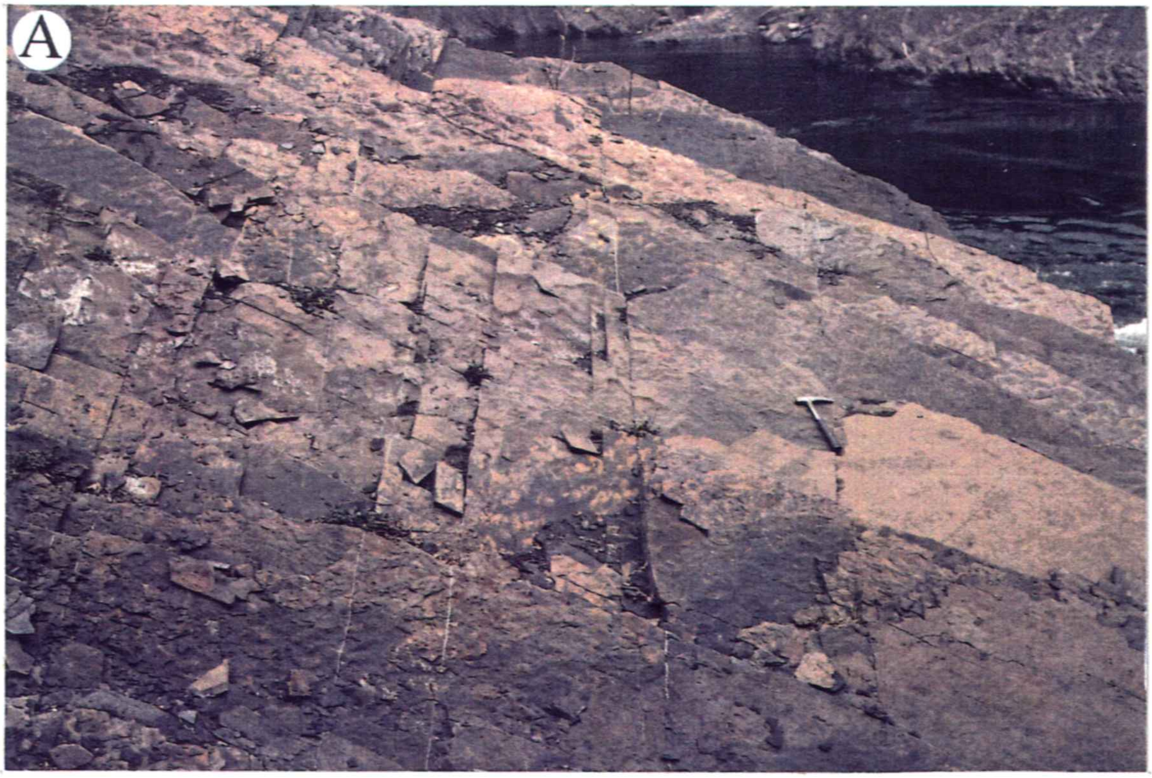

A
5 cm.
B

Figure 28. A) Parallel fracture sets in the Jumping Pound Sandstone that directly overlies the Second White Specks Formation, Highwood River outcrop (see Table 1 for location). B) Close-up of A shows clearly that bedding-perpendicular fractures are filled with calcite. Hammer (33 cm in length) is oriented parallel to direction of thrusting (σ_1 = principal compressive stress).


A


B

Figure 29. A) Calcite-filled, bedding-perpendicular fractures (below notebook) and bedding-parallel fractures (above notebook). Note difference in fracture set spacing. Notebook is 21 cm in length. Highwood River outcrop (see Table 1 for location).B) Oil stains on fresh fracture surface. Highwood River outcrop.


B
A

Figure 30. A) Bedding perpendicular calcite-filled fractures. Strata at this location are complexly folded and these fractures result from folding-inducd extension. Mill Creek Bridge outcrop (see Table 1 for location). B) Close up of fracture fill cement in A. Thin laminations give way to coarse spar suggesting successive cementation events in response to increased fracture volume. Note small Inoceramid impression (arrow).

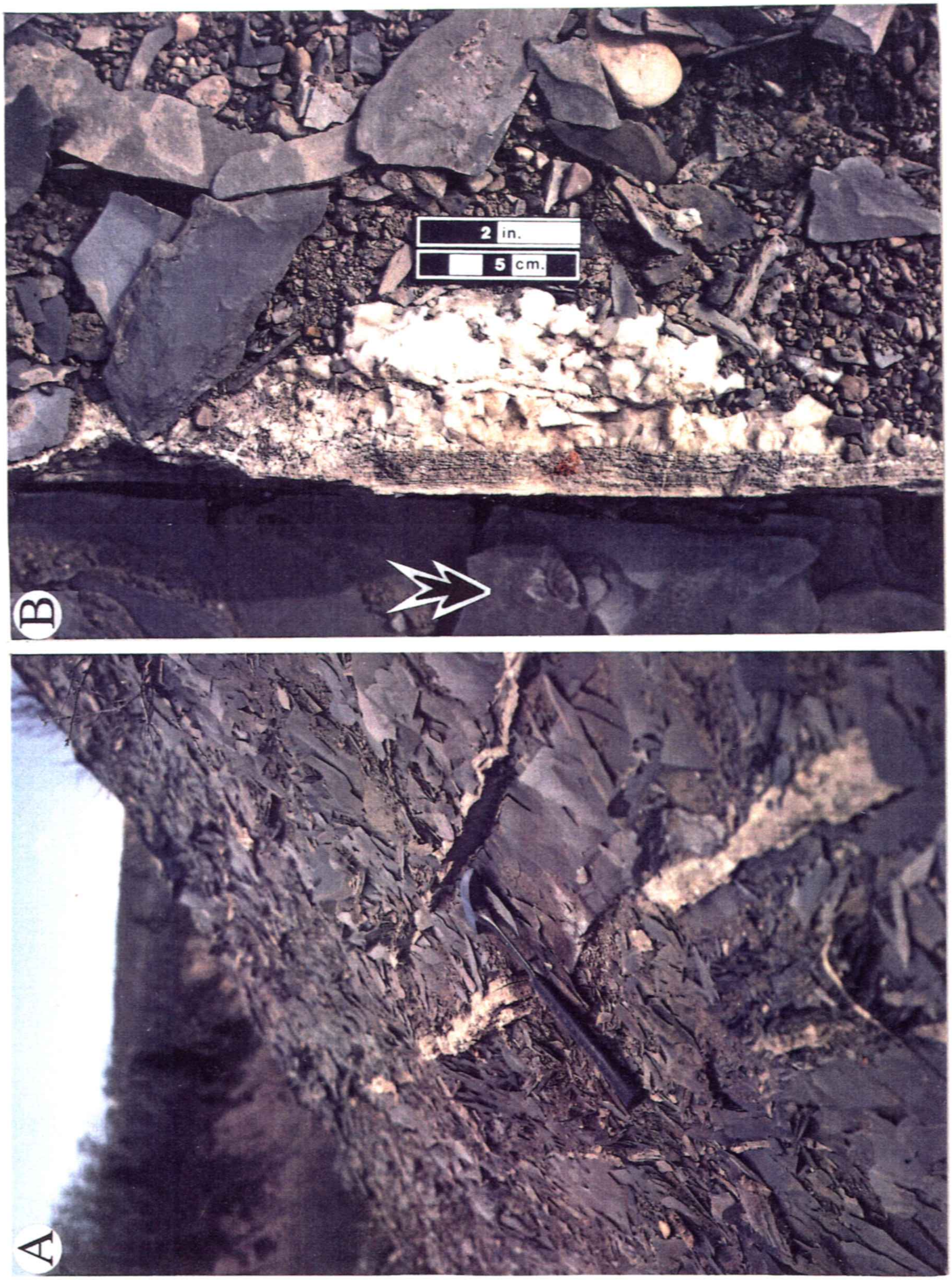
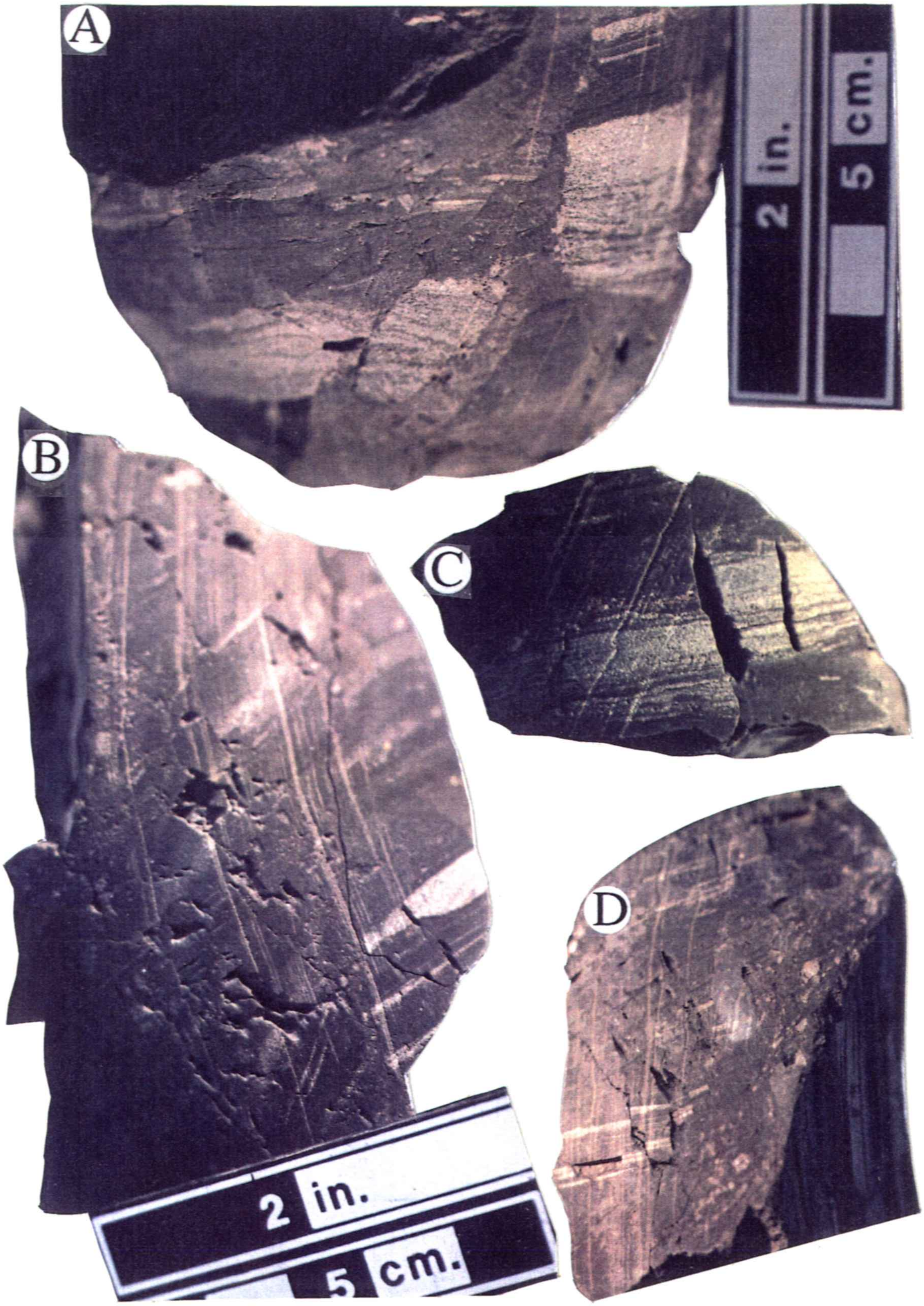

B
2 in.
5 cm.
A

Figure 31. A) Fractured sandstone bed indicates brittle behaviour whereas mudstone shows ductile deformation. B) Fracture porosity is preserved in ductile mudstone. C) Well-preserved fracture porosity. D) Annealed fracture porosity. Note slickensides on dark core face. All samples from Dome et al Claresholm well (14-29-11-28W4; 2502-2521 m depth).


A
2 in.
5 cm.
B
C
D
2 in.
5 cm.

undergone a moderate to perhaps advanced degree of diagenetic alteration. This suggests that diagenetic alteration and perhaps hydrocarbon generation may play a role in fracture formation.

ISOTOPES AND THE TIMING OF FRACTURE FORMATION

Isotopic data from concretions and fracture-fill cement may be used to constrain the conditions and relative timing of mineral-filled fracture formation. Core and thin-section observations, including preserved ichnofossils, uncompacted matrix fabrics, and pinch and swale structures, indicate that siderite and calcite concretions within Colorado Group shales formed relatively early. Carbon and oxygen isotopic data are also consistent with an early diagenetic origin (Fig. 32). Calcite concretions from the Second White Specks Formation are very depleted in ^{13}C and relatively enriched in ^{18}O when compared with siderite concretions from other formations. This suggests formation from basinal fluids of nearly marine oxygen isotopic composition in or above the zone of sulphate reduction. The very depleted ^{13}C values reflect intensive sulphate reduction and resulting OM oxidation and the carbon isotopic signature suggests most carbon is sourced from OM. In contrast, fracture-fill calcite (Fig. 32) is enriched in ^{13}C and depleted in ^{18}O. Paired concretion and fracture-fill calcite show a consistent difference in $\delta^{18}O$ of approximately 10.2‰.

The isotopic composition of fluid from which authigenic carbonates precipitate may be calculated using the appropriate isotopic geothermometer (see Longstaffe, 1989, for a review) if the temperature of formation is known or can be constrained. Utilizing concretion $\delta^{18}O$ values and assuming an early diagenetic origin (20 °C) for concretion calcite formation, calculated fluid compositions are between -1.5 and -4.0‰ (Fig. 33). If fracture-fill calcite is

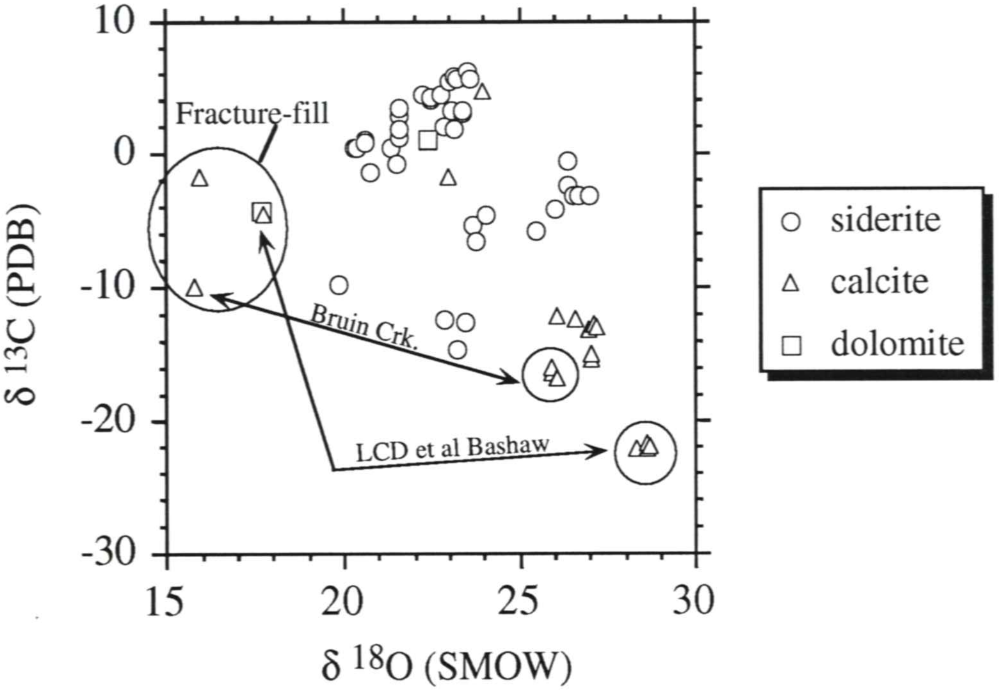


Figure 32. Isotopic data from concretions and fracture-fill cements. Siderite concretions are from the Westgate and Belle Fourche formations. Calcite (with dolomite) concretions are from the Second White Specks Formation. Arrows join paired concretion and fracture-fill samples. See Table 1 for paired sample locations.

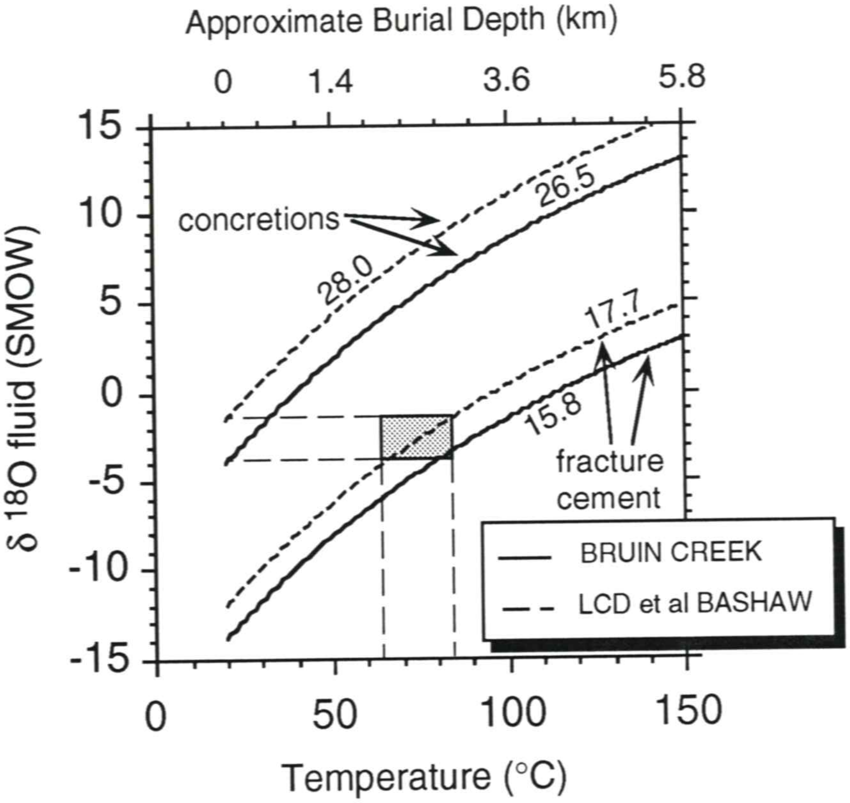


Figure 33. Temperature and approximate burial depth versus calculated $\delta^{18}O$ values of fluid from which solids may have precipitated for paired samples shown in Figure 32 using geothermometer of Friedman and O'Neil (1977). Stippled box indicates inferred temperature range of fracture-fill calcite cement formation assuming recrystallization of primary concretion carbonate. $\delta^{18}O$ values of the solid used in the calculation are indicated on each curve. See text for discussion.

derived from the dissolution-precipitation of early calcite, and fracture-fill cement is coeval with fracture formation, temperatures of between 65 and 85 °C are indicated for fracture formation. This suggests fracture formation between 2.0 and approximately 2.8 km of burial utilizing the present geothermal gradient of 22 °C/km (Majorowicz et al., 1985; Bloch and Staniland, unp. data) and assuming a 20 °C surface temperature. This corresponds to inferred maximum burial depth and temperature (Bustin, 1991; Bloch and Staniland, unp. data).

The origin of the relatively enriched ^{13}C values of the fracture-fill cement is not clear. Two sources of ^{13}C enriched carbonate are apparent. The first is the early concretion siderite which shows a range of $\delta^{13}C$ values from about -6 to 6 ‰ PDB. Assuming an average value of -5 ‰ for $\delta^{13}C$ of fracture-fill cement, approximately 60-65 % of the carbon would have to be derived from the dissolution of concretion siderite with an average value of 4 ‰. A siderite origin for the fracture-fill calcite is not indicated by the oxygen isotopic data. In addition, there is also no significant Fe-enrichment in the fracture-fill cement. An alternative source of ^{13}C-enriched carbonate is OM maturation. Both biogenic and thermogenic gas generation result in ^{13}C enrichment in the residual OM. This effect is more pronounced during biogenic gas generation. Oxidation of this material would result in dissolved bicarbonate with relatively high $\delta^{13}C$ values. A late diagenetic origin for fracture formation implies an organic source for the carbon isotopic composition of fracture-fill cement.

CONCLUSIONS

Possible source rocks of the Albian to Turonian portion of the Colorado Group in the WCSB include the Westgate, Fish Scales and Belle Fourche formations. The Second White Specks Formation in the westernmost part of the basin is an effective source-rock. The Westgate and Belle Fourche formations contain dominantly Type III organic matter and are therefore gas prone. They are mature west of approximately 114 ° Longitude. East of this area, they may be characterized as potential source rocks. The Fish Scales Formation contains a mixture of Types II and III organic matter and therefore may be capable of generating oil. The Second White Specks Formation contains dominantly Type II organic matter has probably generated significant quantities of hydrocarbons. It is mature west of approximately 115 ° Longitude in northwestern Alberta and matures rapidly to the west along the hinge zone that parallels the deformation front in the Fold and Thrust Belt in front of the Rocky Mountains. The source-rock characteristics of these formations are affected primarily by depositional processes that determine the type and abundance of organic matter within each formation as well as burial history.

The distribution of organic matter within each formation suggests that variable amounts of migrated hydrocarbons are present within the Westgate, Fish Scales and Belle Fourche formations. The presence of migrated hydrocarbons is recognized by the occurrence of oil-staining in core and outcrop, anomalous TOC abundances, and high production index values in immature to marginally mature rocks. Migration fronts or residual migrated hydrocarbons are present in southwestern Alberta in the area west of Keho Lake and possibly in northwestern Alberta.

The movement and/or expulsion of hydrocarbons requires effective fracture porosity and permeability. Localized fractures are observed in core and outcrop but the extent and effectiveness of fracture systems as conduits and storage capacity within the Colorado Group shales is unknown. Isotopic data suggests that some fracture formation within the Second White Specks Formation occurred between 65 and 85 °C at approximate maximum burial depth of 2.0 to 2.8 km. Fracture-filling cements were formed from the dissolution and precipitation of matrix carbonate and/or the oxidation (maturation) of organic matter. The inferred timing of fracture formation and the localized nature of observed hydrocarbon migration suggest that fractures are/were instrumental in the expulsion of hydrocarbons from the Second White Specks Formation and probably control hydrocarbon migration within the Colorado Group.

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