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TECTONICALLY ALTERED COAL RANK, BOULDER CREEK FORMATION, NORTHEASTERN BRITISH COLUMBIA

(93P/3)

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KEYWORDS: Coal geology, vitrinite reflectance, tectonic heating, reflectance anisotropy, microscope automation.

INTRODUCTION

Fieldwork during the 1988 season involved investigation of the thermal affects of tectonic movement on vitrinite reflectance near the Quintette Coal Limited mining operation in northeastern British Columbia. Two samples, collected in 1987, from the same seam on either side of a fault, suggested a significant rank increase associated with the structure. These sites were revisited and sampled together with additional sites, to gain a better understanding of the process. Rank variations within the seam at one site proved greater than between the original pair of samples. Significant reflectance anisotropy was found, which is due to distillation of coal, and confirmed heating greater than coalification. The samples were also the test-set for a new reflectance data collection and analysis procedure which increases precision and provides a measure of the error associated with each reflectance reading. This article describes the procedures used and results obtained.

GEOLOGY

The study area is located immediately east and south of the Mesa pit of the Quintette Coal Limited mining operation near Tumbler Ridge (Figure 4-5-1). The seams investigated are located in the lower portion of the Lower Cretaceous Boulder Creek Formation of the Fort Saint John Group. The Boulder Creek Formation is overlain by the marine Hasler Formation and underlain by the marine Hulcross Formation, which separates it from the economically important coal measures of the Gates Formation.

Within the study area the Boulder Creek Formation is repeated by a folded thrust fault. Bedding-to-fault angles of about 30 degrees are associated with the fault which dips steeply east. The bedding is vertical to overturned (Figure 4-5-2). A shear zone, 8 centimetres wide, is located in the lower seam of the footwall beds. The sequence is cut by the mine access road providing excellent exposure of the coal seams and fault. Two samples collected from the lower seam and analyzed previously, 87-37 and 87-40, (Kilby and Johnston, 1988) suggested that the coal in the hangingwall of the thrust had experienced greater coalification than the equivalent seam in the footwall. More detailed sampling confirmed the earlier values but determined that there is an even greater variation in vitrinite reflectance (rank) within a single seam close to a thin shear zone.

More detailed mapping during the 1988 study has resulted in some modest adjustments to the interpretation presented earlier. The major change is that the fault appears to remain in the Boulder Creek Formation for a greater distance to the east. This interpretation increases the displacement associated with the thrust. Orientation of the fault above the access road remains the same (Figure 4-5-2). It is now felt that the fault is parallel to the massive conglomerates of the Boulder Creek Formation for a distance of about 200 metres below the road exposure where it then cuts upsection through the competent lower portion of the formation before becoming subparallel to bedding in the upper Boulder Creek Formation.

Table 4-5-1 presents the results of the new samples together with the two samples reported in Kilby and Johnston (1988). Measures $\bar{R}_M$, R_{MAX}, R_{INT}, R_{MIN}, R_{ST} and R_{EV} are developed and described in Kilby (1988). Note the error in the original reporting of the value of sample 87-40. The revised value, though lessening the difference between the two samples, is still a significant variation and does not alter the previous conclusions. A total of 14 samples were collected during the 1988 study but two of these proved too severely weathered for analysis. The sample sites are located on a cross-section illustrating the structural geology of the outcrop (Figure 4-5-2).

METHOD

Samples were prepared and examined using standard techniques. The interpretation of the raw data was based on Kilby (1988). Reflectance crossplots provide the means to obtain a significantly greater description of the reflectance characteristics of a coal than the traditional measures of $\bar{R}_{oMAX}$ and $\bar{R}_M$. $\bar{R}_M$ remains a valid description of the overall sample coalification but is not unique. $\bar{R}_{oMAX}$ is theoretically invalid when the reflectance indicating surace (RIS) is not uniaxial negative, Kilby (1988) showed that only about 25 per cent of the samples from the Rocky Mountains and Foothills meet this criterion. Samples from this study cover the spectrum of possible RIS-shapes from uniaxial negative to uniaxial positive (Figure 4-5-3).

Refinements have been made to the standard methodology of recording and evaluating vitrinite reflectance values. Traditionally reflectance readings are obtained from individual vitrinite particles by measuring the amount of polarized light reflected during a single revolution of the microscope stage. Generally the reflectance values form an ellipse when plotted against the respective stage angles. Until recently the majority of researchers collected only the apparent maximum values during stage rotation (R'_{MAX}). Kilby (1986) illustrated the value of also collecting the apparent minimum reflectance obtained for each vitrinite particle (R'_{MIN}). Development of a new analysis technique, the reflectance

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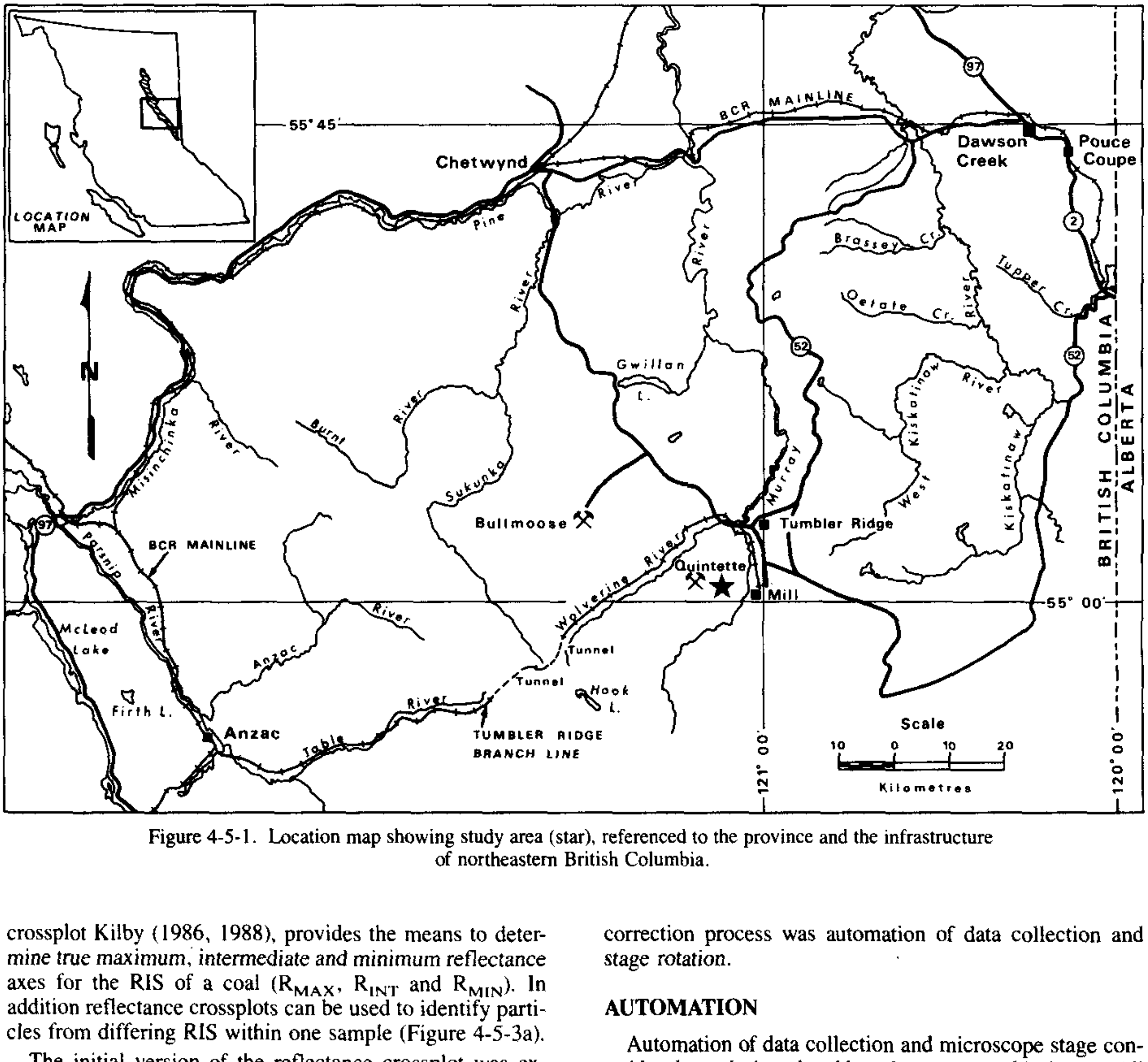


Figure 4-5-1. Location map showing study area (star), referenced to the province and the infrastructure of northeastern British Columbia.

crossplot Kilby (1986, 1988), provides the means to determine true maximum, intermediate and minimum reflectance axes for the RIS of a coal (R_{MAX}, R_{INT} and R_{MIN}). In addition reflectance crossplots can be used to identify particles from differing RIS within one sample (Figure 4-5-3a).

The initial version of the reflectance crossplot was explained in Kilby (1986); subsequent work (Kilby, 1988) developed measurement values associated with it. A computer-enhanced interpretation program has been developed which allows interactive on-screen interpretation of reflectance values and calculation of various reflectance measures (Figure 4-5-3). Increased use of R'_{MIN} values in this methodology identified susceptibility of this measurement to technical problems resulting in anomalously low values. Several conditions may cause invalid low readings;

(1) foreign material in immersion oil (dust or air bubbles),

(2) poor polish on pellet surface, or

(3) electrical problems.

R'_{MAX} values are also susceptible to anomalously high readings, primarily due to electrical problems. As a result it became essential to be able to determine the best-fit ellipse for datasets and use this average ellipse to determine R'_{MAX} and R'_{MIN} values for each particle. The first step in this correction process was automation of data collection and stage rotation.

AUTOMATION

Automation of data collection and microscope stage control has been designed and largely constructed in-house. All

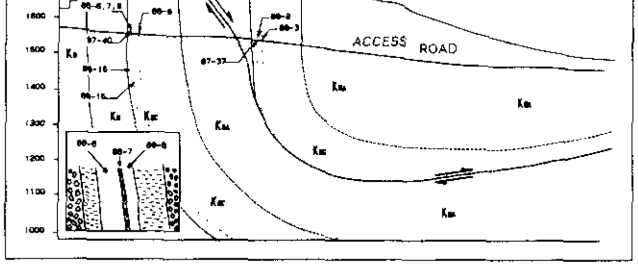
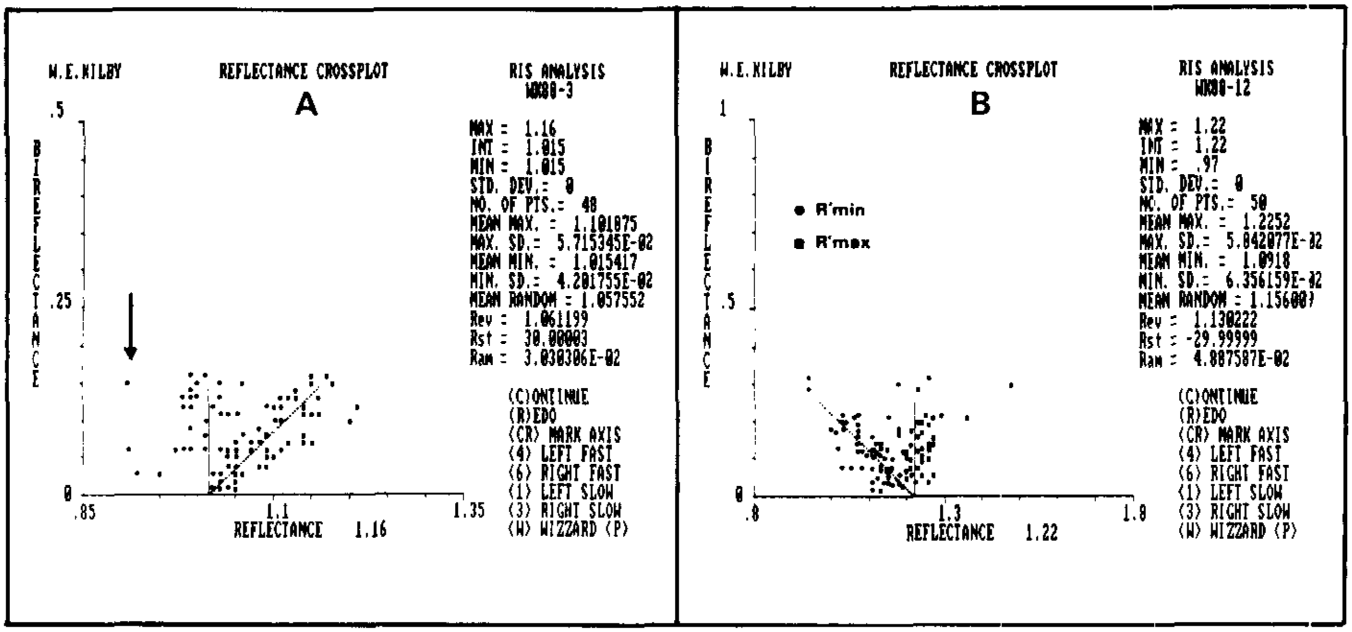


Figure 4-5-2. Cross-section of the study area showing sample locations. Insert is one metre across. Dotted lines are coal seams. Formation codes are; K_G = Gates, K_H = Hulcross, K_{BC} = Boulder Creek and K_{HA} = Hasler.



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RIS ANALYSIS
WK88-3

MAX =  1.16
INT =  1.015
MIN =  1.015
STD. DEV.=  0
NO. OF PTS.=  40
MEAN MAX. =  1.101075
MAX. SD.=  5.715345E-02
MEAN MIN. =  1.015417
MIN. SD.=  4.201755E-02
MEAN RANDOM = 1.057552
Rev =  1.061199
Rst =  30.00003
Ram =  3.030306E-02

    (C)ONTINUE
    (R)EDO
    (CR) MARK AXIS
    (4) LEFT FAST
    (6) RIGHT FAST
    (1) LEFT SLOW
    (3) RIGHT SLOW
    (W) WIZZARD (P)
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RIS ANALYSIS
WK88-12

MAX =  1.22
INT =  1.22
MIN =  .97
STD. DEV.=  0
NO. OF PTS.=  50
MEAN MAX. =  1.2252
MAX. SD.=  5.042077E-02
MEAN MIN. =  1.0918
MIN. SD.=  6.356159E-02
MEAN RANDOM = 1.156007
Rev =  1.130222
Rst = -29.99999
Ram =  4.007587E-02

    (C)ONTINUE
    (R)EDO
    (CR) MARK AXIS
    (4) LEFT FAST
    (6) RIGHT FAST
    (1) LEFT SLOW
    (3) RIGHT SLOW
    (W) WIZZARD (P)
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Figure 4-5-3. Reflectance crossplots of samples 88-3 and 88-12 showing the two possible end-members of RIS-shapes. Plots are screen dumps from microcomputer. Note the second minor RIS population in sample 88-3 (arrow).

controlling software was written by the author. An Octagon Systems SYS-2A microcontroller forms the heart of the system. Communication with the controller is through standard serial interface protocol with any computer. Twelve bit analog to digital conversion is used to sample a 0 to -5 VDC current representing the reflectance values from the microscope. Two of the eight available digital output lines from the controller are used to drive a KEM 802-12 (Kaientai Electronics Merchants Ltd.) stepper motor driver. A stepping motor with a stepping angle of 1.8° was mounted centrally under the microscope stage. With the one-half step capabilities of the motor driver 0.9° stage steps are realized.

Prior to stage automation the stage was rotated manually while the reflectance signal was sampled 100 times over a 6-second time period. The maximum and minimum values of the one hundred readings were saved as the R'_{MAX} and R'_{MIN} of the vitrinite particle. This procedure, though mimicking the completely manual method, is susceptible to erratically high or low readings, as is the manual method. To examine and overcome this problem readings are now taken every 9° of stage rotation. The stage is rotated 9°, then five reflectance readings are taken. The largest of these five readings is recorded. A complete stage rotation of 360° will result in 40 values. If these 40 readings are plotted using polar coordinates, an ellipse (reflectance ellipse) will be formed. Examination of this ellipse will reveal conformity to a theoretically perfect ellipse and highlight erratic values. Figure 4-5-4 shows representative reflectance ellipses from vitrinite particles taken from some of the samples in this study.

A variety of problems are apparent with the reflectance ellipses in Figure 4-5-4. The left ellipse is severely deformed. This shape is probably due to some foreign material interfering with reflecting light transmission. R'_{MAX} and R'_{MIN} values from either the raw data or fitted ellipse would be erroneous. The centre ellipse illustrates the case where a very good elliptical shape was formed by the raw data and closely approximates the fitted ellipse. The right ellipse is an example where several anomalously low readings are obtained, which could result from some floating material in the immersion oil. In this study standard deviations greater than 0.05 per cent resulted in the particle being discarded. Methods of patching ellipses with greater than half the values being valid are being tested. If they prove useful, then particles which are now discarded could be used in the analysis of the coal.

During this study two methods of fitting an ellipse to the raw sample data were tested. A regression analysis and an eigen-vector technique gave virtually identical results. The eigen-vector technique proved to be much faster in obtaining the solution to the data, and was adopted. Eigen vectors and

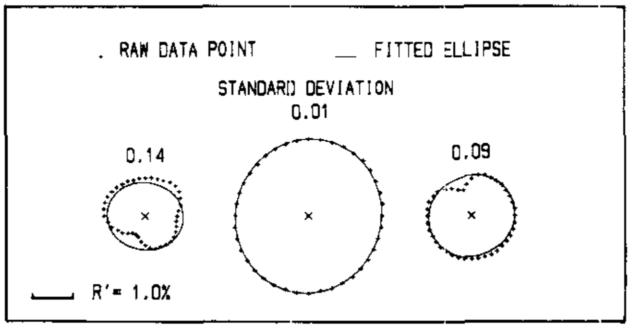

Figure 4-5-4. Examples of reflectance ellipses taken from several samples. The left ellipse illustrates the affect of anomalously low readings, the centre ellipse is an example of a very good dataset and the right ellipse is an example of extremely poor raw reflectance data.

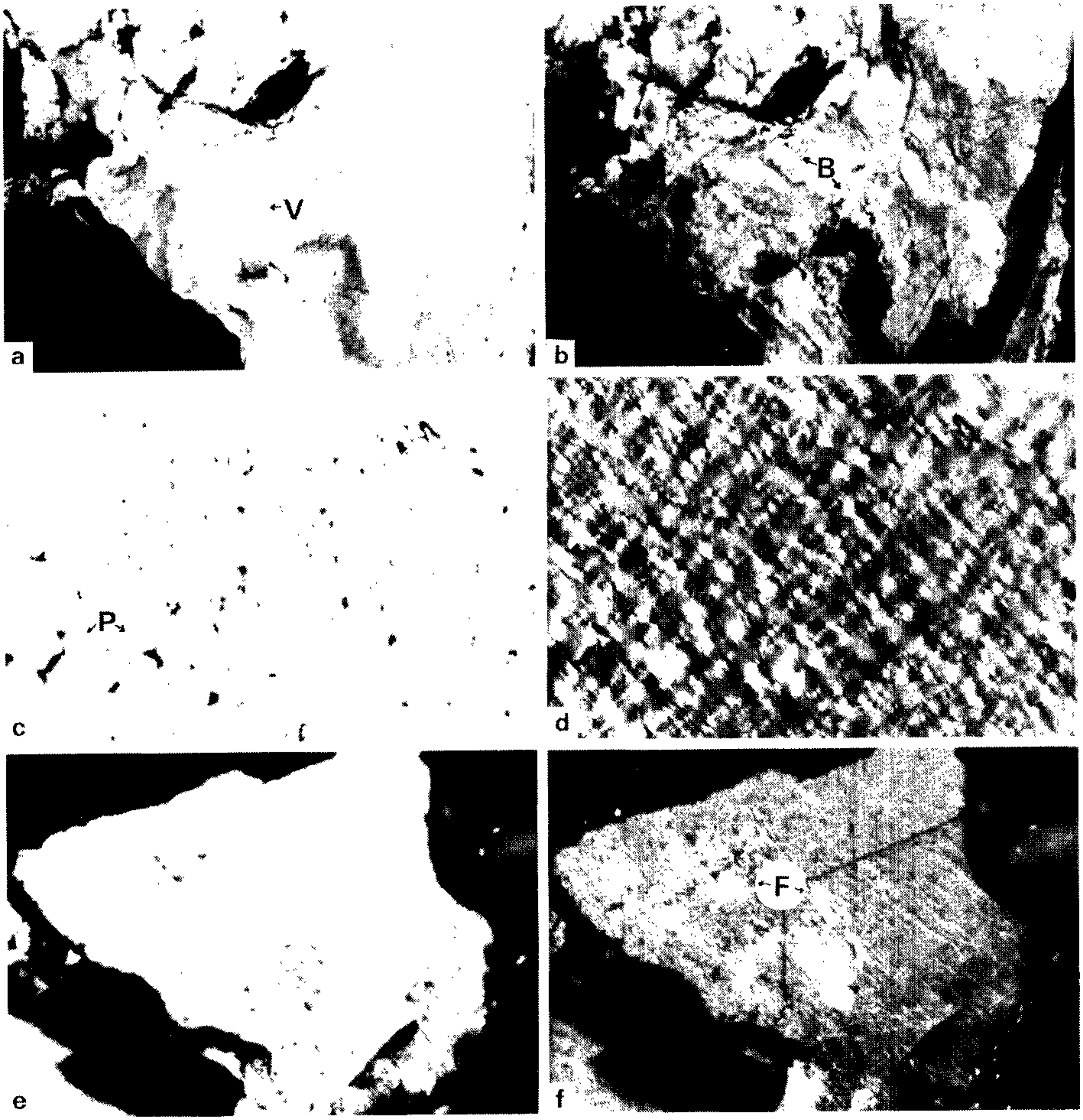

Plate 4-5-1. Sample 88-6 (a,b) shows fine-grained mosaic anisotropic texture in vitrinite (V). (1b) same view as (1a) but with partially crossed polars. Note mottled anisotropy in vitrinite and strong anisotropy in inert maceral (B). (1c), sample 88-6, contains a large vitrinite grain showing mottled texture under plain polarized light. Pore opening likely caused by devolatilization of coal (P). (1d), sample 88-6, under crossed polars shows strong cross-hatched anisotropy. (1e), sample 88-7, under plane polarized light, showing large vitrinoid grain with relic cell structure and pyrolitic carbon. (1f), sample 88-7, viewed under partially crossed polars showing extreme anisotropy of pyrolitic carbon (F).

eigen values were obtained from a 2-by-2 matrix whose elements are weighted two-dimensional direction cosines of the stage angles at which readings were taken. The weighting factor is the reflectance value obtained at each reading stage angle. The eigen-vector method was modified after Charlesworth *et al.*, (1976). Input to either method of analysis must be based on an unbiased sample distribution of the reflectance ellipse circumference. Sample distributions based on equal angular increments are biased towards the minimum apparent reflectance axis value. To overcome this bias, a new set of reflectance data were calculated, based on equal spacing along the ellipse circumference. This modi-

TABLE 4-5-1
RESULTS OF SAMPLE ANALYSIS

Sample	$\bar{R}_M$	$\bar{R}_{MAX}$	R_{MAX}	R_{INT}	R_{MIN}	R_{ST}	R_{EV}	Biref	Anisotropy
87-37	1.21	1.29	1.37	1.25	1.05	–3.4	1.20	(.24)	Mod
87-40	0.87	0.96	1.06	0.90	0.72	–9.2	0.88	(.24)	High
88-2	1.19	1.25	—	—	—	—	—	.21	Low
88-3	1.06	1.10	1.17	1.01	1.01	30.0	1.06	.16	Low
88-6	0.95	1.00	—	—	—	—	—	.14	High
88-7	1.04	1.10	—	—	—	—	—	.27	Mod-High
88-8	1.74	1.84	1.92	1.77	1.57	–4.7	1.75	.30	Mod-High
88-9	1.12	1.17	—	—	—	—	—	.17	Mod
88-11	0.95	0.99	—	—	—	—	—	.15	Mod-High
88-12	1.16	1.23	1.22	1.22	0.97	–30	1.13	.30	Mod
88-13	1.02	1.08	1.16	1.02	0.91	4.0	1.02	.20	Mod-High
88-14	1.07	1.12	1.17	1.03	1.03	30.0	1.07	.17	Mod
88-15	1.14	1.18	1.23	1.15	1.06	–1.0	1.14	.19	Low
88-16	1.03	1.09	—	—	—	—	—	.19	Mod-High

Missing values are due to uninterpretable reflectance crossplots. 1987 sample results not interpreted using eigen-vector method.

fication provided excellent fits to the raw data (Figure 4-5-4b). In addition to the R'_{MAX} and R'_{MIN} values, the orientation of the R'_{MAX} axis and the standard deviation of the raw data about the mean ellipse are reported. The standard deviation provides a measure of the validity of fitting an ellipse to the data.

ANISOTROPY

Reflectance anisotropy was identified in samples 87-37 and 87-40 by Goodarzi (personal communication, 1988). Cross-polarized reflected light was used to examine all samples in this study for this phenomenon. Development of reflectance anisotropy within single maceral grains is due to heating higher than that associated with normal coalification and is a standard feature of coked coals. Natural causes of this anomalous heating are: coal-seam fires, igneous intrusions, coal-swamp fires, tectonic heating and detrital high-rank coals (Goodarzi and Murchison, 1985 and 1986).

Coal-seam fires and igneous intrusions may be discounted within the study area as there is no evidence of either and exposure is excellent along the road cut. Coal-swamp fires and detrital high-rank coals can also be discounted as the anisotropic particles are ubiquitous rather than minor components of the samples. The remaining cause of anomalous heat is tectonic friction; the proximity of a large folded thrust fault and an obvious shear zone within the coal seam is ample evidence of tectonic activity. Analysis of anisotropy was made on the basis of type and intensity present (Table 4-5-1). Examples of some common reflectance anisotropic features are shown in Plate 4-5-1.

Different types and intensity of reflectance anisotropy are recognized in the sample set. The weakest form is fine-grained mosaic anisotropy which may occur throughout the vitrinite maceral or only as patches or streaks within the particle (Plate 4-5-1a, 1b). Granular mosaics are thought to form at temperatures of greater than 450°C and involve the active decomposition of coal substance and the onset of plasticity (fluidity) (Goodarzi and Murchison, 1972). A cross-hatched pattern of anisotropy often forms the background to a particle with ubiquitous fine-grained mosaic anisotropy. Occasionally an intense cross-hatched pattern may be present without any fine-grained mosaic texture, but this may be due to complete overprinting (Plate 4-5-1c, 1d). Wavy anisotropy then appears to develop in vitrinites and, at about this stage, inert macerals begin to display anisotropy. Coarse-grained mosaic anisotropy, though rare in these samples, tends to develop after the fine-grained mosaic anisotropy. Pyrolitic carbon forms during thermal cracking of carbonaceous material (500 to 1100°C). Plate 4-5-1e and 4-5-1f illustrate pyrolitic carbon which has formed in a vitrinoid maceral. The intensity (brightness) of the anisotropy also increases as the patterns become more developed. Eventually flow structures become visible as a result of the coal melting during carbonization (this feature, though not seen in this study, is common in coke ovens and high-grade metamorphism). Devolatilization voids form at various stages of heating to become a major component of a coked swelling coal.

The validity of typical reflectance measures, including those obtained from a reflectance crossplot, are questionable under high anisotropic conditions where the whole sample is not described by a single RIS. Multiple RIS-shapes on a single-reflectance crossplot will result in a uninterpretable plot where the R'_{MIN} and R'_{MAX} datafields overlap and have increased standard deviations. Large standard deviations were noted by Bustin (1983) from samples taken near faults and these may be due to similar features. In the case of mosaic anisotropy, more than one RIS could easily fall within the analysis field (5 to 10 micrometres). The results from such a situation would be valid only if the two RIS were parallel to each other and of equal value, otherwise the result would be based on a composite RIS and therefore invalid. Several of the samples in this study have uninterpretable reflectance crossplots which are largely due to this feature.

DISCUSSION

Tectonism has increased the rank of coals within the study outcrop. Frictional heating associated with the major thrust fault may be responsible for the increaseding $\bar{R}_M$ values of coals near the thrust by 0.2 per cent reflectance. The separation between these increased rank coals and the fault is about 20 metres, which is significantly larger than the 5-centimetre heating zone of influence found by Bustin (1983). There is not a large increase in reflectance anisotropy associated with this rank increase.

The largest variation in reflectance is associated with intra-seam faulting. An $\bar{R}_M$ increase of 0.75 per cent was noted across a 10-centimetre shear zone within a single seam. The elevated reflectance value is located above the shear. The sample site was more than a 100 metres from the major fault, and the rank increase is not attributed to it, but rather to heating along the shear zone formed as a result of flexural slip between the competent conglomerate units being concentrated within the coal seam. Reflectance anisotropy at this sample location is strong and suggests temperatures in excess of 450°C.

Techniques and equipment were developed to evaluate reflectance data obtained from discrete angular increments for each measured vitrinite particle in a sample. The procedure reduces the problem of noisy data and provides a measure of error associated with each reflectance measurement.

Reflectance crossplots provide better analysis parameters than traditional techniques. In this study they provided the means to identify the full spectrum of reflectance indicating surface shapes from uniaxial negative to uniaxial positive. Multiple RIS populations can be identified in reflectance crossplots. Uninterpretable reflectance crossplots (mixtures of several populations) may prove to be a method of predicting reflectance anisotropy. If this anisotropy is due to shearing of the coal, this tool would have application in predicting disturbed seams in mining situations.

A semiquantitative measure of reflectance anisotropy correlates well with visible shearing, increased vitrinite reflectance and multiple RIS populations. Identification of reflectance anisotropy in complicated reflectance profiles, often present in the Peace River coalfield, may provide an explanation based on tectonic structures.

ACKNOWLEDGMENTS

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