

The quality of Western Canadian coking coal

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ABSTRACT

Western Canadian coking coals are located in the Rocky Mountains and foothills of British Columbia and Alberta. They are typical of non-marine coals, characterized by total sulphur contents of less than one per cent and with ash contents of 10-30 weight per cent. This mineral matter is composed principally of kaolinite and quartz.

The petrographic compositions of most of the coking coals which constitute the 2.065 billion tonnes of British Columbia's measured reserves, and the compositions of the metallurgical coal currently exported from Alberta, show them to be rich in the inertinite macerals, macrinite, fusinite and semifusinite. When the mean maximum reflectance of vitrinite in oil ($R_{O\max}$) is used as the coal rank parameter, this high inertinite content is reflected in the lower volatile-matter yields, but the relatively inert character is also displayed by lower free swelling indices (FSI), lower maximum dilatations, lower maximum fluidities and lower coke strengths than other coals of the same rank, but richer in the reactive macerals, vitrinite, exinite and semifusinite. Despite these reduced values in the so-called caking tests, inertinite-rich coals produce strong coke.

A system of classification of coking coals is introduced which is based on rank, as indicated by $R_{O\max}$, and either petrographic composition, maximum dilatation, maximum

fluidity or, to a lesser extent, FSI and volatile-matter yield. Six principal coal groups can be distinguished among coking coals using this versatile classification. Inertinite-rich coals are assigned to the Keystone Group (G1), Balmer Group (G3) or Moura Group (G4), each group being named for a coal typical of that population of coals. Reactive-rich coals are assigned to the Pittston Group (G2), Kellerman Group (G5) or Big Ben Group (G6). A multiple-regression analysis of coal quality versus price shows how the value of coking coal in the Japanese market appears to be related to reflectance and the free swelling index, and confirms the economic viability of the classification.

British Columbia's measured reserves of coking coal contain representatives of four of these groups; Balmer Group (73%), Moura Group (16%), Pittston Group (3.4%) and Kellerman Group (7.6%).

This analysis of the quality of Western Canadian coking coal indicates that despite the need for large proportions of inertinite-rich coking coal in blends produced in the Japanese steel industry, there is nevertheless a demonstrated overabundance of Balmer Group and Moura Group coals available to the international coking coal market.

Introduction

Western Canadian coking coals are located in coalfields in the Rocky Mountains and foothills of British Columbia and Alberta in two major stratigraphic zones, both of lower Cretaceous age. These coalfields are the Peace River coalfield and the East Kootenay coalfield (Fig. 1). In 1971, the size of this coal resource was estimated to be 86.1 billion short tons, of which 57.4 billion short tons was in British Columbia (Latour, 1972). The figures for British Columbia were revised in 1976 when the coking coal resource was estimated to be 30.7 billion short tons (Gilchrist, 1976). Although the size of the resource is reasonably known and measured reserves of over 2.065 billion tonnes are reported by companies, little has been written about the quality of the coal. The purpose of this paper is to (i) establish the quality of coking coals in British Columbia and Alberta in relation to others that enter the international coking coal market, (ii) demonstrate how the price of coking coal is dependent on quality, (iii) examine the role of inertinite-rich coals in blends and (iv) assess the composition of British Columbia's measured reserves.

Composition and Rank of Coals

The natural constituents of coal can be divided into two groups: (i) the organic fraction, which can be further subdivided into microscopically identifiable macerals; and (ii) the inorganic fraction, which is commonly identified as ash subsequent to combustion, but which may be isolated in the form of mineral matter by low-temperature ashing (LTA). The organic fraction can be further subdivided on the basis of its rank or maturity.



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Dave Pearson was born in England, but raised and schooled in Wales. He received a B.Sc. from the University College of Swansea in 1967 and a Ph.D. from the University of Wales in 1971. He was awarded a NATA Research Scholarship in 1968 to study at the University of Oslo, Norway.

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He has had wide field experience and has published papers on aspects of Precambrian tectonics, precious-metal mineralization and, most recently, on coal. He is currently active in coal research at the Ministry's Coal Laboratory in Victoria.

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Keywords: Coal, Western Canada, Coking coal, British Columbia, Alberta, Keystone Group, Balmer Group, Moura Group, Pittston Group, Kellerman Group, Big Ben Group, Coal composition, Coal rank, Petrography.

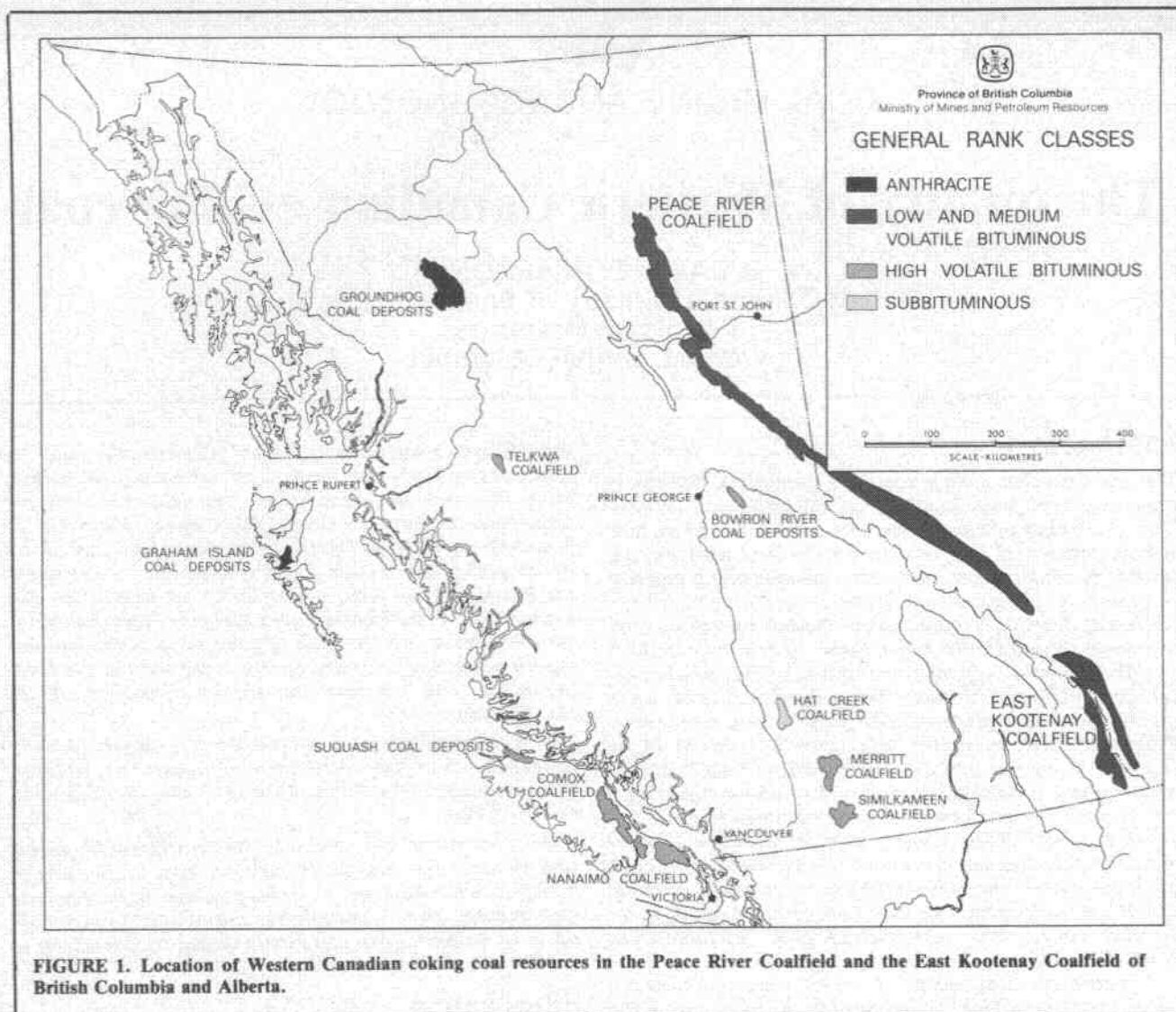


FIGURE 1. Location of Western Canadian coking coal resources in the Peace River Coalfield and the East Kootenay Coalfield of British Columbia and Alberta.

Maceral Composition of Coals

Coal is composed of microscopically recognizable constituents, called macerals, which differ from one another in form and reflectance. Macerals are analogous to minerals in inorganic rocks. Three principal maceral groups are identified and these are, in increasing order of carbon content, exinite, vitrinite and inertinite (Table 1). In a single coal, vitrinite, which is usually the commonest maceral, has a higher reflectance than the associated exinite, but a lower reflectance than inertinite. There is, therefore, a correlation between carbon content and reflectance and this is used to precisely determine rank. Petrographers in Canada and many other countries use the mean maximum reflectance of vitrinite in oil (R_o max), at 546 μ m, as the level of organic maturity, or rank, of a coal sample.

Vitrinite (Fig. 2) is thought to be derived mainly from the original woody tissue of trees in peat swamps. In Pennsylvanian-age coals of Western Europe and the eastern United States, it often constitutes 60-80% of the macerals (I.C.C.P. Handbook 1971), whereas in Permian-age Gondwana coals of the southern hemisphere it rarely exceeds 80%, and in some cases comprises less than 50% of the total macerals (Chandra and Taylor, 1975).

Exinite (Fig. 2), which is derived from pollen, spores and leaf epidermis, is technologically important, because it enhances the fluidity of coal (Krevelen, 1961). Exinite contents of 1% are common in Gondwana coals of the southern hemisphere, but generally they are lower than Pennsylvanian-

TABLE 1: Macerals commonly identified in black coals.

Group	Exinite (P)	Vitrinite (P)	Inertinite (P)
Macerals	Sporinite (P) Cutinite (P) Resinite Alginite Liptodetrinite	Telinite Collinite Vitrodetrinite	Macrinite (P) Micrinite Semifusinite (P) Fusinite (P) Sclerotinite Inertodetrinite (P)

P - Photomicrograph of maceral shown in Figure 2

age coals, which possess exinite contents of 5-20%. Both exinite and vitrinite are capable of yielding petroleum-type hydrocarbons (Teichmüller and Teichmüller, 1975).

The inertinite group of macerals (Fig. 2) derives its name from its more or less non-reactive character shown during the carbonization process. Whereas exinite and vitrinite melt, with an evolution of volatiles, inertinites generally remain intact. Inertinite is derived from fungal remains, charcoal and partly charred wood. Gondwana coals in general and many lower Cretaceous Kootenay Formation coals of British Columbia and Alberta specifically are characteristically enriched in inertinite macerals. For example, in Australia, Taylor and Cook (1962) found up to 85% inertinite macerals in a whole seam section; lower Kootenay coals usually comprise 20-30% inertinite (Cameron 1972, Pearson and Grieve 1978 and in prep.).

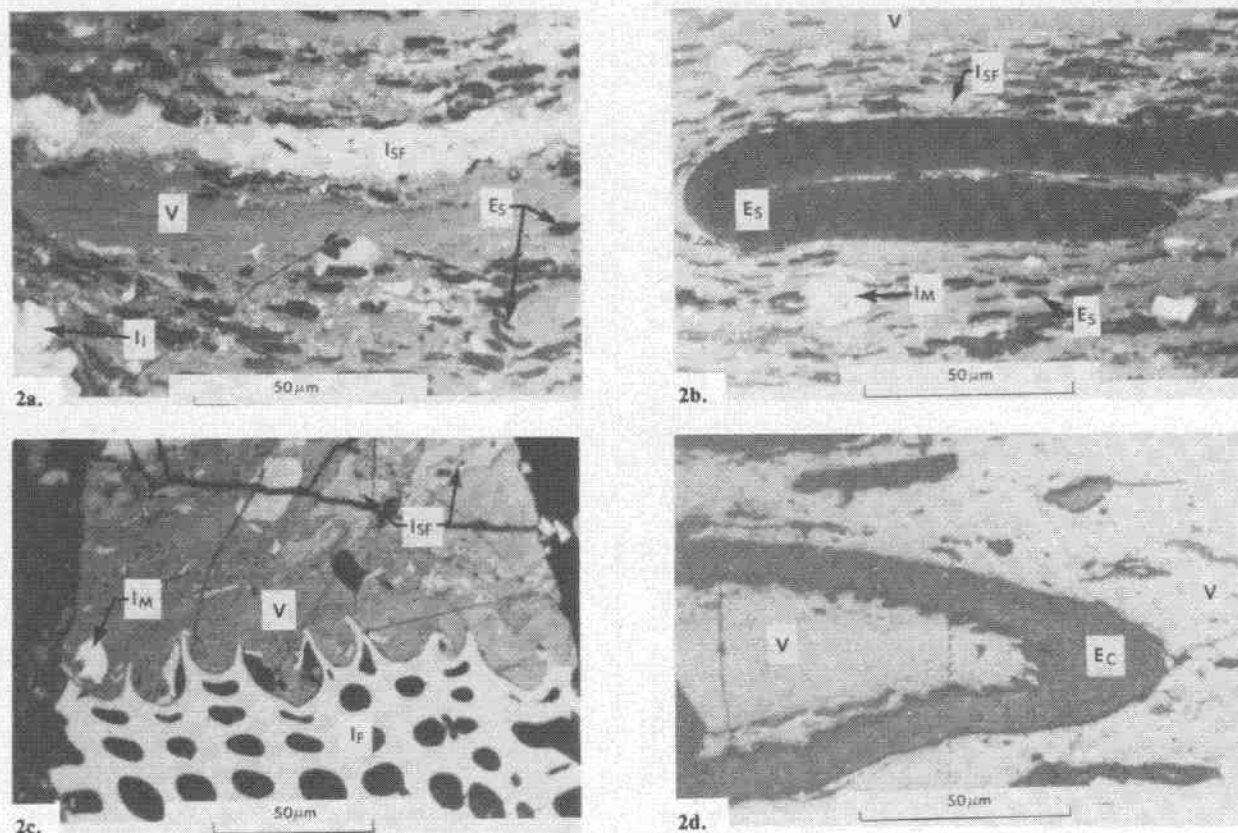


FIGURE 2. Photomicrographs of coal macerals under polarized light and oil immersion. Magnification x500. 2a, 2b and 2c, West Virginia Pennsylvanian-age coal. 2d, British Columbia lower Cretaceous-age coal.

2a: V = vitrinite, Es = sporinite, microspore, Isf = semifusinite, Ii = inertodetrinite
 2b: V = vitrinite, Es = sporinite, megaspore, microspore, Im = macrinite, Isf = semifusinite

2c: V = vitrinite, Isf = semifusinite, Im = macrinite, If = fusinite
 2d: V = vitrinite, Ec = cutinite

Pennsylvanian-age coking coals generally possess 5-20% inertinite.

The maceral content and volatile-matter yield of a coal may be considerably influenced by the post-depositional chemical environment to which the normally acid peat is subjected. In the case of a marine cover to a peat, the maceral proportions remain unaffected, but anaerobic bacteria flourish and promote advanced decomposition, together with reduction of seawater sulphate to sulphide. This leads to a per-hydrous coal, rich in sulphur, with a higher volatile yield than normal (Francis 1961, Teichmüller and Teichmüller 1975). By contrast, in those cases where peats are covered by fresh water, if coupled with periodic oxidizing conditions, volatile-matter yields are reduced, and the inertinite content may be increased at the expense of vitrinite and exinite.

In the East Kootenay coalfield, all seams have roof strata and sulphur contents which indicate non-marine conditions, and in the Peace River coalfield only two instances are known where marine strata form the seam roof. Thus, the influence of the post-depositional chemical environment contributes to the inertinite-rich character and probably explains why measured reserves of Western Canadian coking coals, with few exceptions, are rich in inertinite macerals.

Figure 3 shows the petrographic composition (expressed as inerts, or the percentage of inertinite macerals plus inert semifusinite, plus ash computed by the Parr formula) and rank (expressed as R_0 max) of some coking coals that enter world trade. Included in the diagram are those coals that constitute British Columbia's measured reserves of coking coal. The "optimum inert" line represents the optimum amount of inert components that would produce the strongest coke for each

rank. Coal compositions to the left of the line are inertinite-rich, and those to the right are reactive-rich. It is apparent that most of British Columbia's coking coals are rich in inerts (inertinite macerals and mineral matter).

Mineral-Matter Composition of Coals

The ash of a coal is the uncombustible oxide residue which remains after combustion. By contrast, mineral matter is the natural mineral assemblage of a coal that contains syngenetic, diagenetic and epigenetic species. Mineral matter is recorded during petrographic examination of coals, but is identified more accurately by X-ray diffraction analysis of low-temperature ash (LTA) obtained by radio-frequency plasma-ashing of coal (Rao and Gluskoter, 1973; Mitchell and Gluskoter, 1976; Pearson and Kwong, 1979).

The post-depositional chemical environment of a peat swamp, as well as being an influence on the maceral composition of a coal as noted above, is the major factor determining the amount and kind of mineral species present in coal. Although there is little doubt that some minerals present in coal are detrital, a large proportion are authigenic. Therefore an evaluation of mineral assemblages can suggest the physico-chemical conditions in the peat swamps. For example, where a peat swamp is known to have had a marine cover, the change in pH from acid to alkaline is accompanied by advanced bacterial action, the production of sulphide and a consequent nucleation of pyrite. Calcite and illite may also be formed. In the case of a fresh-water cover, the acid nature of the swamp is preserved, and the absence of seawater-salts limits total sulphur to that which is contained in plant and animal protein (Teichmüller and Teichmüller, 1975). The acid environment is, however, ideal for the nucleation of kaolinite. Thus, fresh-

water coals are characterized by kaolinite-quartz and low sulphur contents, and marine-influenced coals are characterized by high sulphur contents and mineral assemblages of pyrite-calcite-illite-quartz. Figure 4 shows LTA-diffractograms typical of early Cretaceous non-marine coals from British Columbia (Balmer, Fording and Denison's Belcourt property) and, for contrast, a marine-influenced Pennsylvanian-age coal (Herrin-Illinois No. 6).

Figure 5 shows the two assemblages portrayed as functions of total sulphur and ash content. Included on the diagram are: Cretaceous-age coals from the Peace River and East Kootenay coalfields of British Columbia; Cretaceous- and Tertiary-age coals from the non-marine coalfields of Wyoming, Montana, Colorado and Utah; non-marine Permian-age coals from New South Wales and Queensland; and Pennsylvanian-age marine coals from Illinois, West Virginia, Kentucky and Pennsylvania. Data on these coals were obtained from confidential coal files of the B.C. Ministry of Energy, Mines and Petroleum Resources, from the 1978 Keystone Coal Industry manual and from the 1975 Tex Report.

Rank of Coals

Two principal methods of determining coal rank are currently being used by exploration companies and coal-producing companies in Western Canada. The most popular method, which is also the cheaper of the two, uses the volatile-matter yield of a coal sample. In this standard American Society for Testing and Materials (ASTM) test (D 3175-73), one gram of coal is weighed in a platinum crucible and heated to $950^{\circ}\text{C} \pm 20^{\circ}\text{C}$ for seven minutes. The loss in weight, exclusive of moisture, is the volatile-matter yield of the sample.

Volatile-matter yield, converted to a dry, mineral-matter-free basis, is the principal parameter on which the ASTM "Classification of Coals by Rank" is based (D 388-66). In this system, agglomerating bituminous coals which possess less than 22% volatile matter on a dry, mineral-matter-free basis (= 23% volatile matter dry, ash-free basis) are of low-volatile rank, whereas those coals with less than 31% volatile matter (dmmf) (= 32.5% volatile matter daf basis) are medium-volatile in rank and those with over 31% volatile matter are high-volatile in rank. The vertical lines in Figure 6 show these boundaries. With a decrease in volatile matter, low-volatile bituminous coal passes into semianthracite, whereas with an increase in volatile matter and a decrease in calorific value, high-volatile bituminous coals pass into the subbituminous class.

The other method of determining rank employs reflected-light microscopy and, although it is more precise, it is also more expensive, and is therefore less commonly used in routine exploration. In this test, a sample of ground coal (<20 mesh, <850 μm) is mounted in a thermoplastic or cold-set resin, and polished. The maximum reflectance of the vitrinite maceral is then measured in oil at 546 μm on 100 grains and the mean of these values, R_0 max, is taken as the rank of that coal sample. The method is described in a number of publications; for example, the ICCP Handbook (1963), and Hacquebard and Donaldson (1970).

Reflectance determinations on vitrinite can be used to designate approximate ASTM rank groups following the recommendations of McCartney and Teichmüller (1972), as shown in Table 2.

TABLE 2. Rank categories based on reflectance

Reflectance	Rank
0.50 - 1.12%	High-volatile bituminous
1.12 - 1.51%	Medium-volatile bituminous
1.51 - 1.92%	Low-volatile bituminous
1.92 - 2.50%	Semi-anthracite
>2.50%	Anthracite

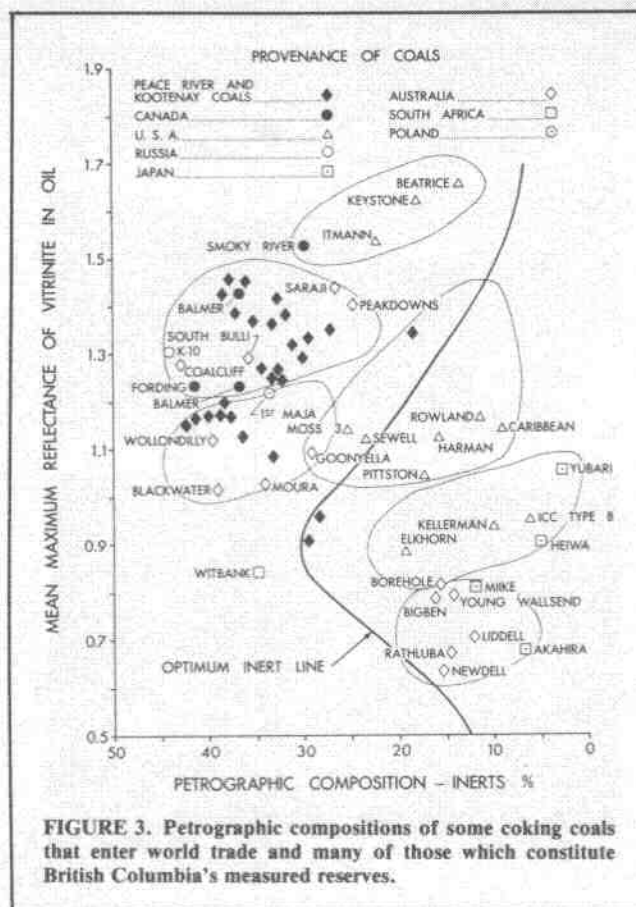


FIGURE 3. Petrographic compositions of some coking coals that enter world trade and many of those which constitute British Columbia's measured reserves.

Figure 6 shows rank as measured by the mean maximum reflectance of vitrinite in oil (R_0) versus volatile-matter content (dry, ash-free basis) of coals from the non-marine Cretaceous-age East Kootenay and Peace River coalfields, from the non-marine Permian-age German Creek seam of Queensland (Beeston, pers. comm.) and from some marine-influenced Pennsylvanian-age coals in the United States. The diagram shows that the volatile-matter content of all coals decreases with increasing rank (R_0). The continuous line shown on the diagram is the relationship between volatile matter and vitrinite reflectance for Pennsylvanian-age coals from Europe (Kötter, 1960). In general, the non-marine Cretaceous-age coals possess lower volatile yields than both the non-marine Permian-age coals and the marine-influenced coals of the same rank. In the rank range of $R_0 = 1.1$ -1.2, for example, the variation between these different coals is about 11% volatile yield. This variation is a consequence of compositional differences. Thus, Western Canadian coking coals of non-marine origin and Cretaceous age which are characterized by relatively high inertinite contents have correspondingly lower volatile yields, whereas Pennsylvanian-age, marine-influenced coals of similar maturity have higher volatile yields.

Because volatile-matter yield is dependent on both rank (R_0) and maceral composition, analysis data on coals rich in the inertinite component are not indicative of true rank (McCartney and Teichmüller, 1972). This point is displayed in Figure 6, where coals with a dry, ash-free volatile yield of 23% cover the range of $R_0 = 1.12$ -1.51. This range of reflectance covers the entire medium-volatile bituminous rank range recommended by McCartney and Teichmüller (1972), and shown on the ordinate in Figure 6.

The reflectance of the vitrinite maceral is a measure of the metamorphism or geochemical maturity that a coal has undergone. It is a precise measurement that can also be performed on oxidized coal samples and is therefore an excellent exploration tool. Because it is an independent variable that is superior to volatile-matter yield as a rank parameter, vitrinite

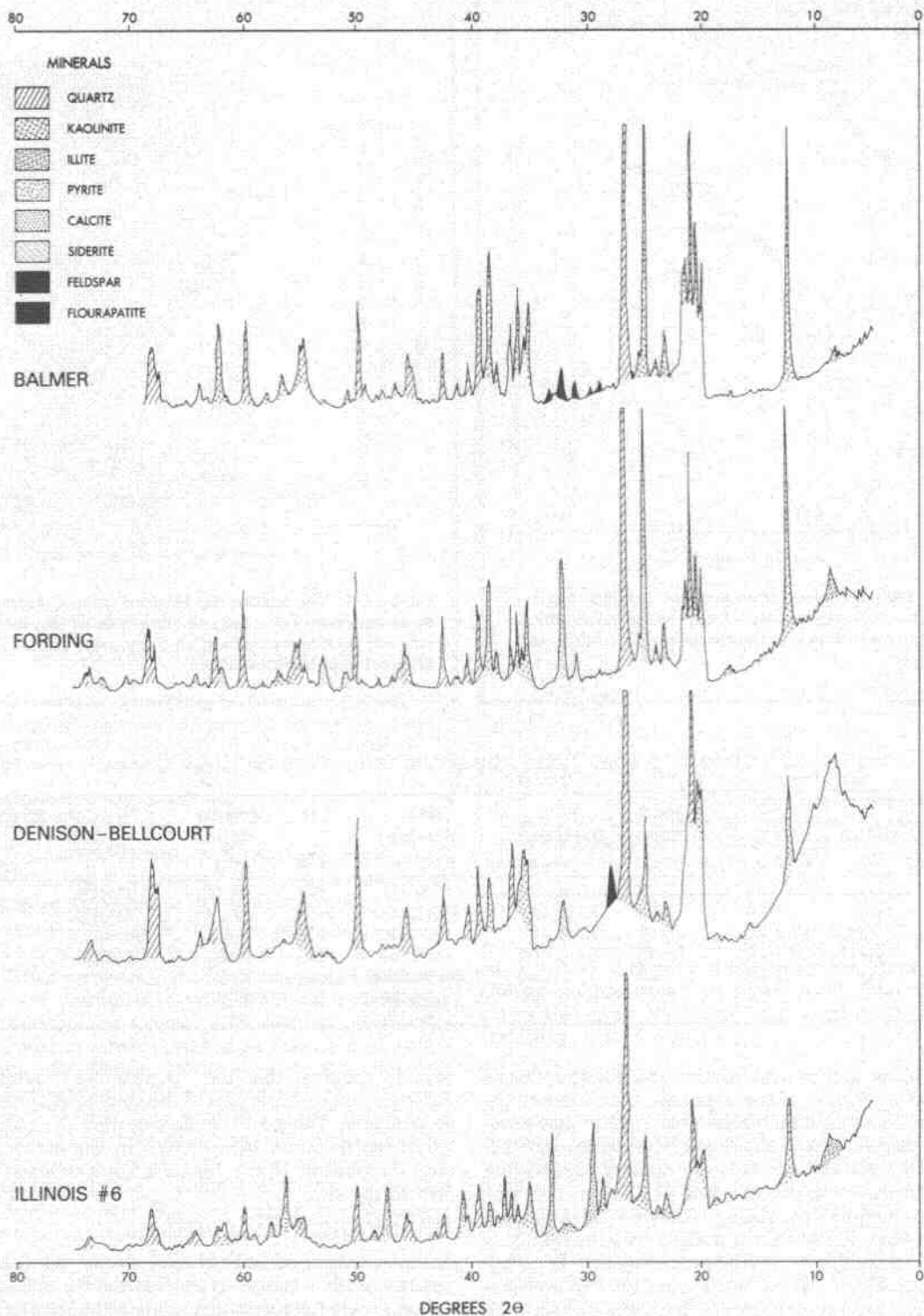


FIGURE 4. Diffraction patterns of low-temperature ash (LTA). Balmer, Fording and Denison-Belcourt are typical kaolinite-quartz assemblages. Illinois No. 6 is a typical Pennsylvanian-age pyrite-calcite-illite-quartz assemblage.

reflectance is used throughout this paper as the principal rank parameter.

The Quality of Coking Coals

One need only listen to an optimistic coal exploration geologist to realize that all coking coals are not the same. He will explain that seams on his property are of superior, excellent or prime quality, and he may even hint that seams elsewhere in the

coalfield are inferior to those which he is attempting to market! An examination of the international price structure of coking coals confirms that levels of excellence do exist, with superior quality coals commanding higher prices than others. To the layman, it is all very confusing and the problem is compounded when one realizes that 'coal quality' has a different meaning to other professions in the coal industry. A coal preparation engineer, for example, speaks of improving the

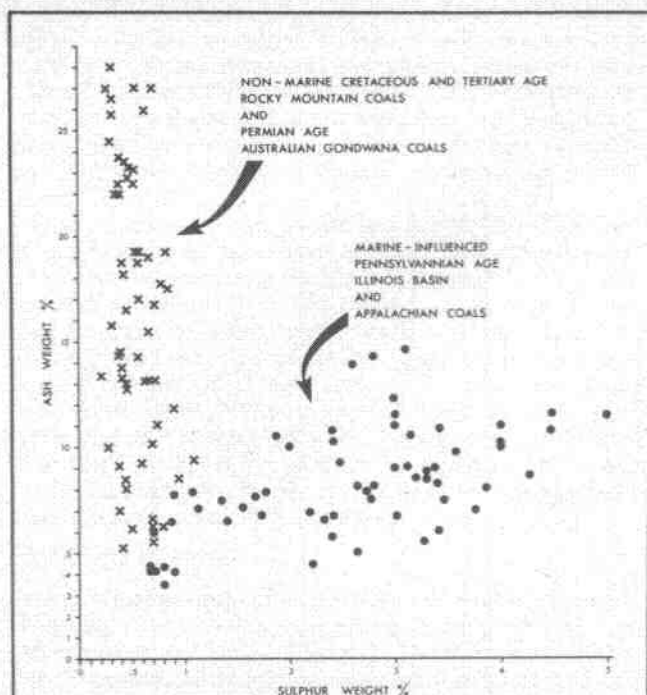


FIGURE 5. The populations of non-marine, kaolinite-quartz-bearing coals and marine-influenced, pyrite-calcite-illite-quartz-bearing coals shown as functions of ash content and sulphur content.

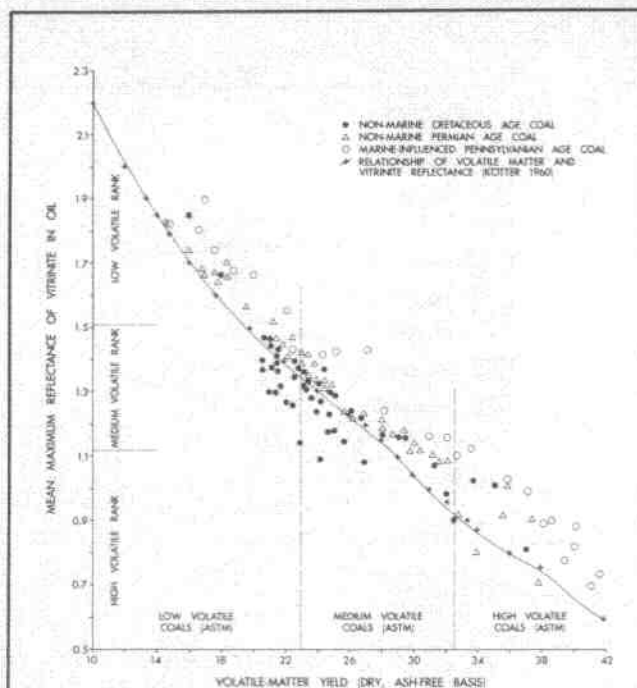


FIGURE 6. The relationship between rank, measured by the mean maximum reflectance of vitrinite in oil (R_o max) at 546 μ m, and volatile-matter yield on a dry, ash-free basis, of three different populations of coal.

TABLE 3. Classification of coking coal quality by group (after Nippon Steel Corp.)

Group Name	Group No.	Rank (\bar{R}_O max %)	Inert Content (%)	Max. Dilatation (%)	Max. Fluidity (D.D.M)	FSI	Volatile Matter (%)	Coke Strength	
								JIS D ₁₅ ³⁰	ASTM 25mm
KEYSTONE	G1	>1.50	8-30	0 to 70	5-100	6-9	16-19	92-93.5	50-65
PITTSTON	G2	1.0-1.4	8-30	80 to 260	1500-30000	7-9 +	22-34	91-94	48-65 +
BALMER	G3	1.2-1.5	25-45	-10 to 100	3-1500	5-8	19-26	90.5-93.5	40-62
MOURA	G4	0.9-1.2	25-45	-10 to 100	3-2500	5-8	25-32	90-92.5	45-57
KELLERMAN	G5	0.8-1.0	0-25	100 to 300	1500- >30000	7-9 +	32-38	75-90.5	20-48
BIG BEN	G6	<0.9	5-20	-10 to 100	3-1000	5-7	37-40	50-80	0-30

quality of a coking coal by beneficiation and, inasmuch as he is reducing the proportion of contaminants, that is indeed the case. There is, however, an inherent 'coal quality' that is imparted by the maceral composition, and this remains essentially unaltered by beneficiation. It is the maceral composition which determines the response of a coal to all of the tests currently used to determine coal quality. Therefore, in this paper, the quality of coals is determined initially by petrography as shown in the classification of coking coal quality by group (Table 3). However, as there is only a small overlap between the groups, and because they remain mutually distinct even when other parameters are used to define them, coking coal quality groups can be recognized by dilatation, fluidity and FSI if the rank (R_o max) is also known.

The classification of coking coal quality by group, as shown in Table 3, is used by Japan's Nippon Steel Corporation. Although the company's coal assessment methods have been described (Miyazu *et al.*, 1975), the nature of the classification has remained obscure despite the fact that "populations" of coals have been shown in diagrams prepared by the company (Miyazu *et al.*, 1975, Figure 15; Matsuoka 1976, Figure 4, 5b). The existence of natural populations among coking coals only became obvious to the author when data on fluidity, dilatation and coke strength (taken from Miyazu 1975, Matsuoka 1976 and Kojima 1973), were redrawn on the R_o/I diagram. It then

became apparent that the "populations" outlined by the Japanese authors form part of the same subdivisions described as groups in Table 3. The classification of coking coals by group has therefore been derived by the author, but credit must be granted to the Japanese authors whose papers implanted the idea.

Rheological Properties

A characteristic of coking coals is that on heating in the absence of air, volatiles are evolved and the coal agglomerates to form coke. Because of the technological significance of this phenomenon, a number of tests have been devised to quantify the amount of swelling involved. The commonest of these tests involve rapid-heating expansion or free swelling index (FSI), slow-heating expansion or dilatation and apparent fluidity, all of which are parameters in the classification of coking coal quality by group (Table 3).

(1) Free Swelling Index

To determine the free swelling index (FSI) by the ASTM method (D720-67), one gram of finely powdered coal (+60 mesh or +250 μ m) is rapidly heated to 820°C and the silhouette of the resulting coke button is compared with a series of standard profiles. The FSI of the sample is the number of the standard profile (0-9) which it most closely

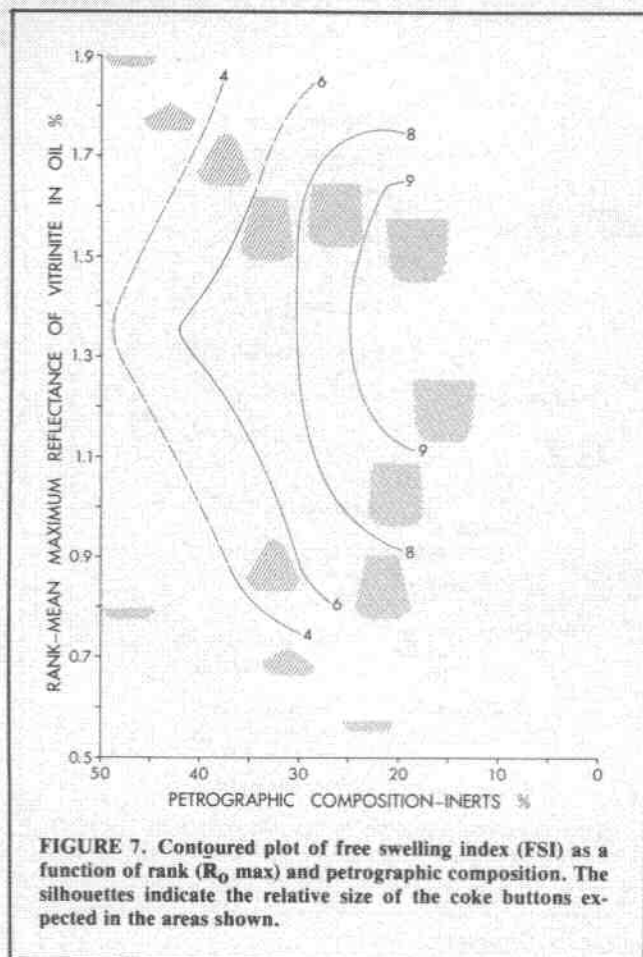


FIGURE 7. Contoured plot of free swelling index (FSI) as a function of rank (R_0 max) and petrographic composition. The silhouettes indicate the relative size of the coke buttons expected in the areas shown.

resembles. The method is rapid and relatively precise, and, because it is sensitive to oxidation, it is used in exploration adits to determine the extent of the oxidation zone.

Figure 7 shows FSI as a function of rank (\bar{R}_0) and petrographic composition (inert content). The figure was derived by determining the FSI of 138 samples of coal with known rank and petrographic compositions and contouring the results (Pearson and Grieve, 1978; Pearson, 1979). The diagram is similar to others produced by Strauss *et al.* (1976) and Shibaoka and Bennett (1976) showing FSI values of Australian, Japanese and Indonesian coals. Of the coals used in the diagram, 99 were from Western Canada and 39 were from the German Creek seam of Queensland, Australia (J.W. Besston, pers. comm.). Data on the Western Canadian coals were obtained from the B.C. Ministry of Energy, Mines and Petroleum Resources coal files and from Kaiser Resources Ltd. (R. Venzey, pers. comm.).

The figure shows a series of isoswelling lines for unoxidized non-marine coals, with some representative button profiles. The figure demonstrates that for any rank, the swelling values increase as the quantity of inerts decreases. It also shows that for a fixed composition, superior swelling is obtained at intermediate rank values.

In evaluating FSI values, it is important to compare only those coals with similar ash contents. Clearly, ash values contribute to total inert contents and affect FSI values (Fig. 7).

Figure 8 plots FSI against rank values for unoxidized non-marine Cretaceous-age Western Canadian coking coals and the Permian-age German Creek seam. The values shown represent coals with ash contents of $10 \pm 2\%$. The two curved lines drawn on the figure form an envelope for samples of the German Creek seam. They actually represent upper and lower limits of inert contents of this seam, approximately 22% and 32% inerts (Beeston, 1977). Included on the figure are the ap-

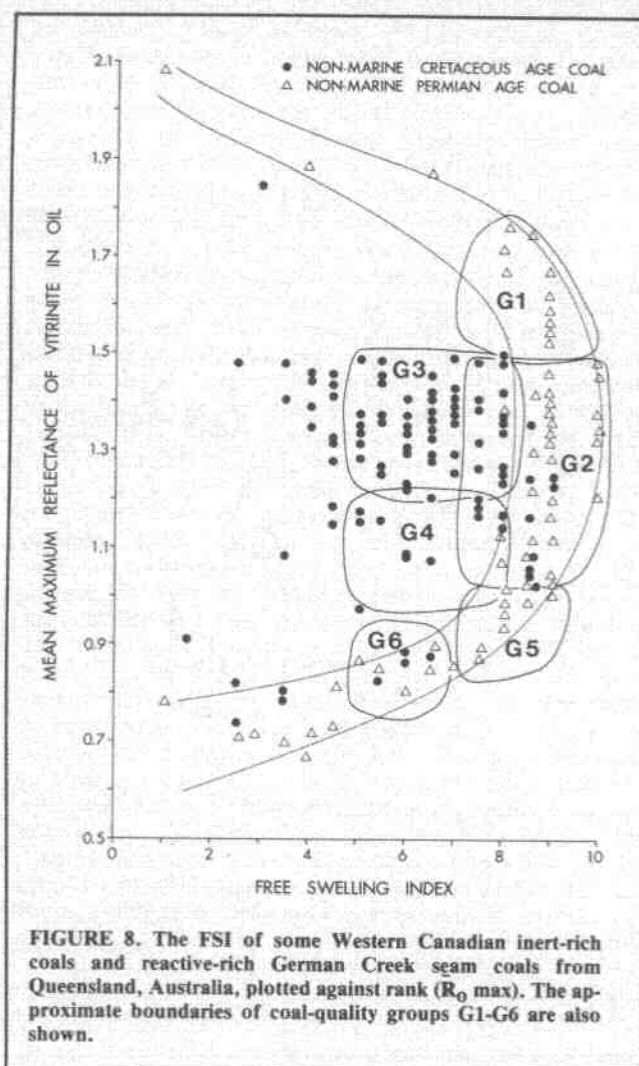


FIGURE 8. The FSI of some Western Canadian inert-rich coals and reactive-rich German Creek seam coals from Queensland, Australia, plotted against rank (R_0 max). The approximate boundaries of coal-quality groups G1-G6 are also shown.

proximate positions of the coal quality groups, G1-G6, defined in Table 3. Compared with the German Creek seam, British Columbia coking coals are rich in inerts. This apparently explains the lower FSI values characteristic for the Western Canadian coals in Figure 8.

(2) Dilatation

Whereas the semi-coke button produced in the FSI test above is heated rapidly with no external constraints (except for the crucible lid), the semi-coke pencil produced in the dilatometer is the result of slow heating in a confined tube. A 60-mm pencil of finely ground coal (+60 mesh, +250 μ m) is heated at a rate of 3°C per minute from 330°C to 600°C. The change in the length of the pencil in relation to the temperature is continuously recorded on a rotating chart. The resulting curves are an indication of caking capacity.

The important parameters recorded are: the softening temperature; the maximum contraction and the temperature at which it occurs; the maximum dilatation and the temperature at which it occurs. Although there is a mathematical function which links these parameters in a single value (Simonis *et al.*, 1966), in practice the important value is maximum dilatation.

In effect, the maximum dilatation can be regarded as a more precise measure of swelling. For example, two coals which both give an FSI of 8 may have quite different maximum dilatations. The distinction is somewhat academic, however, as any coal with an FSI of 8 is obviously a good coking coal.

Figure 9 shows rank (R_0) and maximum dilatation for coals from a number of localities in the East Kootenay coalfield, and fourteen samples from three areas in the Peace River

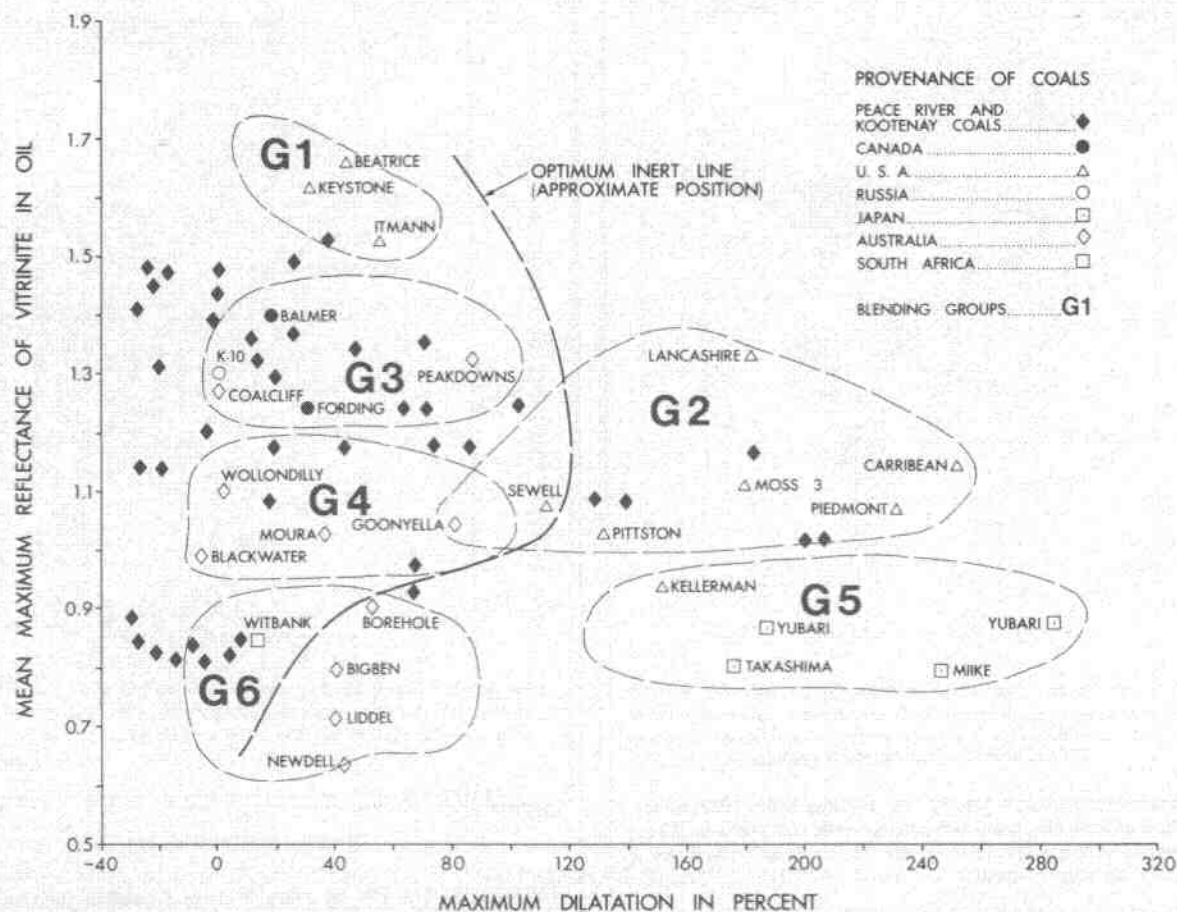


FIGURE 9. The maximum dilations of some coking coals that enter world trade and many of those which constitute British Columbia's measured reserves, together with the coal-quality groups, G1-G6, plotted against rank (R_0 max).

coalfield, together with some of the principal coking coals currently entering world trade. The diagram is similar to that used by Matsuoka (1977), except that in this instance R_0 max and not volatile matter is used as the rank parameter. Also shown in the figure is the approximate position of the optimum inert line, which represents the inert content that each rank of coal requires to produce the strongest coke (Schapiro *et al.*, 1961). The six principal coal groups, G1-G6, defined in Table 3, are also shown.

The figure shows that maximum dilatation is dependent on both rank and petrographic composition and that the highest maximum dilations are recorded between 0.8-1.2% reflectance. It also shows that the highest maximum dilations are obtained in medium-volatile and high-volatile coals of the Pittston Group (G2) and Kellerman Group (G5), both of which are rich in the reactive macerals vitrinite and exinite. A recently proposed classification of coking coals (Marshall, 1976) shows a similar negatively skewed narrow-peaked distribution with highest maximum dilations in the rank range $R_0 = 1.0-1.4\%$. Figure 9 also shows that inertinite-rich coals (to the left of the optimum inert line) possess lower maximum dilations than reactive-rich coals. The ideal maceral composition, for both individual coking coals and blends, lies on the optimum inert line. Therefore, the use of highly dilating coals of the Kellerman Group, for example, in a blend, requires the use of lower-dilating Balmer Group coals to ensure that optimum balance is maintained.

Figure 10 is a preliminary plot of maximum dilatation values as a function of rank (R_0) and petrographic composition. There are not adequate data available at present to describe more accurately the isodilatation curves. The figure shows that

inertinite-rich medium-rank coals, typical of the Balmer Group, have similar dilatation values to the Keystone and Moura Groups and to parts of the reactive-rich, high-volatile, "soft coking coals" typical of the Big Ben Group. It also shows that the highest maximum dilations are obtained in high-volatile and medium-volatile coals of the Kellerman Group (G5) and Pittston Group (G2), both of which are rich in the reactive macerals vitrinite and exinite.

(3) Fluidity by Gieseler Plastometer

To determine fluidity, according to ASTM standards (D 2639-74), 5 grams of finely ground coal (+40 mesh, 425 μ m) is placed in a crucible with a 10-kg load. The sample is heated at a rate of 3°C per minute between 300°C and 550°C. A constant torque is applied to a mechanical stirrer within the sample and the apparent fluidity is measured by the number of rotations per minute of a dial attached to the stirrer. The important parameters recorded are: the initial softening temperature (dial movement reaches one dial division per minute); the maximum fluid temperature; the maximum fluidity; and the solidification temperature.

Figure 11 shows rank (R_0) and maximum Gieseler fluidity of coals from the same locations as those shown in Figure 9. The approximate position of the optimum inert line is also included in the figure. The six principal coal groups, G1-G6, are included for reference. The diagram is similar to that of Miyazu *et al.* (1974), which showed reflectance data measured at 525 μ m. In this instance, reflectance is measured at 546 μ m.

The figure shows that maximum Gieseler fluidity is a function of rank and petrographic composition, with highest maximum fluidities occurring between 0.8%-1.2% reflectance. It

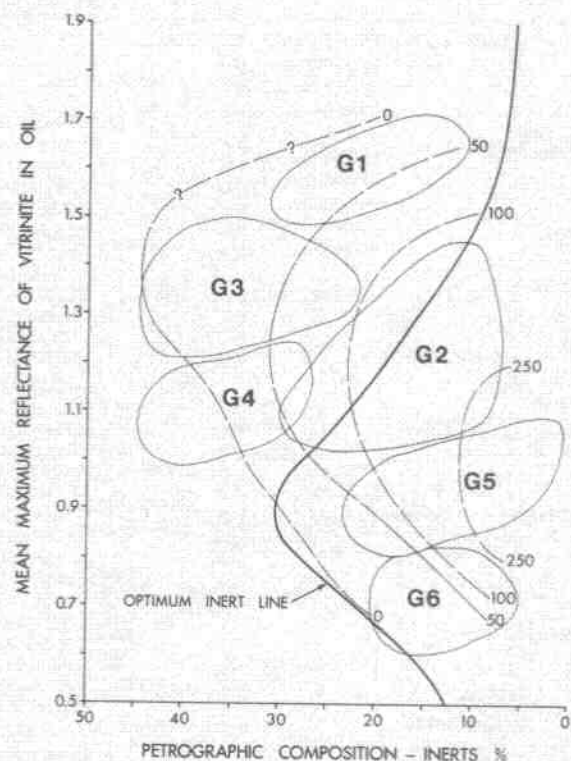


FIGURE 10. Contoured plot of predicted maximum dilatations in coal quality groups, G1-G6, as a function of rank (R_O max) and petrographic composition.

has been noted in an earlier section that exinite contributes to fluidity and it is therefore significant that fluidity decreases rapidly above $R_O = 1.3$, where exinite can no longer be distinguished. Figure 11 shows that inertinite-rich coals (those to the left of the optimum inert line) have lower Gieseler fluidities than reactive-rich coals.

The comments made above with respect to dilatation and blending are equally applicable to Gieseler fluidity and blending. The use of highly fluid, reactive-rich high-volatile coals of, for example, the Kellerman group (G5) in a coke oven blend requires the addition to the blend of Balmer Group (G3) inertinite-rich, low-fluidity coal. This keeps the composition of the blend near the optimum inert line and ensures adequate fusion of the oven charge.

Figure 12 shows a preliminary plot of maximum Gieseler fluidity as a function of rank (R_O) and petrographic composition. Once again, the precision of the location of the curves is limited by the small quantity of data available. It is evident, however, that the Balmer Group (G3) and Moura Group (G4) have inherently lower fluidities than, for example, Kellerman Group (G5) and Pittston Group (G2) coals.

Coking Capacity

The influence of petrographic composition and rank on volatile-matter yield, swelling capacity, dilatation and Gieseler fluidity has been demonstrated above. Their influence on coking capacity will be examined here.

Tumbler Stability of Coke

Coke provides two functions in a blast furnace. It must be strong enough to support the furnace charge and it must provide adequate heat to smelt that charge. A principal measure of coke quality is therefore strength or resistance to impact and abrasion, which may be measured by a tumble drum test. Several types of such tests are in use in different countries. In the ASTM test (D 294-64), the coke stability factor is obtained

by tumbling 10 kg of +50 mm, -75 mm coke in a drum of specific dimensions at 24 rpm for 1400 revolutions. The coke is then screened, and the weight percentage remaining on a 24-mm sieve is called the ASTM stability factor. Another parameter, the hardness factor, is the cumulative weight percentage of coke remaining on a 6.3-mm sieve. The Japanese Industrial Standard (JIS), D_{15}^{30} , and Micum value M_{10} , used in Europe, represent similar tests of the stability factor.

Prediction of coke strength using rank and petrographic composition parameters has been the aim of petrographers for some years. To distinguish between methods used, a petrographically predicted coke strength is referred to as a stability index, whereas the tumbler-determined value is the stability factor. Ideally, the stability index has the same value as the stability factor. Although Schapiro *et al.*, (1961) and Benedict *et al.*, (1968) report good correlations of stability index and stability factor with Pennsylvanian-age eastern U.S. coals, application of their methods to coals of other geographic areas and age is not as successful (Williams, 1971; Ignasiak, 1976). Recently, a semiquantitative method of predicting coke strength of Western Canadian coals as a function of volatile-matter yield (d.a.f.) and free swelling index was demonstrated (Pearson and Grieve, 1979; Pearson, 1979) (Fig. 13). This notwithstanding, a simplified version of the Schapiro *et al.*, (1961) method has been developed to allow rapid prediction of coke stability using rank and inert content as coordinates (Fig. 14) (Pearson and Grieve, 1978, and in prep.). This diagram is, however, not empirical, as in the case of Figure 13. From Figure 14, it is apparent that a wide compositional variety of bituminous coals agglomerate, but that good coke (ASTM stability greater than 50, JIS D_{15}^{30} greater than 92) is generally produced from medium- and high-rank ($R_O = 1.0$ - 1.7%) coals. It is also apparent that in this rank range, a decreasing content of inert material in inertinite-rich coals and an increasing content of inert material in reactive-rich coals leads to the production of stronger coke.

The optimum inert line in Figure 14 defines the petrographic composition of the strongest coke, plotted against rank. There is not, however, a symmetrical distribution of iso-strength contours about this optimum line. Between R_O values of 1.25% and 1.45%, on the inertinite-rich side, a convex bulge on the 60 iso-stability index increases in amplitude with decreasing values of stability index. This is of particular interest because Western Canada has large resources of coal that occupy the compositional area occupied by the bulge.

Figure 15 shows the coordinates of world-wide coking coals on the R_O -I diagram. It is obvious that Canadian coking coals, which are non-marine coals, always occur on the more inert side of the diagram relative to the Pennsylvanian-age, often marine-influenced coals of the eastern United States. By comparison of Figure 14 with Figure 15, it is also clear that U.S. low-volatile coal and U.S. medium-volatile coal produce stronger coke when carbonized alone than do Canadian or Australian coals of similar rank. It is also evident that Australian and Japanese high-volatile coals produce structurally weak cokes when carbonized alone.

Logistics of Coke Making

The influence of petrographic composition and rank on the coking capacity of coals has been demonstrated above. Rarely, however, are coals carbonized alone. Coke production today is the most expensive aspect of steel production and it is hardly surprising that in the last two decades coke technology has focussed on the production of the strongest metallurgical coke for the smallest financial outlay. The aim is therefore to blend cheaper coals, which two decades ago would have been regarded as inferior, with smaller proportions of the expensive so-called superior-quality coals to produce good coke.

This section therefore examines the influence of petrographic composition and rank (R_O) on the price and blending potential of Western Canadian coking coal.

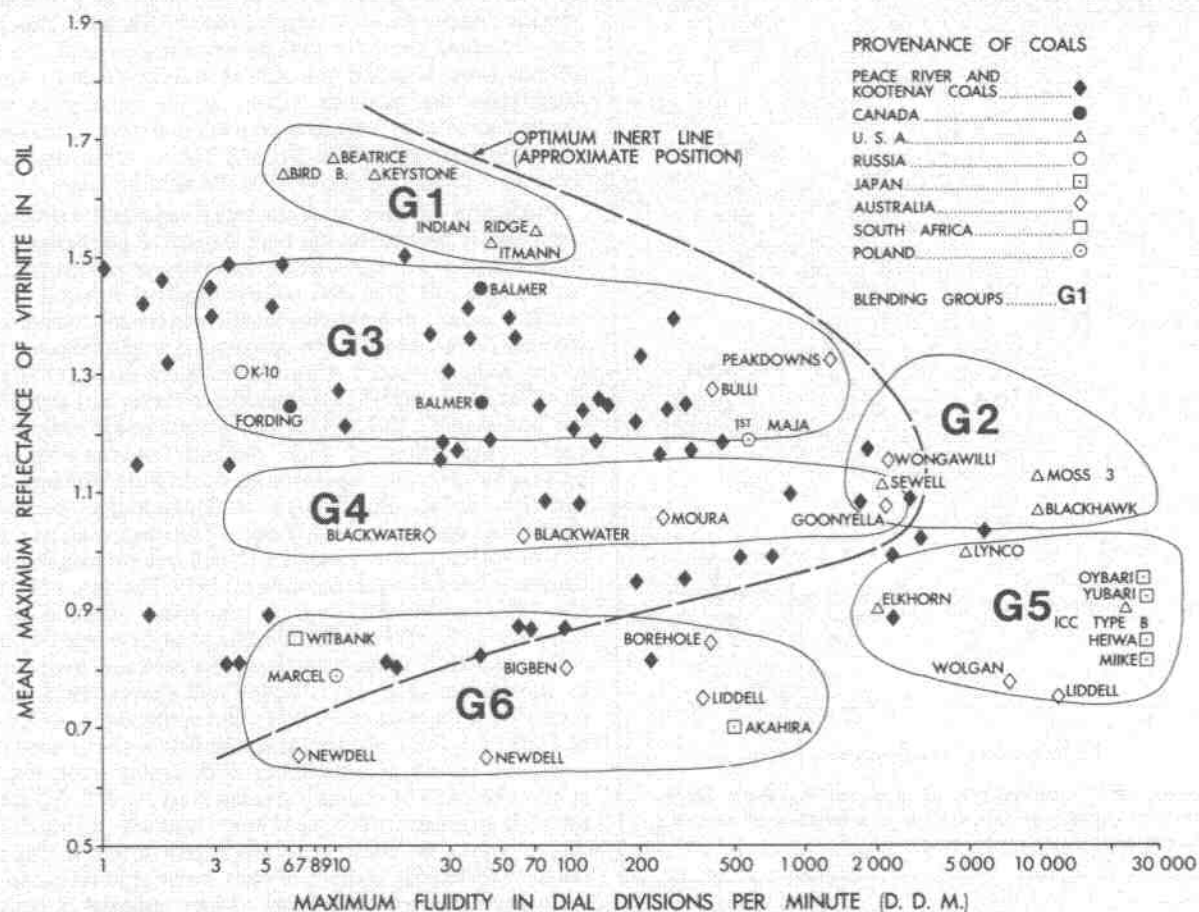


FIGURE 11. The maximum Gieseler fluidity of some coking coals that enter world trade and many of those which constitute British Columbia's measured reserves, together with the coal quality groups G1-G6, plotted against rank (R_0 max).

Coal Price

Figure 16 shows prices in \$(U.S.) per ton, FOB port (Coalweek; July, 1978), for individual coking coals that enter the Japanese market, as functions of rank and petrographic composition. It shows that at a reflectance value of 1.15% R_0 , for example, coal price increases from \$(U.S.) 51.81 to \$(U.S.) 60.50 per ton as the inert content drops from 40% to 10%. It also shows that at a constant petrographic composition of, for example, 15% inerts, coal price increases from \$(U.S.) 43.54 to \$(U.S.) 72.21 per ton as the rank increases from 0.6% to R_0 to 1.68% R_0 . An interpretation of these data is that coal price is related to rank and caking power, with rank being the more important characteristic. To test this hypothesis, a stepwise linear regression analysis, using Sharp APL software (Sharp *et al.*, 1976), was performed on 33 international coking coals (Table 4), using the following eleven variables: ash content; sulphur content; term of contract; annual tonnage contracted; mean maximum reflectance, R_0 ; petrographic composition, inerts per cent; free swelling index; fixed carbon (dry, ash-free basis); dilatation; fluidity; and a dummy variable for availability based on the size of measured reserves. Price, per long ton, in \$(U.S.), FOB port, was the dependent variable. Eighty-eight per cent of the variation in coal price could be explained by these variables. The only statistically significant variables, however, in order of importance, were FSI (68%), R_0 (8%) and ash (4%), which together explain 80 per cent of the price variation. The regression model is:

$$\text{Price} = 32.24 + 2.3(\text{FSI}) + 13.4(\bar{R}_0) - 1.24(\text{Ash})$$

$$R^2 = 80, F = 33.9, F(2,26,0.99) = 4.7, \text{S.E.E.} = 4.4$$

The regression analysis confirms the significance of the rank and caking parameters determined by inspection of Figure 15,

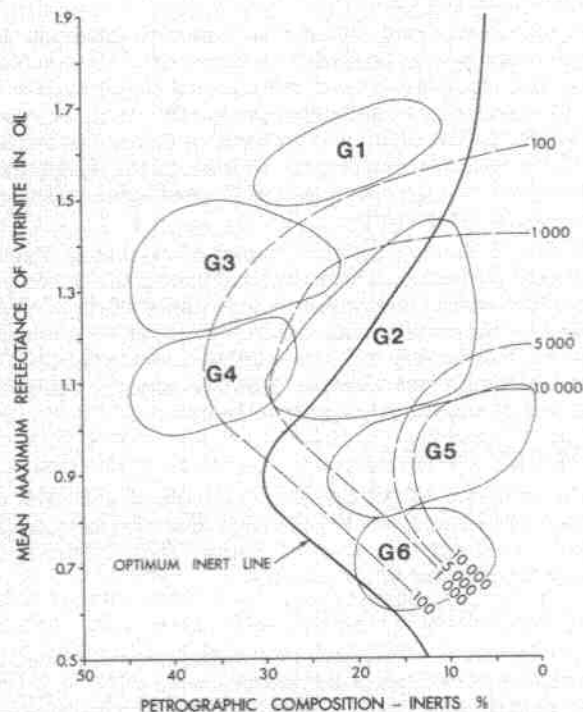


FIGURE 12. Contoured plot of predicted maximum Gieseler fluidity in coal quality groups, G1-G6, as a function of rank (R_0 max) and petrographic composition.

TABLE 4. Values of variables used in the multiple regression analysis

Coal Brand	Ash (%)	Sulphur (%)	Contract Term (yrs)	Annual Tonnage (10 ⁶)	\bar{R}_0 max	Inerts (%)	FSI	F.C. (DAF) (%)	Dilatation	Fluidity (DDM)	Availability (Dummy)	Price, (US\$) (FOB, LT)
UNITED STATES												
KEYSTONE	5.5	0.8	6	0.13	1.64	18	9	79.0	35	18	1	72.00
ITMANN	5.5	0.8	2	0.9	1.52	21	9	81.5	55	47	1	70.60
BEATRICE	4.5	0.7	3	0.66	1.66	14	9	82.0	44	10	1	72.21
PITTSTON	7.0	0.7	12	3.5	1.04	17	8	66.0	132	3,000	1	69.80
ROWLAND	6.5	0.8	3	0.7	1.30	12	9	70.0	215	20,000	1	60.50
ICC TYPE B	4.25	0.8	3	1.0	0.91	10	7	61.0	170	25,000	1	54.50
GILBERT	9.5	0.8	1	1.0	0.90	20	8	68.0	130	3,000	1	64.48
SPRAGUE	6.0	0.8	1	1.0	0.90	20	9	69.0	130	3,000	1	60.72
KELLERMAN	5.5	0.8	15	1.0	0.94	10	9	67.0	152	15,000	1	57.00
MASCO	6.5	0.9	1	0.6	1.10	20	9	65.5	150	15,000	1	53.00
HARMAN	6.0	0.8	1	0.45	1.00	20	9	71.0	145	6,000	1	60.00
AUSTRALIA												
COAL CLIFF	10.3	0.4	13	2.26	1.27	45	6	76.3	-15	5	0	53.17
SOUTH BULLI	10.3	0.4	5	1.24	1.20	36	6	75.8	-15	400	0	53.17
WOLLON DILLY	10.0	0.4	5	2.90	1.10	49	5	68.5	4	30	0	51.86
BLACKWATER	8.3	0.5	10	3.19	1.14	37	6	71.0	-5	25	0	51.46
GOON YELLA	7.3	0.65	13	3.93	1.10	30	7	71.5	82	2,300	0	51.40
MOURA	8.0	0.55	13	1.77	0.90	17	7	66.5	38	300	0	49.27
PEAK DOWNS	9.3	0.65	12	2.95	1.42	24	7	77.0	87	1,200	0	50.42
SARAJI	9.5	0.7	10	2.65	1.42	24	8	78.2	87	1,200	0	50.34
SO. BLACKWATER	6.8	0.55	15	1.47	1.02	37	6	70.0	-5	25	0	50.83
BIG BEN	9.5	0.64	5	0.88	0.77	22	54	60.6	41	100	1	42.88
DAIYON	8.5	0.75	10	1.47	0.77	22	44	60.4	35	70	1	42.88
LIDDELL	8.5	0.6	1	0.98	0.71	16	5	58.6	44	350	1	43.54
LEAMINGTON	8.5	0.5	10	1.00	0.85	19	5	58.9	41	450	1	43.54
NEWDELL	8.5	0.6	1	1.37	0.64	15.5	5	58.6	44	30	1	43.54
RATHLUBA	8.5	0.85	5	0.34	0.77	13	5	59.1	-15	205	1	42.88
YOUNG WALLSEND	8.5	0.8	1	0.14	0.85	15	5	58.6	2	170	1	42.88
SOUTH AFRICA												
WITBANK	7.0	0.7	15	1.53	0.85	30	24	64.0	15	6	0	37.72
CANADA												
BALMER	9.5	0.4	15	4.75	1.35	36	7	77.0	19	40	0	52.45
FORDING	9.5	0.45	15	3.00	1.25	39	7	75.0	30	6	0	52.45
LUSCAR	9.25	0.37	15	1.70	1.17	39	7	72.0	25	15	0	51.96
SMOKY RIVER	7.0	0.5	3	0.94	1.60	30	7	86.0	60	70	0	59.43
VICARY	11.5	0.6	3	0.89	1.17	39	6	75.5	30	7	0	52.81

but surprisingly, caking is the more significant variable (c.f. Fig. 7).

By using the regression model shown above, price data were computed for forty-two (X.Y.) points in Figure 16, corresponding to six different values of FSI along seven separate rank (\bar{R}_0) traverses for (i) ash contents of 5% and (ii) ash contents of 9%. Contours representing iso-price lines were then fitted to the data. Figure 16 shows contours plotted for 9% ash, which is a good approximation for Australian and Canadian coking coals. However, U.S. coals generally have ash contents of 4-7% and will receive between \$2.50 and \$5.00 more per ton than is inferred by the contours shown.

Several points arise from an analysis of this diagram that deserve comment. Although only 80 per cent of the price variation is explainable using this model, there is nevertheless a relatively good fit to the actual prices plotted. Individually, however, there are some unusual prices paid; for example, the low price of the two Australian coals on the reactive side of Balmer Group G3, and the high price of the U.S. coal on the low-rank side of Pittston Group G2. The low price paid for the Australian coal could imply that currently it is a "buyers market" for coal, but the high price paid for the U.S. coal argues against this.

Blending Potential

Figure 17 shows three typical Japanese coking coal blends, circa 1976, arranged in order of increasing Canadian coking coal content. Each blend contains a different number of coals, varying proportions of low-volatile, medium-volatile and high-volatile coals, and a different ratio of hard coals to soft-coking coals. The nationality of each coal is identified along with the coal quality group to which it belongs. The optimum inert line is included together with the target area for blend composi-

tion. Coals to the left of the optimum inert line are inertinite-rich; those to the right are rich in reactive macerals. Figure 18 shows the different proportions of the coal quality groups in each of the three blends.

The petrographic compositions of the coals identified in the three blends were described as vectors and added as linear combinations to obtain the blend compositions shown in Figure 17. This is an oversimplification which considers rank and petrographic composition (and properties that are functions of these) as additive properties, and there is abundant evidence that this may not always be so (Williams, 1971). Nevertheless, the predicted coke quality is not too far from the actual value. In discussion of his paper, Matsuoka (*op. cit.*, p.261, 262) indicated that this is the practice at Nippon Steel Corporation.

Traditionally, Pennsylvanian-age Keystone Group (G1) coals were blended with lower rank coals, to reduce the pressure they exert on coke-oven walls and to lower the cost of the coke, while maintaining high coke yields. In the \bar{R}_0 -I diagram, connecting lines between constituent coals in such blends would be subparallel to the ordinate axis. In modern blends, however, it is apparent that the connecting lines are roughly perpendicular to the optimum inert line and thus form a sigmoidal curve. Thus, by incorporating the inert-rich, low-fluidity, low-dilatation Western Canadian coking coals (or their Australian equivalents), coke-makers can utilize cheaper, soft-coking, high-fluidity, high-dilatation coals of Australia and Japan. Moreover, they need less of the expensive low-volatile American coals. The net result is good metallurgical coke, at lower cost.

Market Considerations

This section examines the supply-and-demand relationship in

the context of the quality of Western Canadian coking coal reserves.

Reserves of Coal by Blending Group

Figure 19 shows the distribution of coal quality groups in the measured reserves of both British Columbia and Queensland, Australia. The data for British Columbia coals were extracted from the confidential coal files of the Ministry of Energy, Mines and Petroleum Resources and represent the most up-to-date estimate of measured reserves. Data on Queensland coals were obtained from the Queensland Government Mining Journal for December 1978.

It is apparent that 89 per cent of British Columbia's measured reserves and 82 per cent of Queensland's measured reserves are of the inertinite-rich Balmer Group (G3) and Moura Group (G4) coals respectively. Despite the fact that Japanese blends require about 60 per cent of these inertinite-rich coal, there is nevertheless an overabundance of these two coal quality groups available to the world coking coal market.

Recognition of this fact has caused a change in exploration strategy in Queensland. Kellerman Group (G5) coals at the Gregory property and Keystone Group (G1) coals at Hail Creek and Norwich Park are recent additions to Queensland's measured reserves, and current exploration of the German Creek seam will add considerable tonnages of Pittston Group (G2) coal.

Current production from the Luscar and Vicary Creek mines in Alberta is of Balmer Group (G3) coal, whereas Smoky River is the only producer in Western Canada of Keystone Group (G1) coal. To remain competitive and to add an alternative source of supply to the international coking coal market, Western Canada should widen its group-base of measured reserves to include, where possible, Pittston Group (G2) coals and Kellerman Group (G5) coals. With the burden of transportation costs, it is doubtful whether the lower-priced

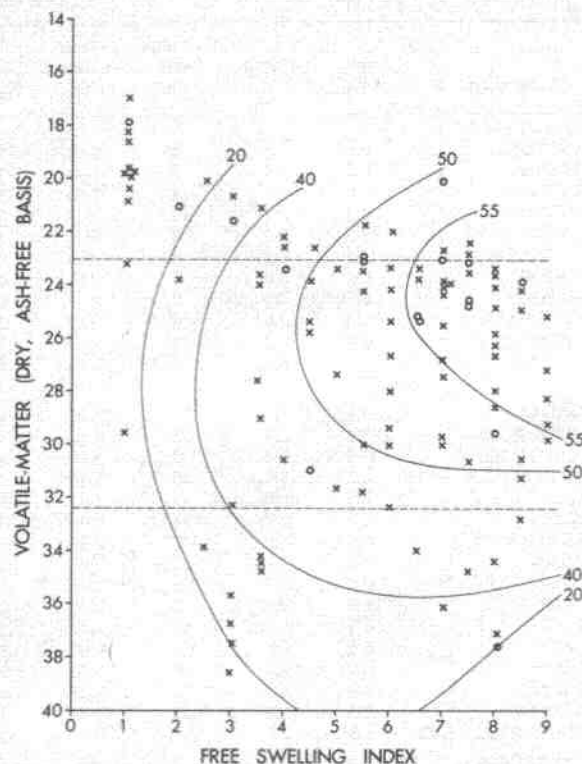


FIGURE 13. Contoured plot of the actual stability factors of 109 experimental cokes produced from British Columbia coals. Circles indicate data points with stabilities either higher or lower than inferred by the enclosing curves.

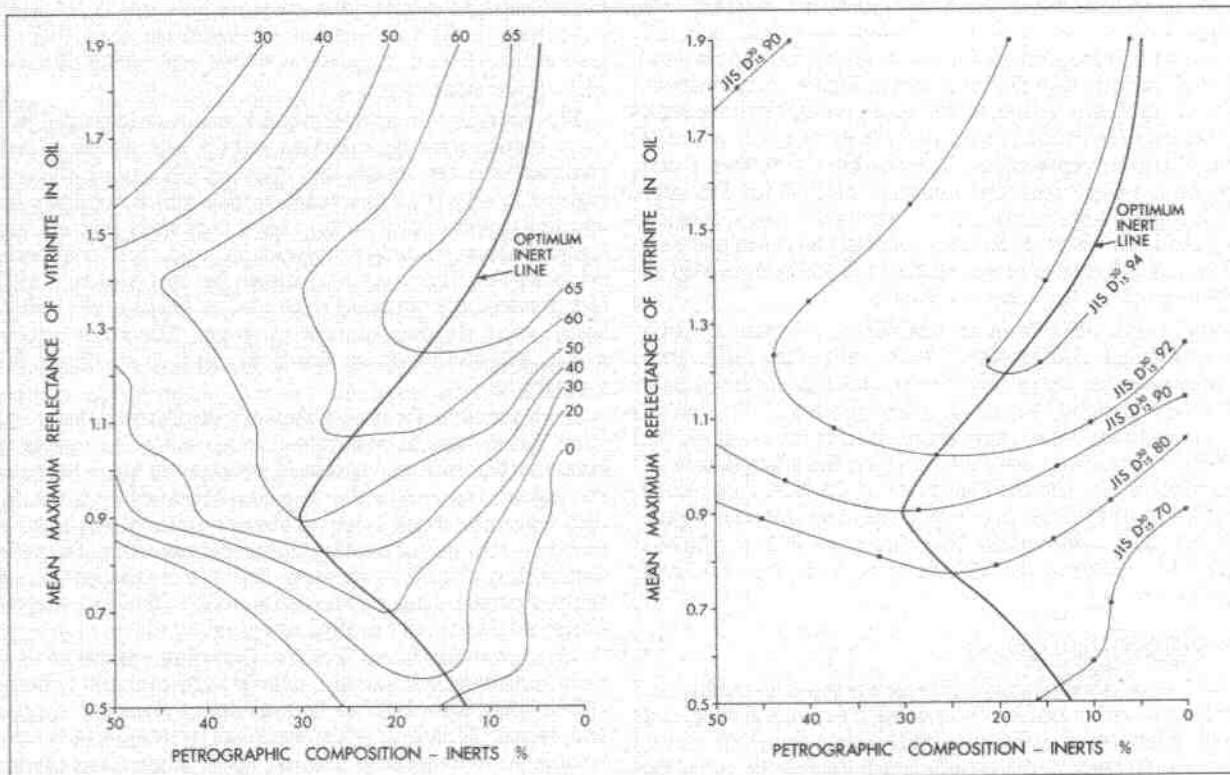


FIGURE 14. Contoured plot of predicted stability indices in ASTM and JIS D₁₅³⁰ as a function of rank (\bar{R}_0 max) and petrographic composition.

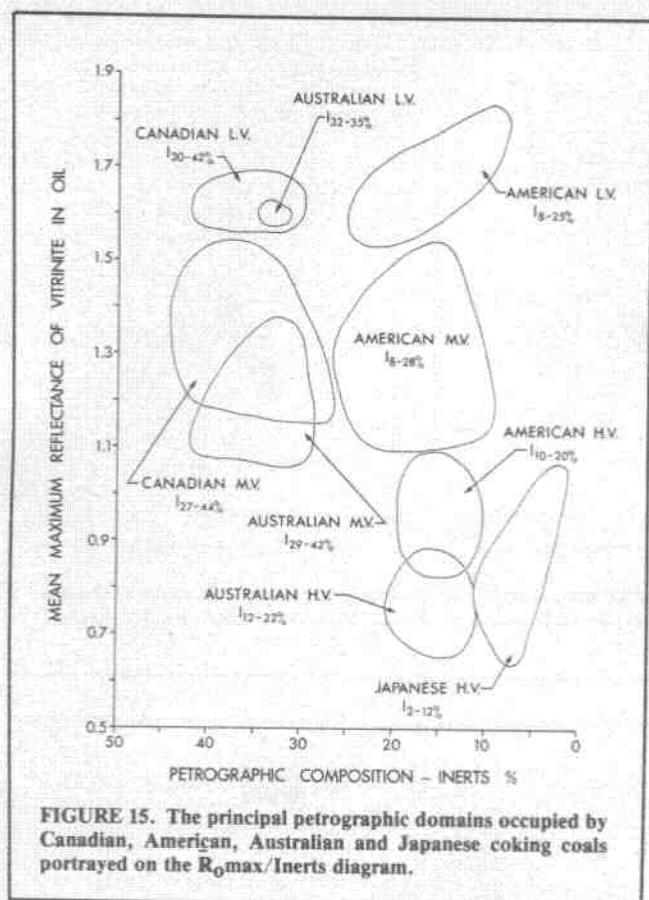


FIGURE 15. The principal petrographic domains occupied by Canadian, American, Australian and Japanese coking coals portrayed on the R_0 max/Inerts diagram.

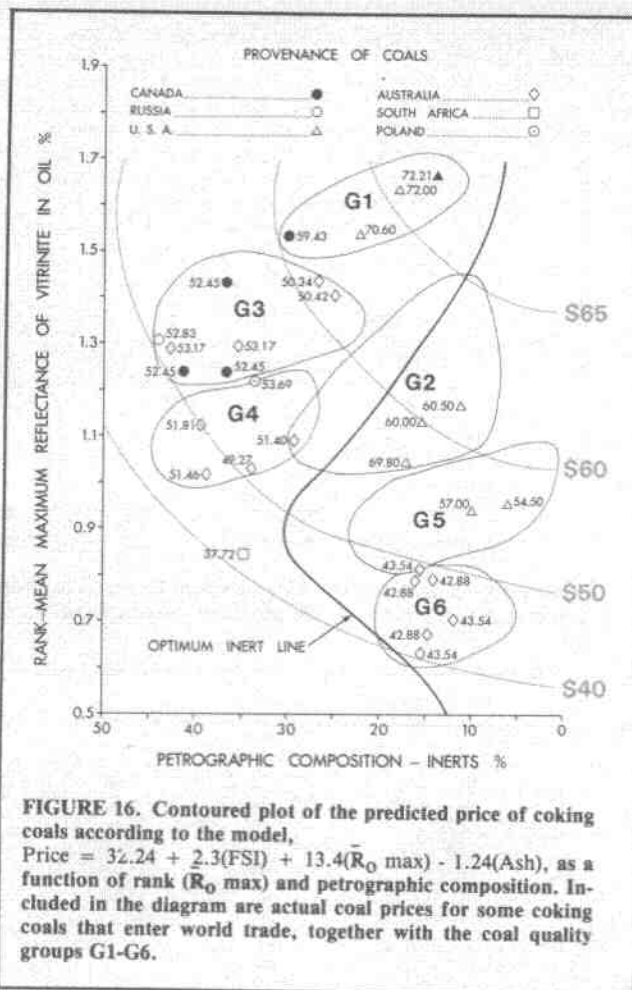


FIGURE 16. Contoured plot of the predicted price of coking coals according to the model, $\text{Price} = 32.24 + 2.3(\text{FSI}) + 13.4(\bar{R}_0 \text{ max}) - 1.24(\text{Ash})$, as a function of rank (R_0 max) and petrographic composition. Included in the diagram are actual coal prices for some coking coals that enter world trade, together with the coal quality groups G1-G6.

Big Ben Group (G6) coals from the Rocky Mountains of Western Canada could compete in the international market.

Acknowledgments

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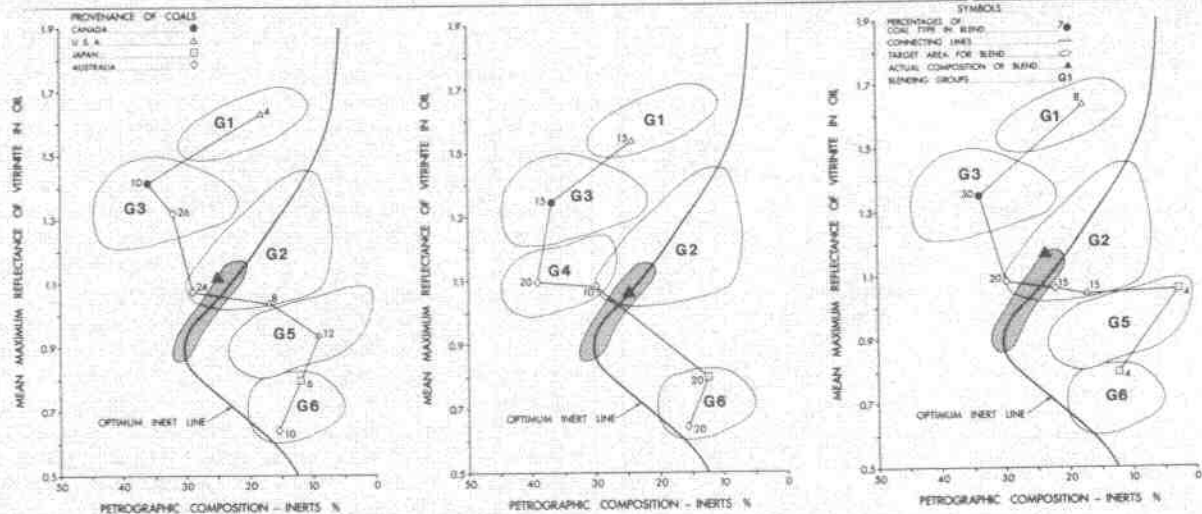


FIGURE 17. Three Japanese coking coal blends, circa 1976, showing the nationality of the constituent coals, the proportions of the constituent coals in the blend and the calculated composition of the blends plotted as functions of rank (R_o max) and petrographic composition.

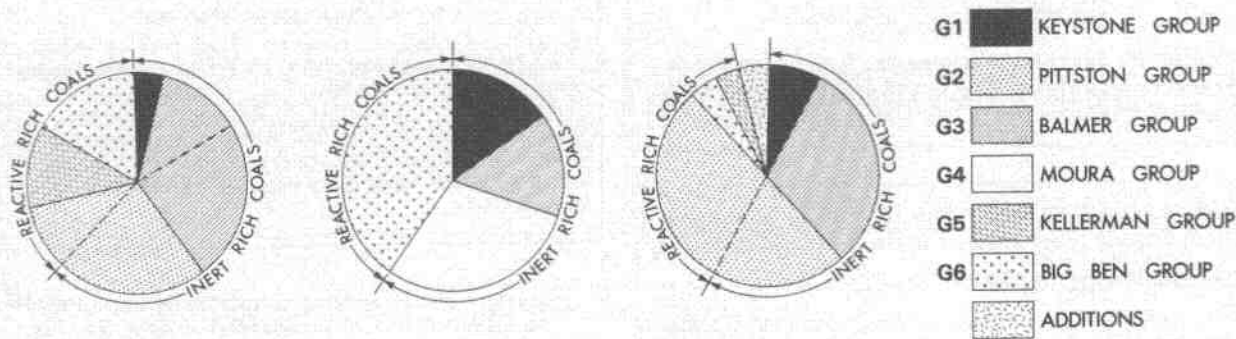
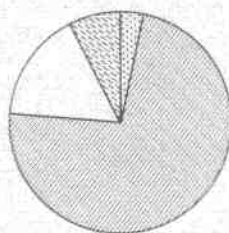
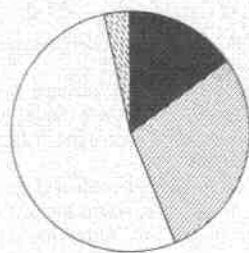


FIGURE 18. Pie-diagrams showing the proportion of the coal quality groups in the three coking coal blends shown in Figure 17.

QUEENSLAND
2.120 BILLION TONNES

BRITISH COLUMBIA
2.065 BILLION TONNES



G1 KEYSTONE GROUP
G2 PITTSTON GROUP
G3 BALMER GROUP
G4 MOURA GROUP
G5 KELLERMAN GROUP

FIGURE 19. Pie-diagrams showing the distribution of coal quality groups G1-G6 in the measured reserves of British Columbia and Queensland, Australia.

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