THE CHEMICAL PROPERTIES AND DERIVED SEDIMENTATION PATTERNS OF THE COAL SEAMS IN THE WITBANK-HIGHVELD AREA

by

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It is useless amassing quantities of facts without seeking to reconcile them with hypothesis capable of explaining their significance, thus contributing to the development of science.

HENRY B. MILNER

ABSTRACT

From available records and data of colliery product samples, an area within the Witbank and Highveld coalfields was selected for this study. The petrographic and elemental nature of the coal seams have been derived from the relationship between the volatile matter content and the calorific value, both expressed on a dry ash-free basis (Snyman et al, 1983; Barnard, 1987).

These derived values were complemented by ash analyses of colliery product samples, paleotopographic data and seam thickness. These data provided information on the paleoenvironmental conditions during peat accumulation and deposition.

Computerized subsurface mapping techniques were applied to record various chemical and petrographic parameters. The existence of major channel complexes culminating in outwash streams towards the south is postulated. During the formation of the basal seams these trunk channels were up to 6 km wide and trended generally from east to west and from north to south along low gradients. The channels follow topographical lows and skirt topographical highs. The vegetation-stabilized channels aggraded upwards at a rate consistent with peat accumulation. The channels were fed by melt-water which originated from the northwards receding glacial ice-cap.

Low energy currents led to the wide lateral distribution of autochthonous coal seams. The channels led to the transportation and redeposition of inertodetrinitric material of hypautochthonous origin. The coal seams associated with channel areas are generally thinner and the resultant coals are usually inertinite-rich. These coals have a brittle character and tend to become more shaley towards the south.

A close relationship was established between the mineral matter characteristics and coal type of the No. 2 Seam. The inertinite-rich coals within the major channel areas contain mineral matter which is richer in acidic minerals. These minerals are quartz, normative rutile

and kaolinite. Coals which formed in interchannel areas and swamps have generally higher vitrinite contents. The mineral matter of these coals contains relatively more pyrite, carbonate minerals and illite.

This relationship between mineral matter and coal type is indicative of different paleoenvironmental conditions in which the peat was formed. Vitrinite-rich coals resulted from peats which were subjected to brackish water conditions where moderately high pH and a lower redox potential prevailed. The inertinite-rich coals were derived from peats formed in acidic waters in an aerobic environment.

Fluvial channel environments had a control on seam geometry and the petrographic profile which characterizes coal seams. Most of the vitrinite-rich coal seams have a distinctive cyclic pattern: a vitrinite-rich base which grades upwards into inertinite-rich coal. This petrographic pattern may be repetitive within the seam and is mostly reversed in the coal seams which were deposited in channel areas where a vitrinite-rich cap grades downwards into an inertinite-rich base.

The influence of the topography of the pre-Karoo basement is evident throughout the succession of major depositional units, especially in the Witbank coalfield. Nevertheless, the paleoenvironments which existed during the formation of the various seams differed in extent. The different seams each have their own areal distribution, seam geometry and petrographical and chemical characteristics.

SAMEVATTING

Van beskikbare inligting asook data van steenkoolprodukte is 'n studiegebied in die Witbank- en Hoëveldsteenkoolvelde uitgesoek. Die petrografiese en elementsamestellings- eienskappe van die steenkoollae is afgelei uit die verband tussen droë as-vry vlugstof en hittewaarde (Snyman _et al_, 1983; Barnard, 1987).

Hierdie afgeleide waardes is aangevul met assamestellingsanalises van steenkoolprodukte, paleotopografiese data en laagdiktes. Uit hierdie data is inligting oor die toestande wat tydens veenvorming en afsetting geheers het, ingewin.

Gerekenariseerde ondergrondse karteringstegnieke is gebruik om verskeie chemiese en petrografiese eienskappe aan te dui. Die bestaan van hoofkanaalkomplekse wat na die suide uitspoelstrome tot gevolg gehad het, word veronderstel. Gedurende die vorming van die onderste lae was hierdie hoofkanale tot 6 km breed en het die roetes met 'n matige gradiënt oor die algemeen van oos na wes en van noord na suid gestrek. Die kanale volg topografiese laagtes en om topografiese hoogtes. Die plant-gestabiliseerde kanale het geaggradeer teen 'n tempo wat met veenvorming tred gehou het. Die voedingsbron van die kanale was smeltwaters afkomstig van die noordwaarts terugbewegende gletserbedekking.

Lae-energie strome het 'n wye laterale verspreiding van autochtone steenkoollae tot gevolg gehad. Die kanale het die vervoer en herafsetting van inertodetrinitiese materiaal van hipautochtoniese oorsprong te weeg gebring. Die steenkoollae wat met die kanaalareas geassosieer is, is oor die algemeen dunner en hierdie steenkool is gewoonlik inertiniet-ryk. Dié steenkool is ook bros en is geneig om suidwaarts skalierig te word.

'n Goeie verband tussen die mineraaleienskappe en steenkooltipe van die No. 2 Steenkoollaag is vasgestel. Die inertiniet-ryke steenkool wat in die hoofkanaalgebiede voorkom bevat mineraalbestanddele wat ryker

is aan suur minerale. Hierdie minerale is kwarts, normatiewe rutiel en kaoliniet. Steenkool wat in tussen-kanaalareas en moerasse ontstaan het, het oor die algemeen 'n hoër vitriniet-inhoud. Die mineraalbestanddele van hierdie steenkool bevat relatief meer piriet, karbonaatminerale en illiet.

Hierdie verwantskap tussen mineraalbestanddele en steenkooltipe is aanduidend van verskillende paleo-omgewingstoestande waarin die veen gevorm het. Vitriniet-ryke steenkool het ontstaan uit veen wat aan brakwatertoestande onderwerp was waar matige hoë pH en 'n laer redokspotensiaal geheers het. Inertiniet-ryke steenkool word met veenvorming in suur waters onder oksiderende toestande geassosieer.

Rivierkanale het 'n beheer op laagverspreiding en die petrografiese profiel wat kenmerkend van steenkoollae is, uitgeoefen. Die meeste van die vitriniet-ryke steenkoollae het 'n kenmerkende patroon: 'n vitriniet-ryke basis wat opwaarts gradeer na inertinitiese steenkool. Hierdie petrografiese profiel mag herhaal word in 'n steenkoollaag en is meesal omgekeer in steenkoollae wat in kanaalareas afgesit is waar 'n vitriniet-ryke boonste gedeelte van die laag afwaarts gradeer na 'n inertiniet-ryke basis.

Die invloed van die topografie van die voor-Karoo vloer is deurgaans in die opeenvolging van die hoofafsettingseenhede waarneembaar, veral in die Witbank-steenkoolveld. Nietemin het die paleo-omgewings wat tydens die vorming van die verskeie steenkoollae geheers het, van mekaar verskil. Die verskillende lae het elk sy eie oppervlakteverspreiding, laaggeometrie en petrografiese en chemiese eienskappe.

1. INTRODUCTION

The Witbank and Highveld coalfields are of extreme strategic and economic importance relative to any other coalfield currently being exploited in South Africa. A sustained interest has therefore been generated in these coalfields, both from a scientific and technological point of view.

The stratigraphy and sedimentology of the Witbank and Highveld coalfields have been extensively documented by a number of authors (Wybergh, 1922; Graham and Lategan, 1931; Cadle and Hobday, 1977; Cairncross, 1979; Le Blanc Smith, 1980a; Winter, 1985 and Barker, 1986). Limited attention has, however, been paid to the chemical and physical properties of the coal seams as such.

Historically, coal chemists studied coal as a unit composition. However, coal petrographers have discovered that all coals are composed primarily of three groups of macerals. These groups differ widely in their chemical and physical properties. This initiated a new approach to coal science. Coal chemists began to study each of these three maceral groups and found their composition to be dependent on rank (Stach _et al_, 1975, p. 1). Coal petrography has proved its value in applications to many geological problems, including the interpretation of depositional, structural and geothermal histories of coal basins (Bustin _et al_, 1983, p. 1).

Analytical data which were recorded at the National Institute for Coal Research (NICR), formerly known as the Fuel Research Institute, were used in this study (the National Institute for Coal Research is now known as the Division of Energy Technology of the CSIR). For historical and economical reasons, the data were mostly confined to proximate analyses and calorific values. In some cases, sulphur and phosphorus contents were also recorded. From a commercial point of view, this was considered adequate in evaluating coal properties. Petrographic data are almost non-existent and ultimate analyses are limited to those localized areas where colliery products were analyzed (Boshoff, 1986, p. 21-29).

A number of authors who studied Laurasian coals have referred to the chemical properties of various maceral groups (Speight, 1983, p. 85; Van Krevelen, 1981, p. 130; Stach et al, 1975, p. 68).

Studies initiated at the then Fuel Research Institute characterized the chemical properties of South African coal products (van Vuuren, 1975). This work was supplemented by studies in which the petrographical properties of coal could be related quantitatively to coal chemistry. It is now possible to derive petrographical data from dry ash-free calorific values and volatile matter contents, and extensive use was made of these relationships in this study (Snyman et al, 1983; Barnard, 1987).

The purpose of this work is, therefore, confined to the study of the formation and the characteristics of the coal seams per se. The study includes the regional variation in the chemical and petrographic properties as well as the associated mineral matter characteristics of the seams. The relationship between these variables has been applied to postulate environmental conditions at the time of peat deposition and subsequent coalification.

Based on the available data and guided by the extent of coal mining activity, a study area was selected in the Witbank and Highveld coalfields (Fig. 1).

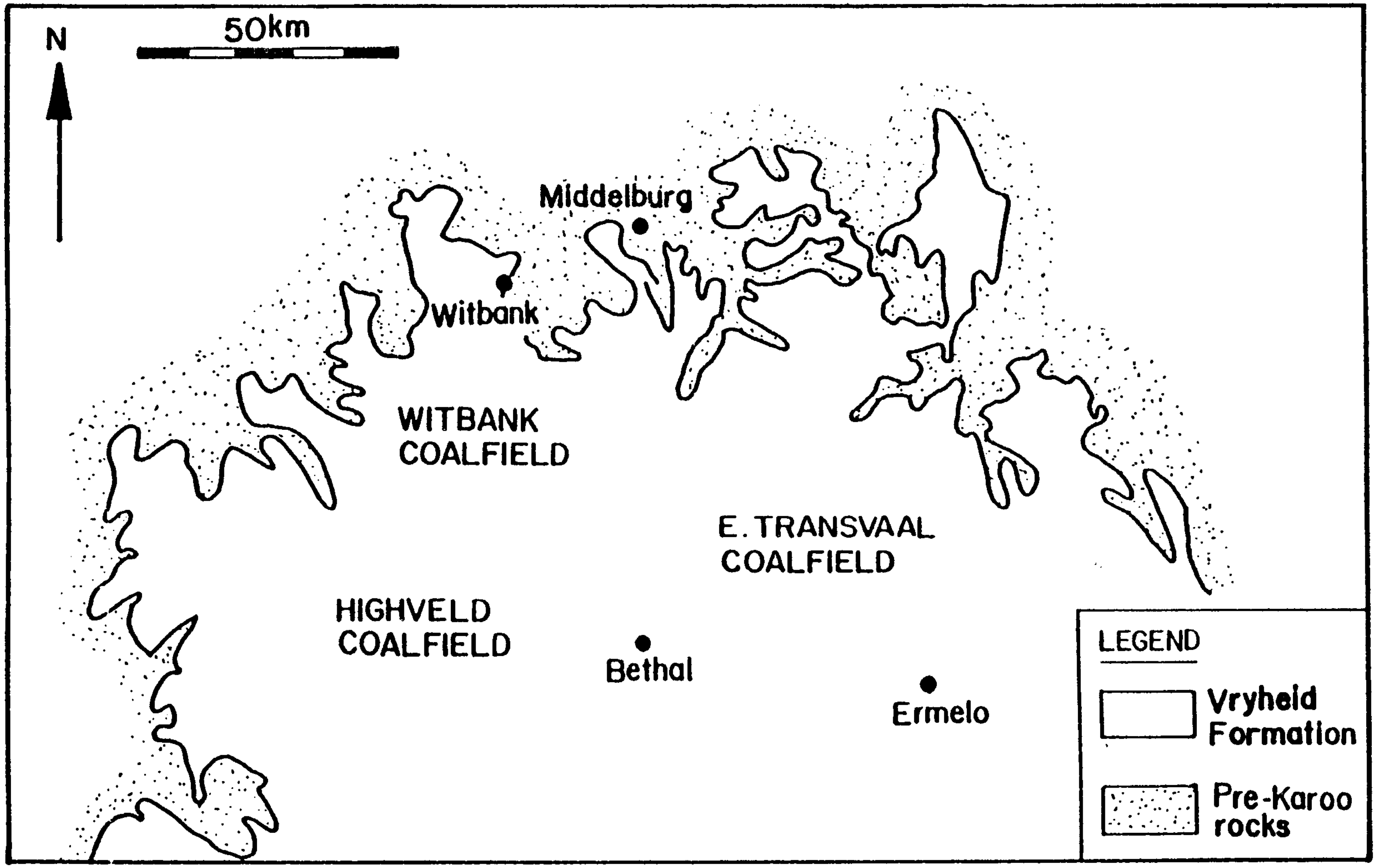


Figure 1 : Geological map of the north-eastern Karoo Basin in which the study area is located. (modified after GEOLOGICAL SURVEY, 1986)

2. GEOLOGY OF THE COAL MEASURES

2.1 THE KAROO SEQUENCE

The so-called coal measures belong to the Vryheid Formation of the Karoo Sequence and are well exposed in the mountains near Vryheid (Table 1). In the northern portion of the study area only the Dwyka and the Vryheid Formations are developed. The rocks in the northern facies of the main basin are slightly basined or horizontal, except at the eastern limit in which the dip is eastwards (Lurie, 1977, p. 51).

The Dwyka Tillite Formation is characterized by a sequence of glacial deposits. The formation comprises matrix supported tillites followed by mudstone and siltstone which grade upwards into sandstone and is overlain by conglomerates (Le Blanc Smith, 1980a, p. 24).

Dwyka ice-caps occurred in several more or less independent centres of Southern Africa (du Toit, 1954, p. 276). This Permo-carboniferous glaciation resulted in ice-sheets moving in a southerly and south-westerly direction (Fig. 2). The Transvaal ice-sheets scoured a series of elongated glacial valleys into the underlying pre-Karoo floor within the Witbank and Middelburg area (Le Blanc Smith, 1980a, p. 67). Glaciers retreated northwards and debris was deposited by the ice wherever the ice started to melt. Depressions were covered with moraine. Due to climatic warming, the relict moraine was reworked by melt-water which influenced the environment (Cairncross, 1979, p. 8). These sediments develop their maximum thickness along the axis of southerly-trending valleys. These deposits are irregular, thin out or are absent against the flanks of valleys and on topographically high areas (du Toit, 1954, p. 273-274; Le Blanc Smith, 1980a, p. 68-71). Glacial lakes were formed in valleys where ridges and mounds of moraine acted as barriers and prevented free drainage (Plumstead, 1957, p. 5; Snyman, 1984, p. 24).

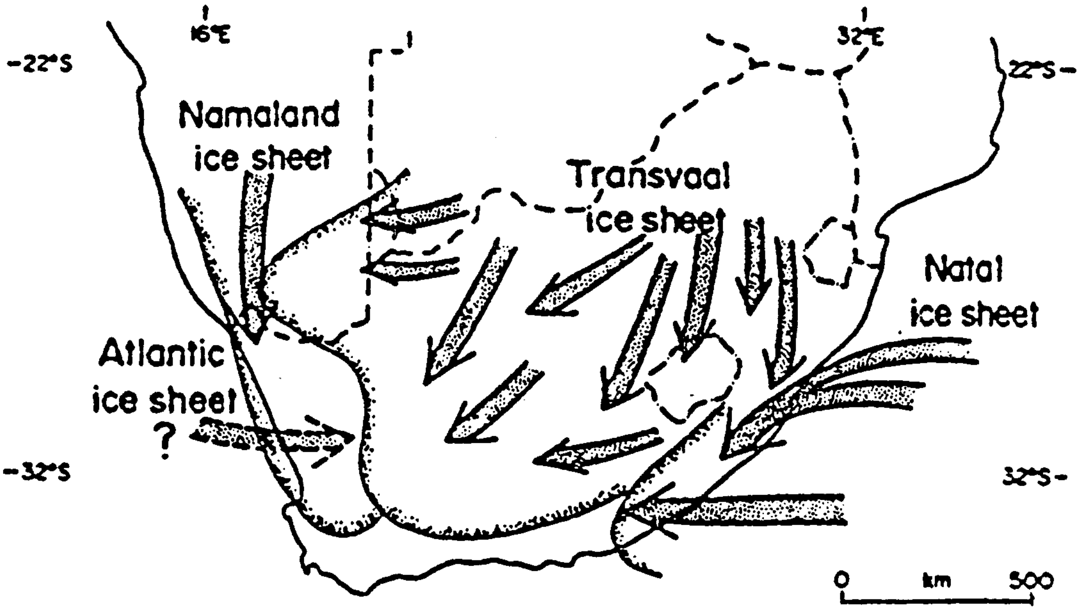


Figure 2 : Directions of ice movement from the major centres of glaciation (Tankard *et al*, 1982, p. 368).

TABLE 1 : THE LITHOSTRATIGRAPHY OF THE NORTHERN PORTION OF THE MAIN KAROO BASIN (SACS, 1980, p. 555).

GROUP	FORMATION	LITHOLOGY
	Drakensberg Clarens Elliot/Nyoka Molteno/Ntabene	Basalt Sandstone Mudstone, Shale Sandstone
Beaufort	Emakwezini	Mudstone, Sandstone, Shale
Ecca	Volksrust Vryheid Pietermaritzburg	Shale Sandstone, Shale, Coal Shale
	Dwyka	Tillite, Shale

The basin was thus segmented into a series of fresh-water lakes by the fluviodeltaic deposits of the Ecca Group in the main coal bearing areas. Deglaciation led to accumulated glaciolacustrine and glacio-fluvial sediments in moraine-filled depressions. As the glacial valleys became filled with sediments, conditions gradually changed to a prograding fluviodeltaic character (Snyman, 1984, p. 24-25; Tankard et al, 1982, p. 364, 370).

The Vryheid Formation can be followed through Natal extending in a northerly direction within the main Karoo basin to the coalfields of the Transvaal. The Vryheid Formation thins towards the north (SACS, 1980, p. 560).

In the Witbank coalfield, the Ecca Group is represented only by the Vryheid Formation, which overlies the Dwyka Formation. Towards the south-east, the deposition of the Pietermaritzburg Formation served to reduce the effect of the pre-Karoo topography (Snyman, 1984, p. 28). The environment towards the south gradually changed due to the infill of silts and clays which further smoothed out floor irregularities (Beukes, 1978, p. 35). The sediments of the Vryheid Formation were formed in this fluviodeltaic environment.

The Volksrust Formation is absent in the coalfields due to the present level of erosion, which has also resulted in the denudation of the upper coal measures in localized areas.

In a study of the Witbank coalfield, Le Blanc Smith (1980a, p. 11, 127) recognized ten genetic increments of strata (GIS) which were grouped into four major genetic sequences of strata (GSS). These comprise the stratigraphic column of the Witbank basin (Fig. 3). This column is also broadly applicable to the Highveld coalfield (Le Blanc Smith, 1980b, p. 325).

The stratigraphic column was subdivided into a number of distinct sedimentary facies and two broad depositional models were formulated; a coarsening-upward deltaic sedimentary model and a fining-upward fluvial sedimentary model.

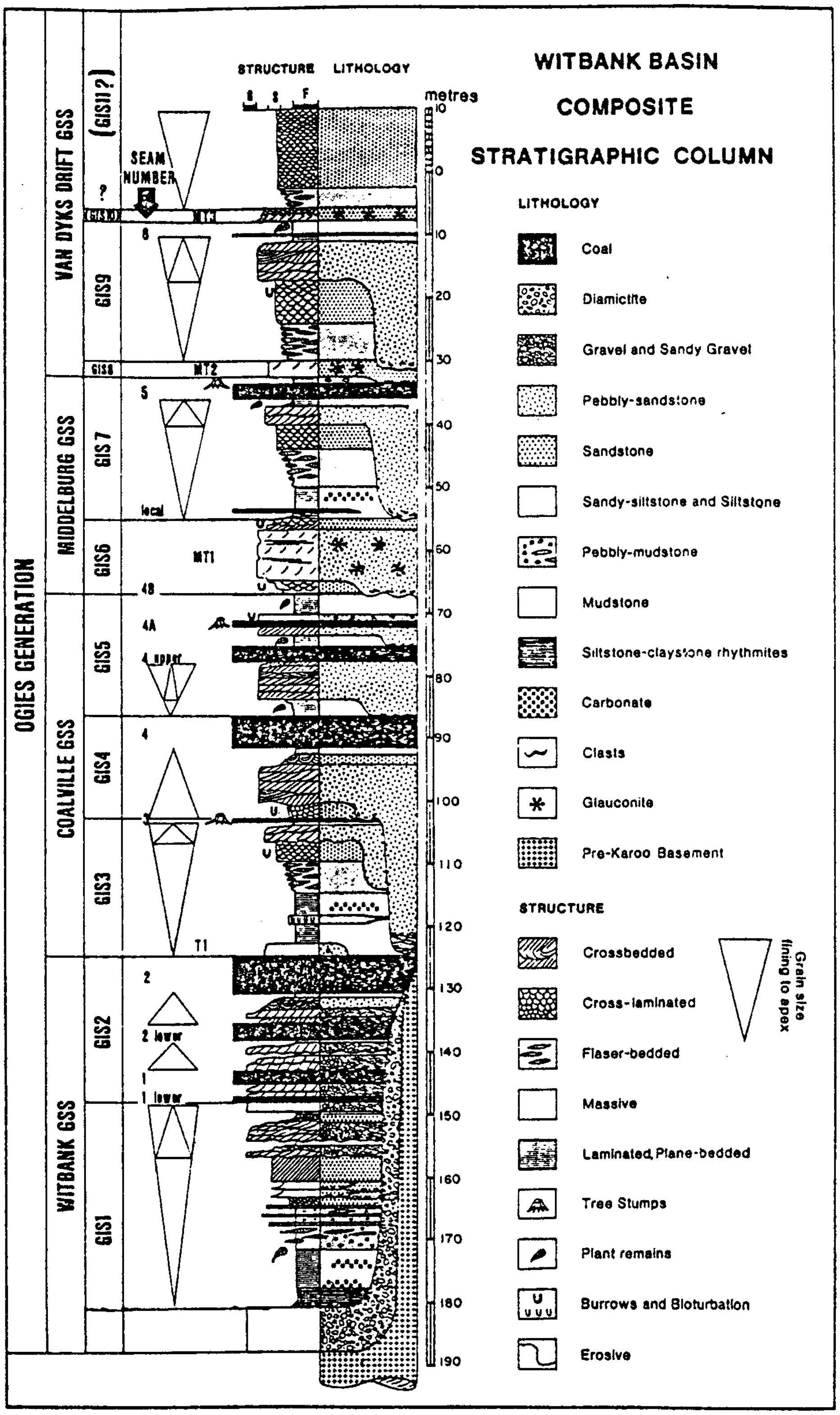


Figure 3 : Witbank basin stratigraphic column.
(Le Blanc Smith, 1980a, p. 14).

The pre-Karoo basement topography and the overlying strata had an influence on succeeding depositional sequences (Le Blanc Smith, 1980b, p. 314-315).

The first depositional sequence represents tillites at the base followed by an upward-coarsening arrangement of depositional facies. These fluvioglacial sediments accumulated from melt-waters in a prograding outwash delta (Le Blanc Smith and Eriksson, 1979, p. 78). Growth of vegetation resulted in the abandonment of the outwash plain and the formation of swamps. Sediment influx at the end stage of the proglacial period is mostly confined to anastomosing channel systems (Le Blanc Smith and Eriksson, 1979, p. 78-79). Fluvial sedimentation and paleotopography were the principal controls of distribution and thickness of the basal seams in the Witbank and Highveld coalfields. Paleotopographical depressions resulted in thin and impersistent lower seams. The paleovalleys provided routes for sediment transport and high rates of sedimentation inhibited the accumulation of peats (Winter, 1985, p. 11). This sequence terminates at the top of the No. 2 Seam.

The second depositional sequence comprises an upward-coarsening succession of siltstone and sandstone which is capped by the No. 3 Seam. This is overlain by a combination of fine-grained conglomerate and sandstone fining-upwards into siltstone which is capped by the No. 4 zone coals (Le Blanc Smith, 1980a, p. 130-132). According to Cadle (1982), this complex seam splitting is caused by braided stream sedimentation during peat accumulation.

The third depositional sequence comprises sediments contained between the top of the No. 4 Upper (or No. 4A Seam where present), and the top of the No. 5 Seam. The glauconitic sandstone and siltstone above the No. 4 Seam are interpreted by these authors as barrier-island sediments. The clastic sediments below the No. 5 Seam are interpreted as lagoonal and shallow water deltaic deposits. This would account for the persistent lateral extent of the seam.

The fourth depositional sequence includes all the overlying strata above the No. 5 Seam. The sequence comprises sandstone and an upward-coarsening succession of shales, siltstone and sandstone (Le Blanc Smith, 1980a, p. 196).

2.2 THE KAROO DOLERITES

The Karoo Sequence commonly hosts dolerites, believed to be feeders of the Drakensberg lava. These dolerites occur in the form of dykes and sills, the former often found in arenaceous rocks and the latter frequently in laminated argillaceous sediments (Lurie, 1977, p. 53).

Dolerite dykes and sills penetrated the Karoo sequence affecting coal seams to a lesser or greater degree. In the northern-most boundary of the basin, the igneous activity was limited; therefore the Witbank coalfields were relatively unaffected by these intrusions. The igneous activity increased southwards, however, to the extent of eliminating coals of various seams in the Highveld coalfields, locally sterilizing large potential reserves (Barker, 1986, p. 101-102).

3. THE PROPERTIES OF COAL

Coal is a complex rock which has been defined in numerous ways. An apt, if lengthy definition is contained in the DICTIONARY OF GEOLOGICAL TERMS (1962, p. 91). "Coal is the general term for naturally occurring commonly stratified rock-like, black to brown derivatives of forest type vegetation that accumulated in peat beds which by burial and dynamochemical processes, was compressed and altered to material with increasing carbon content and that does not contain so much incombustible material as to be unfit for fuel".

Over and above the organic substances in coal, coal consists of impurities or mineral matter. Hence, from a scientific point of view, three fundamental and independent variables in coal can be distinguished (Snyman et al, 1983, p. 1), namely

- grade : the degree of purity, (i.e. ash content)
- type : the maceral composition, (i.e. vitrinite, exinite and inertinite content)
- rank : the degree of metamorphism (i.e. reflectance of vitrinite)

Of the above variables, only type and grade are primarily related to the depositional environment of the original peat.

3.1 THE CHEMISTRY OF COAL

The chemistry of coal is complex due to the presence of organic and inorganic phases. Elements contained in the organic substance are carbon (C), hydrogen (H), nitrogen (N), sulphur(S) and oxygen (O). With the exception of nitrogen, these elements are also common to the inorganic substance. Furthermore, changes occur in the mineral matter in coal upon incineration (Speight, 1983, p. 142).

The inorganic matter has an influence on the analytical results obtained by most test procedures. Caution must, therefore, be applied when interpreting analytical data on coal.

Most coal analyses are reported on an air-dry or as-determined basis for technological purposes. Considered from a scientific angle, many coal properties can only be evaluated on a pure-coal or organic basis. This requires that the total mineral matter content be accurately known, so that the effect of coal grade can be eliminated. The determination of the total mineral matter content in coal is tedious and not routinely undertaken.

As the ash content in coal represents the non-volatile portion of the mineral matter, several formulae have been proposed for the calculation of the latter. None of these are entirely satisfactory as they tend to underestimate the mineral matter content of South African coals.

The most comprehensive is the King, Maries and Crossley formula from which the mineral matter content can be estimated (Speight, 1983, p. 129).

$$M = 1{,}09\ A + 0{,}5\ Sp + 0{,}84\ CO_2 - 1{,}15\ SO_3\ A + SO_3\ C + 0{,}5\ Cl$$

where M = percentage mineral matter in coal
A = percentage ash
Sp = percentage pyritic sulphur in coal
CO_2 = percentage carbon dioxide in coal
SO_3A = percentage SO_3 in ash
SO_3C = percentage SO_3 in coal
Cl = percentage chlorine in coal

To simplify the problem the mineral matter content can be substituted by the ash content, which is readily available. In this manner a close approximation of various analytical parameters to those of a pure coal substance can be obtained.

Any valid parameter (K) expressed on an air-dried (a.d.) basis can be calculated to an expression on a dry ash-free (d.a.f.) basis.

$$\% \text{ K (d.a.f.)} = \frac{\% \text{ K(a.d.)} \times 100}{100 - \% \text{ Ash} - \% \text{ Moisture}}$$

Parameters such as the calorific value, volatile matter or elemental composition can be expressed on a d.a.f. basis to determine certain characteristics of coal. Comparisons of these values for different coals are valid for relatively low ash contents. Serious errors are introduced where the ash content is high.

3.2 INTERPRETATION OF RESULTS

3.2.1 Sampling and sample preparation

The sampling of coal and sample preparation must ensure that an analytical sample is representative of the mass of coal from which the sample was taken. Any precise analytical result depends entirely on the reliability of the sample.

The sampling procedure for coal is well documented (ISO 1988-1975, p. 21). Coal samples are taken from stockpiles, conveyor belts and railway trucks for testing of a colliery product. A vertical channel sample is taken at an exposed coal face of a seam in a mine. The channel sample is usually subdivided into samples of different bands of coal as they occur within the seam. This allows for a detailed study of the characteristics of a seam. Core samples are obtained from coal seams in exploration programmes. Samples may be taken of individual coal bands, based on their macroscopic appearance. Together with geological descriptions, detailed analyses can provide much information of a particular seam.

The coal sample is prepared for analysis by stages of particle size reduction and division. In a two-stage sample preparation, the coal sample is reduced from its initial top-size to an intermediate size and divided to a smaller mass. After the second-stage, the sample is reduced in size to 1 mm for petrographic analysis or to 0,2 mm for general analyses. A three-stage sample preparation is usually employed if the top-size of the original sample exceeds 120 mm (ISO 1988-1975, p. 21-23).

The more important chemical data and their interpretation are discussed below.

3.2.2 Calorific value ①

The usefulness of the calorific value is evident as most coals are sold on the basis of their heating value.

The calorific value (expressed as MJ/kg) is determined by a calorimeter under specified, pressurized conditions at constant volume. This value is known as the gross or higher calorific value of coal and is the standard method used for reporting the calorific value of coal.

In industrial practice, coal is burnt at atmospheric pressure and the latent heat associated with the loss of moisture and associated volatile products must be corrected for. The net calorific value under constant pressure is a more relevant parameter for industrial purposes, and is some 3% lower than the gross value (Snyman, et al, 1983, p. 9).

The calorific values quoted in this study refer only to the gross calorific values. The calorific value in coal is derived essentially from the carbon and hydrogen in the coal.

3.2.3 Proximate analysis

From a practical point of view, the proximate analysis is normally determined as it is rapid and precise. The proximate analysis gives a measure of the moisture content of the coal, the organic and inorganic volatile matter and the organic and inorganic non-volatile matter contents. The analysis provides most useful data for the assessment of the general characteristics of a coal. The proximate analysis comprises the inherent moisture content, the ash content, the volatile matter and fixed carbon contents, all expressed as mass percent.

The proximate analysis is expressed on an air-dry basis. The tests that are performed are empirical. The results reflect the physical behaviour of the coal under specified conditions and the results cannot be regarded as absolute.

3.2.3.1 Inherent moisture content ②

The inherent moisture in coal is in itself not important, other than being a diluent. It is necessary for the calculation of a parameter to a dry or dry ash-free basis. As coal is a porous substance, the inherent moisture in the coal attains equilibrium with its surroundings. The porosity of coal decreases with increasing rank up to the anthracitic stage. The inherent moisture content of coal gives an indication of rank; the higher the inherent moisture content, the lower the rank.

The inherent or air-dried moisture content is the loss of mass as a percentage when a coal sample is heated at a temperature of 105-110°C over a prescribed period.

3.2.3.2 Ash content ③

The ash content of a coal is the non-combustible inorganic matter which remains after complete combustion. The determined ash content is always less than the mass of mineral matter originally present in the coal. This is due to the loss of carbon dioxide from the carbonate minerals, the loss of sulphur from the sulphide minerals and the loss of the moisture of constitution of the clay minerals.

The ash is a diluent in coal; a high ash coal is, therefore, of low grade and less suitable for utilization.

Ash is determined by gradual heating of a coal sample to 815°C in a ventilated furnace. To prevent fixation of sulphurous gas by alkaline oxides, a two-stage heating cycle is used, by raising the temperature first to 500°C. This allows for the dissociation of sulphide minerals and the venting of sulphur compounds before the carbonate minerals lose carbon dioxide.

3.2.3.3 Volatile matter content

The volatile matter content of coal consists primarily of hydrocarbons and oxides of organic origin, but also includes moisture which is corrected for. The volatile matter also includes carbon dioxide from carbonate minerals, about half the sulphur from sulphide minerals and the hydroxyl groups from clay minerals.

Volatile matter is liberated in the absence of air at 900°C over a period of 7 minutes. The mass loss is expressed as a percentage.

3.2.3.4 Fixed carbon content

The fixed carbon is the organic residue remaining after the volatile matter has been liberated. It may contain small amounts of nitrogen or hydrogen. The fixed carbon is the percentage obtained when the sum of the moisture, ash and volatile matter contents is subtracted from 100.

3.2.4 Ultimate analysis

The organic substance of coals consists essentially of carbon, hydrogen, nitrogen, sulphur and oxygen. The ultimate analysis comprises the determination of all these elements.

3.2.4.1 Carbon and hydrogen contents

In the determination of the carbon and hydrogen contents, the carbon is usually not corrected for the carbon from carbonate minerals. The hydrogen content is corrected for the hydrogen which originates from the inherent moisture content, but is not corrected for the moisture of constitution of clay minerals.

Expressed on a dry ash-free or pure coal basis, the relationship between the carbon-hydrogen-oxygen contents pre-determine many coal characteristics. These elemental ratios quantify the coal rank and coal type and can be used in classification systems. Apart from ash content or coal grade, these elemental ratios relate to coal behaviour in various technological applications.

As the rank of coal increases, the carbon content increases with corresponding decreases in oxygen and hydrogen contents.

Carbon and hydrogen are determined by oxidation at 1350°C and the oxidation products are absorbed separately and their mass determined. The percentages of carbon and hydrogen are calculated from the increase in mass of the absorbents.

3.2.4.2 Nitrogen content

Nitrogen originates from side-chains in cyclic structures (Van Krevelen, 1981, p. 170). Analyses of nitrogen determined on maceral concentrates, and on various density fractions indicate that vitrinite is richer in nitrogen than inertinite. South African low-rank coals tend to have lower nitrogen contents. This also applies to low-rank vitrinite-rich coals situated in the Northern Transvaal, i.e. in the Springbok Flats and the Waterberg area.

Nitrogen can be determined by classical wet chemical methods. Nitrogen, together with carbon and hydrogen, can also be determined by modern elemental analyzers.

3.2.4.3 Sulphur content

Very little is documented on the organic sulphur in coal. Based on South African coal product samples, the organic sulphur varies from about 0,2% to less than 1,0%. It appears to be related to a limited extent to the volatile matter and, hence, is in part of aliphatic origin.

The percentage organic sulphur is obtained by subtracting the sum of the percentages of mineral and sulphate sulphur from the total sulphur content.

3.2.4.4 Oxygen content

The oxygen content is a function of the type and rank of a coal. The oxygen content decreases with an increase in rank. The lower the vitrinite content, the higher the oxygen content for South African coals of similar rank. In practical terms, oxygen is a diluent resulting in a lower calorific value for equal ash-content coals.

The oxygen content, expressed as a percentage on a d.a.f. basis is obtained by subtracting the sum of carbon, hydrogen, nitrogen and sulphur, all expressed on a d.a.f. basis, as a percentage from 100.

3.3 PETROGRAPHIC ANALYSIS

A coal sample is carefully crushed to a top size of 1 mm in such a manner as to produce a minimum amount of fines. Particulate blocks are prepared from the coal particles which are bonded in an epoxy resin. One side of the block is carefully polished for microscopic examination in reflected light.

3.3.1 Maceral composition (coal type)

A comprehensive maceral analysis may comprise the identification of all individual macerals, submacerals, maceral varieties (Table 2) and visible mineral matter.

If a maceral analysis is required for technological purposes, it is normally sufficient to distinguish between the three group macerals. Each maceral group has a characteristic range in reflectance, hence, a somewhat similar chemical composition for a particular rank (Stach et al, 1975, p. 252).

A binocular microscope fitted with a reflected light system with an oil immersion objective and oculars of suitable magnification is used for the analysis. One adjustable ocular is fitted with a graticule. The coal specimen is shifted laterally by a stage and various transects are traversed. On a point to point (0,3-0,5 mm) and a line to line (0,3-0,5 mm) basis, any maceral coincident to the intersection of the crosshairs is counted (Stach et al, 1975, p. 254).

As a rule, 500 maceral counts are recorded on a point counter. It has been shown statistically that for a total of 500 points counted, the probable error for any component is less than 5% absolute (Snyman et al, 1983, p. 21; Stach et al, 1975, p. 255).

The maceral composition (or coal type) is quantitatively expressed on a volume per cent basis. In this study, the maceral composition is given on a visible mineral-free basis.

TABLE 2 : SUMMARY OF THE MACERALS (Stach et al, 1975, p. 58)

GROUP MACERAL	MACERAL	SUB-MACERAL
Vitrinite	Telinite	Telinite 1 Telinite 2
	Collinite	Telocollinite Gelocollinite Desmocollinite Corpocollinite
	Vitrodetrinite	
Exinite	Sporinite Cutinite Resinite Alginite Liptodetrinite	
Inertinite	Micrinite Macrinite Semifusinite	
	Fusinite	Pyrofusinite Degradofusinite
	Sclerotinite	Fungosclerotinite
	Inertodetrinite	

3.3.2 Description of macerals

Coal consists of various organic constituents. The microscopically visible organic constituents are called macerals. Macerals are distinguished from each other by reflectance, colour, shape and polishing hardness (Snyman et al, 1983, p. 20; Stach et al, 1975, p. 54-55).

3.3.2.1 The vitrinite group

Three different macerals can be distinguished within this group, namely telinite, collinite and vitrodetrinite.

Telinite retains a distinct cell structure. These cell cavities are mostly filled with collinite, and less frequently with resinite or clay (Stach et al, 1975, p. 59).

Collinite is defined as being derived from gels. The variety named telocollinite is also commonly used for the determination of rank by reflectance measurements.

Gelocollinite has its origin from genuine gel. Desmocollinite has a weaker reflectance and is of a perhydrous nature. Oval massive bodies are referred to as corpocollinite (Stach et al, 1975, p. 59-64).

Vitrodetrinite is detrital fragments of vitrinite. Its origin has been ascribed to degradation in the peat stage of coal formation, or to pressure. More recently, it has been identified as hypautochthonous material deposited secondarily in channel areas (Stach et al, 1975, p. 19, 193).

The reflectance properties of vitrinite are intermediate between those of exinite and the higher reflecting inertinite.

3.3.2.2 The exinite group

The exinite group comprises the macerals sporinite, cutinite, resinite, alginite and liptodetrinite (Stach et al, 1975, p. 200-216).

Sporinite represents the exines of micro- and macrospores (Snyman, 1976, p. 244) and pollens (Stach et al, 1975, p. 69).

Cutinite originates from the cuticles or wax layers of leaves or stems and the cuticles may occur as distinctive bands with or without appendages (Snyman, 1976, p. 244).

Resinite represents the resins and oils that occur in living plant material.

Alginite originates from certain types of algae. It forms a minor constituent in South African humic coals, but is the characteristic component of torbanite or boghead coal (Stach et al, 1975, p. 92).

3.3.2.3 The inertinite group

Under the microscope micrinite is light grey to white in colour and is characterized by its rounded shape and the extremely small size of its grains (Stach et al, 1975, p. 103).

Macrinite can be described as a more or less amorphous non-granular groundmass of relatively high reflectance showing practically no structure.

Sclerotinite represents mainly the sclerotia, spores and hyphae of fungi.

Fusinite is partly derived from fossil charcoal and has a cellular structure. These carbonized cell walls and hollow lumens are sometimes crushed (Van Krevelen, 1981, p. 61), and is then referred to as "Bogenstruktur" in German. In German brown coals, fusinite which is associated with a thin natural coke layer, is classified as pyrofusinite (Stach et al, 1975, p. 97). Degradofusinite originates from woody tissue extensively altered by bacterial and fungal attack (Falcon and Snyman, 1986, Plate 10, Fig. 1-2).

Semifusinite occurs as a transition from fusinite to vitrinite. Its reflectance falls between that of fusinite and vitrinite (Van Krevelen, 1981, p. 61).

Inertodetrinite consists of relatively high-reflecting fine particles, normally smaller than 30 µm. These particles can be fragments of fusinite or semifusinite, fragments of fungal spores or of sclerotia or fusinized microspores (Stach et al, 1975, p. 101). Inertodetrinite may occur in coals deposited in channel areas or may have been transported to distal regions.

3.3.2.4 Reactive semifusinite

Vitrinite and exinite are regarded as "reactive" macerals insofar that they become plastic on heating. Inertinite does not exhibit "reactive" properties and is, therefore, considered inert. A portion of the semifusinite, which is a transition from fusinite to vitrinite, may be reactive. Barnard (1987) has quantified the relationship between the vitrinite content and the reactive semifusinite (RSF) for South African raw coal products (Fig. 4). The RSF content can be determined quantitatively and is generally inversely proportional to the vitrinite content (Barnard, 1987, p. 102-103).

Hence, if the vitrinite content of a coal is known, the RSF content can be derived therefrom. From a technological point of view, the RSF content in South African coal contributes to the total reactivity of coal. The total reactivity of a coal is significant as it influences the behaviour of coal in numerous technological applications, such as combustion, coke manufacture and hydroliquefaction processes.

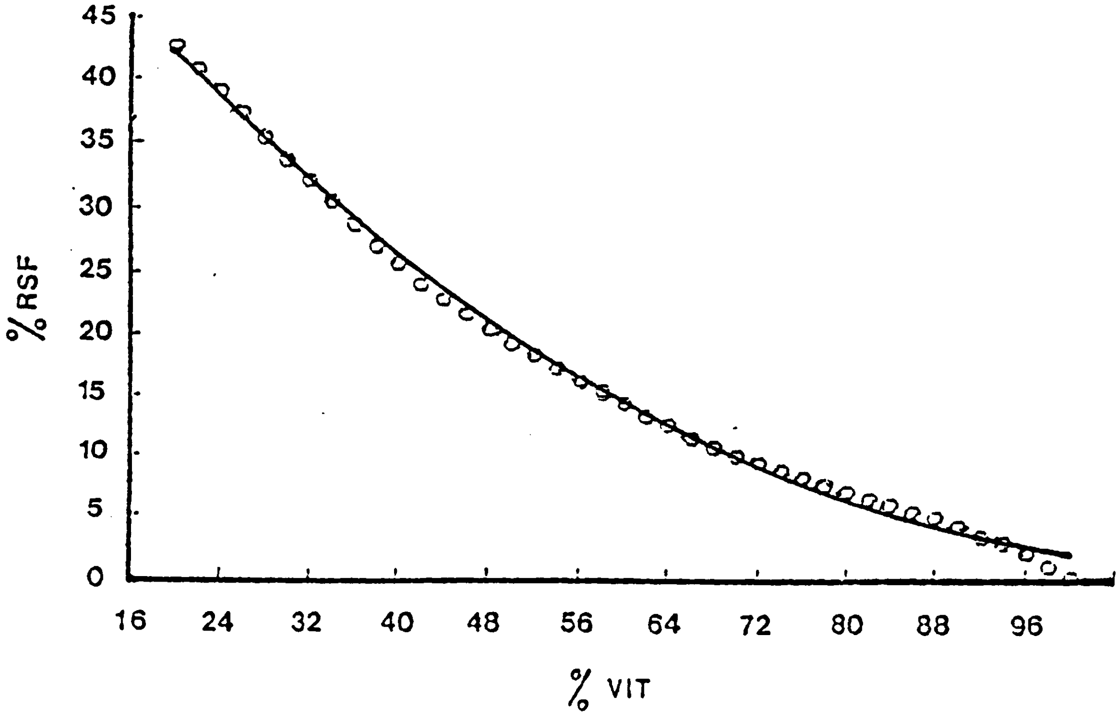


Figure 4 : The correlation between the % vitrinite and the % RSF in South African coal products (Barnard, 1987, p. 102).

3.3.3 Origin of macerals

The genesis of macerals relates to the original plant material and its decomposition before and during the peat stage, as well as the degree of coalification (Stach et al, 1975, p. 180).

3.3.3.1 The vitrinite group

Cellulose of plant cell walls and lignin in lignified cell walls decompose into humic substances in an aerobic environment. Gaseous and liquid products are lost, but some solid residue remains. The lignin and cellulose remains are resistant to further oxidation or bacterial attack. Humic acids infiltrate humic detritus of the peat (Stach et al, 1975, p. 184-185).

Vitrinite formed during the peat stage by humification and gelification. By gradual oxidation and desiccation, humic acids can exist in the presence of cations as Na-, Ca-, Mg-, Fe- and Al-humates.

Humification is followed by gelification in the subbituminous stage. Humic tissues are converted into a colloidal solution which dries to a gel in situ. The biochemical gelification occurs during the transition from peat to brown coal (Stach et al, 1975, p. 185).

Vitrinite formed under relatively stagnant conditions within a swamp. The dead plant remains sank rapidly into stagnant, anaerobic water (Van Krevelen, 1981, p. 72).

3.3.3.2 Exinite group

Exinite is best preserved in acidic to neutral conditions and non-oxidising environments. A high content of carbonate minerals is therefore seldom associated with a high exinite content in coal (Stach et al, 1975, p. 144).

3.3.3.3 Inertinite group

The inertinite macerals are generally considered as having been derived from the same or similar kind of plant material as vitrinite. The inertinite macerals have undergone chemical changes due to processes of charring, oxidation, mouldering and fungal attack at an early stage of deposition (Van Krevelen, 1981, p. 72).

Where swamp trees die and do not fall into the enclosing peat, this leads to the formation of inertinite or even to complete decay.

Fusinite is thought to have originated from plant fragments that have suffered partial combustion. Semifusinite has properties intermediate between vitrinite and fusinite and is regarded to have suffered a lesser degree of degradation than fusinite (Ward, 1984, p. 106). There is a transition between vitrinite and semifusinite, but not between semifusinite and fusinite (Stach et al, 1975, p. 152). It may be concluded that the transition material was formed under similar conditions as vitrinite, but was exposed to prolonged or more severe oxidation conditions prior to its conservation.

Discrete inertodetrinite particles are formed by the degradation of massive inertinite or of eroded peat during transport from the original place of accumulation (Hagelskamp and Snyman, 1988, p. 1). These are deposited in quiet subaquatic conditions. Micrinite is associated with high water levels and low redox conditions and may be the result of the polymerization of hydrogenated degradation products derived from spores (G.H. Taylor, 1988: Stach colloquim, Aachen). The reverse holds true for macrinite (Ward, 1984, p. 80, 101).

Inertinite generally formed under aerobic conditions. The conditions in the swamp were relatively dry with a relatively low groundwater table, or with moving, aerated water. The association of the clastic minerals with inertinite indicates that generally acidic conditions prevailed. This is also supported by the lower preference of carbonate minerals and illite towards inertinite.

3.3.4 The chemical composition of coal macerals

The literature contains only limited data on the elemental composition of individual macerals (Stach et al, 1975, p. 68; Van Krevelen, 1981, p. 130; Speight, 1983, p. 85). These authors tabulated the carbon and hydrogen contents for vitrinite.

In comparison with values published by Stach et al, analytical results show that South African coals have a lower hydrogen, lower carbon and higher oxygen contents (Boshoff, 1986, p. 21-29) than the European counterpart on an equal volatile matter content basis.

Vitrinite and inertinite concentrates were prepared by making use of a centrifuge. Liquids were used by which the relative density can be controlled to 0,005. Depending on the intergrowth of macerals, vitrinite can be concentrated up to 95% purity and inertinite to more than 80%. The ash content of vitrinite is usually below 3% and that of inertinite varies typically between 15% and 30%. Mineral matter has a relative density of about 2,6. The apparent relative density of the maceral concentrates are largely controlled by differences in mineral matter content.

Narrow relative density ranges can be used to obtain optimum yields of concentrated macerals. This holds the disadvantage that macerals are selectively concentrated. Macerals with a relative density falling just above or just below the density range selected are discarded. One advantage is that macerals from the same sample, hence of the same rank, can be analysed. The chemical composition of the concentrate may then be computed to a pure-maceral basis.

Due to its relatively low content and its intimate association with other macerals in South African coals, exinite cannot readily be concentrated. However, its properties are not dissimilar to torbanite which have been documented.

The chemical properties of vitrinite and inertinite for South African bituminous coals are compared and tabulated with increasing rank (Table 3). The approximate empirical composition using oxygen as unity is also included.

TABLE 3 : CALCULATED CHEMICAL COMPOSITION OF VITRINITE AND INERTINITE WITH INCREASING RANK (modified from Snyman et al, 1983).

	VITRINITE				INERTINITE			
% RoV	% C	% H	% O	Empirical Composition	% C	% H	% O	Empirical Composition
0,6	77,5	5,5	14,0	$C_7 H_6 O$	77,4	3,4	16,7	$C_6 H_3 O$
0,7	80,5	5,8	10,7	$C_{10} H_9 O$	78,6	3,6	15,3	$C_7 H_4 O$
0,8	84,0	5,9	7,1	$C_{16} H_{13} O$	79,8	3,7	15,0	$C_7 H_4 O$
0,9	87,0	5,8	4,2	$C_{28} H_{22} O$	81,3	3,8	12,4	$C_9 H_5 O$
1,0	88,1	5,6	3,4	$C_{34} H_{26} O$	82,8	4,0	10,7	$C_{10} H_6 O$

From the tabulated results vitrinite has a higher carbon, higher hydrogen and lower oxygen content than inertinite, throughout the rank range. The inertinite is also much more resistant to chemical change with increasing rank than vitrinite.

A number of authors, with reference to European coals, have shown that inertinite has a higher carbon content than vitrinite (Speight, 1983, p. 85). This may be accounted for by the fact that the inertinite of these coals consists predominantly of fusinite (K Kruszewska, 1988 per. comm). Fusinite has a carbon content of typically 94% (Van Krevelen, 1981, p. 120). The variation in the composition of the inertinite of European coals is attributed to fusinitization and carbonization. South African coals have relatively low fusinite contents, and the inertinite group was subjected to conditions which promoted oxidation rather than a carbonization transformation.

3.3.5 Minerals in coal (coal grade)

All coals contain mineral matter of which the amount and composition vary considerably and depends on the depositional history of a coal (Speight, 1983, p. 119).

The inorganic constituents in coal may be divided into two classes, namely, inherent and adventitious mineral matter (Francis, 1954, p. 483). Mineral matter which had its origin in the coal forming plants is classified as inherent mineral matter. Adventitious mineral matter was brought into the coal-forming deposit from external sources by mechanical means. This mineral matter could have been transported as dust by air or as suspended or dissolved material carried by water (Speight, 1983, p. 116).

The above definitions for inherent or adventitious mineral have limited application. They do not distinguish between the inorganic constituents that are colloidally associated within the plant tissues and those combined with some constituent of those tissues (Francis, 1954, p. 483).

Adventitious mineral matter is, therefore, subdivided into syngenetic and epigenetic minerals. The syngenetic minerals may be of clastic origin or may have formed as chemical precipitates during the depositional and diagenetic stages of coal formation. Epigenetic minerals were deposited after the diagenetic stage and occur in cracks or along cleats in coal. Due to the long period of biochemical coalification, syngenetic minerals may have formed successively (Murchison and Westoll, 1968, p. 312). Syngenetic minerals are further subdivided into two groups. The first group represents minerals introduced by mechanical means (allogenic). This group comprises those clastic minerals transported into the coalification area. The second group represents those minerals that originate from colloidal or genuine solutions (authigenic)(Murchison and Westoll, 1968, p. 312).

Grain size and shape of the allogenic clastic material give some insight into the source and conditions of flow to the region of coal deposition. Allogenic minerals do not give much information of the conditions under which macerals were formed. In this respect, the occurrence of authigenic minerals, for which the initial conditions for the genesis of some are known, is of greater importance.

3.3.5.1 Clay minerals

Kaolinite is the most predominant clay mineral in coal (Gaigher, 1980, p. 41). Illite usually accounts for less than 10% of the total as kaolinite is much more resistant to chemical degradation than illite (Murchison and Westoll, 1968, p. 313).

Clay minerals occur in relatively small amounts as authigenic constituents in vitrinite. The clays may occur as petrifications or cell-cavity infillings (Ward, 1984, p. 63). Allogenic kaolinite is a clastic mineral which was introduced into the coal forming environment as suspended sediments (Stach et al, 1975, p. 122) or as detrital debris of feldspar and mica. In the Witbank and Highveld areas, kaolinite occurs regionally in association with inertinite-rich coals which were deposited in topographically depressed areas. High contents of kaolinite in the mineral matter in coal are also associated with higher ash content coals. Coals occurring in channel areas and hypautochthonous coals usually have a higher proportion of kaolinite. Illite occurs more frequently as an authigenic mineral in less acidic environments which contributed to its preservation.

3.3.5.2 Oxide minerals

The most common oxide mineral is quartz. Clastic quartz was transported by wind or water and occurs as more or less rounded grains (Stach et al, 1975, p. 129). Allogenic quartz grains are relatively small (5-25 µm in diameter) and are frequently associated with allogenic kaolinite. Silica is in a sense mobile, since due to the weathering of silicate rocks, silica passes into solution (Speight, 1983, p. 125). Silica formed from solution has a finely-crystalline structure. According to Kunstmann et al, (1968), these particles are generally less than 10 micron in diameter.

The occurrence and content of TiO_2 in South African coal ashes is remarkably consistent. Expressed as rutile, it is largely associated with inertinite, but occurs as a minor constituent. The mineral is allogenic and is preserved in an acidic environment.

3.3.5.3 Sulphide minerals

The most common sulphide mineral is pyrite although marcasite is also found in South African coals. Syngenetic pyrite occurs, with few exceptions, in the form of small concretions finely dispersed in the coal. Syngenetic pyrite, which is associated with vitrinite, formed under anaerobic conditions (Murchison and Westoll, 1968, p. 316). Brackish waters with a moderately high pH favour the formation of syngenetic pyrite. Davies (quoted by Raymond and Adrejko, 1983, p. 27) found that the organic sulphur in brackish peats was significantly higher than the organic sulphur in fresh-water peats.

Two hypotheses for the formation of pyrite are suggested. According to the first, sulphate ions are reduced by sulphur bacteria; the second hypothesis is that sulphur arises from plant material and animal albumen (Murchison and Westoll, 1968, p. 316).

Syngenetic pyrite appears to be authigenic due to the rigid conditions that govern its formation. Pyrite is very susceptible to oxidation and cannot form under aerobic conditions. Passat and Kullend (quoted by

Raymond and Adrejko, 1983, p. 164), suggest that pyrite which formed under high pH conditions (above 7) is more stable than pyrite formed under lower pH conditions (below 5). Under more acidic conditions, the formation of marcasite rather than pyrite might be expected.

In addition to syngenetic pyrite types, pyrite is found in fusinite and may be either of a syngenetic or epigenetic origin. Epigenetic pyrite is commonly found in cracks and fissures in coal (Murchison and Westoll, 1968, p. 316).

3.3.5.4 Carbonate minerals

Carbonate minerals are the salts of carbonic acid and a variety of metals (Speight, 1983, p. 126). Carbonate minerals can form during the first and second stages of the coalification process (Stach et al, 1975, p. 126). The formation of the syngenetic and epigenetic carbonate minerals is related to alkaline conditions. These minerals include calcite, dolomite, ankerite and siderite, all of which are associated with vitrinite. Siderite is usually more abundant in coals with a lower pyrite content. This probably represents the interaction of iron with dissolved carbon dioxide in the peat waters where the sulphur concentrations were too low for pyrite formation (Ward, 1984, p. 64).

During the second stage of coalification, epigenetic calcite, dolomite, ankerite and siderite are formed in veins or as nodules or lenses in the coal (Stach et al, 1975, p. 128).

3.3.5.5 Phosphate minerals

Although phosphorus may originate from organic material, apatite or other phosphorus-containing minerals are frequently associated with other calcium-containing minerals. The environmental conditions which favour the formation of apatite are to some extent, similar to those that apply to the formation of calcite and dolomite.

3.3.6 Reflectance (coal rank)

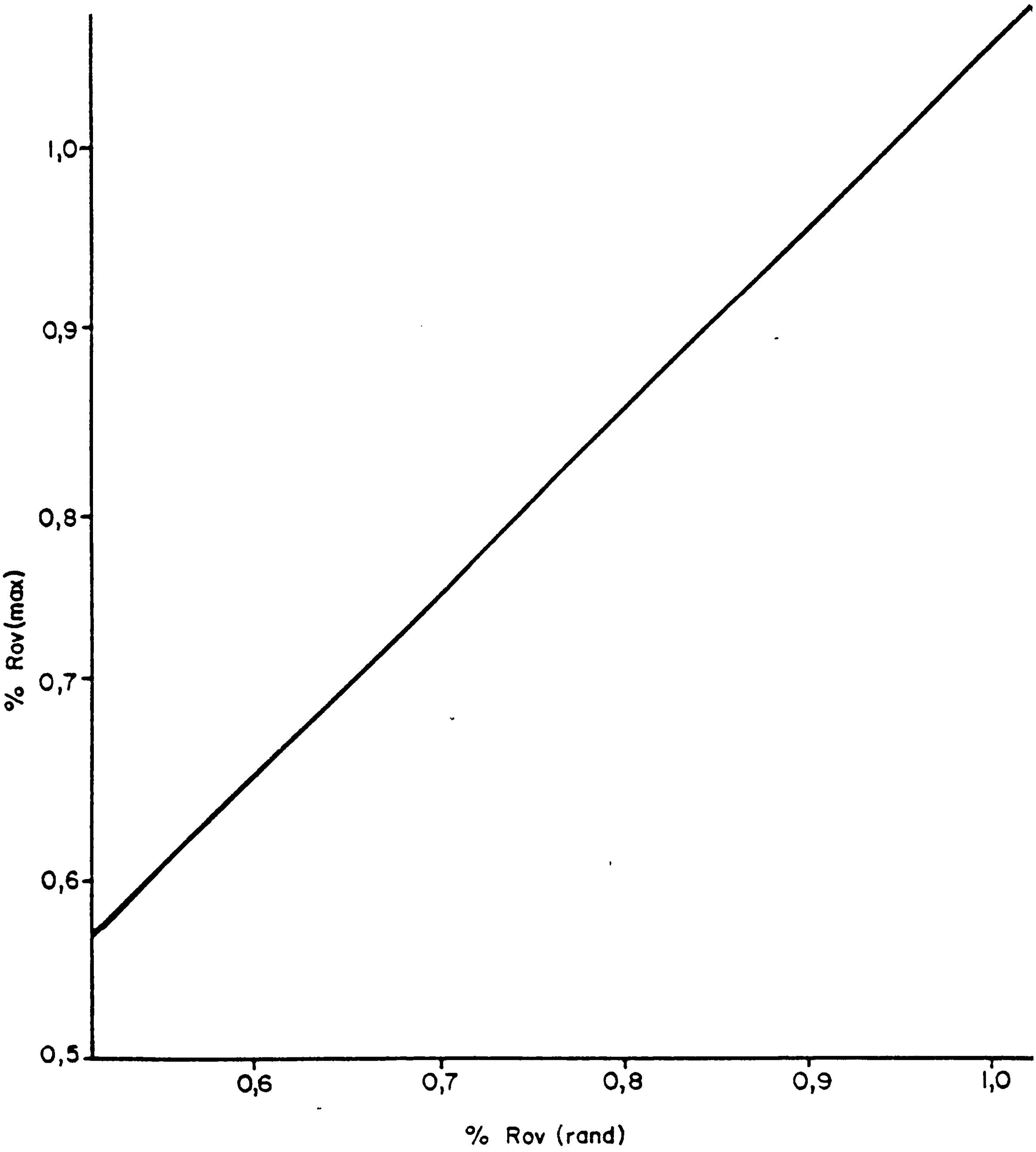
The progressive transformation from peat through brown coal, subbituminous and bituminous coal to anthracites and meta-anthracites is termed coalification (Stach et al, 1975, p. 34). The biochemical stage of coalification relates to those changes that occur within the peat swamp during deposition and is related to various environmental conditions (Moore, 1940, p. 168-170).

From the brown coal or subbituminous stage of coalification, the later or geochemical coalification factors which influence rank are time, pressure and heat. In South Africa it is considered that heat derived from dolerite intrusions was more important in causing the rank increase to the extent of producing anthracite (Lurie, 1977, p. 68; Murchison and Westoll, 1968, p. 336-343).

The reflectance of vitrinite increases with increasing rank. The reflectance of vitrinite is measured in green light with a wavelength of 546 nm. However, the reflectance of different vitrinite particles in a polished block varies, hence, the mean value of a number of readings must be established. It is standard practice to record 100 readings, according to the International Handbook of Coal Petrography (1971) and Stach et al, (1975, p. 266).

Due to the anisotropy of vitrinite, a specific vitrinite particle has a constant maximum and a variable minimum reflectance in plane polarized light. The maximum reflectance can be measured by rotating the specimen using polarized light until a maximum value is obtained. The % RoV (max) is commonly used as the measure of rank. If the reflectance of vitrinite is measured without using polarized light, the random reflectance (RoV (rand)) is measured. The relationship between % RoV (max) and % RoV (rand) for South African coals has been established by Barnard (1987) and is given in Figure 5.

In this study all references to vitrinite reflectance are given as % RoV (max).



<u>Figure 5</u> : The relationship between % RoV (max) and % RoV (rand) for South African coal products (Barnard, 1987, p. 109).

Chemical and physical properties of coal change with an increase in the % RoV and examples are given in Table 4 for coals of similar type.

TABLE 4 : COMPARISON OF VARIOUS RANK PARAMETERS FOR SOUTH AFRICAN BITUMINOUS COALS (d.a.f. basis)

% RoV	CALORIFIC VALUE MJ/kg	VOLATILE MATTER %	CARBON %	HYDROGEN %	OXYGEN %
0,5	29,2	33	76,5	4,1	16,9
0,6	30,2	32	78,1	4,2	15,2
0,7	31,3	32	79,8	4,4	13,3
0,8	32,3	30	81,7	4,6	11,2
0,9	33,2	28	83,1	4,7	9,7
1,0	33,9	27	84,5	4,7	8,3
1,1	34,2	25	85,5	4,6	7,4
1,2	34,3	23	86,0	4,5	7,0

It can be seen that the carbon content and calorific value are better indicators in the lower rank range. In the higher rank range the % RoV and volatile matter contents are more reliable parameters. Volatile matter and hydrogen contents are unreliable for the subbituminous and bituminous coals, but are very useful parameters of rank in the lean and anthracite coal range.

4. THE DEVELOPMENT OF COAL FACIES

Coal facies refers to the primary genetic types of coal which are dependent on the milieu under which peats originate. The facies of a coal expresses itself through the maceral and mineral contents of the coal, the chemical properties of isometamorphic coals and certain textural properties (Stach et al, 1975, p. 18). Some factors are more important in determining the primary characteristics of coal seams. These are the type of deposition, the peat-forming plant communities, the depositional milieu, the pH value and the redox potential (Stach et al, 1975, p. 19). Many of these factors are interrelated.

Autochthonous coals develop from plants which after death form peat _in situ_. Hypautochthonous coals are formed from material which was transported over relatively short distances and may be characterized by a finely detrital composition. Vitrodetrinite and inertodetrinite are typical hypautochthonous constituents of coal seams (Stach _et al_, 1975, p. 193, 226; Hagelskamp and Snyman, 1988, p. 312). These constituents are often intimately associated with allogenic kaolinite and quartz. Allochthonous coals are generally too rich in mineral matter to be economically viable and are formed from finely disintegrated peat detritus (Stach _et al_, 1975, p. 19).

4.1 PEAT FORMATION

The late Paleozoic flora in the Northern Hemisphere comprised mainly the families Lepidodendraceae, Sigillariaceae and Calamitaceae. Luxuriant and diverse swamps existed which were characterized by the order Cycadofilicales (seed-ferns) and the class Cordaitopsida (both primitive gymnosperms) (Harder _et al_, 1958, p. 478, 480, 487; Bustin _et al_, 1983, p. 7). Many of these families which are characteristic of the Laurasian flora are not represented in the Gondwana flora. The exceptions are the Cordaitaceae and the Calamitaceae. The order Cycadofilicales is, however, represented by an abundance of species belonging to the family Glossopteridaceae. This plant association has become known as Glossopteris flora or Gondwana flora (Stach _et al_, 1975, p. 140).

Four swamp types can be distinguished on the basis of plant communities (Stach _et al_, 1975, p. 20), viz.

(i) Open-water areas with water plants and subaquatic sedimentation of allogenic minerals and vitrodetrinite and inertodetrinite. This environment is also typical of the formation of sapropelic coal, which formed under a relatively higher pH and neutral to reducing conditions.

(ii) Open reed swamps, which on the basis of palynological evidence from South African coals, were characterized by the abundance of Equisetalean flora (Falcon, 1975, p. 344), i.e.

related to the Calamitaceae. A higher pH and anaerobic brackish conditions which contained a relatively high sulphur content were characteristic of these swamps (Stach *et al*, 1975, p. 29-31).

(iii) Forest swamps on slightly higher ground than the open reed swamps. In South Africa, these swamps are characterized by Cordaitopsida or Confer flora (Falcon, 1975, p. 344). The forest swamp facies may be connected with subaquatic elements (Stach *et al*, 1975, p. 21) which gave rise to vitrinite-rich coals. The water table was sufficiently high to ensure luxurious plant growth and an eutrophic nature of the water. Rapid accumulation of vegetable matter under good preservation conditions, a moderately high pH and relatively low redox conditions favoured the formation of vitrinite (Bustin *et al*, 1983, p. 18-19).

(iv) Present moss swamps are typically high moors. These oligotrophic swamps have a stunted plant growth as they are almost entirely dependent on rain-water for their growth. Peats formed in these areas were subjected to lower pH and higher oxidation conditions which lead to the formation of inertinite and semi-fusinite.

The visible sequence within a seam can therefore be interpreted in terms of these swamp types. Various such sequences are found in thicker seams (Stach *et al*, 1975, p. 20).

Peats deposited in a brackish environment are commonly rich in hydrogen, sulphur and nitrogen. Because of the higher pH, bacterial degradation is greater; therefore, humic substances are strongly decomposed and the vitrinite is structureless. The alkali-metal content is also increased with a decrease in acidity. Coals which were deposited in calcium-rich swamps show similar properties to marine-influenced coals (Francis, 1954, p. 19; Stutzer, 1940, p. 13-15; Speight, 1983, p. 34-35). With moderation of the pH, anaerobic bacteria reduce the sulphate-ions to sulphide-ions and this leads to the precipitation of sulphides, e.g. pyrites.

Table 5 shows the effects of oxygen availability on the transformation of peat.

TABLE 5 : TRANSFORMATION OF PEAT IN RELATION TO OXYGEN SUPPLY (Stach *et al*, 1975, p. 32)

	PROCESS	PRODUCT		
AEROBIC	DISINTERGRATION	NO SOLID RESIDUE		
↑ INCREASE IN OXYGEN SUPPLY	MOULDERING	MOULD	HUMIC COALS	INCREASE IN H AND N IN TRANSFORMATION PRODUCTS ↓
	PEATIFICATION	PEAT	SAPROPELIC COALS	
ANAEROBIC	PUTRIFACTION	SAPROPEL		

Where an abundant supply of oxygen is available from water or the atmosphere, the peat may oxidize to gaseous products. With less oxygen available, mouldering takes place as a result of aerobic bacteria and fungal activity. Peatification occurs with restricted oxygen availability, but oxygen is required to form humic acid from lignin. Anaerobic bacteria consume oxygen from organic material, transferring it into hydrogen-rich products, and this process is known as putrifaction (Stach *et al*, 1975, p. 33).

Thick peat deposits develop where a slow, continuous relative rise of the groundwater table occurs, i.e. due to subsidence balanced by the accumulation of peat. The supply of fluviatile sediments must be restricted which would otherwise interrupt peat formation (Stach *et al*, 1975, p. 9; Francis, 1954, p. 4). The topography on which the peat is deposited influences the thickness and lateral extent of the coal. The environment within the swamps determine the composition of the coal.

Post-depositional environments may lead to the removal of part of the peat due to channelling and to the introduction of brackish waters which may affect the peat chemistry (Bustin et al, 1983, p. 9).

Paralic (coastal marine) and limnic (inland) settings are distinguished, depending on their original geographic position (Stutzer, 1940, p. 159-161; Stach et al, 1975, p. 10-16; Murchison and Westoll, 1968, p. 337).

South African coals lack the typical characteristics of paralic coals (e.g. large dolomite concretions or coal balls, high sulphur and chlorine contents and the presence of marine fossils either in the seams or in the floor and roof rocks) and are therefore limnic in origin. In Europe, paralic coal deposits occur frequently (Murchison and Westoll, 1968, p. 337). Limnic coals are considered to have been deposited in regions where the water level was controlled by local conditions like flooding (Bustin et al, 1983, p. 14).

Limnic peat deposits may be allochthonous or autochthonous. According to Ethridge (quoted by Bustin et al, 1983, p. 14) thicker coals originate adjacent to the main trunk streams and in a groundwater recharge and discharge area. Thin coals commonly contain shale interbeds and discontinuous coal seams are interpreted as deposits in areas of better drainage and, therefore, lower groundwater levels.

5. WORK APPROACH

In view of the relatively large area covered by the Witbank and Highveld coalfields data points were selected generally at a distance of 3 km to 10 km apart. This resulted in 392 data points within the study area.

Each data point was selected on a more or less random basis and in the event that the coal was severely affected by dolerite intrusions, another data point was selected to represent, as far as possible, the normal occurrence of the coal seam in that particular area. As this study covers a regional area, no corrections were made for the displacement of strata due to dolerite sills. The exception to the rule of random selection of information was that preference was given to analytical data determined at the then F.R.I. Data were selected where analysis on multiple samples through the cross-section of the seams was available.

The data extracted from various sources were supplemented by analytical data available on seam channel samples taken in mines. Data were available from investigations undertaken by other organisations and from the surveys of analyses of raw coal and product samples collected by the F.R.I. from collieries existing at that time.

The available data were in some instances subject to the following limitations and omissions:

(i) Incomplete or no information was available for 89 data points situated in the selected area. This can be due to the fact that no records are available because the coal seams have been burnt and eliminated by dolerites or because the data points are located outside the coal-bearing limits of the basin.

(ii) Due to the occurrence of frequent minor faulting a measure of uncertainty existed whether undulating coal seams occurred or whether some portions were faulted out of position.

(iii) The effect of dolerite intrusions on the coal seams were in many instances not apparent; in severe cases it was more obvious. This gave rise to changes in rank in certain local areas which cannot be reconciled with the normal development of rank due to pressure and the normal thermal gradient.

(iv) In some instances, only the upper seams regarded of apparent economic value were analyzed. It was fairly common practice in the pre-1960 era that where the raw coal ash exceeded 20-25%, no proximate or further analysis was undertaken. Thinner uneconomical seams were frequently not sampled, although these were typically described as being of "good quality bright coal".

(v) Sample selection was not adequate. Sampling was frequently done by selecting one sample, often regarded as representing an entire seam irrespective of thickness, even if it was of considerable width.

(vi) Sampling was performed on an ad-hoc basis. Multiple samples were in some instances taken at more or less fixed intervals. This masked the occurrence of a succession of bright or dull coal layers or of the occurrence of shaley coal bands.

(vii) Apparent analytical anomalies, mostly in calorific values and inherent moisture contents came to light. These results were provided by earlier laboratories which were poorly equipped and hampered by a lack of sophistication, such as relative humidity controlled environments.

(viii) A lack of uniformity in the correlation of coal seams was evident. This applied especially where split seams occurred or where the seams were poorly developed towards the flanks of the basin. Split seams sometimes merged which resulted in some confusion in the stratigraphical interpretation of the seams.

(ix) Considerable differences in analytical results over relatively short lateral distances could be encountered. This suggests that the selected analysis would not necessarily be representative of a specific local area; possibly due to the development of channel or valley deposits adjacent to elevated areas.

(x) It should also be pointed out that north-south trending zones, up to a few kilometers wide, occur where weakly developed seams or no coal seams are apparently present. These zones are more or less evenly distributed throughout the study area and may be attributed to topographical highs in the paleobasement. Over certain areas in the northern part of the basin, the No. 1, 3, 4, 4 Upper and 5 Seams are absent. Basin infilling of sediments also resulted in the absence of the No. 2 Seam in the south-eastern portion of the Highveld coalfield.

Some of the upper seams were locally eliminated due to dolerite intrusions in the study area.

To ensure continuity of isolines in the contouring process, data were reconstructed from data available adjacent to the barren areas.

5.1 METHODS OF CALCULATION AND DATA EVALUATION

The air-dry calorific value of a coal is directly related to its fixed carbon and volatile matter contents for a given rank, or inversely related to its inherent moisture and ash contents. Bright or perhydrous coals have a higher calorific value than dull or subhydrous coals. Lower ranking coals with higher inherent moisture contents have lower d.a.f. calorific values. These relationships have been well established and are useful to assess the expected accuracy of analysis.

Allowance must be made for deviations in these relationships for high ash coals and for coals with high carbonate contents. The carbonate minerals dissociate endothermally with a resultant lower calorific value, whereas the opposite holds true for highly pyritic coals.

The influence of the calorific value (d.a.f.) of a coal on the inferred type and rank is not very significant. An increase in the calorific value of 1 MJ/kg corresponds to an increase in the inferred vitrinite content by about 5% and an increase in the inferred % RoV (max) by about 0,1%. This applies to typical coals from the Witbank and Highveld areas.

The air-dry volatile matter of a coal is influenced by inorganic volatile constituents derived mainly from high carbonate contents or from the moisture of constitution of clays in high ash coals.

The influence of the volatile matter content (d.a.f.) on the inferred type and rank is also small. An increase of 1% in volatile matter content results in a 4-5% increase in inferred vitrinite content and a marginally small reduction in the inferred % RoV (Snyman et al, 1983, p. 87, Figure 7).

The type and rank can therefore be inferred with a considerable degree of confidence provided that the proximate analysis is fairly accurate or that adjustments are made for analytical anomalies.

Due to the influence of the mineral matter content on the calorific value and proximate analysis, analytical results were selected to fall within a limited ash content range. In order to ensure a reasonable measure of consistency, analysis of which the ash content varied between 15-25% was selected where possible. Raw coal analysis with lower ash contents had to be processed directly.

Analyses of coals with an ash content above 30% were generally not acceptable, except in instances where no other data were available. In such cases the d.a.f. calorific value was recalculated to an equivalent of a 25% ash content. The air-dry volatile matter content for the high ash coals was corrected for an assumed 10% water of constitution of the clay minerals based on the ash content.

In many instances, coals were washed either at one relative density (traditionally at a RD of 1,58 at the F.R.I.); or at a pre-determined series of densities.

No individual density fraction analysis was used at all, as the original raw coal characteristic would of necessity change, especially in the Witbank coals. Use was therefore made of cumulative results and the cumulative analysis was selected with an ash content closest to 20%. This was found to reflect fairly closely the nature of the organic components in the raw coal.

A micro-computer was used for recalculation of the data. The calculations had to accommodate and convert out-dated expressions, such as thickness, distance or calorific value units. Furthermore, the validity of a calorific value for a particular proximate analysis had to be tested. Allowance was made for the option of adjusting either the calorific value or the air-dry moisture content in a few instances to ensure a more acceptable result.

Based on the available data, the following were calculated, using d.a.f. calorific values and d.a.f. volatile matter contents as the prime parameters:

(i) The carbon, hydrogen, nitrogen and oxygen contents, all expressed on a d.a.f. basis. An organic sulphur content of 0,5% was assumed in all cases.

(ii) The coal type and rank, i.e. the inferred reactives expressed as % vitrinite as well as the % mean maximum reflectance of vitrinite.

Various empirical formulae, derived from numerous analyses determined at the F.R.I., were used to calculate the above expressions.

5.1.1 Calorific value

The calorific value can be computed from the proximate analysis (Van Vuuren, 1975). The equation which applies to coals from the Witbank and Highveld areas and which was used primarily to check the validity of the data is as follows:

$$CV = f - m - 0{,}408\ A$$

where CV = calorific value (air-dry basis) MJ/kg
f = 35,9 for dull bituminous coal
= 36,2 for typical No. 2 and No. 4 Seam coals
= 36,6 for bright, typical No. 3 and No. 5 Seam coals
= 37,0 for heat affected coals
m = inherent moisture (%)
A = ash content (%)

The dry ash-free calorific value can be used as a useful guide in assessing coal analyses. A high moisture, low rank coal would have a d.a.f. calorific value in the order of 30 MJ/kg. For an ash content in the order of 20% for most coals from the Witbank area, the d.a.f. calorific value would range from about 31-33 MJ/kg, depending on rank. Higher ash coals tend to give lower values whereas for coals which have been moderately heat affected the d.a.f. calorific value may be expected to exceed 33 MJ/kg.

5.1.2 Carbon and hydrogen

Three sets of formulae have been developed from which the d.a.f. carbon and hydrogen content can be calculated from the d.a.f. calorific value and volatile matter content (Van Vuuren, 1975; Snyman et al, 1983 and Barnard, 1987). Any of the sets of formulae can be applied to a normal range of coals as they all give results in close agreement, comparable to the tolerances allowed in the experimental analytical procedure. The formulae given by Snyman et al are generalized and are applicable to all coals from various geographic areas. Barnard developed a series of formulae which differentiate between geographic areas, volatile matter content, ash content and coal rank. It was found that various coals from the various seams in the Witbank area have diverse characteristics. Some of these characteristics overlap in the various areas distinguished by Barnard. This leads to some anomalies, and tends to overestimate the hydrogen content of high volatile matter content coals. For these reasons, the methods of calculation of carbon and hydrogen contents developed by the writer were preferred:

Volatile matter (d.a.f.) < 30%:

$$C = 1,38\ CV - 0,190\ VM + 43,3$$
$$H = 0,174\ CV + 0,060\ VM - 2,97$$

Volatile matter (d.a.f.) > 30%:

$$C = 1,38\ CV - 0,262\ VM + 45,5$$
$$H = 0,174\ CV + 0,084\ VM - 3,69$$

where C = carbon (%)
H = hydrogen (%)
CV = calorific value (MJ/kg)
VM = volatile matter (%)

all expressed on a dry ash-free basis.

5.1.3 Nitrogen, sulphur and oxygen

Based on the nitrogen contents determined on vitrinitic and inertinitic coals, Snyman et al (1983) extrapolated values to correspond to pure vitrinite and pure inertinite. Nitrogen contents of 2,3% for vitrinite and 1,6% for inertinite were estimated for South-eastern Transvaal coal. These values were used for the derivation of the nitrogen content of coal from the inferred vitrinite content. An organic sulphur content of 0,5% was assumed in all cases. The oxygen content was obtained by subtracting the sum of carbon, hydrogen and nitrogen from 99,5%.

5.1.4 Type and rank

Barnard (1987) presented various formulae for the calculation of type and rank of coal from the d.a.f. calorific value and volatile matter content.

The formulae which applied to area 1 in the Seyler diagram (Barnard 1987) were selected. These formulae which apply to coals from Transvaal with ash contents above 12% were used for the calculations. Although these formulae apply to coals with a d.a.f. volatile matter content above 30%, the formulae were extended to a lower volatile matter limit of 25%. The formulae used to derive type and rank are given below (Barnard, 1987, p. 97, 106):

% Vitrinite (equivalent) = 3,54 CV + 3,75 VM - 196,6
% RoV = 0,044 CV - 0,017 VM - 0,13

5.1.5 Calculation of ash analysis into normative (standard) minerals

A relationship exists between the mineral matter content of a coal and the composition of its ash. Using the epinorm of Niggli (Snyman et al, 1983, p. 39), the oxide constituents were converted to cationic proportions to calculate the normative minerals. Pyrite was calculated directly from the pyritic sulphur content.

5.2 RECONSTRUCTION OF DATA

All the data, actual, calculated or inferred were tabulated with the corresponding coordinates for the No. 1, 2, 3, 4, 4 Upper and 5 Coal Seams. Where data were missing, for whatever reason, on seams in which lateral continuity was expected, data were reconstructed manually from available information in the close proximity. The reconstructed data was considered necessary to avoid interrupted or discontinuous isolines.

The following parameters were selected for isomaps for all the seams:

The relative seam floor elevation, seam thickness, inherent moisture content, vitrinite content and % RoV (max). In addition, on a d.a.f. basis, the calorific value, volatile matter, carbon, hydrogen and oxygen contents were tabulated.

The topographic isolines were calculated from a fixed base-line where one unit approximates two metres.

Use was made of the Surface II computer programme linked to the Main frame at the University of Pretoria. Editing values were selected to ensure adequate smoothing of isolines of acceptable density and spaced at suitable intervals. This resulted in the displacement of contour lines to some extent which does not, however, affect the validity of the isoline maps as presented. In the case of thickness contours, a nil-value was assigned around the periphery of the seam to demarcate the extent of the major seam development.

In this study, isolines of all the selected parameters are given for the No. 2, 4 and 5 Seams. To avoid a measure of repetition, for the other seams, only the floor elevation, thickness, vitrinite content and % RoV are given. In all cases serrated contours indicate minima.

6. THE CHARACTERISTICS AND FORMATION OF THE SEAMS IN THE WITBANK AND HIGHVELD COALFIELDS

6.1 POSTULATION OF MAJOR CHANNEL ROUTES

The major channel systems which existed during the formation of each seam could be inferred from the interrelationships of various parameters. These are primarily the floor topography, thickness distribution and the petrographic nature of the seams.

Certain limitations are imposed on the interpretation of the channel morphology. In this study the floor topography of the seams have not been corrected for displacement by dolerite intrusions. Differential compaction or minor faulting which occurred after seam formation resulted in changes in the original paleotopography. Computer isoline smoothing would furthermore account for minor distortions in the mapping of the various parameters.

Valleys and areas of lower topography towards the northern and eastern margins of the study area controlled the flow and the likely points of entry of the channel water supply. Secondary channels, probably solely dependent on a rainwater supply, originated from isolated topographic highs. Waterflows and drainage patterns followed the steeper gradients to topographically lower areas. The channel routes during the initial stages of peat formation were governed by the paleotopography that existed at the time.

As peat continued to form, its distribution and development would have had some influence which may have resulted in minor changes in the original flow patterns of the channels. These channel routes could be expected to have some control on the seam geometry and the petrographic nature of the seams. A good relationship is found between the postulated channel complex which existed just prior to the termination of peat formation and the seam floor paleotopography, seam thickness and the petrographic profile of the seam. This would indicate the general stability of the channel complex throughout the period of peat accumulation leading to the formation of a particular seam.

The factors from which the channel directions during the formation of the No. 2 Seam could be derived, are given below. Some of these could also be applied to the formation of the other seams.

(i) Seam floor topography

Based on the most likely entry points water flow would have followed the steeper slopes through the study area as indicated by the seam floor topography.

(ii) The thickness of the seam

In channel areas the seam is expected to be thinner as a result of peat erosion. Thinner seams are, however, also found on topographical highs and towards the perimeter of seam development. Thicker seams often occur adjacent to channels where growth conditions were more favourable, or where large amounts of vitrodetrinite and inertodetrinite, derived from eroded peat, were deposited as a result of overbank sedimentation.

(iii) The development of the No. 2 Seam in the close proximity to the Dwyka tillite.

In a number of instances in the Witbank area the underlying Dwyka tillite is close to the floor of the No. 2 Seam. This formation is thick in topographically low areas and its occurrence in some instances indicates the locality of channels. In other instances the Dwyka tillite is found directly below the No. 2 Seam at high elevations and towards the western periphery of the study area.

(iv) The petrographic profile and composition of the No. 2 Seam

Channel coals tend to have an inertinitic character. Inertinite-rich coals do, however, also occur laterally between the channel deposits, either at more elevated sites or these coals may be of hypautochthonous origin, in which case they occupy relatively low lying areas as a result of overbank sedimentation. Large areas of thin inertinite-rich coals are associated with the channel flows, especially towards the south.

(v) Peat thickness

The compression of peat, from the peat stage to the bituminous-coal stage, depends on the coal facies. The degree of compression for peat to form vitrinite-rich coal seams is approximately 7:1 (Stach _et al_, 1975, p. 17, 18). No published data for inertinite-rich coals are available. Microscopic observation of grain shape and grain orientation of inertodetrite in polished blocks suggests a ratio between peat and inertinite-rich coal of about 2:1 (Snyman, C P, 1988, pers. comm.). These differences in compaction ratio indicate that no meaningful genetic interpretation of the variation in seam thickness is possible unless the petrographical composition is taken into account. Thinner peat deposits in lower lying areas are often associated with channel routes.

(vi) The mineral matter composition of the No. 2 Seam

The No. 2 Seam generally contains mineral matter of an acidic nature where it occurs in the vicinity of channel routes. The acidic nature of the mineral matter tends to change towards a more basic character in medial to distal regions from the channel feed-source.

6.2 THE BASAL SEAMS

6.2.1 The No. 1 Coal Seam

The No. 1 Coal Seam can be considered to be a subset of the No. 2 Seam (Barker, 1986, p. 105). The occurrence of the No. 1 Seam, where it is recognized as such, is mostly restricted to the Witbank coalfield (Fig. 6). The No. 1 Seam often rests directly on the Dwyka Formation in the northern portion of the Witbank coalfield. The seam also overlies or is found in the close proximity to the Dwyka tillite in topographical lows.

The floor topography of the seam and the postulated channels are shown in Figure 6. A topographical high occurs at G3-G4. Other elevated areas occur towards the north and north-east of the coalfield. Several depressions or paleovalleys are present at H3, F4, I6 and J9. The area has a generally southerly slope of about 1:1000. A steeper gradient of about 1:300 is found from K9 towards the southwest at I7. These topographical features must have had a considerable influence on the subsequent coal deposition. The main drainage channels are largely deduced from the patterns of the contour lines. The estimated channel frequency over the study area is about 2 per 1000 sq km which relates to a channel density of about 30 km per 1000 sq km.

The No. 1 Seam seldom reaches a thickness exceeding 3 m (Fig. 7). Thick seam development is observed to the east of the high at G3 which coincides with the depression at F4. The seam is also better developed in the depression at I6 and to a lesser extent in the depressions at I3 and J9. An abundant water drainage from the channels would favour

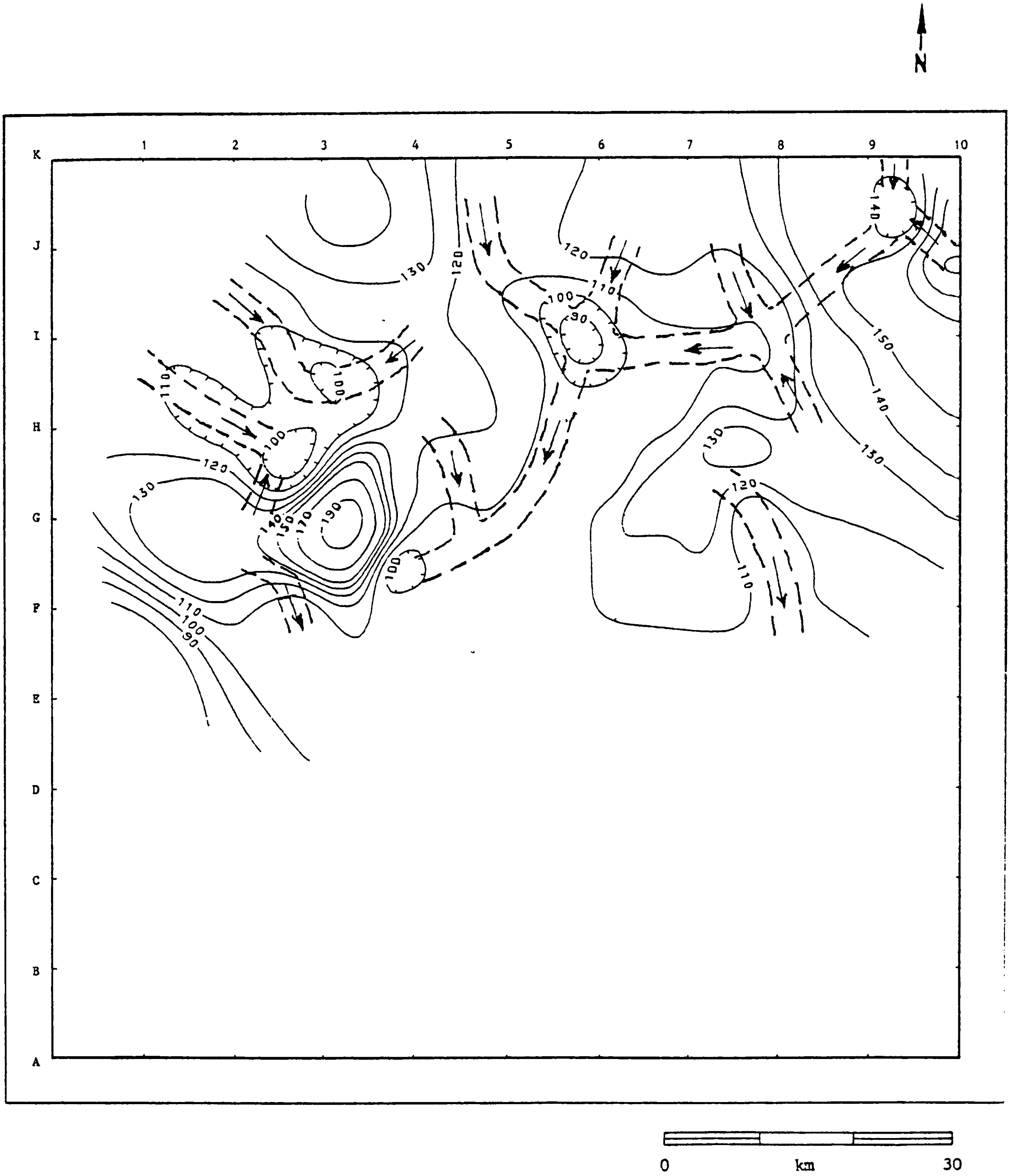


Figure 6 : The floor topography of the No. 1 Seam with the postulated channels.

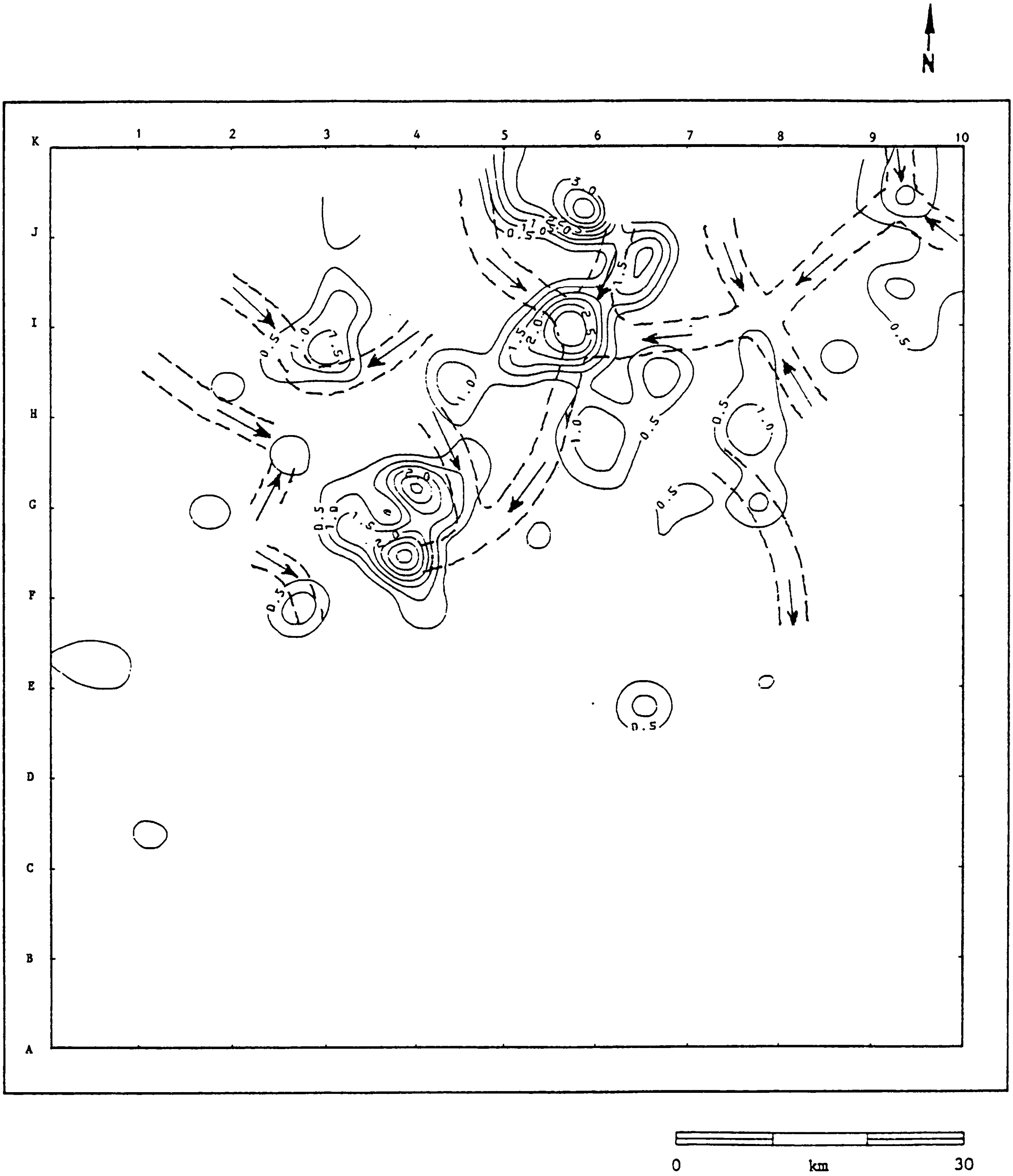


Figure 7 : The thickness (m) and distribution of the No. 1 Seam.

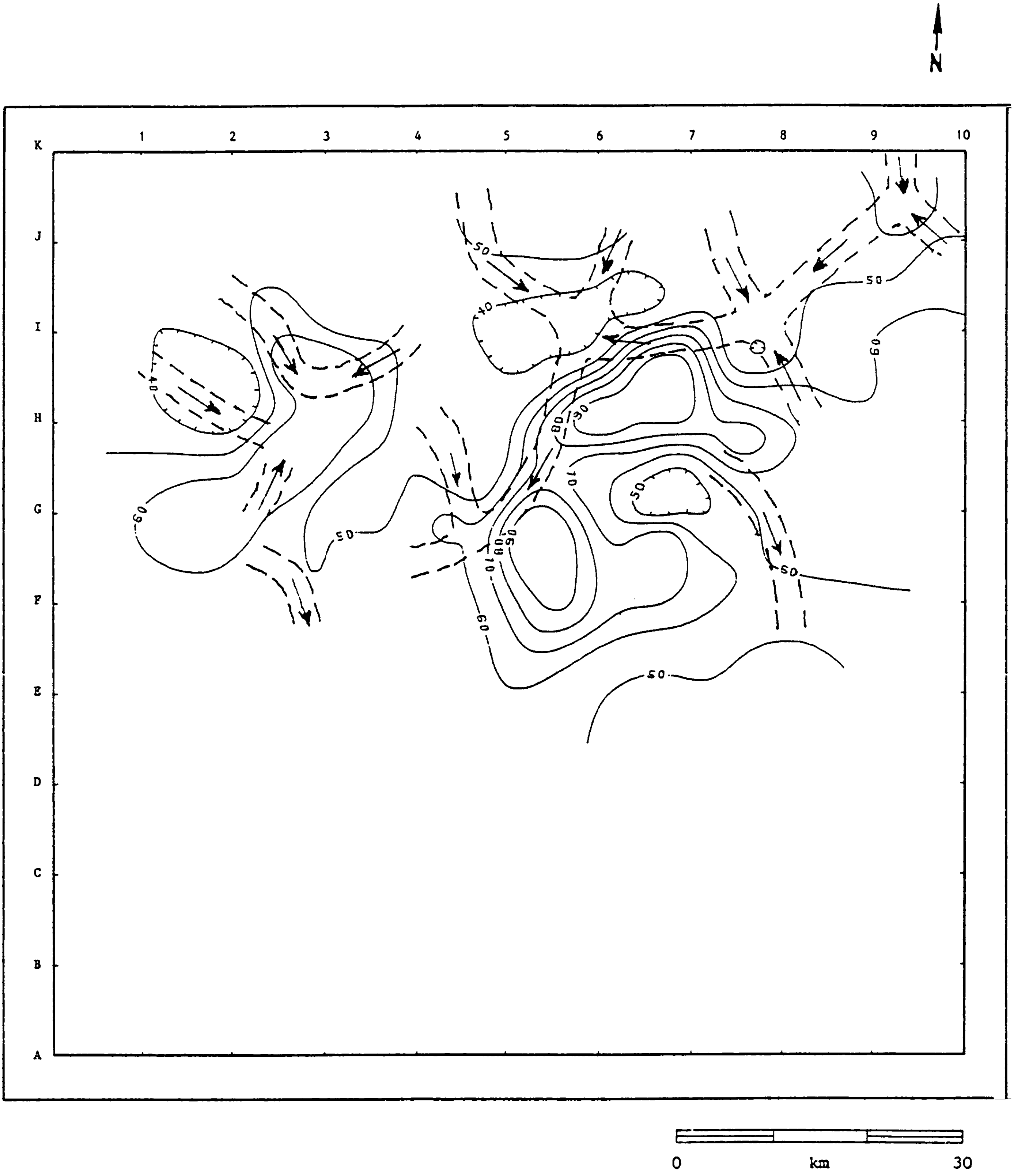


Figure 8 : The vitrinite content of the No. 1 Seam.

vegetal growth in these lower lying areas. In some cases, relatively thick seam development also coincides with topographically highs in the floor, for example at H8, I9 and J9, in areas which are adjacent to the postulated channels.

A preponderance of hypautochthonous constituents such as inertodetrinite and allogenic minerals would be expected to accumulate in depressions. Channel activity would be higher along steeper gradients adjacent to depressions, although sediment discharge is controlled, among other variables, by vegetation (Blatt et al, 1972, p. 24). The thick seam development in the depression at I6 coincides with a high inertinite content and a low (< 40%) vitrinite content (Fig. 8). This may be ascribed to the deposition of large amounts of hypautochthonous inertodetrinite. The high inertinite content at G7 coincides with a paleohigh with a gentle southerly slope and a relatively low peat thickness of two to six metres. The inertinite is therefore probably present as euautochthonous constituents such as macrinite and semifusinite (indicating relatively aerobic conditions) or as hypautochthonous inertodetrinite which was deposited in spite of the slope. The peat thickness at I6 varied from 10-14 metres and at J6-K6 from 10-23 metres. Between I6 and J6 the peat thickness was some 8 metres which represents the probable locality of a channel which drained in a southerly direction. At F4-G4 the peat thickness is up to 19 metres, where the deposition of coal coincides with a paleolow. The extreme thickness of the seam at F4 suggests that a large proportion of vitrodetrinite and inertodetrinite was washed into the depression from the steep slope to the north-west. The coal formed in this depression has a fairly high vitrinite content of at least 50%. Fairly vitrinite-rich coal formed at J9, possibly under similar conditions, where detrital broken up peat was washed in from the higher ground from the north (Fig. 7). The high vitrinite coal of the No. 1 Seam at H6-H7 occurs on marginally lower ground and formed peat layers typically 5 m thick, apparently in forest swamp environments (Stach et al, 1975, p. 20-22). The swamp controlled the rate of production of vegetal matter which was high enough to protect the resultant peat against excessive oxidation. These vegetal degradation products may have been supplemented to a small extent by peat detritus introduced by southward flowing rivers and streams. This resulted in a thin vitrinite-rich seam with a vitrinite content of up to 90%. The seam is at places only a few centimetres thick towards the south.

The No. 1 Seam generally contains a higher vitrinite content towards the flanks of its major development. The seam usually consists of a bright coal base containing an excess of 50% vitrinite. This is capped by the upper portion with a vitrinite content of 40% to 50%. The notable exception is at I5-I7 (Fig. 8). In this area, the lower portion of the seam contains about 30% vitrinite followed by the upper portion which typically contains 40% vitrinite.

Figure 9 shows a seam profile between H1 and J8. The profile indicates the relative lateral thickness and the relative vitrinite contents of the lower and upper portions of the seam. The relative thicknesses of the upper and lower portions of the seam are variable and are not indicated in the profile.

The petrographic profile of the No. 1 Seam is fairly uniform over a large lateral distance. The sedimentation patterns, other than in channel regions, imply relatively stable conditions that existed during peat formation. Two major depositional cycles are noted. This may be the result of a progressive change to a higher redox potential and higher pH conditions, or to a disturbance of the equilibrium between the rates of peat formation and of subsidence, so that more hypautochthonous constituents were washed into the swamp from high-lying areas to the north.

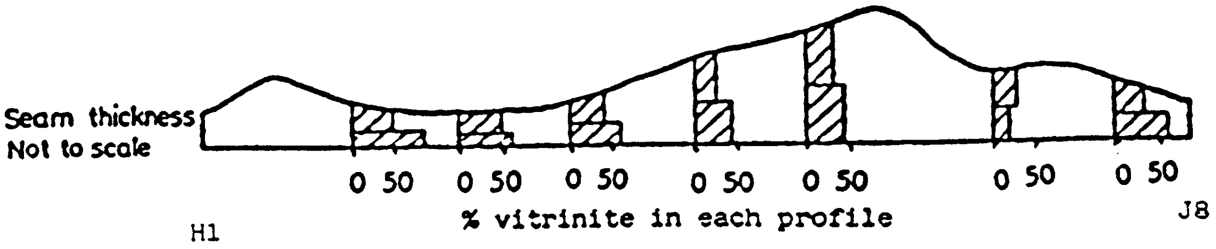


Figure 9 : Schematic vitrinite profile of the No. 1 Seam between H1 and J8.

The rank of the No. 1 Seam is given by the % RoV isolines in Figure 10. Generally, the RoV ranges from 0,70% to 0,80%. The exception is at G1 and F5 to H7. In the latter cases the RoV is below 0,65% and coincides with the vitrinite-rich occurrences of the seam. This may be a reflection of the perhydrous nature of the vitrinite in areas where little oxidation of the vegetable matter has taken place. The lower RoV may be due to the unreliability of the subjective selection of vitrinite grains suitable for reflectance measurements. For this reason, Barnard (1987), pointed out that the modal reflectance would be a better parameter of rank than the weighted average, as the latter is not affected by sporadic high or low values.

6.2.2 The No. 2 Coal Seam

During the time interval that separated the deposition of the No. 1 and No. 2 Coal Seams, gravitational instability resulted in fluvioglacial sedimentation (Tankard et al, 1982, p. 370). Sandstones, shales and siltstones were deposited by melt-waters over the Pietermaritsburg shales in the Highveld area where the No. 1 Seam is not developed.

These sediments attain a thickness of 30 m to 60 m above the pre-Karoo floor in the central Highveld area and up to 90 m towards the south-east in the Highveld area. This resulted in smoothing of the overall topography above the basement. In the Witbank area the paleotopography which preceded the deposition of the No. 2 Seam was largely inherited from the topography which existed after the deposition of the No. 1 Seam. Towards the northern margin of the Witbank coalfield, the No. 2 Seam developed in the close proximity of the No. 1 Seam. Towards the south and east a parting up to 10 m thick, consisting mostly of shales, separates the two seams.

The floor topography of the No. 2 Seam (Fig. 11) shows a low general southerly slope of about 1:800 (J1 to C1) in the west and about 1:1200 along the central north-south line in the Witbank coalfield. The gradient towards the south-west (J9 to C1) is about 1:600 and from F10 to F8 it is about 1:300. The prominent high at G3, first observed in

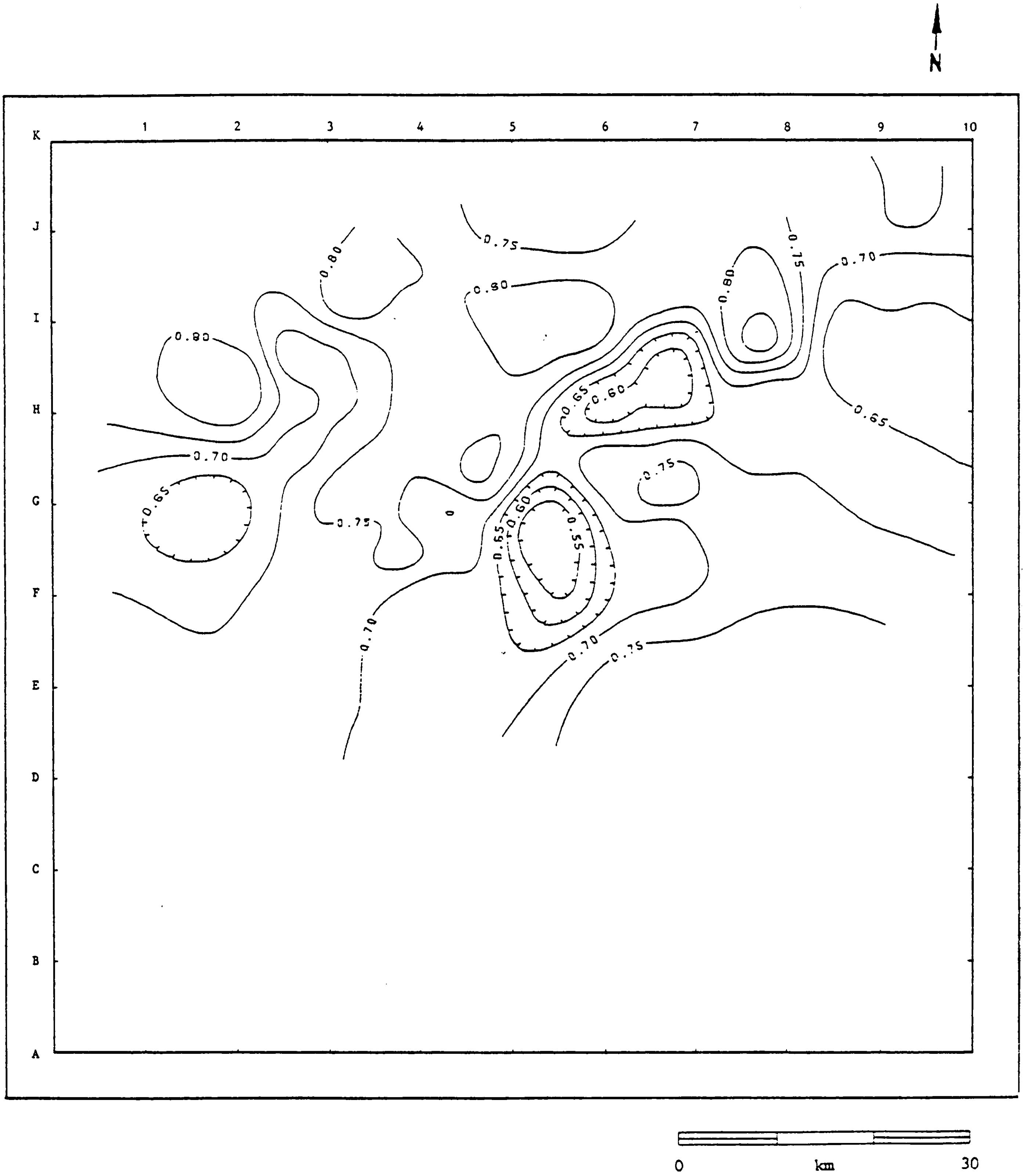


Figure 10 : The % RoV of the No. 1 Seam.

the floor of the No. 1 Seam is still present. Another topographical high occurs at E5.

Several depressions are present, notably at F2, H2, D5, I6, I7-I8 and J9. Some of them coincide with depressions in the floor topography of the No. 1 Seam, notably H2, I6 and J9. These features are significant relative to their immediate surroundings rather than on a regional scale. Basin infilling at the northern periphery of the study area was limited. The major topographical depressions found in the floor of the No. 2 Seam was therefore mostly inherited from the pre-Karoo basement.

An anastomosing drainage system can be inferred on the basis of the floor contours (Fig. 11). This drainage system is supported by the distribution, thickness and petrographic composition of the seam. The channel directions are more random than in the case of the No. 1 Seam. This is to be expected in view of the fact that, due to basin-infilling, the No. 2 Seam floor has a lower southerly slope compared to that of the No. 1 Seam, resulting in a higher channel density of about 75 km per 1000 sq km and a higher channel frequency of about 3 to 4 per 1000 sq km.

It is deduced from the low gradients of the No. 2 Seam floor that channel flows were of low energy and intensity. Quartz grains of less than 100 µm in diameter are commonly dispersed in inertodetrite in the seam. The shear velocity to keep quartz grains of 100 µm in suspension is about 1,8 metres per hour. The actual average velocity of waterflow is about 6 times the shear velocity which suggests a channel flow of less than 11 metres per hour or 3 mm per second (Blatt *et al*, 1972, p. 103). The velocities may even be lower as many quartz grains have even smaller diameters. Nevertheless, in view of the low slopes and low flow velocities large areas were essentially floodplains with more or less stagnant water. This favoured abundant vegetation on these glaciofluvial plains (Beukes, 1978, p. 33).

The No. 2 Seam is extensively developed throughout the study area, except in the south-eastern portion of the Highveld coalfield where alluvial sedimentation took place. The No. 2 Seam in this portion is represented by a carbonaceous shale (Hagelskamp, 1987, p. 45-47).

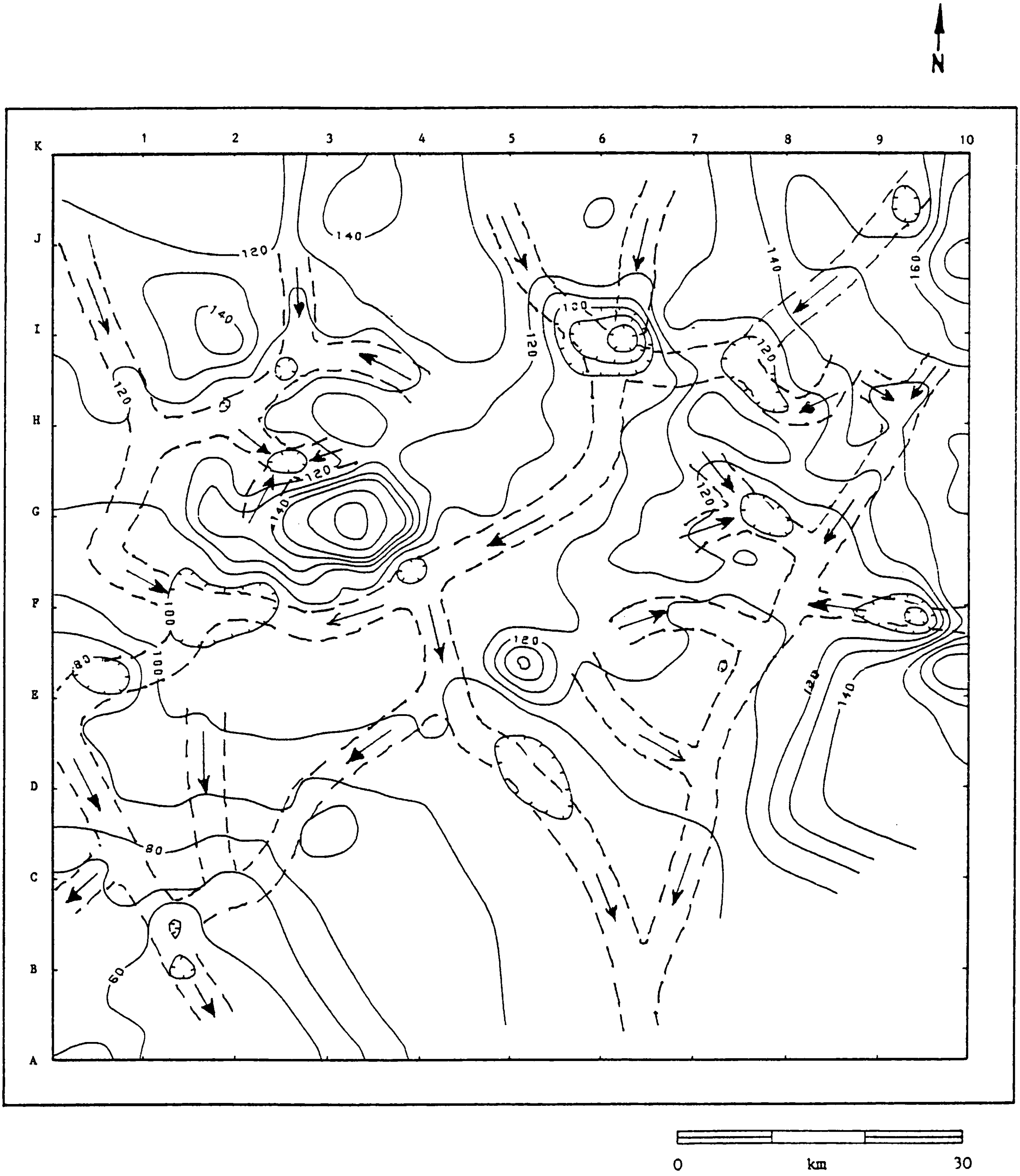


Figure 11 : The floor topography of the No. 2 Seam with the postulated channels.

The No. 2 Seam frequently attains a thickness of 8 m or more, especially in the Witbank coalfield (Fig. 12). A feature of these thicker coal deposits is that they often occur in interchannel areas where the environment was reasonably stable. These thicker deposits are frequently elongated in the general direction of the channels, and exhibit a geometry which indicates that major channels did not incise into the peat during its formation. Thicker coal deposits are, however, not necessarily confined to the topographical features of the floor of the coal seam; thick coal seams were also formed in depressions, for example at I6 and F1-G1. In both these examples, the thickness of the seam can be ascribed to the deposition of hypautochthonous constituents by channel activity as they correspond with areas of relatively low vitrinite content (Fig. 13). Thick coal deposits also formed adjacent to the topographical highs at G2 and F6 where these highs provided a sheltered environment favourable for peat accumulation. On the other hand, vitrinitic coals of substantial thickness formed on topographically elevated areas where the rapid accumulation of vegetal debris in forest swamps contributed to its preservation (e.g. H6-H7 and E4-E5, in Figs. 12 and 13).

The No. 2 Seam tends to be more vitrinite-rich towards the east and in the central areas which correspond to relatively elevated areas. Areas of inertinite-rich coal occur especially towards the western part of the study area (Fig. 13).

The thicker development of the seam at H3-I4 suggests that a large proportion of vitrodetrinite and inertodetrinite was washed into the depression from the steep slope to the north-west. Broken-up peat detritus was also brought into the depressions at I6 and H7-I8 from the surrounding higher areas. The higher vitrinite coal at H6-H7 occurs on higher ground. The peat formed in fairly thick layers, apparently in forest swamp environments (Stach et al, 1975, p. 20-22) where the growth rate of the vegetation was sufficiently rapid to protect the underlying material from excessive oxidation.

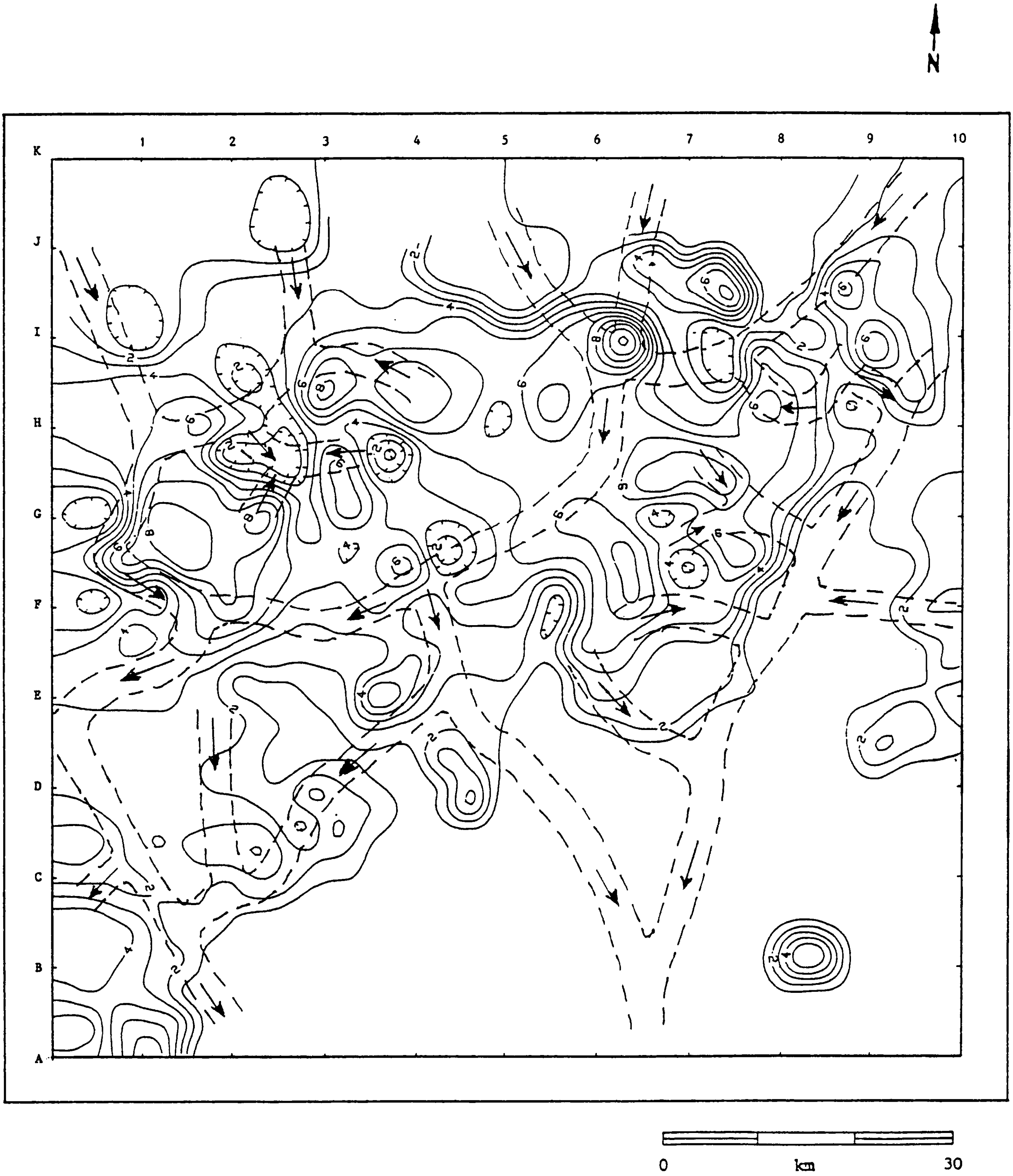


Figure 12 : The thickness (m) and distribution of the No. 2 Seam.

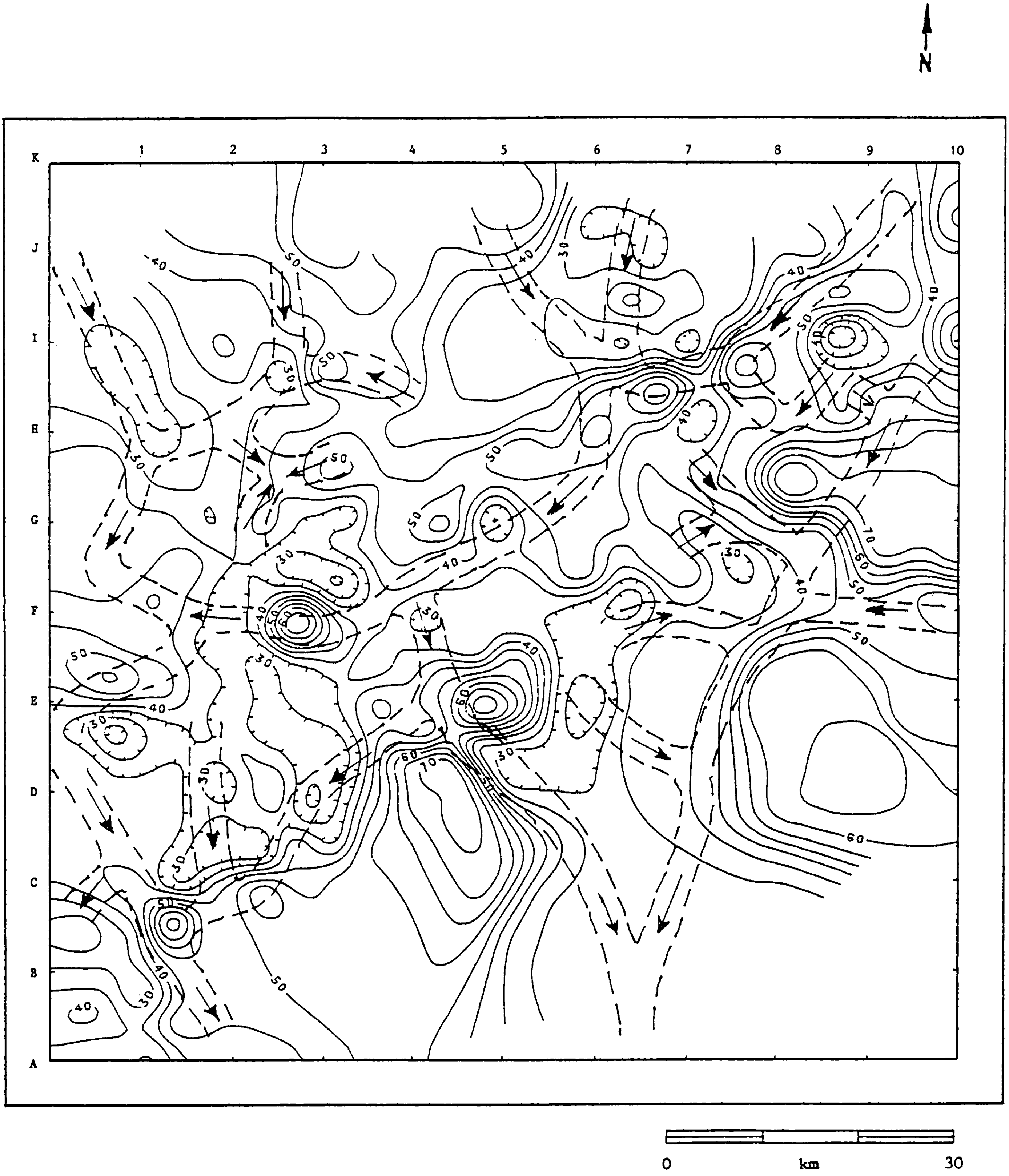


Figure 13 : The vitrinite content of the No. 2 Seam.

Vitrinite-rich coal was deposited over large areas adjacent to or between channels. This supports the view (Stach et al, 1975, p. 20-22) that the vitrinite-rich coals were not necessarily formed from peats preserved in deeper water. It must be concluded, however, that the peat was preserved in a stagnant water-logged environment. The No. 2 Seam was therefore deposited on relatively flat basinal surfaces. The seam is nearly level with slight undulations and this is consistent with fairly uniform paleoenvironmental conditions prevailing throughout the long period of deposition (Wybergh, 1922, p. 17).

In contrast to the occurrence of vitrinitic coal, large areas of inertinite-rich coals are almost invariably traversed by the channel complex (Fig. 13, D5, E6, F6-F7, I6-J7, and H1) suggesting the important role of inertodetrinite. Some of the inertinitic coals also formed on gentle slopes where the peat was more susceptible to oxidation (Fig. 13, D2-E2, G3, E6-F6 and I8-I9). Seepage of aerated channel water may also have contributed to the formation of inertinite.

It has been shown that inertinite-rich coals in South Africa are generally hypautochthonous (Hagelskamp and Snyman, 1988, p. 307-313). In order to verify the possible detrital nature of inertinite-rich coals, the No. 2 Seam products of nine collieries in the Witbank area were examined microscopically. Each of these samples contained less than 50% vitrinite, and with one exception, the inertodetrinite content varied from 39% to 65%. This suggests that although a part of the coal seam may have been formed in situ, substantial parts of the coals of the seam were initially formed further upstream and the original peat was subsequently transported into the area of deposition.

Although it is common for the vitrinite content to diminish upwards in a profile within a bench or seam, the opposite does occur, notably in channel areas. A bench or seam is in some cases capped by a relatively vitrinite-rich coal which grades downwards to a vitrinite-poor base. In active channel areas, transported material in oxygenated water may result in inertinite-rich coal towards the base of the seam. Quiescent periods and channel inactivity may account for a vitrinite-rich cap.

The No. 2 Seam commonly consists of 2 to 5 benches, each of which is generally characterized by a vitrinitic base which grades upwards into inertinite-rich bands. A water-table rising at the same rate as peat buildup would favour the formation of vitrinite and it would continue to form while a relatively high water-level is maintained.

Based on available data, the No. 2 Seam can often be subdivided into two major sections. Each section may be regarded as representative of the environmental depositional conditions. Figure 14 shows the typical vitrinite profile of the No. 2 Seam between the points F0 to J9. The petrographic profile was constructed from some 30 data points projected on to the cross-section. Each point shows the relative vitrinite content in the upper or lower part of the seam. The relative thickness of the upper and lower portions of the seam are variable and not indicated in the profile. Towards the west, the coal is inertinitic. In channel areas, the seam is generally vitrinite-poor in the lower portions of the seam.

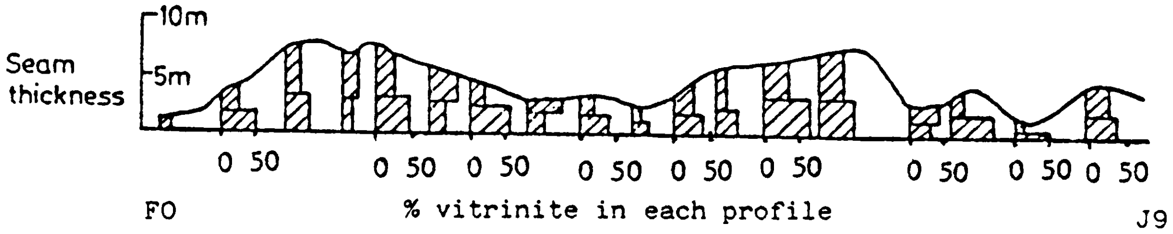


Figure 14 : Schematic vitrinite profile of the No. 2 Seam between F0 and J9.

The coal type of the No. 2 Seam is therefore, to some extent, dependent on the channel routes in the Witbank area. Thin inertinite-rich areas of the seam, generally less than 2 m thick, but which may be up to 5 meters in places, are associated with channels. Coals which have developed adjacent to or between channels are typically 4-10 m thick with a variable vitrinite content (Fig. 12 and Fig. 13; I7-J7, I9 and E4).

In order to establish differences in the chemical properties of vitrinite and inertinite, maceral concentrates were prepared from a No. 2 Seam sample collected at a colliery in the Witbank area. The analysis was performed at the NICR.

The dry ash-free properties of the maceral concentrates are given in Table 6.

TABLE 6 : ANALYSIS OF MACERAL CONCENTRATES (NO. 2 SEAM)

		VITRINITE	INERTINITE
Apparent RD		1,29	1,45
Calorific Value MJ/kg		34,4	32,0
Volatile Matter	%	40,3	25,2
C	%	87,7	80,1
H	%	5,8	3,8
O	%	3,6	13,7

The dry ash-free analysis given above confirm trends in the composition of macerals as inferred from the Seyler diagram developed by Snyman et al, 1983.

The estimated thickness of the No. 2 Seam peat was calculated from the compaction ratio of 7:2 for vitrinite : inertinite. Figure 16 gives a presentation of the peat thickness in metres in terms of the mean thickness $\bar{t}$, and contour intervals of 1 standard deviation, in relation to the postulated channel complex. This approach gives a more precise evaluation of some of the channel patterns as the data are not partly obscured by isoline mapping techniques. A lower peat thickness is generally found to correlate fairly well with the channel complex as deduced from the floor topography, thickness and petrographical nature of the No. 2 seam. Some anomalies may be explained by thinner peat development in high lying areas, or secondary channels within the major anastomosing channel system. Towards the south the relationship between channels and thinner peat development is less clear as the seams are thin and inertinite-rich (Fig. 12 and Fig. 15).

In order to test the postulated channel pattern, the peat roof topography was calculated. It shows a fairly good agreement with the channel routes (Fig. 16), and confirms to some extent the role of the differential compression of the peat. The correspondence between the peat roof topography and the channel pattern shows that the channels were aggrading vertically and that the channel banks were largely stabilized by vegetation. It has been pointed out by Winter (1985, p. 101-107) that anastomosed or braided river systems are contained within the channel areas by vegetation.

The mineral matter composition of the No. 2 Seam varies both vertically and laterally throughout the seam. The main channels transported clastic sediments of which kaolinite, quartz and to a lesser extent, TiO_2 are characteristic. The clastic sediments are interpreted as fluvial in origin and as weathering products of mainly mica and feldspar. Areas with active clastic deposition would be inundated frequently by aerated water. This causes degradation of the peat and an enrichment in the inorganic matter along a narrow belt adjacent to the channels, according to McCabe (quoted by Rhamani and Flores, 1984, p. 23, 24, 31). These aerated channel waters tend to be acidic and coals formed in such environments tend to have a lower content of carbonate and sulphide minerals. This contrasts with the generally higher carbonate and sulphide mineral contents in most coals formed adjacent to, but further away from the channels.

Typical ash analyses were selected from products of 21 collieries in the Witbank coalfield. Approximately 9 of the analyses represent coals associated with the postulated channel systems. In the case of washed products, the inherent (largely syngenetic) mineral matter would be enhanced relative to the adventitious mineral matter. The range in ash composition from the two distinct environments in the Witbank coalfield are compared in Table 7.

Certain deductions can be made in spite of the overlap for certain constituents. The channel coals contain higher SiO_2 and Al_2O_3 and lower Na_2O and K_2O contents. This implies that the coals associated

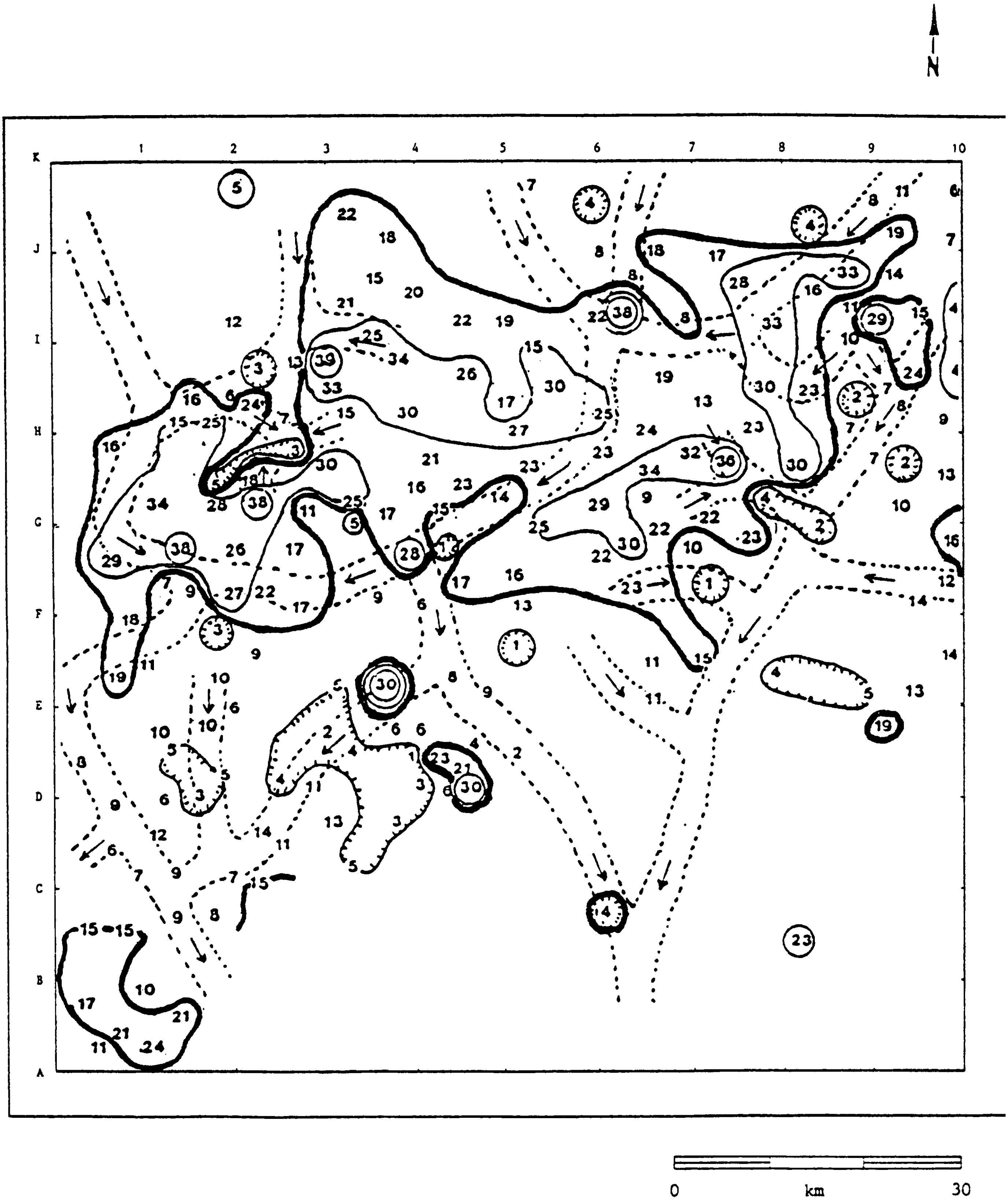
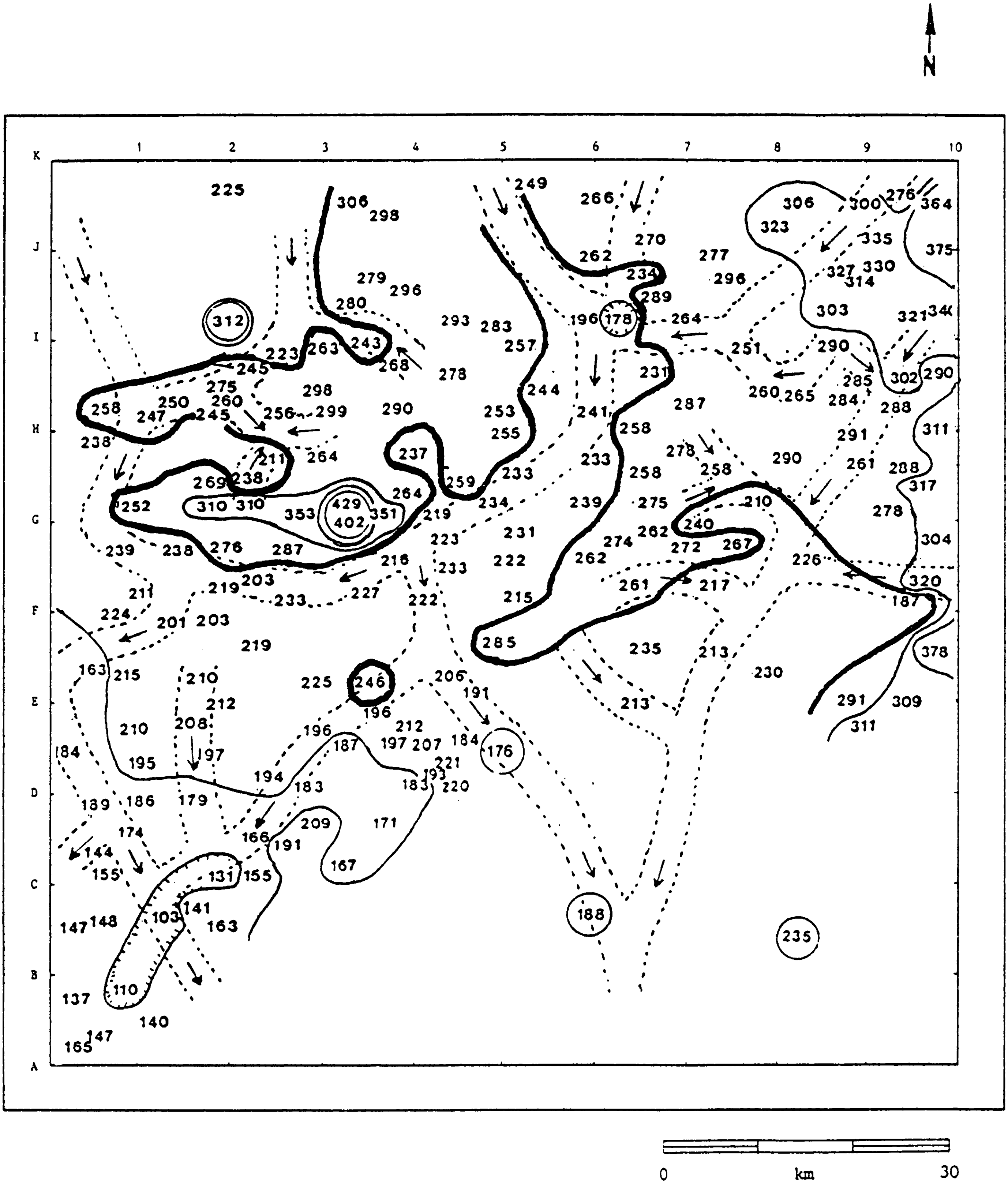


Figure 15 : The calculated thickness (m) of the peat of the No. 2 Seam and the relationship with the channels. The mean thickness of the peat is 15 m and contour intervals are shown in terms of the standard deviation (10 m).



<u>Figure 16</u> : The calculated roof topography (m) of the peat of the No. 2 Seam and the relationship with the channels. The mean height is 245 m and contour intervals are shown in terms of the standard deviation (55 m).

with the channel areas contain more kaolinite and less illite. The excess of SiO_2 over Al_2O_3 implies a higher quartz content. TiO_2 is higher in channel coals.

TABLE 7 : ASH CONSTITUENTS OF COALS IN CHANNEL AND INTERCHANNEL AREAS

	CHANNEL COALS	INTERCHANNEL COALS
	%	%
SiO_2	51 - 60	41 - 49
Al_2O_3	30 - 38	22 - 36
Fe_2O_3	1,9 - 11,4	6,3 - 11,9
P_2O_5	0,1 - 1,5	1,1 - 1,9
TiO_2	1,6 - 2,3	1,5 - 1,7
CaO	0,8 - 8,4	6,8 - 14,9
MgO	0,1 - 1,7	2,0 - 3,2
K_2O	0,3 - 0,5	0,5 - 0,6
Na_2O	0,1 - 0,3	0,2 - 0,5

The interchannel coals, on the other hand, contain higher Fe_2O_3. If sufficient sulphur is available this would result in a higher pyrite content, and the excess of iron over sulphur would result in a higher siderite content. A high MgO content indicates a high normative dolomite content and the excess of CaO over MgO is mainly present as calcite. These two minerals are notably higher in coals formed in interchannel areas. Apatite or other phosphorus minerals are usually higher in interchannel coals.

Kaolinite, quartz and rutile are generally associated with inertinite and are therefore indicative of aerobic and acidic conditions and of hypautochthonous coal formation. Calcite, dolomite, pyrite and apatite are formed under slightly acidic to alkaline conditions, and pyrite and siderite also indicates anaerobic conditions which can be related to the occurrence of euautochthonous vitrinite.

TABLE 8 : THE MORE IMPORTANT SYNGENETIC MINERALS IN SOUTH AFRICAN COALS, THEIR CHEMICAL FORMULAE AND THEIR PREFERRED MACERAL ASSOCIATION.

ALLOGENIC MINERALS		AUTHIGENIC MINERALS	
MINERAL	PREFERRED MACERAL ASSOCIATION	MINERAL	PREFERRED MACERAL ASSOCIATION
Quartz SiO_2	Inertodetrinite Vitrodetrinite Sporinite	Pyrite FeS_2	Vitrinite Fusinite*
Rutile TiO_2	Inertodetrinite Sporinite	Calcite $CaCO_3$	Vitrinite Fusinite
Kaolinite $Al_2Si_2O_5(OH)_4$	Inertodetrinite Vitrodetrinite Sporinite	Dolomite $CaMg(CO_3)_2$	Vitrinite Fusinite
		Siderite $FeCO_3$	Inertinite* Vitrinite
		Ankerite $Ca(Mg,Fe)(CO_3)_2$	Vitrinite
		Illite $KNaAl_4(Si_6Al_2)O_{20}(OH)_4$	Vitrinite
		Apatite $Ca_5(PO_4)_3F$	Vitrinite

* Denotes weaker associations of minerals and macerals.

Table 8 gives the preferred association of the allogenic and authigenic minerals with the major maceral groups. Only the more common syngenetic minerals found in South African coals are listed.

There are exceptions to the general rules given in Table 8. Coals that formed in channel areas close to the point of water influx contain mineral matter of a strongly acidic character, whereas in distal regions the allogenic minerals are less acidic. The mineral-maceral associations also become weaker with increasing distance away from the point of water influx.

The composition of the mineral matter in coal gives an indication of the environmental factors influencing the formation of different macerals (Francis, 1954, p. 496). This applies to both autochthonous and hypautochthonous coals.

Figure 17 shows the location and Table 9 the typical normative mineral matter contents of the No. 2 Coal Seam in relation to the channel pattern in the northern Witbank coalfield.

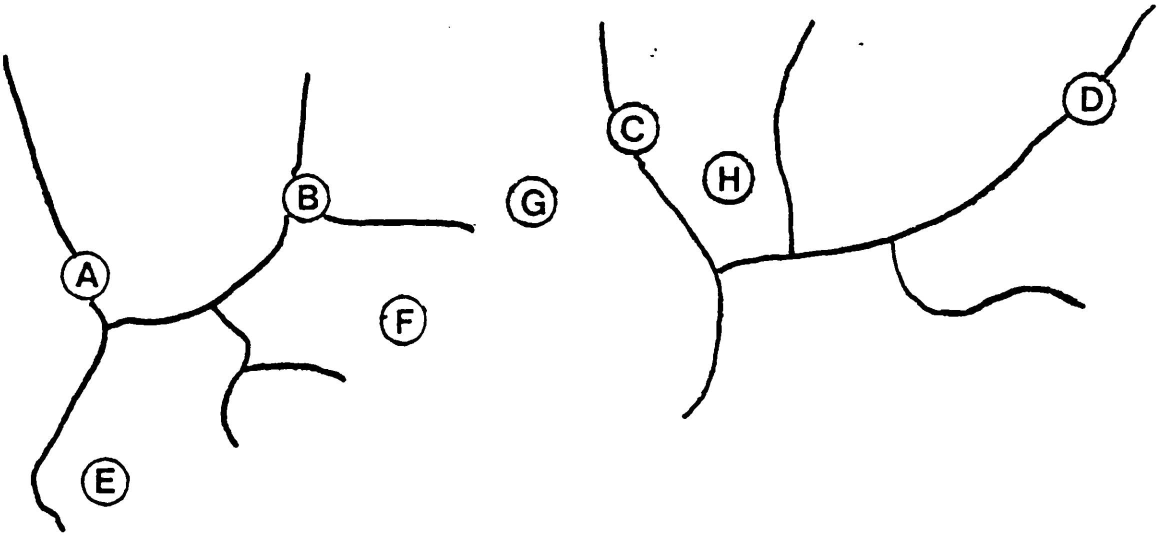


Figure 17 : The approximate origin of colliery product samples of the No. 2 Seam in relation to the channel system. From the average ash composition, the normative mineralogical composition was calculated.

The vitrinite content (visible mineral matter free), the ash content and the normative mineralogical composition (based on ash composition) through a vertical profile of the No. 2 Seam from the central-northern area of the Witbank coalfield are compared in Figure 18.

There is a strong inverse correlation between the vitrinite and kaolinite contents throughout the seam profile, and a sympathetic relationship between the vitrinite and pyrite and dolomite contents. The illite content correlates weakly with the vitrinite content in the

TABLE 9: THE NORMATIVE MINERALOGICAL COMPOSITION CALCULATED FROM THE AVERAGE ASH ANALYSIS OF COALS FROM THE LOCALITIES SHOWN IN FIGURE 17.

	CHANNEL AREAS				INTERCHANNEL AREAS			
%	A	B	C	D	E	F	G	H
APATITE	0,5	3,0	1,7	2,2	5,4	3,9	3,4	4,3
RUTILE	1,6	1,4	1,8	1,6	1,5	1,3	1,4	1,6
PYRITE	4,6	3,7	3,4	4,8	6,3	10,9	7,1	4,0
SIDERITE	5,1	0,7	2,4	0,0	0,0	0,8	0,0	2,7
DOLOMITE	0,8	5,3	2,0	3,8	11,2	8,0	7,7	6,7
CALCITE	3,3	8,9	2,2	2,8	11,9	8,7	10,4	7,4
ILLITE	3,8	2,4	4,6	2,7	3,3	4,7	4,8	5,2
KAOLINITE	59,5	63,7	70,0	61,6	59,6	58,3	62,5	63,8
QUARTZ	20,7	10,7	12,0	20,4	0,8	3,2	2,8	4,3
TOTAL:	99,9	99,8	100,1	99,9	100,0	99,8	100,1	100,0
KAOLINITE (QUARTZ - FREE BASIS)	75,0	71,3	79,5	77,4	60,1	60,2	64,3	66,7

lower half of the seam. In the upper half of the seam, higher illite contents are found with corresponding low vitrinite contents. Van Vuuren (1980) noted that the phosphorus content of the coal in the No. 2 Seam was often concentrated at the base or at the top of the seam. In Figure 19, only a weak affinity of apatite towards vitrinite is noted from the base of the seam upwards. The apatite content increases significantly towards the top of the seam. Pyrite, calcite and dolomite show a very good correlation with vitrinite content, except towards the top of the seam. The siderite content may have an inverse correlation with the pyrite content and, hence, with the vitrinite content. Pyrite forms preferentially in association with vitrinite, but a sulphur deficiency promotes the formation of siderite.

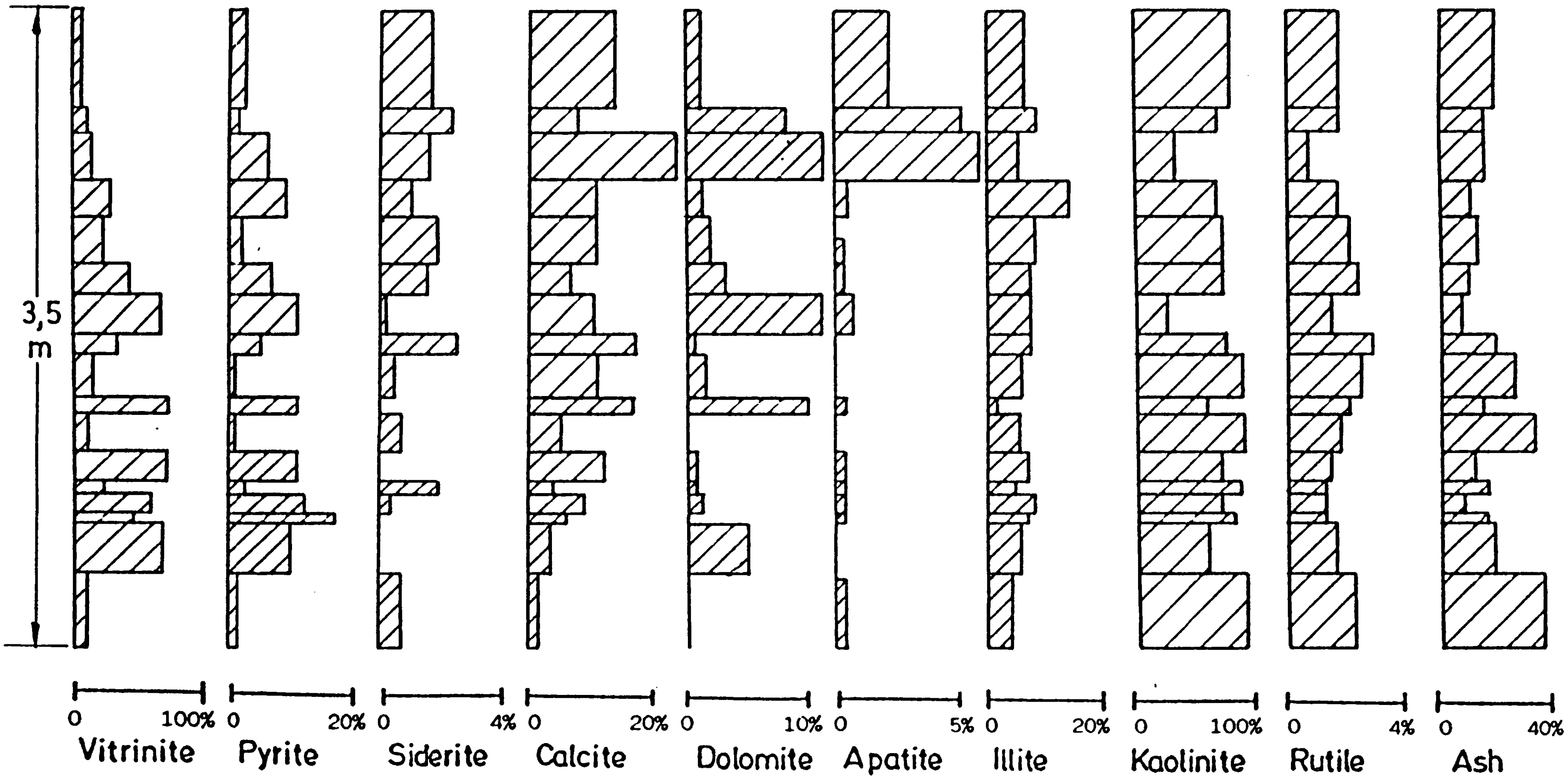


Figure 18 : A comparison of the vitrinite content (visible mineral matter free), the ash content and the normative mineral content (100% mineral matter basis) through a vertical profile of the No. 2 Seam in the Witbank coalfield.

Where strong positive or negative correlations of vitrinite and individual minerals can be observed, these minerals are mostly of syngenetic origin. The occurrence of minerals which correlate strongly with vitrinite content would indicate that they formed under environmental conditions which also favoured the formation of vitrinite. The low vitrinite content in the top portion of the seam indicates the end of a depositional cycle in which environmental conditions were less stable. The relatively high proportions of siderite, calcite and dolomite in the upper portions of the seam would indicate that these are mostly of epigenetic origin.

The calorific value in the No. 2 Seam varies from 28,0 MJ/kg to 34,0 MJ/kg (Fig. 19). The calorific values and therefore rank, generally decrease from east to west and north to south in the study area.

The volatile matter content is generally between 30,0% and 36,0%, but higher volatile matter coals are found in the central-eastern and central-western parts of the area (Fig. 20). It correlates rather well with the vitrinite content (Fig. 13), indicating that at low rank the volatile matter content is a better parameter of type than of rank.

The variation in carbon content of the No. 2 Seam is given in Figure 22. The carbon contents are generally above 80,0% and typically up to 83,0%, but may increase to over 84,0%. It correlates fairly strongly with the calorific value (Fig. 19).

The variation in hydrogen contents are given in Figure 22. The volatile matter and hydrogen contents of a coal are related to its vitrinite content. A comparison of the isopleths of these parameters show a very good relationship (Fig. 13, Fig. 20 and Fig. 22). High vitrinite content coals of the No. 2 Seam contain up to 40% volatile matter and up to 5,4% hydrogen. In contrast high inertinite coals have volatile matter contents below 30% and hydrogen contents as low as 4,2%. However, no clear relationship emerges from the isopleths of type and carbon and oxygen contents. The latter two parameters are more readily influenced by changes in rank in bituminous coals (Fig. 13, Fig. 21 and Fig. 23).

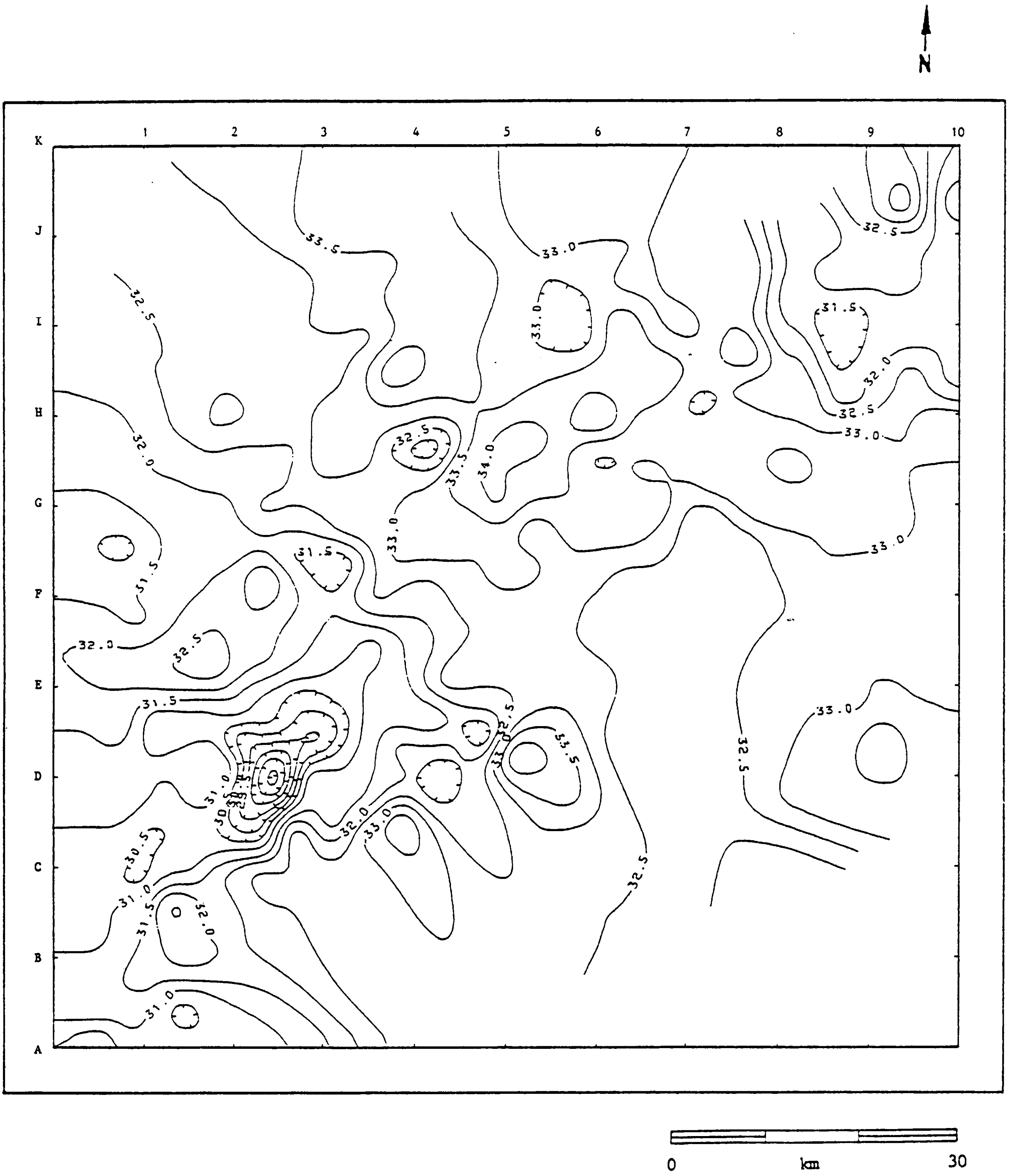


Figure 19 : The d.a.f. calorific value of the No. 2 Seam.

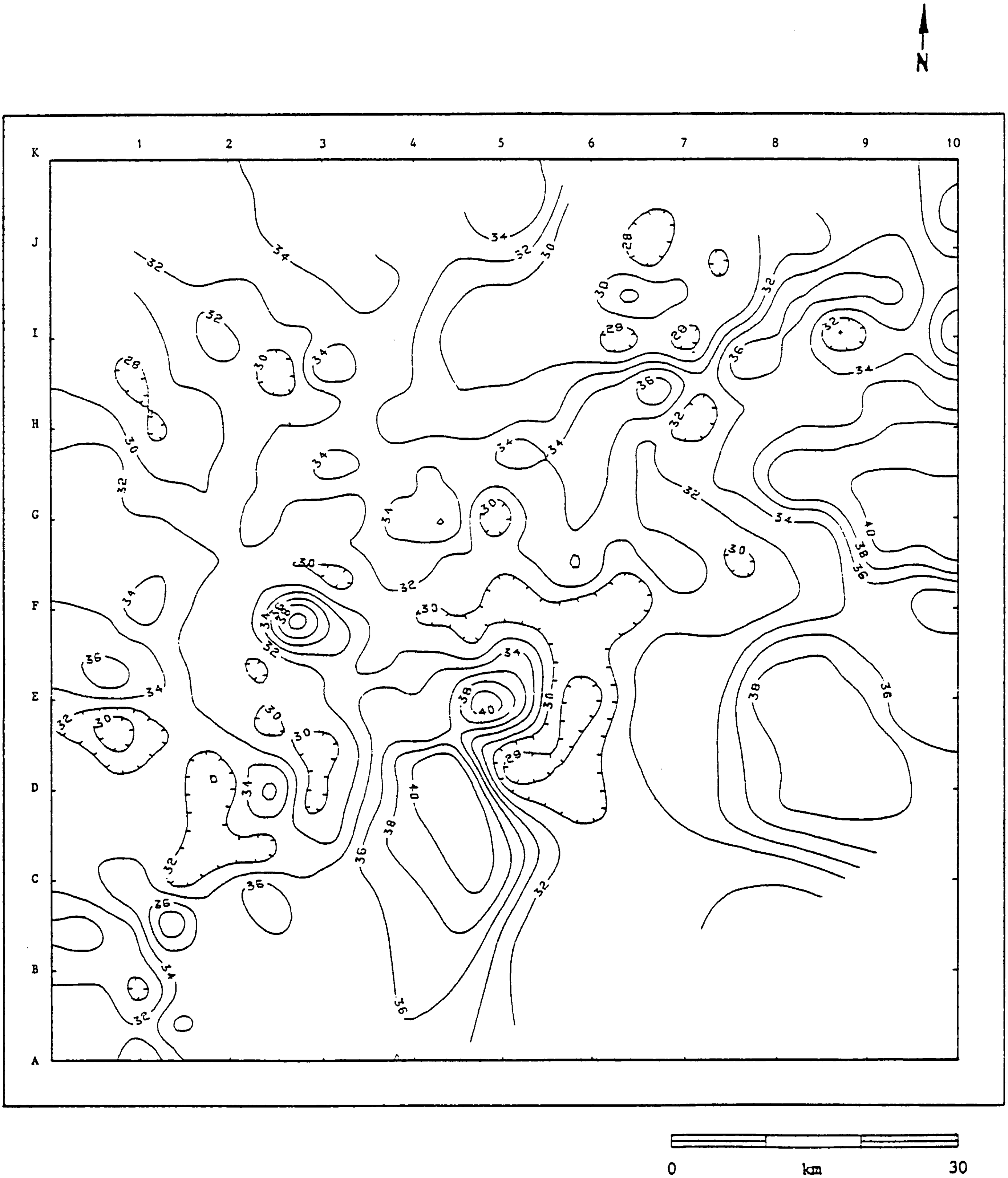


Figure 20 : The d.a.f. volatile matter content of the No. 2 Seam.

Although the parameters carbon, oxygen, calorific value and, to a lesser extent, volatile matter can be used as indicators of rank, each of these relates to rank in a different manner. Nevertheless, some relationship can be noted between the isopleths of these dry ash-free parameters.

The inherent moisture content of the No. 2 Seam which is also rank-related, varies from below 2,0% in the Witbank coalfield to above 6,0% in the Highveld coalfield (Fig. 24).

Throughout the No. 2 Seam RoV varies from 0,60% to above 0,85% (Fig. 25) which is of the same order as in the No. 1 Seam. As in the case of the No. 1 Seam high vitrinite coals are characterized by low RoV values and vice versa, once again indicating the difficulty in choosing grains suitable for reflectance measurements in inertinite-rich coals. The rank of the No. 2 Seam within the study area increases generally northwards. This is also indicated by other chemical parameters (Figs. 19, 22, 23 and 24). Towards the north, west and central portions of the study area, the seam has an RoV of 0,75% to 0,85%. As dolerite sills are frequently encountered between the coal seams, these intrusions must have had some influence on the rank of the seam.

6.3 THE UPPER SEAMS

6.3.1 The No. 3 Seam

The No. 3 Seam is laterally impersistent in both coalfields. The seam is absent over the prominent topographical high at G3 (Fig. 27). Other paleohighs occur at J3, H4-I5, G7 and E5-E6. There is a regionally southerly slope of about 1:700 which increases up to 1:250 in a southerly direction in the Highveld coalfield. Based on the topographic contours and the thickness and distribution of the seam, a channel system is deduced. Over the areal extent of the study area the channel frequency is about one to two per 1000 sq km with a density of about 34 km per 1000 sq km.

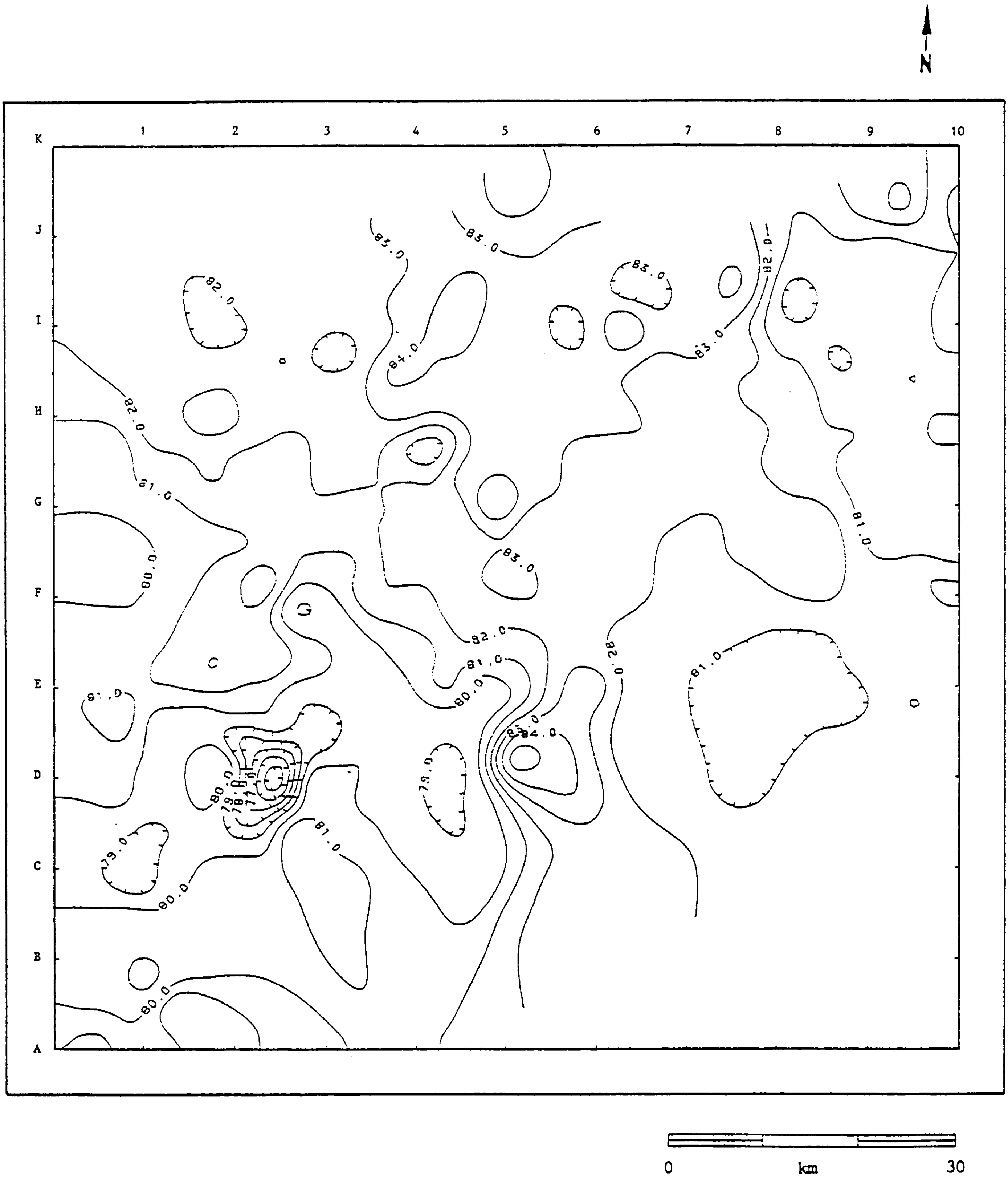


Figure 21 : The d.a.f. carbon content of the No. 2 Seam.

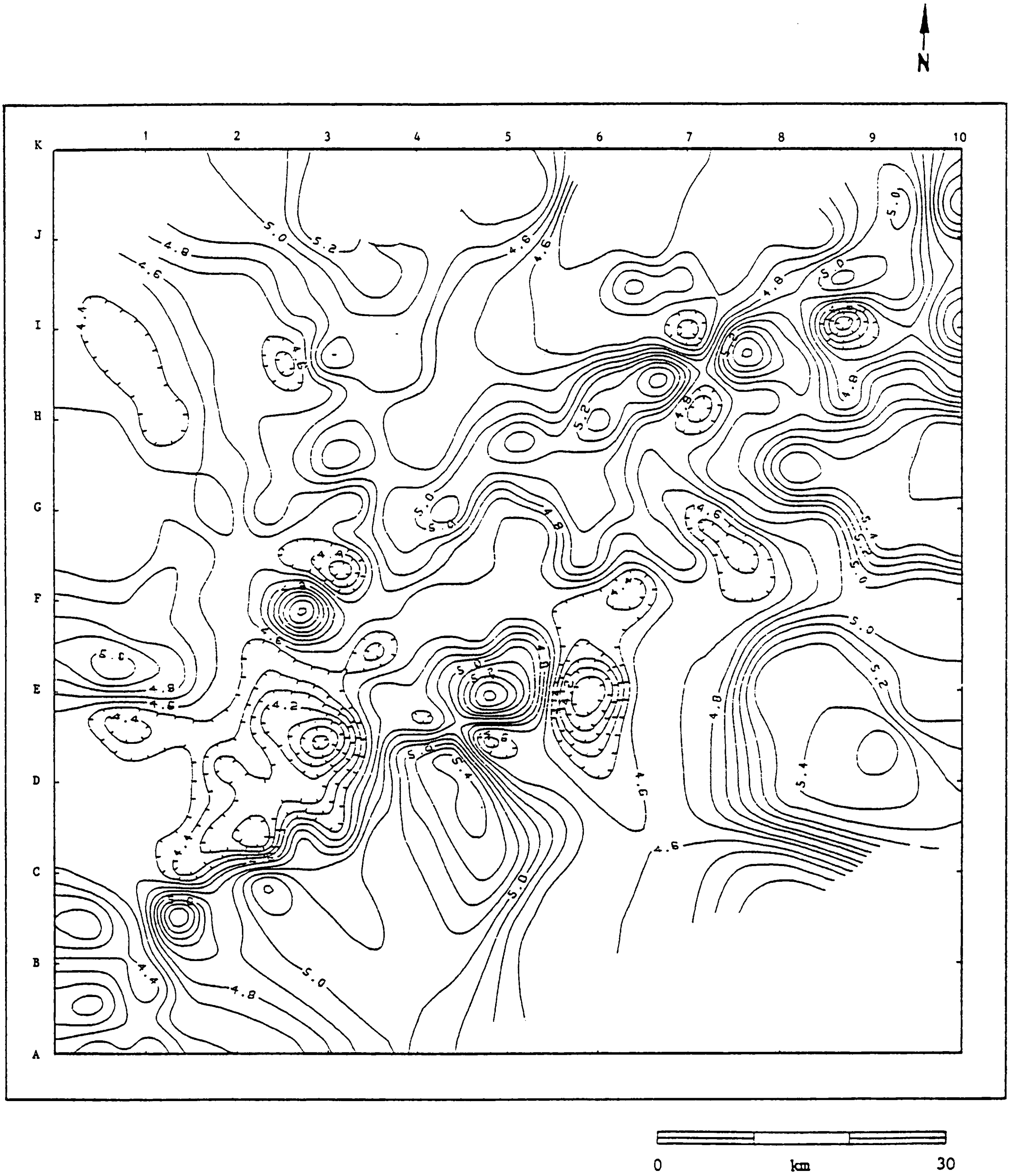


Figure 22 : The d.a.f. hydrogen content of the No. 2 Seam.

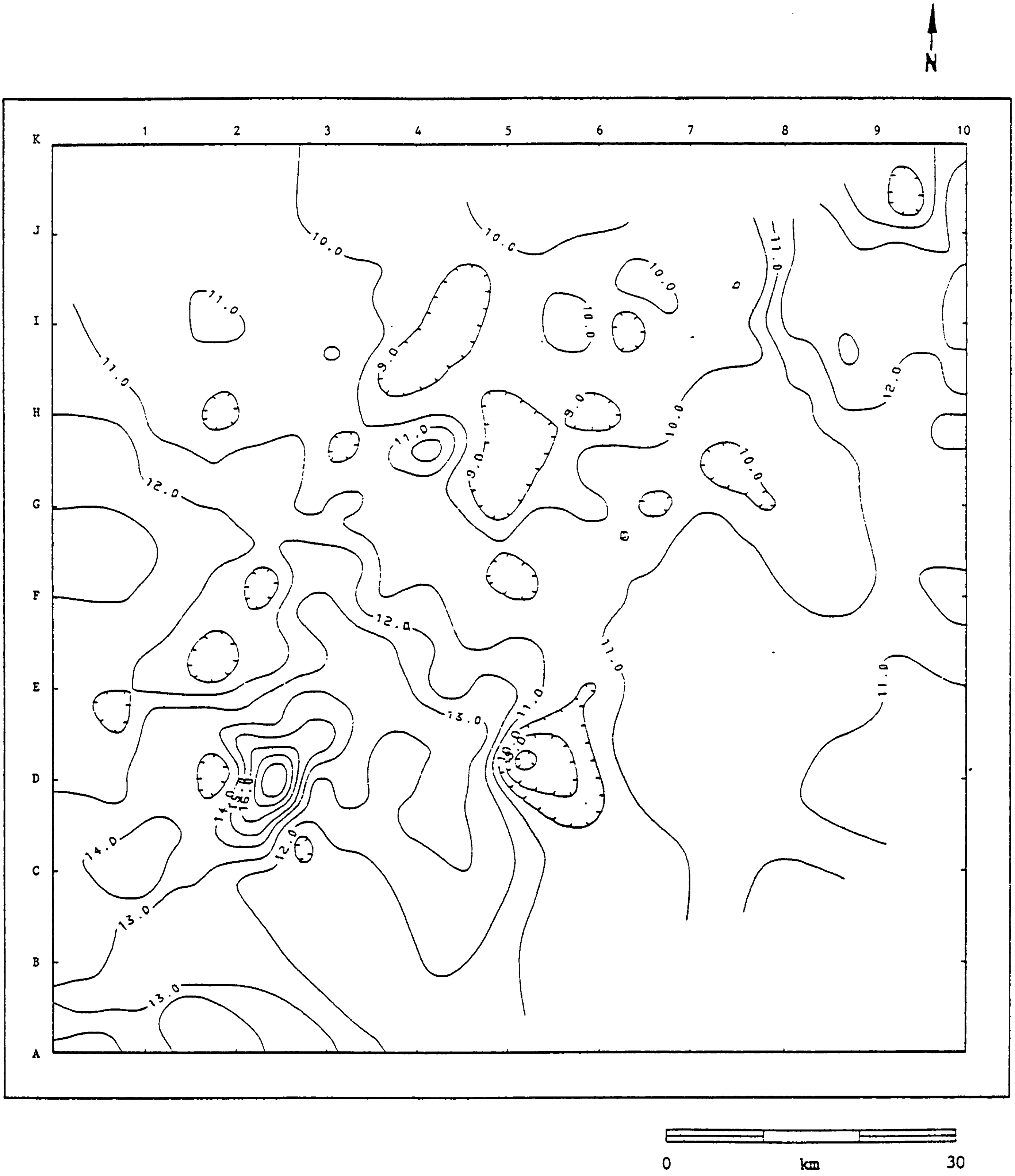


Figure 23 : The d.a.f. oxygen content of the No. 2 Seam.

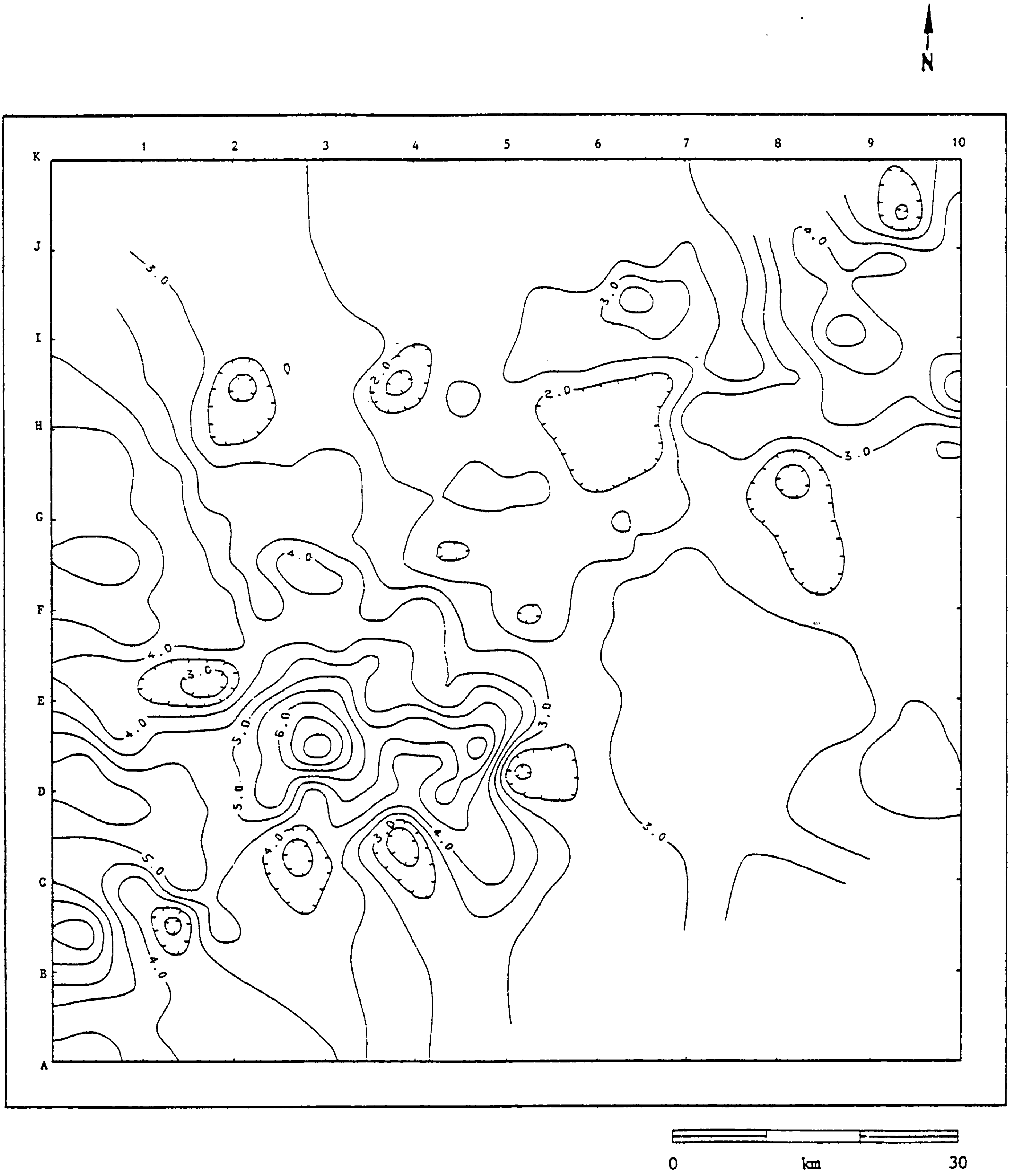


Figure 24 : The inherent moisture content of the No. 2 Seam.

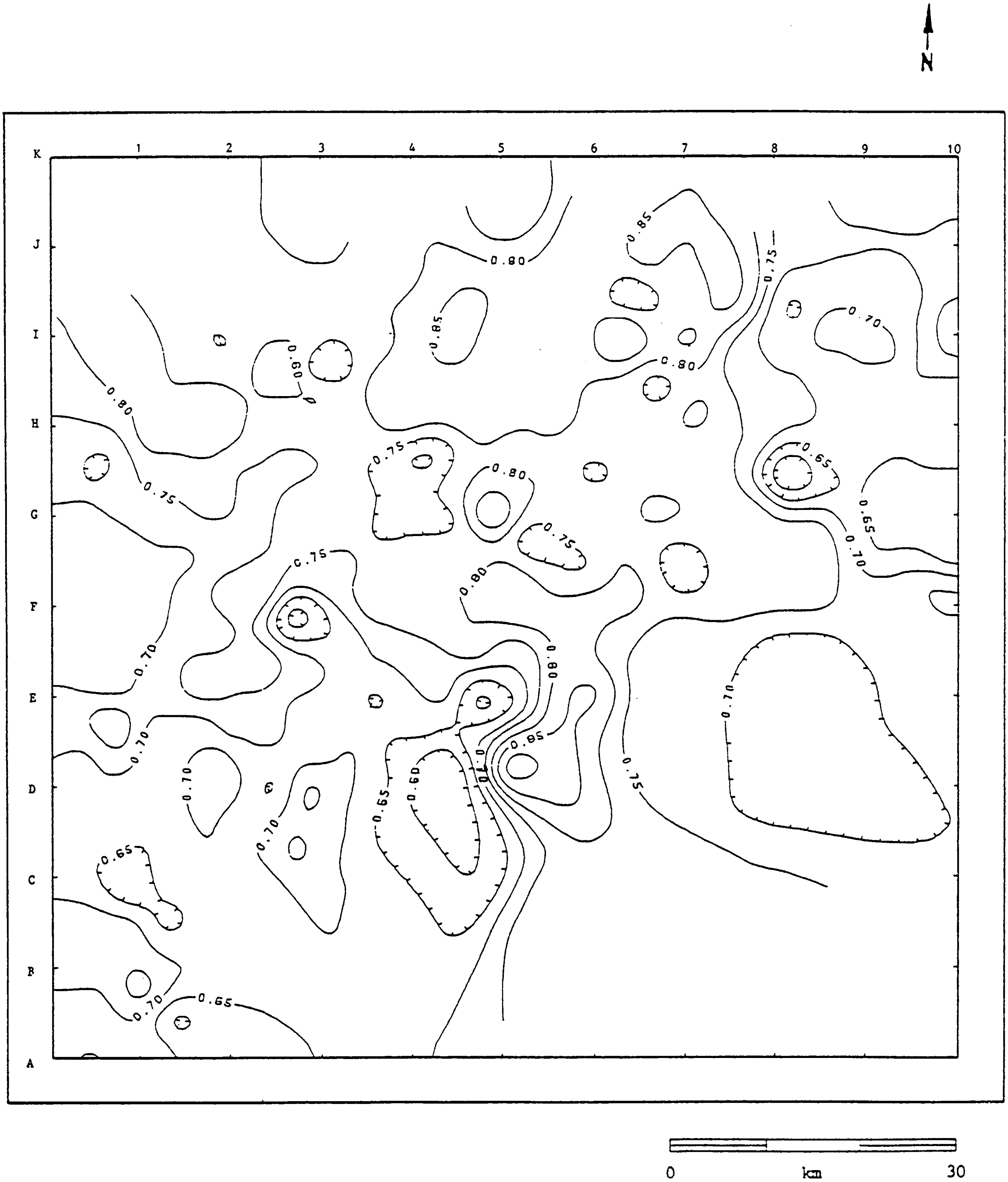


Figure 25 : The % RoV of the No. 2 Seam.

The low channel density and frequency suggests a lower water supply during the formation of the No. 3 Seam, than during the formation of the No. 2 Seam.

The No. 3 Seam has little commercial significance due to its limited distribution and limited thickness (Fig. 27). The seam is better developed in the topographical depression at G4-G5 where the influx of water favoured peat growth to form vitrinite-rich coal. The thicker seam development in the depressions at I3-I4, and F1-G2 which are both adjacent to high ground suggests that large amounts of hypautochthonous peat were washed into the depressions to form coal relatively rich in vitrodetrinite. The thickness of the seam varies from 0,2 m to about one metre (Fig. 27). The type isopleths of the No. 3 Seam, as shown in Figure 28, show that the No. 3 Seam is generally rich in vitrinite, but maxima coincide with areas where the seam is generally less than 0,5 m thick. At I3-I4, the calculated peat thickness varies typically from 1 m to 5 m, the latter corresponding to the thicker development of the seam. Elsewhere, based on available data, the calculated peat thickness is most consistently between 1,5 m to 3 m.

The rank of the No. 3 Seam increases from typically 0,60% - 0,65% RoV in the south to 0,70% - 0,75% towards the north with a maximum of 0,80% at H4, as is shown in Figure 29. Here again, the RoV maxima tend to coincide with minima in the vitrinite content.

6.3.2 The No. 4 Seam

A feature of the topography of the floor of the No. 4 Seam is that it seems to have a denser drainage than that of the No. 2 Seam (Fig. 30). The topography of the base of the No. 4 Seam has a southerly slope in the central portion of the study area of about 1:1000. This is slightly less than a north-east - south-westerly slope of about 1:1200. The topographical high at G3, first noted in the lower seams, is still prominent. Topographically elevated areas occur at J9 and E10 with local highs at E6, H3 and H7. A number of larger depressions are noted at G2-H2, I6, F5-G5, G7-G8 and F9. Several smaller depressions are found in the Highveld coalfield.

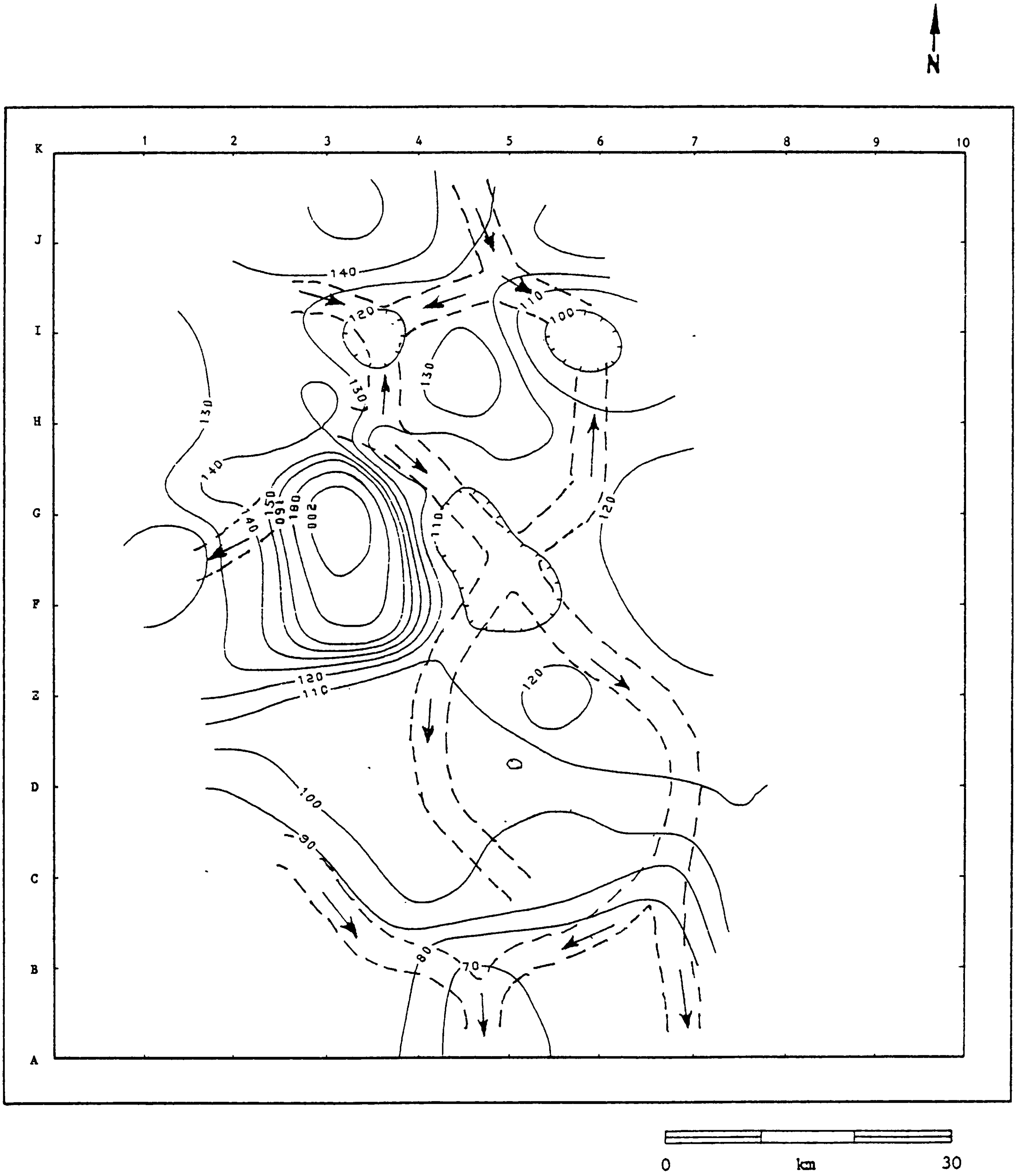


Figure 26 : The floor topography of the No. 3 Seam with the postulated channels.

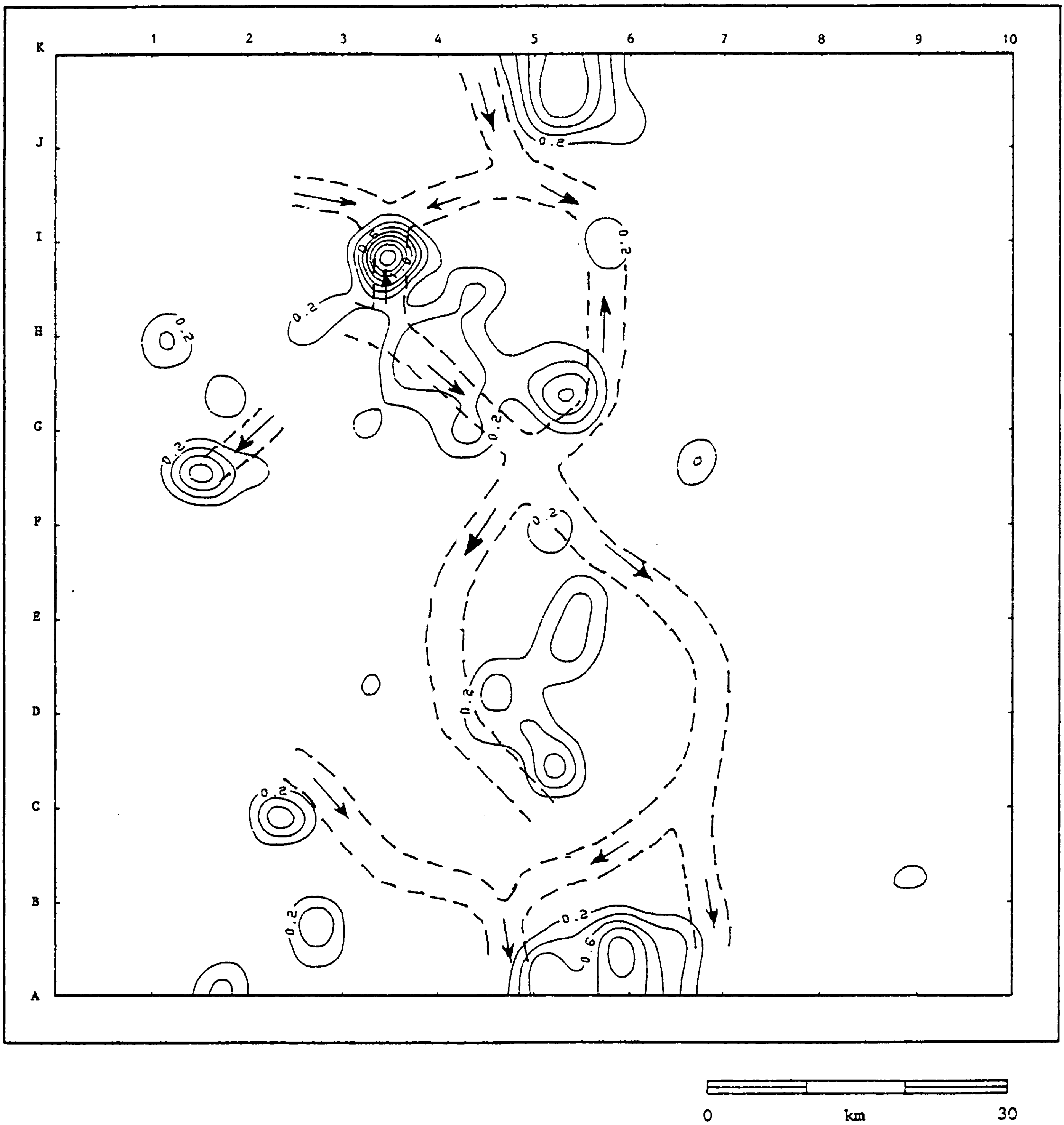


Figure 27 : The thickness (m) and distribution of the No. 3 Seam.

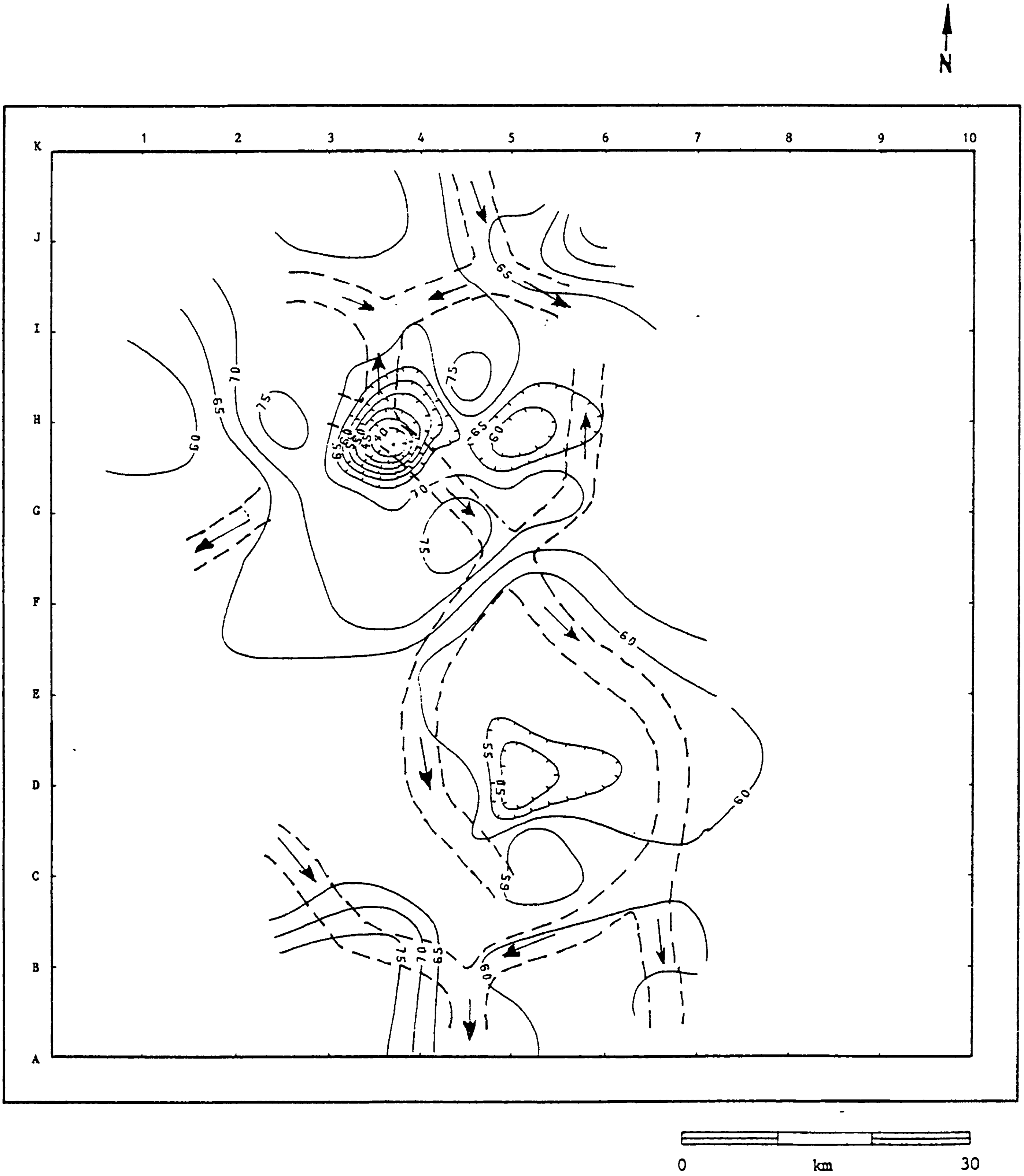


Figure 28 : The vitrinite content of the No. 3 Seam.

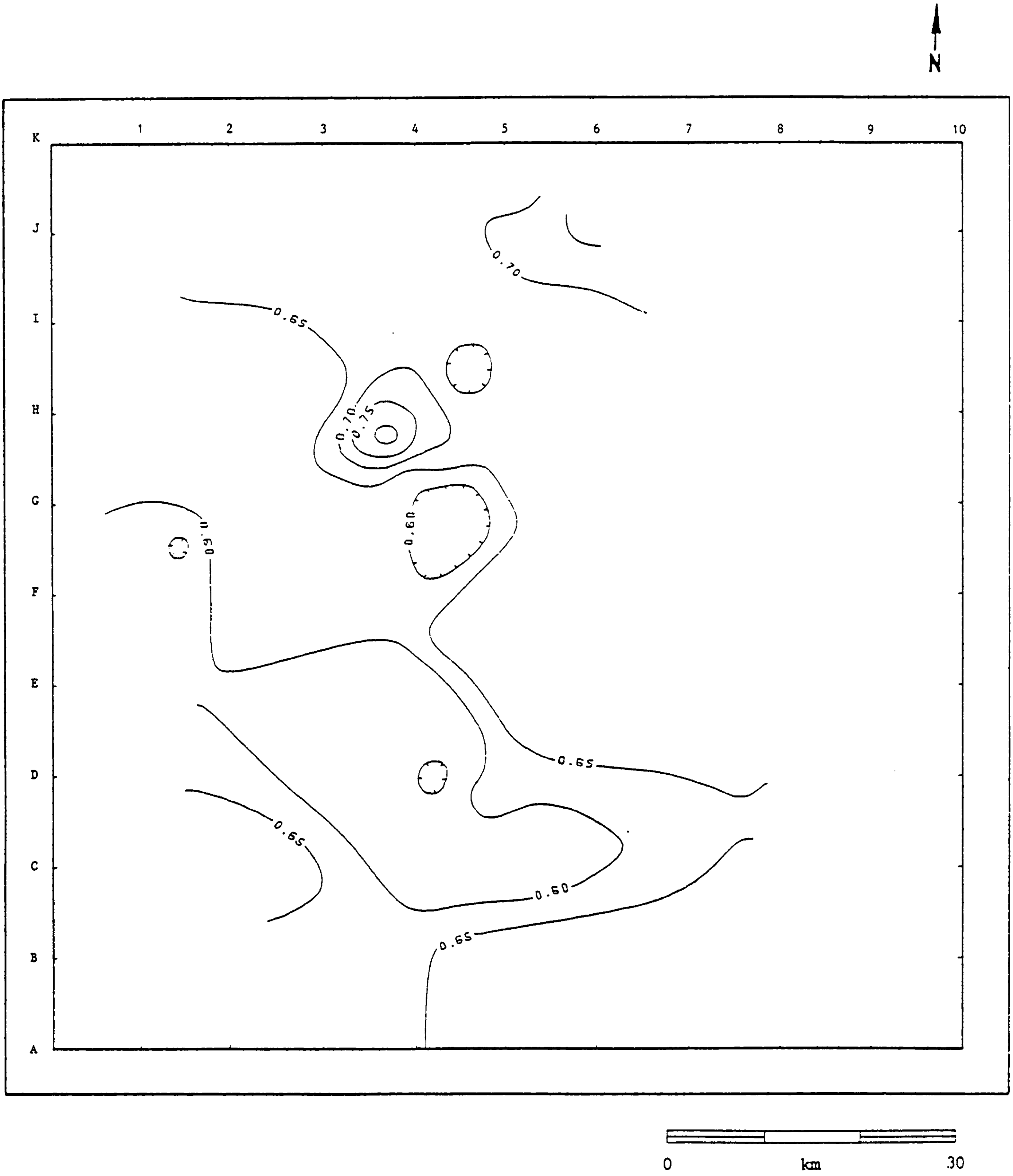


Figure 29 : The % RoV of the No. 3 Seam.

In view of the reduced relief, more anastomosing channels are apparent than in the case of the No. 2 Seam. The channel systems were deduced from the floor topography of the No. 4 Seam. Channel density is estimated at 93 km per 1000 sq km and the channel frequency at 5 per 1000 sq km. The regionally gentle slopes suggest a rather low energy flow of the channel water.

The seam is absent in the northern portion of the study area. The influence of the two topographical highs at G3 and F6 is still evident in the No. 4 Seam. The seam attains a thickness of several metres at H4 and F6 where it abutts against these highs towards the south (Fig. 31).

Thick seam development occurs over other elevated areas such as at I9-J9 and also in the depressions at I3 and D1. The seam, adjacent to the major channels, formed in situ on higher ground in forest swamp environments. Locally, towards the west, the seam has an inertinitic character where it occurs in lower lying areas (e.g. B2-C3, Fig. 32). The deposits have been shown to be of hypautochthonous origin (Hagelskamp and Snyman, 1988, p. 307). The peat originally formed under good preservation conditions and was later transported and redeposited. The peat was physically disintegrated and became partly oxidized. The coal is regarded to have formed on floodplains and backswamps of a major river belt. The seam is rich in inertodetrinite (Hagelskamp and Snyman, 1988, p. 312, 313).

A varying milieu that existed during the formation of the No. 4 Seam resulted in a variable character of the seam over its whole distribution area. This applies not only to its varied thickness, but also to its type and grade. The seam commonly contains 25-40% of vitrinite mainly in the northern and south-western areas. Elsewhere the vitrinite content varies from 40-60%, but seldom exceeds 65%. The nature of the seam suggests that over extended periods of the time of formation, relatively dry and oxidizing conditions prevailed, and that forest swamps were less well developed.

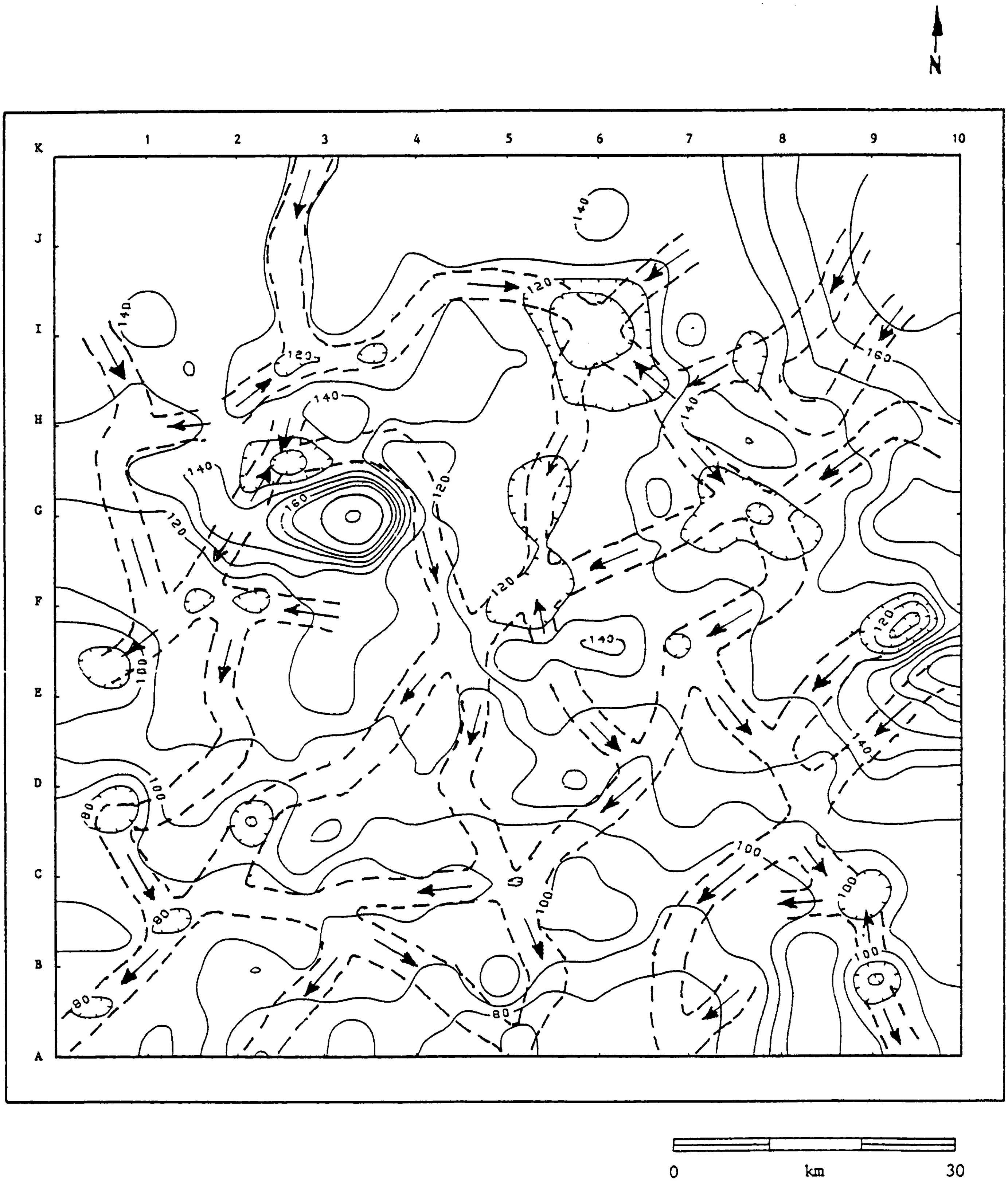


Figure 30 : The floor topography of the No. 4 Seam with the postulated channels.

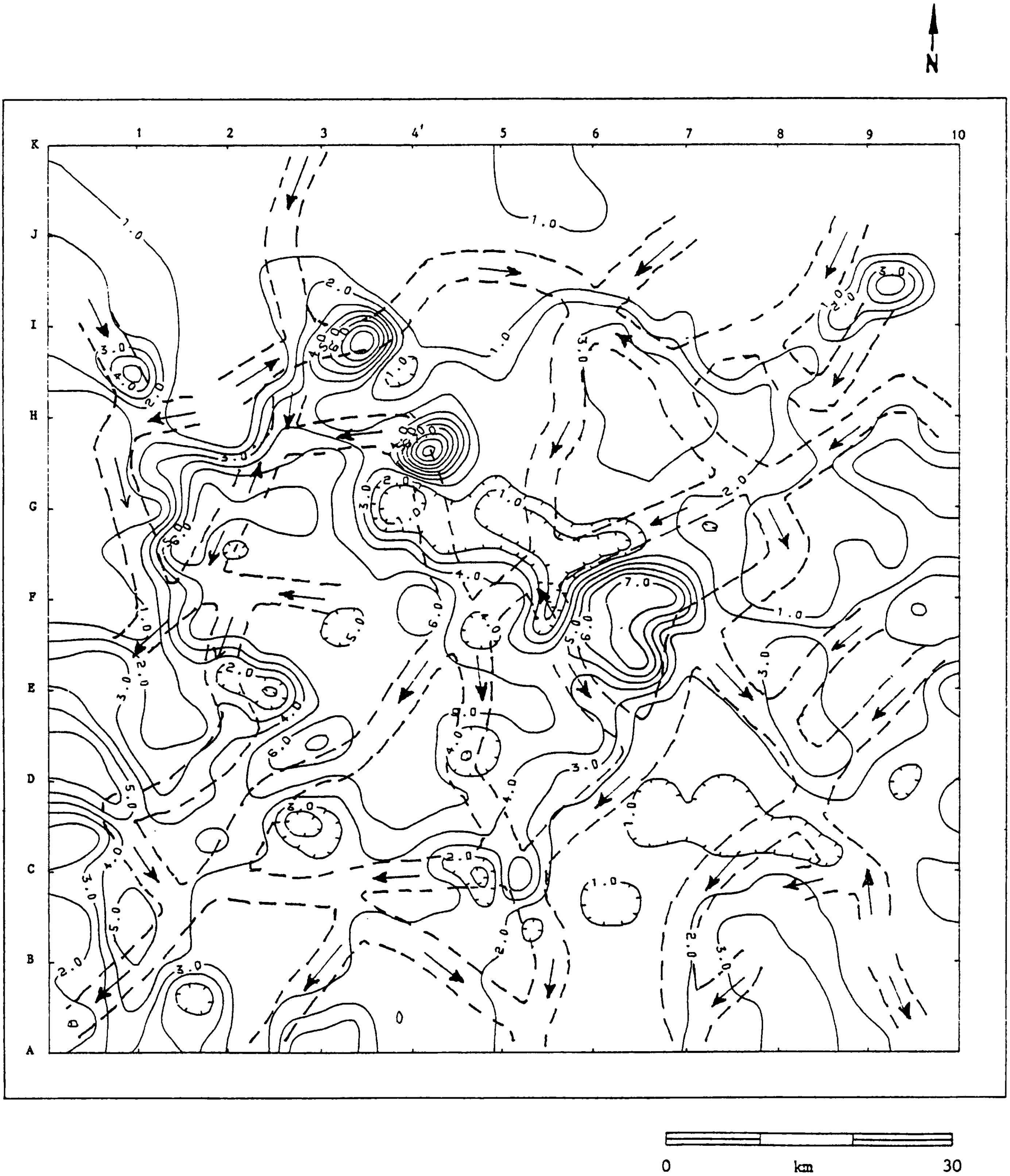


Figure 31 : The thickness (m) and distribution of the No. 4 Seam.

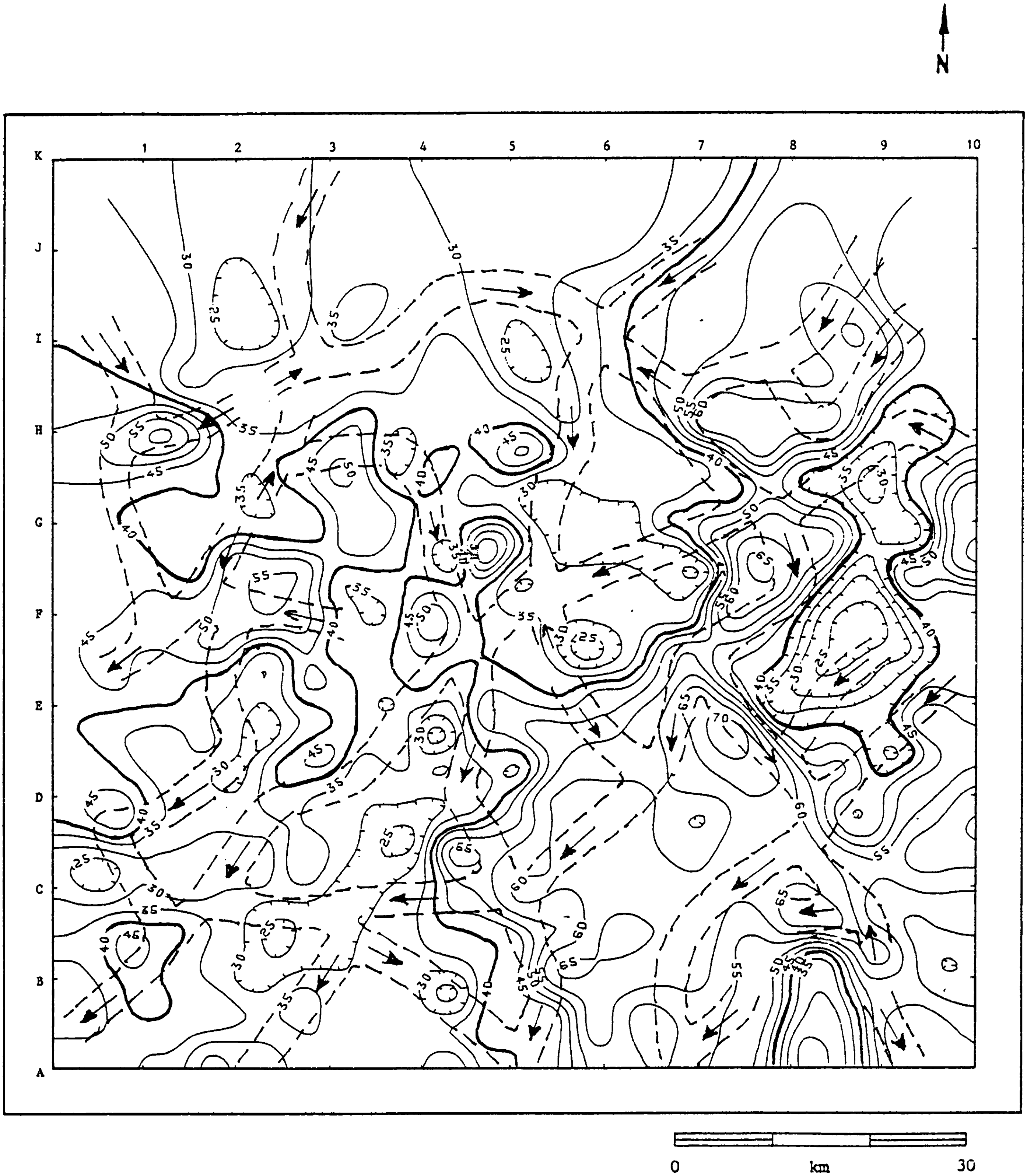


Figure 32 : The vitrinite content of the No. 4 Seam. Shaded areas indicate coals with a vitrinite content below 40%.

Owing to the economic importance of the No. 4 Seam, considerable analytical data are available. The study area can be divided into a series of elongated north-south trending areas, which is illustrated by accentuation of the 40% vitrinite contour lines in Figure 32. In the shaded areas the seam generally has an inertinite-rich base which represents about half of the areal development of the seam.

Based on vitrinite content, two to four distinct plies in the No. 4 Seam are generally evident. On this basis at least two cyclic patterns in the seam profile can be delineated. One consists of a relatively vitrinite-rich base followed by a relatively inertinite-rich portion which in turn may or may not be capped by vitrinite-rich coal. Where the seam has an inertinite-rich base, the profile might retain a generally inertinitic character or the seam may be capped with distinctly vitrinite-rich coal. In these cases, the seam may be relatively thin and is often associated with channel areas.

A typical petrographic profile of the No. 4 Seam between E0 and E10 is given in Figure 33.

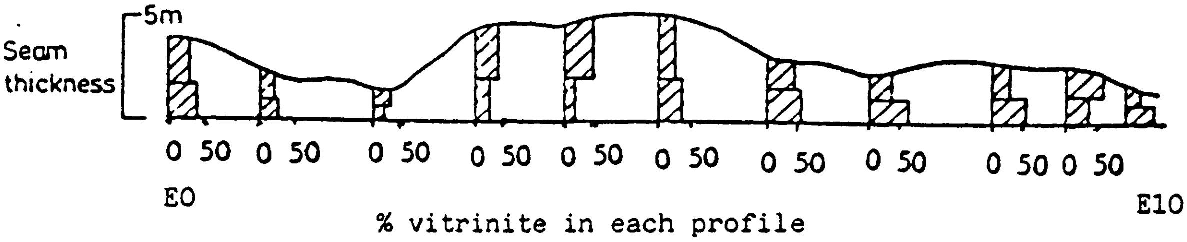


Figure 33 : Schematic vitrinite profile of the No. 4 Seam between E0 and E10.

The calculated peat thickness throughout the study area commonly varies between 10 m and 30 m (Fig. 35). Thick peat deposits frequently occur on slightly elevated areas such as at E6 and G4-H4 in forest swamp environments or in depressions (H2-G2). As is the case with the No. 2 Seam, the thinner peat deposits are in many cases associated with channel areas. Thin deposits are, however, found in the more elevated areas (e.g. G9-G10).

Figure 35 shows the calculated peat roof topography of the No. 4 Seam. Especially in the north-east (H8, G9 and F8), a correlation seems to exist between the channels and the areas of relatively lower roof topography of the peat.

The calorific value varies from below 30 MJ/kg to 33,5 MJ/kg, but is mostly lower than 32,5 MJ/kg. The No. 4 Seam has a low calorific value towards the southwest (Fig. 36, D3 and D4) and elsewhere typically ranges between 31,5 MJ/kg and 32,5 MJ/kg, especially in the Highveld coalfield.

The volatile matter content is a reasonably good reflection of the petrographic composition as would be expected in low rank coals. The volatile matter content of the seam is as diverse as is the coal type (Fig. 37). The volatile matter content is generally below 30% which corresponds to inertinite-rich coal. Toward the west, the volatile matter content is fairly consistent at around 34% which corresponds to the seam containing 40-50% vitrinite.

The carbon content of the No. 4 Seam varies considerably and is related to coal type rather than rank (Fig. 38). In the Highveld area the carbon content ranges from 78% to 82,5%. The carbon content of the seam in the Witbank area typically ranges from 80% to 83%.

The hydrogen content of the No. 4 Seam is related to the vitrinite content, due to the reasonably consistent rank of the Seam. Inertinite-rich coal have hydrogen contents mostly between 4,2% to 4,6% and the more vitrinitic coals a hydrogen content of up to 5,4% (Fig. 39).

The oxygen content is given in Figure 40 and ranges from about 9,5% to 15,0% (Fig. 39). As oxygen content is a good rank parameter for bituminous coals, there is a reasonably good inverse relationship with the calorific value. The oxygen content generally increases southwards in sympathy with the lower rank.

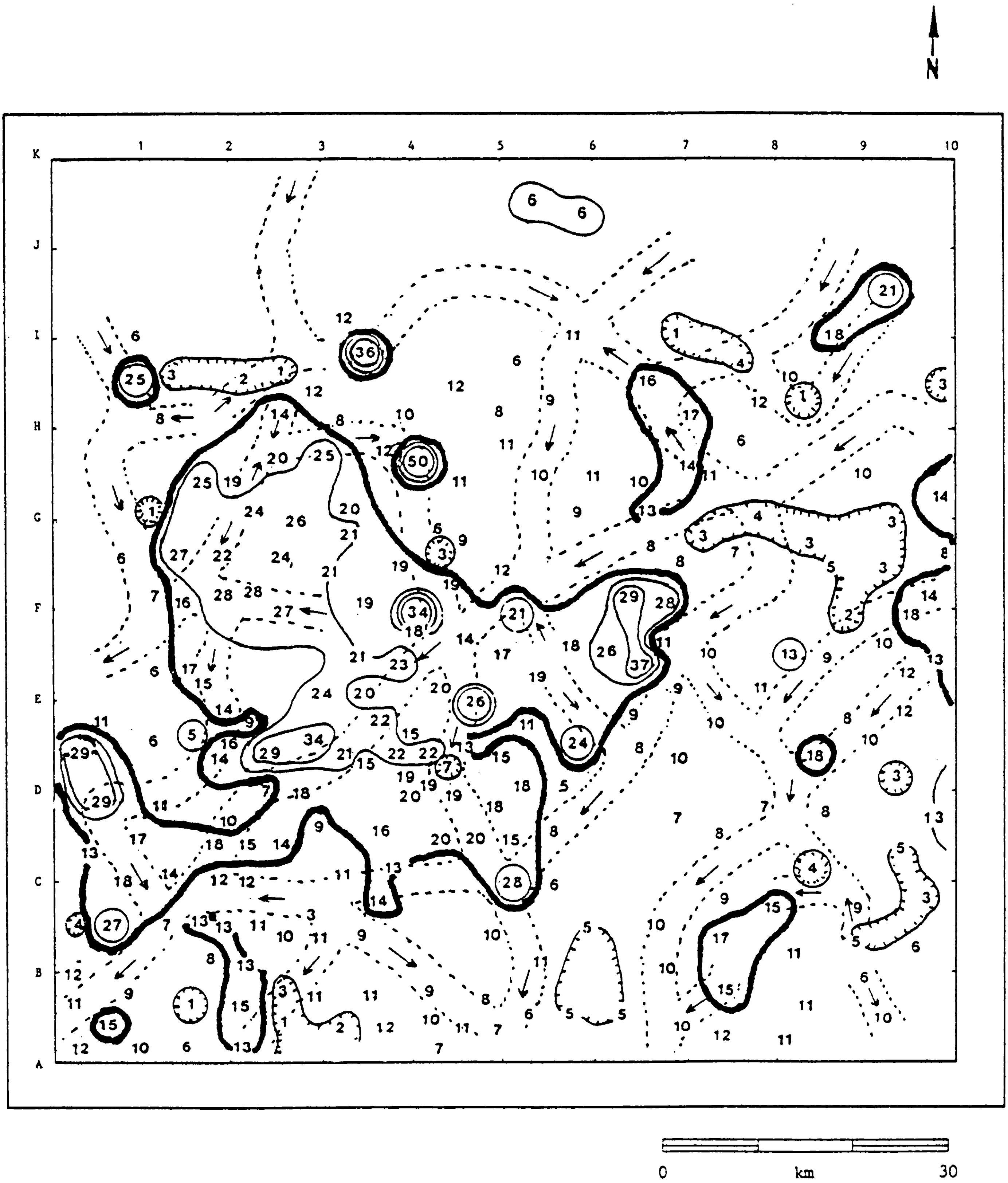


Figure 34 : The calculated thickness (m) of the peat of the No. 4 Seam and the relationship with the channels. The mean thickness of the peat is 13 m and contour intervals are shown in terms of the standard deviation (8 m).

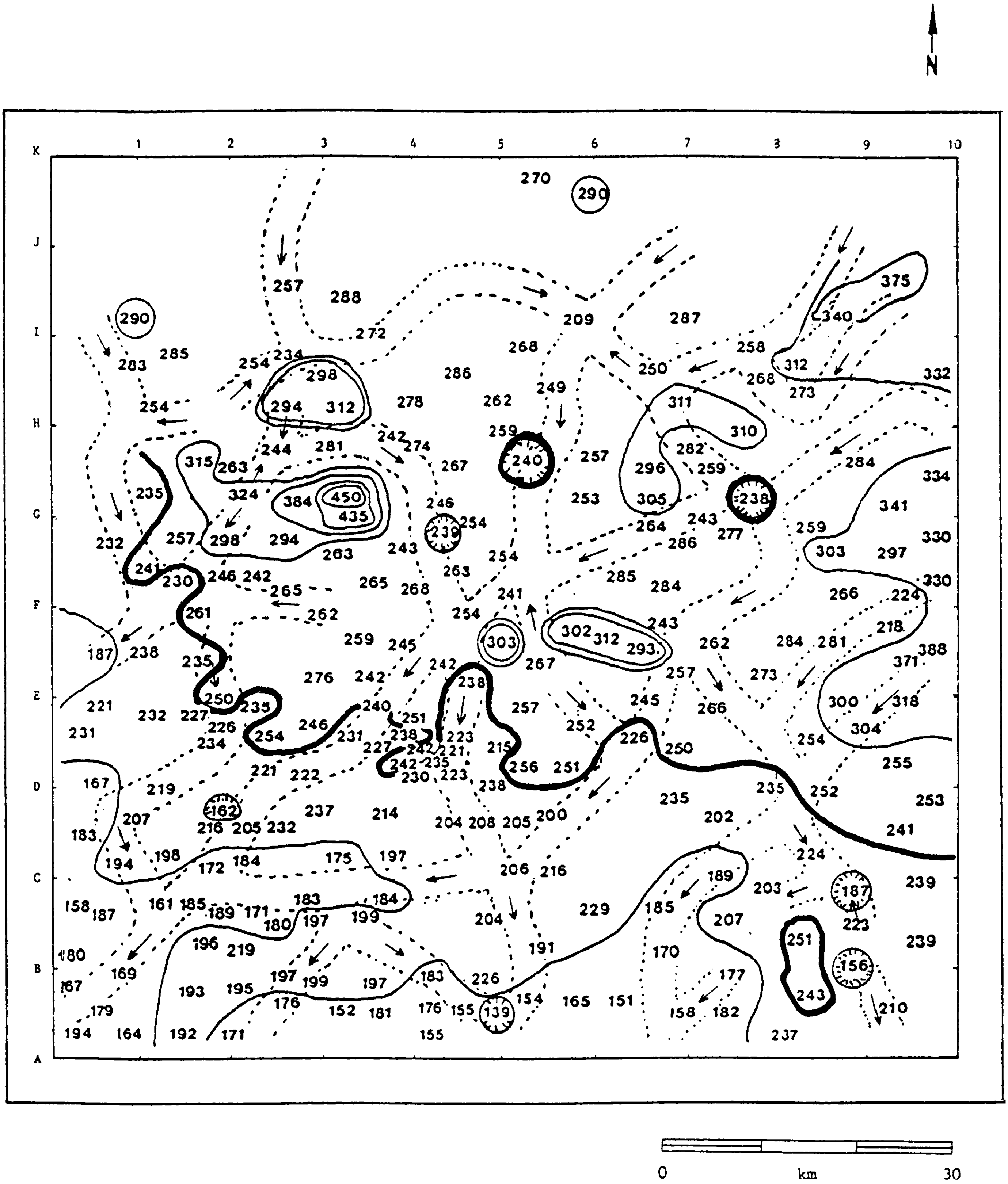


Figure 35 : The calculated roof topography (m) of the peat of the No. 4 Seam and the relationship with the channels. The mean height is 240 m and contour intervals are shown in terms of the standard deviation (50 m).

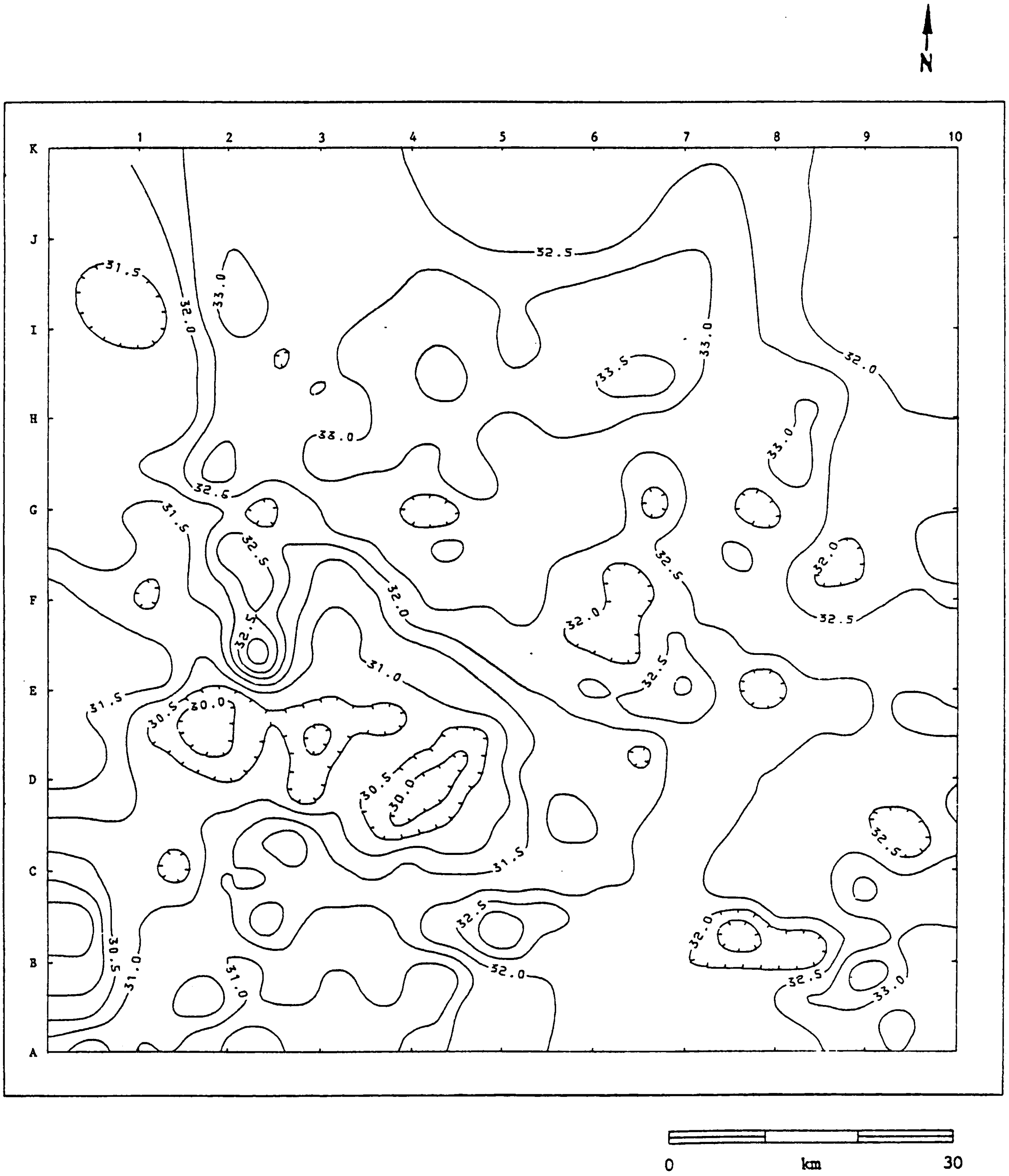


Figure 36 : The d.a.f. calorific value of the No. 4 Seam.

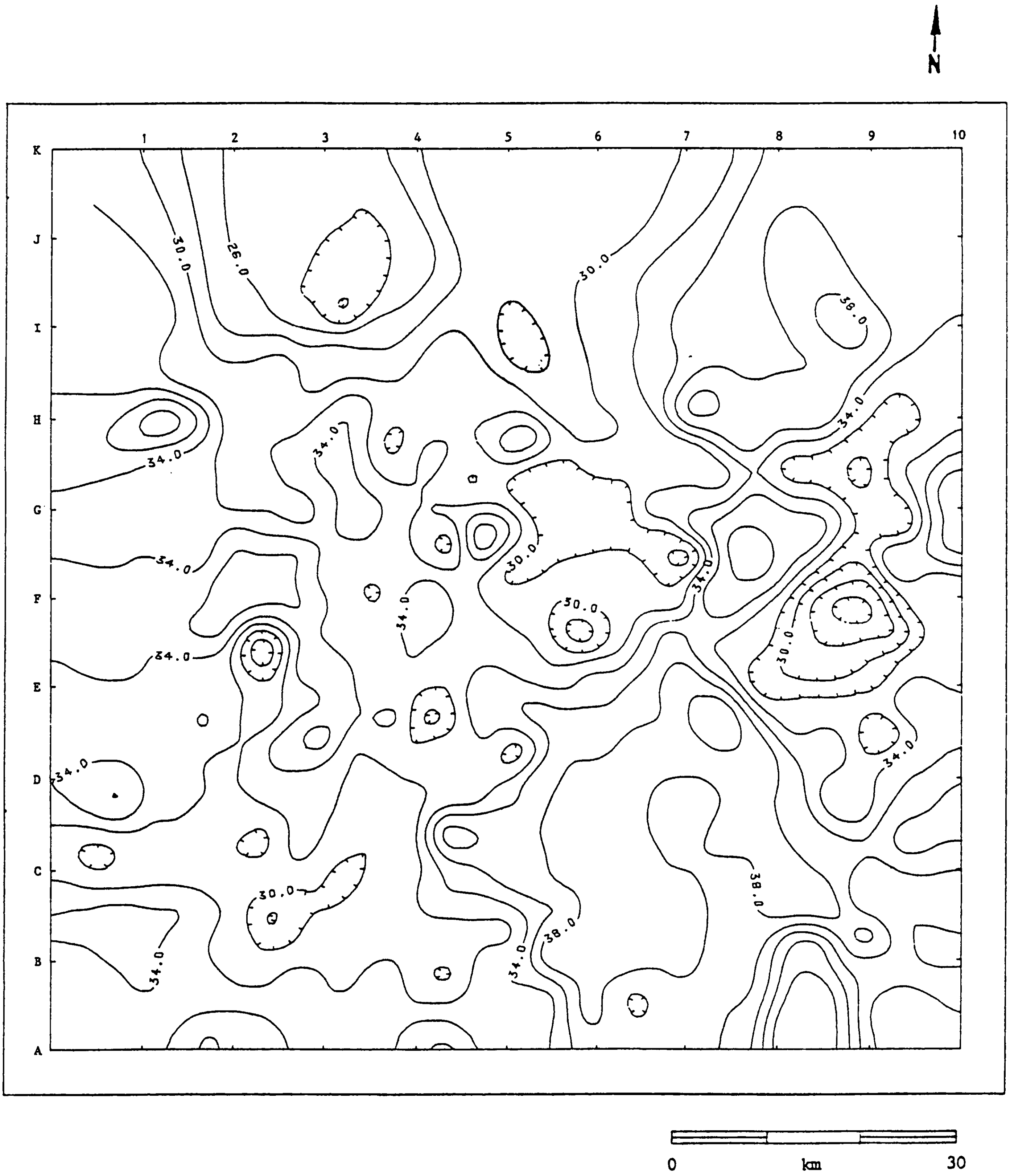
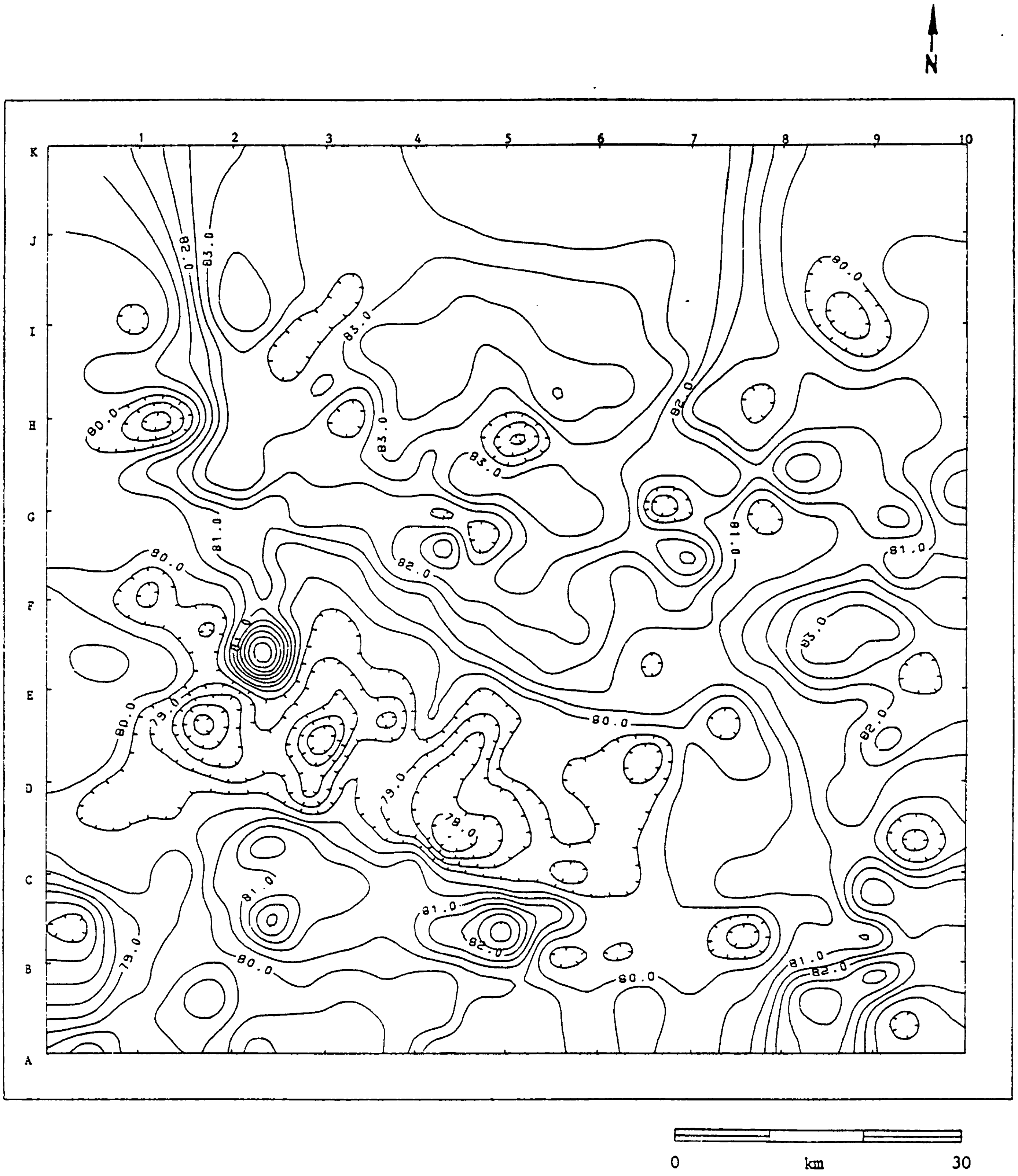


Figure 37 : The d.a.f. volatile matter content of the No. 4 Seam.



<u>Figure 38</u> : The d.a.f. carbon content of the No. 4 Seam.

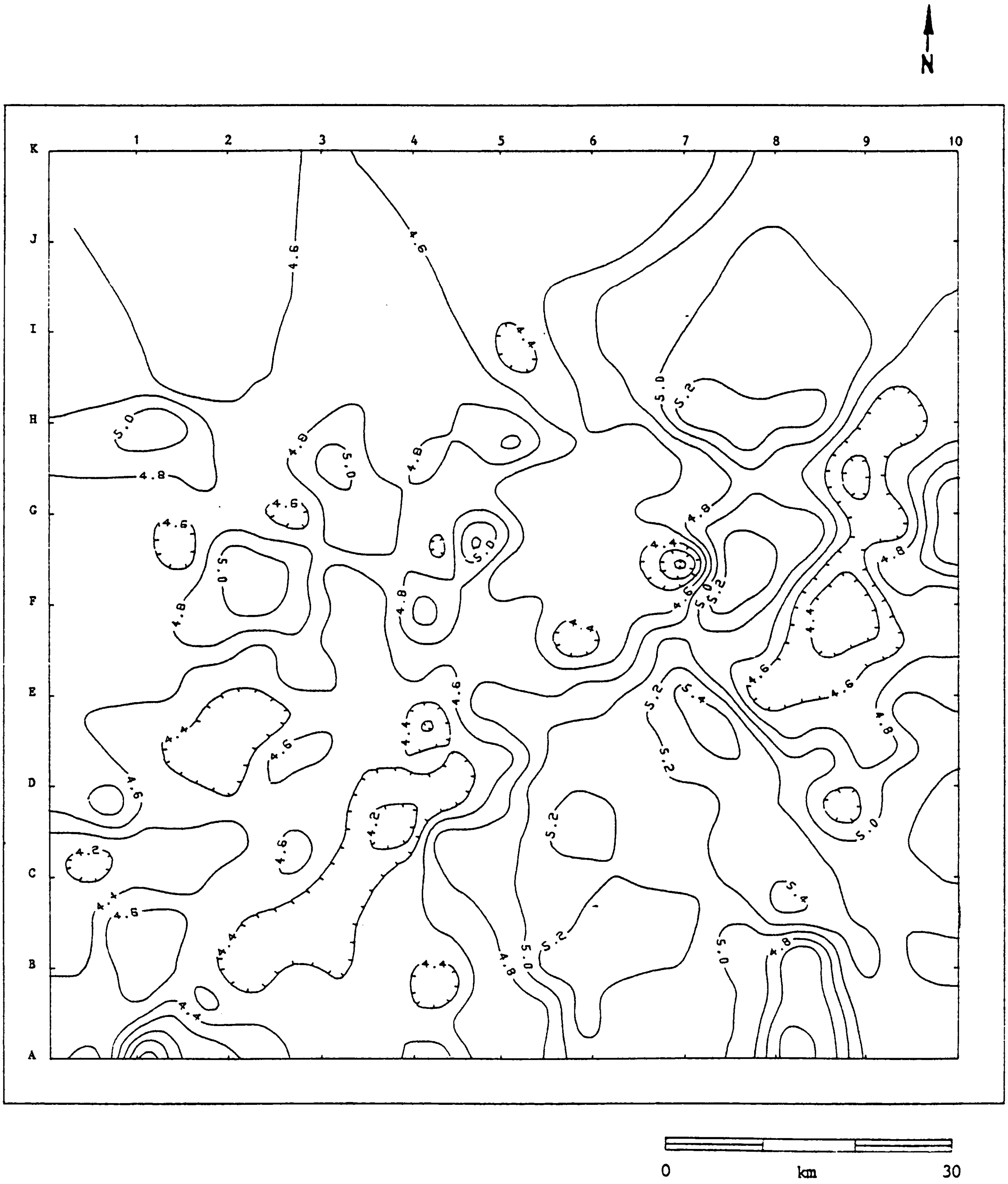


Figure 39 : The d.a.f. hydrogen content of the No. 4 Seam.

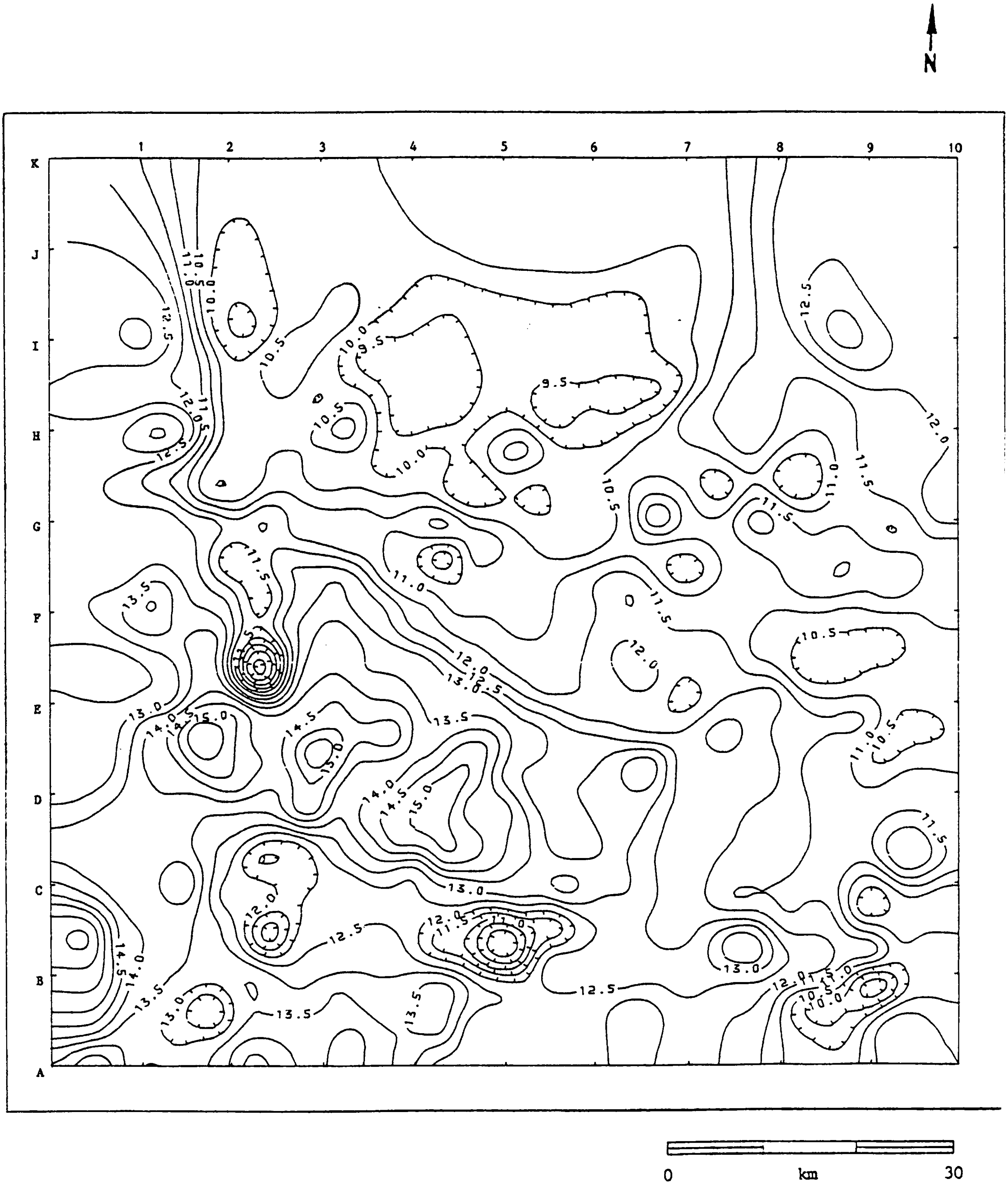


Figure 40 : The d.a.f. oxygen content of the No. 4 Seam.

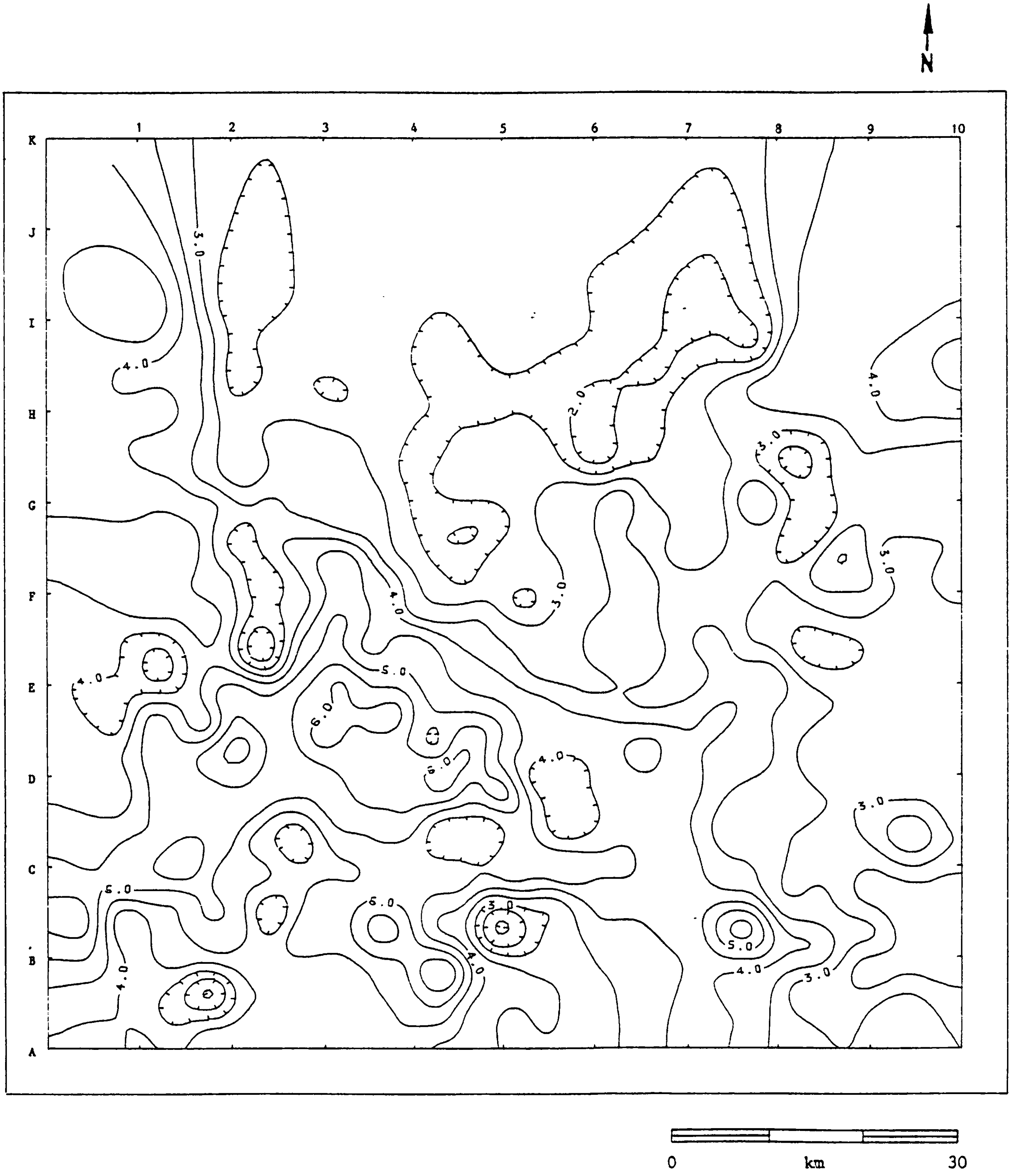


Figure 41 : The inherent moisture content of the No. 4 Seam.

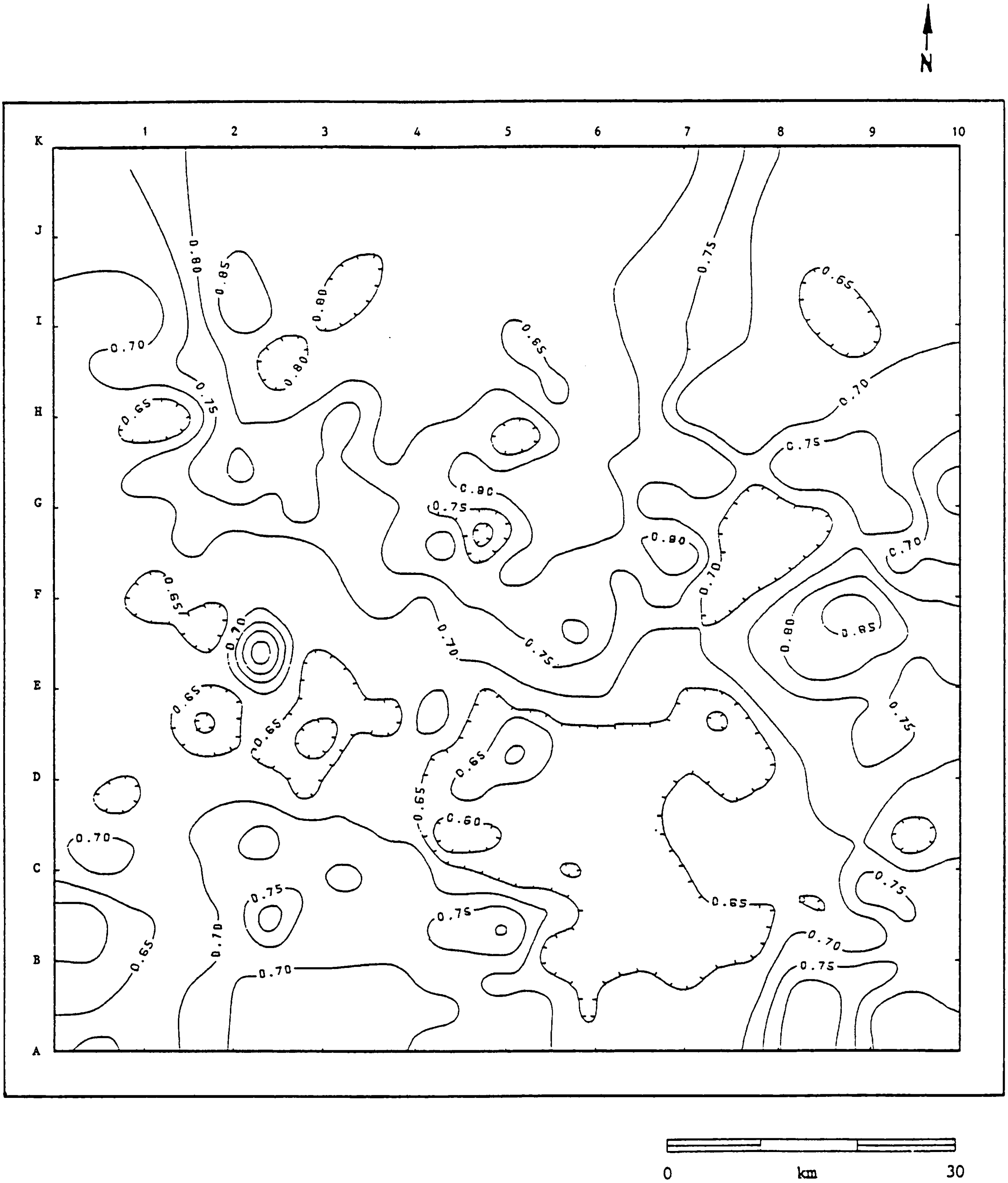


Figure 42 : The % RoV of the No. 4 Seam.

The air-dry moisture content is mostly higher in the No. 4 Seam than the underlying seams, generally 3,0% to 4,0% in the Witbank coalfield. The moisture content increases to 5,0-5,5% in many localities in the southern portion which also corresponds to the lower ranking coal in the south (Fig. 41).

The rank of the No. 4 Seam in the Highveld area as given by RoV is generally from 0,60% to 0,75%; locally it may be as high as 0,85%. Some of the higher ranking coals (RoV from 0,75% to 0,85%) are known to be heat affected in some areas, but the correlation between type (Fig. 32) and RoV (Fig. 42) once again reflects the unreliability of the weighted average of the reflectance in the case of inertinite-rich coals. In the Witbank coalfield the No. 4 Seam is of slightly higher rank, with an RoV from 0,70% to 0,85%, than in the Highveld coalfield.

6.3.3 The No. 4 Upper Seam

The floor topography of the No. 4 Upper Seam has been smoothed by the deposition of older sediments compared to the floor topography of the No. 4 Seam, especially towards the south. Most of the depressed areas in the paleotopography of the No. 4 Upper Seam were not inherited from previous seams and may be the result of differential compaction during consolidation of the underlying sediments. The paleohigh at G2-G3 is still present (Fig. 43). Other highs are noted at H4-I5, H7-I8 and at G9. Depressions occur at G4-H4, G7, D1 and B9. The paleofloor has a southerly slope of about 1:800 and a south-westerly slope about 1:750 between G8 and B2.

Channels are inferred from the paleotopography of the floor of the seam and from the seam characteristics. The channel pattern is still anastomosing and has a stream density and a stream frequency estimated at 50 km per 1000 sq km and 2 per 1000 sq km respectively (Fig. 43). As the contours of the floor topography of the No. 4 Upper Seam has been smoothed, a direct comparison of these values with those of the No. 4 Seam is not possible.

The seam is absent on the high ground towards the north and also at E4-I7 (Fig. 44). In the Witbank coalfield it has its best development along an east-westerly trending zone. Along the east and west of the study area, the best seam development occurs in north-south trending zones, and to some extent in the direction of the postulated channels. The No. 4 Upper Seam is generally thin, and seldom attains a thickness of more than one metre, except at H1, A2-B2, E6 and G7-H8, where the thickness is up to two metres. The seam occurs towards the eastern and western flanks of the Highveld coalfield in marginally elevated areas. The absence of the seam in the central portion of the coalfield may be accounted for by the merging of the No. 4 and No. 4 Upper Seams. This viewpoint is supported by the similar elevations of the extrapolated and superimposed isolines of the No. 4 Upper Seam and those of the No. 4 Seam and also by the fact that the No. 4 Seam is generally thicker in areas where the No. 4 Upper Seam is absent.

In the east the coal seam contains 60% to 80% vitrinite at the base, capped by coal containing 30% to 40% vitrinite (Fig. 45, B8 to E6). Northwards, the coal contains 50% to 55% vitrinite at the base of the seam. At C2 to D2 in the west, the lower portion of the seam contains coal with a vitrinite content of about 80%. In the upper portion of the seam the vitrinite content is mostly below 30%. The persistence of a relatively vitrinite-rich base of the seam over such a large area indicates that during the earlier stages of seam formation, environmental conditions favoured the preservation of peat and subsequent vitrinitization.

The coal type of the No. 4 Upper Seam is strongly influenced by the paleotopography of the floor of the seam. Inertinite-rich coal is associated with topographical highs and with the channels at H5 to H6 and F9 (Fig. 45). It is suggested that at these localities a very shallow water environment or redeposition of eroded peat favoured the formation of inertinite. The depressions at H4 and H7 are adjacent to higher ground. The highly inertinitic coals probably formed from peat debris washed into the depressions or into channel areas (e.g. at H4 and H8) from the surrounding higher ground; these coals are therefore of hypautochthonous origin. The vitrinite content varies from 30% to

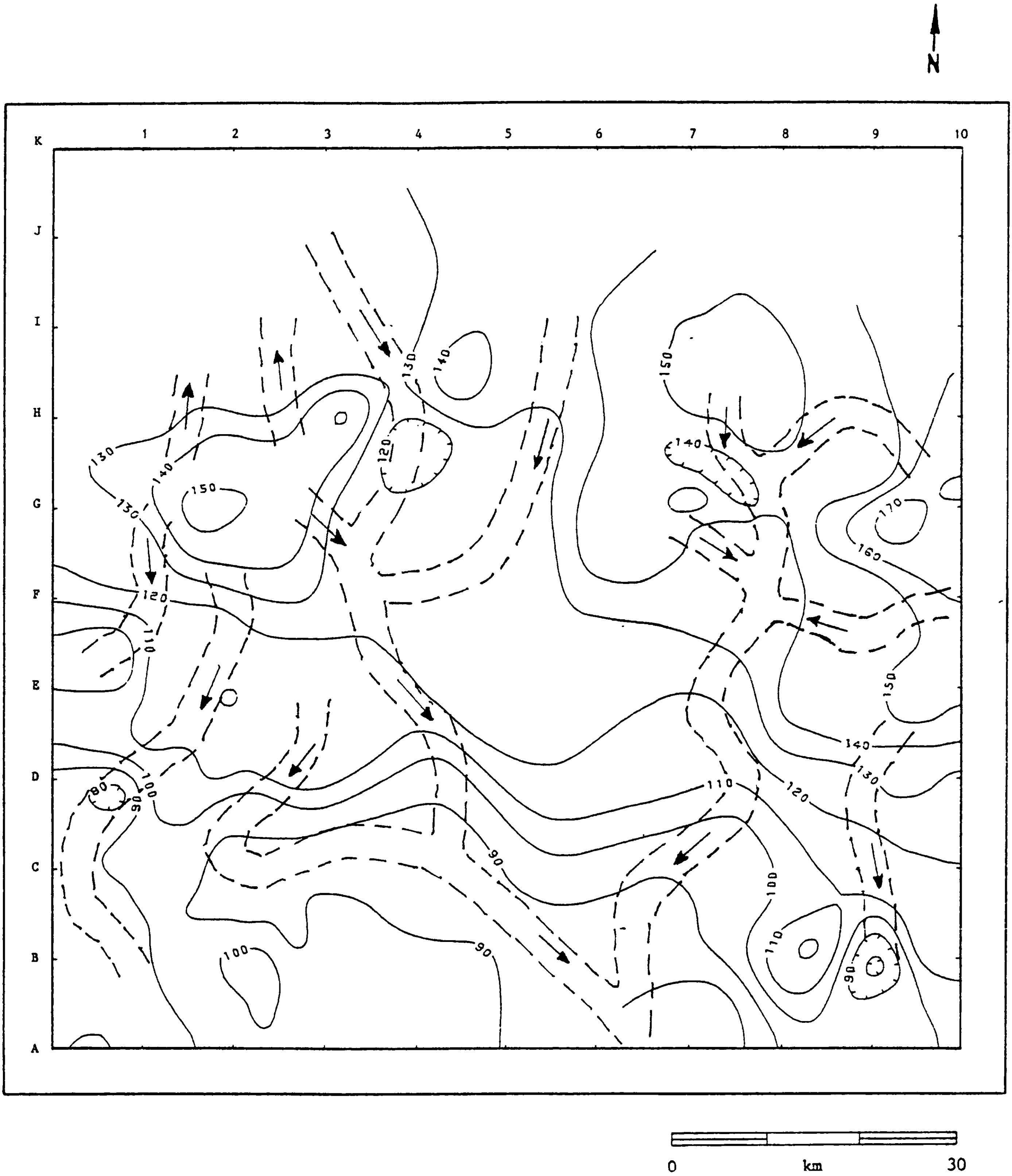


Figure 43 : The floor topography of the No. 4 Upper Seam with the postulated channels.

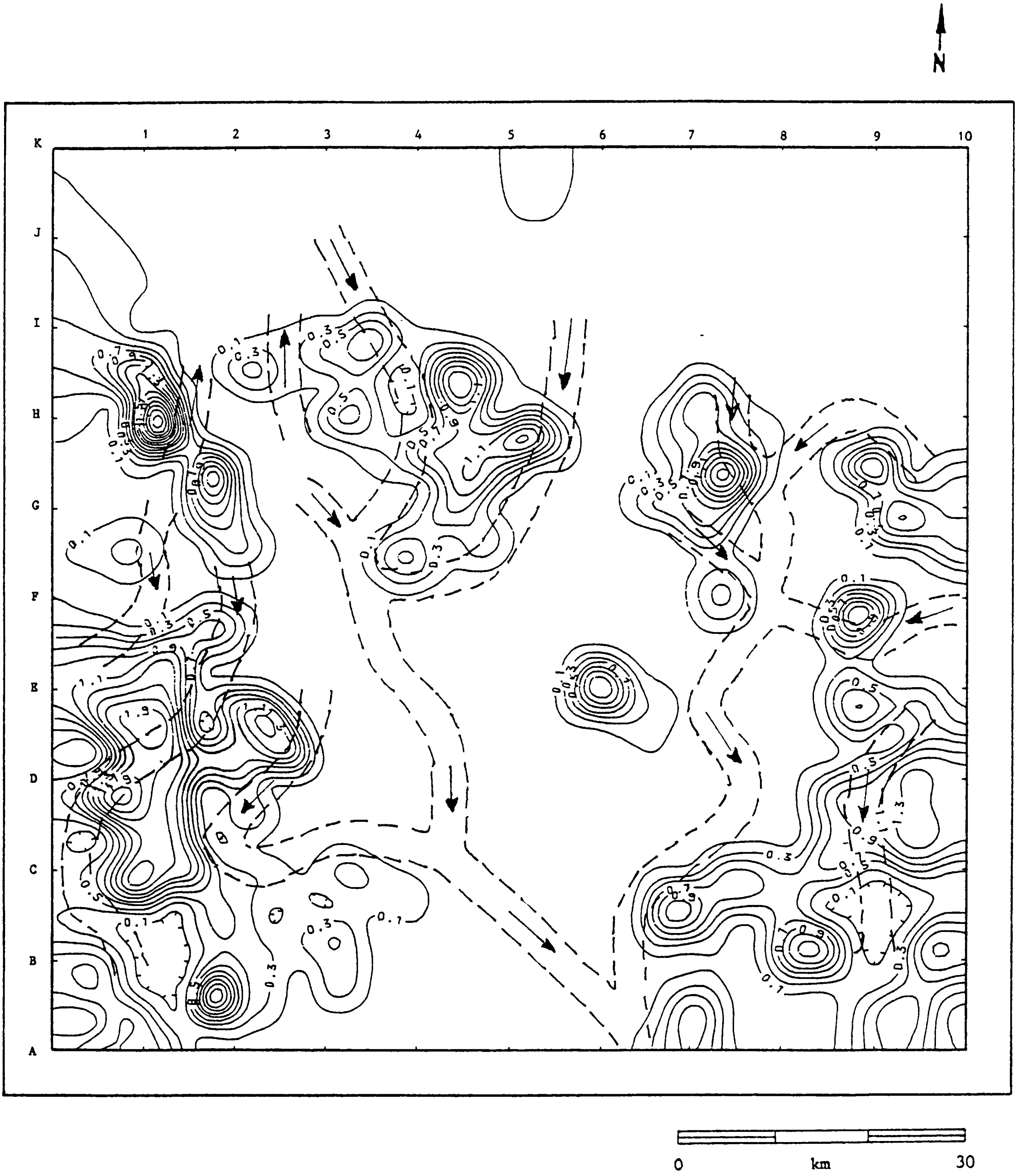


Figure 44 : The thickness (m) and distribution of the No. 4 Upper Seam.

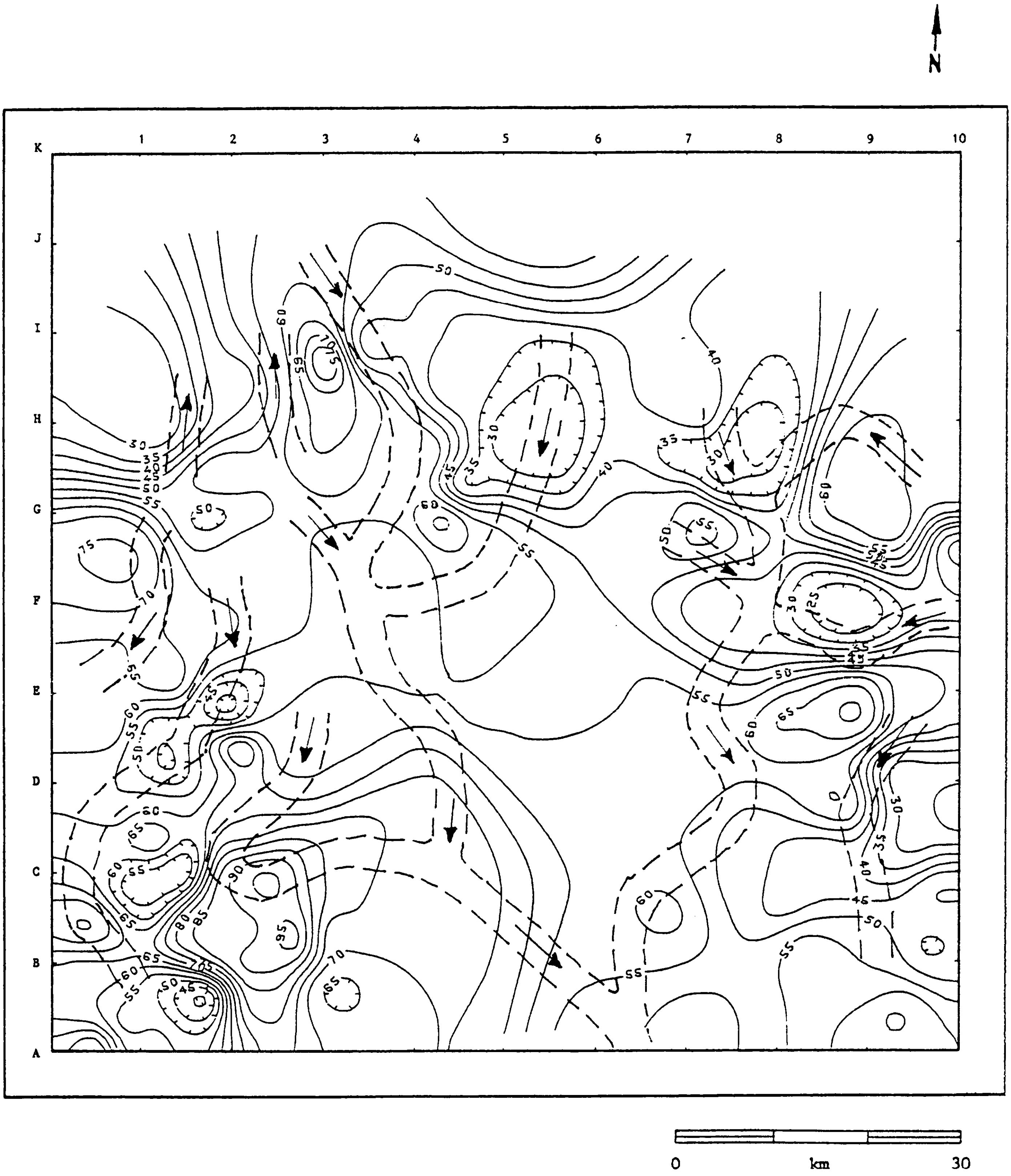


Figure 45 : The vitrinite content of the No. 4 Upper Seam.

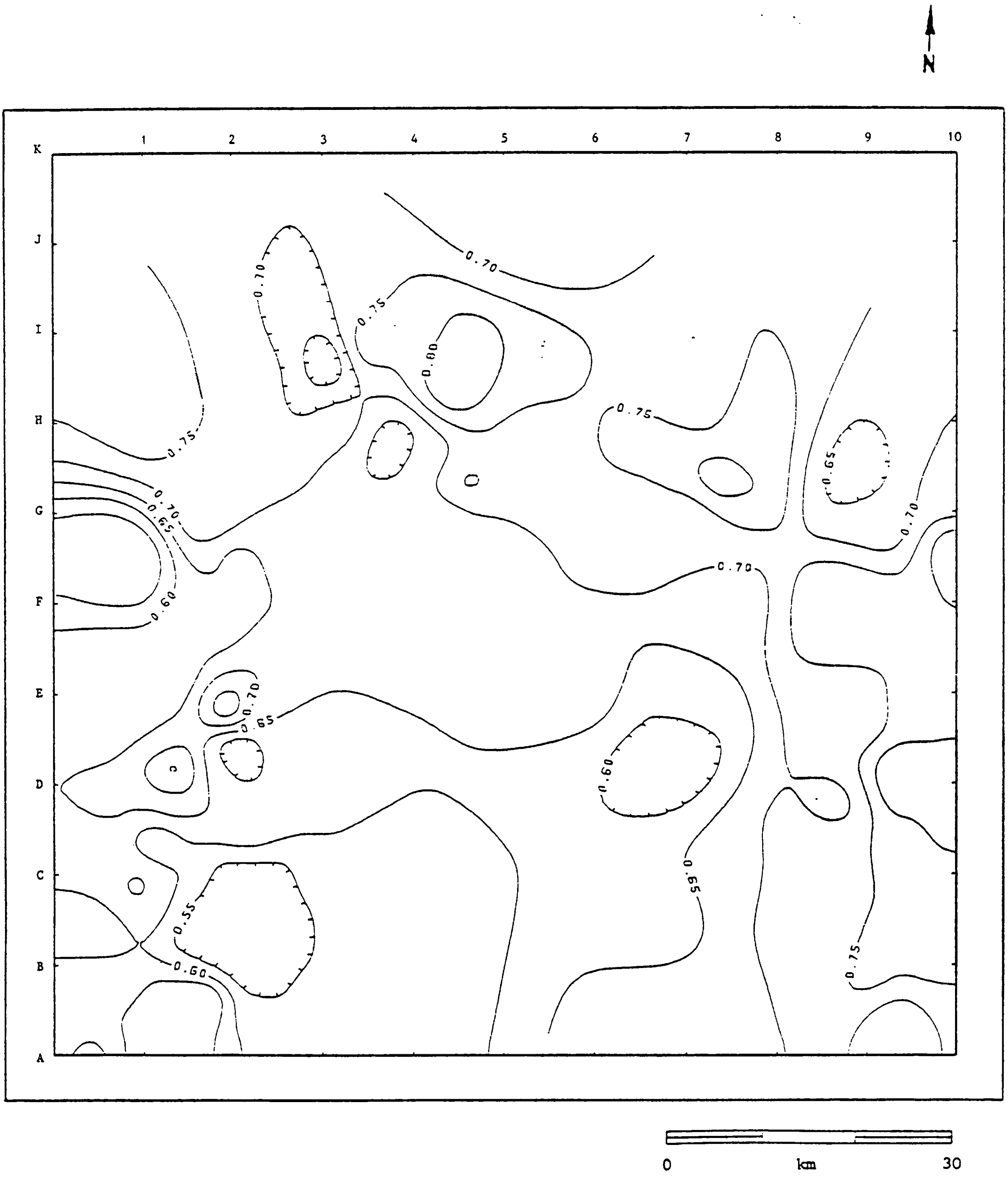


Figure 46 : The % RoV of the No. 4 Upper Seam.

70% in the seam, but the vitrinite-rich occurrence of the coal (e.g. at G10, B2 and I3) is probably mostly of autochthonous origin.

The calculated thickness of the peat from which the No. 4 Upper Seam was formed reaches a maximum of about 10 metres at C1 and H1. Over the central coalfield the peat thickness varies typically from 3 to 7 metres.

The rank of the No. 4 Upper Seam as given by the vitrinite reflectance is typically 0,60% to 0,70%. The exception is the occurrence of the seam in the north-central and eastern areas at H5 and G8 where the RoV of the coal increases to as much as 0,80% (Fig. 46).

6.3.4 The No. 5 Seam

The No. 5 Seam has been of considerable interest to the coal mining industry due to its blend-coking properties. Before erosion it was fairly widespread throughout the study area, but the present-day distribution is limited to relatively high ground (Barker, 1986, p. 105).

The prominent high in the floor of the No. 5 Seam at G3 is still evident and topographical highs are also found at G9-G10, E9-E10 and B8-C9 (Fig. 47). In this regard the floor is similar to that of the No. 4 Upper Seam (Fig. 43). Depressions occur at C9, D1, F9, G4, H3, H9 and I2. Some of these depressions, notably those at D1, C9, F9 and G4-G5, have been largely inherited, especially when compared to the floor topography of the No. 4 Seam (Fig. 30) where more detailed information is available than is the case for the No. 4 Upper Seam.

A south-easterly slope from J1 to G4 appears to be probably less than 1:2000. From G4 to A4 it increases to about 1:1100. In the east, from F7 to B6 the slope is about 1:600. The north-westerly slope from G9 to I6 is approximately 1:300. These variable directions of the slopes suggest that the drainage patterns operating at the time of formation of the older seams do not seem to have played any significant role

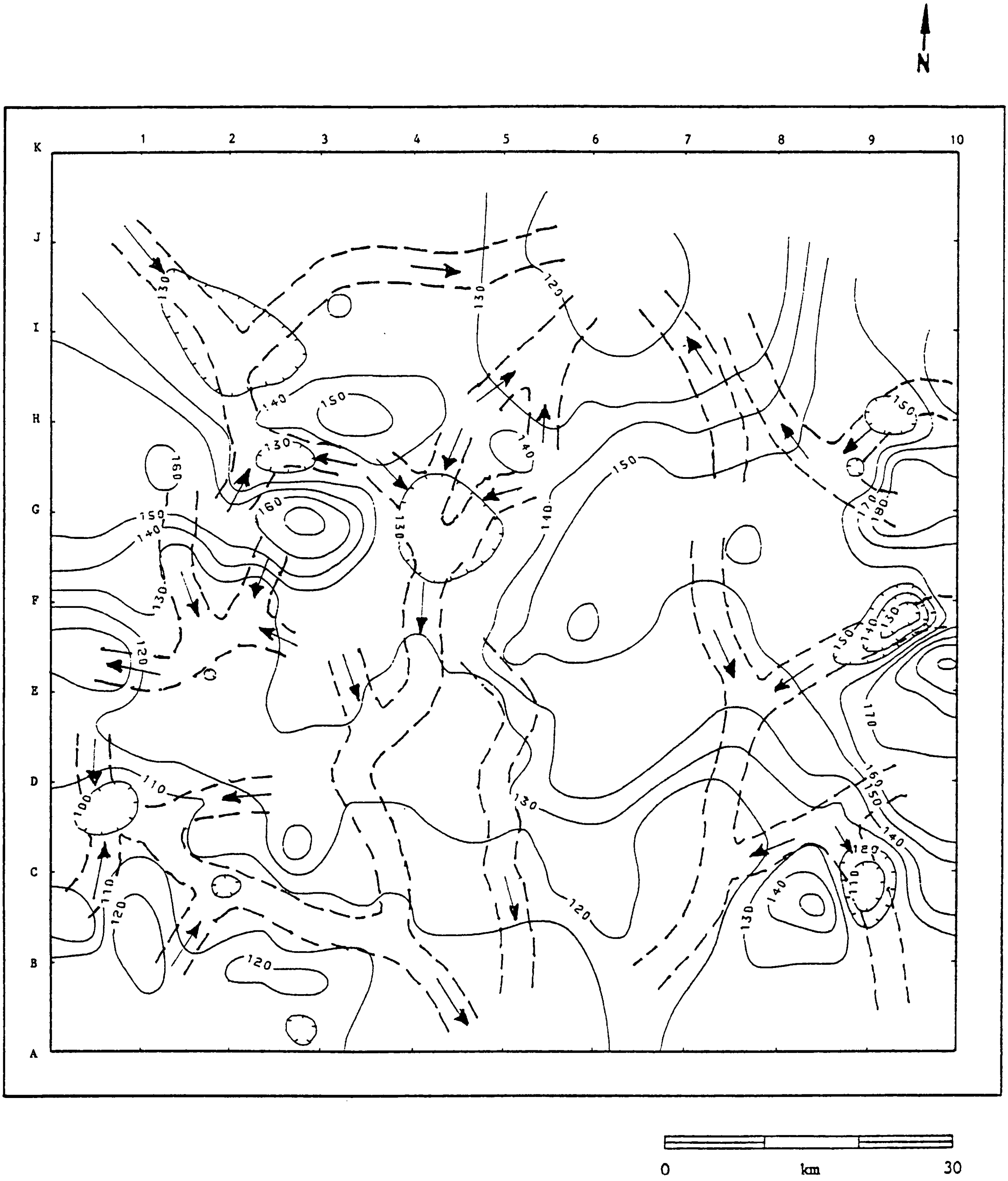


Figure 47 : The floor topography of the No. 5 Seam with the postulated channels.

during the formation of the No. 5 Seam. These low and variable slopes resulted in a complex anastomosing channel system with very low energy streams that flowed mainly towards the south.

Drainage was mostly northerly and easterly in the Witbank area and southerly in the Highveld coalfield with interrupted watersheds roughly at G2, H3 and G7. The channel frequency and channel density appears to have been about 4 per 1000 sq km and 64 km per 1000 sq km respectively.

The seam is only present as stringers or it is absent over elevated areas in the central to eastern portions (Fig. 48, G5-E9). Thicker seam development is seen at G2-H2, G7 and G9. These coals were deposited on slopes and are probably partly autochthonous although their inertinitic character (Fig. 49) suggests a partly hypautochthonous origin. The relatively thick coal seam at B7-C7 and B8 was deposited in depressions and is also relatively rich in inertinite (Fig. 48 and 49). The same applies to the coal deposited in the depressions at E2 and D3.

The No. 5 Seam is generally less than 2 metres thick and the peat was preserved under conditions favourable for vitrinitization, probably in forest swamp environments, even on relatively high ground (E3, E7, C3, B6-C6) (Fig. 48 and 49).

The vitrinite content is generally in excess of 60% and at many places the seam contains 75%-85% vitrinite (Fig. 49, C4, E3 and H2-I2). These localities correspond to areas where the seam tends to be thinner. Almost without exception, the base of the seam contains more than 60%, and more commonly, 70%-80% vitrinite. The upper portion of the seam has a more variable vitrinite content, which ranges between 30%-50% towards the south-west and to the north. In the central and eastern areas, the upper portion of the seam contains 50%-80% vitrinite.

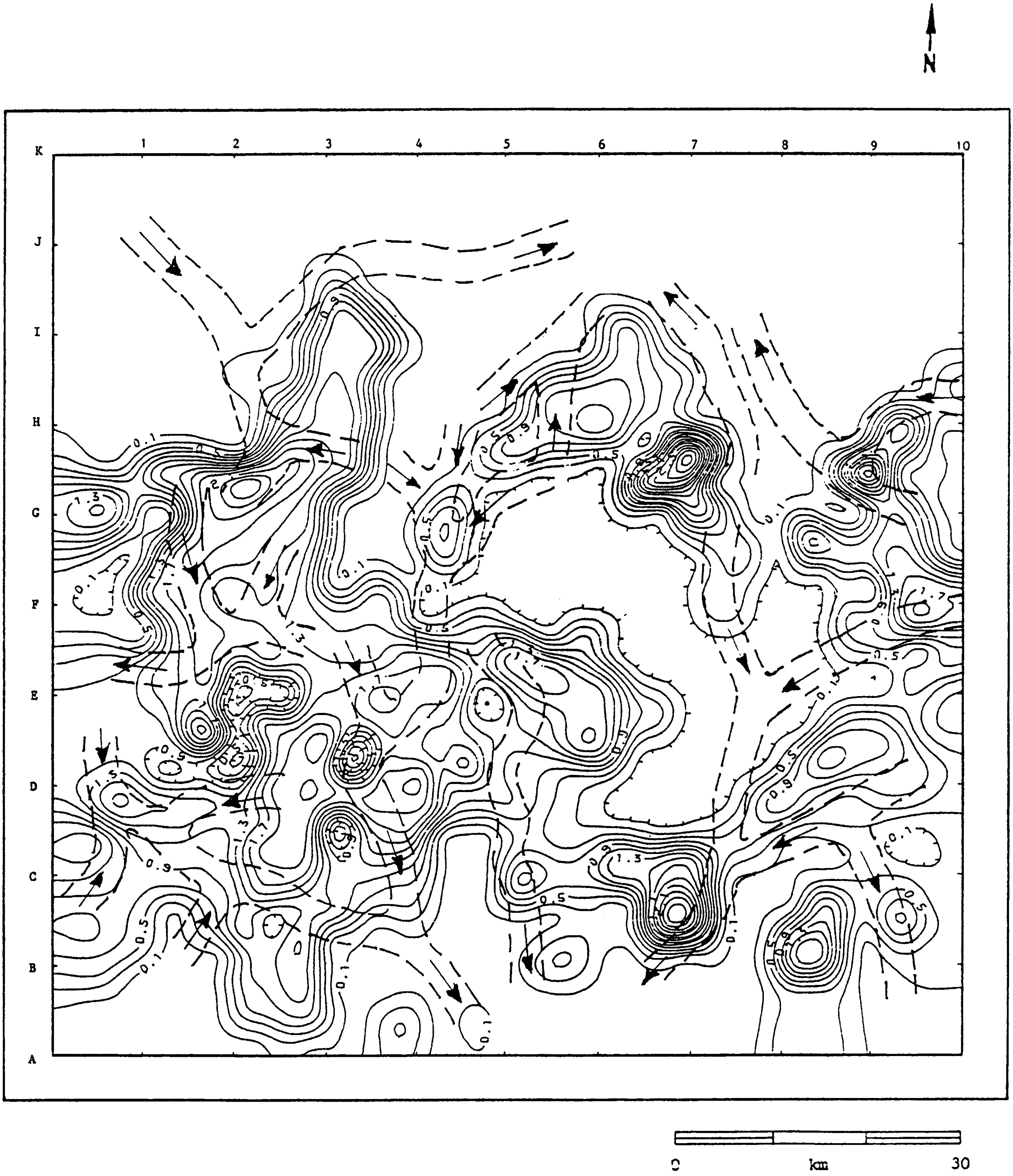


Figure 48 : The thickness (m) and distribution of the No. 5 Seam.

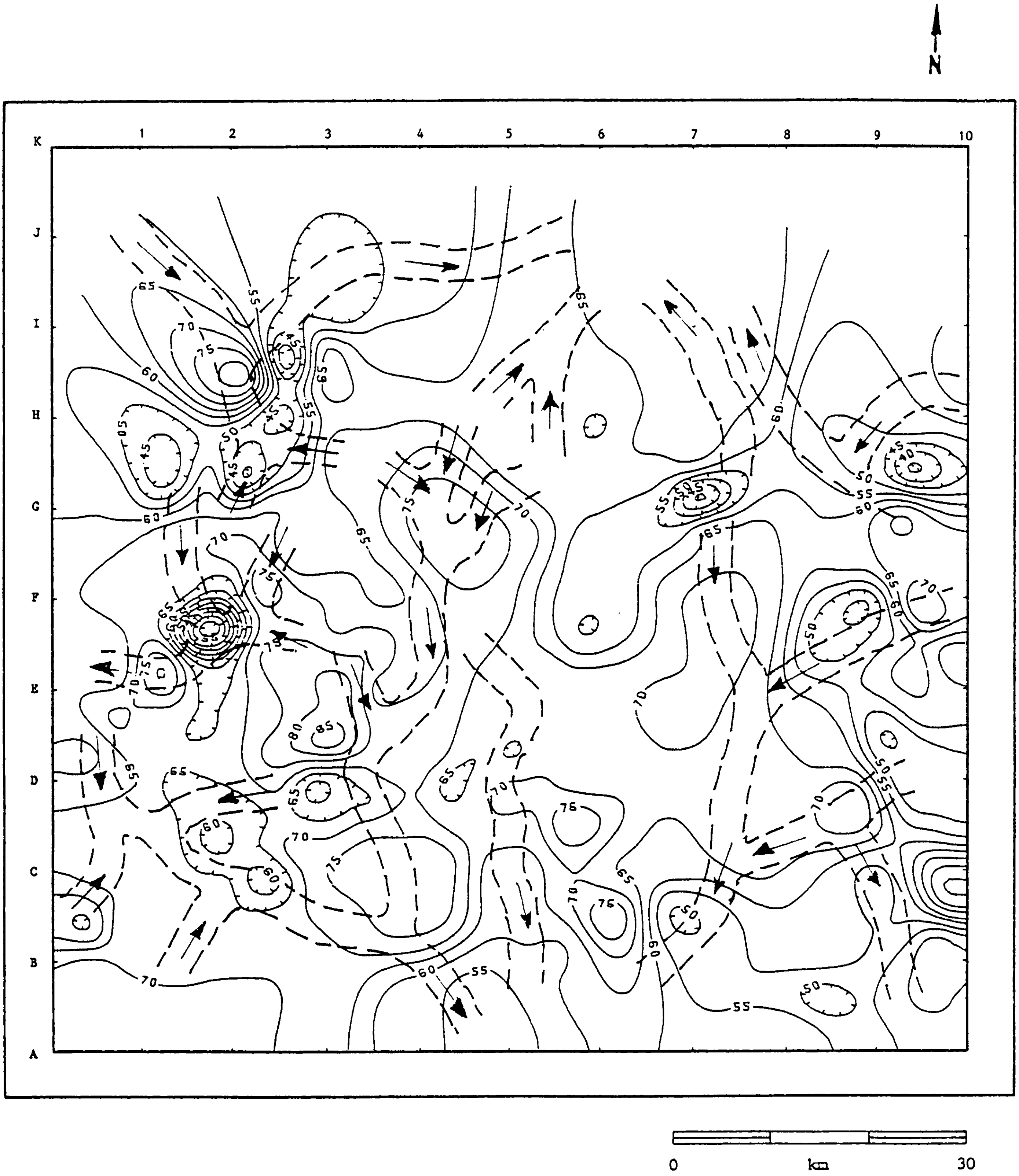


Figure 49 : The vitrinite content of the No. 5 Seam.

Figure 50 shows a petrographic profile through the seam between the points F0 and D6 where the upper and lower portions are of variable thickness.

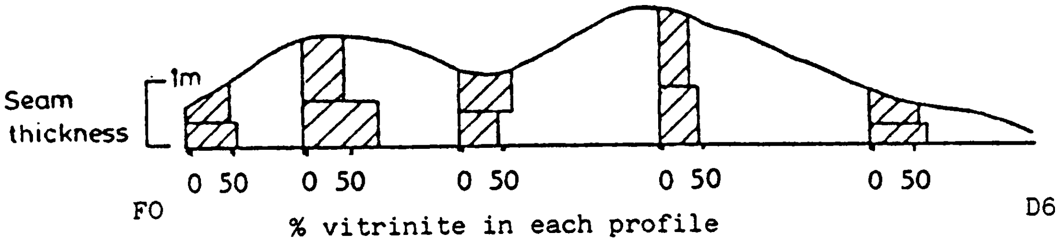


Figure 50 : Schematic vitrinite profile of the No. 5 Seam between F0 and D6.

The calculated peat thickness is almost without exception below 13 m, and generally ranges from 2 m - 10 m. The thinner peats occur mostly in the close proximity of the channel pathways (e.g. E2) or on elevated areas (e.g. G6-H6).

The calorific values are generally lower for the No. 5 Seam when compared to the lower seams. The calorific values are commonly below 32,0 MJ/kg, but may be as high as 33,5 MJ/kg. The exception is the occurrence of the No. 5 Seam at I6 and H7 where calorific values of 34,0 MJ/kg are noted in spite of a relatively low vitrinite content (Fig. 51).

The No. 5 Seam is generally known as a bright coal which is reflected by an almost consistently high volatile matter content, compared to other seams. The volatile matter content typically ranges between 36,0% and 42,0% (Fig. 52) and reflects to a large extent the vitrinite content distribution (Fig. 49).

The carbon content of the seam is generally lower than that of the No. 2 or the No. 4 Seams. This is due to its lower rank. The carbon content ranges from 76,0% to over 82,0% where the seam has been heat affected, but it may increase locally to 84,0% (Fig. 53, F2).

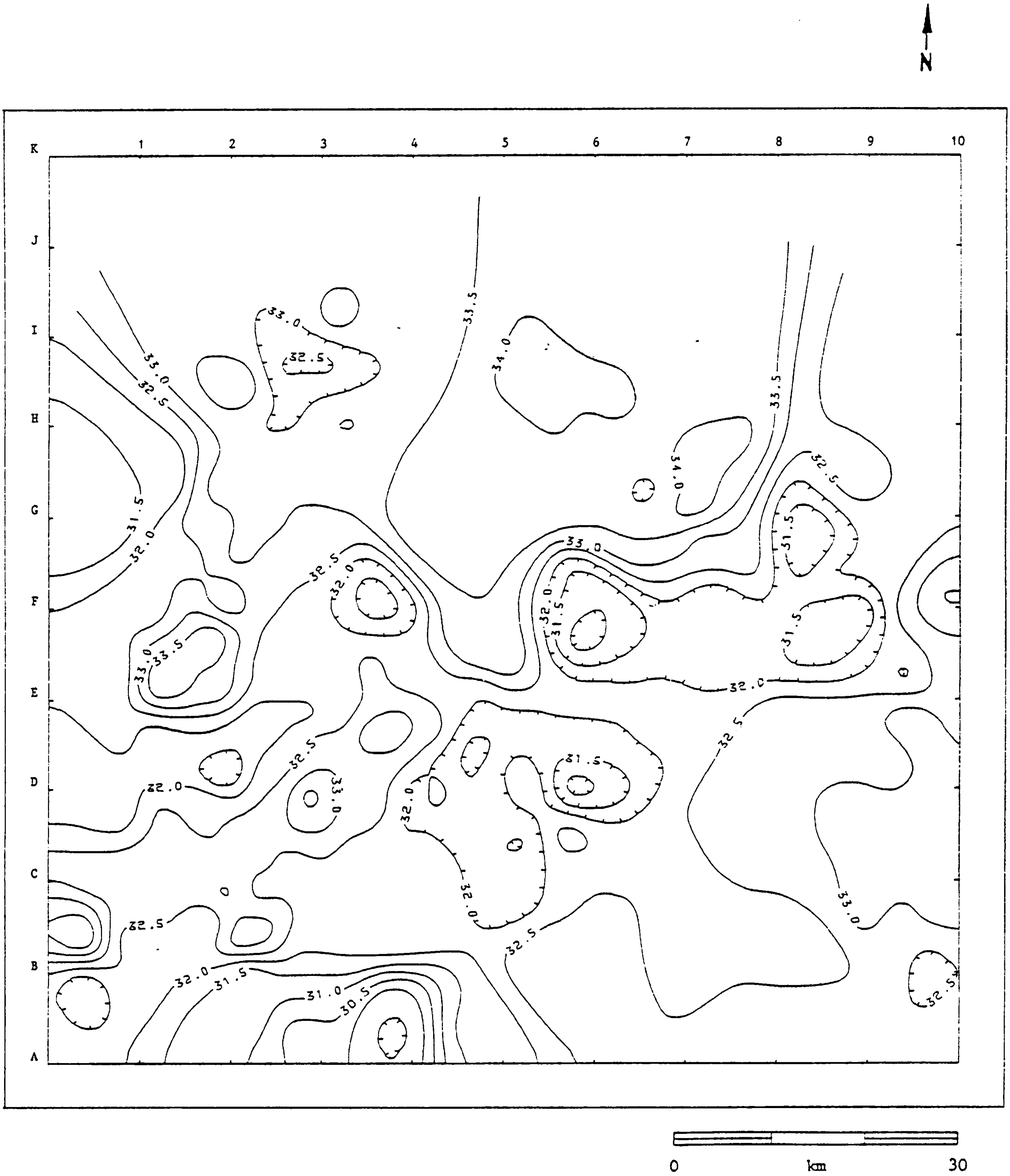


Figure 51 : The d.a.f. calorific value of the No. 5 Seam.

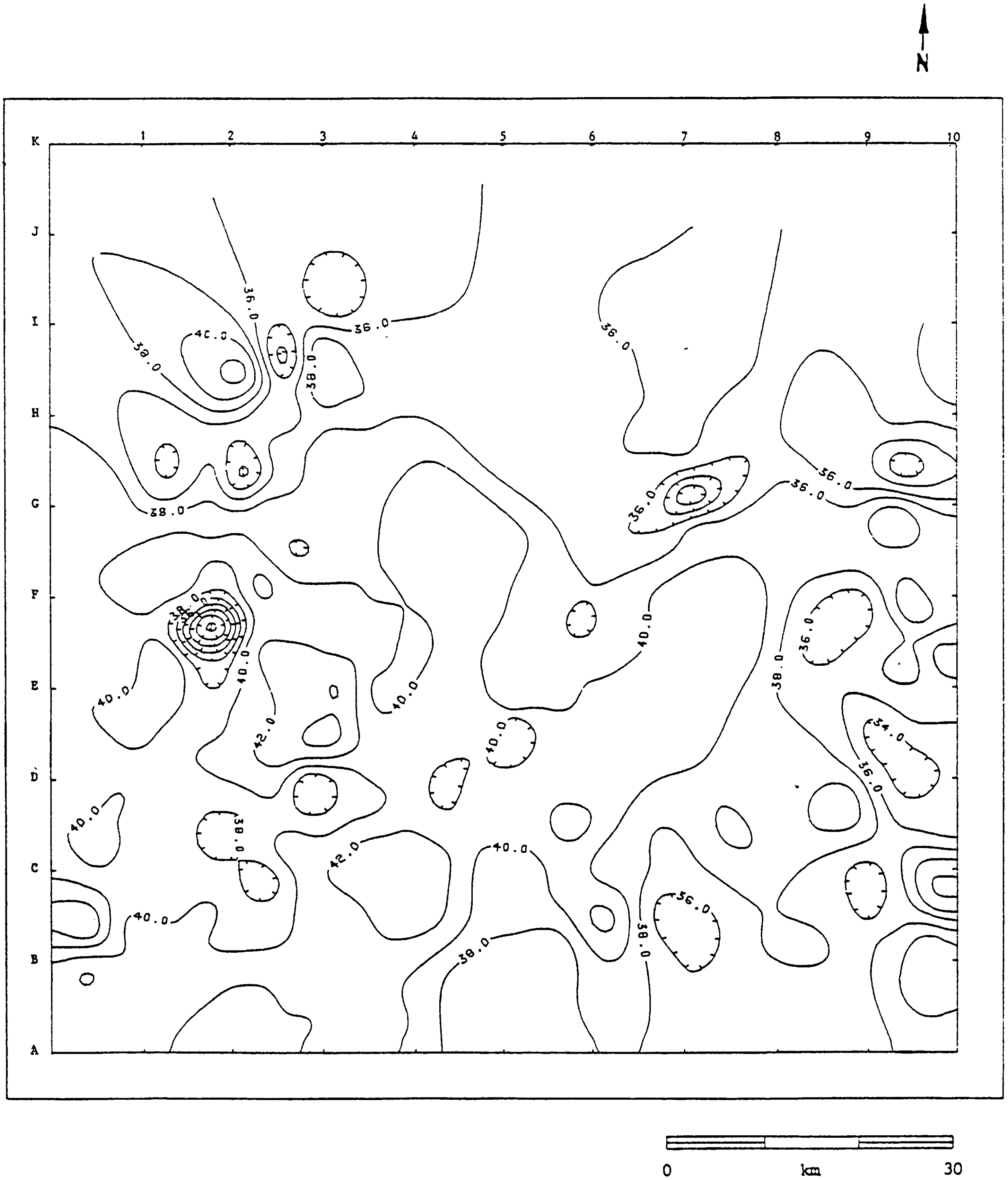


Figure 52 : The d.a.f. volatile matter content of the No. 5 Seam.

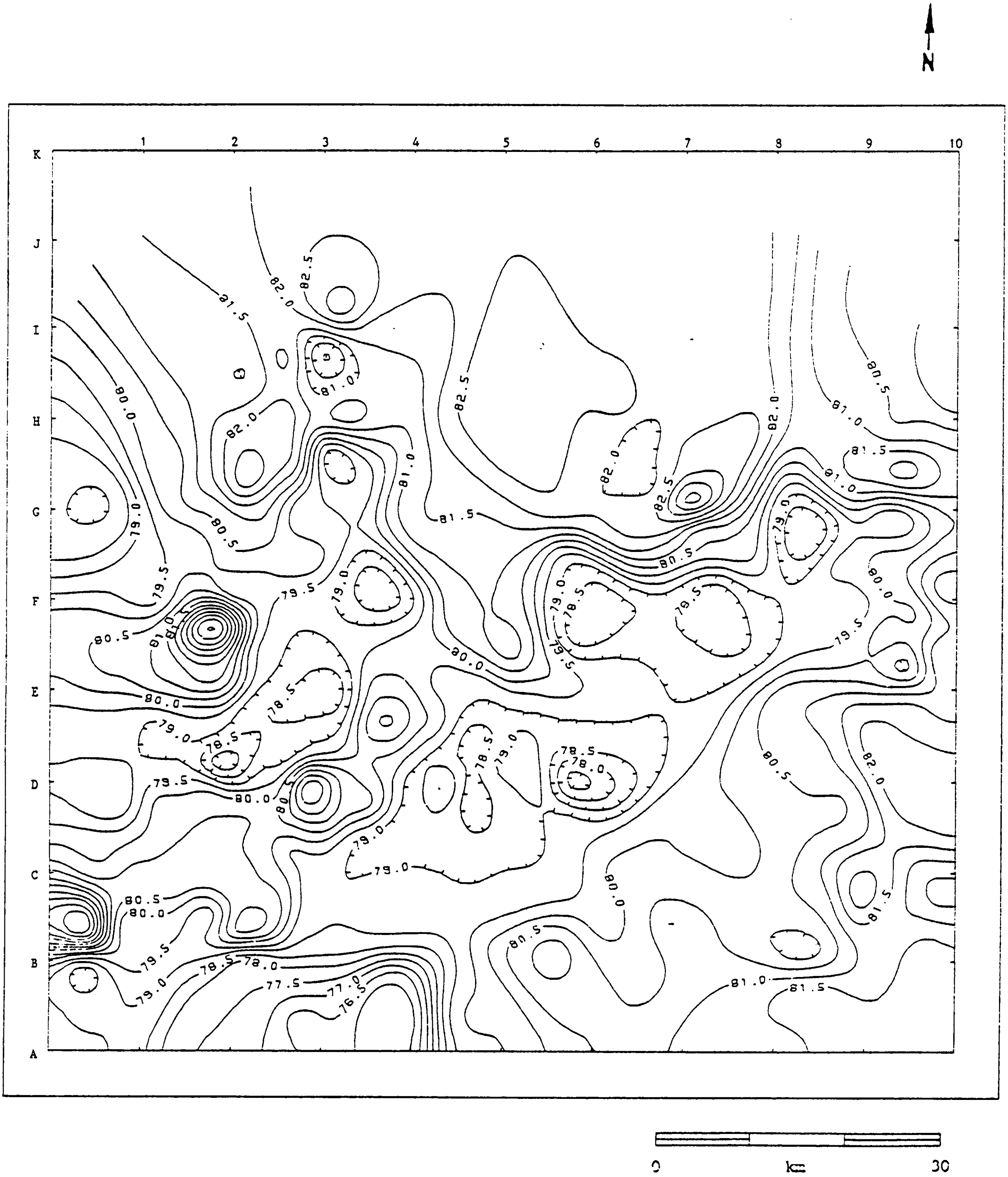


Figure 53 : The d.a.f. carbon content of the No. 5 Seam.

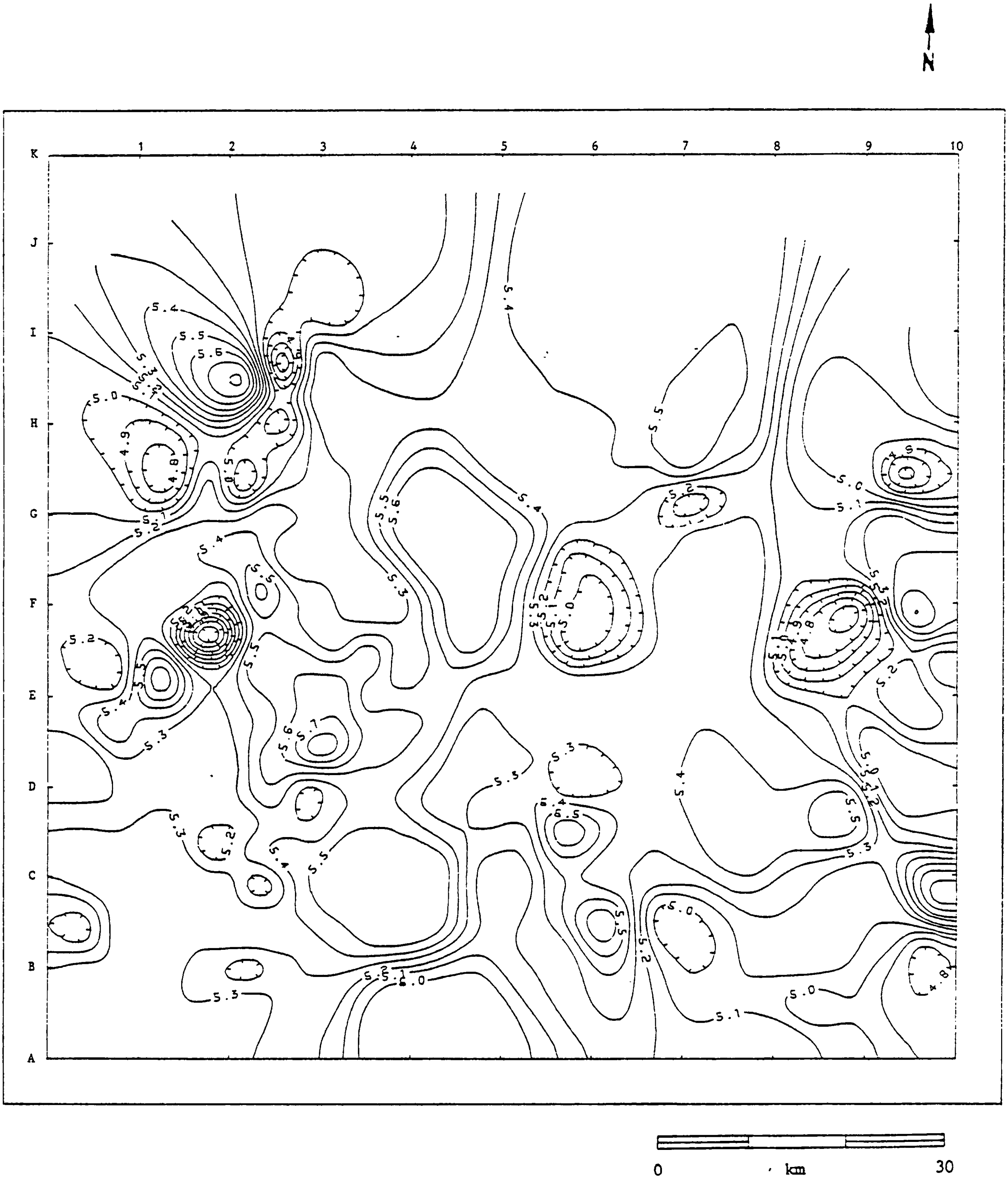


Figure 54 : The d.a.f. hydrogen content of the No. 5 Seam.

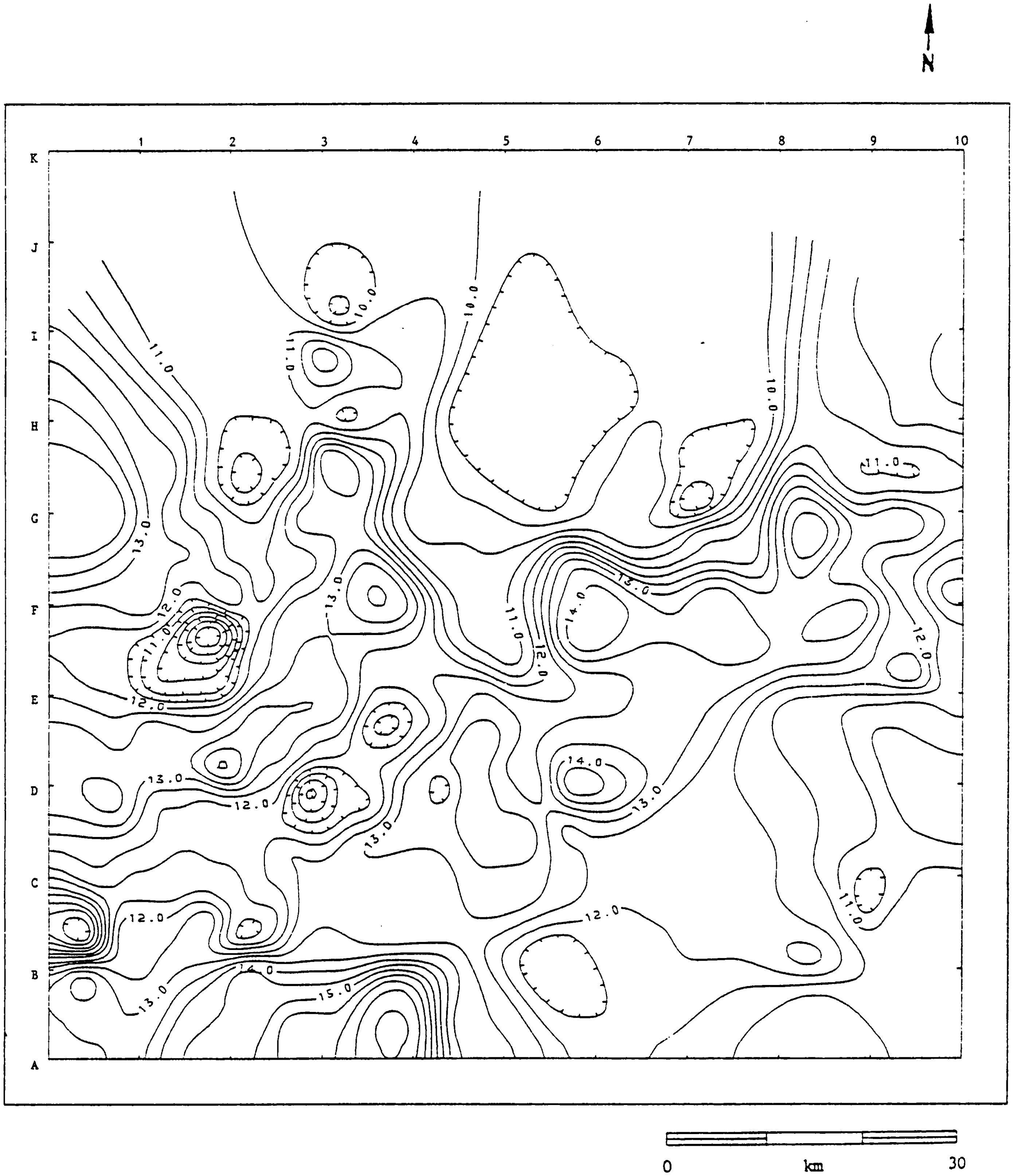


Figure 55 : The d.a.f. oxygen content of the No. 5 Seam.

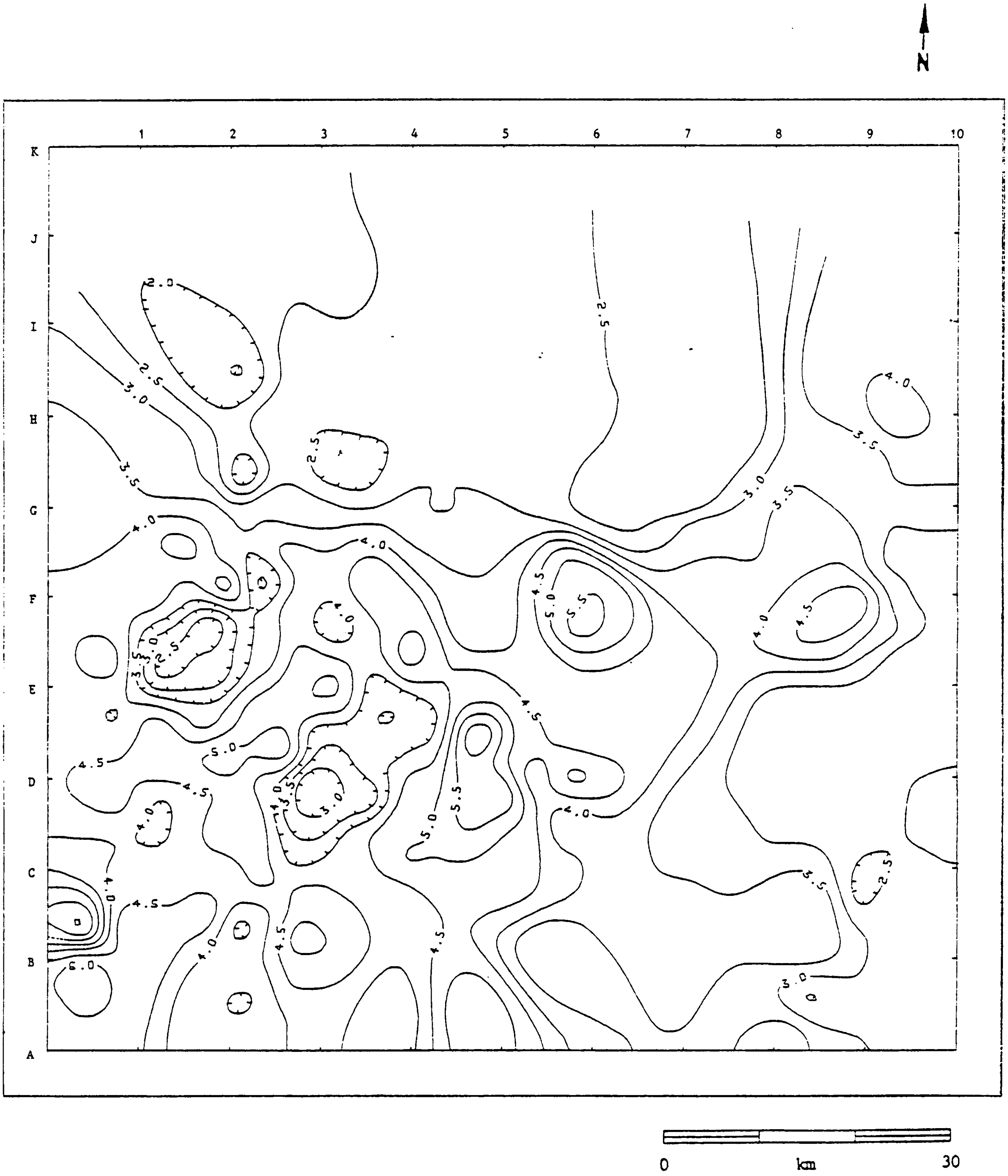


Figure 56 : The inherent moisture content of the No. 5 Seam.

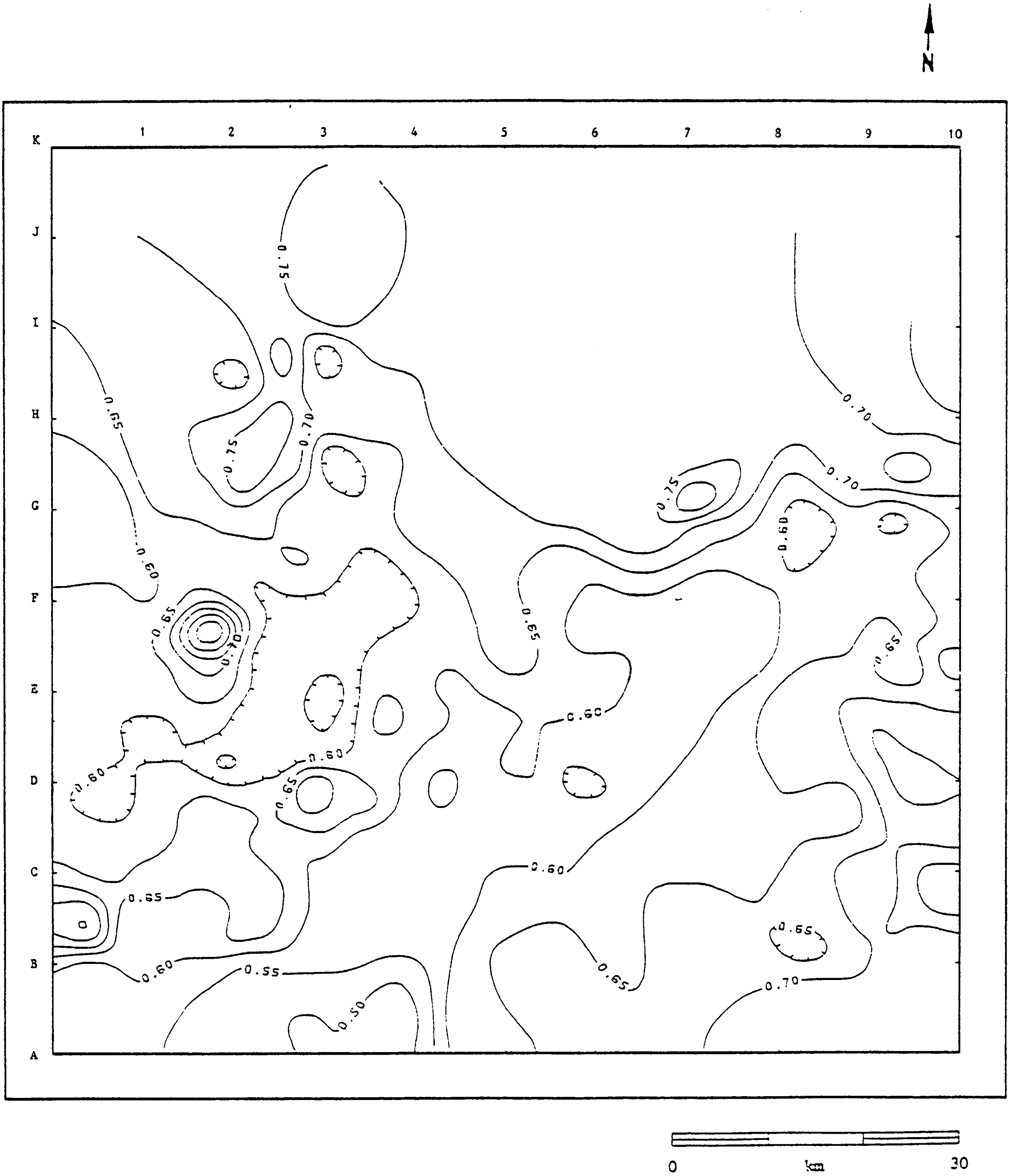


Figure 57 : The % RoV of the No. 5 Seam.

The hydrogen content of the No. 5 Seam typically ranges from 5,0% to 5,6% (Fig. 54). This corresponds to a volatile matter content of about 36,0% to 42,0%. The hydrogen and volatile matter isopleths correspond to the vitrinite type lines. Due to rank changes the volatile matter content is slightly lower towards the north for a given vitrinite content.

The oxygen content decreases from 14,5% to 10,0% in a northerly direction (Fig. 55) which confirms the same trend in increase in the rank.

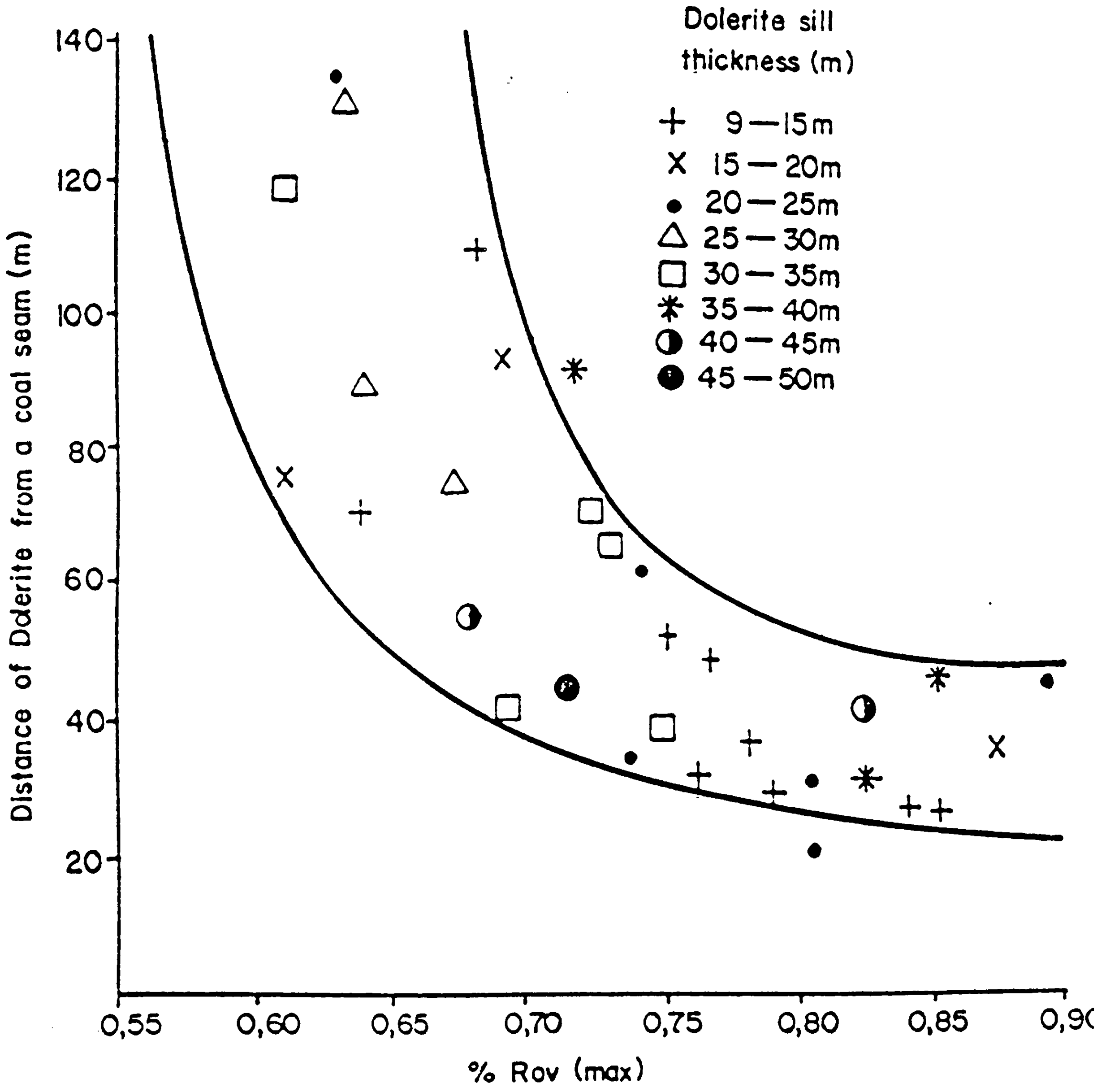
The inherent moisture content of the No. 5 Seam varies from just less than 2,0% in the north-west to 6,0% in the Highveld coalfield (Fig. 57), again reflecting a northerly increase in rank.

The northerly and easterly increase in rank is also clearly substantiated by the % RoV (Fig. 57). The rank of the No. 5 Seam is therefore lower in the Highveld coalfield than in the Witbank coalfield. The higher rank of the No. 5 Seam in the Witbank area may perhaps be attributed to dolerite sills which have existed above the coal succession, which have subsequently been removed by denudation.

6.4. EXTERNAL FACTORS INFLUENCING THE CHARACTERISTICS OF THE COAL SEAMS IN THE WITBANK AND HIGHVELD COALFIELDS

The Highveld coalfield has been fairly severely affected by dolerite sills, especially towards the central and southern portions of the coalfield. Dolerite sills seldom occur in the south-eastern parts of the Witbank coalfield and one or more of the upper seams have been locally eliminated. Dolerite is commonly found above the No. 3, No. 4 or No. 5 Seams.

In most cases, the coal seams appear to be of marginally lower rank in the Highveld than in the Witbank coalfield. However, this rank difference may in some cases be more apparent than real as the weighted average of the reflectance values (given as % RoV) is affected by the inclusion of reflectance values of reactive semifusinite in the reflectogram of vitrinite, as pointed out previously. Vitrinite-poor coals therefore tend to have a higher value of RoV than vitrinite-rich coals although the rank may be the same (Fig. 13 and Fig. 25). Where this northward rank increase had been verified by chemical parameters (e.g. inherent moisture and calorific value) it can only be explained by an increased heat-flow in the north as the frequency of dolerite intrusions cannot explain the increase in rank.



<u>Figure 58</u> : The effect of the thickness and the distance of a dolerite sill from a coal seam on the rank of the coal.

From Figure 58, it is evident that a dolerite does not affect coal over a distance of more than about one to two times its thickness. There are, however, many anomalies in this relationship. This may be due to variations in the initial temperature of intrusions and the heat conductivity of the intervening strata. The relationship has been established from 32 cases for an RoV below 0,90%. The thickness of the intrusions varied from 9 m to 47 m. Comparing the distance of the dolerite from the coal to the % RoV, a band was constructed which satisfied most of the cases studied. Higher % RoV values may be the result of the high inertinite content of the samples. In view of this RoV values for coals unaffected by dolerites might range from 0,60% to about 0,75%. Only values above 0,75% RoV may be considered to represent dolerite affected coals.

7. CONCLUSIONS

Based on analytical data from various sources, petrographical and dry ash-free chemical parameters were obtained or inferred for the seams in the study area.

The paleotopography of the pre-Karoo basement appears to have had a dominant effect on the paleoenvironments in which the succession of coal seams were formed. The influence of the basement topography is apparent in all the coal seams.

Towards the north of the present Witbank coal basin, a stable shelf provided a setting for a succession of major channel complexes. Clastic sediments were deposited southwards in the study area. These sediments, up to 90 m in thickness, formed a wedge between the pre-Karoo basement and the No. 2 Seam. The resultant smoothing of the basement created a setting which was favourable for the development of the No. 2 and subsequent seams.

Paleotopographical highs provided a protected environment for seam development in the Witbank coalfield. Clastic sediments accumulated towards the south-western and south-eastern portions of the study area, resulting in areas devoid of coal.

Major channel complexes which existed during the formation of the various seams have been postulated. The channel routes have been derived from the seam floor topography, supplemented by seam thickness and distribution as well as the petrographic characteristics of the seam. Calculated peat thickness and peat roof topography tend to confirm these postulated channel routes.

Channel areas are generally associated with thinner coal except in local depressions where the seams may have an above average thickness. In both cases the seams are rich in inertinite which formed by redeposition of eroded peat. These coals are inertodetrinitic and of hypautochthonous origin. These coals are richer in allogenic minerals such as kaolinite, normative rutile and quartz. A low energy regime in the channels is inferred from the settling velocity of fine grained quartz particles. Flow rates were mostly less than 11 metres per hour over gradients of about 1:1000.

Thicker vitrinite-rich seams generally formed in forest swamps on relatively elevated ground between the channels. The rapid accumulation of plant debris led to good preservation conditions allowing large-scale vitrinitization of the peat. Coals formed under these conditions are of autochthonous origin.

The No. 1 Seam is only present in the Witbank coalfield and has its best development in the northern central part of the basin. The seam is locally thicker where it abutts against the topographical highs.

The No. 2 Seam is extensively developed except along the northern margin of the basin, and in the south-western and southern portions of the Highveld coalfield it is shaley or absent due to the dominance of clastic sedimentation. Its thickness typically varies between 2 and 8 metres. In one extreme case, it reaches a thickness of over 12 metres. The No. 2 Seam is characterized by two or more benches. The seam generally has a vitrinite-rich basal portion where it developed between channels. The reverse is mostly true within channel areas where the seam is richer in inertinite. The seam has a vitrinitic character towards the southern limits of its development and also towards the east where indications of brackish water and stable conditions existed and the peat was therefore better preserved. Elsewhere, the coal generally has a vitrinite content of below 50%, especially in the Witbank coalfield.

The No. 3 Seam is laterally impersistent and has its best development in topographically depressed areas. It is generally less than a metre thick and with few exceptions has a high vitrinite content between 50% to 80%.

The No. 4 Seam occurs throughout the study area, except along the northern periphery of the basin. It is generally thicker in the interchannel areas where it has a vitrinite-rich basal portion. Within the channel regions the seam is thinner and inertinite-rich towards its base. The seam thickness typically varies from 1 to 5 metres, although it may also be thicker. A characteristic feature of the No. 4 Seam is its variable petrographic character. The Witbank and Highveld areas can be divided into rather distinct north-south trending zones, of alternating inertinite-rich and vitrinite-rich coal. The inertinite-rich areas of the seam contain variable amounts of inertodetrinite indicating a predominantly hypautochthonous origin. The vitrinite-rich coal, mainly in the top of the seam may be of autochthonous origin. This has recently been confirmed by microscopical investigations.

A zone containing various minor seams occurs above the No. 4 Seam. The No. 4 Upper Seam is the most prominent and is best developed towards the eastern and western boundaries of the study area. It is absent in the central and southern portions of the area where it merges with the underlying No. 4 Seam. The No. 4 Upper Seam is generally thin and is predominantly vitrinitic.

The No. 5 Seam occurs over a large portion of the Witbank and Highveld coalfields. The seam thickness varies from a few centimetres to as much as 3 metres, but mostly attains a thickness between one and two metres. The seam is better developed in areas of lower relief in the central and western portions of the study area. Peat was preserved under conditions favourable for vitrinitization so that the vitrinite content of the seam is mostly in excess of 60%.

A common characteristic of all the seams, with the exception of some areas of the No. 4 Seam, is that a vitrinite-rich basal portion grades upwards into a more inertinite-rich coal. Similar cycles may be repeated several times within a seam. Coals formed in interchannel areas tend to be richer in vitrinite than coals formed in channel areas. In the former the peat was preserved in brackish water with a moderately high pH and a limited oxygen supply due to the rapid accumulation of plant material.

Inertinite-rich coals are indicative of aerobic, acidic conditions under which the peat was partly oxidized. This could have taken place _in situ_ in the case of macrinitic, semifusinitic and fusinitic coals. However, in the case of inertodetrinitic coals the oxidation must have taken place during the transport of eroded and broken up peat that had previously been partly vitrinized. The redeposition of this eroded peat as inertodetrinite took place in relatively low-lying areas of the peat swamp.

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