# Geological and geotechnical factors controlling the occurrence and flow of methane in coal seams

by
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## ABSTRACT

The reliability of the methods applied both in predicting and controlling methane emissions in coal seams and in predicting the performance of surface degasification boreholes is dependent upon the accurate characterisation of coal seams as reservoirs. Research into the gas contents of coal seams in Britain have shown that the methane content depends on the rank, stratigraphic history, geological structure and petrographic composition of the coal.

Gas pressure and permeability are the two main reservoir properties governing the release and flow of methane through coal seams. Geotechnical parameters such as overburden pressure and mining induced stresses affect both the matrix and fracture compressibility of coal seams and can increase or decrease the permeability by orders of magnitude.

The paper reviews the geological and geotechnical mechanisms controlling the reservoir characteristics of coal seams. The results of research into pre- and post-failure permeability behaviour of British coal seams are discussed and the developed stress permeability relationships presented.

## INTRODUCTION

This paper reviews research findings on the geological and geotechnical processes which influence the gas bearing and transmission properties of British coal seams. The research has led to a greater understanding of the geological controls on seam gas content and facilitated the development of computer modelling techniques for predicting gas emission behaviour in strata disturbed by mining.

Although the results of investigations refer to British coal seams, the basic principles are universal, only the magnitudes of effects being coalfield or site specific.

## THE ORIGIN OF COAL SEAM GASES

Under the influence of normal geothermal temperature the composition of plant remains systematically change with depth and time liberating gases as by-product of the reactions. This process, known as coalification, represents a continuum starting from peat, passing through the lignite and brown coal stage into the high, medium then low-volatile bituminous region and culminating with anthracite. It has been estimated that up to 1300 $m^3$ of various gases were generated per tonne of coal produced during the coalification process (Patching, 1970). The methane-rich thermogenic gas generated from bituminous and anthracitic coals is known as firedamp. Firedamp, as encountered in Britain, consists of 80 to 95% methane but also contains higher alkanes, nitrogen and carbon dioxide with traces of argon, helium and hydrogen.

The proportion of heavy alkanes appears to decrease with increase in coal rank, the heaviest hydrocarbons disappearing first followed by progressively lighter hydrocarbons (Gedenk, 1963). It is no surprise, therefore to find that the ratio of ethane to methane in coal seams tends to decrease with increase in coal rank (Figure 1). Scatter is due to local enhancement of ethane and higher alkanes from petroleum sources and also due to fractionation when, at some time in their history gases have migrated along the seams.

Anomalously high concentrations of ethane and higher hydrocarbons occasionally encountered in coal seams, often in close proximity to faulting, probably represent migrating petroleum derivatives "captured" by the coal. A close association between methane of coal seam origin and petroleum related gases is not unexpected as the temperature conditions favourable to the generation of oil from organically rich sediments falls within the high-volatile coal rank range.

Theoretical volumes of gaseous coalification products can be calculated at various rank stages from coal analyses. Methane production in the high-volatile bituminous to anthracite range of more than 200 $m^3/t$ has been estimated (Juntgen and Karweil, 1966) although this figure could be reduced if account is taken of alkanes heavier than methane. Nevertheless it is generally acknowledged that quantities far exceed the quantities of gas now found in coal seams.

The volumes of gas now found in the coal seams are therefore considered to represent the difference between the gas formed during burial and the gas subsequently lost over geological time.

## GEOLOGICAL CONTROLS ON SEAM GAS CONTENT

The effect which ancient erosion periods have had on seam gas contents of mature seams has been studied in detail in Britain. In evaluating seam gas reservoir potential, erosion history and rank are the two most important factors to consider.

Methane contents of British coal seams generally show a systematic relationship with vertical depth, a tendency to increase with coal rank and a decrease on approaching the ancient Permo-Carboniferous erosion surface. The latter observation can be explained by in-seam migration of methane to the surface during the erosion period, prior to cleat mineralisation and subsequent reburial (Creedy, 1988); the thickness of sediments deposited on the deeply eroded Coal Measures was insufficient to initiate secondary coalification. A diagrammatic section across the East Midlands coalfield showing the relationship between seam gas content and the unconformable base of the Permian strata is given in Figure 2.

The effect was compounded in the Kent coalfield by the occurrence of significant erosion periods during the Permo-Triassic and the Cretaceous periods. The paucity of gas despite the relatively high rank (medium to low volatile) is therefore not unexpected.

A relationship between erosion history and seam gas content is not unique to Britain. A similar process may explain the occurrence of coal seams containing less than 2 litres/tonne methane at depths approaching 400 m in Bangladesh where coals of Permian age are buried beneath some 100 m to 150 m of Miocene sediments (Norman, 1992). The period over which gas loss could have occurred was 260 million years.

Structural controls in the form of folding and faulting are important in that they largely determine the seam outcrop pattern during erosion and may also modify rank-depth-gas content relationships. Faulting affects the continuity of coal seam reservoirs.

Igneous activity can result in major changes to the gas reservoir. For example, in parts of Australia variable amounts of carbon dioxide, introduced into coal seams displacing some or a large part of the original firedamp, has been attributed to intrusive igneous activity (Smith and Gould, 1980). Methane desorption from coal is substantially enhanced in the presence of carbon dioxide (Creedy, 1985) which not only explains the apparent replacement of methane by carbon dioxide but also suggests a potential technique for enhancing methane recovery from post or pre-drainage methane drainage boreholes. In the North-East of England a series of coal seams in a particular area have been virtually totally degassed possibly as a result of local geothermal activity. Although there is a circumstantial spatial association with igneous dykes, for them to be responsible implies an unprecedented range of thermal influence. Research into the anomaly continues.

## THE GAS STORAGE POTENTIAL OF COAL AND COAL SEAMS

### Sorption properties

Much larger volumes of gas can be accommodated within the coal substance than could be held by simple compression of a gas due to a process known as adsorption. For a particular temperature the quantity of methane q adsorbed at a pressure P can be represented mathematically by the Langmuir isotherm: [1]

$$q = \frac{AbP}{(1 + bP)}$$

where A and b are constants; A being defined as the (maximum) methane capacity.

The capacity of a coal to adsorb methane increases with coal rank but is reduced with increase in moisture content and increase in temperature. The adsorption properties of coal also depend on petrographic composition (Creedy, 1979).

The term "sorption" is commonly used to represent the adsorbed gas together with the free gas occupying macropore or fracture space within the coal substance. If using a gravimetric method to determine sorption isotherms it is important to recognise that the measured coal density may be under-estimated, and hence the internal fracture space overestimated due to the relaxation of the coal sample after removal from the seam.

The sorption characteristics of the coal substance fundamentally influence seam gas content and goes some way towards explaining why similar ranks of coal exhibit similar ranges of gas content in different countries and different geological environments.

The methane sorption capacity (A) of a coal effectively places an upper limit on the gas content of the seam; excessively high gas pressures would result if the value was exceeded, far beyond any recorded in practice. The limiting capacity is probably that obtaining at the maximum temperature reached during burial. Figure 3 illustrates the effect of elevated temperature on methane sorption capacity for coals of two different ranks.

Coal samples must not be allowed to lose their natural moisture if sorption results representative of in-situ coal are required and the measurements should be conducted at a temperature commensurate with the strata temperature or an appropriate correction applied. Experimental work on gravimetric sorption measurement, conducted by Creedy, indicated that moisture losses could be minimised by cooling coal samples to 4°C prior to evacuation. Some results indicating the likely trend of the methane capacity of coal retaining its in-situ moisture with coal rank are shown in Figure 4.

### Coal seam reservoirs

British coal seams can be excellent gas reservoirs in terms of storage capability but poor producers unless disrupted by strong tectonic activity or disturbed by mining.

Artificial stimulation of methane flow from virgin seams by hydraulically inducing fractures and then propping them open with sand has met with economic success in some parts of the USA. The economics of such technology have yet to be established in Britain but geological favourable locations are being sought.

### Natural gas reservoirs

Although coal seams provide the most consistent reservoirs of firedamp, free gas which has migrated from a coal seam source at some time in the geological past may be encountered in non carbonaceous horizons associated with structural or stratigraphic traps. Free gas reservoirs, of no commercial value, in well-jointed sandstones or limestones have occasionally been disturbed by longwall coal mining giving rise to abnormally high methane flows in the underground environment.

Free gas methane reservoirs in the North Sea Basin are of considerable economic importance to Britain. The zones in which most gas has been found appear to be adjacent to areas where uplift resulted in deep Permo-Carboniferous erosion of the coal bearing strata and where the seams have matured the most as a result of late deep burial i.e.., secondary coalification has occurred. On land the gas content of coal seams approach zero at subcrop beneath the Permo-Triassic cover in the absence of sufficient post Permian cover to promote secondary coalification.

Abandoned coal mines are a special case of free gas reservoir, the source being the continuing but decaying emission of methane from old waste areas. High methane pressures and purities have occasionally been experienced on intersecting old mine workings, even at shallow depths, presumably as a result of hydraulic pressurisation caused by partial flooding in the absence of provision for venting.

## THE GAS EMISSION PROPERTIES OF COAL AND COAL SEAMS

Lumps of coal weighing a few tens of grammes, freshly sampled from British seams, typically exhibit low rates of gas emission. For example, a solid crack-free fragment of high-volatile bituminous coal of about 40g may take from 2 weeks to more than 9 months to desorb 2/3 of its initial methane content. The emission rate depends on the degree of internal fracturing within the fragment, the rank, composition and ambient temperature. Any comminution during handling leads to an increase in emission rate.

Theoretical rates of methane diffusion in an idealised continuous solid virgin coal seam are extremely slow. For example, diffusion over a distance of about 12m at a temperature of 20°C would take about 50 million years. Clearly, for gas to flow through a coal seam an open fracture or cleat network must be present.

The ability of a seam, which has not been disturbed by mining, to release gas depends on the inherent gas pressure, the transmissivity of the cleat and the degree of water saturation.

### Seam gas pressure

Seam gas pressure data obtained via methane sorption isotherms appears to indicate that British coal seams are generally under-pressured. However, values obtained in such a way have sometimes not been borne out by borehole testing in the USA although the error could have been in the adsorption isotherm measurement method or in the in-situ testing method. Seam gas pressures in Britain are usually less than one fifth of the hydrostatic pressure with the exception of parts of North Wales where pressures approaching hydrostatic have been encountered.

The occurrence of normal and over pressured seams in the USA, for instance, implies an interconnected cleat or fracture network. Localised reduction of fluid pressure by dewatering a production borehole allows gas to both desorb from the coal and flow to the borehole.

In the central coalfields of Britain there is evidence to suggest that the coal seams are devoid of free water as the relatively low volumes pumped from the mine are generally comparable in magnitude to the volume introduced into the mine for engineering purposes (NCB, 1982). However, mining disturbance, geological faulting or borehole hydrofracturing could bring coal seams into contact with aquifers within the coal measures.

### Cleat and cleat mineralisation

The flow characteristics of fluids through coal seams depend on the nature of the cleat network. Cleat is thought to be developed during burial as a result of volume changes taking place during coalification with stress relief during uplift contributing to its final stages of development (Spears and Caswell, 1986). The transmissivity of the cleat to fluids depends on both the tectonic history of the coalbeds and the mineralisation history. Improved understanding of cleat mineralisation through studies of the paragenesis of cleat minerals could be helpful in developing pre-drainage of methane technologies.

When comparing the emission characteristics of coal samples as determined in the laboratory with the behaviour of in-situ coal it is important to understand the differences which will arise due to the differences in states of stress. For instance, rates of gas desorption from coal lumps can be correlated with the proportion of fusinite in the sample but it is the bedding fractures associated with fusinite that are responsible for the relationship (Creedy, 1991). However, in considering flow through in-situ strata then vertical discontinuities such as cleat assume greater importance.

## GAS PRODUCTION FROM COAL SEAMS DURING MINING

The gas emission properties of coal seams are considerably modified from their natural state once disturbed by mining. Much research has been done in this field because of the safety and production implications of firedamp release in underground coal mining activities. Gas emission, geotechnical and stress-permeability studies have been conducted to facilitate a greater degree of understanding of the processes which take place and to enable increasing levels of coal production to be safely achieved from deep mining operations.

In underground coal mining, the release of gas from coal seams, and its subsequent migration towards the airways is dependent on the permeability of the coal seams and coal measures strata, the seam gas pressure and gas content. Research has shown that permeability of coal seams and the strata around working longwall faces is greatly influenced by the extraction of a coal seam.

The study of methane flow in coal seams therefore involves the following three areas:

1. Stress analysis - the response of coal seams and the coal measures strata to mining activity,

2. Stress-permeability analysis - the effect of stress and fracturing on coal permeability, and

3. Flow analysis - empirical and numerical flow models

### Variations in stress patterns around working longwall faces

Mining induced stresses around longwall faces underground create several regions of interest in terms of methane flow through coal seams. Prior to mining, coal seams are loaded by the weight of the overburden where the stresses ate uniformly distributed . As the coal is extracted, stress conditions around the longwall panel will be readjusted and, at some stage, a new equilibrium is reached. This new state of stress is expressed in the form of "high" and "low" pressure zones in the ground surrounding the extracted region.

Finite element analysis of stresses around longwall panels have shown that coal seams and the coal measures strata around the panel would experience continuous changes in stress conditions (Durucan, 1981). The state of stresses around a longwall extraction can be summarised as follows:

- the front abutment zone where the strata is triaxially compressed;
- the yield zone where the vertical stress reaches a peak and the state of stresses is complex;
- the stress relief zone where the stresses are complex and low in magnitude; and,
- the recompaction zone where the triaxial state of stresses is re-established (Figure 5).

Coal seams will behave differently under the above stress conditions and the structural changes occurring during these stages will determine their permeability to gas flow.

### Stress-permeability relationships for intact and fractured coals

The changes in the structure and permeability of a number of British coal seams were investigated through a series of laboratory stress-permeability measurements simulating the stress conditions described above. The work was carried out using a state-of-the-art servo controlled electro hydraulic press which allowed the continuous monitoring of the changes in stress, axial and volumetric strain and permeability of coal before, during and after failure is initiated (Durucan, 1981 and Durucan *et al.*, 1987). Permeability measurements were made, in a modified triaxial cell, on cores taken from large lumps of coal, drilled perpendicular and parallel to the bedding planes.

Figure 6 shows the changes in permeability of intact and fractured coal under triaxial compression. This behaviour represents the changes coal seams would undergo in the front abutment and recompaction zones of longwall coal faces (Figures 5 and 7). The analysis of these results have shown that coal permeability is highly stress-dependent and the permeability of coal seams could decrease by up to two orders of magnitude in the front abutment zone of a longwall coal face. Under triaxial compression, microfracturing of the coal matrix may take place in the front abutment zone, however, this would not have a significant effect on permeability. The flow of methane in non-fractured coals is mainly governed by the extent to which the applied stress changes the size of inherent fissures and pore channels. This, in fact, is directly related to the structural characteristics of the coal seam concerned (Durucan and Edwards, 1986).

Fracturing and failing of coal, in and around the seams being worked, is most likely to occur in the yield zone resulting in a significant increase in coal permeability. Figure 7 shows the results of post-failure tests and the relationship between axial/radial stress and axial strain, volumetric strain and permeability. The failure of coal under triaxial compression and the subsequent changes in volumetric strain corresponds to a marked increase in coal permeability. It is believed that the permeability of coal seams can increase by up to three orders of magnitude in the yield and stress relief zones of longwall faces and the source seams above and below. It is significant that fracture permeability under triaxial compression remains constant once the residual strength of coal is reached. The flow of methane through fractured coal under triaxial stress is controlled mainly by the fracture width which was found to be comparable for most coals tested. Figure 8 shows the relationship between confining stress and fracture permeability of coal seams in the yield, stress relief and recompaction zones of longwall faces.

### Gas emission zones around longwall panels

The above observations on the effects of stress on permeability of coal seams and the theoretical analysis of stresses around longwall faces led to the development of generalised stress-permeability profiles for coal seams around longwall extractions (Durucan, 1981). Figure 9 shows one such profile for the immediate roof level of a working longwall face where the failure zones developed immediately ahead of the face and in the overlying strata is characterised with a significant rise in coal permeability. The permeability of coal seams in these failure zones is greatly enhanced due to the opening-up of new flow channels and as the size of the openings are increased, the failure zone in the overlying strata will propagate accordingly. Due to the dynamic nature of mining these areas are usually re-stressed in the recompaction zone with a residual effect on coal permeability.

Figure 10 shows the different permeability zones and the flow paths of methane around a working longwall coal face. Ahead of the face, permeabilities of coal seams are very low due to high abutment stresses. The outer boundaries of this low permeability zone are defined by the parabola on the right hand side of the figure. Permeability of the strata will start to increase in the yield zone which lies between the inner parabola and the maximum permeability line. Behind the face, areas of maximum permeability will lie at angles of approximately 60° and 45° above and below the working horizon. The majority of the gas flowing towards the workings will emanate from the areas behind this maximum permeability line, within which permeability remains very high. Coal seams outside the shaded area are not expected to be highly affected by the mining induced stresses and the permeability of the strata in this area will remain constant with negligible volumes of gas flow towards the workings.

## THE MODELLING AND PREDICTION OF METHANE FLOW IN COAL SEAMS

### Underground methane flow prediction using Airey's gas emission theory

Airey (1968, 1971) treated coal as aggregates of individual lumps the size of which depended on proximity to the coal face abutment zone. Gas emission rate was calculated from an empirical equation which invoked a time constant of emission, a parameter related to the ratio of principal stresses. This approach although necessitating a number of broad assumptions has proved remarkably successful and forms the basis of the practical emission prediction methods used throughout the British coal industry (Dunmore, 1981; Curl, 1978 and CEC, 1988).

The firedamp prediction techniques have proved to be invaluable for ventilation and methane drainage planning, for assessing the potential for introducing or enhancing colliery methane utilisation schemes and for determining the likely limitations on coal production imposed by gas emission (Creedy, 1992).

The method takes account of the fact that in addition to emissions from the worked seam itself and cut coal, firedamp is released into mine workings from all the adjacent seams fractured by the mining activity. The size of the de-stressed zone around the workings from which gas emission occurs depends on coal face length, coal face height, seam depth, strata strength and the proximity of older workings. Studies which involved comparing predictions obtained from a theoretically based gas emission model with measured emission data from longwall faces indicated that the gas emission zone could extend up to 200m above and 70m below the worked seam (Kershaw, 1989).

The actual rate of gas flow into a mine district depends on the gas contents, number and thicknesses of coal seams in the disturbed zone, the proximity of the seams to the workings, the age of the district and the rate of extraction.

**Numerical simulation models**

Methane production from coal seams, both by underground and surface drainage wells, has been investigated by many researchers and a number of numerical models have been developed over the last three decades. A comprehensive review of all major models developed was recently published by King and Ertekin (1989).

At Nottingham University, research on the simulation of methane flow using numerical methods has mainly concentrated on the prediction of flow into underground drainage boreholes and airways (Keen, 1977; O'Shaughnessy, 1980; Ediz, 1991). The model is based on the following equation derived from Darcy's Law: [2]

$$2\phi\mu\frac{\partial p^2}{\partial t} = \frac{\partial}{\partial x}\left(k_i\frac{\partial p^2}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_k\frac{\partial p^2}{\partial y}\right) + \frac{\partial}{\partial z}\left(k_j\frac{\partial p^2}{\partial z}\right)$$

where,

$p$= pressure

$\mu$= dynamic viscosity

$k_i$= permeability in the i direction

$\phi$= porosity

The following assumptions have been made in deriving the above equation:

- the flow is laminar, single-phase and isothermal
- methane obeys the ideal gas law
- molecular slip may be ignored
- methane desorption effect may be ignored

Equation 2 is linearised by introducing a field variable, $\varphi = p^2$: [3]

$$2\phi\mu\frac{\partial \varphi}{\partial t} = \frac{\partial}{\partial x}\left(k_i\frac{\partial \varphi}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_k\frac{\partial \varphi}{\partial y}\right) + \frac{\partial}{\partial z}\left(k_j\frac{\partial \varphi}{\partial z}\right)$$

The distribution of methane pressure around longwall faces and the gas flow into drainage boreholes and airways are calculated using the PAFEC'75 finite element software package. Figure 11 shows the methane pressure contours around a longwall face practising roof and floor drainage (Ediz, 1991).

The coal matrix is heterogeneous and is characterised by two distinct porosity systems - macropores and micropores. Micropores account for up to 95% of the internal coal surface area and a large proportion of the methane stored in the coal matrix exists in an adsorbed state. Most models assume that the gas adsorbed onto the micropore is in a continuous state of equilibrium with the free gas pressure in the macropores and have some limitations in their applicability due to oversimplifications such as unrealistic assumptions behind dual-media characterisation of methane flow in coal beds, not accounting for the time lag incurred during transport of the gas through the micropores or not considering the effects of one phase being transported in solution in the other phase. In order to overcome these limitations, a two-phase, unsteady state non-equilibrium sorption model was developed in the Department of Mineral Resources Engineering at Imperial College. The model is used both in predicting the performance of surface degasification wells and in evaluating the yield of underground methane drainage boreholes in longwall coal mining. It is a fracture model which accounts for dual-porosity and dual-permeability effects including desorption of methane using a specially formulated rate term based on Langmuir's isotherm. Complex non-linear flow equations are linearised using a fully implicit method and discretised by the finite difference approach. New features which have been developed and incorporated into the model include the solution of gas in the water phase, the solution of water vapour in the gas phase and the pressure and mining induced stress dependent behaviour of reservoir permeability (Foley, 1992; Shi, 1992).

The model is based on the following standard equations derived from Darcy's Law and the continuity equation: [4]

$$\Delta(R_{sgw} T_w \Delta\Phi_w) + \Delta(T_g \Delta\Phi_g) + Q_g + Q_d = \frac{\partial}{\partial t}\left(\phi\left(R_{sgw}\frac{S_w}{B_w} + \frac{S_g}{B_g}\right)\right)$$

[5]

$$\Delta(T_w \Delta\Phi_w) + \Delta(T_g R_{swg} \Delta\Phi_g) + Q_w = \frac{\partial}{\partial t}\left(\phi\left(\frac{S_w}{B_w} + R_{swg}\frac{S_g}{B_g}\right)\right)$$

where,

$T = (kk_r/B\mu)$ , phase mobility, (subscripts: $g =$ gas property, $w =$ water property)

$k =$ permeability

$k_r =$ relative permeability

$B =$ phase formation volume factor

$\mu =$ dynamic viscosity

$\Phi =$ phase potential

$R_{sgw} =$ solution of gas in water

$R_{swg} =$ solution of water vapour in gas

$Q_g = q_g + R_{sgw} q_w$, gas flow-rate term

$Q_w = q_w + R_{swg} q_g$, water flow-rate term

$Q_d =$ desorption rate term

$\phi =$ porosity

$S =$ phase saturation, $(S_g + S_w = 1)$

Figure 12 shows the predicted methane production rates from a single seam reservoir using this model.

## CONCLUSIONS

Research carried out in the UK over many years into the occurrence and behaviour of methane (firedamp) in coal, has been principally concerned with the prediction and control of environmental conditions underground. Much of this work has been directed towards an understanding of the geological factors that control the quantity, pressure and composition of the gas, it's spatial distribution and the processes whereby methane is released into the mine workings as a result of mining activity. More recently, this research has examined the basic mechanisms of gas flow through and emission from coal seams based upon an analysis, using rock mechanics principles, of the stresses induced by mining in the surrounding strata, and a knowledge of the stress-permeability behaviour of coal. The results of this work have shown that realistic values for methane can be predicted given adequate data.

Although the research described above has been based upon mining experience it should be emphasised that the more recent work, using a more fundamental approach, applies equally to any prescribed geological setting. Thus, an analysis of the behaviour of, for example, a stimulated surface degasification well could be carried out given the basic information on the coal and the results of laboratory tests on stress-permeability behaviour. In coalbed methane application terms this work could have a significant part to play in the prediction of well performance and the drainage characteristics of the seam.

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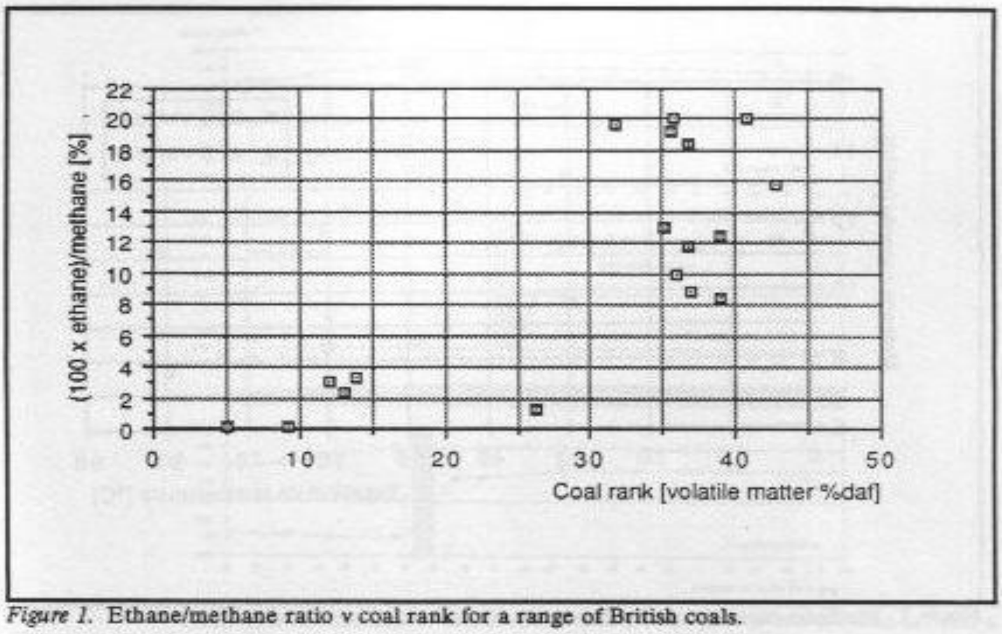

*Figure 1.* Ethane/methane ratio v coal rank for a range of British coals.

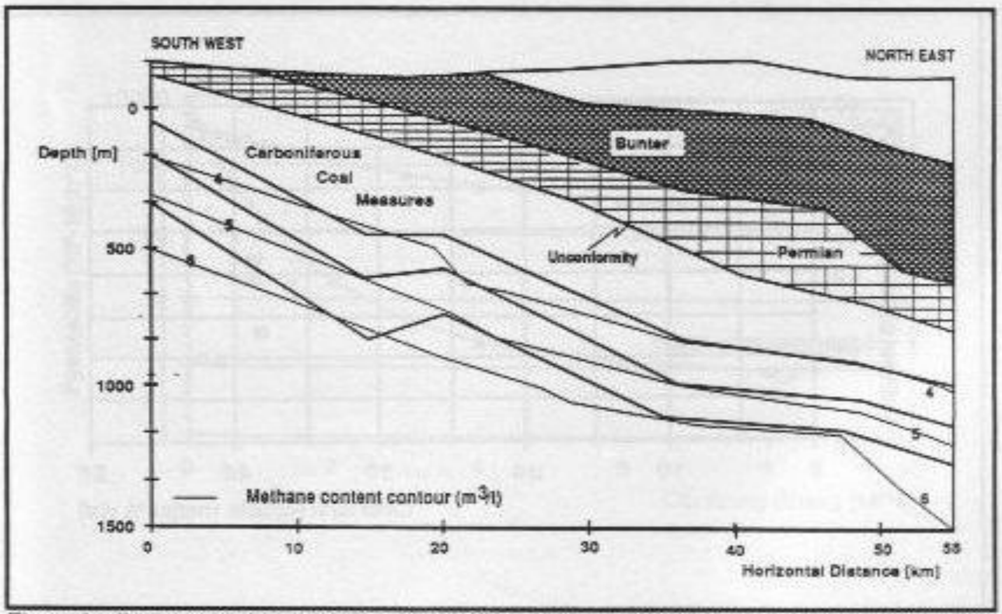

*Figure 2.* Diagrammatic section across the East Midlands coalfield showing the relationship between seam gas content and unconformable base of the Permian strata.

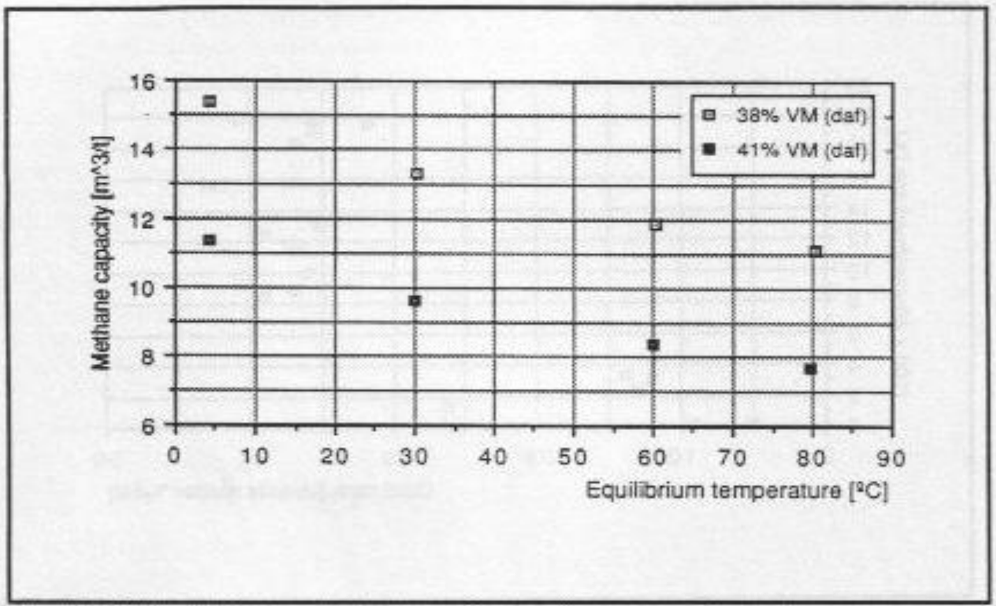

*Figure 3.* Methane capacity v temperature, moisture saturated, ash-free coal.

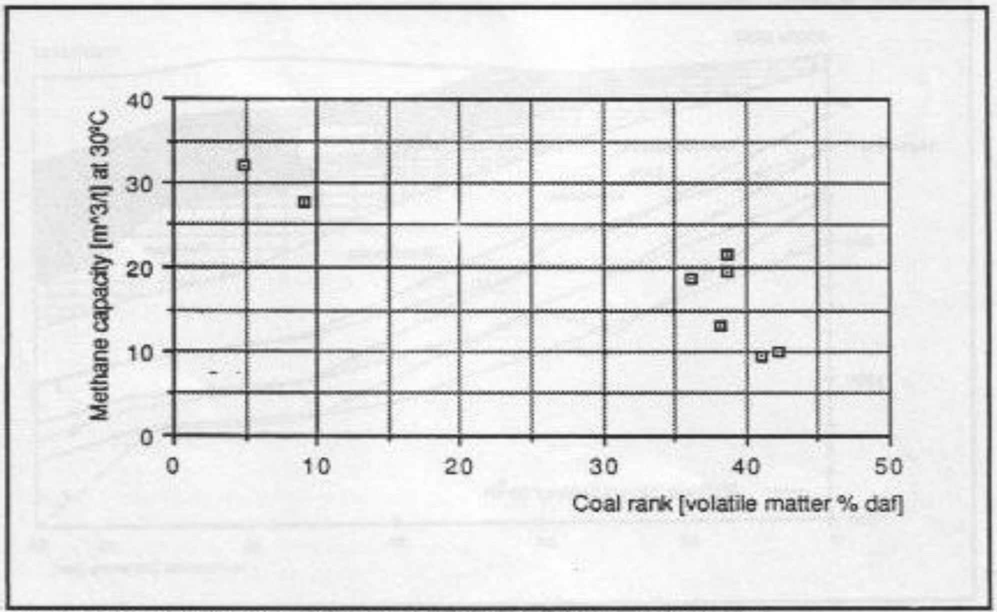

*Figure 4.* Methane capacity v coal rank, moisture saturated, ash-free coal.

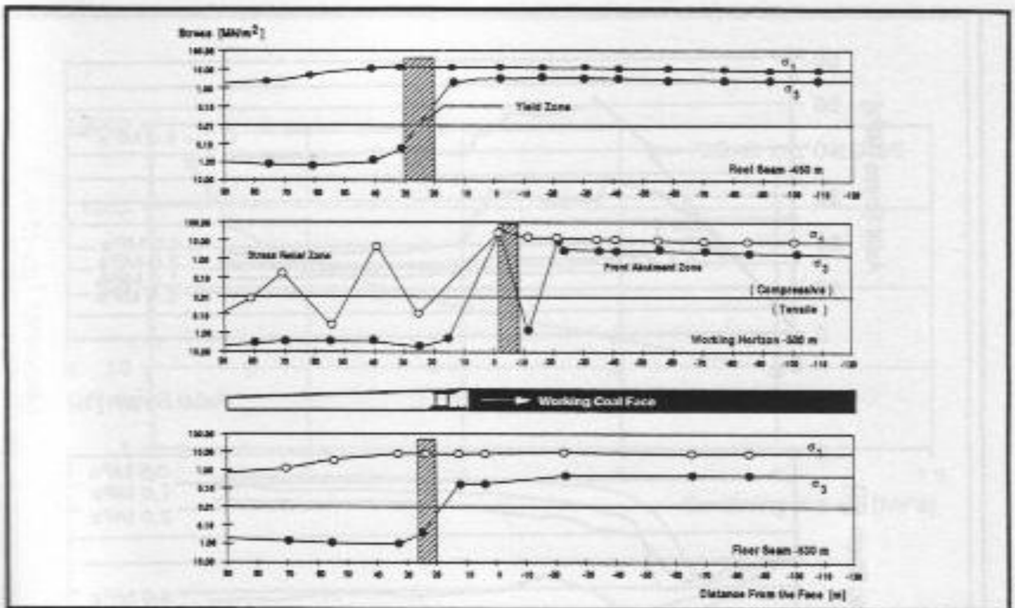

*Figure 5.* Theorectical maximum and minimum principal stress distribution profiles around a 500 m working longwall face (after Durucan, 1981).

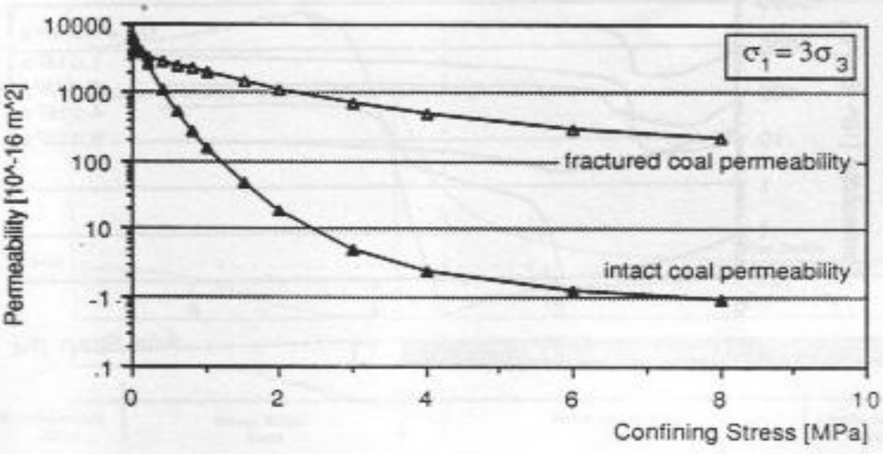

*Figure 6.* Stress-permeability relationships for intact and fractured coal, Great Row seam, Silverdale Colliery.

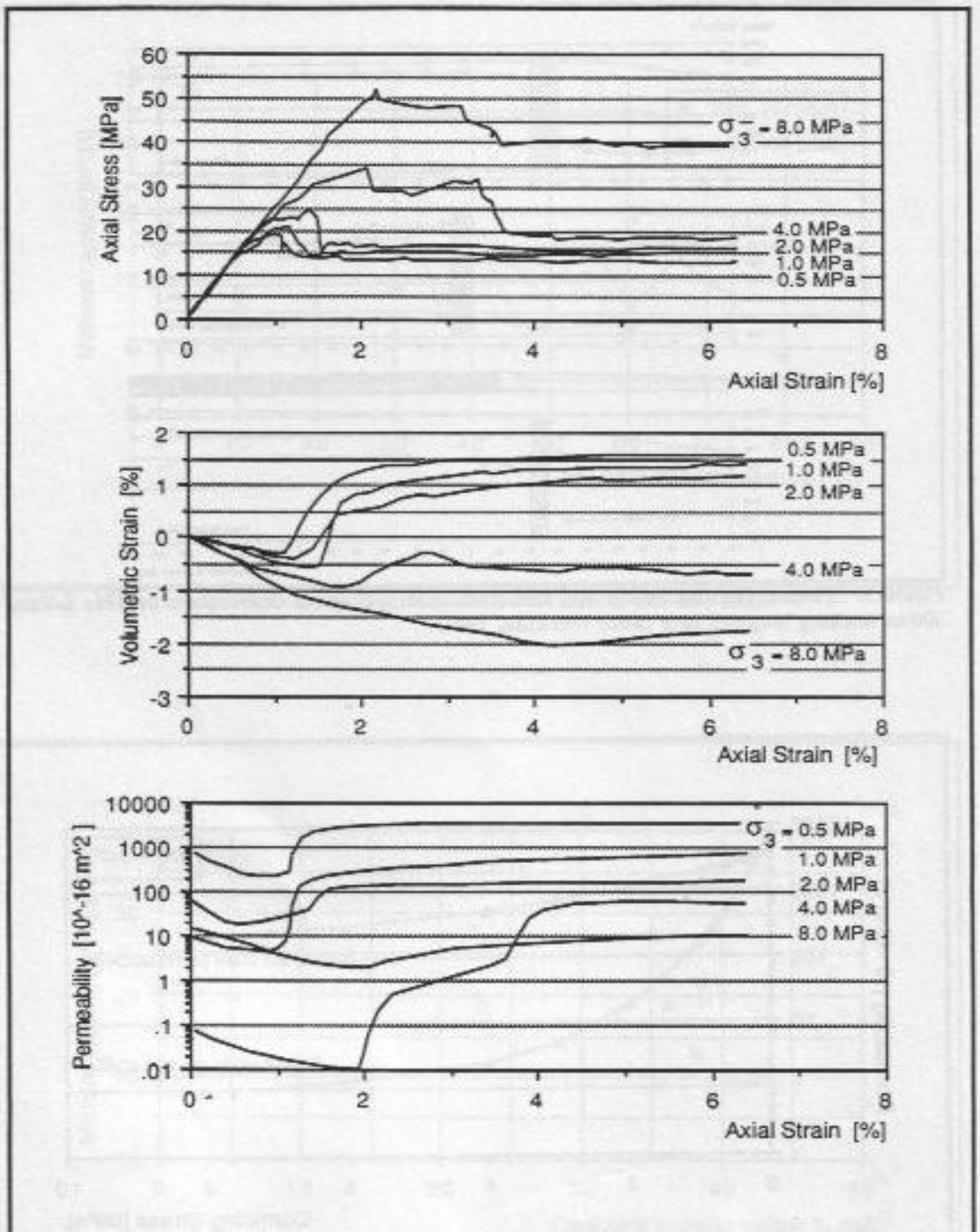

*Figure 7.* Post-failure stress-strain -permeability relationship for Great Row Seam, Silverdale Colliery.

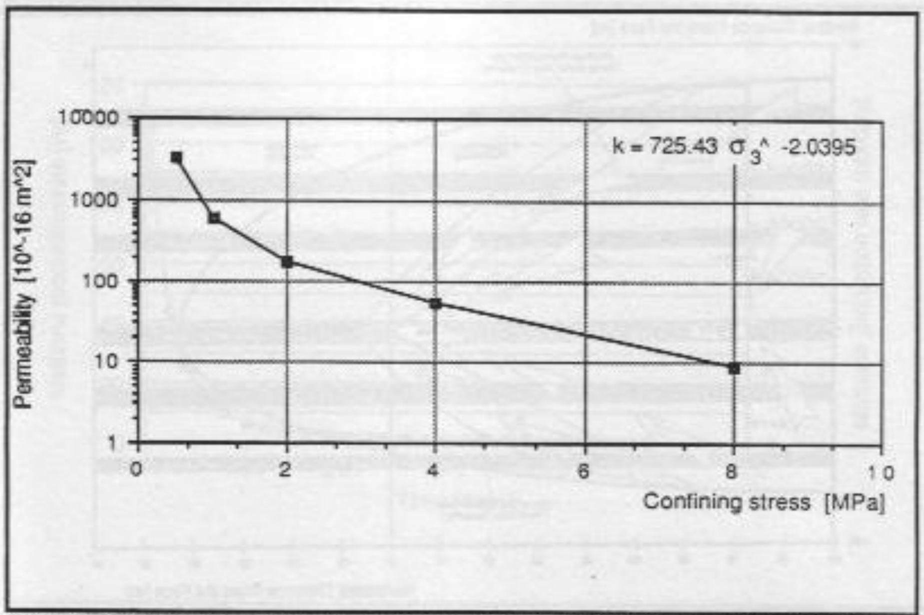

*Figure 8.* Fracture permeability in the yield and recompaction zones, Great Row Seam, Silverdale Colliery

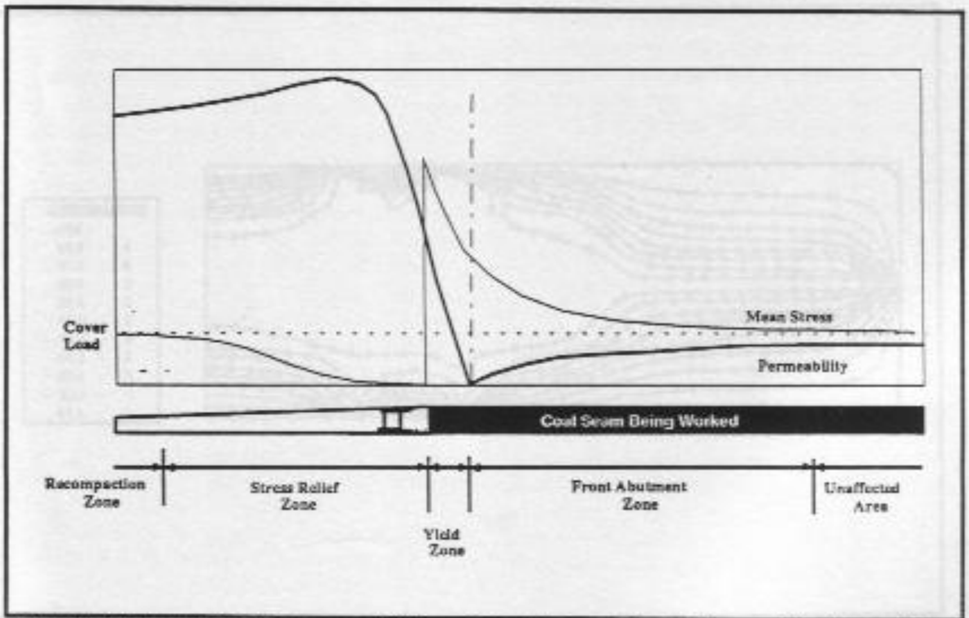

*Figure 9.* Generalised stress-permeability profile at the roof level of a working longwall face (not to scale), (after Durucan, 1981).

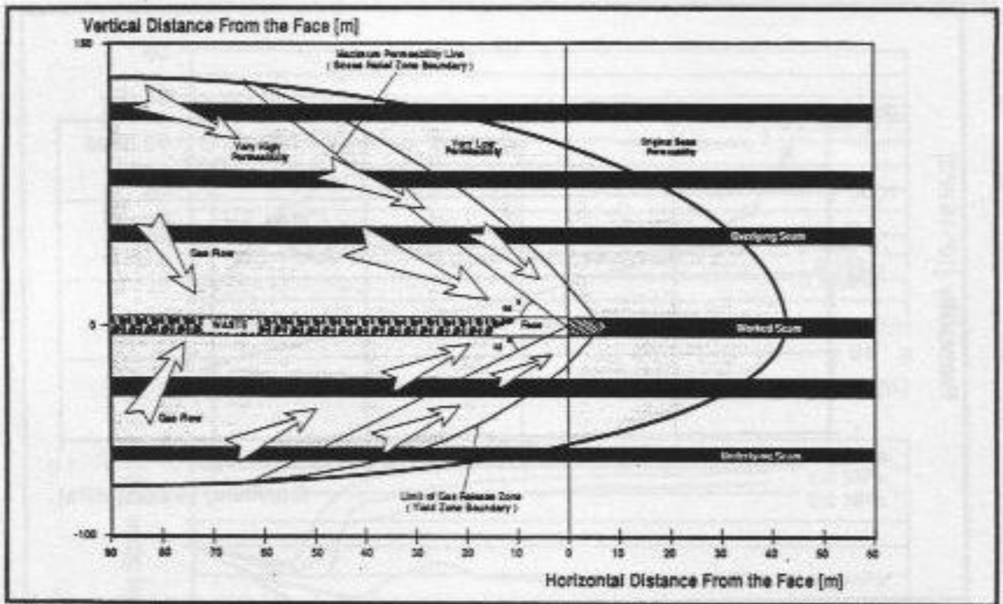

*Figure 10.* Different permeability zones and flow paths of methane around a working longwall coal face (after Durucan, 1981).

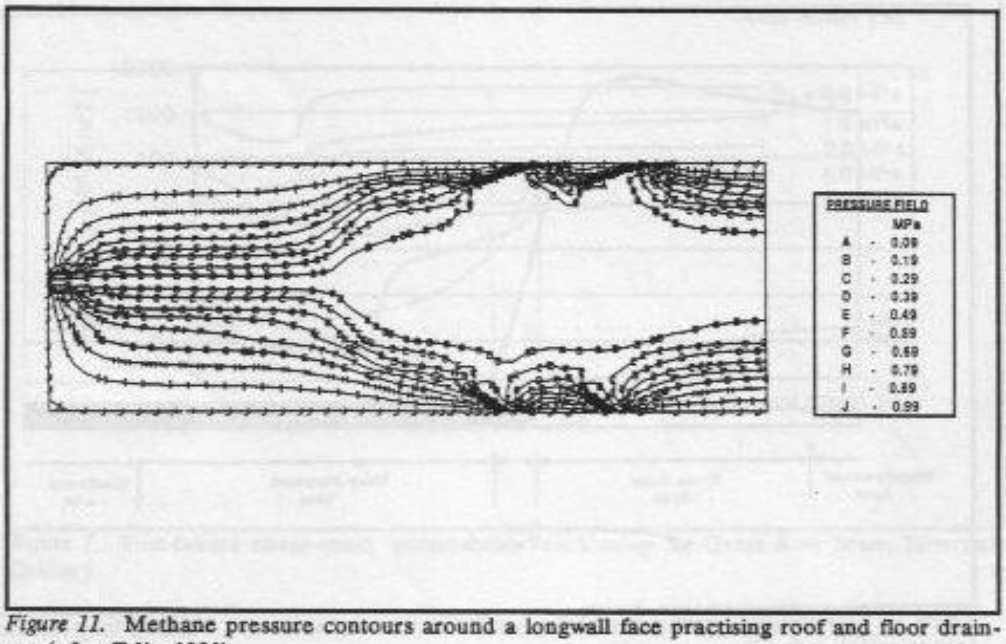

*Figure 11.* Methane pressure contours around a longwall face practising roof and floor drainage (after Ediz, 1991).

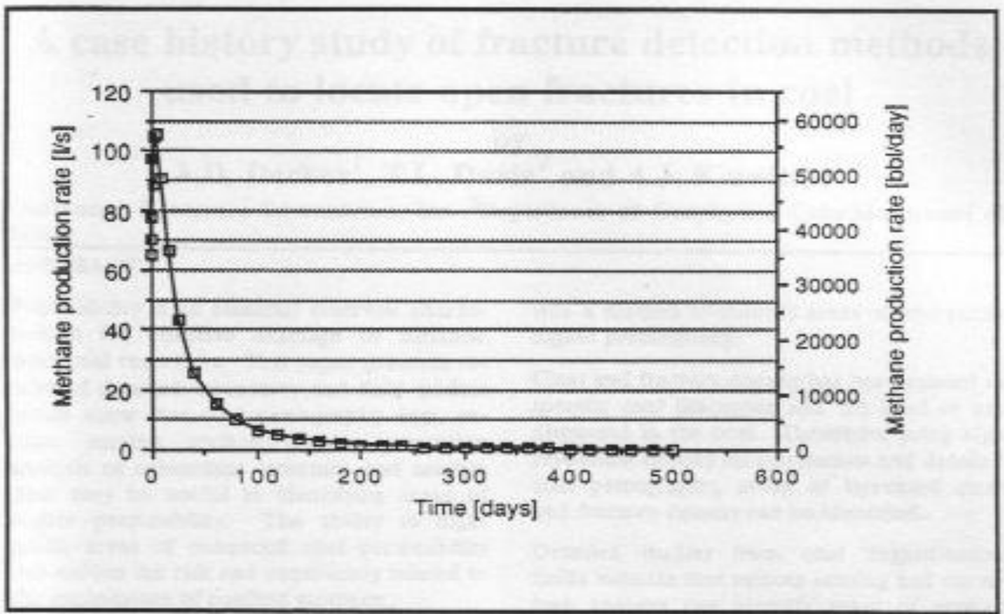

*Figure 12.* **Methane production rates predicted for a single seam methane reservoir.**