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A preliminary investigation of predictors of the cutting forces for some South African coals

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SYNOPSIS

This paper discusses the possible use of petrological data and proximate analyses in the prediction of cutting forces for coal. It is restricted to the development of univariate predictors based on data from thirteen collieries in five major Transvaal and Orange Free State coalfields and three coal provinces. The aim of the work was the identification and development of the best predictors of mean peak cutting force and Hardgrove grindability index from among the independent variables evaluated.

The data, which were obtained by use of the penetrometer developed by the Chamber of Mines Research Organization, were processed according to the SPSS computer package. The analysis revealed reasonable correlations between the Hardgrove grindability index and

(1) the volatiles and vitrinite content in the Vereeniging-Sasolburg and South Rand Coalfields,
(2) the contents of vitrinite, vitrinite plus exinite, and minerals plus inertinite in the Eastern Transvaal Coalfield.

SAMEVATTING

Hierdie referaat bespreek die moontlike gebruik van petrologiese data en kort analises in die voorspelling van synkragte vir steenkool. Dit word beperk tot die ontwikkeling van eenveranderlike voorspellers wat gebaseer is op data afkomstig van dertien steenkoolmyne in vyf belangrike Transvaalse en Vrystaatse steenkoolvelde en drie steenkoolprovinsies. Die oogmerk van die werk was die identifikasie en ontwikkeling van die voorspellers van die gemiddelde spitsnykrag en Hardgrove-maalbaarheidsindeks uit die onafhanklike veranderlikes wat geëvalueer is.

Die data wat verkry is met gebruik van die penetrometer wat deur die Kamer van Mynwese se Navorsingsorganisasie ontwikkel is, is verwerk volgens die SPSS-rekenaarpakket. Die ontleding het redelike korrelasies aan die lig gebring tussen die Hardgrove-maalbaarheidsindeks en

(1) die vlugtige bestanddele en vitrinietinhoud in die Vereeniging-Sasol- en Suid-Randse steenkoolvelde,
(2) die vitriniet-, vitriniet-plus-eksiniet-, en minerale-plus-inertinietinhoud in die Oos-Transvaalse steenkoolveld.

Introduction

In recent years the South African coal-mining industry has undergone significant changes, the most important being a rapid increase in coal output and a trend towards a higher degree of mechanization.

The rapid expansion in the coal industry prompted the Chamber of Mines Research Organization to embark on a comprehensive research programme into the various facets of coal cutting and the factors affecting it. This research has been directed along various lines, including the monitoring of a continuous miner, *in situ* measurements of cuttability with a penetrometer, and the use in the laboratory of a hydraulic planer operating on coal blocks removed from underground. The aim of the research is directed at the derivation of a coal cuttability index for South African coals.

More recently, part of the research programme has been directed towards the possible effect of coal petrology on coal cuttability, and the initial results indicate that certain correlations may exist[1]. Correlations of coal petrology and coal strengths have, for instance, been noted elsewhere[2-4].

This paper considers the possible use of petrographic and other predictors of mean peak-cutting forces and Hardgrove grindability index for some South African coals. The results of cutting forces that were taken into account are those obtained by use of the penetrometer[5] instrument developed by the Chamber of Mines of South Africa. Since the paper is based on data from only 164 analyses, obtained from 13 collieries in 3 coal provinces, the findings should be regarded only as preliminary.

A glossary of the terms used is given at the end of the paper.

Coal Petrology

Coal is notoriously unhomogeneous, comprising a mixture of combustible metamorphosed plant remains that vary in both physical and chemical composition. The diversity of the original plant materials and the degree of metamorphism or coalification affecting these materials are the two major reasons for the variety of physical behaviour in coal[6].

Sedimentary rocks such as siltstone, shale, and sandstone are found interbedded with coal. Also occurring with coal are various clay minerals, carbonates, sulphides, oxides, and quartz (Table I). These minerals comprise both syngenetic and epigenetic forms, and are known to have a marked effect on certain mechanical properties of coal[1,2].

The basic units of the system are the group macerals (vitrinite, exinite, and inertinite) consisting of various forms (macerals), which are equivalent to mineral types in a rock (Fig. 1). The properties of the group macerals are summarized in Table II. Various proportions of the macerals constitute the microlithotype (Table III).

Macroscopically, four major lithotypes are recognized. These are durain, vitrain, clarain, and fusain (Table IV). The lithotype is useful as an indicator of the palaeo-environment, composition[6], and mechanical strength of the coal[2-4,7].

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TABLE I
MINERALS ASSOCIATED WITH COAL (AFTER FALCON[6])

Mineral	Syngenetic		Epigenetic
	Deposited by water or wind	Originally formed in peat	Deposited in cleats and fissures
Clay minerals, carbonate minerals	Illite, kaolinite	Sericite Siderite, Dolomite, Calcite } Accretions	Calcite, ankerite
Sulphide minerals		FeS_2 $CuFeS_2$ ZnS	Pyrite, marcasite, zinc blende, galena, copper pyrites
Oxides		Limonite Hematite	Goethite
Quartz	Granular quartz	Chalcedony and quartz (decomposition)	Quartz, chalcedony
Salt	Rock salt, gypsum		

TABLE II
PROPERTIES OF MACERALS (AFTER FALCON[6])

Maceral groups	Chemical enrichment	Reactivity	Predominant purpose	Relative density in low ranks	Average relative proportions in South Africa %	Average relative proportions in Europe %	Relative reflectance in low ranks
Vitrinite	O	Reactive	Coking and gas	1,2 to 1,3	40	70	Medium grey
Exinite	H	Reactive	Tar and gas production	1,1	0 to 50	15	Darker grey
Inertinite	C and O	Inert to semi-reactive	Char	1,4 to 1,55	60 (±20)	15	Lighter grey to white
Minerals	S, Fe, P, etc	–	–	>1,5	14	3	Variable

TABLE III
PROPORTIONS AND PROPERTIES OF MICROLITHOTYPES IN SOUTH AFRICA (AFTER FALCON[6])

Microlithotype group	Maceral group composition	Average proportion in South Africa	Reactivity	Chemical enrichment
Vitrinite	V > 95%	10 to 60%	Reactive	0 >
Liptite	E, L > 95%	<10% approx. Fusite 10 to 20%	Reactive	H >
Inertite	I >95%	10 to 95%	Inert	C+O >
Clarite	V+E >95%	⩽ 10%	Reactive	O+H >
Vitri-inertite	V+I >95%	⩽10%	Semi-reactive	O+C
Durite	I+E >95%	⩽ 6%	Semi-reactive	C+H+O
Trimacerite	V > I, E E > I, V I > E, V V, E, I >5%	10 to 50% approx.	Semi-reactive	C H or O

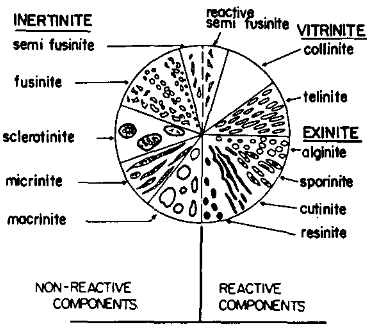


Fig. 1—The microscopic (organic) components of coal macerals and sub-macerals

Cutting Procedure

The first step in the investigation of the cuttability of a seam involves the choice of a suitable test site. A face should be tested as soon as possible after exposure so that the effect of overburden stressing is avoided. The next step is logging of the seam profile and recording of the various layers (lithotypes) comprising the seam. A minimum of two diamond-drill holes 1,2 m long and 93 mm in diameter are drilled into each layer. The core samples from each hole are bagged and retained for petrographical and proximate analyses. The holes are normally drilled a few degrees above the horizontal to prevent water remaining in the hole.

The essential feature of the penetrometer is that it can be inserted into a borehole 93 mm in diameter drilled into the coal face. The 15 mm long, steel, hydraulically operated, diametrically opposed picks housed on the head of the instrument are forced into the sidewall of the borehole. The head is then pulled towards the mouth of the hole by a hydraulically operated piston assembly at the collar of the borehole. The picks that perform the work cut two grooves in the coal that are 200 mm long and 15 mm deep. Six tests (three vertical and three horizontal) are carried out in each borehole; the number of holes tested depends upon the height of the seam and the number of coal layers defined. The recording of the required forces to indent the picks and cut the grooves in the coal is in analogue form on a four-channel instrumentation tape recorder. The data obtained from the tests are processed in the laboratory by use of an analogue-to-digital converter to provide suitable input data for a desk-top computer. These data are stored and analysed by the computer to produce average indentation forces, mean cutting forces (MCF), and mean peak cutting forces (MPCF).

During the transfer of the penetrometer from one hole to another, all the coal chippings that fall from the hole when the head is removed are carefully collected. This sample is combined with the material remaining in the hole, which is removed at a later stage, to provide a complete sample of the coal cut by the picks in that hole. The specific energy (SE) is calculated for each hole. The mean cutting force for the six tests performed is multiplied by the length cut (1200 mm) and divided by the mass of coal removed from the hole. This gives a measure of the cutting efficiency and is defined as the work done in the excavation of a unit mass of coal (J/g).

Petrological Analyses

A minimum of 60 g of coal is required for the preparation of a petrological sample. The first step in the preparation process is to crush the coal to pass through an 850 μm sieve. This is done in two steps: firstly, by the use of a mortar and pestle, and then with a coffee grinder. The sample is then split twice with a homogenizer.

The next step involves the moulding of the sample: 15 g of sample is mixed with 4,8 g of Midbond C60 resin and 0,2 g of Midbond catalyst, and the mixture is placed into a hollow mould 3,16 cm in diameter (inner dimension) and the plunger inserted. (Both the mould and the plungers are made of EN 24 heat-treated steel.) The mould is then placed in a clamp and pressurized at 37 MPa in a hydraulic press for 8 hours. The equipment used in crushing and moulding is shown in Fig. 2.

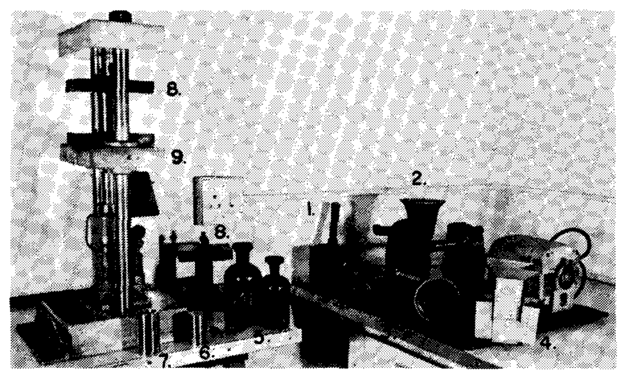


Fig. 2—The equipment used in the crushing and moulding of coal samples for petrological examination

1. Mortar and pestle	6. Plunger
2. Coffee grinder	7. Mould
3. Sieve 850 μm	8. Pressure clamp
4. Riffle	9. Hydraulic press
5. Catalyst and resin	

After being removed from the mould, the sample is polished by use of a Buehler Polisher Ecomet III and Grinder and Buehler Carbimet paper discs (320, 400, and 600) with distilled-water lubrication. The final polish is carried out by use of a Beuhler Texmet adhesive polishing cloth lubricated with 0,3 μm Alpha alumina and of a Buehler AB selected silk polishing cloth lubricated with 0,05 μm gamma alumina. (Both grades of alumina are mixed with distilled water.) The specimen holder allows five samples to be polished at a time.

Once the samples have been polished, they are removed from the specimen holder and dried in an oven at 40°C for 1 hour or for 15 hours in a desiccator. The polishing equipment is shown in Fig. 3.

The microscopic analyses are carried out in accordance with standards laid down by the International Committee for Coal Petrology (1971). During these analyses, maceral/mineral count and rank (reflectance of vitrinite) are recorded (Fig. 4) by the use of oil immersion (Cargille Type B immersion oil) on a Leitz Orthoplan Microscope with the relevant accessories (point counter and digital reflectance reader).

The preparation of coal samples for the petrographical analysis is summarized in Fig. 5.

The petrological analyses for the present investigation were carried out at the Bernard Price Institute, University of the Witwatersrand, in accordance with standards laid down by the International Committee for Coal Petrology (1971).

TABLE IV

PROPERTIES OF LITHOTYPES (AFTER FALCON[6])

Lithotype	Appearance	Relative density	Crushability (de-ashed)
Vitrain	Shiny black bands	±1,3	3,8
Clarain	Laminated shiny and dull bands	±1,3	5,1
Fusain	Charcoal-like fragments	1,25 to 1,45	1,8
Durain	Dull, usually massive	Soft 1,35 to 1,45 Hard >1,6	13,6

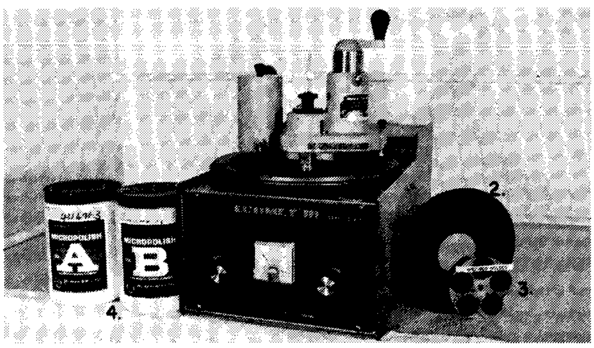


Fig. 3—The polishing equipment for use on petrological coal samples
1. Polisher **3. Specimen holder**
2. Polishing disc **4. Gamma and alpha alumina**

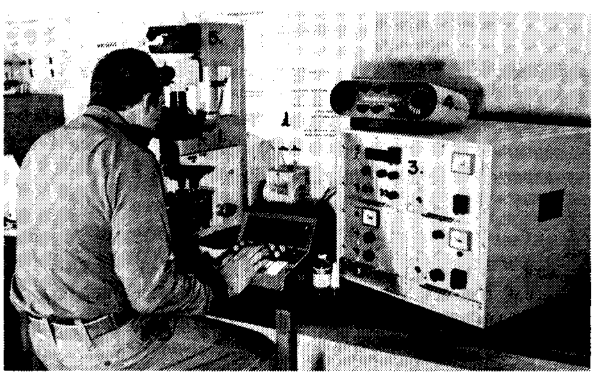


Fig. 4—The equipment used for microscopic analyses in coal petrology
1. Microscope **4. Camera control**
2. Point counter **5. Camera**
3. Digital reflectance reader

Analyses of Physical Properties

Core samples obtained from the drilling programme are also kept for proximate analyses and for tests on certain physical properties.

Data obtained from the proximate analyses include those relating to the contents of moisture, ash, volatiles, fixed carbon, volatiles (dry, ash-free (d.a.f.)), and carbon (d.a.f.), which are expressed as percentages. The physical properties considered include impact strength index (ISI), Hardgrove grindability index (HGI), abrasiveness, point load index (PLI), and density.

The results recorded here were obtained in accordance with standards laid down by M & L Laboratories (SABS, ISO).

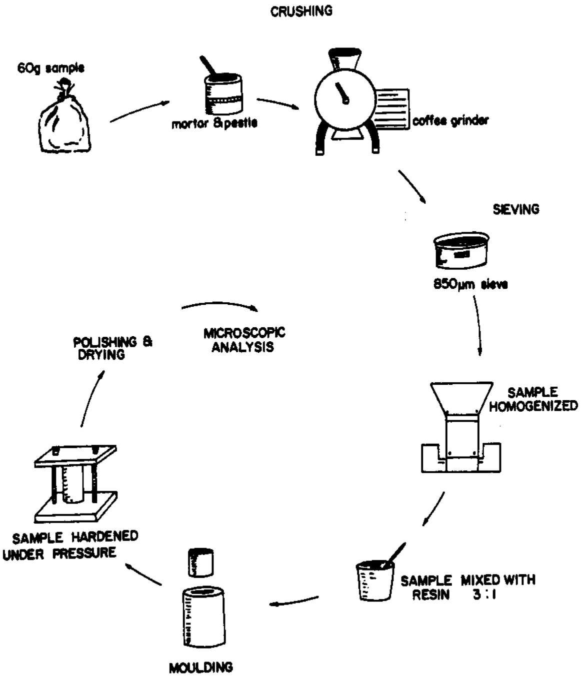


Fig. 5—Flow diagram showing the preparation of coal samples for petrological analyses

Method of Data Handling

The sources of the data included in this report are summarized in Table V.

Initially, the results from the petrographic, proximate, physical, and cuttability tests were examined for any correlations between these factors[1], use being made of the SPSS computer package. Of particular interest in this program is the facility of the correlation coefficient. Two variables can be plotted against each other in the form of a scattergram, and a multiple regression analysis can be performed to give R, the multiple correlation coefficient. The initial results indicated that certain correlations do exist.

This paper considers only certain variables, which are summarized in Table VI.

The data were handled in four sets, S1 to S4, according to coal province:

S1 Data from WBS coal province (Witbank–Belfast–Standerton Middle Ecca Stage)
S2 Data from ETN coal province (Eastern Transvaal–Natal Middle Ecca Stage)
S3 Data from SVB coal province (Sasolburg–Vereeniging–Balfour Middle Ecca Stage)
S4 The block or combined data.

In phase I of the analysis, each of the four sets of data was entered into a series of regression analyses.

In phase II, emphasis was placed on a comparison with the results of phase I for the data sets S1, S2, and S3, especially since it was expected[8] that analysis of the data on the basis of coal province would yield statistically more significant results than treatment of the data as a block. A flowchart of the data handling is given in Fig. 6.

The two controlling tests of tolerance level and F level[9] were used in the analysis to decide whether a given variable term should be entered on the next step

TABLE V

SUMMARY OF THE DATA USED

Colliery	Province	Coal province	Coalfield	Reports	Data	Seams
Greenside	Transvaal	WBS	SW	2	13	2 and 5
Kriel		WBS	HV	1	11	4
Matla		WBS	HV	1	5	5
Tavistock II		WBS	SW	1	11	2
Arnot		WBS	SW	1	10	2
[illegible]		WBS	HV	2	18	4

Minerals + inert maceral content, %	Independent	[illegible]
Mean peak cutting force, kN	Dependent	MPCF
Hardgrove grindability index	Dependent	HGI

Note: Vitrinite and exinite were included in the regression analyses to represent the reactive macerals minus the reactive semi-fusinite. It should be noted, however, that the physical properties of these are vastly different, the vitrinites usually being rather brittle and the exinites (especially sporinite) tough.

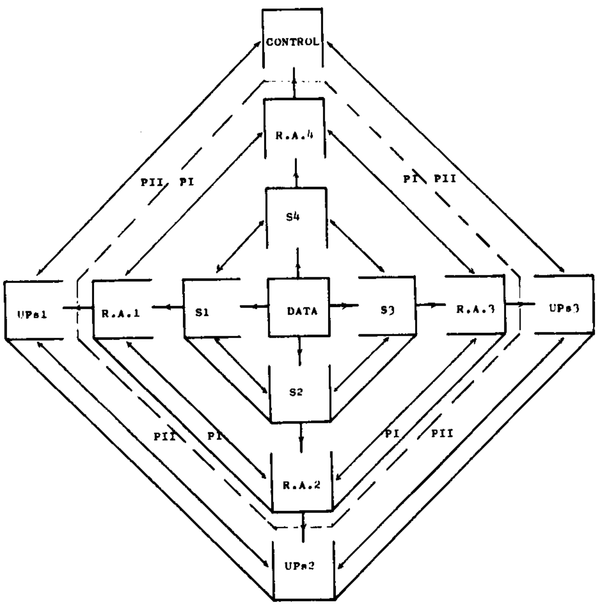


Fig. 6—Schematic representation of the data-handling system
PI Phase I **S Data set**
PII Phase II **UPs Univariate predictors**
R.A. Regression analysis **⟷ Compare and contrast**

of a regression. For this purpose, the following criteria were adopted:

Tolerance level $T \geqslant Tc$, where $Tc = 0,05$ (i.e. 5%)

F level $F \geqslant Fc$, where $Fc = [f(V_1, V_2, 0,95)]$ (5% significance level)

V_1 = regression step number

$V_2 = N-(V_1+1)$, where N = number of data.

Forward stepwise inclusion of the variable terms is the approach employed by the SPSS REGRESSION procedure for the analyses. By this method, variable terms are entered in single steps from best (i.e. greatest amount of unexplained variance in dependent explained) to worst (i.e. least amount of unexplained variance explained). In other words, the variable term chosen for entry at a given step is the one that has the largest squared partial correlation with the dependent variable.

For the classification of the correlations on the basis of the squared multiple correlation coefficient statistic[10], the classes were defined as shown in Table VII.

TABLE VII

DEFINITION OF CLASSES

Correlation class	R^2 of regression	$(R^2 \times 100)\%$ of regression	Comments
0	-	-	No terms entered
1	$<0,25$	$<25\%$	Very low R^2
2	$0,25 \leqslant R^2 < 0,50$	$25\% \leqslant R^2 < 50\%$	Moderate to high R^2
3	$>0,50$	$>50\%$	Very high R^2

It was decided that only correlation in classes 2 and 3 would be considered acceptable as univariate predictors, whereas class 1 relationships may be considered for inclusion in multiple regression analyses in any future search for good multivariate predictors.

Presentation of Results

A summary of the results of the regression analyses conducted according to the SPSS procedure is given in Table VIII, and the classes of curves are summarized in Fig. 7.

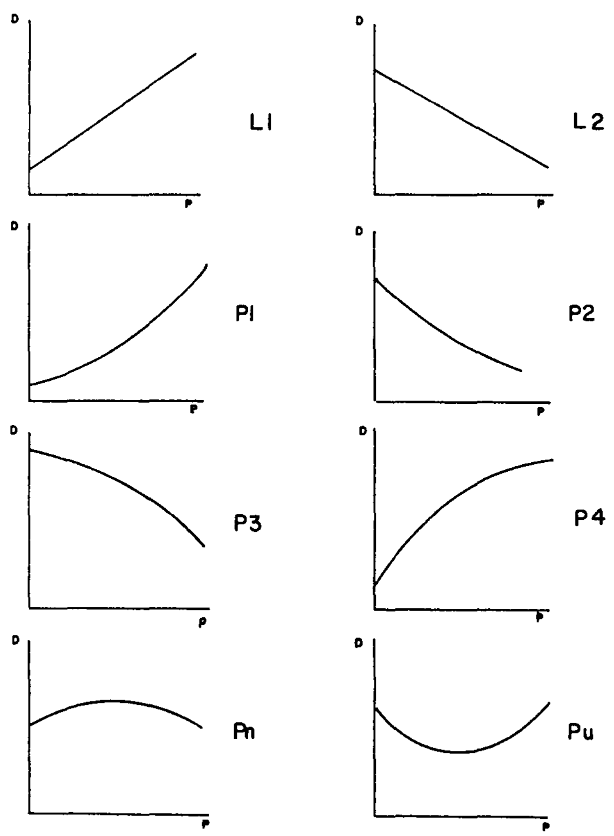


Fig. 7—Classes of curves
D Dependent variable **P Predictor variable**

The results for each coal province were tabulated, and the regression equations for each data set were produced graphically. In addition, for all the linear regressions in correlation classes 2 and 3 of data sets S1 to S3, the 95 and 80 per cent confidence limits for the estimate were calculated[11] and drawn.

Figs. 8 and 9 are representations of R^2 and SEE statistics plotted against predictor variables by province for HGI and MPCF dependents respectively.

TABLE VIII

SUMMARY OF THE RESULTS OF THE REGRESSION ANALYSES PERFORMED BY THE SPSS PROCEDURES (INCLUDES ONLY CLASS 2 AND 3 CORRELATIONS)

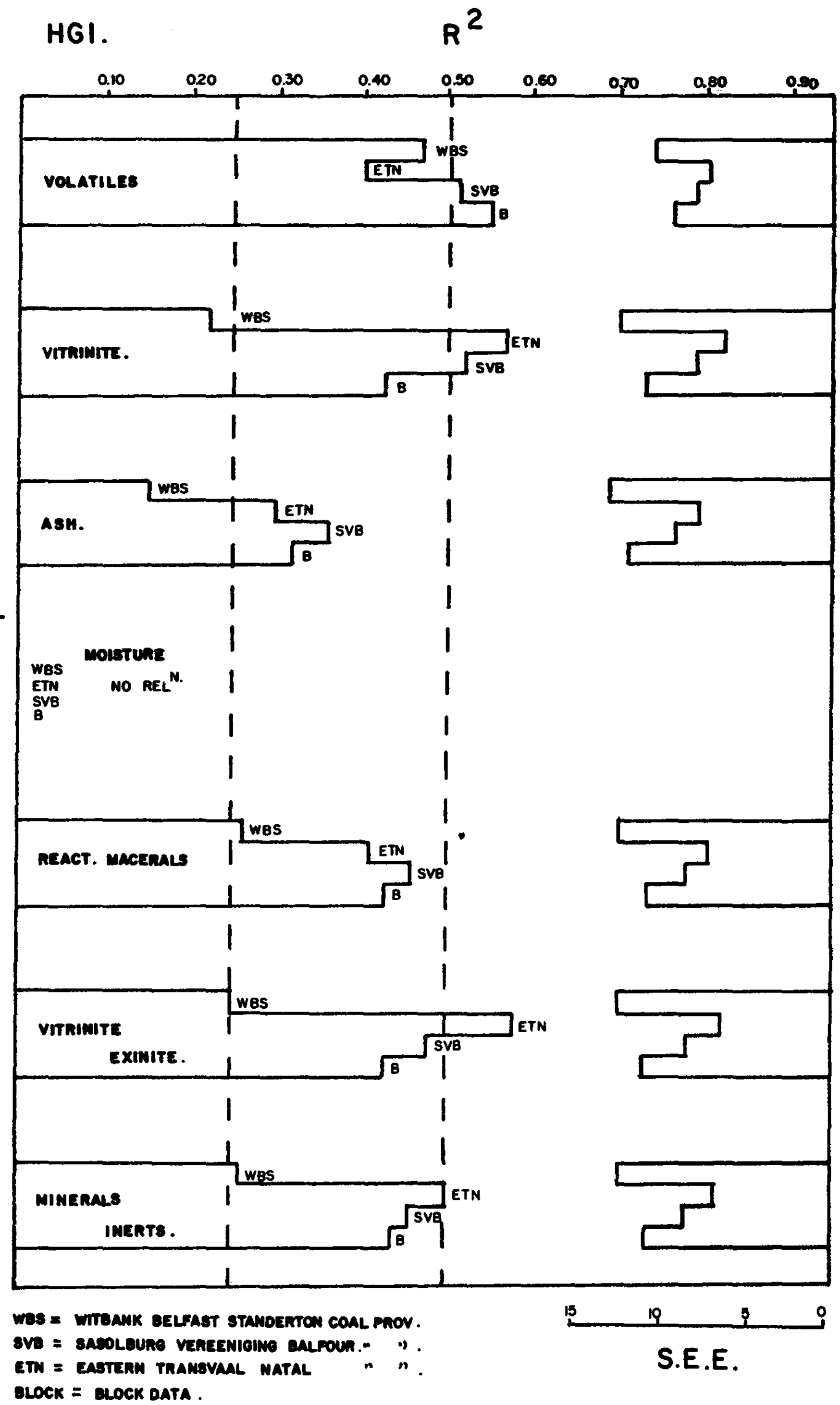
Dependent variable	Predictor variable	'Block'	R^2 %	Correlation class	SEE	Class of curve
MPCF	VOL	WBS	30	2	5,7	L1
	VOL	SVB	39	2	5,7	L1
	VOL	Block	40	2	6,7	L1
	VIT	WBS	25	2	6,0	Pn
	VIT	ETN	31	2	5,2	L1
	VIT	SVB	43	2	5,5	Pn
	VIT	Block	43	2	6,5	Pn
	ASH	SVB	25	2	6,3	Pu
	REACTMAC	ETN	30	2	5,2	L1
	REACTMAC	SVB	26	2	6,2	L1
	REACTMAC	Block	31	2	7,1	L1
	VITEX	ETN	31	2	5,2	L1
	VITEX	SVB	36	2	5,9	Pn
	VITEX	Block	37	2	6,8	Pn
	MININERT	ETN	35	2	5,0	P3
	MININERT	SVB	26	2	6,2	P3
	MININERT	Block	34	2	6,9	P3
HGI	VOL	WBS	47	2	10,4	L2
	VOL	ETN	40	2	7,2	L2
	VOL	SVB	51	3	8,1	L2
	VOL	Block	55	3	9,7	L2
	VIT	ETN	57	3	6,3	Pu
	VIT	SVB	52	3	8,0	Pu
	VIT	Block	43	2	10,9	P2
	ASH	ETN	30	2	7,9	P1
	ASH	SVB	36	2	9,2	Pn
	ASH	Block	32	2	11,9	Pn
	REATMAC	WBS	26	2	12,3	L2
	REATMAC	ETN	41	2	7,2	L2
	REATMAC	SVB	46	2	8,4	L2
	REATMAC	Block	43	2	10,8	L2
	VITEX	WBS	25	2	12,3	L2
	VITEX	ETN	58	3	6,3	Pu
	VITEX	SVB	48	2	8,3	L2
	VITEX	Block	43	2	10,9	P2
	MININERT	WBS	26	2	12,3	P1
	MININERT	ETN	50	3	6,6	P1
	MININERT	SVB	46	2	8,4	L1
	MININERT	Block	44	2	10,7	P1

Fig. 10 represents the values of mean MPCF and (100 – mean HGI) for the different coalfields represented in the data, while Fig. 11 is a comparison of variance accounted for (R^2) and SEEs according to the coal provinces.

A 3-D representation of values of $(1-r^2)$ from the S1 to S3 data sets for regressions between individual linear terms of the independent variables is presented in Fig. 12. An arbitrary r^2 value of 0,16 was chosen so that only variable pairs with r^2 values of 0,16 are considered suitable for possible combination in multiple regression analyses in the future.

Fig. 13 is a comprehensive summary of the data incorporating local profiles, possible correlations, and a section through the various data sources (collieries).

Fig. 8—R^2 and SEE statistics versus predictor variables by province for HGI



Discussion of Results

The most important features arising from the results of this investigation are as follows.

(1) Generally, for the S1, S2, and S3 data sets, the regression curves for a given predictor-dependent pair are close together and of roughly similar shape. Exceptions to this are the MPCF–MOIST and HGI–ASH regressions.

(2) There is a tendency for an ordering of the regression curves. For MPCF it is ETN→WBS→SVB (high → low values), and for HGI the order is reversed.

(3) In all cases where one or two of the S1 to S3 regression curves are non-linear, the S4 (block data) regression curve is also non-linear.

(4) The regressions involving VIT or VITEX are non-linear in the case of S1 and S3 data (for MPCF), S2 and S3 data (for HGI–VIT), and S2 data (for HGI–VITEX). However, those involving REACTMAC (closely related to VIT and VITEX) are all linear. (Linearization involves a significant loss of accuracy for nearly all the regressions.)

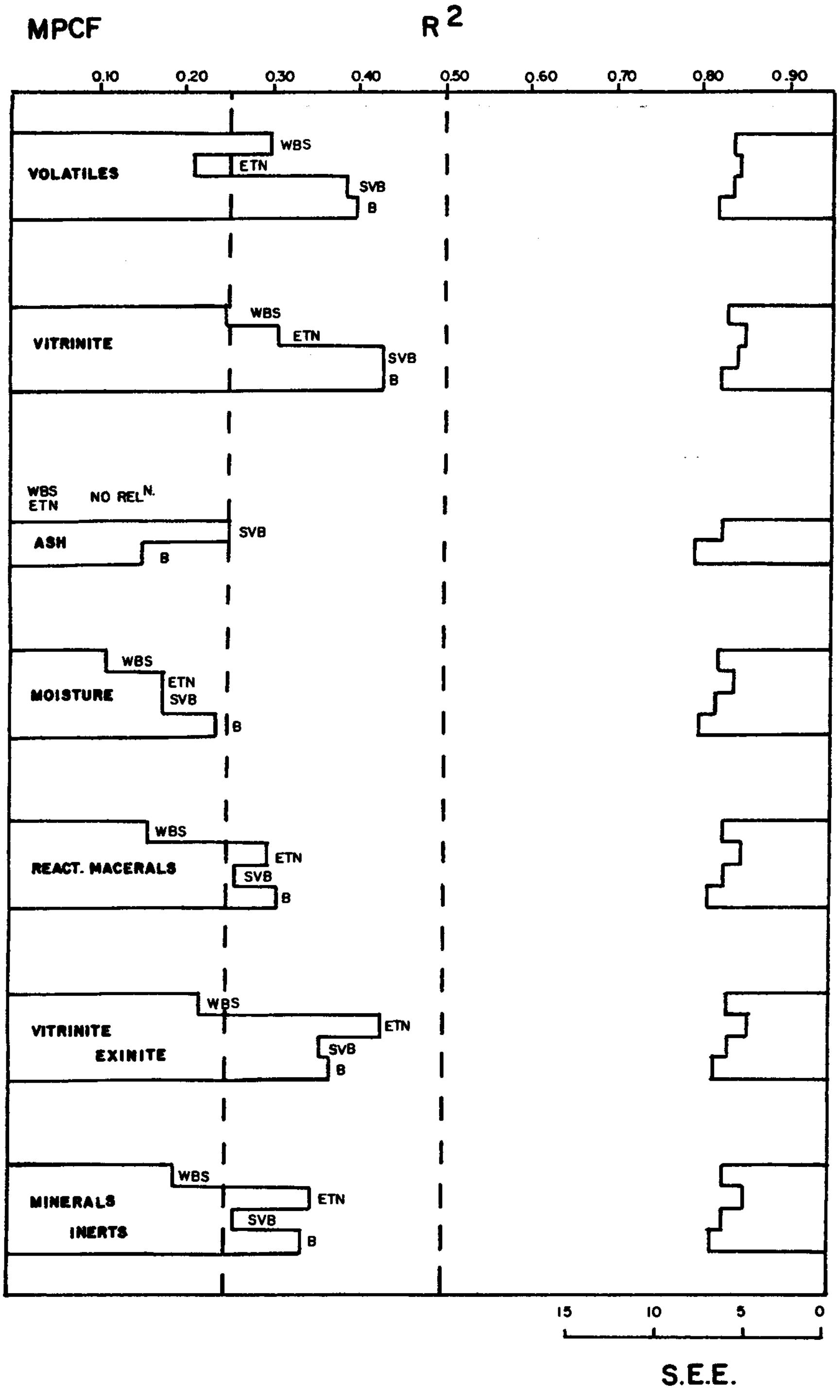


Fig. 9—R^2 and SEE statistics versus predictor variables by province for MPCF

(5) Ash is a better predictor of HGI than of MPCF.
(6) Moisture is a better predictor of MPCF than of HGI (no regression steps were achieved at all with the HGI–MOIST regressions).
(7) Volatiles is a better predictor of HGI than of MPCF.
(8) There is a great improvement in R^2 values for the ETN coal province when VIT is employed as a predictor of HGI rather than MPCF
(9) REACTMAC, VITEX, and MININERT are all better predictors of HGI than of MPCF.
(10) Generally, high cutting forces (that is, high peak cutting forces) are associated with high VOL and REACTMAC and low MININERT values. Low HGI values are associated with high VOL, VIT, REACTMAC, and VITEX values, and with low MININERT values. Other cases are less obvious.

The graphical presentation of the results from the regression analysis shows a regular increase of HGI along decreasing volatile matter. However, Van Vuuren[12] shows that the correction may be true only within 20 to 40 per cent of VM. Below 20 per cent of VM, the results are somewhat scattered and show a general decrease of HGI values. In anthracites between 4 and 7 per cent of VM, HGI values are already on the level of 30 to 40. Tenden-

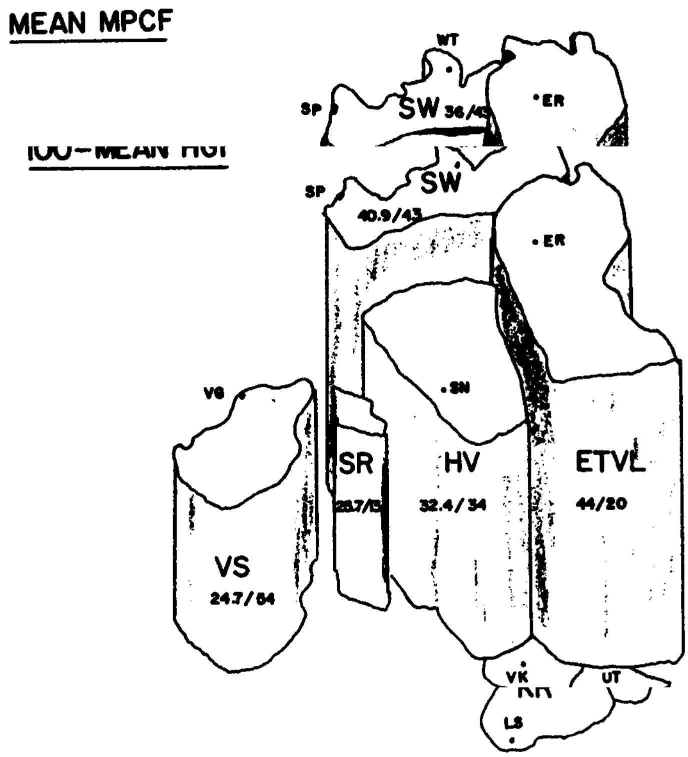


Fig. 10—Representation of values of mean MPCF and 100 – mean HGI for the various coalfields.

ETVL	Eastern Transvaal	LS	Ladysmith	SR	South Rand	VK	Volksrust
ER	Ermelo	NC	Newcastle	UT-VR	Utrecht-Vryheid (no data)	VR	Vryheid
HV	Highveld	SN	Standerton			VS	Vereeniging-Sasolburg
KR	Klip River (no data)	SP	Springs	VG	Vereeniging	WT	Witbank

34/43 Variable value/No. of data   1 mm vertical = 1 variable unit

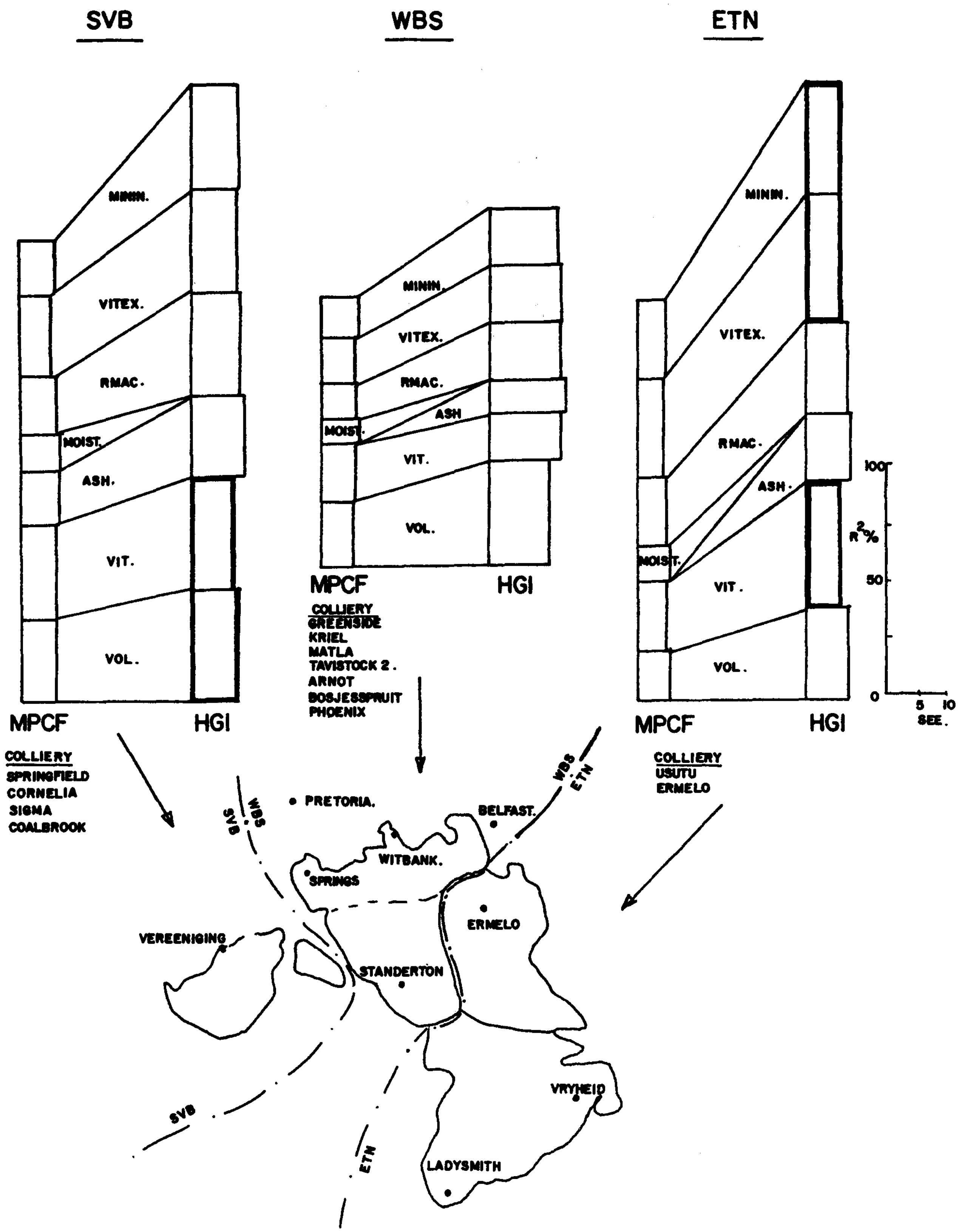


Fig. 11—A comparison of percentage variance accounted for and standard errors of estimates for predictors of MPCF and HGI by coal province

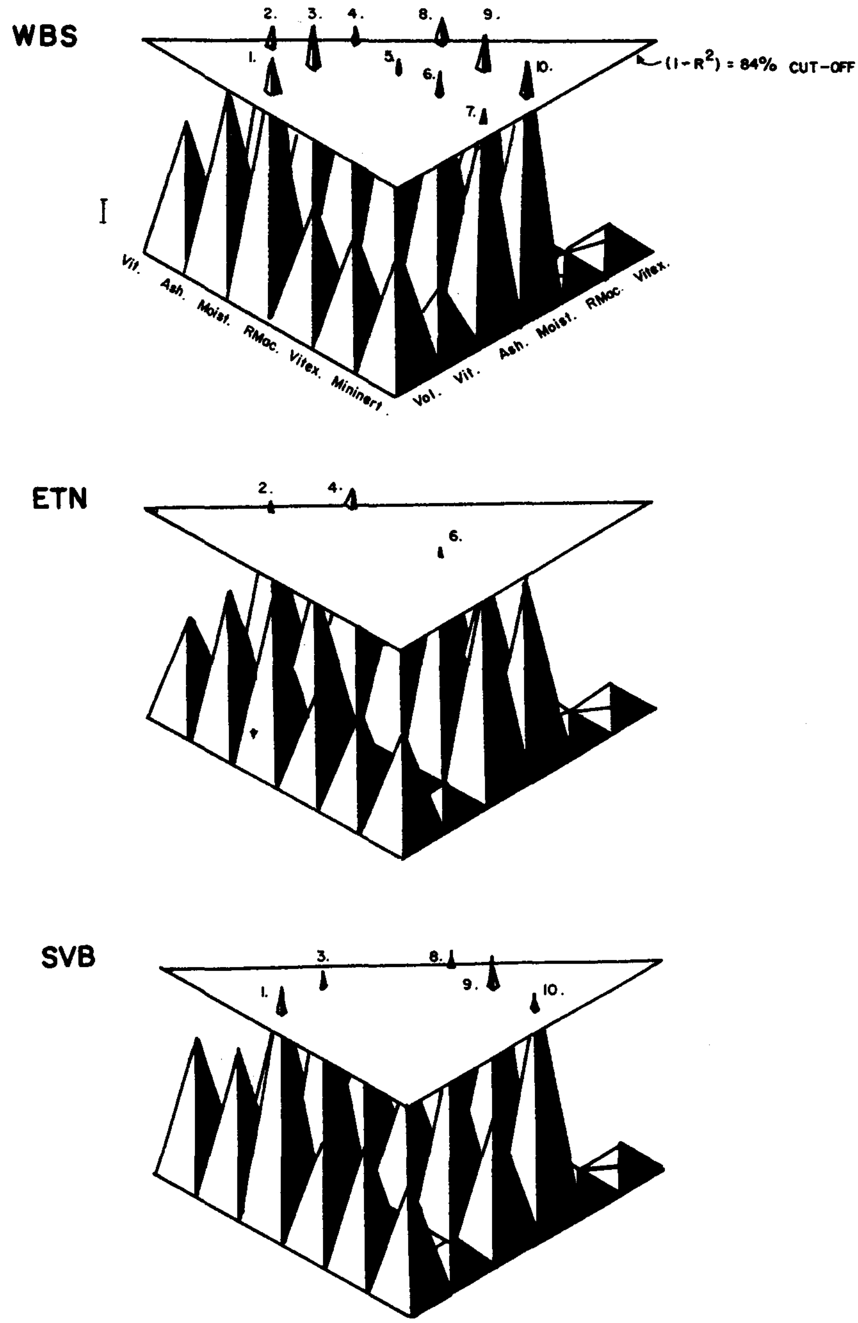


Fig. 12—The correlation between the independent variables

1. **Volatiles–Moisture**
2. **Vitrinite–Ash**
3. **Vitrinite–Moisture**
4. **Ash–Moisture**
5. **Ash–Reactive macerals**
6. **Ash–Vitrinite + exinite**
7. **Ash–Minerals + inerts**
8. **Moisture–Reactive macerals**
9. **Moisture–Vitrinite + exinite**
10. **Moisture–Minerals + inerts**

cies for high MPCF values to be correlated with medium to high VIT and VITEX percentages, and high HGI values with medium to high ASH percentages, do exist.

(11) With reference to Figs. 8 and 9, several important points are relevant. For MPCF regressions, the SEE have a general order of decreasing value:
SEE (Block) > (WBS) > (SVB) > (ETN) with exceptions for VOL and MININERT regressions where
SEE (Block) > (WBS) > (SBV) > ETN) for MOISTURE regressions where
SEE (Block) > (SVB) > (WBS) > (ETN).

(12) For HGI regressions, the SEE have the following order of decreasing value:
SEE (WBS) > (Block) > (SVB) > (ETN).

(13) The R^2 values for the regression do not follow such well-established trends. Generally, for MPCF regressions, S1 (or the data for the WBS coal province) give the lowest values, and the S4 (or block data) give either the highest or next highest R^2 statistic. For HGI regressions, the order of R^2 values is generally the same as for MPCF regressions, except that the S3 (or data for the SVB coal province) give greatly improved values relative to those for the S4 (or block data).

(14) The HGI regressions show a much improved visual correlation between R^2 and SEE statistic values (an inverse relationship as would be expected) over that for MPCF regressions.

The interpretation of these results is complicated by several factors.

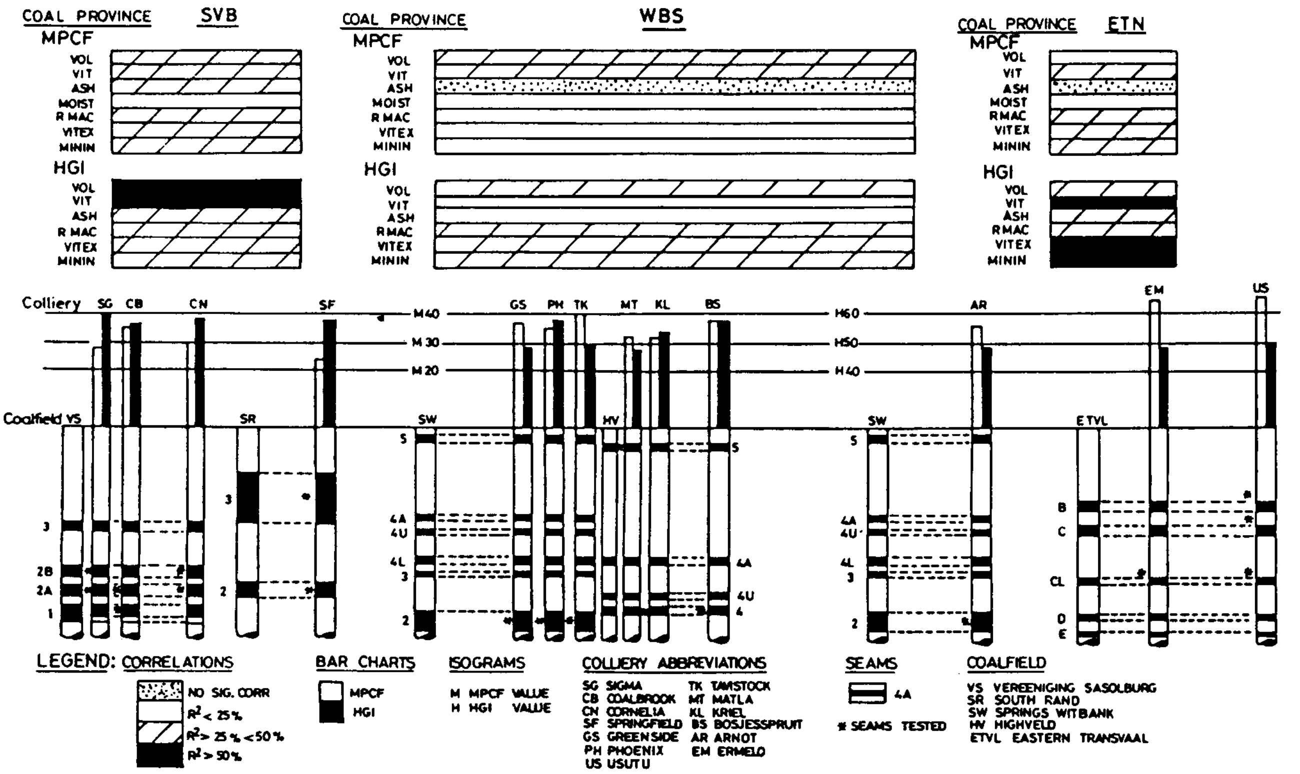


Fig. 13—Summary diagram

(a) The difference in the seams tested at different mines in the same coal province is a confusing factor.
(b) Local structural factors in the vicinity of the holes tested may affect the MPCF values to some degree. For example, crushing of the pillar at the 2A seam site at the Sigma Colliery has been mentioned as a likely cause of the low cutting forces recorded at that site[13]. This factor will affect only the MPCF correlations, and not those of HGI for obvious reasons.
(c) The underground sampling of the seam may not have been entirely statistically random.

It can be seen from Fig. 9 that the errors in the prediction of HGI for all the regressions of S1 data (WBS province) are very large compared with the errors for the S2, S3, and S4 regressions. Also, the R^2 statistics of nearly all the regressions (both MPCF and HGI) on S1 data are the lowest calculated. A wide variation in cutting forces among the mines in the WBS coal province has been noted by other workers. This variation depends on the seam being tested, No. 4 seam being the easiest to cut and No. 2 seam the hardest[13].

The most accurate predictors of cutting force and grindability vary with the coal province. For MPCF predictions, WBS province has only one significant predictor (VOL), although VIT just falls within correlation class 2. In the ETN province VIT, REACTMAC, VITEX, and MININERT are all class 2 correlations, while for the SVB province VOL, VIT, VITEX are the best predictors, with REACTMAC and MININERT just being included in correlation class 2 along with ASH, which has an R^2 correlation of 0,25.

For HGI, VOL is the only good predictor for the WBS province. Other class 2 correlations include REACTMAC, VITEX, and MININERT. ETN province is well represented by having six predictors, three of which are class 3 correlations. The SVB province is much the same as the ETN province, having the same six predictors, although only two of them are in correlation class 3.

Generally, the results for the block (S4) data showed medium to high R^2 values but somewhat high SEEs. However, it seems that, for the prediction of HGI for mines in the WBS province, use of the S4 regression equation, rather than the S1 equation, would be more accurate owing to the far higher R^2 and lower SEE values of the former. It can be seen that the prediction of grindability (HGI) within the WBS province is very problematical.

The significant predictors for each coal province are summarized in Fig. 14. A FORTRAN IV computer program for the prediction of MPCF and HGI values on the basis of univariate predictors from petrological and proximate analyses is at present being written based on this flow chart.

Conclusions

(1) The significant predictors of MPCF and HGI are dependent on coal province.
(2) Separate developments of predictors at the coal province level is justified in the majority of cases examined, but the HGI predictions for the WBS province are less accurate than HGI predictions based on ungrouped data.
(3) Separate development of predictors at the coalfield level may well be justified, at least in some cases (e.g. WBS province), but this has to be weighed against the need for prediction equations that have as wide an application as possible.
(4) HGI is more accurately predictable than MPCF.

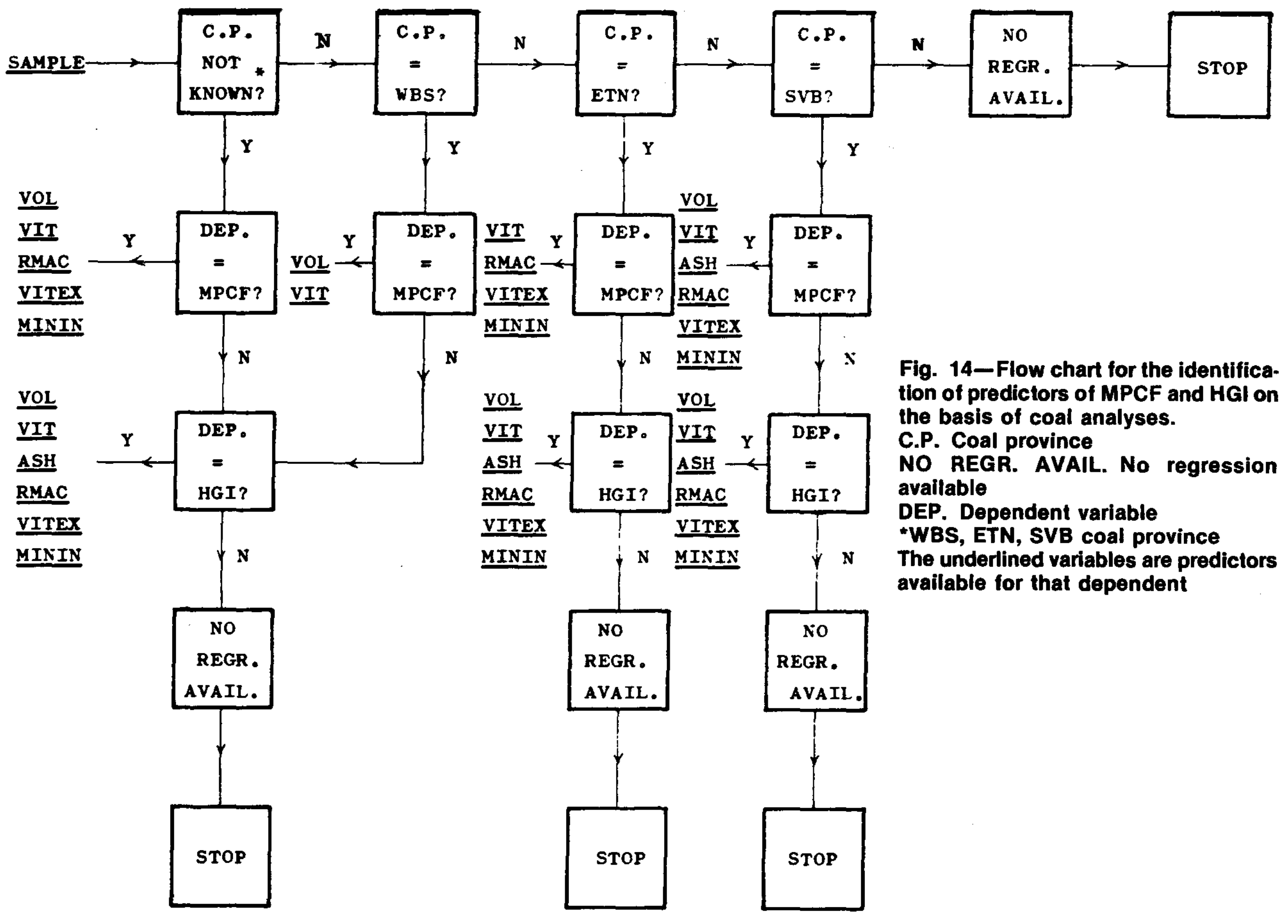


Fig. 14—Flow chart for the identification of predictors of MPCF and HGI on the basis of coal analyses.
C.P. Coal province
NO REGR. AVAIL. No regression available
DEP. Dependent variable
*WBS, ETN, SVB coal province
The underlined variables are predictors available for that dependent

Future Work

Future work should include the following:

(a) collection of more data and statistical treatment of the data at the seam level throughout the coalfields; comparisons between similar seams from different coalfields, as well as between different seams from the same coalfield, should produce valuable results;
(b) refinement of methods of prediction, including multiple regression and discriminate analysis techniques and the computerization of the entire process;
(c) investigation of the advantages and disadvantages in the development of prediction equations at the coalfield level;
(d) correlation of MPCF and HGI with other variables, such as the pick consumption of continuous miners;
(e) extension of the region for which prediction is possible, especially to include the Natal coalfields;
(f) recognition of the importance of both rank and microlithotype to the physical characteristics of a coal; current and future work is being orientated towards factors that affect the physical properties of the coal, rather than the chemical properties.

Glossary of Terms

Ash is the residual ash after complete combustion of the coal[14].

Coalfield is a division of a coal province based in some instances primarily on the physical separation of the areas, or on conspicuous or slight stratigraphical differences in the coal succession, or even on a geographical basis purely for convenience of description[14] (p. 247).

Coal province is in the first place a geographical unit, although fragmented due to original discontinuity or due to earth movement and erosion; it is also a morphological unit in which it is considered that the environments for plant growth and the formation of coal were largely the same and uniform, and somewhat different from the conditions in another, even adjacent, province[14] (p. 297).

Confidence limits are the upper and lower boundaries of a confidence interval, which is a range of values within which an estimate is likely to fall to a specified percentage confidence, called the Coefficient of Confidence[15] (p. 165).

Control is an experiment one uses in checking the results of other experiments by maintaining the same conditions except in one particular and thus inferring the causal significance of this varied factor. (In this study, for example, S4 data formed the *control* and the selection of data (S1, S2, S3) was the varied factor.)

Correlation is the degree of association between two or more variables.

Correlation coefficient (r, R) is the quantitative measure of correlation. The squared correlation coefficient (r^2, R^2) can be thought of as the proportion of variance in the dependent variable accounted for by the regression on the predictor(s).

Criterion is a standard on which a decision or judgement can be based.

Dependent (variable) is the variable in an experiment upon which the independent variable(s) is (are) presumed to exert its (their) effect(s)[15] (p. 117).

Dimension is one of the fundamental units or powers thereof that enter into the makeup of a derived unit.

Hardgrove grindability index is a measure of the ease with which a coal can be pulverized. The coal is subjected to standard grinding conditions, the amount of fines formed is measured, and the grindability is determined from that value[16].

Independent variable is a variable in an experiment whose effect on another variable is the focus of interest[15] (p. 117).

Macerals are the elementary microscopic constituents of coals by analogy with minerals in rocks. However, unlike rock-forming minerals, macerals form intimate mixtures and do not combine to form solid solutions[14] (p. 292).

Mean peak cutting force (MPCF) is the mean of the highest cutting forces recorded for the penetrometer tests on a given layer of a seam (kN).

Minerals. The most common mineral impurities found in coal are the clay minerals, carbonates, sulphides, and quartz. Mineral matter and macerals are not genetically related[14] (p. 293).

Moisture is the amount of water physically associated with coal and removable by heating to 105–110°C under standard conditions[14] (p. 294).

Multiple regression analysis (MRA) is a general statistical technique through which one can analyse the relationship between a dependent variable and a set of independent or predictor variables[8] (p. 321).

Multivariate has or involves more than one independent variable.

Petrology is the science that deals with the origin, history, occurrence, structure, chemical composition, and classification of rocks.

Predictor is an independent variable.

Reactive macerals are the amount of reactive semi-fusinite (identified optically) plus vitrinite and exinite.

Regression analysis, or least squares regression analysis, is based on the belief that the best-fitting line through a scattergram is the one in which the vertical distances of all the points from the line are minimized. The line itself is called the regression line[8] (p. 278).

Regression coefficient (b) is a coefficient of one of the independent variable terms present in a regression equation.

Significance level is determined by the level at which the Null hypothesis (H_0:$r = 0$ hypothesis of 'no difference' or 'no relationship') can be rejected[15] (p. 119).

Standard error of estimate (SEE) is the standard deviation of actual dependent variable values from the predicted (regression line) values[8] (p. 325).

Univariate has or involves only one variable.

Variance is a measure of the variability, or lack of homogeneity, in a variable[8] (p. 279).

Volatiles are calculated from the loss of mass when 1 g of coal is heated at 900°C (+10°C) for 7 minutes. Volatile matter and carbon are complementary[14] (pp. 293–294).

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