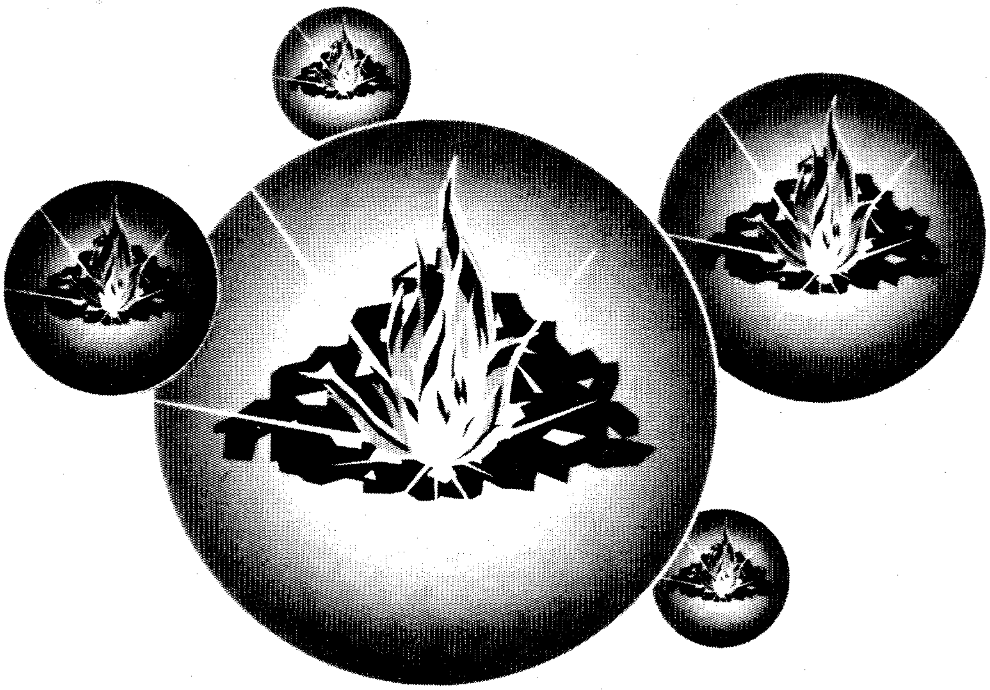
Coal-Bed Methane
Information Series 111

# Introduction to Coal Sampling Techniques for the Petroleum Industry

## Seminar/Workshop Proceedings



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COAL BED METHANE
SEMINAR SERIES

# *INTRODUCTION*
# *TO*
# *COAL SAMPLING TECHNIQUES*
# *FOR THE PETROLEUM INDUSTRY*

COMPILED BY SLAVKO STUHEC

ALBERTA GEOLOGICAL SURVEY
ALBERTA RESEARCH COUNCIL

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**Field Guide Notes**

# COAL SAMPLING SEMINAR/WORKSHOP SCHEDULE

ALBERTA RESEARCH COUNCIL MILLWOODS FACILITY
OCTOBER 10 - 12, 1990

## WEDNESDAY OCTOBER 10*********************************************

| | |
|---|---|
| 9:00AM - 9:15AM | -INTRODUCTION**(DENNIS NIKOLS - ALBERTA GEOLOGICAL SURVEY)<br>(MEG BURES - CSPG) |
| 9:15 - 10:00 | -DESORPTION, DIFFUSION, AND COAL TESTING FOR COAL BED METHANE<br>(GEOFF JORDAN - NORWEST RESOURCE CONSULTANTS) |
| 10:00 - 10:30 | - RANK VARIABILITY AND GAS PRODUCTION<br>( DAVE MARCHIONI - PETRO - LOGIC SERVICES ) |
| 10:30 - 11:00 | ------------COFFEE BREAK------------------ |
| 11:00 - 11:30 | -GEOPHYSICAL LOG INTERPRETATION AND COAL RECOGNITION IN THE SUBSURFACE.<br>(EDGAR HULATT - BPB WIRELINE SERVICES.) |
| 11:30 - 12:30 | --------------LUNCH--------------------------------- |
| 12:30PM - 1:15PM | -STRUCTURAL GEOLOGY AND ITS APPLICATION TO COAL BED METHANE.<br>(WILLEM LANGENBERG - ALBERTA GEOLOGICAL SURVEY.) |
| 1:15 - 2:15 | -CORE DRILLING AND HANDLING TECHNOLOGY FOR THE ASSESSMENT OF COAL BED METHANE POTENTIAL.<br>(KEITH McCANDLISH - ASSOCIATED MINING CONSULTANTS LTD.) |
| 2:15 - 2:45 | ------------COFFEE BREAK------------------ |
| 2:45 - | -PANEL DISCUSSION |

## THURSDAY OCTOBER 11*********************************************

| | |
|---|---|
| 8:30 AM - 11:30 | -CORE SAMPLING AND ITS RELATION TO GEOPHYSICAL LOGS<br>(MIKE DAWSON - GEOLOGICAL SURVEY OF CANADA.)<br>(GREG CAVE - ESSO RESOURCES CANADA.) |
| 10:00 - 10:30 | -------------COFFEE BREAK----------------------- |
| 11:30 - 1:00 | ------------LUNCH------------------------- |
| 1:00 - 2:00 | -SAMPLING OF CORE FOR GAS MEASUREMENT INFORMATION.<br>(ALAIN KAHILL - CANTECK CONSULTING.) |
| 2:00 - 2:30 | -----------COFFEE BREAK---------------------- |
| 2:30 - 3:00 | -COAL RESERVOIRS: GEOTECHNICAL ASPECTS<br>(HANS BIELENSTEIN. - ASSOCIATED MINING CONSULTANTS LTD.) |
| 3:00 - 3:30 | -COAL RESERVOIRS: STIMULATION BY HYDRAULIC FRACTURING<br>(RUSSELL MEYER - NOWSCO WELL SERVICES) |

3:30 -PANEL DISCUSSION

**RIDAY OCTOBER 12** ************************************************************

8:00 AM -DEPART VIA BUS TO WHITEWOOD MINE.(HIGHVALE)

9:00 AM -OUTCROP SAMPLING - METHODOLOGY AND ITS RELATION TO RESERVOIR POTENTIAL.
(DAVE MARCHIONI - PETRO - LOGIC SERVICES.)
(RUDY STROBL - ALBERTA GEOLOGICAL SURVEY.)

12:00 - 1:30 ---------LUNCH AND INFORMAL DISCUSSION---------------

1:30 - 3:00 -RETURN TO EDMONTON AND WRAP UP

* * *

CANADIAN SOCIETY OF PETROLEUM GEOLOGISTS

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# INTRODUCTION TO COAL SAMPLING TECHNIQUES FOR THE PETROLEUM INDUSTRY

OCTOBER 10-12, 1990

On behalf of the CSPG Coal and Coalbed Methane Division I would like to welcome participants to the CSPG/ARC coalbed methane sampling seminar.

Coal is a substance which has unique properties and characteristics, and as a result, behaves differently from conventional gas reservoir lithologies. During this seminar we will be covering how and why coal behaves both as a gas reservoir and as a source rock, its properties and a few of its idiosyncrasies.

We have arranged the seminar in order to begin with the fundamental physical properties of this unique substance: how methane is adsorbed onto coal, the movement of methane through coal, and how all this is affected by the presence of moisture and other materials in coal. A few of the chemical and physical tests done on coal will be explained as they relate to the petroleum industry. We'll then move on to a discussion of coal quality with respect to coal rank and type, and how it relates to methane generation, retention and production.

Geophysical log interpretation specifically for coal will be addressed, with particular comparisons made to oilfield logging, for example density porosity logs (oilfield) vs bulk density logs (coal). Hardcopy examples will be available.

The effect of structural deformation of coal seams on production and generation of coalbed methane and reservoir potential will be discussed.

How to drill for core and still be able to complete the well, along with getting a representative core sample to surface, and the equipment needed for enhanced core recovery will follow. Once we have geophysical logs and core, it's a matter of reconciling the core descriptions to the geophysical logs in order to adjust for core loss (which is important in structurally deformed regions), and in order to pick representative sample intervals. Once at surface, the core is sampled for gas measurement information and methane analyses.

The geotechnical elements of coal seams as gas reservoirs will be covered: the relationship of permeability to natural and enhanced fracture patterns, as well as complications associated with coal seams that may inhibit permeability.

The field trip on Friday to the Highvale mine will be an excellent opportunity to see the lateral and vertical variation in coal seams and associated sediments, and to compare core and sample analyses to what the rock actually looks like in outcrop, as well as the importance of proper statistical sampling. In all, it will be a chance to observe, first hand, many of the features of coal seams that will be discussed in detail over the next two days.

At the end of each afternoon we have allowed time for panel discussions and hope to have all the speakers available to encourage more in-depth or cross-topic discussions. I hope everyone will attend and feel free to participate.

The speakers we have invited to the seminar are all well-known specialists in their own fields and all of whom, I'm certain, we will learn a great deal from.

Finally, I would like to acknowledge the generous support of our sponsors: Christensen Drilling Supplies, LAS Energy Associates Ltd., Loring Laboratories, and Western Atlas International. Their interest and support of the coalbed methane sampling seminar is greatly appreciated.

Meg Bures.

Margaret Bures
Chairman
Coal and Coalbed Methane Division

# DESORPTION, DIFFUSION AND COAL TESTING FOR COALBED METHANE

Geoff Jordan, Norwest Mine Services Ltd.

## INTRODUCTION

Conventional testing procedures for coal are commonly used today as part of the procedure for the assessment of the production potential of coalbed methane. However, the tests that are used were developed many decades ago in response to the use of coal for other purposes. The coalbed methane production potential of the coals so tested is often derived by indirect means or, at least to some extent, by inference. Therefore, in order to determine whether valid conclusions are being drawn from the coal laboratory test data, it is first necessary to appreciate the relationships that exist between the coalbed methane in any coal and the laboratory test results for that coal.

The following material is an attempt to describe the means by which methane is stored in the coal and laboratory test results for the same coal. It is extremely important to realize that conventional coal laboratory tests do not measure the quantity of methane stored in the coal nor its potential to be produced.

## THE PROCESS OF METHANE ADSORPTION ON COAL

Over the last few years many publications have been produced which briefly describe the concept of coalbed methane along with a large number of topics related to this material. In the search for brevity in these publications the mechanism for methane storage in coal is often skipped over. As a result a variety of apparently conflicting views are presented which can lead to confusion on the part of the reader and, potentially, to an incorrect approach to the subsequent exploration and development of this material. One such typical explanation is that methane is adsorbed on the internal surfaces of the pores of the coal and that, during production, the methane diffuses out of the coal matrix to the coal cleats where it desorbs and then flows to the well. The validity of such statements is examined in detail in the following discussion.

It has almost become a convention to describe coal as consisting of a series of matrix coal blocks bounded at the extremities of these blocks by natural fractures called coal cleats. This description was partly developed in order to obtain physical descriptions for coal which could then be used in a variety of computer manipulated mathematical models. The matrix blocks may be given the shape of spheres, cylinders, square or rectangular section columns or cubes, depending on the modeller's preference. The cubic section model appears to be the most commonly chosen geometry for the matrix blocks. All of these models are simplifications of reality and the validity of the computer simulation depends at least in part on the extent to which these models approach reality in any given situation. Note that these models imply that all natural fractures in coal are cleats and there are many who would argue that this is not the case; they imply that there is a very simple and regular geometry to the cleats and this is very often not the case; they imply that all of the fracture sets extend to infinity and this is definitely not the case; and they imply that the cleat surfaces are planar and equally separated along their length which is also not so. Nevertheless, if we accept that the coal consists of matrix blocks bounded by natural fractures, including cleats, and that the cleats or fractures display a variety of geometries with the fracture surfaces having various separation distances and surface characteristics, we can then examine the nature of methane stored in the coal matrix blocks.

Almost every publication on coalbed methane describes the process of coal formation and this one will be no different. Coal evolves as a result of a variety of diagenetic processes that change the initial accumulation of organic vegetable matter. A coal seam is normally bounded by clastic materials that are deposited by sedimentary processes and so the coal itself is often referred to as a sediment. But most coals are not sediments at all; coal is, in fact, the name given to a specific class of metamorphic rocks. The process of coal formation is normally and collectively referred to as coalification. The first steps in this process are physical and biochemical; the plant debris is compacted due to the accumulation of other sediments and as a result water is expelled. Bacteria also act on the plant debris and one of the products of this is methane. Whether significant quantities of this methane remain stored in the coal for later production is not clear but it is commonly believed that much of this gas has had ample opportunity to be lost to the atmosphere through the course of subsequent geological events that have affected the coal.This part of the coalification process declines with time and the continuing burial of the original peat. It is generally considered to have terminated once coals have achieved a degree of maturity or rank in what is referred to as the subbituminous range.

For most coals of present interest for coalbed methane the subsequent and very different processes of coalification are generally considered to be the most important.These secondary processes are a complex series of organic chemical reactions that modify both the physical and chemical properties of the coal. These reactions are of a condensation type; at first longer and longer carbon chain molecules result with "benzine ring" molecular substructures displaying an increasing appearance through this process. The dominant molecular structures are of the long chain type as the degree of maturity of the coal increases through bituminous rank. As the chemical reactions proceed further the benzine rings begin to combine and ultimately form sheet like molecular structures. This type of molecular structure dominates coals that have achieved a very high degree of maturity and which is commonly referred to as anthracite.

The chemical reactions that are described above result in the formation of several byproducts the most important of which are methane, water and carbon dioxide. Thus we have a source of both the product and the primary waste products from coalbed methane wells. In the past it was observed that the rank or degree of maturity of coals often increased with depth of burial at any given location. It was often concluded from this that increase in pressure increased the coalification rate but this assumption ignored the general trend for there to be an increase of temperature with depth. Consideration of the nature of the organic chemical reactions that occur through coalification shows that an increase in temperature increases the rate of these reactions. An increase of pressure, on the other hand, retards the reactions. Thus we can expect the temperature increase with depth to be the primary driving mechanism that accounts for the change of rank with depth. In fact it has been shown that the process of coalification is dependent on temperature over time.

The methane that is evolved and stored in the coal as a result of the coalification process does so in three forms; it may exist in the free state in the pores and open fractures in the coal, it may be adsorbed onto the coal, or it may be dissolved in water held in the coal. The following discussion primarily addresses methane stored in the first two ways and is directed mainly to adsorbed methane.

The process of adsorption is one in which molecules or atoms of one material tend to selectively "stick" to the surface of another material. Different gasses and liquids display this tendency to varying degrees when they are exposed to a variety of different materials. Coal is one material that often shows a relatively strong tendency to adsorb a wide variety of materials and methane is one of these. Thus, unlike absorption, adsorption is a surface effect where molecular bonds of one type or another form between the adsorbate and the adsorbent. The nature of the bonding that occurs may take two general forms; if chemical bonding occurs then the process is referred to as chemical adsorption or simply chemisorption. In order for this type of bond to be broken and the process to be reversed, energy is required and so the forward and reverse paths for the process of chemisorption are not the same with respect to energy distribution.

A second type of bonding may also occur; this type of bonding occurs as a function of the spatial distribution of electrons and the nuclei of the adsorbate and adsorbent. A physical form of attraction occurs and so this process is referred to as physical adsorption. This process is purely reversible in that the amount of energy required to drive the process at any stage of the process is completely liberated as the original physical conditions are reestablished. It is this second type of process that occurs in the adsorption of methane onto coal.

It has been shown that for many coals the pores that are present show a marked tendency to fall within three quite distinct populations of diameter. Names have been given to these populations depending on the diameter size range; those that have diameters less than 20A are referred to as micropores, those that have diameters from 20A to 500A are referred to as mesopores and those that have diameters greater than 500A are referred to as macropores. Compared with many clastic sediments all of these pore diameter populations are quite small but the most important thing is that the total population of micropores is very much larger than the population of the other types of pores. If we consider a fixed volume of porosity, as the number of pores that contributes to that volume increases the sum total surface area enclosed by all the pores increases. Thus, because the pores of coal are very small and most exist within the micropore class and even though the volume porosity might be quite small, for any unit of coal mass the equivalent coal pore surface area is extremely large.

If we imagine an ideal case in which only coal and methane are present, as the physical conditions that promote adsorption are changed more and more methane molecules "stick" or adsorb on the coal pore surfaces until eventually, and theoretically, the whole of the surface will be completely coated by what is referred to as a Langmuir monolayer. The nature of the bonding that occurs allows the methane molecules of this layer to pack closely together, much like the molecular separation that one would expect of a liquid rather than that of a gas. This accounts for the fact that the amount of methane often stored in the coal in the adsorbed state is much greater than that in the free gaseous state. Laboratory work has also shown that the physical properties of methane in the adsorbed state is more like that of methane as a liquid than a gas; for any given set of physical conditions it is found that the density of adsorbed methane is much higher than that of the gaseous form and the energy of adsorption of methane is almost the same as the latent heat of vaporisation of methane.

There has been some experimental work done that suggests that the micropores commonly have the shape of thin cylinders or tubes while the mesopores are more irregular but often exist as small cracks with a more or less penny shaped geometry. The readily visible cleats are included in the macropore class. It is for this reason that coal models often describe coal as matrix blocks containing a fully interconnected system of pore tubes bounded by fractures or cleats.

It is of course possible that other materials than methane are stored in the micropores or adsorbed on the pore surfaces. This might include carbon dioxide and water evolved in the coalification process or several other things. In the Gondwana coals of Australia, for example, it is sometimes found that carbon dioxide is the main component and the amount of methane stored in the coal is quite low. Most of the available data from Western Canada at the present time indicates that the amount of these materials adsorbed in our coals is a small component.

In order to keep the present discussion as succinct as possible only methane stored in the micropores is considered but allowance should be made for the potential presence of other materials.

All of the preceding material describes the commonly offered picture of coal and the methane stored in it but this picture is at best misleading and at worst incorrect. One has the image of coal consisting of small blocks that contain thin tubes on the surfaces of which methane molecules are stuck. Several publications even include diagrammatic illustration to reinforce this image.

The most important misconception that could be gained is that the materials coexist in a static state. This is not so; there is a very powerful dynamic interaction between the various materials of the system and it is actually this dynamic interaction that accounts for the process of methane storage by adsorption, the process of desorbtion, the process of diffusion of methane from the micropores, the interaction between water and methane in coal and other aspects that directly affect coalbed methane reservoir engineering and production.

The behaviour of methane in the adsorbed state cannot be fully appreciated when viewed on a macroscopic scale; it must be viewed at a molecular level. The fundamental relationships can be understood if we consider a simple example of any gas introduced into an evacuated and sealed vessel.

On a macroscopic scale the gas disperses throughout the vessel. After a period of time an equilibrium, which is a function of the constant temperature and pressure of the whole system, is established where there is no mass transport (or flow) of the gas and the gas pressure is everywhere equal throughout the vessel; at this scale it might appear that nothing is moving.

However, when the gas at equilibrium is viewed at a molecular level,there is constant random motion of the individual molecules of the gas; they vibrate, spin, and travel in various directions with various velocities throughout the void space of the vessel. Collisions between molecules of the gas occur as a result and the effect of these collisions is to change both the direction of motion and the velocity of the participants. The molecules may also collide with the walls of the containing vessel and it is this behaviour that is of primary interest in the study of gas adsorption.

In the process of adsorption the molecules that collide with the walls of the vessel do not simply rebound into the void space of the vessel. Adsorption can only occur if the forces that tend to hold a gas molecule to the wall of the containing vessel exceed those that tend to cause the molecule to rebound from the surface. To be technically precise this relationship can be expressed as an energy balance equation.

We now consider the behaviour of methane gas contained within a coal pore and , in particular, the coal micropores. The long chain molecules that form the coal pore walls are not homogeneous at this molecular scale but, in fact, have a variety of different sites, some of which are more suitable (or attractive) for adsorption to occur. As the moving methane molecules become involved in collisions with the pore wall some will rebound into the void while others will be sufficiently held by the local forces of attraction at any given site that they will not be able to rebound into the pore void. Other molecules may then collide with the methane molecules adsorbed on the pore walls. If the amount of energy imparted on the adsorbed molecules is great enough the adsorbed molecules will be dislodged from the wall and return to the gaseous methane in the void; if not the colliding molecule may rebound but the originally adsorbed molecule will remain at its site of adsorption. If a methane molecule is displaced from its site of adsorption in a collision with another of the free gas methane molecules that site will then be open and will thus be available for the adsorption of any other free methane molecule that might collide with it. This ongoing process of molecules from the free state colliding with the wall, possibly being dislodged, and other free molecules then colliding with the same site to either rebound or to temporarily occupy the site is, when viewed at a macroscopic scale, an equilibrium state if the initial physical conditions of the system are not changed.

The equilibrium state described above can be disturbed by making various changes to the physical environment of the system. If the size of the void is not changed but the number of methane molecules within it is increased ( i.e if the gaseous methane molecular concentration is increased)there then would be more molecules available for collisions with the pore wall or methane molecules already adsorbed to it. All of the coal at the pore wall has some tendency to adsorb methane those sites that have the strongest tendency to adsorb methane will be occupied first. As the physical conditions of the system are changed in such a way that adsorption can more easily occur ( i.e. less energy is required for adsorption to take place) those sites on the coal molecules that have progressively lower affinities will then contribute more to the total amount of adsorption on the surface. Eventually, if the number of methane molecules in the void continues to be increased the equilibrium between the coal pore surface with methane molecules adsorbed to it and those of the gaseous methane in the void will have achieved a state where, at any given instant, almost the whole of the coal pore surface would appear to be coated with methane. This is so even though the coating results directly from the continuous bombardment of methane molecules from the gas with those on the pore surface, and even though methane molecules are continuously being dislodged from the surface.

The void space methane concentration develops and maintains the extent of adsorption layer coating. The process is similar in many respects to the boiling of water in a pot; as the water temperature rises water molecules are driven off the exposed surface of the water establishing a certain vapour pressure. As the temperature is increased the number of molecules leaving the liquid water and joining the gaseous or vapour phase adjacent to it increases. Thus the water vapour pressure increases.

Note that, just as in the analogy given above, increasing the temperature of the system reduces the amount of methane that is adsorbed, if the methane partial pressure does not change, because the energy of all the methane molecules is increased. This means that there is an increasing tendency for any of them to have sufficient energy to overcome the adsorption forces and thus exist in the pore void as part of the free methane vapour.

## MIGRATION OF METHANE OUT OF THE COAL MATRIX BLOCKS

Many publications provide only a very brief description of the migration of methane from the coal matrix blocks to the cleat system. Some of these suggest that the methane diffuses through the coal matrix to the cleat where it desorbs and then flows through the cleat system to the well bore. Statements such as these leave the reader wondering exactly how the methane migrates to the cleat; it would be easy to gain the impression that the methane molecules actually pass between the atomic structure of the long chain coal molecules. Or perhaps that the adsorbed methane molecules roll or slide along the coal pore surface to desorb at the cleat. This is not how it works.

In the previous section it was explained that the adsorbed methane necessarily coexists with a free methane vapour or gas phase. The only methane that desorbs at the cleat is methane which is already adsorbed at the cleat. Methane that is adsorbed within the coal pores desorbs there. From the previous discussion it is clear that a reduction of the concentration, or partial pressure of methane in the vapour phase promotes the process of desorbtion as does increasing the temperature of the system. There are also other physical means by which adsorption of methane can be promoted.

It is the gaseous phase molecules that migrate to the cleat and they do so by passing along the void space of the micropore until they reach the pore apertures at the intersection with a cleat, whereupon they join the general flow of fluids in the fracture system. If both the cleats and the micropores only contained methane we would have a form of gas flow through both types of structures, and this is indeed the case. However the nature of the flow of methane in each case is different.

Methane in the cleat system is often described as displaying Darcean behaviour. Flow occurs because a pressure gradient is established and the contained fluids move in order to reestablish pressure equilibrium throughout the system. If this means of flow were achieved while maintaining an equal concentration of methane molecules in a micropore and a cleat adjacent to a cleat/micropore intersection, there would be no driving mechanism to cause flow of the methane vapour out of the micropores, and thus no net change to the adsorbed/vapour phase methane equilibrium (and therefore no net desorbtion). However, if only methane were in the cleat system and a pressure gradient were established such that Darcean flow occurred in the cleat system, a reduction of methane pressure would likewise be transmitted to the location of the micropore intersections. The reduction of methane pressure, in this case, is equivalent to a reduction of the methane molecular concentration at the pore opening. So a methane concentration gradient would be established across that opening. Flow of methane gas-phase molecules would then occur as the molecules diffused in order to establish a new concentration or partial pressure equilibrium. This process of diffusion and concentration reduction would, with time progressively effect the deeper regions of the micropores and, through its length, provide conditions which allow an appropriate amount of net desorbtion of adsorbed molecules to also occur.

The time relationship of this process is an important one. Even if it were possible for an instantaneous drop of the methane pressure in the cleat to occur an equally and instantaneous change of the concentration of gas phase molecules in the micropore would not follow. The delay is a function of the frictional resistance between the gas-phase molecules and the pore walls; for the molecules that collide with the pore walls frictional resistance forces act which tend to impede the mass flow of the gas molecules parallel to the walls. This resistance effect is greatest at the gas/wall contact but is transmitted to other molecules further from the wall through collisions between gas molecules. The effect decays with distance from the walls until the behaviour of the gas mass is unaffected by the surface frictional effects. For a mass of gas molecules contained within a vessel of small diameter, such as a micropore, the volume of gas that is affected by frictional resistance will be a relatively high proportion of the total gas volume. If the vessel is large enough, such as a cleat void, the gas volume affected by frictional resistance to flow might be insignificant.The greater the proportion of gas affected by frictional resistance the slower the rate of change to the gas-phase concentration spreading through the pore. Thus the size of the micropore diameters plays a role in determining the rate at which the concentration gradient changes through a micropore, and thus the rate of diffusion of the gas molecules in response to that concentration gradient, and indeed, the rate at which a net desorbtion of adsorbed methane molecules will then be experienced.

The process of diffusion of the gas-phase methane molecules out of the micropores is sometimes referred to as the desorption rate. In the strictest sense this might be viewed as a misnomer in light of the explanation of the process that take place as given above. It could be argued that the actual process of desorption is essentially instantaneous in all circumstances and that the process being described is diffusion rather than desorption. Many people do exactly this. In any event it is clear that, as long as a significant amount of gas diffusion occurs in any given coal system, that diffusion will be the rate controlling step while desorption (in the strict sense) and Darcean flow will not.

## THE BEHAVIOUR OF WATER IN COAL

At first glance it might appear that a detailed technical discussion of the type given above is somewhat out of place in the context of a session targeted towards the practical aspects of the sampling and testing of coal for coalbed methane. However, understanding of the concept given previously will allow the observers to judge for themselves the merits and significance of the results of various tests for coal that might be made. This is particularly the case when the role that water has in coal is considered.

Water in coal is a major limiting factor both for the amount of methane stored in the coal as well as the most serious impediment to the successful production of the methane that is stored. As indicated above, water is one of the byproducts of the coalification reactions so it might be found to be present in the micropores, along with the methane and other things. This water can also be adsorbed by the coal and so it might occupy sites on the coal that could otherwise house adsorbed methane. By implication there must be a water vapour phase in equilibrium with the adsorbed water in the micropores. Given the size of the water molecules in the micropores and the fact that the adjacent cleat fractures are often water saturated or nearly so at the initial stages of production, it may be difficult at first to create a water molecule concentration gradient across the cleat pore junction which would induce the water to migrate out of the pores to the cleats. The presence of the water in the pores will thus tend to impede the migration of the methane molecules out of the pores.

At any point in the coal system a water vapour concentration gradient can't be established until the free liquid water in the cleat at that point has first been removed. Thus we have one view of why it is so commonly found that coalbed methane will often require a significant period of dewatering before much methane is produced; basically the adsorption equilibrium in the pores will not change, allowing desorbtion to occur, until the adjacent and associated free liquid water is first removed. Others will state that it is first necessary to reduce the reservoir pressure to the level of the adsorption pressure before the methane can desorb and this is commonly achieved by partially dewatering the coal. This is simply a different way of saying the same thing.

## COAL TESTING FOR COALBED METHANE

The preceding discussions indicate the type of testing program that is appropriate for coalbed methane. Firstly it is necessary to obtain data and measurement of the amount of methane that is stored in the coal and this is normally achieved by taking canister samples and directly measuring the amount of methane that is liberated. Secondly it is important to obtain data concerning the types of coal that are present and their potential to have properties that are suitable for the storage of methane and, perhaps, other things. One way to do some of this is by direct observation of coal samples under a microscope and this is referred to as coal petrography. The present discussion addresses information that can be gained in a third way and that is by conducting tests in a conventional coal analytical laboratory.

The information that is required is:

A) What is the water content of the coal?
B) What is the ash content of the coal?
C) Is there likely to be a significant content of sulphur or other pollutants in the produced gas?
D) How "good" is the coal as a storage medium for adsorbed methane?
E) How does the character of the coal vary with depth at a given location or laterally within a given deposit?

We need to know the water content because the presence of water reduces the potential that the coal has to store anything else including methane and, more importantly because it is an impediment to production and the water must be disposed of.

We need to know the ash ( or mineral matter) content because the methane does not adsorb to it anywhere near as much as it does to the coal itself. Thus the coal's storage capacity for methane is reduced with increasing ash content.

The reasons for needing to know about the presence of pollutants and the methane storage capacity of the coal are obvious. Knowledge of the vertical and lateral variation of the nature of coal in a deposit help us to asses the coalbed methane production potential of that target production region.

There are two fundamental types of coal tests performed in a coal analytical laboratory. The first is referred to as a Proximate Analysis while the second is referred to as an Ultimate Analysis. The answers to most of the questions above are gained by performing Proximate Analyses on the coal.

A proximate analysis is not at all like most other types of chemical analytical procedures. The essential procedure of a proximate analysis is to weigh a certain coal sample and then to heat the sample through various stages, reweighing at each step as changes to the coal take place. The changes of weight are then fractions of the samples original weight and these fractions can then be expressed as percentages of that weight. Note that this means that the percentages quoted in the results of a proximate analysis are weight percentages and not volume percentages.

Water in the original sample thus has a major bearing on the weight percentages of the various components that are ultimately determined. However this water (or moisture) can be made to vary considerably for any given sample. The way in which moisture in the sample is treated in a given sample is referred to as the basis for analysis.

The water in any coal sample consists of:

A) Water that is held within the coal itself. This is water molecules that may be physically adsorbed onto the pores or, if chemically adsorbed, that can readily be liberated as free water, or it may simply be water molecules of the water vapour phase contained within the coal pores and which would not otherwise be regarded as free or surface moisture. This water is referred to as inherent moisture and its measurement is considered to reflect a fundamental property of the coal that is being tested. The determination of Equilibrium moisture is often considered to be a determination of the inherent moisture content. The determination of equilibrium moisture is done by first drying the coal sample and then resaturating the coal sample with water in a way that avoids the accumulation of surface moisture; the sample is placed in a sealed vessel at a specific standard pressure and exposed to air with a specific standard relative humidity and temperature. Progressive weighing of the sample until no weight change is seen indicates that the sample has accepted as much of this water as it is capable of holding.

B) In an in situ state, free (or surface) moisture is normally contained within the fracture or cleat system of the coal. It is difficult if not impossible to measure this water accurately because the water drains out of the fractures during the handling procedures from the time of sampling to laboratory testing. Sometimes the free or surface moisture is estimated by first determining the total moisture content of the sample as received and then determining the inherent moisture content in an equilibrium moisture determination. The free moisture is estimated by subtracting the inherent moisture from the total moisture but this is subject to errors as explained below.

C) During the process of sampling, especially by drilling, water that is not part of the original, in situ condition is often introduced to the sample. This is because the drilling fluids are often water based and because it is a common practice to wash any drilling mud from the sample with water once the core samples are retrieved to the surface. If a coal sample were to be taken for testing at this time it would contain the inherent moisture plus the free moisture in the fractures less any of the free moisture that is lost during the handling procedures and it would also contain any water that is artificially introduced to the sample.

In the field the core is retrieved by the drillers and placed in core boxes. Some of the coal cores are placed in canisters for gas testing and the remainder is then available for sampling and testing for other properties. As described above, the core is washed by the drillers to remove drilling mud. Sometimes the coal cores are then sampled as the hole continues to be drilled. More often, however, sampling of individual holes is delayed until the geophysical logs are available which doesn't happen until the hole is completed. This is done because the core is then still available to check with the log responses; errors can be identified and corrected and zones of core loss can be more precisely positioned. If this latter procedure is followed it means that the earliest cored seams have a longer period of time to dry out than do the later ones. Between the artificial introduction of water into the samples and the different drying periods of these samples in the field very large differences of the moisture content of each coal sample can occur.

It is very common to make proximate analyses of coal samples initially on an "as received" basis. The total moisture content of these analyses is subject to all of the non natural variation that was previously described. The results therefore mean very little if anything with respect to coal as it is in the ground, especially for moisture. This type of test actually adds little, if anything, of quantifiable value to an exploration program. An analysis that includes the equilibrium determination of inherent moisture is far more useful and does provide a basis on which to compare various coal samples.

Analyses may also be performed on a "dry" basis. In this case the coal sample is first dried under a specific set of standard conditions such that moisture is not a component of the final stated weight percentages. Only the later measured components (volatile matter, fixed carbon and ash) are considered to be components of the weight of the sample once it has been dried.

For all proximate analyses the weight percentages of the remaining components are determined in the same way. The sample is heated to a standard more elevated temperature under specified conditions to drive off the volatile matter. After this is completed the sample is reweighed to determine the weight percentage of volatiles. Note that these volatiles are in no way connected with coalbed methane which would have long since been lost or driven from the sample. These volatiles are various gasses that are generated as the coal itself is burnt.

Finally the sample is heated again to an even higher temperature to consume the remaining fixed carbon. The final weight of this sample provides a measurement of the ash content of the sample. The amount of fixed carbon that was consumed is calculated as the difference between the total sample weight minus the weights of the various other individual components of the sample.

Some analyses are quoted in an "ash free" basis. this is simply determined by calculation, leaving the weight of measured ash out of the weight percentage calculations. A similar procedure is followed for results quoted on a "mineral matter free" basis only in this case an empirical formula is used which takes into account not only the exclusion of ash but also sulphur content which is otherwise determined.

Ultimate analyses are used to measure hydrogen, oxygen, sulphur and other components of coal. The standard procedures that are followed are of the type that might be expected to be performed by a conventional wet laboratory. They are not described in detail here. The sulphur content and sometimes the phosphorus content are often stated along with the results determined in a proximate analysis. A proximate analysis plus sulphur content may be referred to as a "long prox".

The results of these tests, especially those that include inherent (or equilibrium) moisture along with sulphur provide a good basis on which to examine the variation of the coal seams with depth and laterally within any given region. The results also provide data which allow the rank or maturity of the coal to be defined and, as a result of vast historical records from similar tests all over the world, normal relationships to the amount of coalbed methane that might be expected in any sample in an in situ condition. This is because, although there are several that interplay, the coalification process forms more or less the same coal products at any stage and these products have more or less the same surface characteristics of suitable adsorption sites at any point in the maturity process. Further discussion of this point is addressed in the following presentation.

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## EXPERIENCE:

Geoff Jordan began his career as a Coal Geologist in Australia and since then has worked on coal projects in Canada, Indonesia, the U.S.A., Turkey, New Zealand, Peru, the Philippines, and Swaziland. These activities have involved both exploration and mine geology. The techniques for data collection used included direct methods (core and cuttings logging, mapping, trench logging and sampling etc.) and indirect remote sensing techniques (interpretation of borehole geophysics, high resolution seismic surveys, resistivity surveys, satellite and airborne imagery etc.). The main areas of his technical responsibility include:

- Stratigraphic interpretation and the assessment of sedimentary depositional environments of coal seams and the enclosing strata;
- Seam and strata correlation;
- Structural interpretation in simple and complex environments (both thrust faulted and wrench faulted tectonics);
- Reserve evaluation to various international codes;
- Evaluation of in-situ coal quality for mining projects including the effects of in-seam and out-of-seam dilution, pollutants such as sulphur, the assessment of chemical components such as CAO, K2O and NA2O and physical parameters such as H.G.I. as they have an impact on boiler performance in power and industrial engines;
- Evaluation of various geotechnical parameters affecting surface and underground coal mines including assessment of roof and floor stabilities, directional mining, and input into design of roof support systems; and

- Evaluation of various mining hazards including surface and underground mine in-flows, spontaneous combustion and methane emissions.

**EMPLOYMENT HISTORY:**

| | |
|---|---|
| **1979 - Present** | **Vice-President, Norwest Mine Services Ltd., Calgary, Alberta, CANADA** |
| **1977 - 1979** | **President, G.R. Jordan Consulting Services Calgary, Alberta, CANADA** |
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**PRINCIPAL PUBLICATIONS:**

- Stratigraphy and structure of the Lower Cretaceous Gething Formation of the Sukunka River Coal Deposit in B.C. Co-Author G.R. Wallis. The Canadian Mining and Metallurgy Bulletin, March, 1974.
- Planning, Environmental Protection and Reclamation Techniques on the Saxon Project Peace River Coal Block Co-Author with G.L. Hoffman, First Annual British Columbia Mine Reclamation Symposium, 1977.
- Geophysical Borehole Logging Handbook for Coal Exploration. Co-Author with G.L. Hoffman and G.R. Wallis, Pub. Coal Mining Research Centre, 270 pp., 1982.
- Geologic and Geotechnical Considerations for Longwall Mining. Government of Canada, Department of Energy, Mines and Resources, 1983.
- The Coalfields of the Northern Foothills of the Canadian Rocky Mountains. Co-Author with G.L. Hoffman, pp. 541-549, in The Mesozoic of Middle North America, CSPG Memoir No. 9, 1984.
- Status and Techniques of Coal Exploration in North America, Coal India Limited, 1986.
- Swaziland: Issues and Options in the Energy Sector, Coal representative for the Assessment Mission, UNDP/World Bank Energy Sector Assessment Program, Report No. 6262-SW, pp. 26-39, 1987.

## Coalbed Methane

Mr. Jordan has participated in several projects involving coalbed methane and methane drainage. He co-authored a report for the Canadian Department of Energy Mines and Resources titled "Detailed Review and Evaluation of Methane Prediction Techniques and Their Applicability to Canadian Coal Mines" in 1985. In the same year he co-authored, for the same agency, another report titled "Water Infusion Technology for Dust Control on Longwall Faces in the Sydney Coalfield".

He has in the recent past and is currently completing assignments for petroleum companies aimed at the commercial production of coalbed methane from coal seams within the Western Canada and other parts of the world.

# RANK VARIABILITY AND GAS PRODUCTION

## Notes on Some Fundamental Properties of Coal, the Influences on Gas Generation and Implications for Sampling

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## 1. INTRODUCTION

In any assessment of potential coal bed methane resources there are two basic questions to be answered:

- how much coal is available within the target area at exploitable depths?
- what is the potential for methane generation, retention and production from these coal seams which essentially act as both source rock and reservoir?

The first question is answered from knowledge of the frequency and geometry of the coal seams occurring within the stratigraphic sequence and is not covered here.

The second question can only be answered after gaining knowledge of the character of the coal; this includes both fundamental properties related to the physical and chemical nature of the seams as well as more empirical data related to desorption rates, fracture patterns, potential response to stimulation programs etc. In addition there is a need for more regional information such as the hydrologic regime.

The theme of this seminar series is the sampling of coal for coalbed methane evaluation. What I intend to discuss are some of the fundamental properties of coal which influence methane generation and storage and the methods of determining these properties. So what will be covered are the properties that you would be aiming to determine as a result of your sampling program. That is, the underlying reasons as to why and how you might want to sample a coal seam in the first place.

The underlying theme of this outline, and one which I am sure will be stressed by all speakers is, that despite rumours to the contrary, coal is heterogeneous; it is an organic sediment and, like most sediments, is bedded and shows variation in its properties both vertically and laterally. Consequently, any sampling program must be statistically sound, so as to take into account the variations within the deposit. I will be outlining some of the features of coal's heterogeneity, with the aim of giving you an understanding of why sampling techniques must be designed to ensure that you sample in a statistically valid manner.

## 2. COAL QUALITY

The quality of coal, like the quality of any product, is a relative term, determined by its intended use. Coal quality is defined by the degree to which its properties conform to the ideal properties for a specific process. Thus, a poor quality coal in terms of steel production may be a good quality coal for the purposes of methane generation and retention.
Many of the parameters used to define coal quality are provided by a range of analytical technologists such as chemists, fuel technologists and petrographers. But in many cases, data from different sources can be cross correlated if one understands the fundamental properties which are being determined. Furthermore, the controls on these properties are geological processes and an understanding of these processes can make estimation of these parameters possible.

Coal quality depends on the interaction of two principal sets of attributes of coal:

- Coal Rank (or level of maturity),
- Coal Type - the relative proportions of the micro-components of coal in any particular seam or sample.

The properties of a coal depend on attributes related to both rank and type; properties vary in relation to changes in either attribute. Consequently, sampling should aim to determine properties related to both factors in order to have a complete understanding of the nature of the coal.

### 2.1 Rank Parameters

A coal's rank is essentially the product of low grade metamorphism; coalification is the progressive process leading from the deposition of organic matter - principally plant debris - in a peat forming swamp, through to lignite, bituminous coals, anthracites and ultimately to graphite. This process results in significant physical and chemical changes. The stage that a coal has reached in this series is known as the rank or level of coalification. In the petroleum industry the same process, generally used in relation to dispersed organic matter in source rocks, is known as maturation.

In most countries, coals are classified and described according to the degree of change affected by the coalification process. i.e. according to their rank (Fig. 1).

There are two stages in this process; an early biochemical stage (considered to terminate at the lignite/bituminous coal boundary) and a later, geochemical stage. Methane is generated during both stages.

As the name implies, the principal agents in the transformation of vegetation to peat and to sub-bituminous coal are biological. The most pronounced changes take place near the surface in response to biological attack in a process called humification. The humic materials then go through varying degrees of gelification.

In the second, or geochemical stage, the principal controls are temperature and time; the response to burial and the existing geothermal regime. The two parameters are interdependent; long time and relatively low temperatures can produce similar results to relatively high temperatures and short burial periods (Fig. 2).

What are the changes that take place during the coalification process and what are the implications for a coalbed methane assessment?

Fundamental changes occur at the molecular level and these are mirrored in changes in chemical and physical properties (Fig.3). There is a progressive change from long chain aliphatic and alicyclic, randomly oriented molecules, to increasingly aromatised and orderd molecules. Oxygen- and hydrogen-rich functional groups are lost and as a result, the carbon content increases and the proporation of volatile components decreases. As a result of compaction and of the reordering of molecules parallel to bedding, porosity decreases and density increases. Other properties such as grindability, fluidity, etc. are also strongly influenced by progressive rank change.

Changes can also be illustrated by reference to the types of analyses commonly performed in the coal industry (Fig. 4). As a result of burial and compaction, the moisture content falls markedly, particularly in the early stages. In association with this, the carbon content and the calorific value both increase while volatile matter and hydrogen decrease with increased rank. The reflectance of the vitrinite micro-component increases regularly with rank.

As these chemical and physical properties change through the rank range, they offer potential parameters which might be used to determine the stage of coalification of any particular coal sample. Knowledge of a coal's rank, derived from one parameter, would clearly provide information about other physical and chemical properties. So one of the most important questions in any program to utilise coal is - what is the rank?

Note that none of these chemical changes occur at significant or uniform rates through the entire rank range. Up to the high volatile - medium volatile boundary the most marked changes occur in bed moisture, heating value and carbon content. At higher rank, volatile matter and hydrogen show significant decrease. It is not possible then to use a single chemical rank parameter throughout the range. Historically, calorific or heat value has been used to subdivide classes of coal in the low rank ranges up to the High Vol. - Medium Vol. boundary, and beyond this point to use volatile matter. So this presents somewhat of a problem in defining rank ranges.

There is a second problem with respect to rank parameters and this leads to a need to discuss the second group of fundamental coal properties, collectively referred to as coal "type".

## 2.2 Coal Type Variation

Coal type is controlled by the original swamp ecosystem - i.e. things such as the type of plant community, the climate, and most importantly, the groundwater level, which influences the degree of degradation of the plant material during the biochemical stage of coalification. Coal type influences coal chemistry and is also influenced by coal rank. Different components in the coal have different original properties and these properties change at different rates in response to the process of coalification or maturation. So, coal quality depends on two mutually dependent sets of properties called rank and type.

The basis for an understanding of coal type requires a brief overview of coal petrography. The micro-components of coal can be grouped into organic macerals and inorganic minerals. The macerals can be subdivided into 3 groups on the basis of the botanical precursors and/or changes that have occurred in the earliest stages of diagenesis:

- Vitrinite - derived from woody tissues and having undergone varying degress of humification and gelification,
- Inertinite - generally also derived from woody tissue, but having suffered relatively high degrees of oxidation as a result of forest fires, excessive attack by fungi and bacteria or transport in turbulent and oxygenated waters,
- Liptinite - a group derived from the waxy and resinous parts of plants such as spores, cuticles, pollens, resins, waxes, and also from fresh water and brackish algae.

In petroleum source rock terminology these three groups correspond to types II, III, and IV kerogens respectively,

- Minerals - contained either within clearly defined clastic beds within a seam, finely dispersed within the coal matrix, or within fractures. In analyses, minerals are commonly referred to as "ash", as this component represents the residue from combustion of the coal.

There are many morphological subdivisions used by petrographers, but no further discussion is necessary here. What is important is that these microcomponents are chemically and physically different from each other and consequently, their relative proportions will affect all quality parameters. Fig. 5 illustrates properties of the three major maceral groups in four seams of different rank from Germany. Note that the values are different for each maceral and that these differences decrease with increased rank. In relation to methane generation, it can be seen that there are significant variations in volatile matter and hydrogen content. The inertinites most probably generate little or no methane during coalification; vitrinite will generate substantial volumes, and liptinite will generate the most. Unfortunately, liptinite is generally a minor component.

The relative proportions of inertinites and vitrinites can vary significantly between seams and within seams (Figs. 6 & 7) and consequently, it can be expected that quality parameters will also vary within and between even those seams of similar rank.

To illustrate the interdependency of coal rank and type on chemistry we can look at other examples:

- H/C and O/C ratios display different "coalification tracks" in the different maceral groups. With increasing rank both ratios decrease, but from different initial values and at different rates in the maceral groups (Fig. 8)

- Volatile Matter is quite variable when plotted against a rank parameter and a type parameter (Fig. 9). V.M. decreases with rank up to a vitrinite reflectance of 1.7% (in the Low Vol. Bituminous coals), but at any specific rank level, V.M. increases with the proportion of "reactive" macerals, i.e. vitrinite + liptinite.

The most important thing to note is that given any absolute rank parameter, chemical and physical properties will vary depending on the relative proportions of the coal's microcomponents. But, as mentioned above, Vol. Matter has been used as a rank parameter and it is clear that it is not an absolute parameter. Given a V.M. content, definite correlation with other properties is not accurate unless a type parameter is also known (Fig. 9). So, this leads to the need for a more absolute rank parameter, one that is independent of coal type. This has led to the common use of vitrinite reflectance as a rank determinant.

## 2.3 Vitrinite Reflectance - An Independent Rank Parameter

As mentioned above, vitrinite is the component derived from woody tissue and not subject to excessive oxidation. It is present in varying amounts in all coals and is frequently present in small amounts as dispersed fragments in many non-marine and near-shore marine sediments.

What is measured, via a microscopic technique, is the relative amount of the incident light that is reflected back from the surface of a polished sample. By use of sophisticated optics and electronics, it is possible to accurately measure the small proportion of reflected incident light at levels above 0.3%. Vitrinite reflectance increases regularly and, in terms of our measuring capability, significantly throughout the rank range, (e.g. Fig. 10). Unlike chemical analyses it is not a bulk property, but a property of a microcomponent of the coal and is thus independent of the nature of the seam, or the portion of the seam sampled. As such, it provides an independent rank variable. Besides being a good rank parameter, the technique has several advantages:

- only very small samples are required,
- vitrinite is present in virtually every coal sample and often dispersed in clastic sediments,
- the technique, although requiring expensive equipment, is relatively fast and has very good reproducibility,
- it is widely used in both the coal and petroleum industries.

Further, and very importantly, vitrinite reflectance can be correlated with many other properties. Where coal type is not known, a fairly narrow range of properties can be assessed from V.R. alone. When a type parameter is known, then the range of values in other parameters can be more accurately defined. For example, given reflectance of 1%, we can estimate V.M. as between 21% and 32% (Fig. 9). But, given an additional type parameter such as vitrinite + liptinite = 50% , we can estimate V.M. at about 31%, (Fig. 9). Conversely, given V.M. and V.R., we can predict a type parameter and then estimate many other chemical and physical properties.

## 3. SAMPLING IMPLICATIONS OF RANK AND TYPE VARIATIONS

### 3.1 Rank

If vitrinite reflectance is the chosen rank parameter, then there are few problems for the sampler. Vitrinite is ubiquitous and its reflectance is independent of seam composition. So, any small sample of coal from a particular horizon will provide an accurate assessment of V.R. in a seam. So, samples can come from core, outcrop or cuttings. In addition, it is not even necessary to sample coal. There are often sufficient coaly fragments in clastic sediments to allow the determination of V.R. This is a common practice in the petroleum industry.
Clearly a coal core is the best sample, as we can be certain of its position in the stratigraphic sequence and we have plenty of sample to choose from.

Cuttings are subject to contamination by caving and in the devices that trap cuttings for sampling at the well. However, where logs indicate the presence of coal and this is confirmed by abundant cuttings, one can be fairly certain of the position of the sample. One thing to be very careful about is that cuttings have not been excessively heated during drying. As mentioned previously, V.R. is dependent on rank which is a function of heat and time. Excessive heat, essentially temperatures higher than the sample has experienced in the ground, will adversely affect V.R. and increase it. Fortunately, the optical properties of vitrinite are fairly sensitive and an experienced analyst will detect anomalous heating.

V.R. derived from non-coal horizons are useful, but it has to be borne in mind that there will be differences between V.R. values derived from shales, sandstones, thin coals, and thick coals. This is due to differences in the heat conduction and retention of the different lithologies. These variations still yield closely approximate values and analyses from different sources can be mixed successfully provided that one doesn't search for ultimate accuracy throughout the succession.

In the case of using other rank parameters, it has already been noted that they are not independent of the composition of the sample. So, if a grab sample is used, e.g cuttings or a small sub-sample from core or outcrop, then this will not be representative of the whole seam. It does provide an approximate figure and fortunately, a reasonably accurate one, provided coal type is not particularly abnormal. But one must bear in mind the effect of the possible range in the analysed rank parameter upon any calculations that might be made with regard to other properties such as gas generation, porosity, permeability, etc.

## 3.2 Coal Type

Coal type can vary significantly within a seam or between seams (e.g. Figs. 6 & 7) and, due to the interdependence of rank and type, it is useful in any sampling program to have some knowledge of type variations, or at least of the chemical and physical responses to these variations. Thus it is useful to sample different portions of the seam, and essential to sample in a statistically accurate manner.

The zones in a seam which are likely to have different properties are definable by macroscopic observation of the seam section. Coal geologists produce visual profiles of seams, based on a relatively simple system, that subdivides the sequence on the basis of the relative proportions of bright and dull components. Typically, a relatively fresh surface of coal will show rather fine scale banding on the mm to cm scale, in which very lustrous bands are interbedded with very dull bands. These simple differences reflect underlying compositional differences. The very bright components often contain nothing but vitrinite while the very dull bands may contain abundant inertinite, mineral matter and liptinite. Fig 11 illustrates differences in maceral composition of the lithotypes from an Australian seam. So, a lithotype classification is used that asigns sub-units of the seam to classes based on the relative proportions of light and dull bands in the sequence. This provides a vertical profile of the seam which is useful in correlation, and also frequently serves as the basis for sampling (Fig. 12). (Refer to further discussion in Field Trip Notes).

Of course, if one is only interested in the bulk composition of the whole seam, then there may be no incentive to sub-divide the seam for analysis. What is important here is to somehow ensure that the sample of the seam is statistically representative, i.e that the sample submitted for analysis is a weighted average of each part of the seam, proportional to its thickness (and therefore volume). In practice, this is most easily accomplished by working with sub-sections of the seam. It is quite difficult to sample a full seam section by consistently taking a given portion, e.g. 1/4 of the core or say a channel 5 cm wide and 5cm deep at outcrop. The best approach is to be consistent within a small subsection of the seam and to record the thickness of each subsection. At the lab, statistical portions of each sub-section can be recombined on a weighted basis into a single composite sample. Sub-dividing the seam on the basis of inorganic partings and zones of similar lithotype composition allows for ease of sampling (as individual units are relatively thin) and also provides a series of samples which are likely to encompass the range of coal type within the seam. (further notes on sampling accompany the Field Trip Guide).

## 4. IMPLICATIONS OF RANK AND TYPE FOR METHANE GENERATION AND STORAGE

Methane is formed during both stages of the coalification process; as a result of the biochemical alteration of vegetation in the earliest stages (biogenic methane) and by thermal degradation of organic matter during the second or geochemical phase (thermogenic methane). Diagenetic methane is produced in the range 20 to 50 C (Fig. 13) and if subsidence and burial are rapid, can be trapped in shallow reservoirs. Much greater volumes are generated during the thermogenic stage which commences in coals (humic sources) around 90 C and reaches a peak at around 150C (Fig. 13), at approximately the high vol - medium vol. boundary (Fig. 14).

Relationships have been determined between coal rank and the volume of methane generated during its coalification. Meissner (1984) determined the relationship shown graphically in Fig. 15

$$\text{Vol. } CH_4 \text{ (cc/gm)} = -325.6 \text{ Log(\% Vol. Matter[daf]/37.8)}$$

The $CH_4$ is assumed to be at 20 C and 1atm. By the anthracite stage, a typical coal has generated over 300cc/g of methane (Fig.

15).

It has been noted above that volatile content is also dependent upon coal type. What are the implications of type variations on calculations of methane generated?

For example, suppose we were told that a coal seam had a vitrinite reflectance of 1.1% but that composition was unknown. If we assume that the sample is not extreme in its composition; let's say it is like most coals, with between 25% and 75% vitrinite + liptinite, then Vol. Matter could lie between 26% and 29% (Fig. 9). This would result in calculated cumulative methane generations of 52.6 and 37.5 cc/gm respectively; a difference of 40% of the lower figure. This is quite a significant variation. Within a seam, sub-sections could show even wider variation in coal type and methane generated. Fig. 13 also illustrates the influence of organic matter type; the sapropelic source (i.e. liptinite-rich) generates a greater volume of methane, over a somewhat wider temperature range, than a humic source (i.e.vitrinite-rich). The composition of the overall gases generated is also different between the two different types.

Meissner (1984) has also shown that pore volume storage is at a maximum in the low rank coals and decreases to a minimum in the semi-anthracite range; sorbed volume storage capacity is greater than pore volume capacity at ranks above low volatile bituminous (18% V.M.). The adsorptive capacity and estimated maximum producible methane content are both a product of coal rank and burial depth. Increased depth usually means higher rank and pressure; higher rank results in more gas generated and higher pressure means higher retention capacity (see Figs. 16 and 17).

Rank also influences the density, internal surface area, hardness and grindability (Figs. 3 & 18); all important parameters in generation and production of methane.

Bell and Jones (1989) found that unconfined compressive strength of coal varies with rank (volatile matter, Fig. 27), and that there was a good correlation with the Hardgrove Grindability Index (a common test in the coal industry, Fig. 28), which is strongly influenced by coal type. The compressive strength is at a minimum in the gassiest coals i.e. around 22% V.M at the medium vol. - low vol. boundary. During production, coal gas wells often produce large volumes of fine coal particles which cause problems with production equipment, especially after fracturing. Weak coal strata can also result in extensive caveing of the hole during drilling.

What sort of information could a seam profile contribute ? First, the position of clastic beds and their proportion is defined. The clastics generate no gas and because of their common, very fine grained nature, probably store little gas. As such, without joints across these beds, they effectively seal sub-portions of the seam.

Secondly, subdivisions of the coal portion also provide information. The dull sections are more likely to contain more ash than the brighter horizons and will most likely be richer in inert macerals and so have lower propensity to generate gas. They may be a little more porous due to the character of inert macerals. They will likely be less brittle and so may exhibit a lower frequency of cleat spacing and be subject to different behaviour during fracturing. Compressive strength will be higher.

Conversely, the brighter components will be richer in gas generating macerals, will have closer-spaced cleat (and higher permeability) and be very brittle. These zones will typically have low strength and produce more fines in response to induced fracturing and may cause caving problems and excessive wear on downhole equipment.

The inorganic material in the coal has a significant influence on gas generation and storage. It has been found that gas content of coal has an inverse relationship to the proportion of contained ash (e.g. Law et. al. 1989).

Finally, an assessment of coal type will allow a more accurate determination of the many parameters that, although primarily rank-dependent, most probably have a significant type component.

Even if you were not interested in analysis on a sub-sectional basis, a log of the seam on a compositional basis may provide an excellent framework for future information such as yields, fracturing, production problems, etc.

# 5. GEOLOGICAL CONTROLS ON RANK AND TYPE AND PREDICTION/ PROJECTION OF THESE DATA

## 5.1 Controls on Rank

Coal rank is a function of heat and time, so it is dependent on depth and duration of burial plus the paleogeothermal regime. So it is influenced by the depositional and post-depositional history of the basin.

In general, coal rank as measured by any of the available parameters will increase with increased age and depth in the stratigraphic succession. The rate of increase will vary depending on the time-burial-temperature history of the basin. By sampling through the sequence, a reflectance depth profile of a well or stratigraphic section can be established (Fig. 19). By determining a best fit curve (usually first order in shallow sequences and second order in deeper sequences), it is possible to relatively accurately interpolate the rank of other horizons within the sequence and even project (although less accurately) to lower or higher parts of the sequence.

It should be noted that where sections are reduced or repeated by faulting or removed at unconformity surfaces then there will be an hiatus in the depth-rank profile (Fig. 20).

What about projections laterally across the basin? With sufficient data points (measured or interpolated) within a selected stratigraphic horizon, a contour map of the chosen rank parameter could be constructed. This would allow estimates of rank at that horizon in areas between sample locations (e.g. Fig. 21).

Even with a lot less data you may be able to project rank information provided you have an understanding of the structural disposition of the selected horizon and an understanding of the relative timing of coalification. Depending on basinal history, the target horizons may have attained their present rank level before or after structural deformation took place. This gives rise to the terms pre- and post- deformational coalification.

If a coal seam had been buried deep enough and long enough to attain its present rank before it was folded or faulted (pre-deformation coalification), then the seam will have the same rank no matter at what stratigraphic level it is now found (Fig. 22a), i.e. iso-rank parallels the iso-structure surfaces. Development of reflectance is not reversible, i.e. if the seam is uplifted it will not decrease its reflectance over time. Reflectance will still mirror the response to its former maximum burial. If buried deeper than previously then the rank process can start afresh.

With post-deformation coalification, deformation occurs before an appreciable portion of the coal's ultimate rank was attained. So, most of its rank development takes place after deformation and after the seam was placed into an irregular geometry as a result of folding or faulting. Iso-rank lines will be sub-horizontal (Fig. 22b).

From an exploration viewpoint, the implications are quite important. If coalification was primarily complete before folding and faulting then any specific seam will maintain its rank relatively constant regardless of variations in its structural elevation (Fig. 22a). If coalification occurred substantially after deformation, then iso-rank surfaces will be sub-horizontal and in any particular coal bed, the rank will increase with present day depth. So, if it could be deduced which of these extremes was operating, you could extrapolate simply; e.g. pre-deformational, the seam will have the same rank over a large area; if post-deformational, a seam's rank will depend on present depth and the rank-depth relationships established in sections and wells. Examples of pre- and post-deformational coalification regimes are shown in Figs. 23 & 24).

Of course, the situation is somewhat complicated by the fact that either extreme is rarely realised and there will be a component of both pre- and post-deformation coalification (Fig. 22c). This can be calculated however, and the result incorporated into a scheme for predicting rank in poorly known locations.

## 5.2 Controls on Type

There are often extremes of variation within the profile of a particular seam, e.g. very bright coal that may be 90% or more reactive macerals and no ash to a very dull section with very high inert maceral component, perhaps greater than 80% as well as a high mineral content. This reflects extreme variations in conditions within the precursor peat swamp during its development. The full seam composition is generally much less variable and seams in stratigraphic proximity often have quite similar composition. This is because the overall controls on coal type arise from climate, vegetation, the broad tectonic setting and, at a more detailed scale, from the particular sedimentological setting. For instance, major coal formation did not occur until land plants had evolved, and major coal formation is restricted to relatively few periods within the geological record (the Permian in the southern hemisphere, Carboniferous and Cretaceous in the northern hemisphere).

Coals deposited in foreland basins are brighter, and thus contain more reactive macerals than those deposited in stable shelf environments. In addition, paralic basins contain by far the dominant proportion of the world's coal reserves and within these basins the foredeep zones are richest in coal (Fig. 25).

It is also becoming apparent that coals deposited in similar depositional sites have similar type. Fig. 26 is based on Australian data, but Canadian data are being found to fit reasonably well (e.g. Kalkreuth and Leckie 1989). The axes here are not important; sufficient to say that they are parameters derived from microscopic analysis and contrast the degree of gelification with the degree of preservation of woody plant tissue. Broad fields of distinctive composition can be related to broadly defined sites of accumulation of the peat: back barrier - lower delta plain - upper delta/alluvial plain - and piedmont plain. So the assumption can be made that, given knowledge of coal type and associated chemistry from a particular seam, one could predict similar properties from seams developed in similar depositional settings.

## 6. SUMMARY

In any coalbed methane resource assessment, the two groups of required information relate to the volume of coal available and to the quality of the coal in terms of its ability to generate, store and yield up its gas.

The volume of the coal resource is based on knowledge of the geometry and frequency of the coal beds within the succession. Many of the properties related to gas generation, retention and production are dependent on two groups of coal attributes, namely rank and type. These two groups of properties are mutually dependent. The chemical and physical properties of the coal vary, depending on the relative proportions of the contained coal macerals and inorganic minerals and also, depending on the rank, of the coal.

The primary determinant of gas generation is coal rank which is essentially constant within a seam at a particular location. Rank parameters are influenced by type variations and due, to the heterogeneous nature of coal, it is important to ensure that sampling regimes recognise the vertical and lateral variations in coal composition as well as the variation in rank in response to the structural history of a basin.

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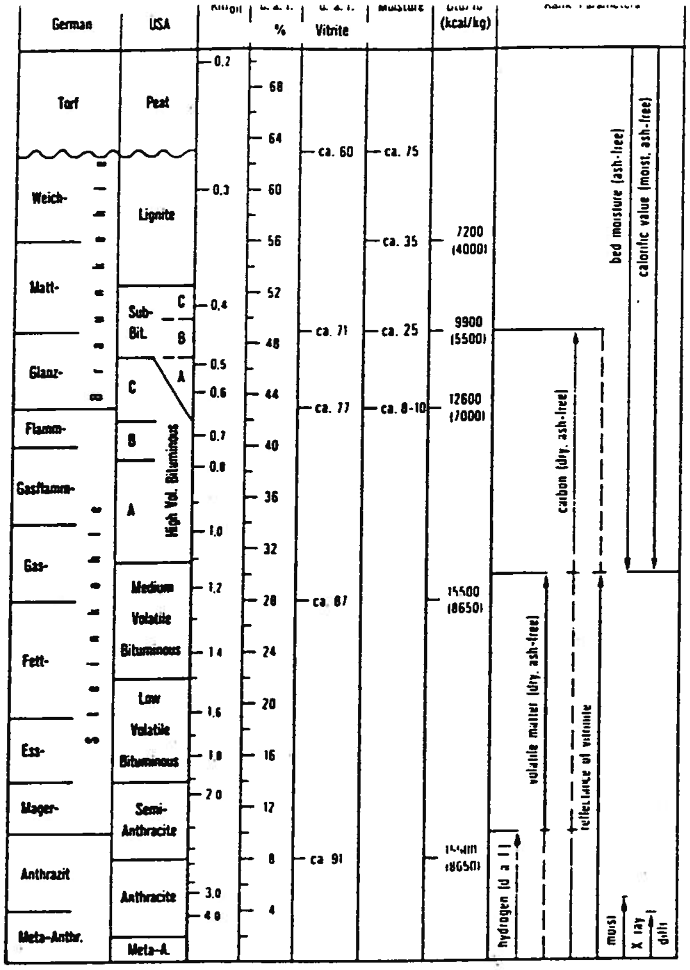


Fig. 1 Rank-based classification of coal according to German (DIN) and North American (ASTM) systems and associated variations in chemical and optical parameters (from Stach et. al., 1982) .

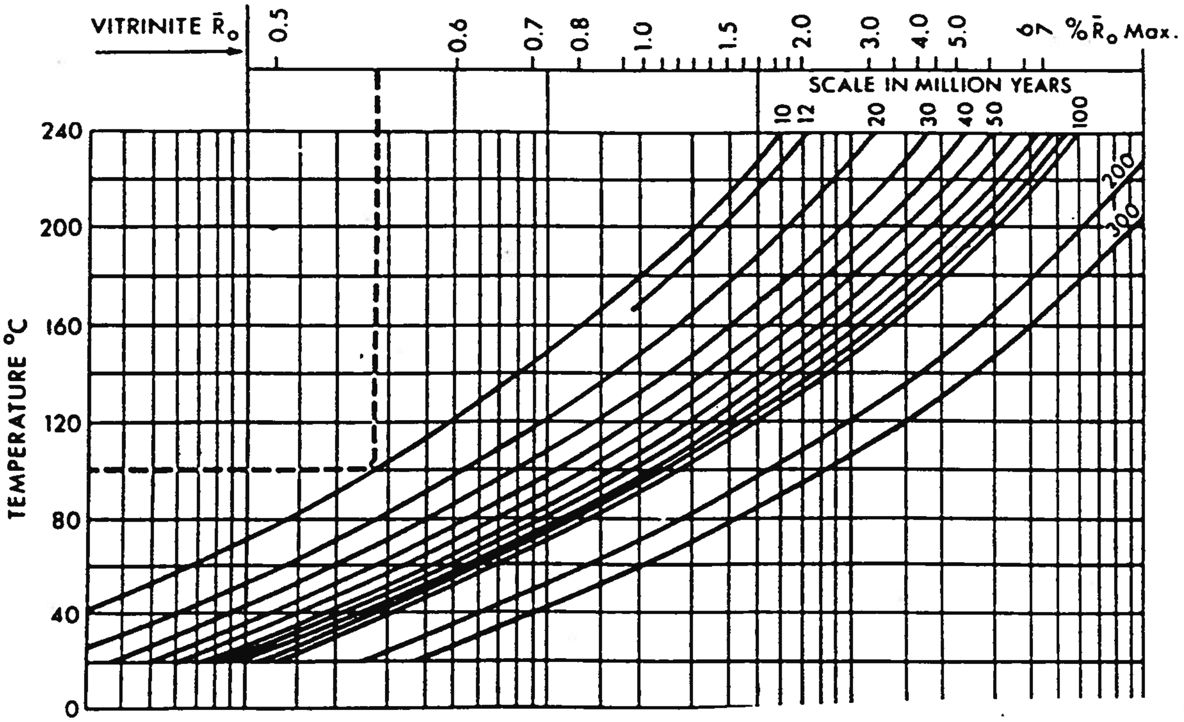
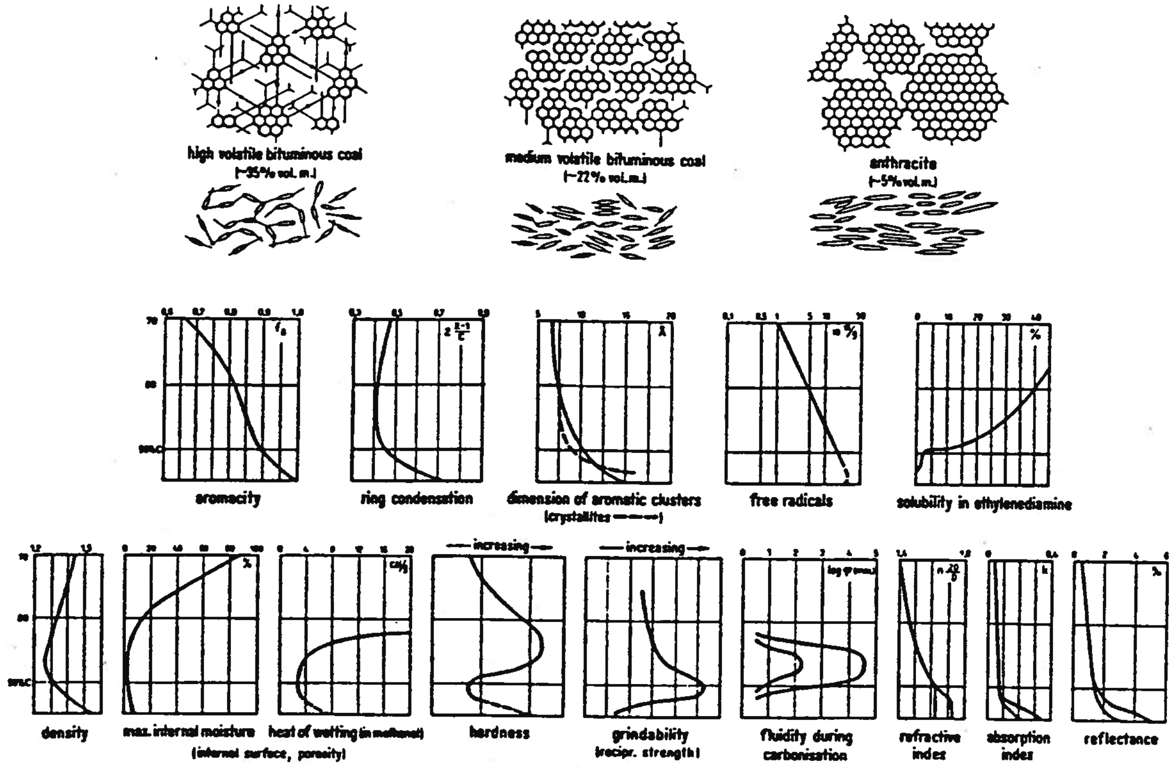


Fig. 2 Relationship between coal rank (vitrinite reflectance), time and temperature of coalification (from Bustin et. al., 1983)



first row: molecular structure
−o− = hydrogen bonding
— = molecular bonding

second row: orientation of molecules perpendicular to the bedding plane
lenses = aromatic clusters
lines = non-aromatic elements

third row: development of chemical properties in relation to carbon content (daf)

fourth row: development of physical properties in relation to carbon content (daf)

Fig. 3 Changes in molecular, chemical and physical properties of vitrinite during coalification (from Stach et. al., 1982)

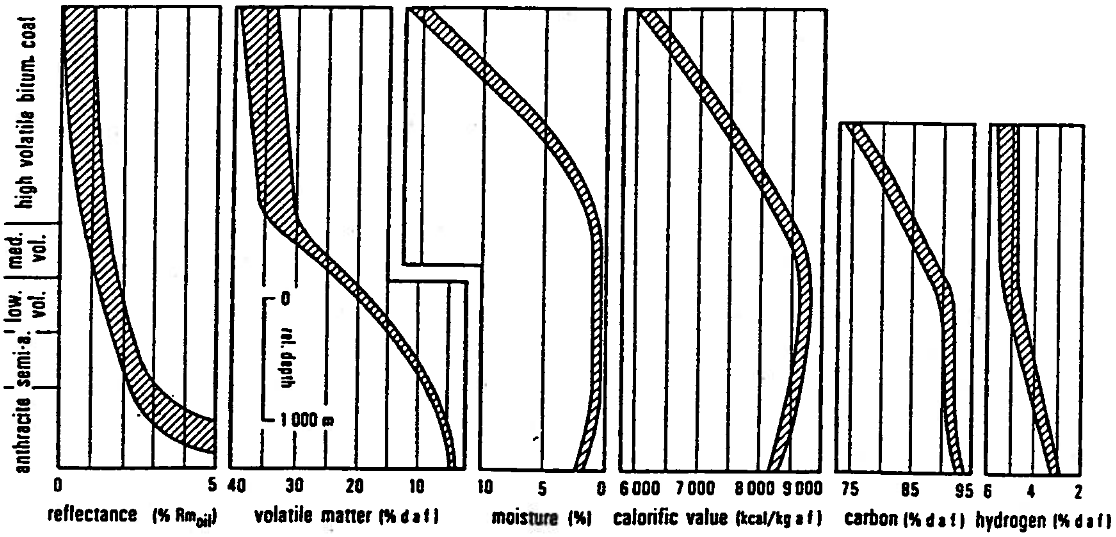
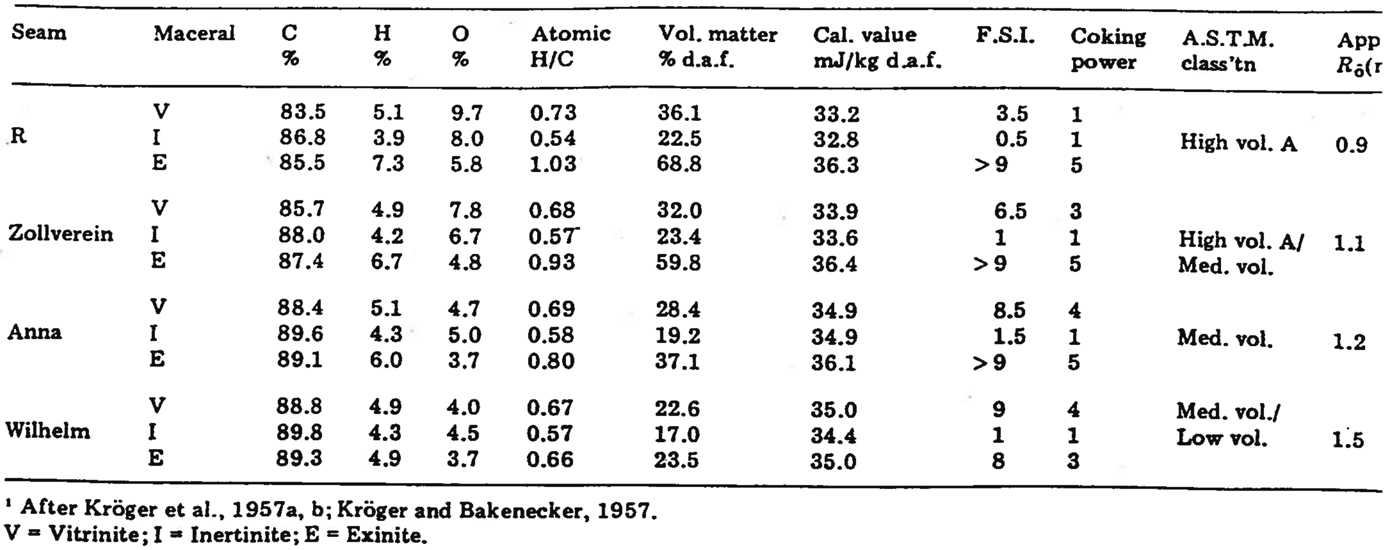


Fig. 4 Changes in optical and chemical properties of vitrinite with increased ranks. Based on analyses from deep boreholes in Germany (from M & R Teichmuller, 1967)



| Seam | Maceral | C % | H % | O % | Atomic H/C | Vol. matter % d.a.f. | Cal. value mJ/kg d.a.f. | F.S.I. | Coking power | A.S.T.M. class'tn | App $R_0$(r |
|---|---|---|---|---|---|---|---|---|---|---|---|
| R | V | 83.5 | 5.1 | 9.7 | 0.73 | 36.1 | 33.2 | 3.5 | 1 | High vol. A | 0.9 |
| | I | 86.8 | 3.9 | 8.0 | 0.54 | 22.5 | 32.8 | 0.5 | 1 | | |
| | E | 85.5 | 7.3 | 5.8 | 1.03 | 68.8 | 36.3 | >9 | 5 | | |
| Zollverein | V | 85.7 | 4.9 | 7.8 | 0.68 | 32.0 | 33.9 | 6.5 | 3 | High vol. A/ Med. vol. | 1.1 |
| | I | 88.0 | 4.2 | 6.7 | 0.57 | 23.4 | 33.6 | 1 | 1 | | |
| | E | 87.4 | 6.7 | 4.8 | 0.93 | 59.8 | 36.4 | >9 | 5 | | |
| Anna | V | 88.4 | 5.1 | 4.7 | 0.69 | 28.4 | 34.9 | 8.5 | 4 | Med. vol. | 1.2 |
| | I | 89.6 | 4.3 | 5.0 | 0.58 | 19.2 | 34.9 | 1.5 | 1 | | |
| | E | 89.1 | 6.0 | 3.7 | 0.80 | 37.1 | 36.1 | >9 | 5 | | |
| Wilhelm | V | 88.8 | 4.9 | 4.0 | 0.67 | 22.6 | 35.0 | 9 | 4 | Med. vol./ Low vol. | 1.5 |
| | I | 89.8 | 4.3 | 4.5 | 0.57 | 17.0 | 34.4 | 1 | 1 | | |
| | E | 89.3 | 4.9 | 3.7 | 0.66 | 23.5 | 35.0 | 8 | 3 | | |

[1] After Kröger et al., 1957a, b; Kröger and Bakenecker, 1957.
V = Vitrinite; I = Inertinite; E = Exinite.

Fig. 5 Differences in chemical and physical properties of the major maceral groups in four German seams ( from Stach et. al., 1982)

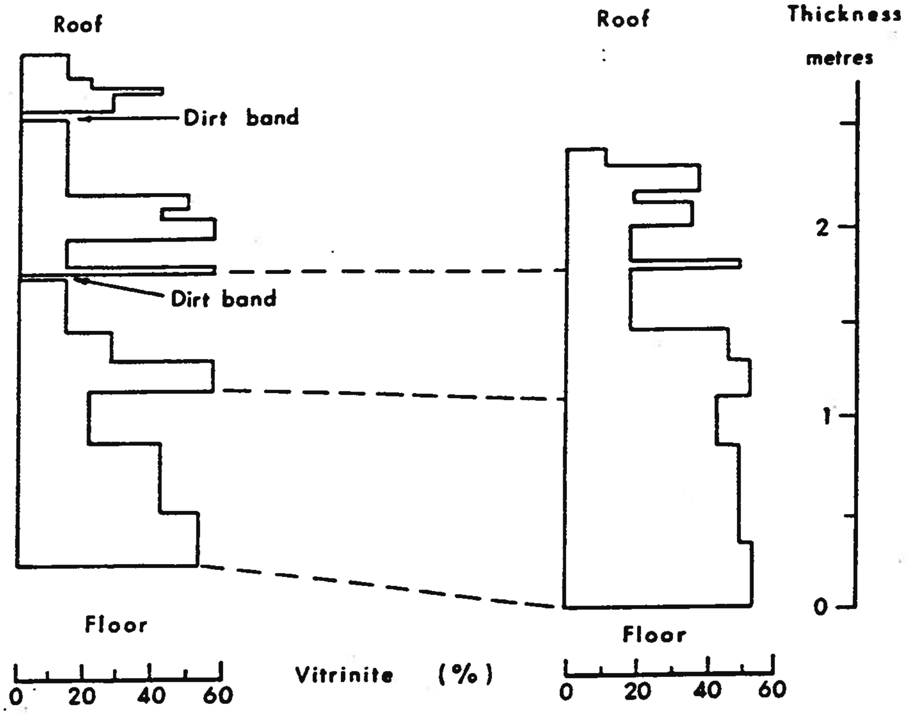


Fig. 6 Vitrinite content in profiles of the Bulli Seam, Sydney Basin, Australia (from Shibaoka & Smyth,1975)

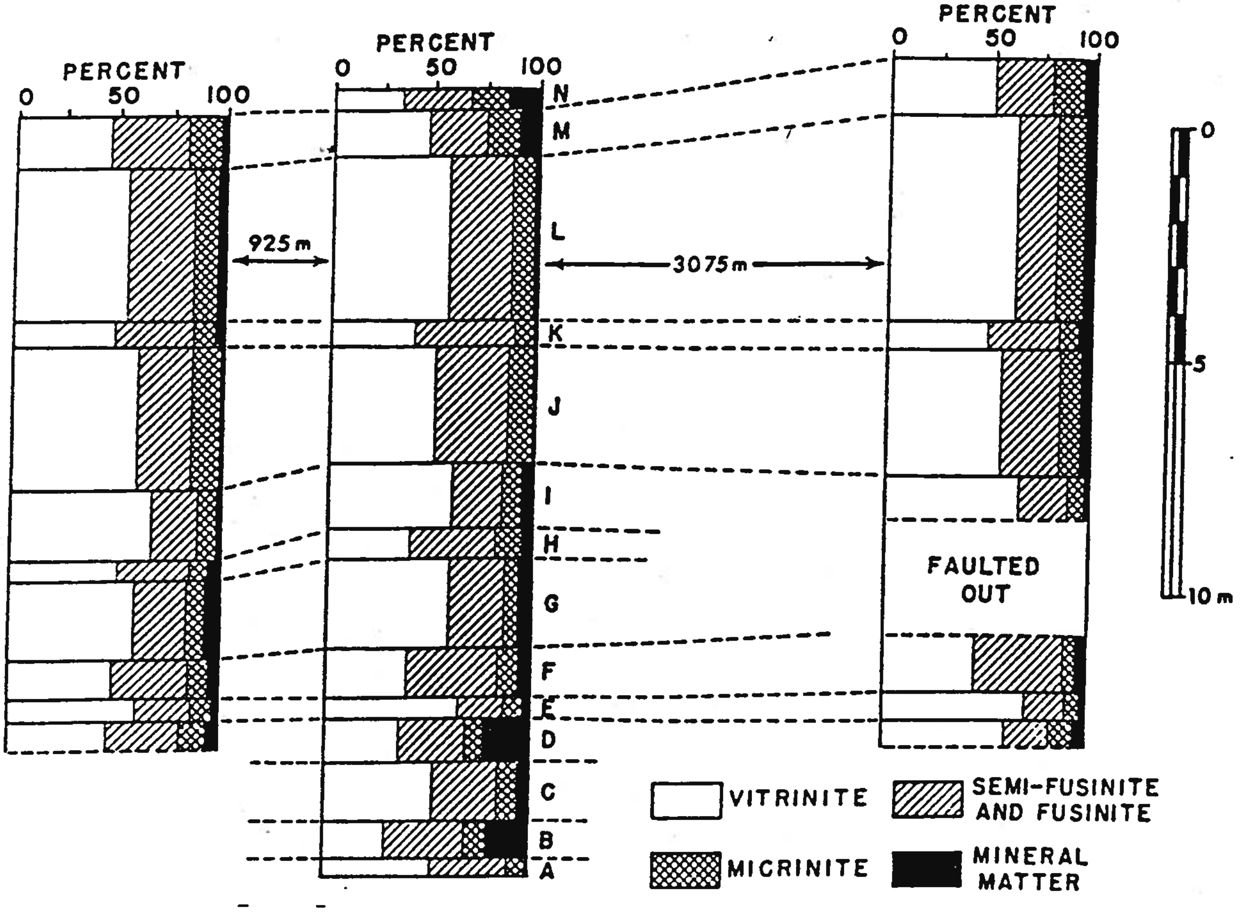


Fig. 7 Maceral variation in profiles of the Balmer Seam, Fernie Basin, S.E. British Columbia (from Cameron and Babu, 1968)

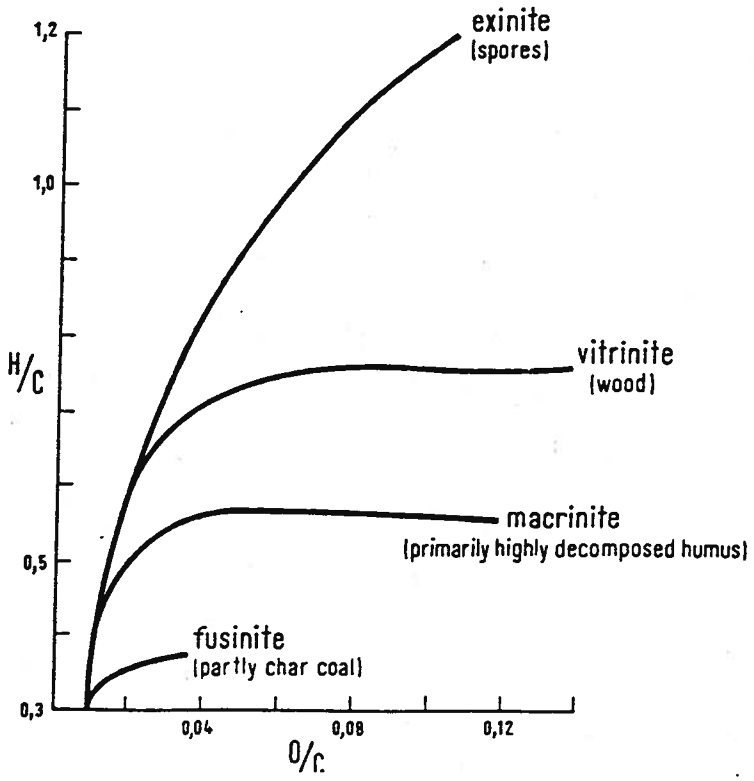


Fig. 8 Coalification tracks of different macerals based on H/C:O/C atomic ratios (from van Krevelen, 1961)

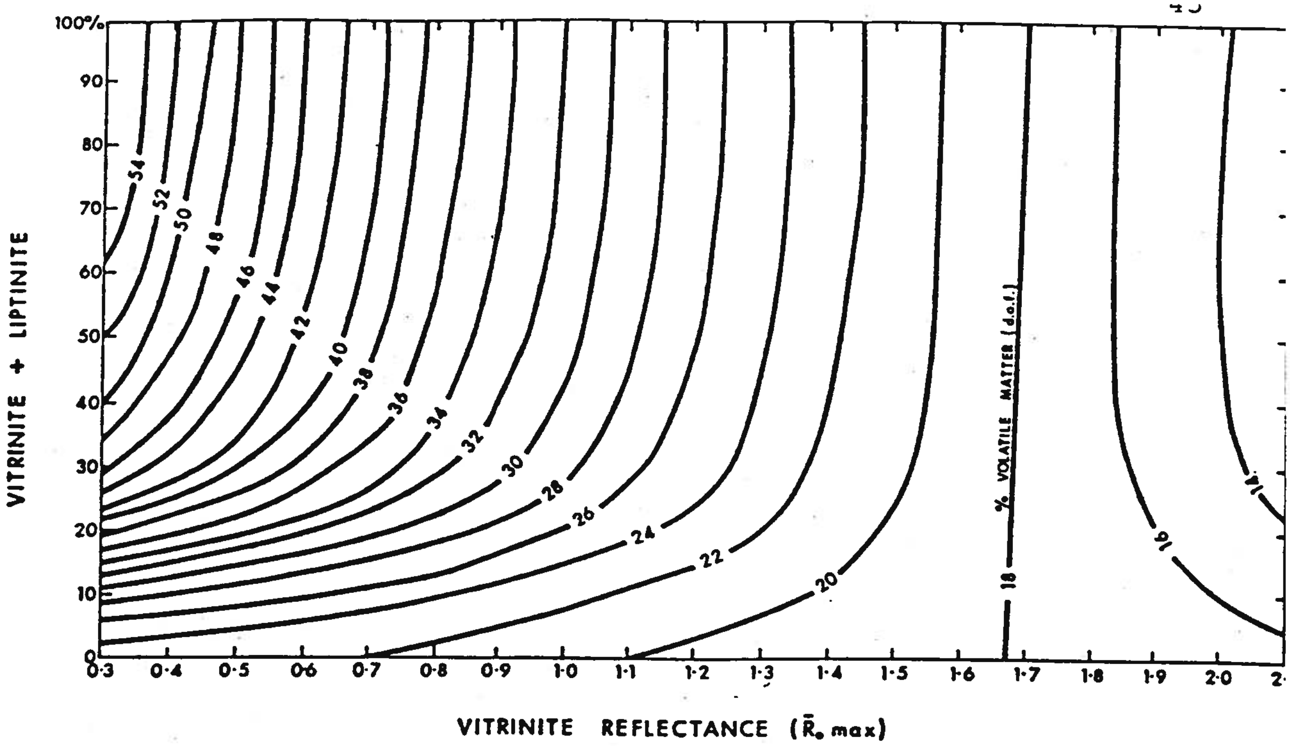


Fig. 9 Volatile matter contents of Australian coals as a function of coal rank (vitrinite reflectance) and coal type (vitrinite + liptinite content) (from Strauss et. al., 1976)

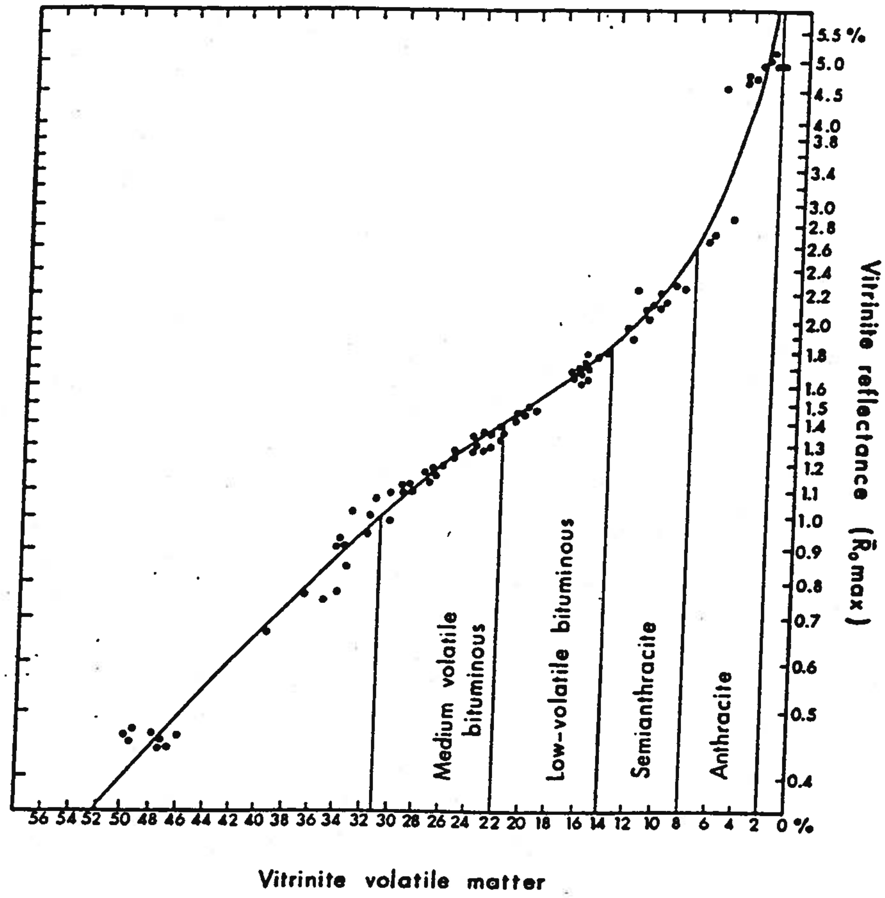


Fig. 10 Relationship between volatile matter and reflectance of vitrinite for European coals. A.S.T.M. rank categories also shown (from Kotter, 1960; Cameron, 1975)

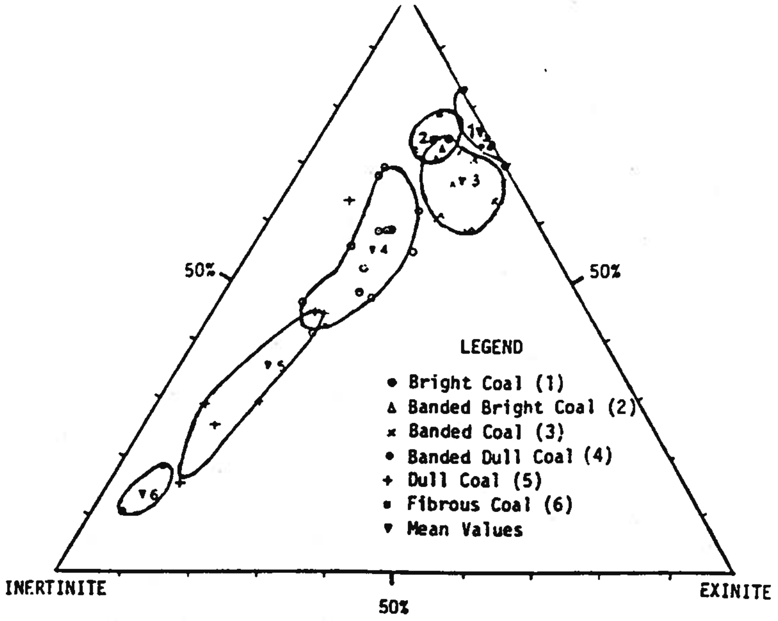


Fig. 11 Ternary diagram depicting range and mean compositions of lithotypes in Liddell Seam, Hunter Valley, Australia (from Marchioni, 1980)

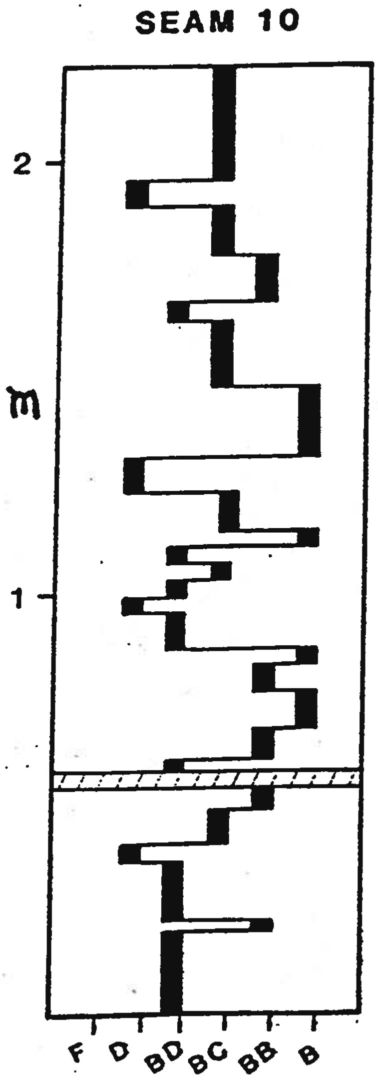


Fig. 12 Lithotype profile of #10 Seam, Gates Formation, Smok River Mine, N.E. British Columbia (from Marchioni an Kalkreuth, in press)
F = fibrous coal
D = dull coal
BD = banded dull coal
BC = banded coal
BB = banded bright coal
B = bright coal

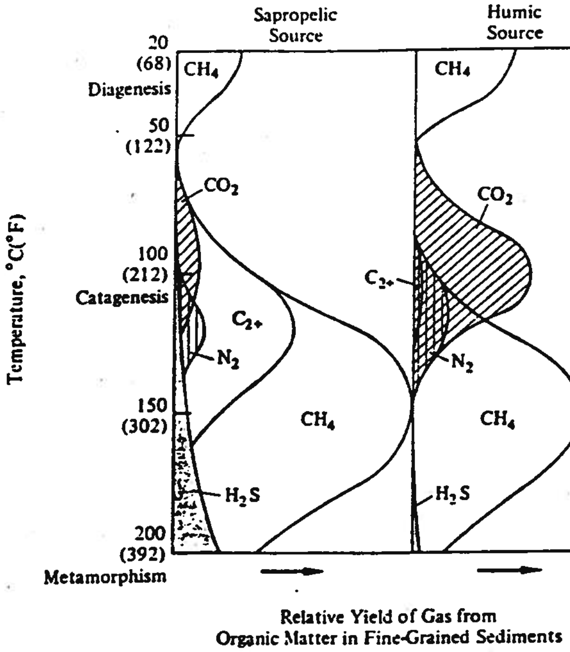


Fig. 13 Methane generation relative to burial temperature and source material (from Hunt, 1979)

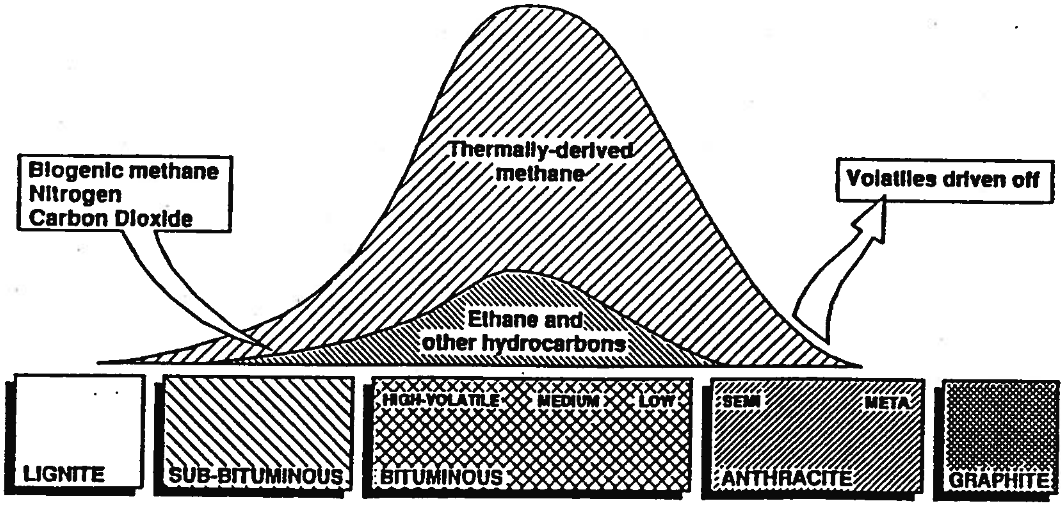


Fig. 14 Gas generation in coal in relation to rank classes

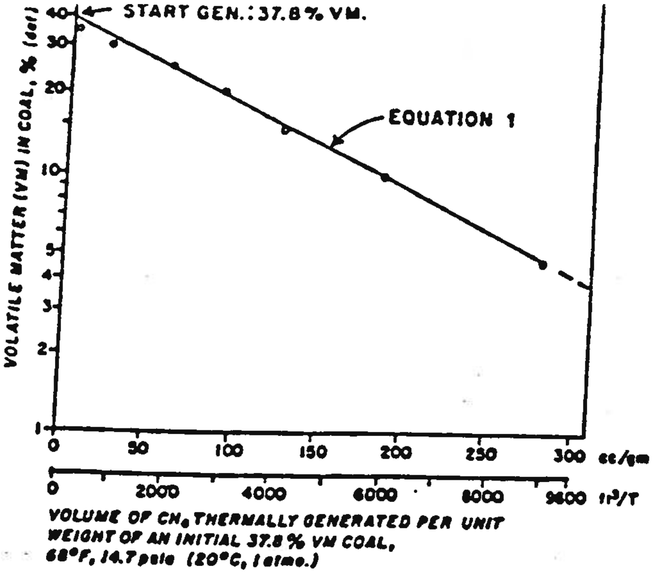


Fig. 15 Graph of log volatile matter (V.M.) in coal versus linear volume of generated methane (from Meisner, 1984; data of Junglen & Karweil, 1966, daf = dry and free)

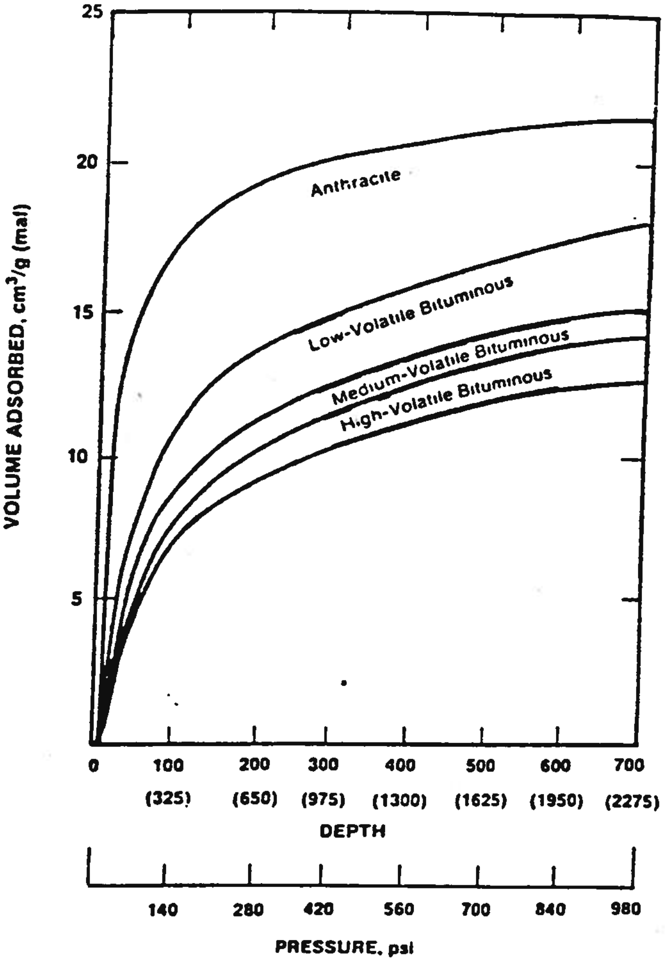


Fig. 16 Adsorptive capacity of coal as a function of depth and rank (from Kim, 1977)

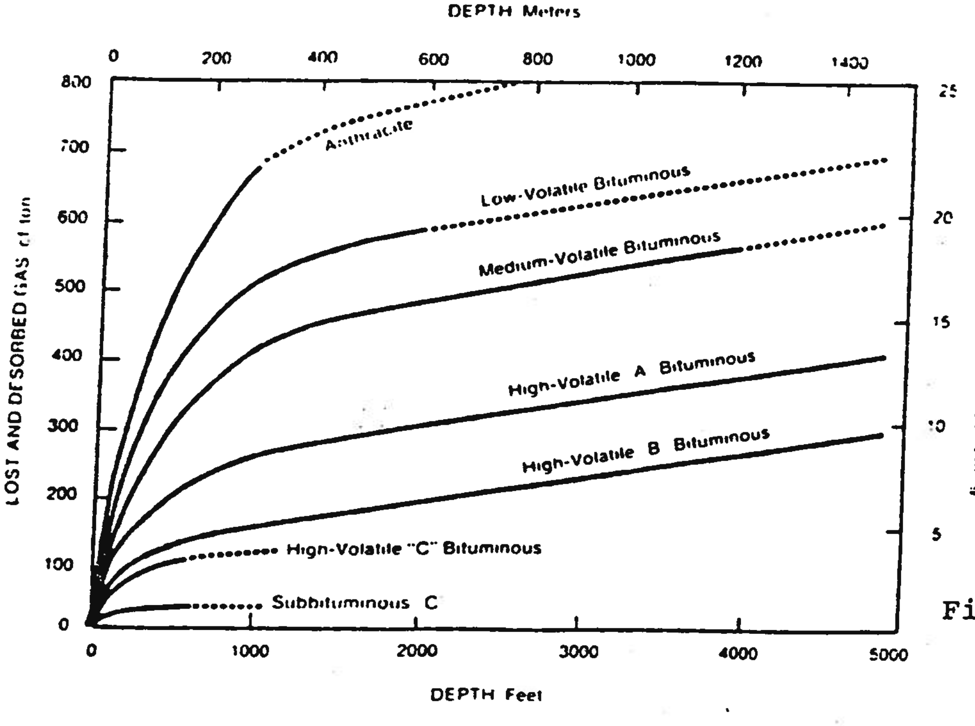
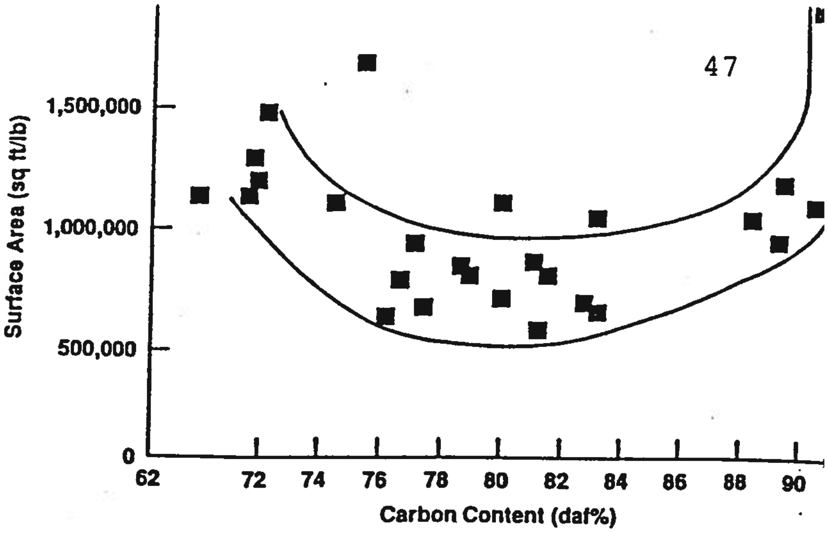


Fig. 17 Estimated maximum producible methane content relative t depth and rank (fr Eddy et. al., 1982

Fig. 18 Internal surface area of coals relative to rank (carbon content)



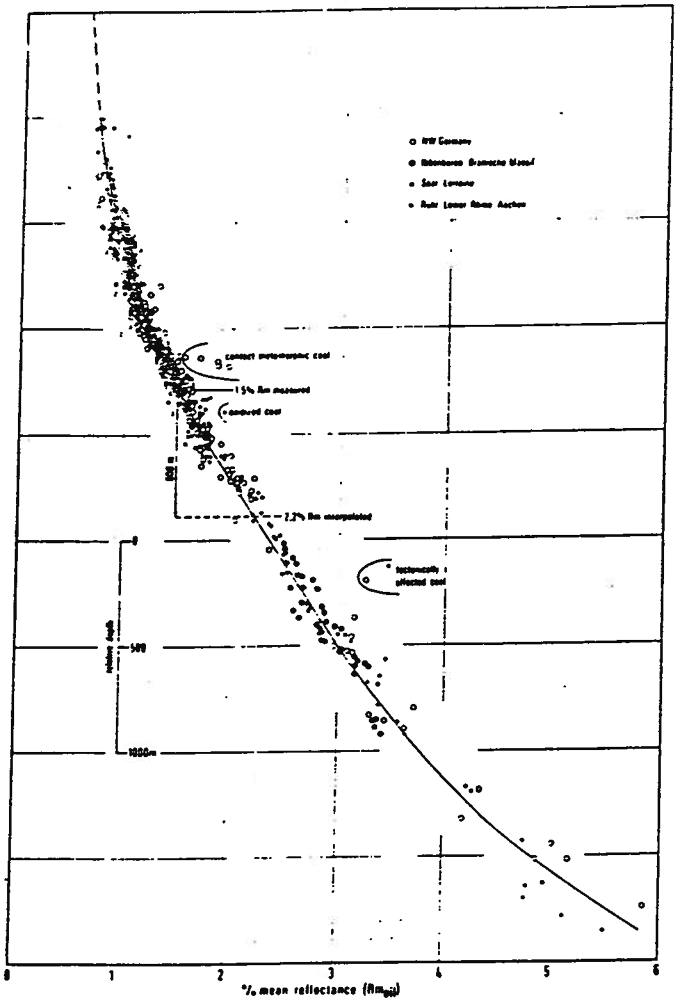


Fig. 19 Relationship between mean vitrinite reflectance and depth in 35 deep boreholes in W. Germany (from Stach et. al., 1982)

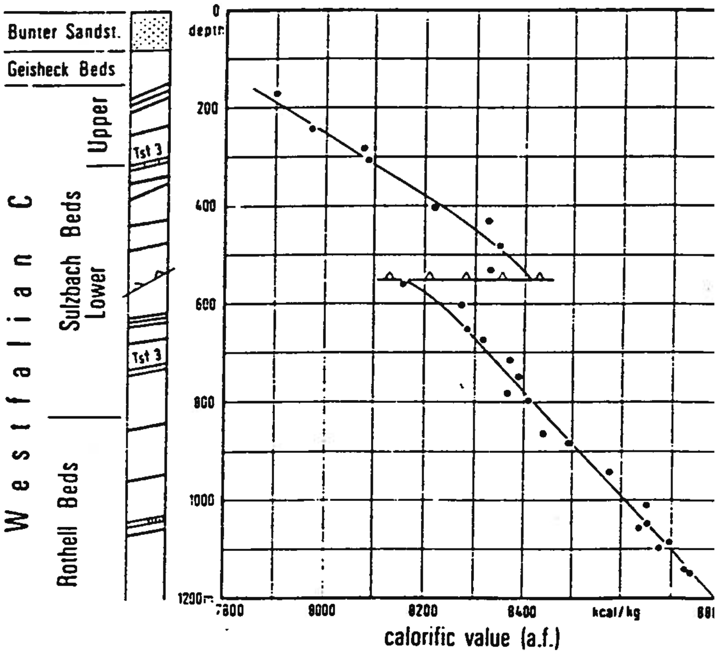


Fig. 20 Displacement of the rank-depth curve (based on calorific value due to an overthrust; Krughette 2 borehole, W. Germany (from Damberger et. al., 1964)

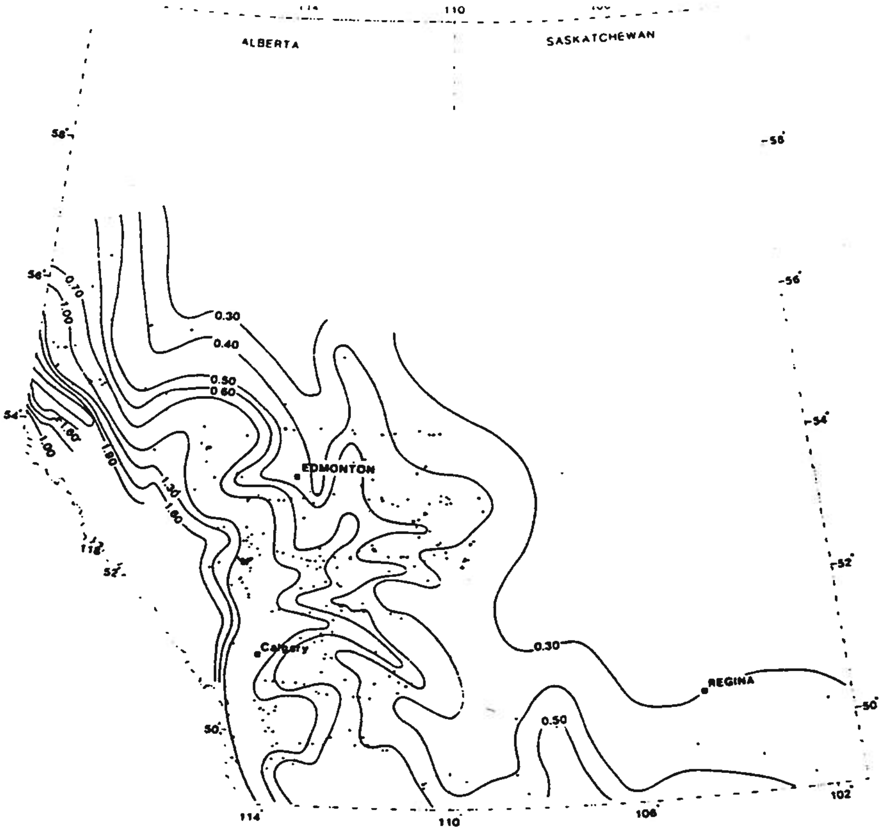


Fig. 21 Rank distribution (vitrinite reflectance) of Mannville Group sediments in southern part of Western Canada Sedimentary Basin (from Osadetz et. al., 1990)

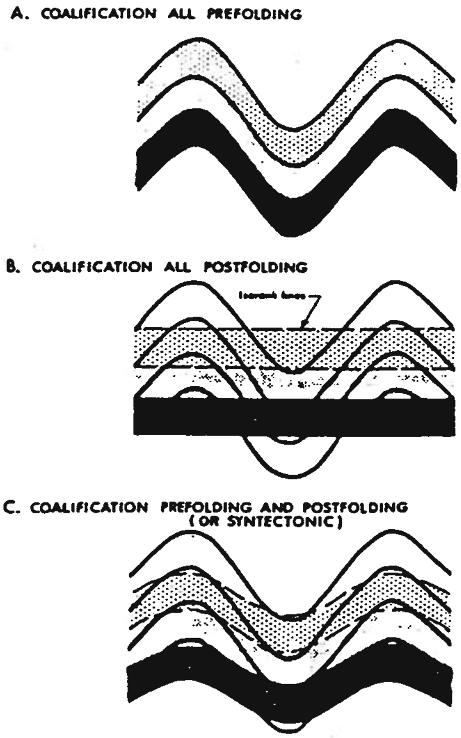


Fig. 22 Idealised relationships between deformed coal seams and isorank lines in relation to timing of coalification:
a) pre-deformational coalification
b) post-deformational
c) syndeformational ( or pre + post deformational)

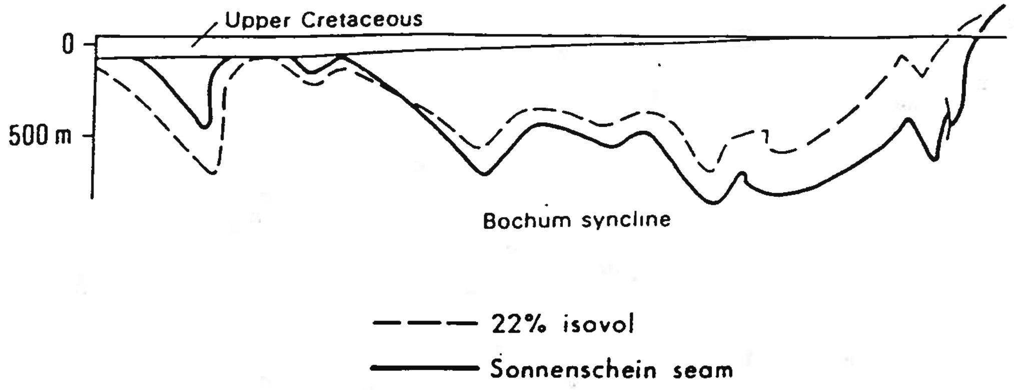


Fig. 23 Cross-section through the Bochum megasyncline (Ruhr Basin) showing pre-deformational iso-rank surface (22% vol. matter) approximately parallel to Sannenschein Seam (from Teichmuller, 1982)

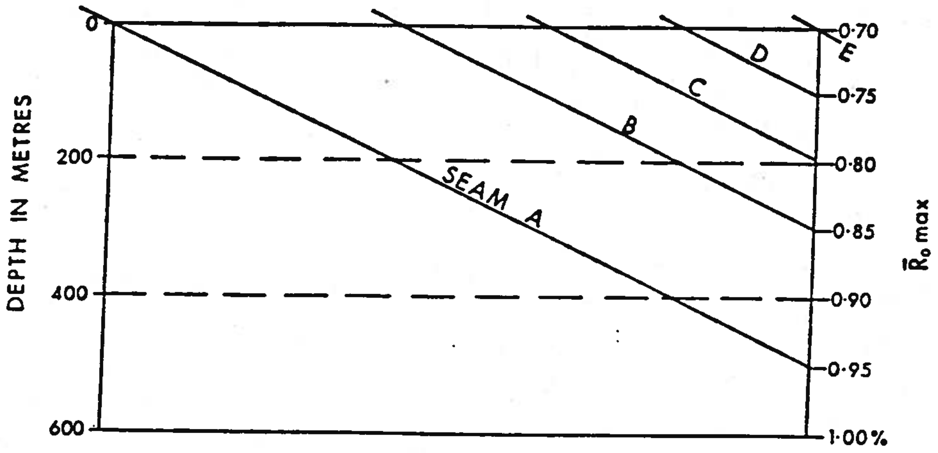


Fig. 24 Cross-section of inclined coal seams (A to E) in Sydney Coalfield, Nova Scotia with horizontal (post-deformational) iso-rank lines (vitrinite reflectance (from Hacquebqard & Donaldson, 1970)

| | |
|---|---|
| Foredeeps marginal to orogenic belts - paralic | 70 |
| Intradeeps of orogenic belts - mainly limnic | 1 |
| Shelf marginal to consolidated areas (cratons) - paralic | 21 |
| Interior of consolidated areas (cratons) - mainly limnic | 8 |

Fig. 25 Correlation between the distribution of world coal reserves (%) and the tectonic setting of coalfields (from Van Bubnoff, 1937)

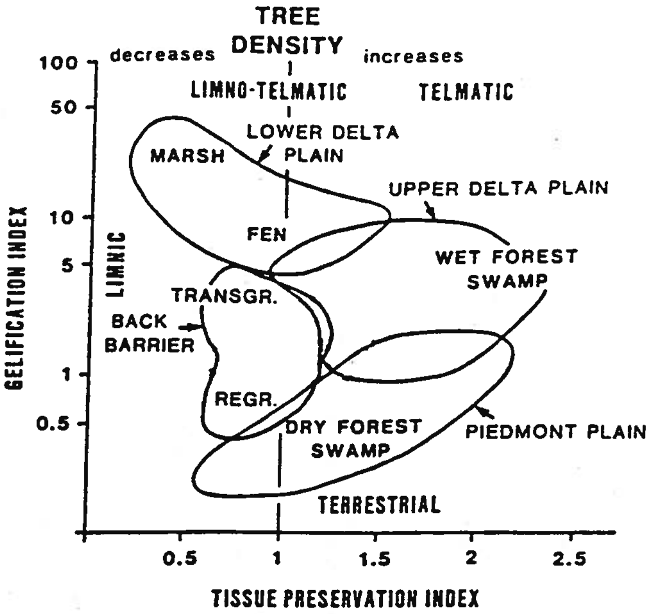


Fig. 26 Composition of Australian coals relative to their depositional environments (modified from Diessel, 1986)

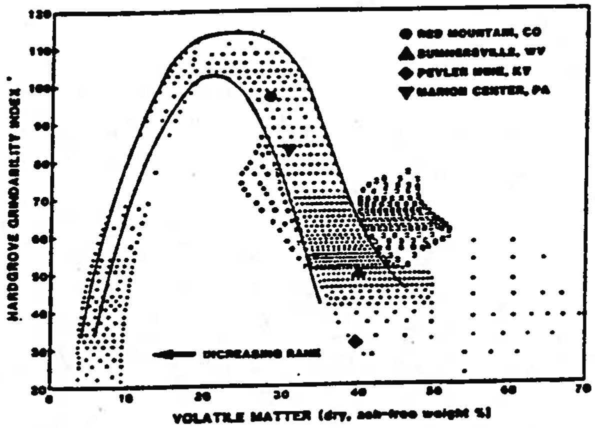


Fig. 27 Variation of Hardgrove Grindability Index with rank, as measured by volatile matter content (from Pomeroy & Foote, 1960)

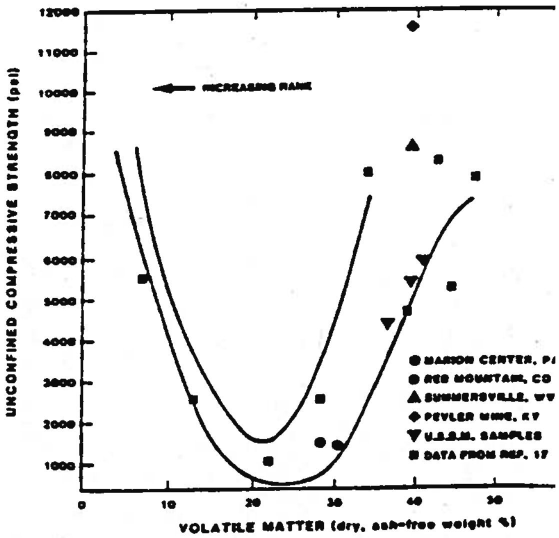


Fig. 28 Relationship between unconfin compressive strength of coal and rank as measured by volat matter (from Brown & Hiorns, 1963)

# GEOPHYSICAL LOG INTERPRETATION
# AND
# COAL RECOGNITION
# IN THE SUBSURFACE

BPB

WIRELINE
SERVICES

# CONTENTS

1. Introduction
2. Identification of Coal Using Geophysical Logs
3. Seam Thickness Determination
4. Coal Seam Evaluation
5. Differences Between Oilfield and Slimline Logging
6. Technical Specification of Slimline Sondes

# 1. INTRODUCTION

Slimline logging systems were developed during the 1960's and early 1970's, to meet the demand for small diameter shallow hole logging in the coal, mineral and tarsands mining industry.

The difference between the mining industry and the oil and gas industry is that the mining industry does not use the borehole as a medium for producing the raw material. Consequently a much smaller borehole in the 2" to 6" diameter range is more efficient and cost effective to drill.

The same measurement principles are used in slimline sondes as oilfield. The main differences are that the source-detector spacing are shorter, source strengths are less and the detector sizes smaller. Slimline tools therefore give logs that have a much higher resolution than oilfield but with much shallower depth of investigation.

In small diameter boreholes with a good caliper log and no invasion the slimline tool will give a comparable measurement to an oilfield tool. In a large or badly carved borehole the borehole correction component can become a significant part of the measurement. In invaded formations it is possible for the slimline tool to read the invaded zone only and not see past this zone to the invaded rock.

## 2. IDENTIFICATION OF COAL USING GEOPHYSICAL LOGS

It is possible to identify coal with certainty in nearly all possible hole conditions. However, where hole conditions are difficult and there is caving or drill stems are left in the hole, care is necessary. The following cases are considered:

Open hole — fluid filled
Open hole — no fluid
Cased hole — fluid filled
Cased hole — no fluid

### Open Hole — Fluid Filled

This is the most usual and easiest condition for coal identification and can be done positively with the combination of the caliper and density log and usually with a caliper and sonic log. In both cases the principle is for the caliper log to define that the hole is consistent, thus confirming that the measurement of either the density or sonic is reading rock formation and not hole abnormality. As a back-up, since most gamma rays read low over a coal section, it is always useful to confirm a low gamma ray. Fig. 8 shows a good quality response of the three logs.

#### Effect of Caving

Development of caves which do not permit the coal combination sonde to sidewall against the borehole cause erroneous results since the area immediately adjacent to the tool is replaced by fluid and not rock. In the case of caved coal with the density of 1.3 and fluid with a density of 1.1, the effect may not be startling. Against normal sedimentary rocks the effect is to lower significantly the apparent density and in the limit when the cave exceeds the depth of penetration of the tool a response similar to coal could be read.

In such conditions it is important to use the deepest penetration tool available — the long spacing density. Unless the cave is very large the LSD tool will read and detect the presence of coal. Where the cave is extensive great care is necessary in identification but it is usually possible to resolve the problem by considering both the short spacing and long spacing density logs and by considering the relative deflection of each with respect to the base line. If the BRD reads a lower density than the LSD, this indicates that cave is non-coal. If both logs respond similarly then coal is present. The condition would of course also happen if the cave was extremely large. Fig. 9 shows how the above principle is employed.

Obviously the caliper should be studied closely.

The sonic log gives very indifferent results in caving and, therefore, is not to be trusted.

## Open Hole — No Fluid

As the sonic log will not work without fluid the density log is the only possibility, although some indication can also be gained from the neutron and gamma ray.

The response is virtually the same as 3.1 except that densities read at a lower value (absence of the fluid) and caving effects are more pronounced, especially with the short spaced logs.

Where caliper is good interpretaion is straightforward but in very large caves where there is no material other than air to scatter back the density radiation, a peculiar effect happens where the density appears to increase (as count rate drops). Because in the absence of fluid and formation there is no medium to scatter back the radiation.

This effect will occur first on the BRD log which will tend to show a higher density than the LSD (the reverse of condition 3.1). Thus when the LSD reads lower than the BRD, coal is present, but when both logs read the same, non-coal or extremely large caving is present (presumably extensive caving is not associated with coal). Fig. 10 summarises these effects.

It is worth noting that old workings which are dry show up with a very high density.

The gamma ray log is not very much affected by fluid, reading perhaps 10/20% higher due to lack of fluid absorption so this can be used in relatively well known areas to help identify coal.

An interesting feature which should be noted with the gamma ray is that when it is run with a combined density sonde when fluid is absent the radiation from the density source will always cause an increase in the gamma ray. This effect is caliper dependent (the effect increasing with hole diameter) and typically in the order of 20% in average diameter coal boreholes. In view of this effect a discontinuity feature occurs when a sonde passes between the water/air interface since once the source is cleared of water there will be an immediate stepped increase on the gamma ray detector which is situated some 6 feet further up the sonde. This effect is shown in Fig. 11. It is now possible to have certain sondes in which this space is increased and the log remains unaffected by the density source (this is known as the dry hole CCS).

Both the neutron and temperature logs can be run without fluid but the neutron's response is extremely difficult and must be watched carefully, and the temperature will lack definition.

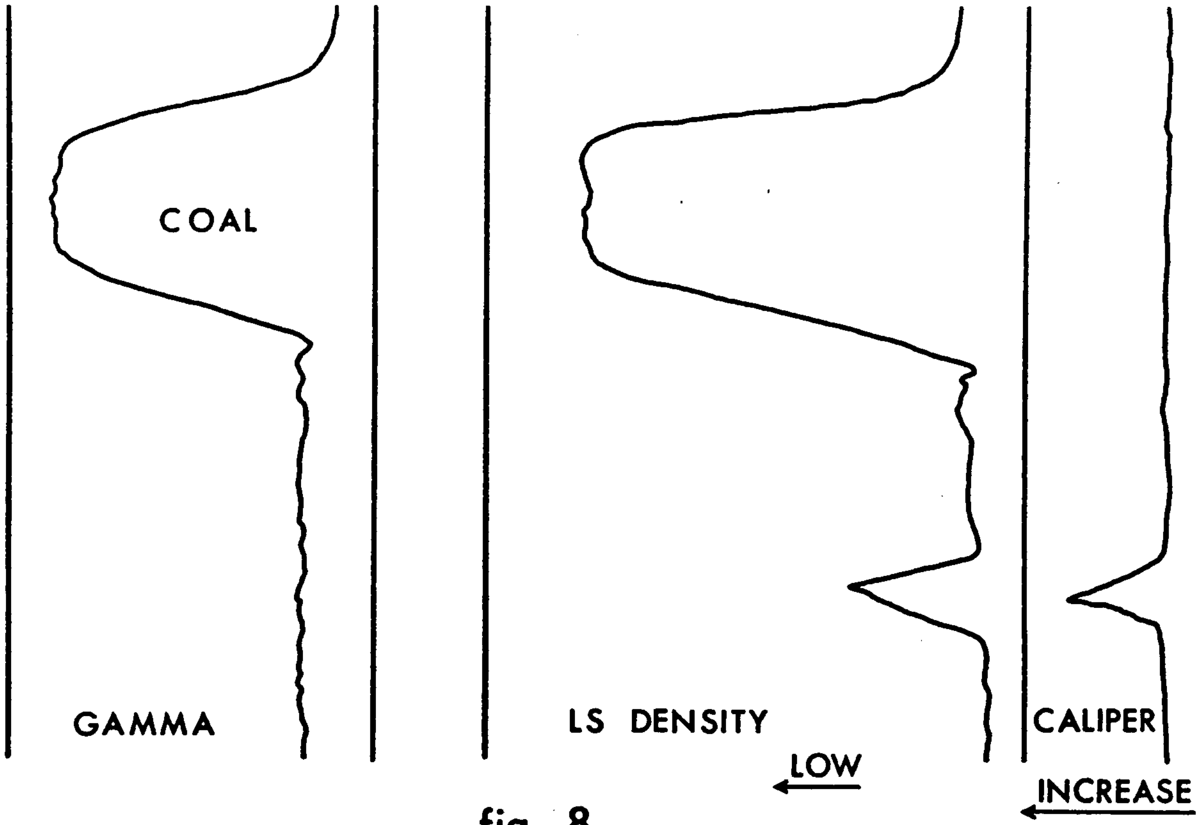


fig 8

POSITIVE COAL IDENTIFICATION

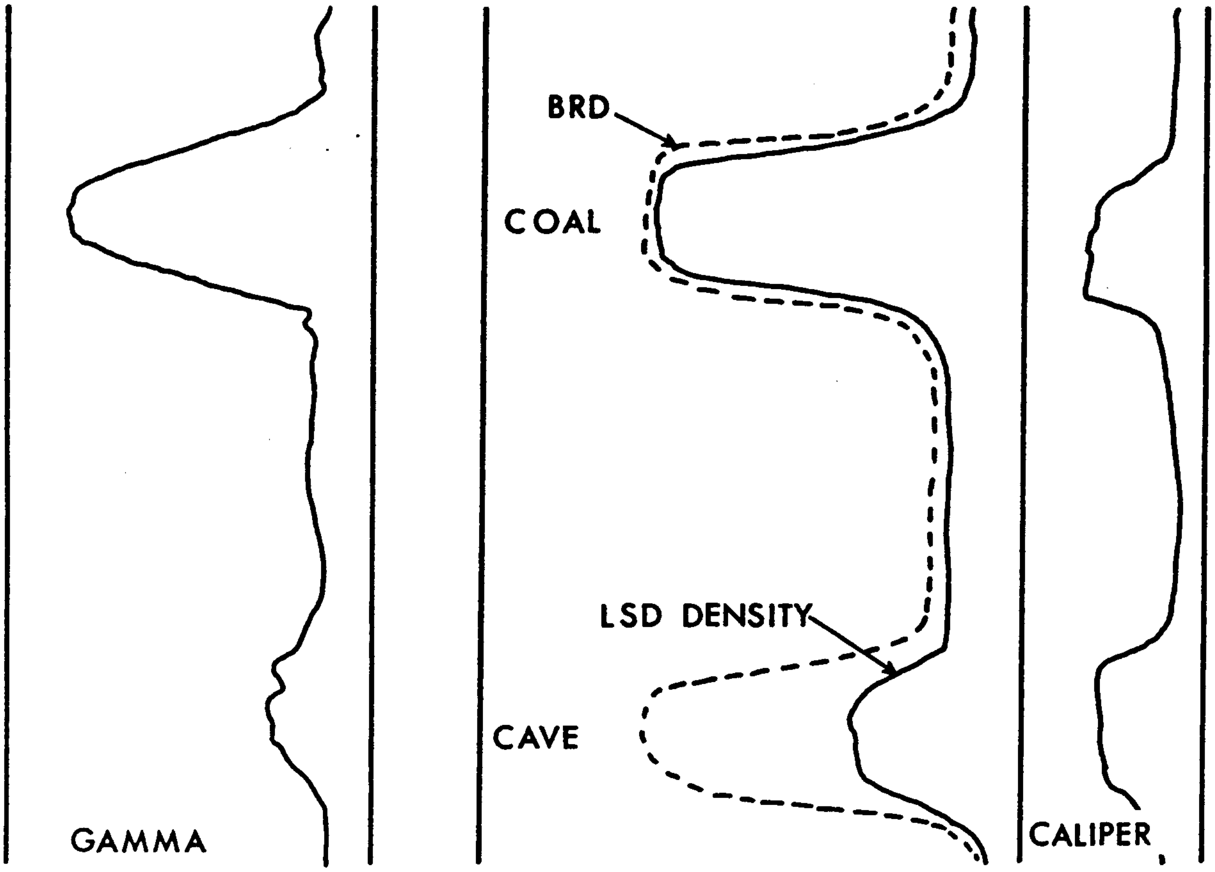


fig 9

CAVING V. COAL

## Cased Hole — Fluid Filled

Density, gamma and neutron are the only logs which can be run in this condition and the effect of casing is two-fold.

i. It means there is no caliper.

ii. The gamma and density measurements suffer a degree of absorption due to the iron (the neutron is much less affected).

The absence of a caliper means that in all interpretations we are now uncertain as to the degree of variation in the borehole walls and thus any interpretation is subject to this proviso.

In any case it is usually possible to make reasonable deductions regarding the caliper by looking at the LSD trace throughout the borehole and to see if it has a fairly consistent response. Fig. 12 shows a split response illustrating what may be expected in a good section compared with a badly caved borehole.

Fig. 12 also shows how the BRD log reflects the changes in caliper due to the shallow penetration of this tool. strong variations in the BRD response, particularly if it appears to exaggerate the LSD features, is some indication of caving.

A caved coal section behind rods may not be identifiable. The best clue will come from the gamma which, if very low in a caved section, is most likely to be coal as sandstone does not usually cave. Beware, however, as in a very caved area a shale will show a low gamma.

## Cased Hole — No Fluid

Very similar conditions as in 3.3 above except the effects of caving are more exaggerated and the reversal effect described in 3.2 will ultimately take place.

## Summary

i. In open hole dry or wet with good caliper the density log can be used with 100% certainty to define coal.

ii. In open hole dry or wet density will give 100% identification except where a really massive caving exists.

iii. In cased holes where good caliper can be deduced, interpretation using the density log is again nearly 100% certain.

iv. In cased holes dry or wet where caliper is bad, great care is necessary but it is usually possible to identify coal.

v. Good coal does not usually cave and it is extremely rare for a condition to arise where caving is so extensive that the LSD does not make some response to the formation.

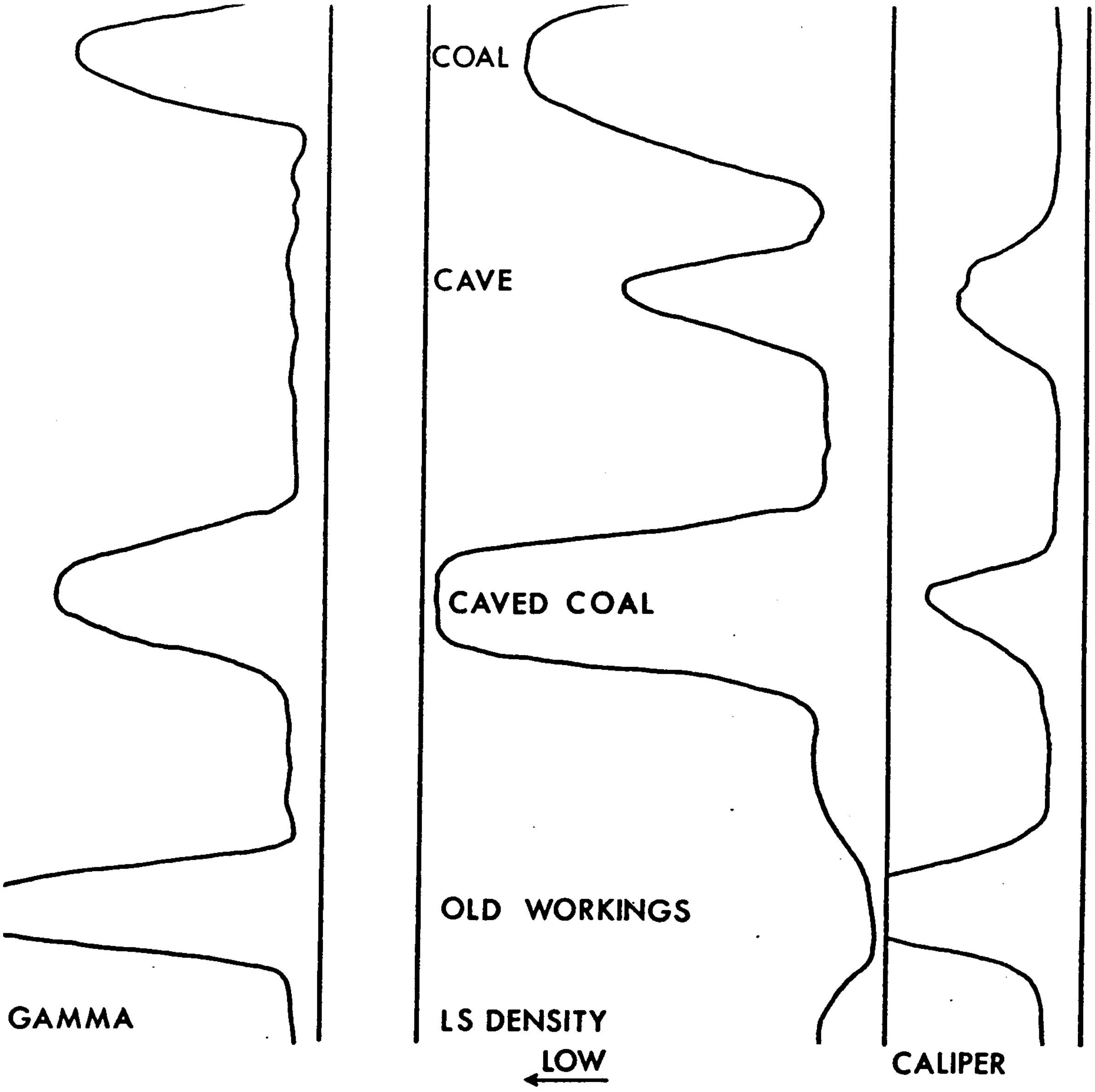


fig 10

DRY HOLE IDENTIFICATION

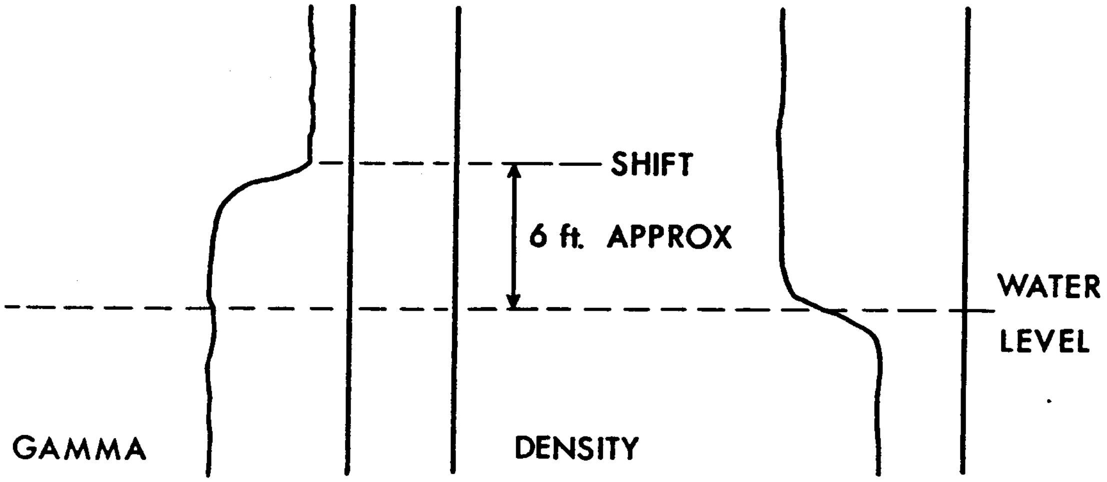
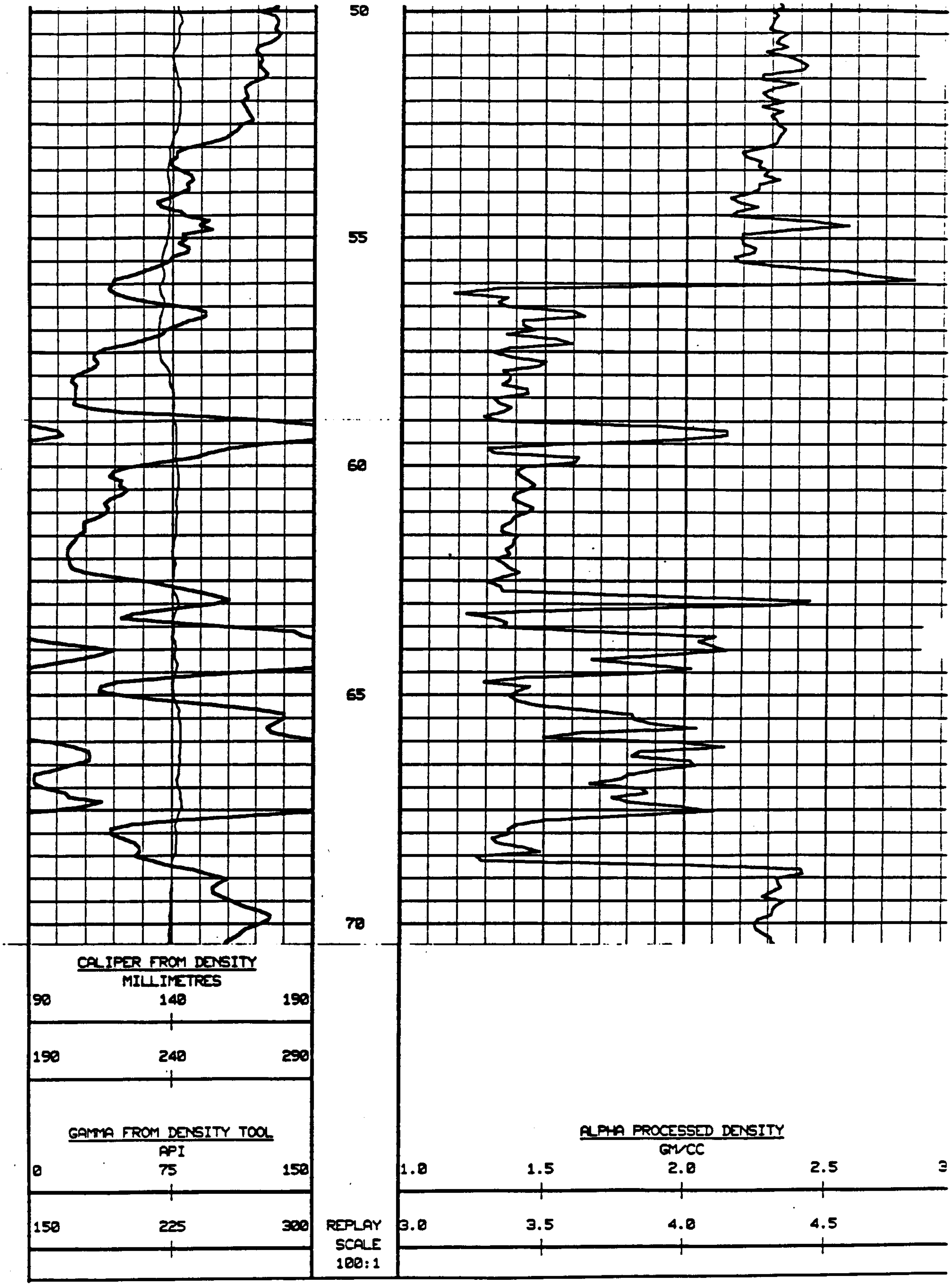


fig 11

DRY HOLE GAMMA SHIFT



SLIMLINE EXAMPLE

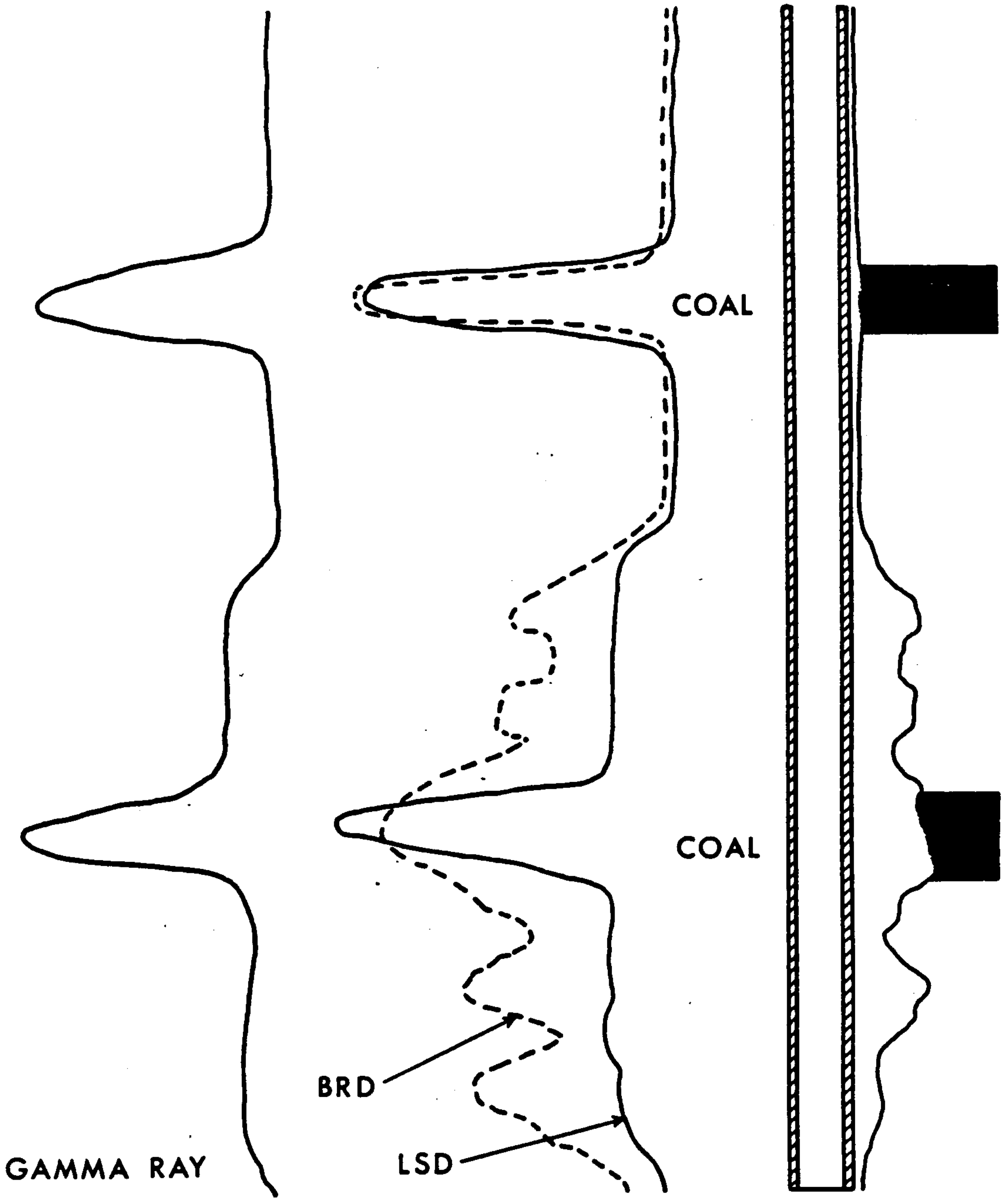
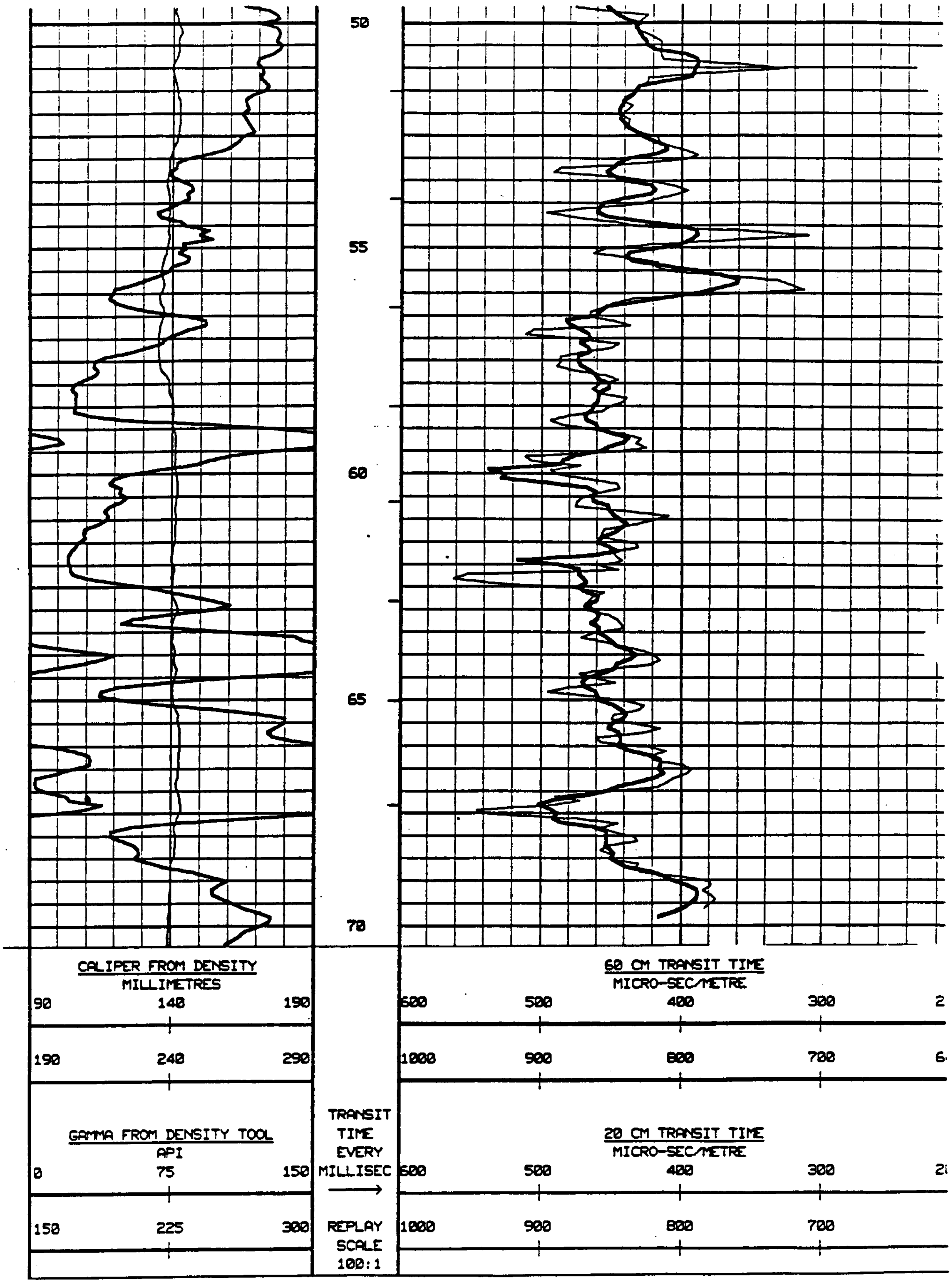
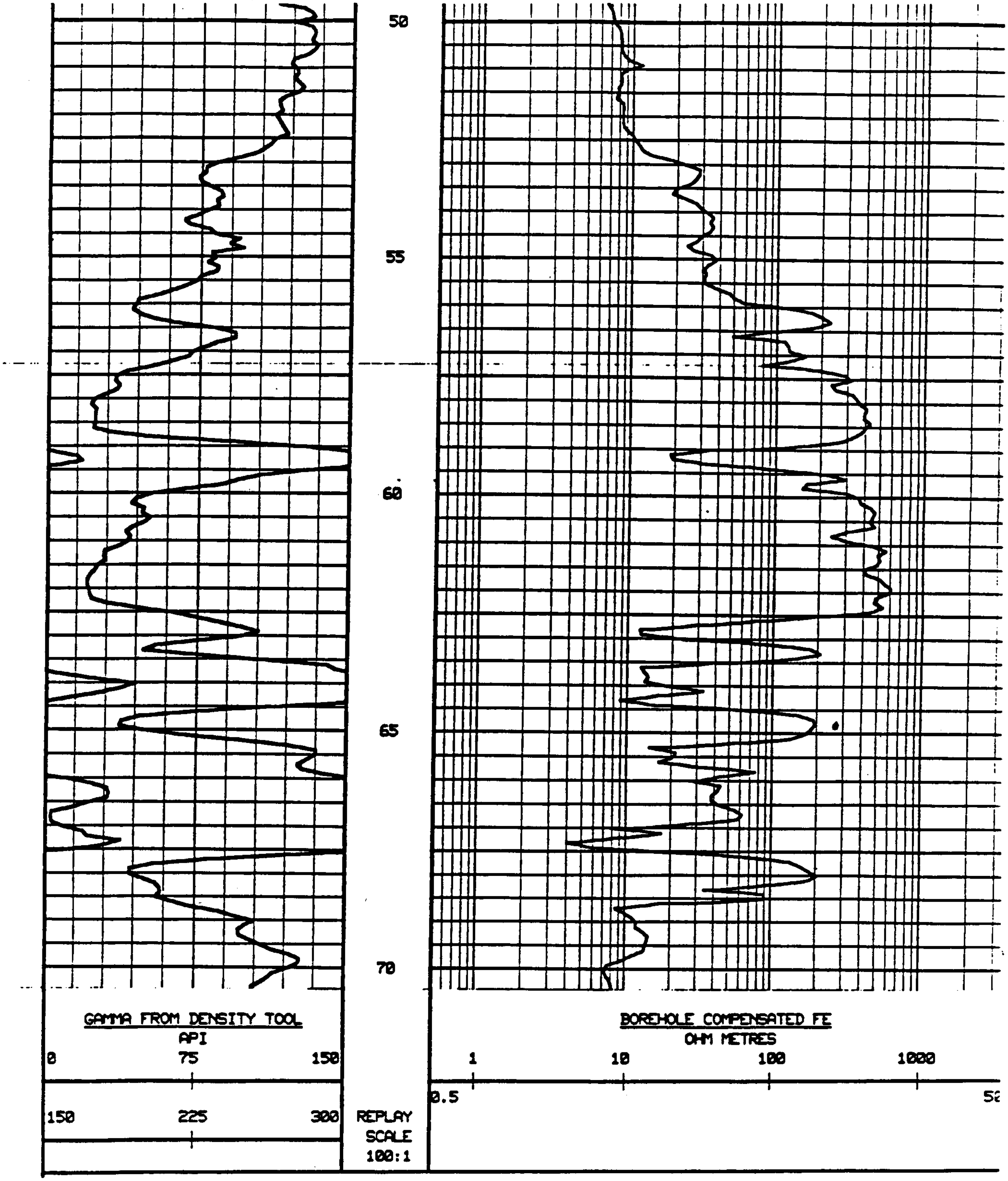


fig 12

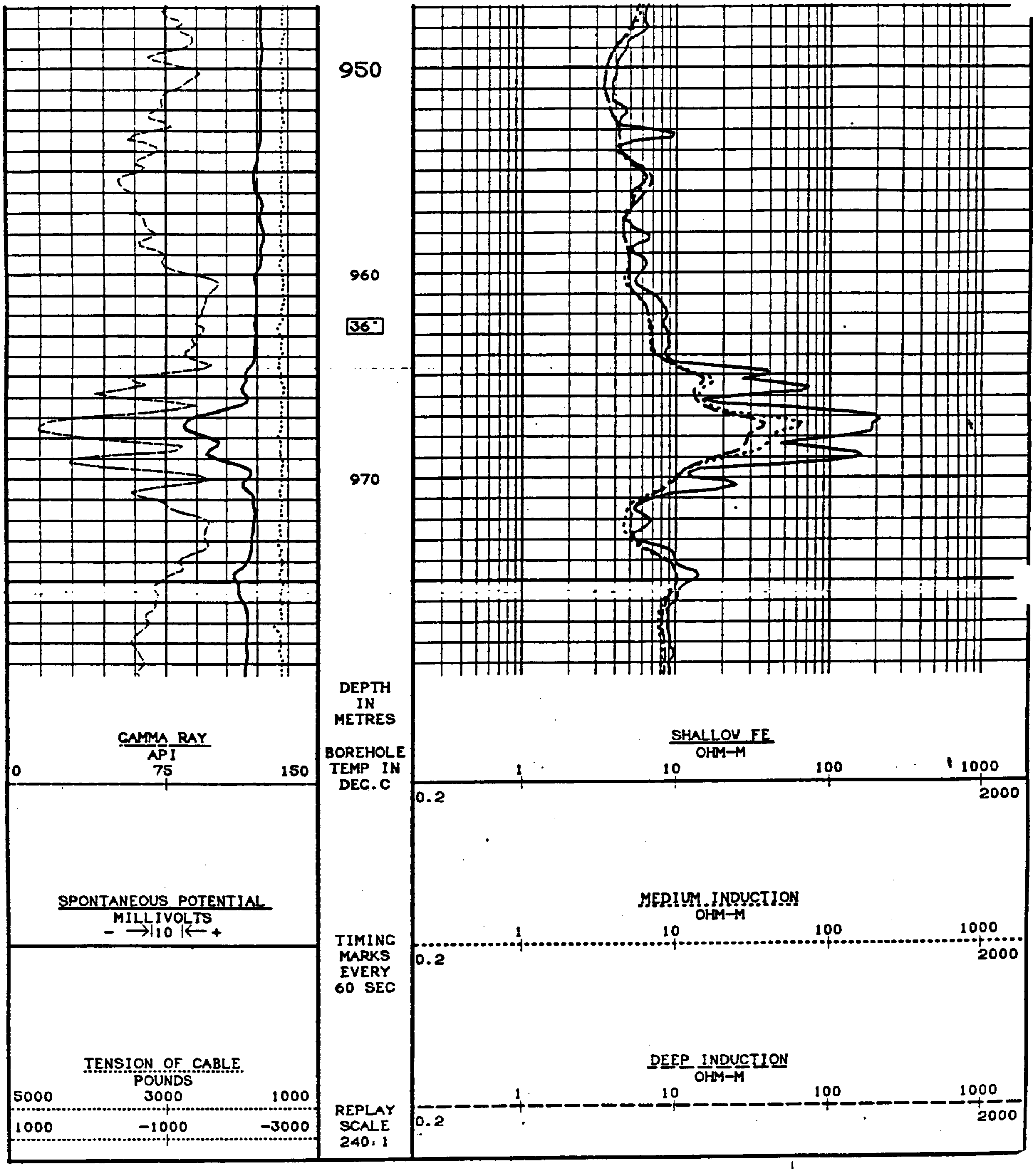
COAL IDENTIFICATION CASED HOLE



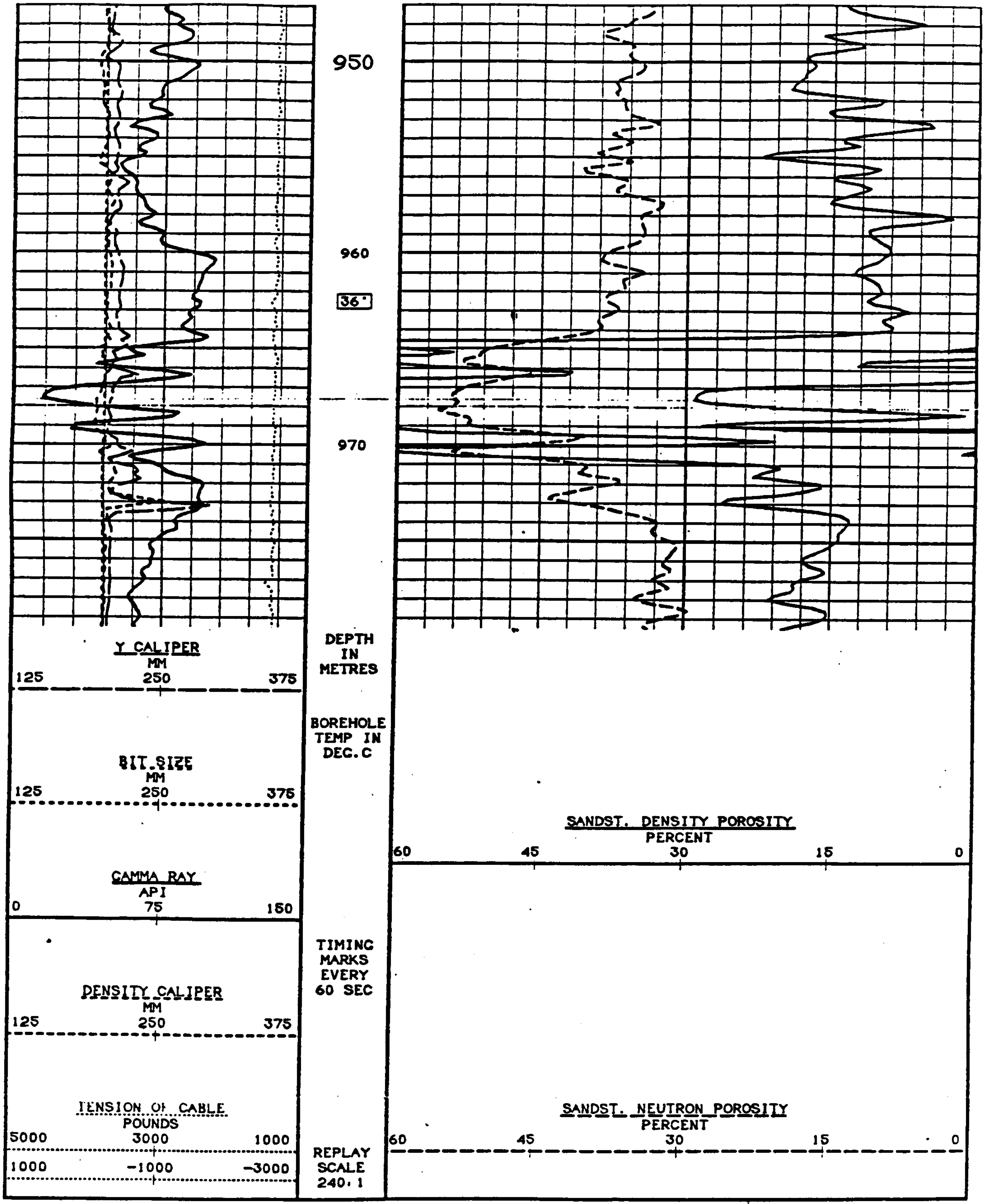
**SLIMLINE EXAMPLE**



SLIMLINE EXAMPLE



**OILFIELD EXAMPLE: DIS - DIGITAL INDUCTION SONDE**



**OILFIELD EXAMPLE: NCS - NUCLEAR COMBINATION SONDE**

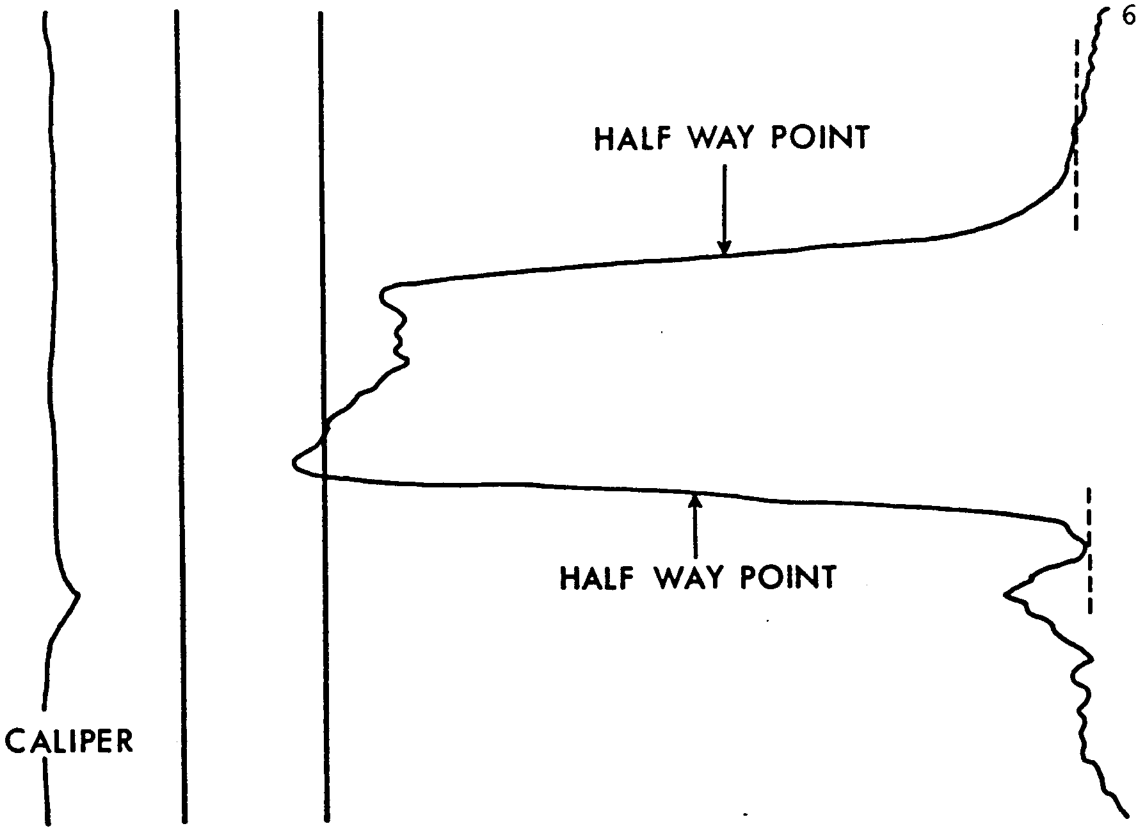


fig 14

SEAM THICKNESS BRD LOG

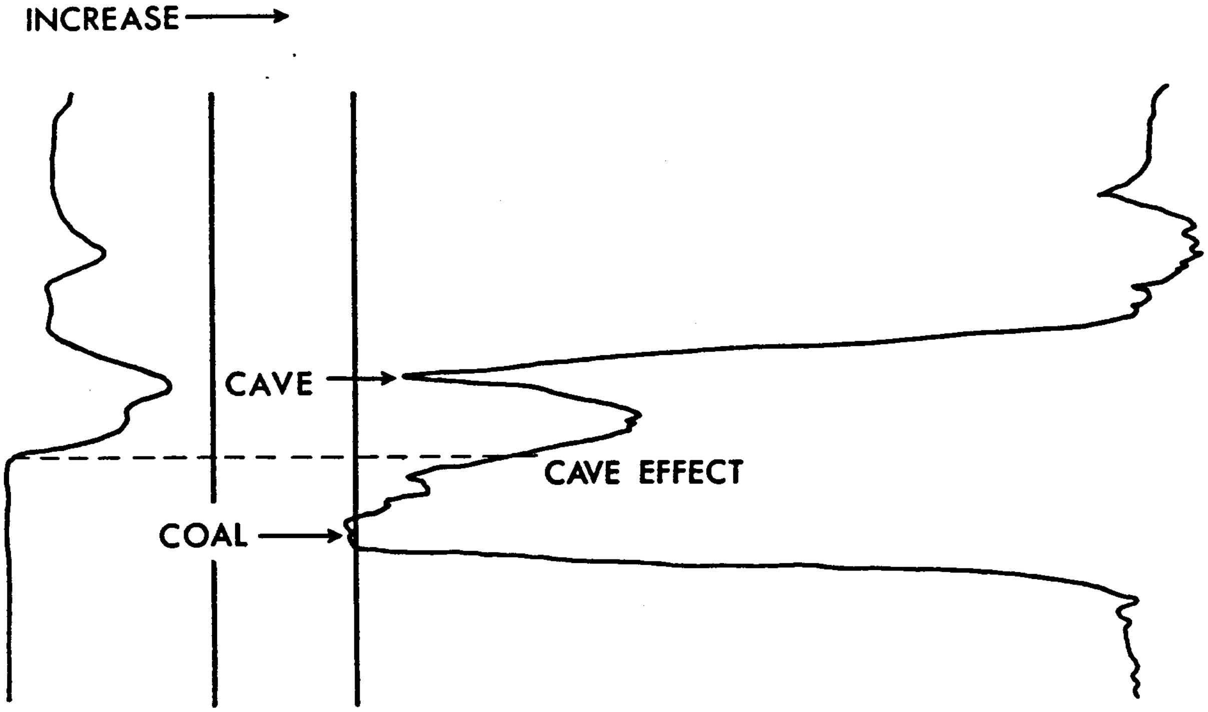


fig 15

BOUNDARY CAVING BRD

## 3. SEAM THICKNESS DETERMINATION

Seam thickness can be measured from the following logs:

- Density
- Gamma Ray
- Neutron
- Micro Resistivity
- Sonic
- Caliper

In all normal conditions by far the best and most reliable thickness determination can be made by using the density together with the caliper log. The shorter the spacing on the density is theoretically better, but as density spacings get too short complications arise and nullify the advantage.

The presentation in the Coal Thickness Log which uses the Bed Resolution Density and the Caliper on expanded scales of 20:1 has been specifically designed to give the best and most reliable thickness determination.

### Coal Thickness Log Interpretation

i. First of all note the 'coal deflection' and see if the caliper response is consistent. If the caliper shows no more than marginal deviation then interpretation is simple. The correct interpretation point is the mid point on the BRD curve which, because this log is linear is the half density point, see Fig. 14. It is possible also to get a good thickness value from the LSD log as shown on the Coal Quality Log.

ii. If the caliper shows significant variations then more caution is needed and the first stage is to compare the caliper response carefully with the 'coal deflections' on the BRD. It can usually be seen that the cave deflections give a similar response on the BRD log and in fact these sections are not coal at all. Coal normally does not cave and therefore the next step is to eliminate from the BRD log the cave areas. The flat parts of the caliper with coal type deflections on the BRD are now coal and deflections here can be interpreted at the half way point. Sometimes the cave is associated with the top of the coal and the half way point is taken between the root and the peak of the graph as far as the cave is concerned. Fig. 15 shows how caves may be identified and coal interpreted.

iii. Because coal does not usually cave it is often quite possible to measure accurately the thickness of the coal seam in a difficult section by examining the caliper log. The interpretation points are shown in Fig. 16, the top point being where the arms of the caliper immediately open into the cave, the bottom point being at the top of the gradation caused by the arms being closed as the caliper moves in to the coal area.

  Coal thicknesses using the above method in reasonable conditions should be interpreted to ± ½ inch, in some cases even better.

## Using the Coal Quality Log

Reasonable thickness can also be deduced from the Coal Quality Log, using the LSD and the gamma ray. LSD has deeper penetration and is less affected by the caves but has a more gradual slope and thus the interpretation point is more difficult to tie down. The correct procedure is to measure from the log heading the density of the peak of the deflection and the density of the root of the deflection, calculate the mean density of these two points, locate the position on the log heading and read the thickness of this position. Fig. 17 shows how this is done.

In normal conditions this position is approximately ⅕th along the curve from the root of the graph. Not, however, that if a processed density is given (see Log Processor Section) the LSD is linear and interpretation point is midway.

The gamma ray can also give an indication, particularly when the coal is sandwiched between shale and mudstone. The interpretation point on the gamma ray is ⅓rd down from the base level of the shale. The reason why the gamma ray interpretation is not symmetrical is that gamma rays travel further in the less dense coal medium, see Fig. 18.

## Cave Boundaries

Often boundaries to coal show caving. The best way to examine this is via the caliper but if for some reason this log is absent, effects of caving can usually be seen on the density log. Fig. 19 shows the effects of a thin cave using the LSD log and the easiest method of interpreting is to draw an imaginary boundary as shown and interpret normally. Fig. 20 shows the same cave as seen on the BRD log and here the interpretation point would be half way between the cave boundary and the peak, as shown on the diagram.

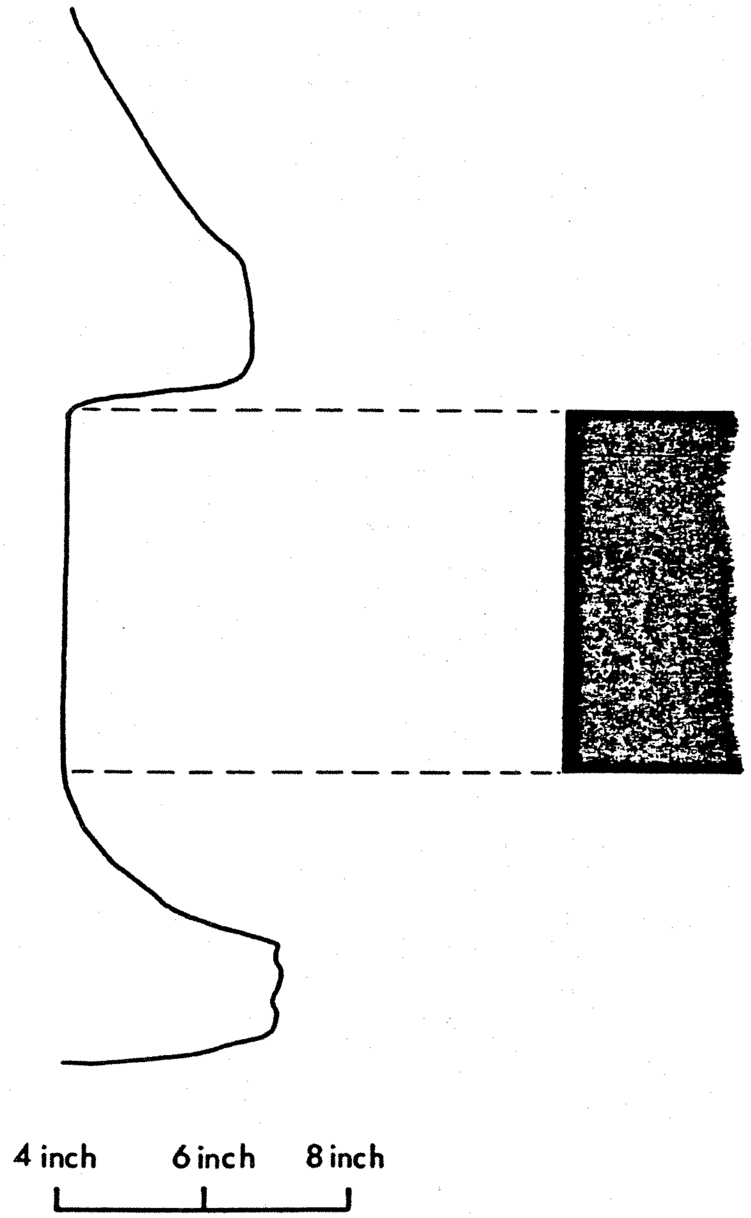


fig 16

SEAM THICKNESS FROM CALIPER LOG

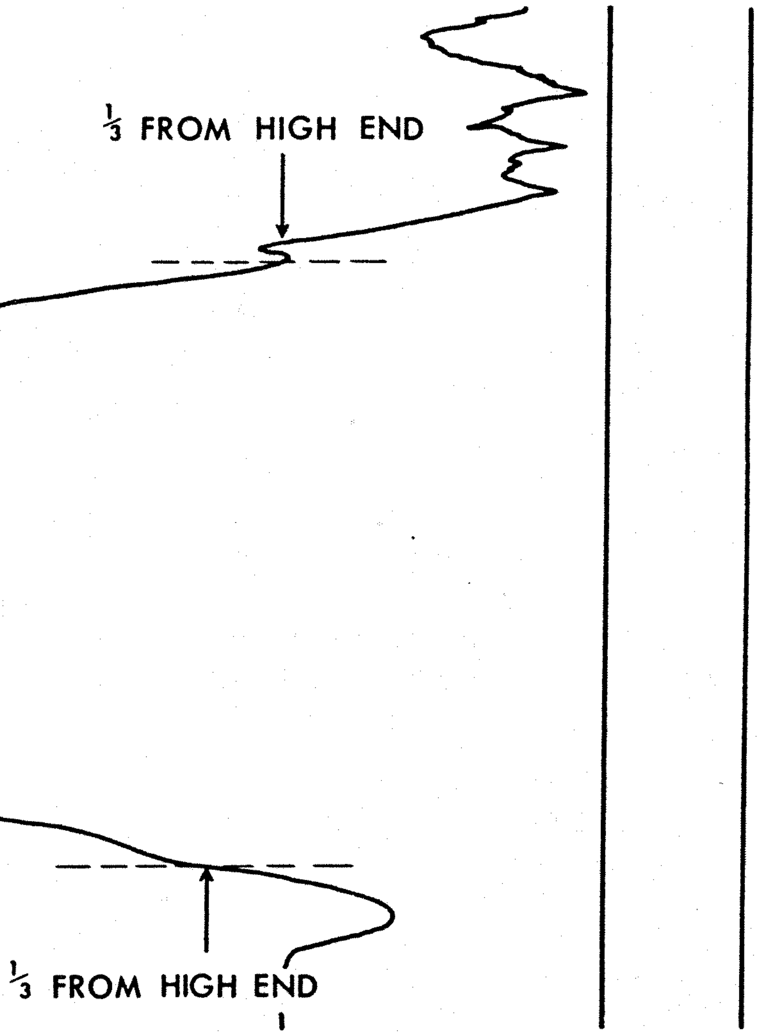


fig 18

SEAM THICKNESS FROM GAMMA RAY

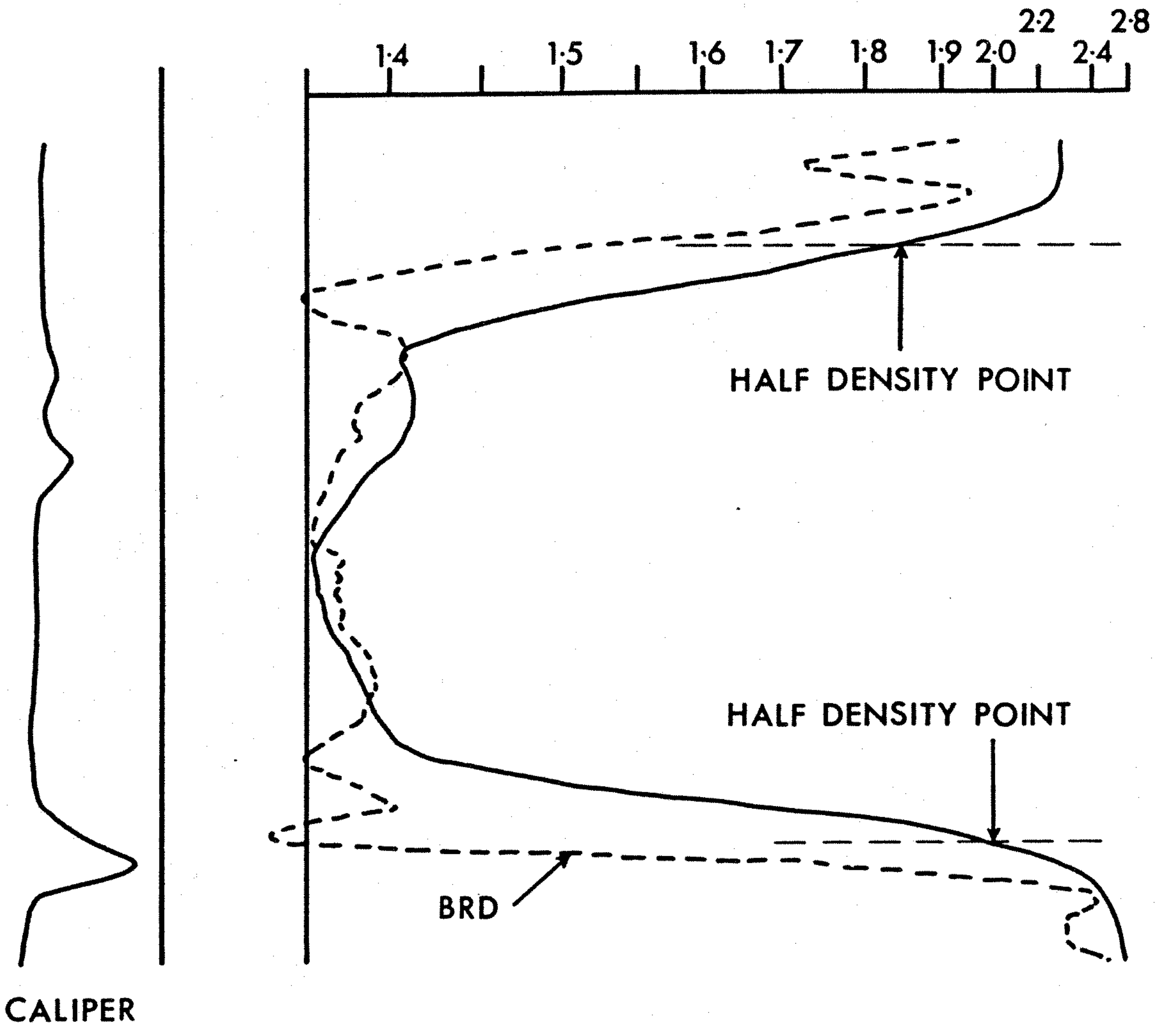


fig 17

SEAM THICKNESS LS DENSITY LOG

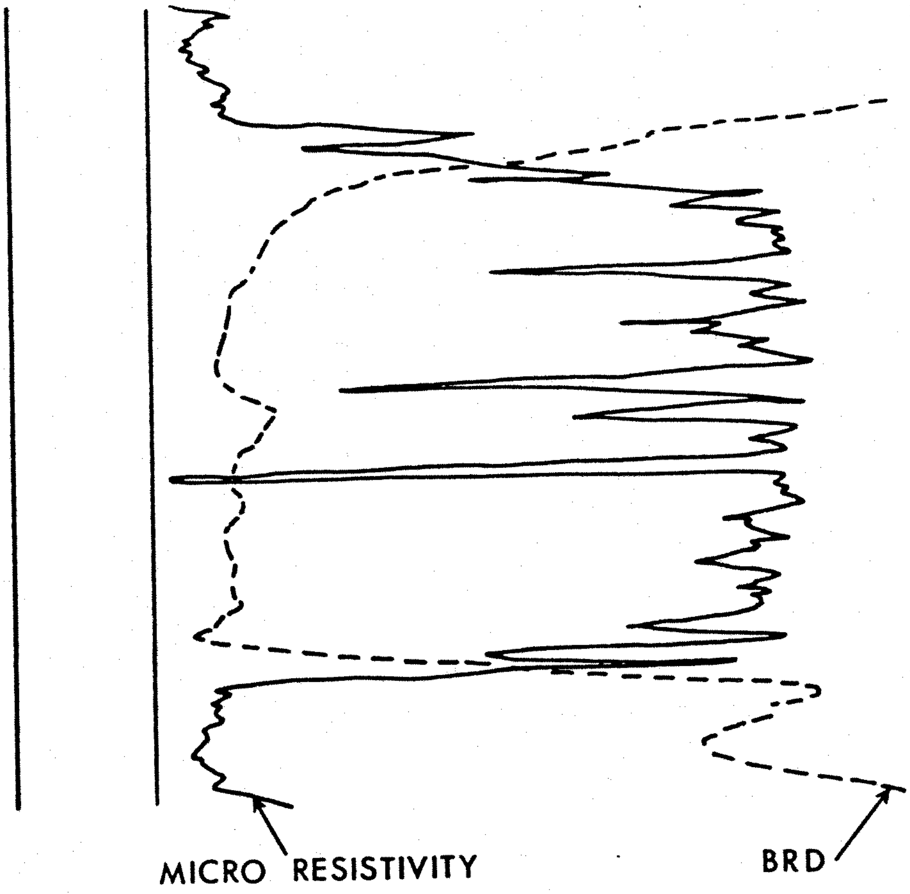


fig 21

MICRO RESISTIVITY DETAIL (V. BRD)

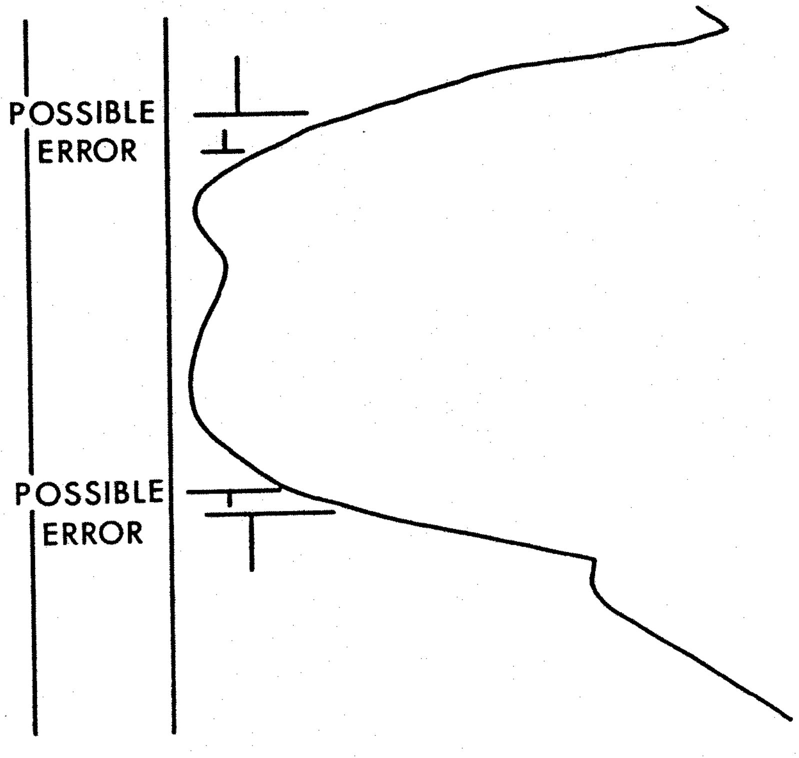


fig 22

NEUTRON RESPONSE OVER BOUNDARIES

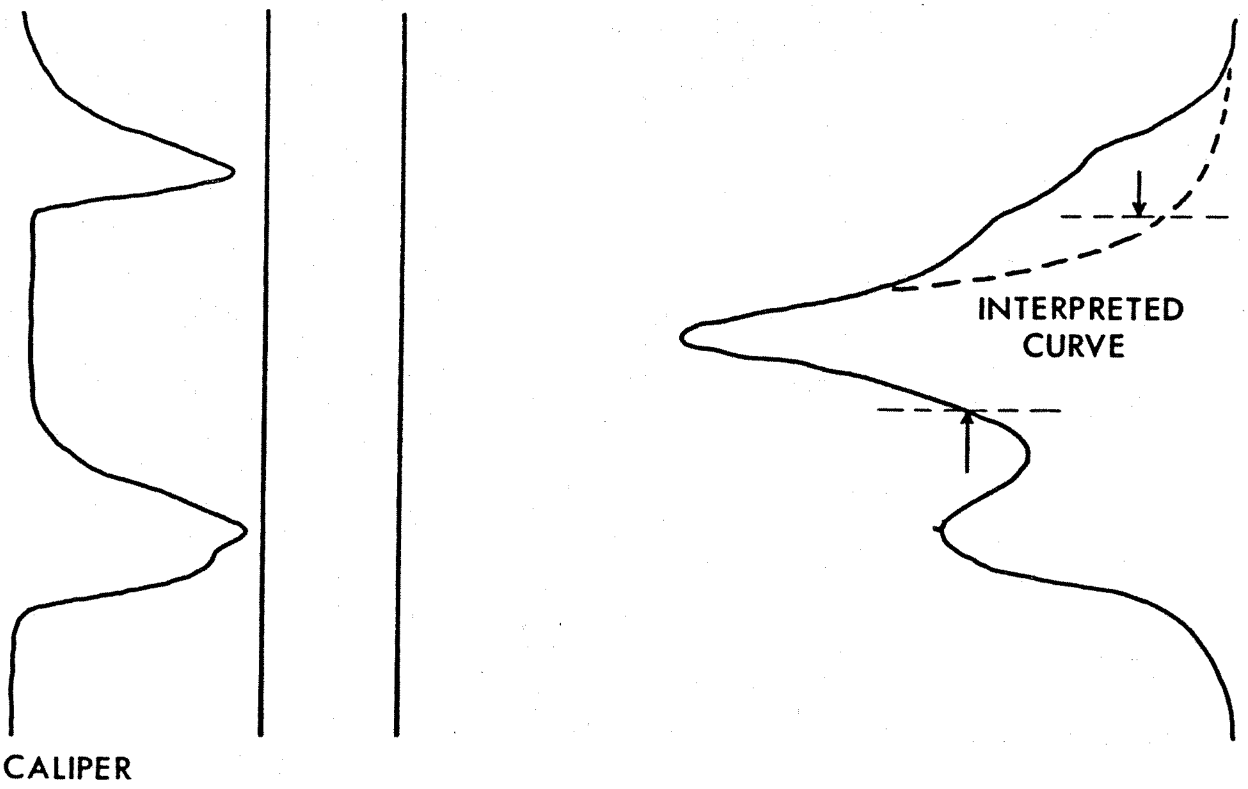


fig 19

CAVED BOUNDARY LS DENSITY

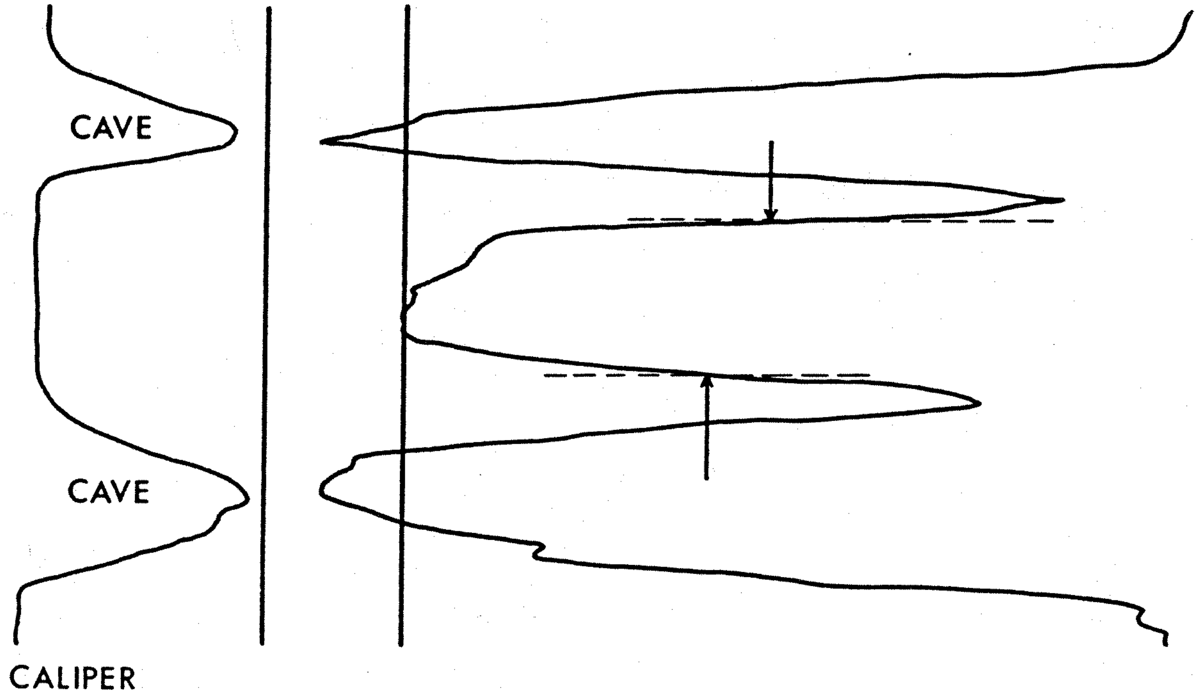


fig 20

BRD COAL V. CAVE

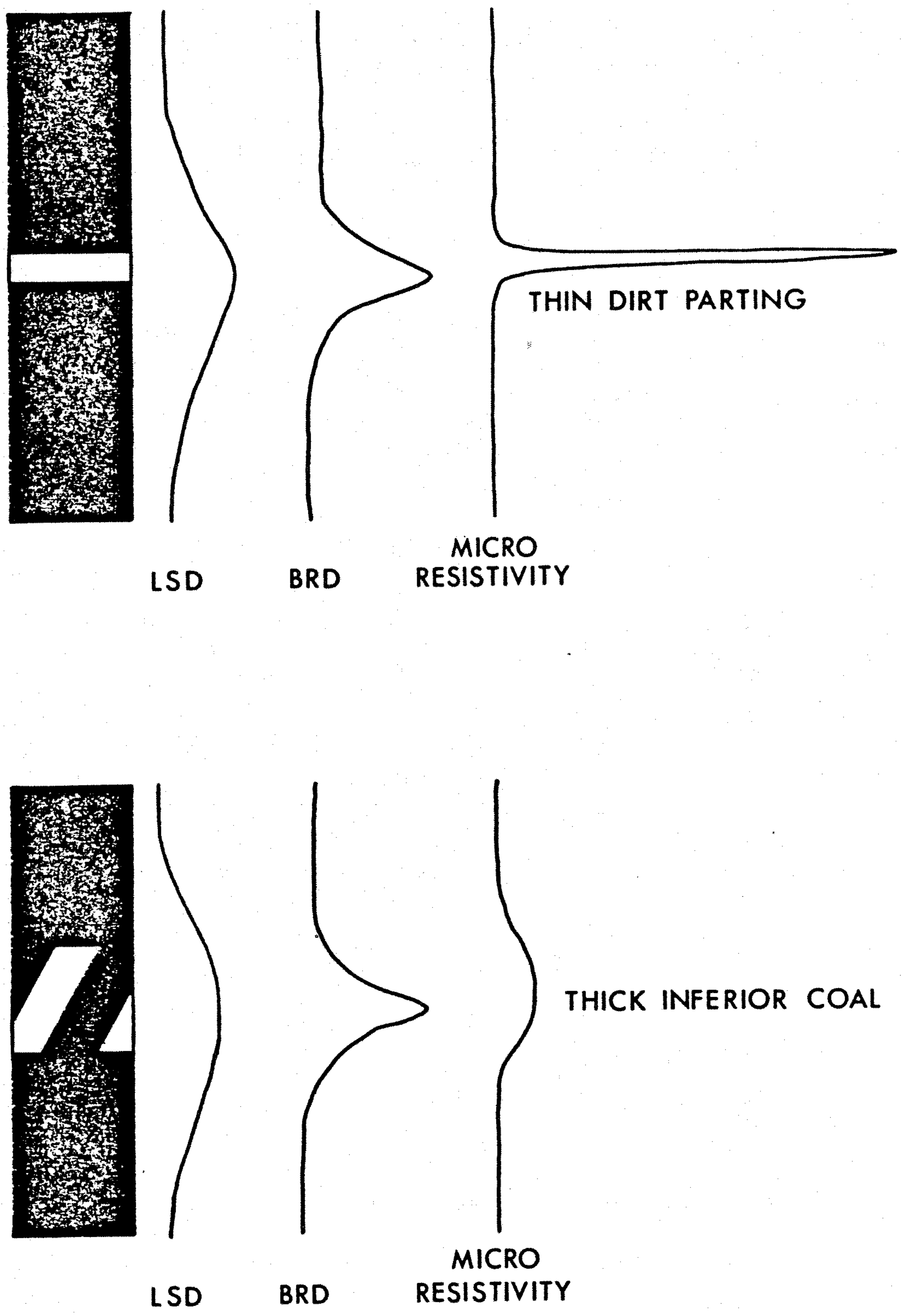


fig 23

THIN BED RESPONSE

## Using the Micro Resistivity Log

The micro resistivity response of the dipmeter or the new CCS tool is extremely sharp and where resistivity contrasts are good it will show coal boundaries very distinctly. As the resistivity measurement is only relative, it is important to make sure by comparing with the density log that the boundaries are really coal/shale and not sandstone/shale, etc. Example of the micro resistivity response is shown in Fig. 21.

## Neutron Log

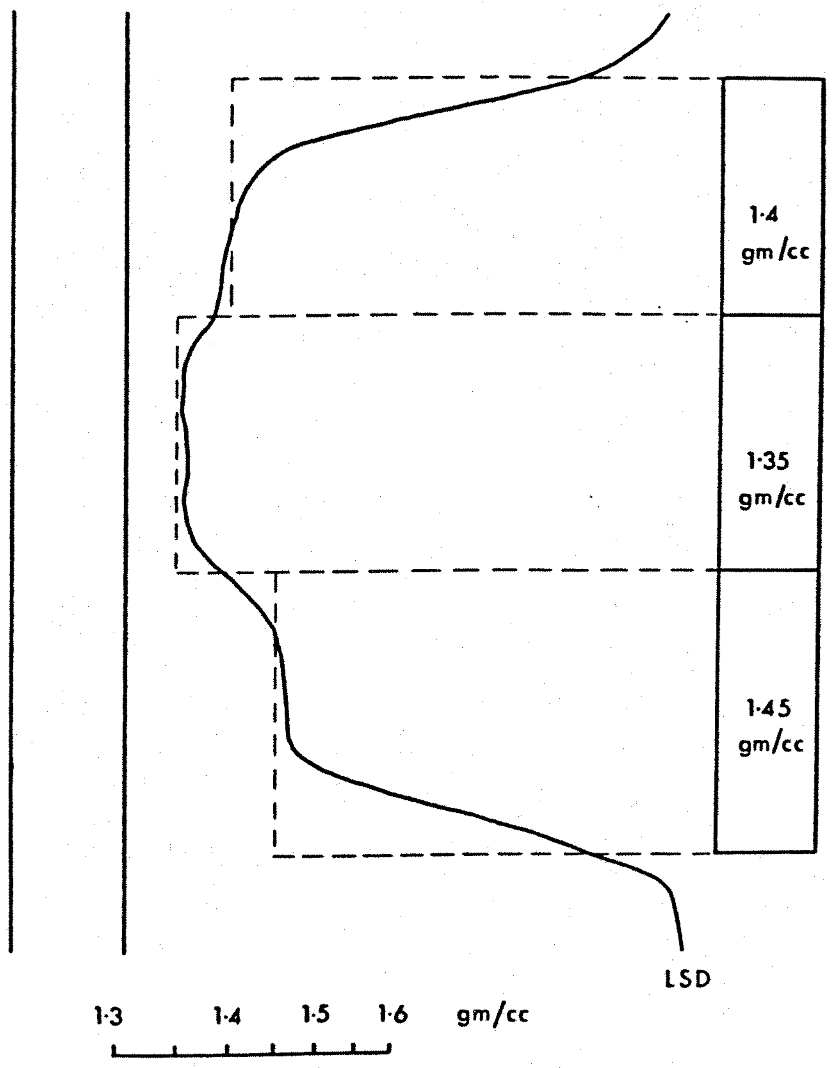
Whilst the neutron log has a somewhat slower response and is difficult for accurate thickness determinations, it is useful when seam boundaries or types of coal seams contain high activity from uranium which effectively masks both the gamma ray and the density response and where, if sandstones are present or the hole is dry, resistivity is unlikely to help. The interpretation point of the neutron is very low down on the 'U' of the curve. An example of this condition is given in Fig. 22.

## Seam Partings

With thick partings, i.e. more than 15 cm., the BRD gives a full response and interpretation is just the same as bed boundaries. However, when below 15 cm. it becomes very difficult to determine if the response is due to a thin bed of dirt or a slightly thicker bed of inferior coal. Fig. 23 shows how this confusion can arise.

To evaluate further it is necessary to use a very high resolution log such as the micro resistivity.

Assuming the density of the ash relationship has been established, turn to the Coal Quality Log and block out the coal seam area in sections. This identifies partings and separates the coal seams into blocks of differing quality. The density of each block can then be read directly by using the log heading scale and hence the ash is calculated, see the following figure.



ASH ANALYSIS BLOCKING

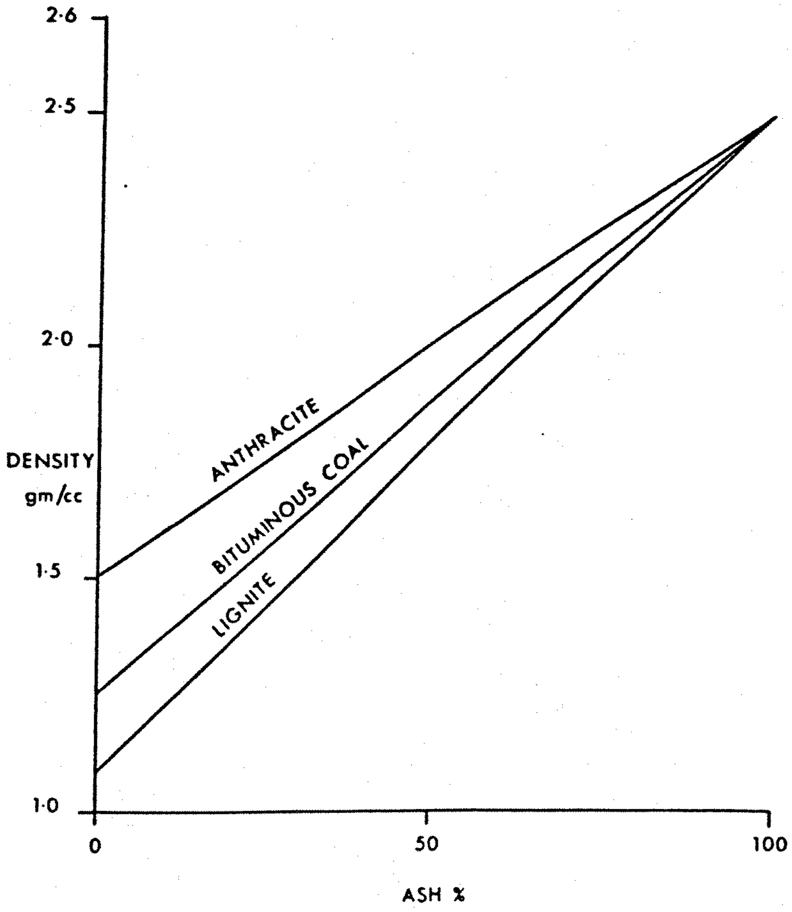
## 4. COAL SEAM EVALUATION

The following is an explanation of 3 methods of coal evaluation:

### Method 1: DENSITY VS ASH CONTENT

Ash is really a mining term to denote the non-coal material in a coal seam. However it is useful for the methane gas operator to be able to get a handle on this parameter as this non-coal material can reduce the permeability of a coal seam. Also more ash means less coal, hence less methane.

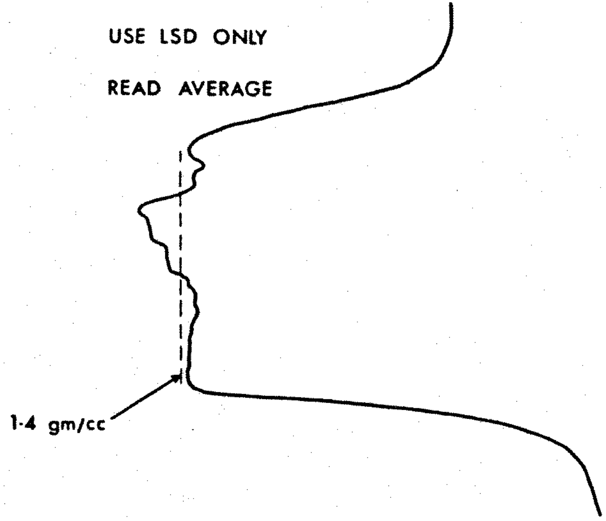
Generally speaking there is a universal relationship between the ash content and the bulk density of a coal sample for a particular type of coal. The figure below shows the general relationship between density and ash content of various coal types and shows that provided the coal type is known, the measurement of density will give an evaluation of ash content.



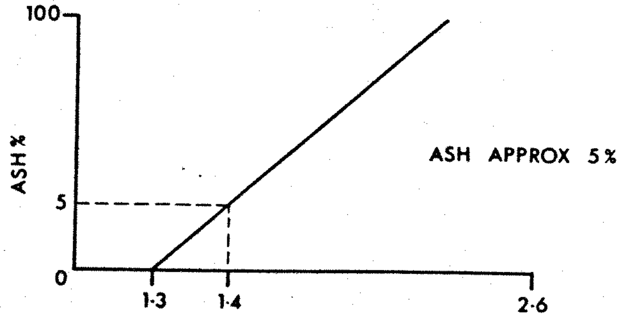
DENSITY V. ASH CONTENT

If the Ash vs Density is not known and provisional answers are required before full core analysis is available, an approximate evaluation can be made as follows:

- Assume 100% ash is 2.5 grams/cc
- Assume 0% ash is 1.1 grams/cc for lignite,
  1.25 grams/cc for young bituminous coal, and
  1.35 grams/cc for older bituminous coals
- Assume a straight line relationship between 0 and 100% ash.
  See the two following figures.



CONSTUCT APPROX. GRAPH



FIELD QUALITY ASSESMENT

If coal cores are available a proper calibration can be attempted:

- Examine the core, together with the log and see if log changes can be related to variations in the core.

- Sample the core on the basis of matching up the core samples with the most consistent response sections of the log. Try to get as many sections as possible at about 2 feet.

Because of the exponential nature of the gamma ray back-scatter response, the most accurate determinations are of lower ash content coals. Typical accuracies which would be expected for individual sections are as follows:

0 - 5% ash, ± 1%
5 - 15% ash, ± 2%
15 - 25% ash, ± 4%

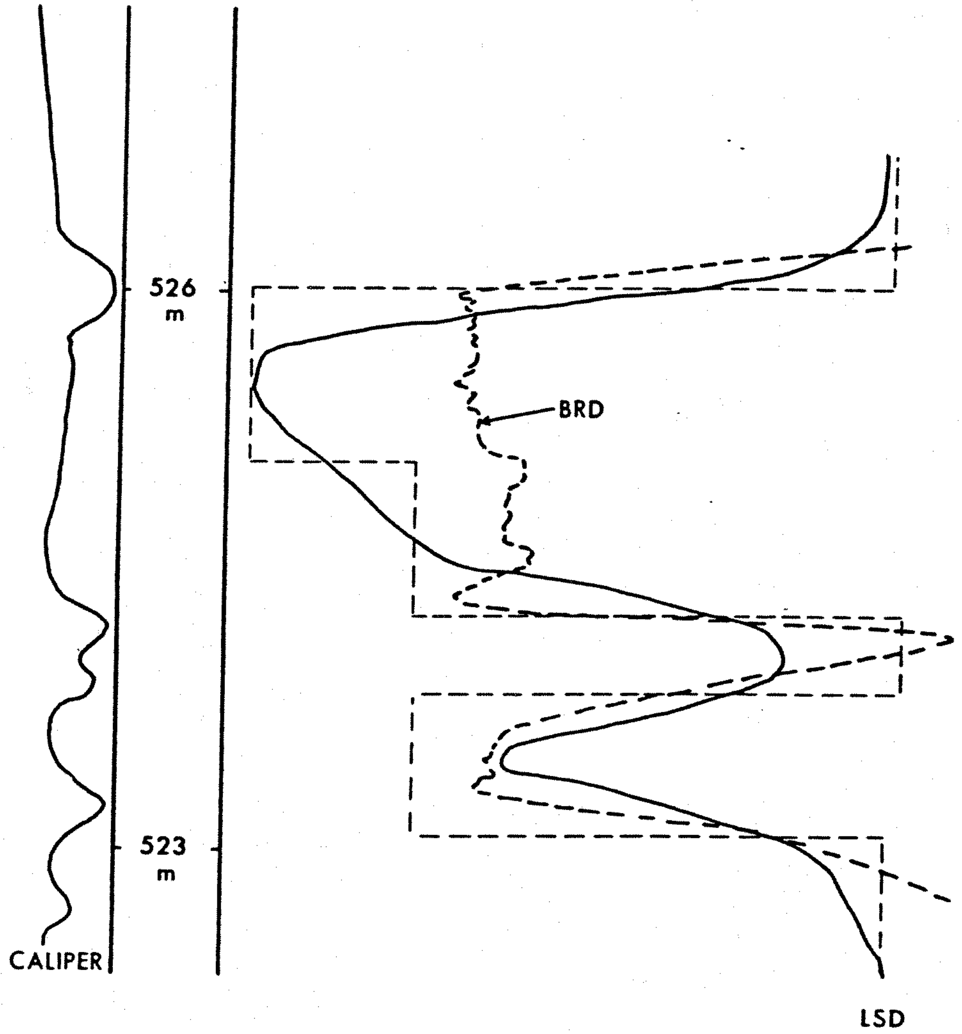
Because of the averaging effect of logs, overall seam section estimations are likely to agree much more closely with the analysis than individual sections.

The blocks often cannot be conveniently drawn and the curve variations may be such that it is impossible to select easily definable blocks. In this case, proceed as follows:

- Block out well defined low quality or dirt parting areas using the BRD log from the coal thickness log to define the boundaries of the blocks.

- Look at the remaining area and block out the largest possible areas of fairly consistent quality. A reasonable average will have to be made of there are no obvious blocks.

- In the remaining areas make an average estimation of the curve variations to complete the blocks. See the following figure.



FURTHER ASH BLOCKING

## METHOD:

The Coal Seam Evaluation package relies upon close interaction between both the Interpreter and the Geologist and their participation in the analysis. It is, of course, a prime requisite that the maximum data should be available of a geophysical, chemical and petrological nature.

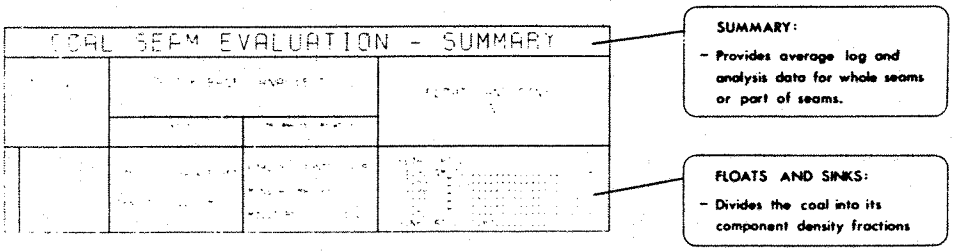
Initially, three geophysical components are described:

— Moisture — being free water held in the pore spaces in the coal

— Mineral Matter — being the inorganic part of coal which becomes ash when burnt

— Coal Substance — the organic part of the coal.

These are the basis of the evaluation which uses simultaneous equations to determine volumes which are then scaled to weights. The solution of the equations is given by a series of end points which will be selected by the interpreter and annotated on the header of the Evaluation. Selection of these end points is performed after cross reference to replays of sonic and density logs, together with crossplots of the logs. At this stage, further important points such as formation compaction and sedimentary environment may be taken into consideration.
The interpretation processing begins first with the production of an environmentally corrected linear density log, followed by close examination of the caliper log. Any areas of poor caliper will be exempted from the final computation and consequently flagged.
Subsequently 'blocking' is performed by the interpreter utilizing a density log with high vertical resolution such as the Bed Resolution Density log, a 'deconvolved' BRD log, or ultimately a Micro Focussed Resistivity log where seams are particularly thin.
Blocking identifies partings in the coals and separates the coal seams into blocks of differing quality. The process now proceeds automatically to define the constituents by weight and produce a summary of the evaluation.



**SUMMARY:**
– Provides average log and analysis data for whole seams or part of seams.

**FLOATS AND SINKS:**
– Divides the coal into its component density fractions

The flexibility of this interpretation process allows empirical ash/density relationships to be substituted in place of the Mineral Matter calculation, which will allow more positive control of field data. In cases where borehole conditions are very good or seams are particularly thick, it is possible to use automatic blocking techniques or fixed increment blocking which is of benefit in multi-hole programmes.

## OTHER CONSIDERATIONS:

Coal Seam Evaluation may be considered as a continuous interpretation progamme over a series of holes and it is recommended that the status of any empirical data and the selection of end points be regularly reviewed.

Coal Lithology Evaluation which provides a volume analysis of lithology in conjunction with bulk strength moduli is complimentary to the above.

Specific interpretation packages may be designed to suit particular special circumstances or to solve specific problems.

## Method 2: SIMULTANEOUS EQUATIONS USING DENSITY AND SONIC

An improvement on the Ash vs Density method given earlier is to make an attempt to evaluate the prime constituents of coal quality, namely ash, moisture, and carbon, as independent measurements. Theoretically this can be done by running two measurements which, whilst interrelated, respond differently to coal. The basis is quite a simple mathematical approach to solving simultaneous equations and can be expressed as follows:

If A = percent ash.
If B = percent moisture.
If C = percent carbon.
the basic coal substance can be written approximately as
$A + B + C = 100\%$ (1).

Similarly, if we denote the density of each of the three materials, mentioned above as $\rho a$, $\rho m$ and $\rho c$ and the sonic velocities as Sa, Sm and Sc, we can write two more equations, namely:

$\rho$ measured $= \rho a \times A + \rho m \times \rho m \times B + \rho c \times C$—for the density measurement (2).
S measured $= Sa \times A + Sm \times B + Sc \times C$ — for the sonic log (3).
From these three equations A, B and C can be solved.

There are some problems with this technique, specifically determining the density of carbon which of course changes with rank and the effect of volatile material and the micro coal porosity. However, in fairly simplified conditions it is possible to solve these equations and obtain a useful analysis. Examples are limited but it is quite clear that this is the type of technique which will grow in the future.

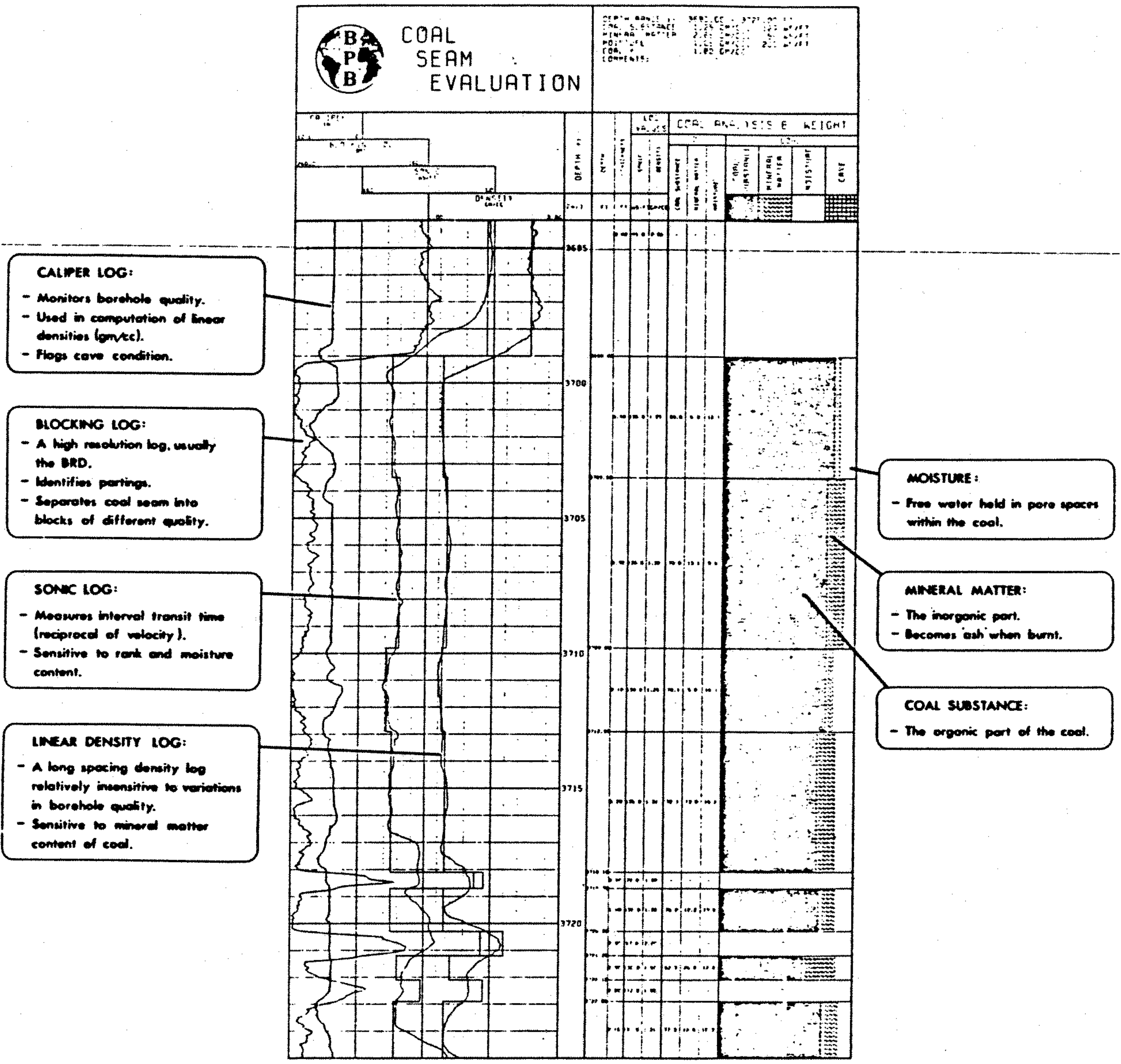
### Method 3: DENSITY VS METHANE

BPB's operations in the United States have produced a simple methane gas content analysis that uses the published equations relating methane gas content to coal rank and depth.

The BPB analysis incorporates seam thickness, ash content and depth of coal from the log. The coal rank is assumed from local knowledge and plugged into the equation. The output is shown in the attached example and gives the total amount of methane that can potentially be recovered from a seam.

The disadvantage with this approach is the actual methane produced from a well depends on a great deal more than the actual methane in place.

**Density, sonic and caliper logs form the basis of the Coal Seam Evaluation interpretation package, which aims to both define Coal Quality and also to introduce a geophysical coal classification which is generally equivalent to Proximate Analysis. Of particular use in field wide exploration studies, the results assist the geologist to tie geophysical data to that of core and laboratory whilst significantly extending the utilization of geo-physical logs.**



**CALIPER LOG:**
- Monitors borehole quality.
- Used in computation of linear densities (gm/cc).
- Flags cave condition.

**BLOCKING LOG:**
- A high resolution log, usually the BRD.
- Identifies partings.
- Separates coal seam into blocks of different quality.

**SONIC LOG:**
- Measures interval transit time (reciprocal of velocity).
- Sensitive to rank and moisture content.

**LINEAR DENSITY LOG:**
- A long spacing density log relatively insensitive to variations in borehole quality.
- Sensitive to mineral matter content of coal.

**MOISTURE:**
- Free water held in pore spaces within the coal.

**MINERAL MATTER:**
- The inorganic part.
- Becomes 'ash' when burnt.

**COAL SUBSTANCE:**
- The organic part of the coal.

## LOGGING SUITE REQUIRED:

**COAL SEAM EVALUATION — DENSITY, GAMMA RAY AND CALIPER LOGS**
**SONIC LOG**

## 5. DIFFERENCES BETWEEN OILFIELD & SLIMLINE LOGGING

| | OILFIELD | SLIMLINE |
|---|---|---|
| Cable | 3/8 inch - 7/8 inch | 1/8" - 3/16" |
| Crew | 3 man crew | 1 man crew<br>(2 in winter) |
| Pressure Rating | 15,000 P.S.A. | 3,000 Psi (6000 P.S.A.) |
| Temperature Rating | 150°C | 75°C (100°C) |
| Depth Limitation | 5000 Metres | 1500 metres<br>(3,000 metres) |
| Resolution | Medium | High Resolution |
| Depth of Penetration | Deep | Shallow |
| Sonde Combinability | Extensive | Limited |
| Data Transmission | 24 channel | Aurora |
| Ideal Borehole Diameter | 6" to 12" | 3" to 8" |
| Borehole Condition | Less affected | More affected |
| Invasion | Less affected | More affected |

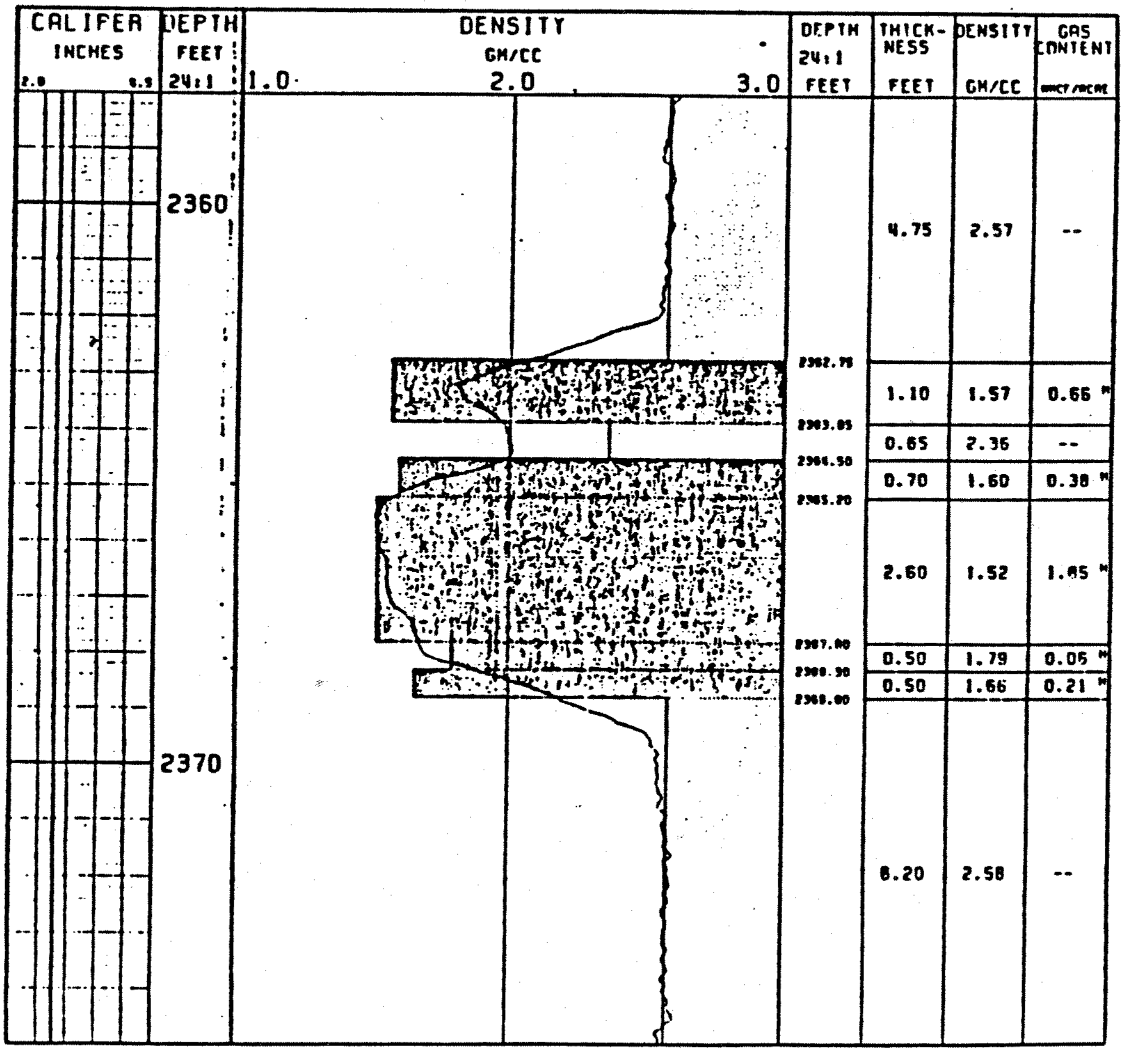
## COMMENTS....

% ASH = A + B.D + C.$D^2$
WHERE A = -297.58 ,B = 214.91 & C = 0.000000
AND D IS THE LINEAR DENSITY ( < 1.85 GM/CC.)

## SUMMARY INFORMATION

| | THICKNESS FEET | % NETT THICKNESS |
|---|---|---|
| NETT GAS | 5.40 | 100.0 |
| >0.5MMCF/ACRE | 3.70 | 68.5 |
| >1.0MMCF/ACRE | 2.60 | 48.1 |
| >1.5MMCF/ACRE | 2.60 | 48.1 |
| >2.0MMCF/ACRE | 0.00 | 0.0 |
| >2.5MMCF/ACRE | 0.00 | 0.0 |

TOTAL GAS CONTENT FOR THIS INTERVAL: 3.16MMCF/ACRE



EXAMPLE: BPB USA OPERATIONS; DENSITY VS METHANE

## 6. TECHNICAL SPECIFICATIONS ON BPB SLIMLINE SONDES

DD1 - Gamma Ray, Caliper, Long Spaced and Bed Resolution Densities

NN1 - Gamma Ray, Dual Spaced Neutron

MS1 - Multi-Channel Sonic; 20cm, 40cm, 60cm resolution, and 20cm unspiked channel for fracture i.d.

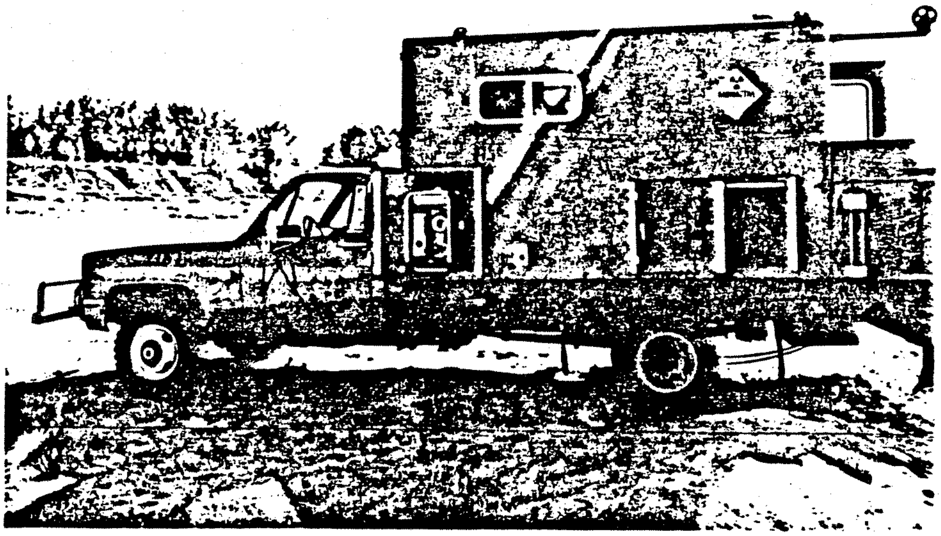
RO1 - Focussed Electric Sonde

RS1 - Spontaneous Potential, Resistance

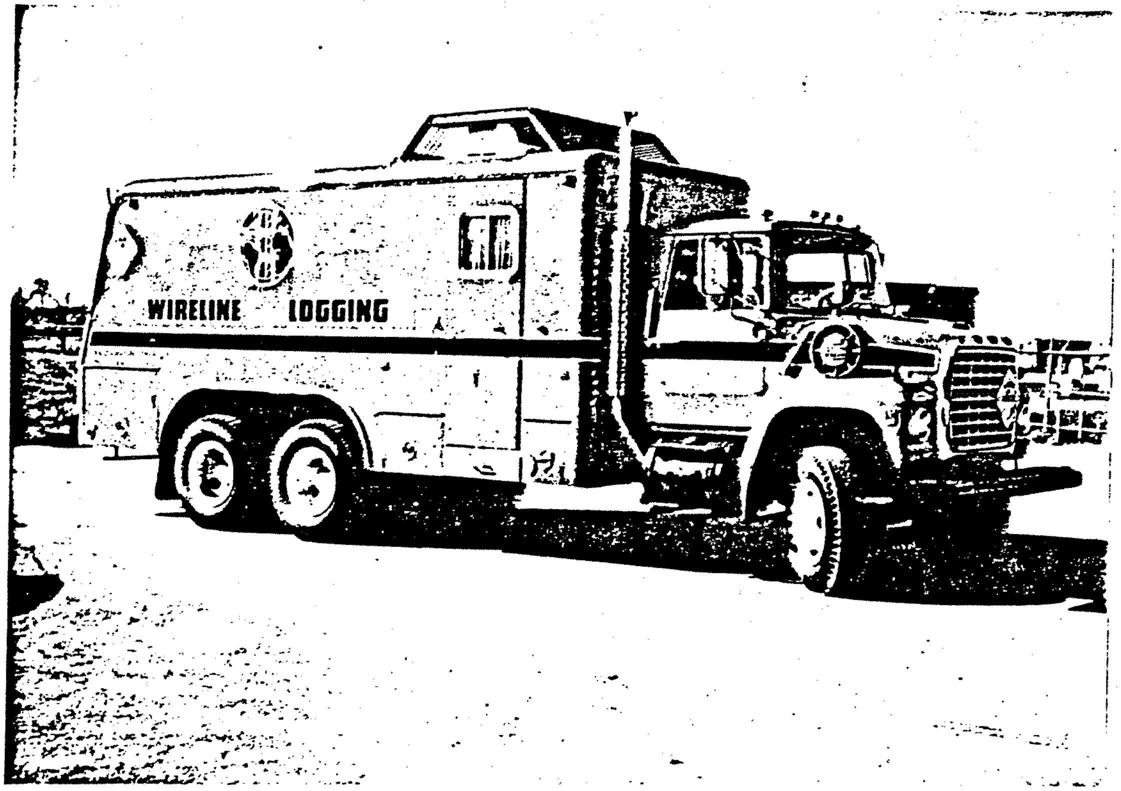
VO1 - Verticality Sonde; Hole Tilt, Azimuth of Hole Tilt, True Vertical Depth, True Hole Position

DV1 - Dipmeter Sonde; Formation Dip Magnitude and Azimuth
The Dipmeter is run in combination with the Verticality Sonde providing a complete hole survey

TT1 - Temperature; Absolute and Differential



EXAMPLE OF A SLIMLINE LOGGING UNIT



EXAMPLE OF AN OILFIELD LOGGING UNIT

# DD1 DUAL DENSITY, GAMMA RAY, CALIPER, SONDE.

(OR COAL COMBINATION SONDE CCS)

## MEASUREMENTS:

LONG SPACING DENSITY (LSD)
BED RESOLUTION DENSITY (BRD)
COMPENSATED DENSITY
GAMMA RAY
CALIPER

The DD1 Sonde has been designed for the full range of borehole diameters, depths and conditions generally associated with slimhole drilling. All logs are recorded in a single run, with a selection of processing and presentation options available to suit specific requirements.

## GENERAL SPECIFICATIONS:

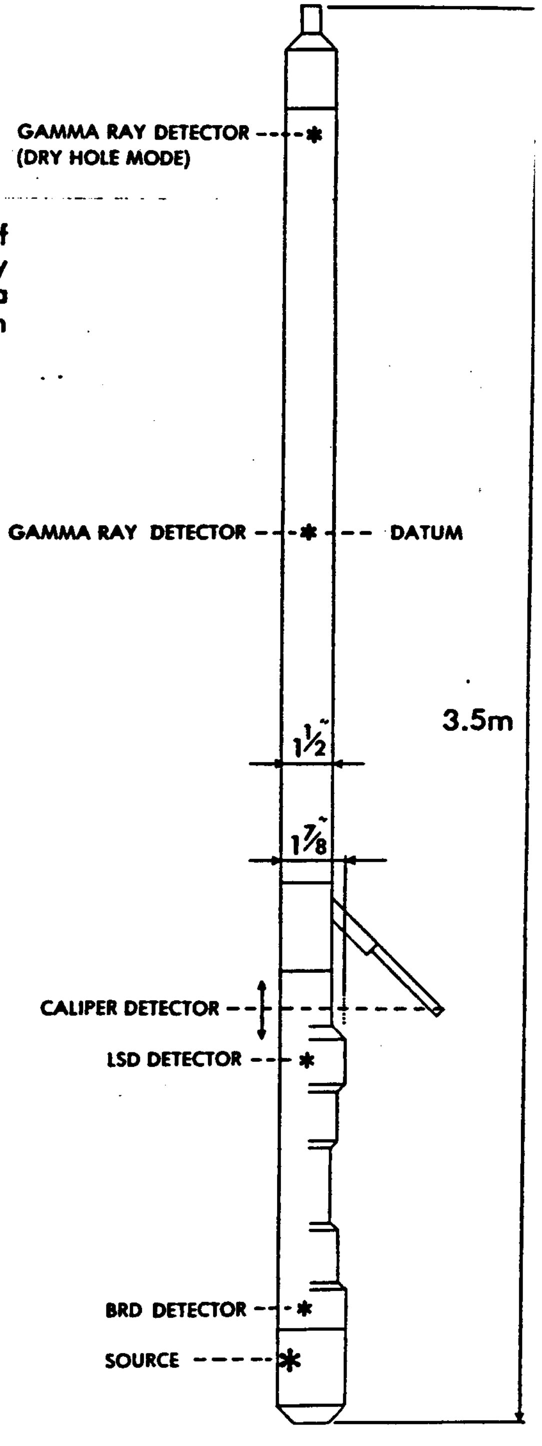
| | |
|---|---|
| Length | — 3.5 m (11.5') |
| Weight | — 20 kg (44 lbs) |
| Diameter | — 4.8 cm (1⅞") max |
| Temperature | — up to 70°C (158°F) |
| Pressure | — up to 210 kg/cm² (3000 p.s.i.) |

## OPERATING CONDITIONS:

Hole Depth — to a max of approx. 2000m (6500')
Hole Diameter — open hole: 6.5 to 30 cm (2.5" to 12")
casing or rods: 5.5 to 30 cm (2.0" to 12")

Logging Speed — standard logging: 9m/min (30'/min)
— detail logging: 2.25m/min (7.5'/min)
Logging Mode — Sidewall, Caliper eccentralised

Optimum calibration requires open, fluid filled holes with diameters less than 20 cm (8"). Results of a more qualitative nature will be obtained through casing or drill rods and/or without fluid. Significant caving of the borehole wall will adversely affect results.



DD1 SCHEMATIC

# TECHNICAL INFORMATION:

GAMMA RAY — Measurement of naturally occurring radioactivity utilizes an uncollimated Sodium Iodide Crystal coupled to a Photo Multiplier Tube based amplifying system. Calibration, by active field jig allows linear presentation in API units with borehole correction. Some sondes offer a remote detector position option, to prevent interference from the source in dry holes.

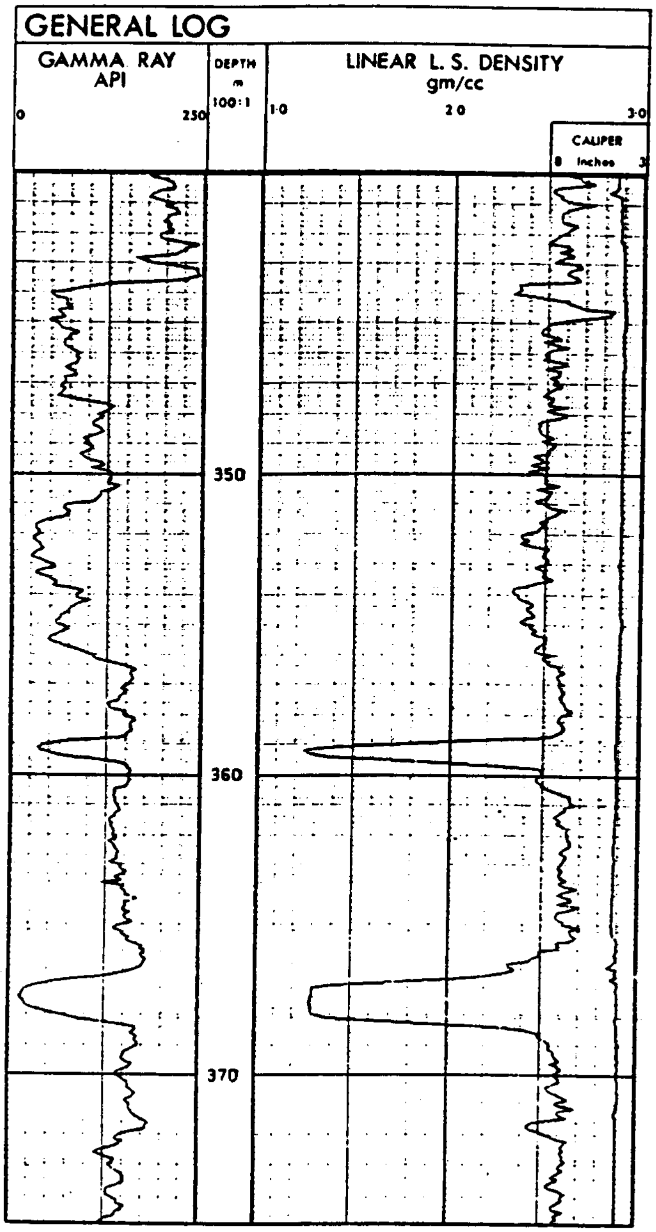


*Fig. 1 — LINEAR DENSITY GENERAL SCALE.*

DENSITY — Measurement of scattered radiation levels is made with two independent detecting systems, both similar to the Gamma Ray detector but incorporating crystal shielding (sidewall collimation) and cable deadtime correcting circuitry. Calibration utilizes large passive base facilities and active field jigs to allow log presentation in gm/cc.

LSD — The deeper reading device, with a source to detector spacing of 48 cm (19"), provides the definitive density log in most borehole conditions and is presented:

— with linear response, facilitating full 1-3 gm/cc range evaluation,

and/or — with logarithmic response, enhancing the 1-2 gm/cc range.

Borehole corrections are applied and compensation is available, incorporating the BRD, to improve density measurement in difficult hole conditions.

BRD — With a spacing 15 cm (6") this shallower reading measurement produces an essentially linear response density log as both:

— an independent high resolution log for precise boundary definition.
Digital and Deconvolution Filter options can, under ideal conditions, provide resolution enhancement down to 5 cm (2").

— an LSD compensation factor.

CALIPER — A single arm electro mechanical device is held closed for entry into the borehole and activated during the logging run. Field calibration produces a precise linear measurement of hole diameter and caving profile. Hole diameter ranges:

| | |
|---|---|
| Standard arm | 4.8 to 20 cm (1⅞" to 8") |
| Long arm | 4.8 to 30 cm (1⅞" to 12") |

SOURCE — A doubly encapsulated sealed source of Caesium 137 at an activity of 100 mCi. is mounted within a sidewall collimated holder and locked securely to the sonde during logging operations. This source holder is transported in a purpose designed shield with a surface radiation level less than 10 mrem/hr.

## PRESENTATION:

Logs are recorded in Metric or Imperial units and presented on a standard 6 track API logging chart with full flexibility of scales and format. 'General' vertical scales range upwards from 100:1 whilst 'Detail' scale options, reserved for closer investigation of zones of interest, range down to 10:1. Some of the more usual presentations include:

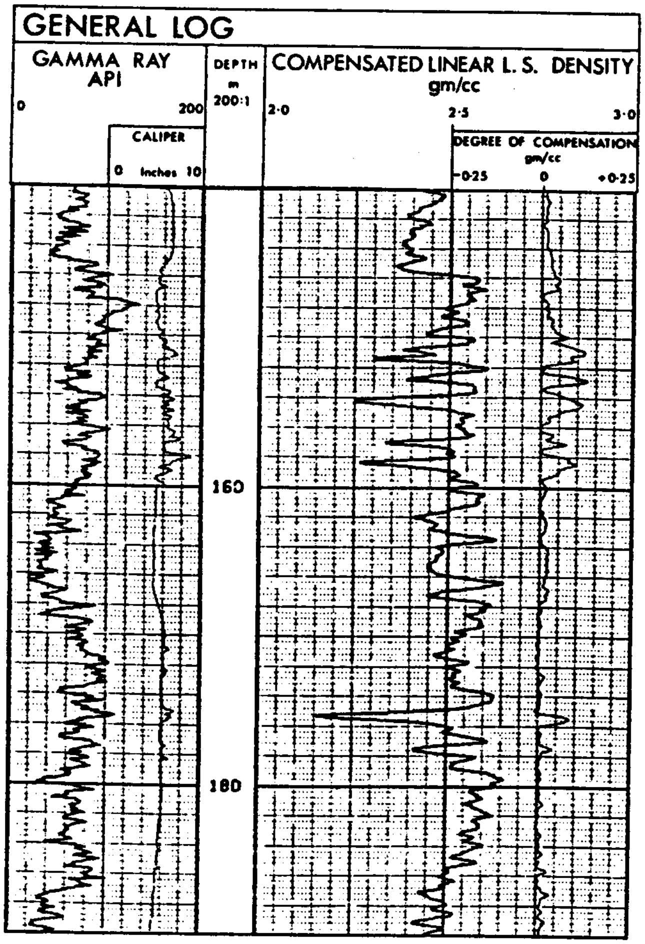


*Fig. 2 — COMPENSATED DENSITY GENERAL SCALE.*

**LINEAR DENSITY** — *GENERAL SCALE (fig. 1)*

Linear LS Density over a range of either 1-3 gm/cc or 2-3 gm/cc depending on density range encountered.

Linear Gamma Ray and Caliper on suitable scales.

**LOGARITHMIC DENSITY** — *GENERAL SCALE*

As fig. 1 except that the LS Density is presented with logarithmic response to provide enhancement over the 1-2 gm/cc range.

**COMPENSATED DENSITY** —
*GENERAL SCALE (fig. 2)*

Similar to fig. 1 except that the LS Density is compensated by the BR Density and the 'degree of compensation' included.

**DETAIL DENSITY** — *DETAIL SCALES (fig. 3a, b, c)*

A comparison of the three density options: LSD Linear, LSD Logarithmic and BRD (Linear), on detail scales; an illustration of scale flexibility and tool performance through seams or zones of interest over the full 1-3 gm/cc range.

Density correction and processing options vary according to the computational power of the surface equipment and may be summarized as follows:

| Corrected/Processed for the effects of: | Surface Equipment | | |
|---|---|---|---|
| | Standard Unit | Log Processor Unit | Computer Graphics Unit |
| Borehole diameter | Yes | Yes | Yes |
| Fixed 1.0 gm/cc mud weight | Yes | — | — |
| Mud weight as input | — | Yes | Yes |
| Formation Z/A effect | Yes | Yes | Yes |
| Detector deadtime | Yes | Yes | Yes |
| Cable deadtime | Yes | Yes | Yes |
| LSD Linearization option | No | Yes | Yes |
| LSD Compensation (with BRD) option | No | Yes | Yes |
| BRD Deconvolution option | No | Yes | Yes |
| Gamma Ray Stripping | No | No | Yes |
| Variable Caliper measuring point | No | No | Yes |

## TECHNICAL INFORMATION:

The Neutron Log is, in a fluid filled borehole, a measure of the ability of the formation to absorb thermal neutrons. This ability is a function of hydrogen in the formation and, therefore, after correction for borehole effects, the Neutron Log may be presented as an Index of Hydrogen and/or in turn as a measurement of formation porosity. High energy neutrons are emitted through 360° around the logging source. In a fluid filled hole these fast neutrons are slowed down (or thermalised) in a region very close to the source. In an air filled hole thermalisation and absorption both take place in the formation.

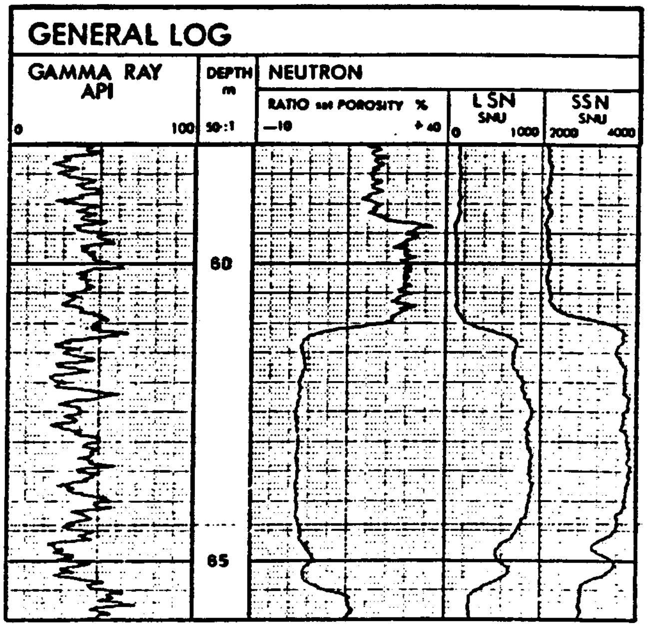
Both Neutron Detectors are uncollimated $Helium_3$ Tubes and are spaced 45 cms (Long Spacing) and 25 cms (Short Spacing) from the logging source. Calibration uses portable passive jigs to allow log presentation in calibrated units for all three outputs. The LSN and SSN are available as individual logs if required, although the Ratio Log provides the definitive porosity measurement.

SOURCE — a double encapsulated sealed source of Americium 241/Beryllium at an activity of One Curie is mounted in a stainless steel holder and locked securely to the sonde during logging operations. The source holder is transported in a purpose designed shield with a maximum surface radiation level of 2 mR/hr (gamma) and 6 mR/hr (Neutron).

The Gamma Ray system is identical to that described in the DD1 leaflet No. 1.

## PRESENTATION:

A range of presentations of Ratio Porosity, SSN, LSN, and Gamma Ray logs are available with a full flexibility of format and vertical and horizontal scales.



## APPLICATION SUMMARY:

| | |
|---|---|
| RATIO | — Lithology Identification and Correlation and, in open fluid filled holes, Hydrogen Index/Porosity measurement for quantitative formation evaluation. |
| SSN | — Porosity indication plus high resolution Lithology Identification, Correlation and Bed Thickness evaluation; particularly useful in higher apparent porosity formations. |
| LSN | — Porosity indication plus Lithology Identification and Correlation. |

Neutron logs are also being used, through empirically established relationships, for Strength and Fracture analysis of coal measure formations.

GAMMA RAY — Shale content, Lithology Identification and Correlation.

The NN1 Sonde is seen as a comprehensive porosity and lithology evaluation package, suited to the full range of slim hole environments. In addition its physical dimensions and the nature of its measurements make the NN1 particularly useful for qualitative logging in less than optimum conditions, e.g. through casing or drill rods, or in dry holes.

# NN1 DUAL NEUTRON, GAMMA RAY, SONDE.

(OR DSN)

## MEASUREMENTS:

RATIO NEUTRON POROSITY
SHORT SPACING NEUTRON (SSN)
LONG SPACING NEUTRON (LSN)
GAMMA RAY

The NN1 Sonde provides dual spacing Neutron (as also available from separate runs of the NO1 Sonde), Neutron Porosity and Gamma Ray logging in a single package. Furthermore, the Ratio based porosity measurement provides a degree of compensation, linearity and caliper independency not possible from a single detector system.

## GENERAL SPECIFICATIONS:

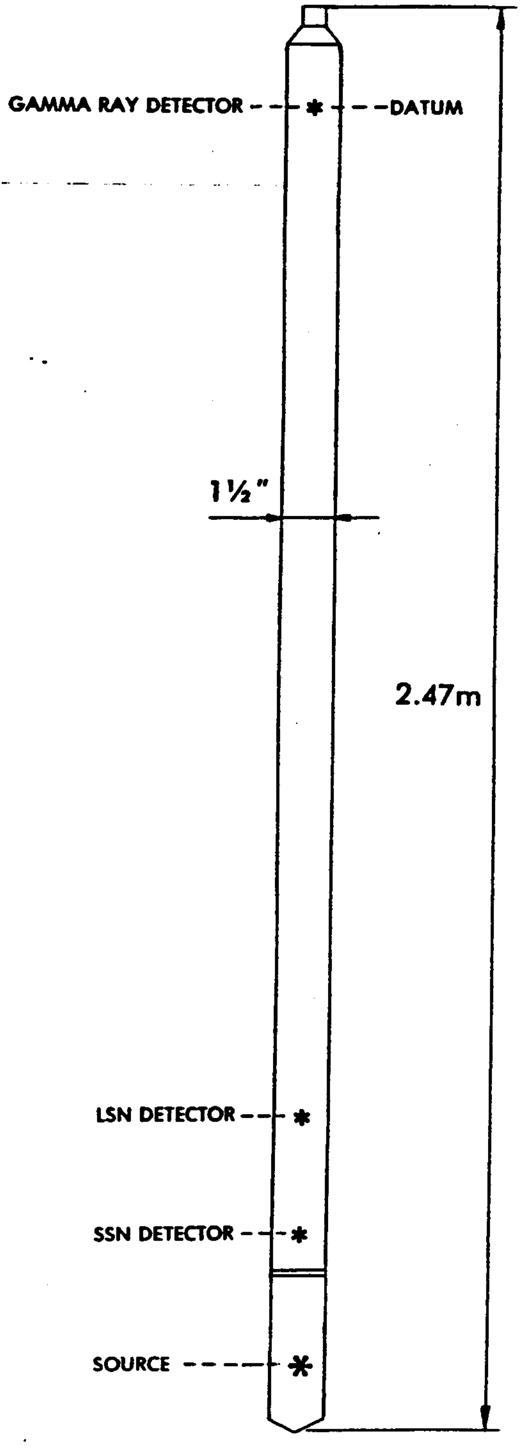
Length — 2.47 m (8.10')
Weight — 14 kg (30 lbs)
Diameter — 3.8 cm (1½")
Temperature — up to 70°C (158°F)
Pressure — up to 210 kg/cm² (3000 p.s.i.)

## OPERATING CONDITIONS:

Hole Depth — to a max. of approx.: 2000 m (6500')
Hole Diameter — open hole: 6.0 to 30 cm (2.5" to 12")
casing or rods: 5.0 to 30 cm (2.0" to 12")

Logging Speed — standardly: 9m/min (30'/min)
detail logging: 2.25m/min (7.5'/min)
Logging Mode — free running

Optimum calibration of Neutron Porosity, based in the NN1 system on the ratio of Long and Short spacing logs, requires open fluid filled holes in reasonable condition. Valuable, although more qualitative logging will continue to be feasible in dry holes, through casing or drill rods and at increased diameters.



*NN1 SCHEMATIC*

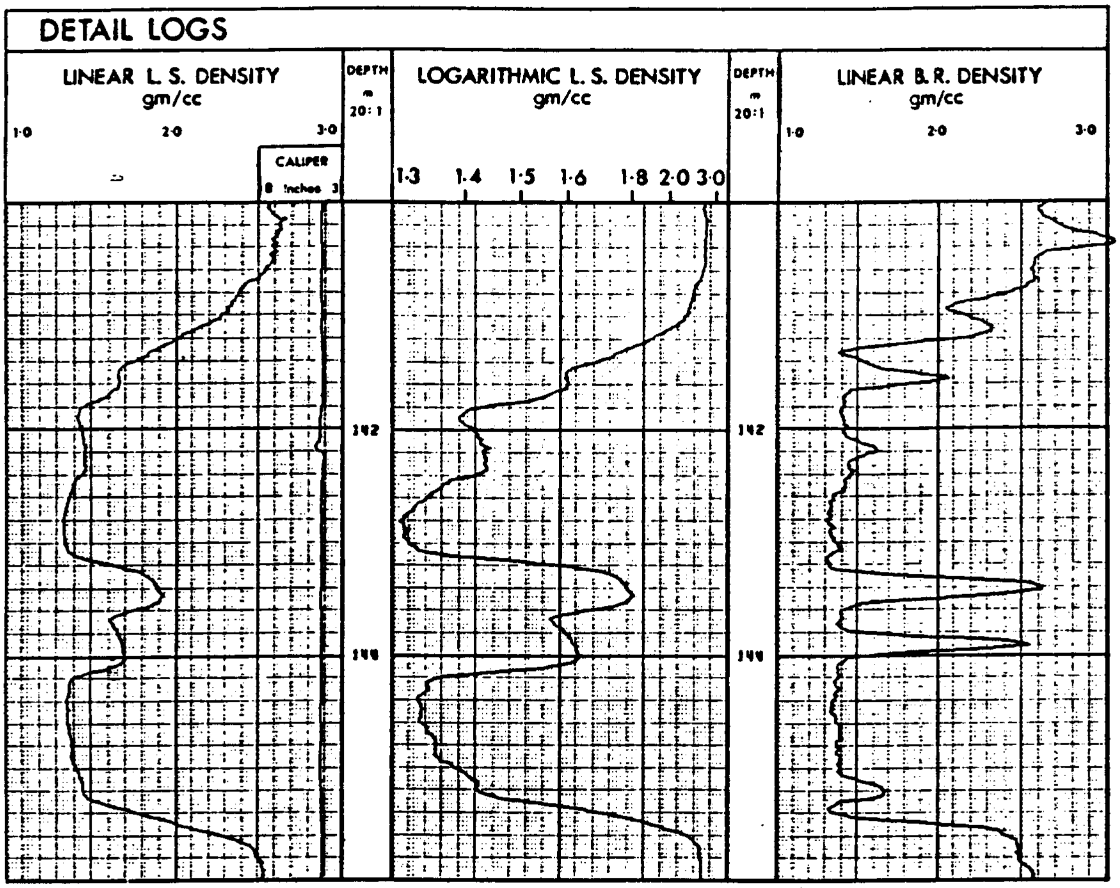


*Fig. 3 — DETAIL SCALE DENSITY PRESENTATION OPTIONS.*

## APPLICATION SUMMARY:

| | |
|---|---|
| GAMMA RAY | — Shale Content, Lithology Identification and Correlation. |
| DENSITY : LSD | — Porosity, Lithology Identification and Correlation plus quantitative evaluation of: Lithology, Formation Properties, and Strength Index (with MC Sonic Sonde). |
| : BRD | — Precise boundary definition usually to ±2 cm (plus LSD compensation). |
| CALIPER | — Borehole diameter and caving profile (plus sidewall configuration and density correction). |

The DD1 suite is seen as a basic slimhole evaluation package, providing both general lithology and detailed seam information in one logging run. Additional sonde runs are available to complement the DD1 service according to specific interpretation requirements.

## REFERENCES:

Further information on many aspects of the DD1 service may be found in the following BPB publications, available on request.

1. BPB Coal Interpretation Manual

2. The Radiation Density Log Applied to the Resolution of Thin Beds in Coal Measures — J.R. Samworth

3. Slimline Dual Detector Density Logging, a Semi-Theoretical but Practical Approach to Correction and Compensation — J.R. Samworth

# MS1 MULTICHANNEL SONIC SONDE.

(OR MCS)

## MEASUREMENTS:

ACOUSTIC VELOCITY LOGS AT:

20cm ( 8") RESOLUTION, DESPIKED
40cm (16") RESOLUTION, DESPIKED
60cm (24") RESOLUTION, DESPIKED
20cm ( 8") RESOLUTION, UNPROCESSED

PLUS INTEGRATED SONIC LOG

The MS1 Sonde provides high quality Sonic Transit Velocity data, within a slim diameter and at a variety of vertical resolutions, throughout a comprehensive range of borehole diameters and conditions.

## GENERAL SPECIFICATIONS:

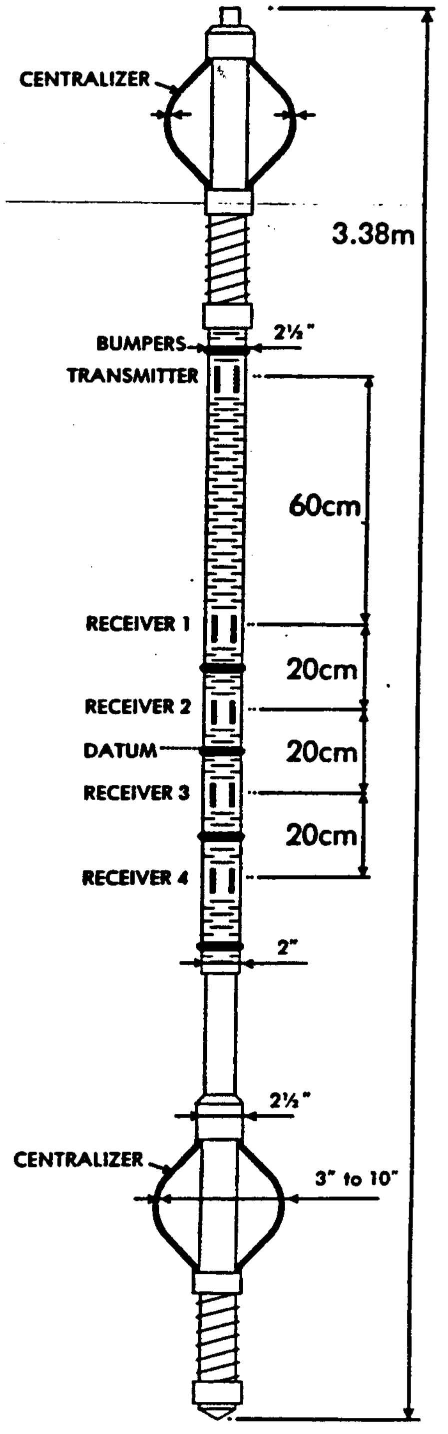
| | | |
|---|---|---|
| Length | — | 3.38m (11.1') |
| Weight | — | 16kg (35 lbs) without centralizers<br>22kg (49 lbs) with centralizers |
| Diameters | — | basic sonde 51m (2") |
| | — | with bumpers/centralizers 65m (2.5") |
| Temperature | — | up to 70°C (158°F) |
| Pressure | — | up to 210 kg/cm² (3000 psi) |

## OPERATING CONDITIONS:

| | | |
|---|---|---|
| Hole Depth | — | to a max. of approx. 2000m (6500') |
| Hole Diameter | — | 65mm (2.5") to 90m (3.5") without centralizers |
| | — | 90mm (3.5") to 300+mm (12+") with centralizers |
| Logging Speed | — | Standardly: 9m/min (30'/min) |
| Logging Mode | — | Centralized, where borehole diameter and conditions permit, with a full 360° window for all 5 transducers (one transmitter and four receivers). |

Precise in-built electronic calibration ensures the accuracy of all transit timings, allowing downhole processing of velocity data, prior to surface transmission. Sonic logging will be successful only in Open (Uncased), Fluid Filled boreholes.

Sonic measurements will become problematic in badly caved sections of the borehole or in unconsolidated (or other) formations where adequate acoustic coupling cannot be achieved.



MS1 SCHEMATIC

# TECHNICAL INFORMATION:

A ceramic transmitter T is fired with a high voltage pulse every 0.1 sec. causing acoustic energy to enter the formation, via the borehole fluid (essential for efficient coupling), as a compression wave. Fig. 1.

Receivers R1, R2, R3, R4 are successively stimulated by this same compression wave after passing through sections of the formation between the transmitter and appropriate receiver. The distance between each of the receivers is fixed, and of course known precisely. Consequently measurement of the time taken for the wave to pass between receiver pairs will enable the calculation of its velocity, normally known as the Sonic Velocity.

By incorporating pre-programmed microprocessors in the sonde various combinations of receiver pairs can be selected and processed simultaneously. The following options are standardly available:

R1-R2 20cm ( 8") —
HIGH RESOLUTION CHANNEL No.1
R2-R4 40cm (16") —
MEDIUM SPACING CHANNEL No. 2
R1-R4 60cm (24") —
LONG SPACING CHANNEL No. 3
R3-R4 20cm ( 8") —
DISCONTINUITY CHANNEL No. 4

The MS1 Sonde calculates each of these four velocities every 0.1 sec. (equivalent to 1.5cm at the standard 9m/min. logging speed), transmitting results for surface recording as continuous depth based logs.

Discontinuities in the formation can often cause interruption to the compression wave, causing unwanted spikes on the log. In Channels 1, 2 and 3, these effects have been identified and removed, again by the use of downhole microprocessors. Channel 4 is presented in its original unprocessed form, providing both a quality control on the processed channels and also a means of identifying zones of high discontinuity, eg fracture detection.

System design ensures that the first arrival of the compression wave at all receivers results, in normal conditions, from transit paths through the formation rather than through the body of the sonde or through the borehole fluid. Limiting extremes of borehole diameter and formation velocity combinations, beyond which 'first arrival' problems will be encountered, are listed in the Application section.

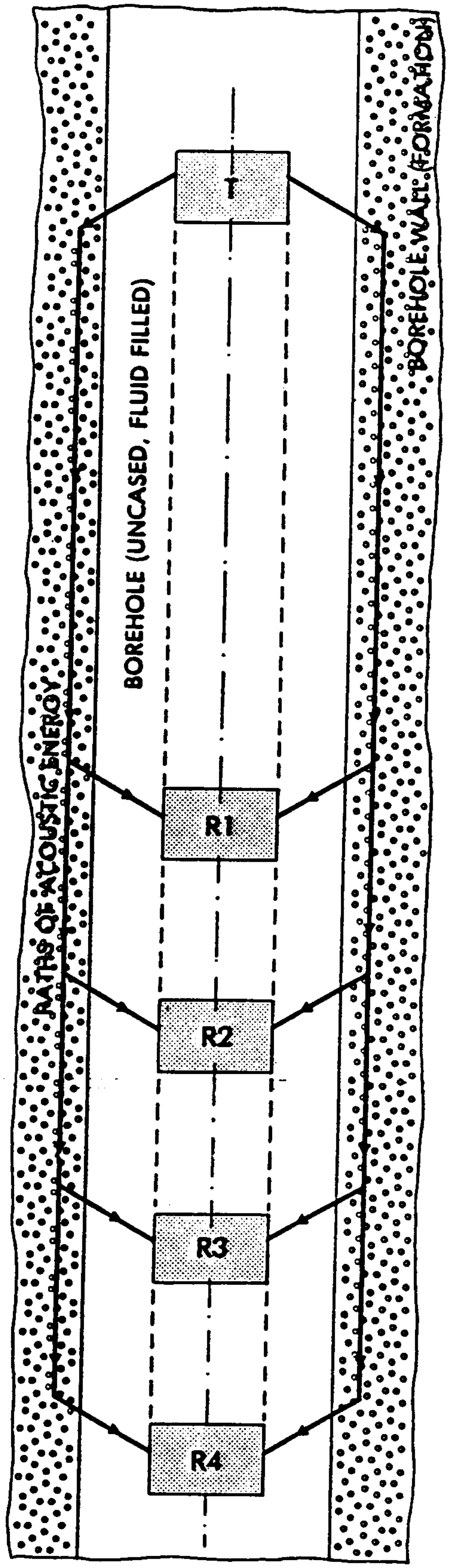


*Fig. 1 — TRANSDUCER SCHEMATIC*

## PRESENTATION:

A full flexibility of vertical scales (either metric or imperial) and presentation formats is available, to include up to all four Velocity Channels and Integrated data.

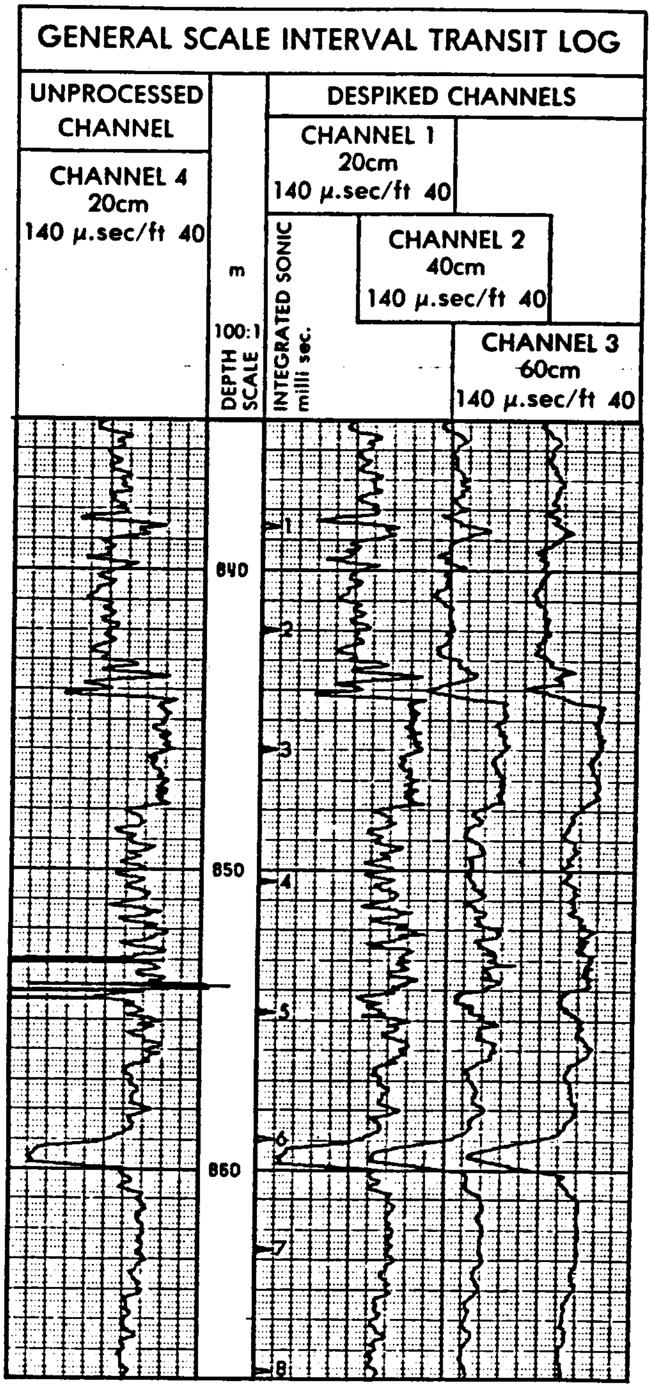


*Fig. 2 — PRESENTATION EXAMPLE*

Fig. 2 is a comprehensive illustration of all Velocity logs, together with a Channel 2 based Integrated Sonic log, at a 100:1 metric scale.

The 'spiking' effects of discontinuity or other features can be readily seen in this example. Channel 4, within the 853-855m interval, contains spiking features which have been automatically identified as geophysically invalid and processed out of the remaining channels.

Notes: — Velocity logs are usually presented in either μ.sec/ft or μ.sec/m.

— The Integrated Sonic Log, based on any of the Velocity Channels, is available as a surface processing option.

— A Channel 1 deconvolution option is available as a surface processing procedure to further enhance the resolution of this high resolution channel, from 20cm to 14cm.

## APPLICATION SUMMARY:

| | |
|---|---|
| LONG SPACING (60cm)<br>CHANNEL No. 3 | — provides the best average formation velocity and minimises the effects of any cavings. This channel is ideal for porosity determination, lithology determination, correlation, forming an integrated sonic log for seismic correlations and for combining with a density log for rock strength determinations. |
| HIGH RESOLUTION (20cm)<br>CHANNEL No. 1 | — is suitable for deliniation of bed boundaries and structures within the seams. The high resolution allows more detailed analyses of rock strength and seam quality. Deconvolution options offer further resolution enhancement. |
| MEDIUM SPACING (40cm)<br>CHANNEL No. 2 | — is required when borehole conditions, mainly because of caving, preclude the use of the HR Channel. This spacing is often preferred in narrow diameter boreholes to the LS Channel as more detail is displayed. |
| DISCONTINUITY (20cm)<br>CHANNEL No. 4 | — monitors the original unprocessed signal and is thus useful for indications of fractures and other conditions likely to produce spiking effects. |
| INTEGRATED SONIC | — Usually derived from either the LS or HR Channel, depending on hole condition, and used as an aid for seismic interpretation. |

N.B. All four channels are valid for rock velocities down to 150μ.sec/ft in holes up to 10" diameter. Additionally for the same range of rock velocities channel 2 is valid up to 13" diameter and channel 4 up to 16".

## REFERENCES:

Further information on the MS1 Service may be found in the:
— BPB Coal Interpretation Manual,
a BPB publication available on request.

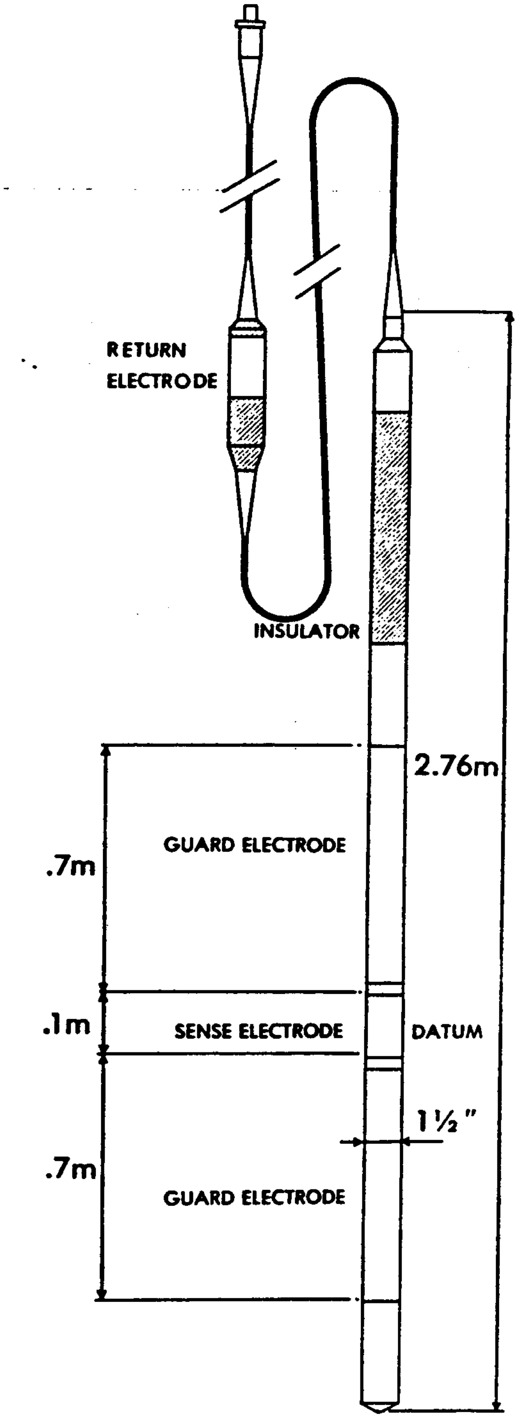
# RO1 FOCUSSED ELECTRIC SONDE

(OR FE MK II SONDE)

## MEASUREMENTS:

FORMATION RESISTIVITY

The RO1 Sonde is a single function 3 electrode laterolog device combining high power of vertical resolution and intermediate depths of investigation. The result is a quantitative measure of formation resistivity well suited to the interpretation of formation properties in slim holes.



RO1 SCHEMATIC

## GENERAL SPECIFICATIONS:

Length — 2.76m (6.5') Sonde
— 12.3m (40.4') Sonde+Bridle (Standard)
— 7.3m (24') Sonde+Bridle (Shallow hole)
Weight — 15kg (33lbs)
Diameter — 3.8cm (1½")
Temperature — up to 70°C (158°F)
Pressure — up to 210kg/cm² (3000psi)

## OPERATING CONDITIONS:

Hole Depth — to a max. of approx. 2000m (6500')
Hole Diameter — open hole 5.0cm to 25+cm (2.0" to 10+")

Logging Speed — standardly 9m/min (30'/min)
Logging Mode — free running
Resistivity range — 0.2 to 20,000 ohm m

Open, fluid filled holes are a prerequisite, and optimum hole diameters less than 20cm (8"). Fluid resistivities should be as low as possible, this requirement being more important in low resistivity formations.

Logging near the surface is limited by the requirement for the bridle to be in the fluid of the open hole. Excessive borehole casing will adversely affect results.

# TECHNICAL INFORMATION:

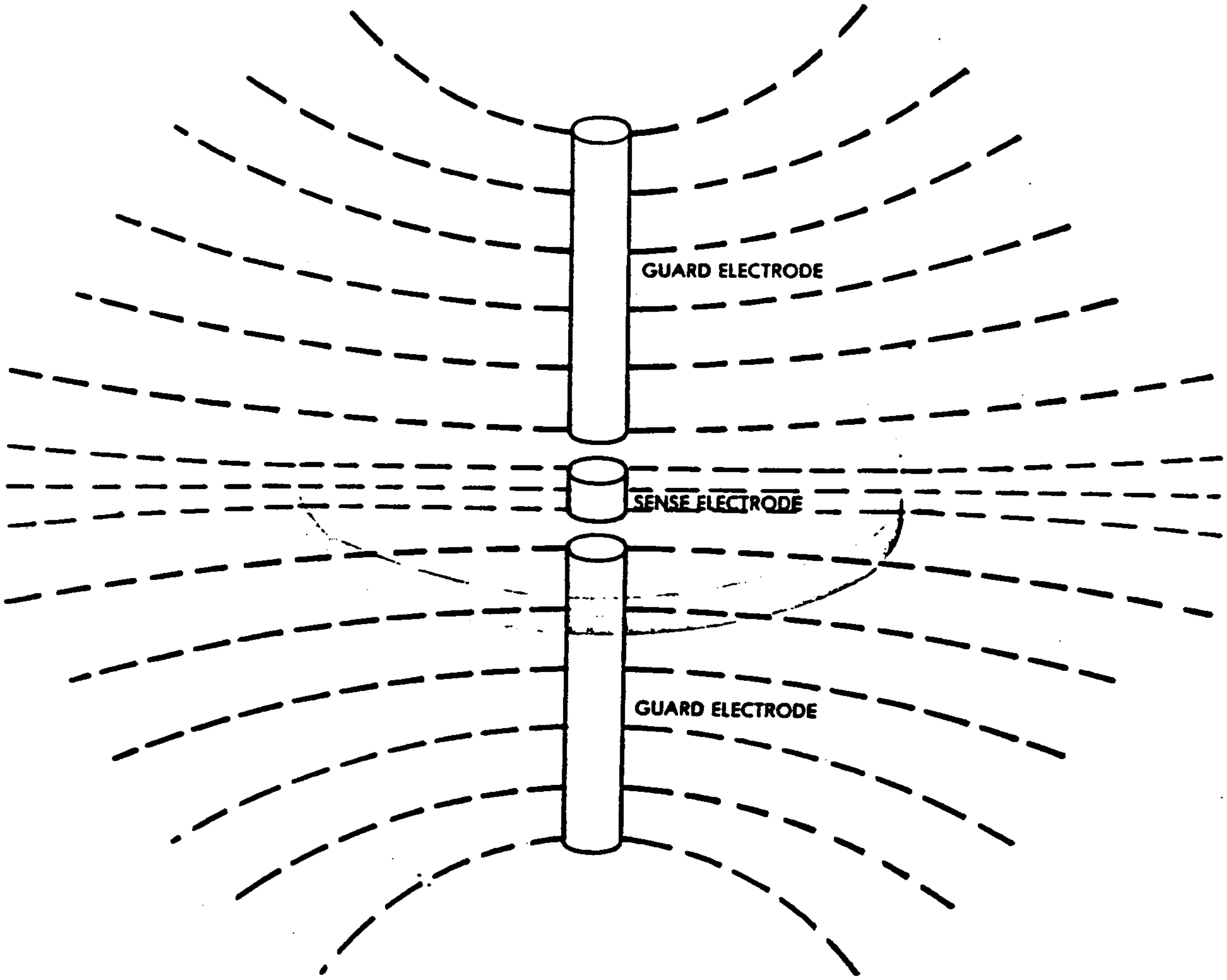


*Fig. 1 CURRENT DIAGRAM*

An electric current is established from the 'sense' electrode via the borehole fluid into the formation, the circuit being eventually completed through surface electronics and logging cable.

The initial focussing of this current (fig. 1) into a narrow 360° cylindrical disc is achieved with a secondary circuit set up from the two larger 'guard' electrodes, this circuit being completed through a further electrode positioned at an optimum distance above the sonde — although this distance can be decreased if near surface measurement is required.

Sonde electronics hold the potential differences between the sense and guard electrodes at zero, hence the focussing effect, and monitor both the sense current and voltage levels throughout the full range of resistivities encountered.

Combination of these values yield, via Ohm's law, a measure of the resistance seen by the sense electrode. Translation of this resistance into a continuous depth based log of formation resistivity follows, with the application of conversion and correction based on sonde geometry, borehole diameter and mud resistivity — see reference 2.

## PRESENTATION:

Logs may be recorded in Metric or Imperial depth scales and are available with a full flexibility of vertical and horizontal scales.

The Focussed Electric measurement is usually presented on a logarithmic scale over several decades, to meet the range of resistivities encountered.

Linear presentation is also available if specifically required.

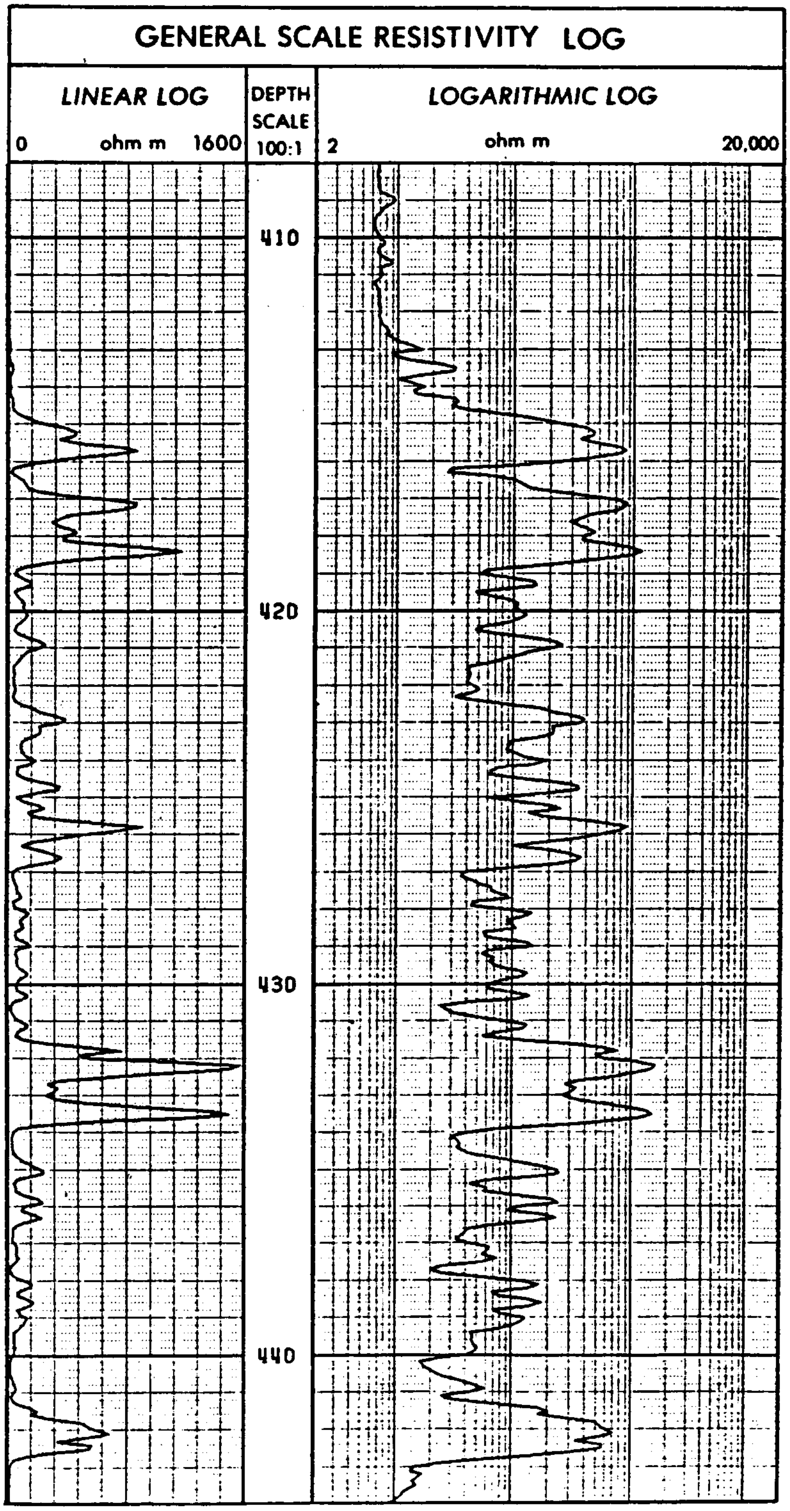


*Fig. 2 LOG PRESENTATION*

## APPLICATIONS:

The RO1 Sonde's Focussed Electric log of formation resistivity combines the advantages of a Single Point device's high resolution (but uncalibrated) with a Normal or Lateral device's calibration ability (although poor resolution) — whilst maintaining a depth of investigation realistic in terms of slimhole conditions.

The resulting log provides not only valuable lithology correlation data but also a quantitative measure of formation properties to enable further interpretation to be considered.

## REFERENCES:

Further information on Focussed Electric measurement may be found in the following BPB publications, available on request:

1. BPB Coal Interpretation Manual.
2. A Focussed Resistivity Tool for Slimline Coal Logging Systems — J R Samworth and M A Cherrie.

# RS1 RESISTANCE, SPONTANEOUS POTENTIAL SONDE

(OR SP/RES SONDE)

## MEASUREMENTS:

RESISTANCE (SINGLE POINT)
SPONTANEOUS (OR SELF) POTENTIAL

The RS1 Sonde is a dual function, single electrode, non focussed device producing simultaneous measurement of formation Potential and Resistance.

## GENERAL SPECIFICATIONS:

Length — 1.48 m (4.8′)
Weight — 6 kg (13 lbs)
Diameter — 3.3 cm (1$\frac{5}{16}$"(
Temperature — up to 70°C (158°F)
Pressure — up to 210 kg/cm² (3000 p.s.i.)

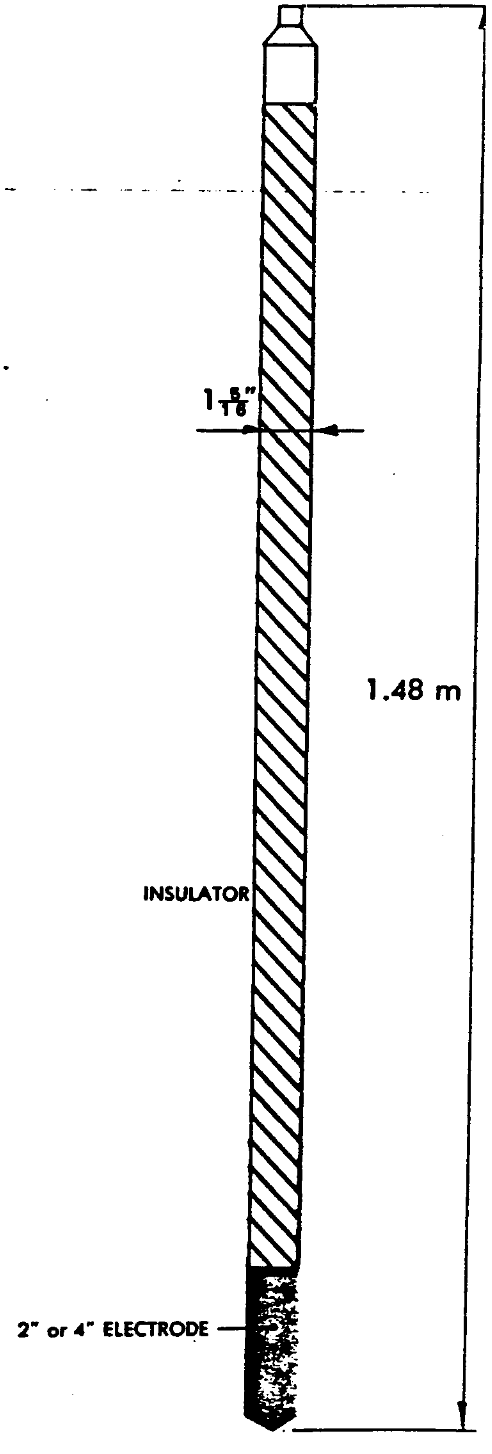
## OPERATING CONDITIONS:

Hole Depth — to a max. of approx.: 2000 m (6500′)
Hole Diameter — open hole: 4 cm to 30+ cm (1.6" to 12+")

Logging Speed — standardly: 9m/min (30′/min)
Logging Mode — free running

Open, fluid filled holes are a prerequisite for both of these electric logs.

Having the lowest replacement value of any BPB sonde, and utilizing no radioactive materials, the RS1 is often used as a first run to assess borehole conditions in unknown or suspect formations.



*RS1 SCHEMATIC*

## TECHNICAL INFORMATION:

The Spontaneous Potential (SP) log is a record of the natural electrical potentials developed between the borehole fluid and the surrounding formations. SP's are generated either by electrochemical e.m.f.'s at the junction of dissimilar materials, or by electrokinetic e.m.f.'s developed when fluid moves through a permeable medium.

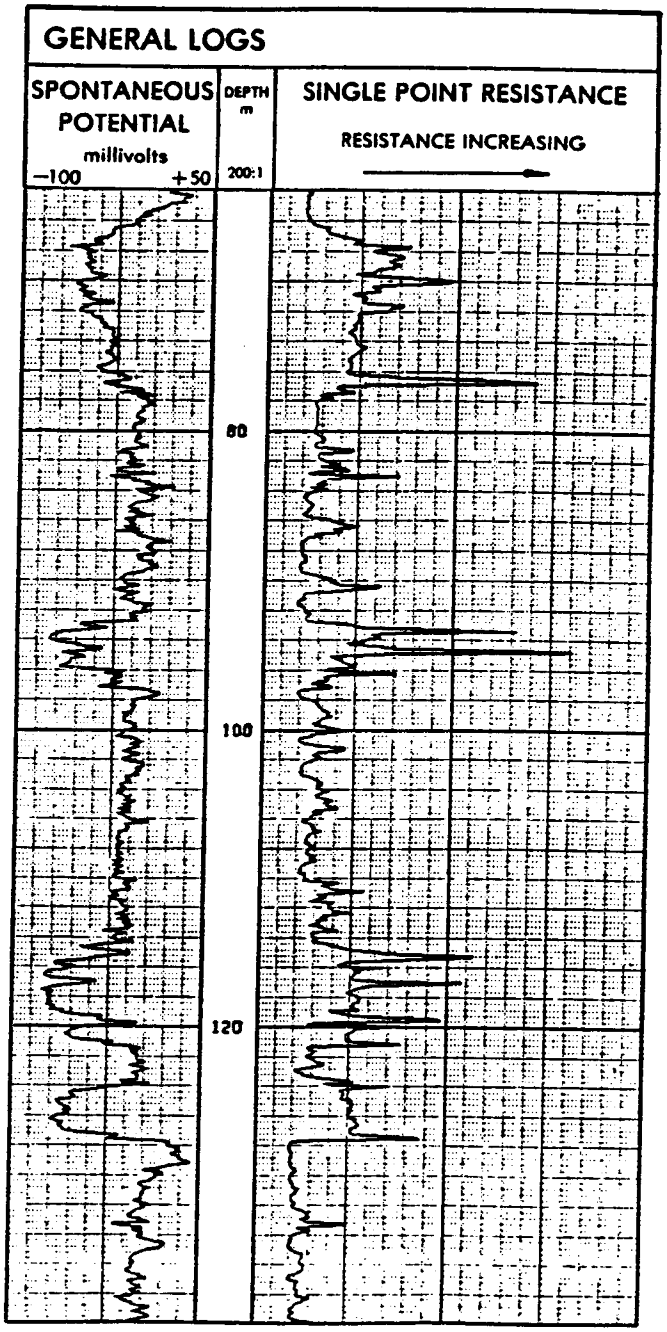
The Resistance (Res) log is a record of the resistance of the formations between a downhole electrode and a surface fish. It is a useful qualitative log with high vertical resolution and shallow depth of investigation.

## PRESENTATION:

Logs may be recorded in metric or imperial units of depth and are available for presentation with full flexibility of vertical and horizontal scales.

The Spontaneous Potential measurement is presented on a millivolts scale with reference to the ground electrode.

The Resistance log is presented as an uncalibrated indicator of formation resistivities.



## APPLICATION SUMMARY:

The SP log is used for geological correlation, bed thickness determination and to differentiate between porous and non porous rocks in sandstone-shale and carbonate-shale sequences. Streaming potentials associated with zones gaining or losing water are sometimes detected.

The Resistance log is very useful for lithology correlation and as a fluid level and casing shoe indicator, with high vertical resolution for the determination of bed thickness. The RO1 Focussed Electric Sonde should, however, be selected whenever quantitative resistivity measurements are required, see Subsurface leaflet No. 4.

# V01, V02

## VERTICALITY SONDES

## MEASUREMENTS:

HOLE TILT
AZIMUTH OF HOLE TILT
TRUE VERTICAL DEPTH
TRUE HOLE POSITION

The Verticality Sonde provides a full and continuous slimhole directional survey, primarily in open hole environments. Tilt and Azimuth data are recorded throughout the logging run with further processing adding True Depth and Position with respect to the upper reference point (surface or casing shoe). Additional options offer a more comprehensive evaluation and graphical presentation of all output.

Two versions are offered: V01 being the standard with V02 offering measurement over a larger range of hole tilt angles.

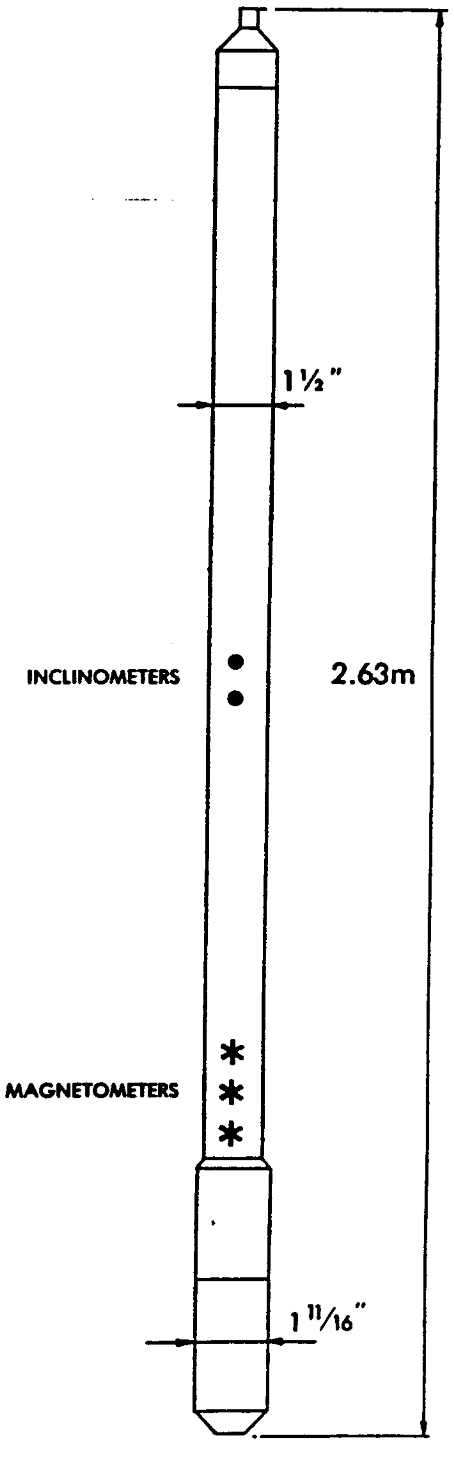
## GENERAL SPECIFICATIONS:

Length — 2.63m (8.6')
Weight — 10kg (22lbs)
Diameter — 4.2cm (1.7") max
Temperature — up to 70°C (158°F)
Pressure — up to 210kg/cm² (3000 p.s.i.)

## OPERATING CONDITIONS:

Hole Depth — to a max of approx. 2000m (6500')
Hole Diameter — open hole: 6.5 to 30cm (2.5" to 12")
Logging Speed — standardly: 9m/min (30'/min)
Logging Mode — free running

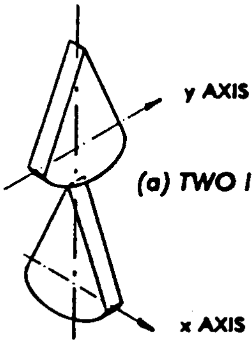
The Verticality Sonde functions equally well in both fluid filled and dry boreholes. It is primarily an open hole survey tool, the use of magnetometer transducers prevents the acquisition of azimuth data (and hence calculation of hole position) through conventional casing or drill rods. This survey is largely unaffected by even quite serious caving in slimhole environments.



*V01/2 SCHEMATIC*

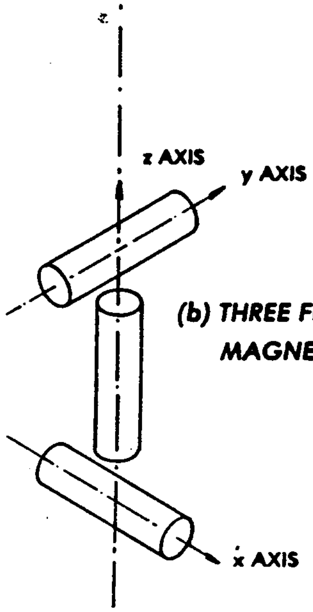
# TECHNICAL INFORMATION:

Five transducers in fixed alignment on the three axes of the sonde enable continuous monitoring of it's orientation. The diameter constraints associated with slimline tool design call for a solid state approach to transducer design, in contrast to the much larger electro-mechanical devices incorporated in conventional oilfield systems.



*(a) TWO INCLINOMTERS*

Two inclinometers define the sonde's minor (x and y) axes (fig. 1a) and provide measurement of both the borehole tilt with respect to vertical and of the direction of tilt with respect to a 'reference'.



*(b) THREE FLUXGATE MAGNETOMETERS*

Three fluxgate magnetometers mounted on the sonde's (x, y and z) axes (fig. 1b) add a knowledge of the rotational orientation of the sonde and, in conjunction with the tilt measurement, provide measurement of the azimuth of the 'reference' with respect to Magnetic North.

Hence: Tilt w.r.t. Vertical and Azimuth of Tilt w.r.t. Mag.N (or True N with the input of the local angle of declination)

*Fig. 1 Transducer Schematic.*

Calibration is performed regularly in a mechanical jig facility backed up with simple field checks made directly before and after the logging of each hole.

The outputs of all five transducers are transmitted for continuous surface recording throughout the logging run,during which they are translated into spot readings of Tilt and Azimuth as a function of log depth.

Various processing options are available upon completion of the logging run to provide True Vertical Depth and True Hole Position as functions of log depth and w.r.t. surface or casing shoe.

Each sonde is standardly set for:

V01 — range 0 to 20°, the standard option for nominally vertical holes with accuracies of ± ½° on inclination and ± 10° on azimuth,

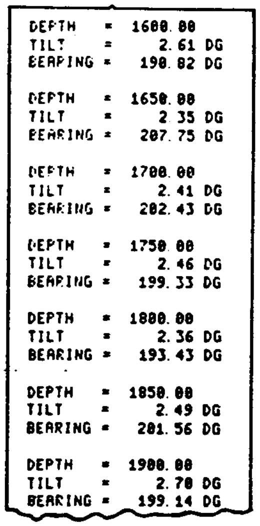
V02 — range 0 to 40°, with accuracies of ± 2° on inclination and ± 10° on azimuth,

although in certain circumstances either sonde may be retuned to provide increased accuracy over a decreased range of inclination.

## PRESENTATION:

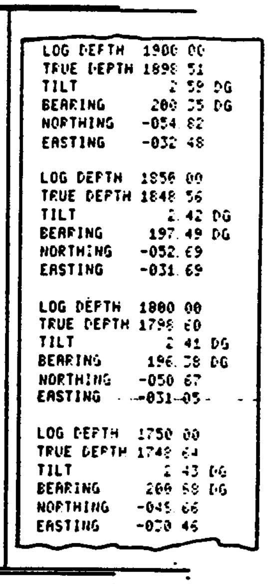
Two forms of output are available, both of which can be set for either metric or imperial units.

(A) VIA LOG PROCESSOR. Hole survey result listings are presented automatically on a fixed 10m (or 50 ft) log depth incremental basis.



```
DEPTH   =  1600.00
TILT    =     2.61 DG
BEARING =   190.82 DG

DEPTH   =  1650.00
TILT    =     2.35 DG
BEARING =   207.75 DG

DEPTH   =  1700.00
TILT    =     2.41 DG
BEARING =   202.43 DG

DEPTH   =  1750.00
TILT    =     2.46 DG
BEARING =   199.33 DG

DEPTH   =  1800.00
TILT    =     2.36 DG
BEARING =   193.43 DG

DEPTH   =  1850.00
TILT    =     2.49 DG
BEARING =   201.56 DG

DEPTH   =  1900.00
TILT    =     2.70 DG
BEARING =   199.14 DG
```

*Fig. 2a. Listing created during the logging run, of Tilt and Azimuth w.r.t. Magnetic or True North (Bearing) as a function of log depth.*



```
LOG DEPTH  1900.00
TRUE DEPTH 1898.51
TILT          2.59 DG
BEARING     200.35 DG
NORTHING   -054.82
EASTING    -032.48

LOG DEPTH  1850.00
TRUE DEPTH 1848.56
TILT          2.42 DG
BEARING     197.49 DG
NORTHING   -052.69
EASTING    -031.69

LOG DEPTH  1800.00
TRUE DEPTH 1798.60
TILT          2.41 DG
BEARING     196.38 DG
NORTHING   -050.67
EASTING    -031.05

LOG DEPTH  1750.00
TRUE DEPTH 1748.64
TILT          2.43 DG
BEARING     200.59 DG
NORTHING   -049.66
EASTING    -030.46
```

*Fig. 2b. Listing created on completion of the logging run adds true depth and hole position w.r.t. the upper reference point.*

(B) VIA COMPUTER GRAPHICS UNIT. Provides full graphical analysis of hole survey data as well as more comprehensive listings of hole position in both Axial and Polar co-ordinates. Other advantages of this approach include:

- — error analysis on hole position
- — presentation scale flexibility
- — cross sections selectable at any specified depth
- — facility to join data from separate logging runs

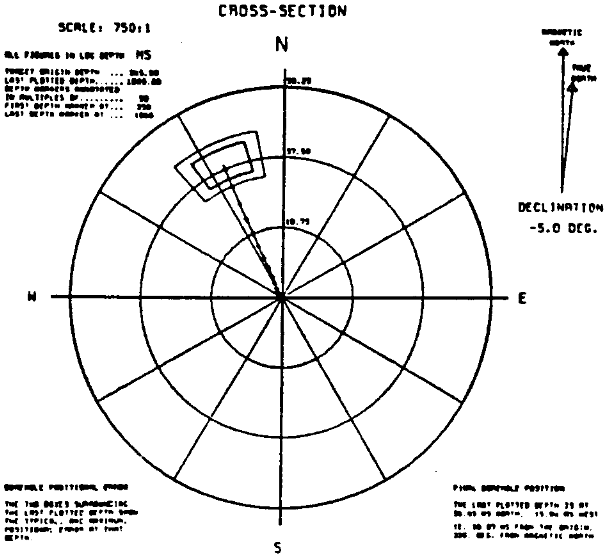


*Fig. 3a Borehole Cross Section, Plan View of the Full Logged Interval.*

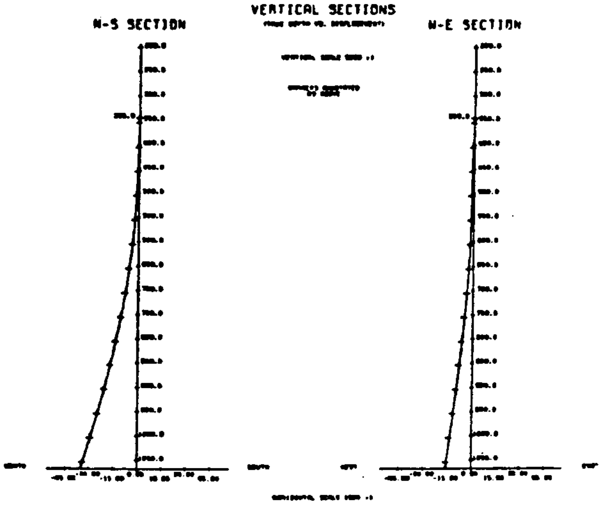


*Fig. 3b Borehole Vertical Sections, Side View of the Full Logged Intervals in N-S and W-E vertical planes.*

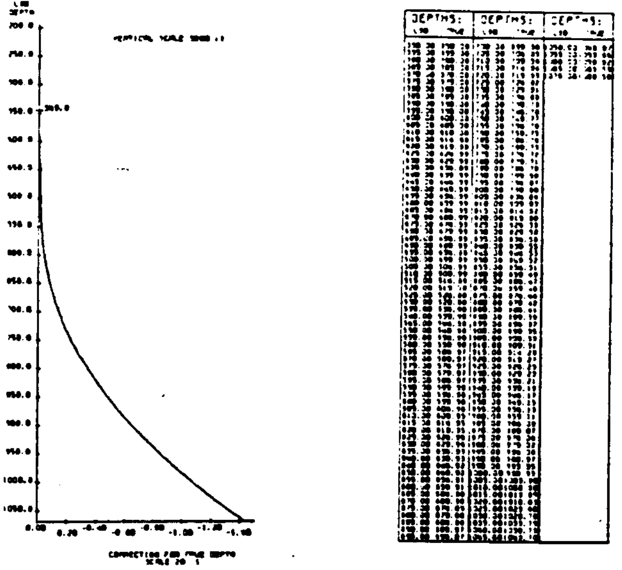


*Fig. 3c Depth Correction Analysis in graphical and tabulated form.*

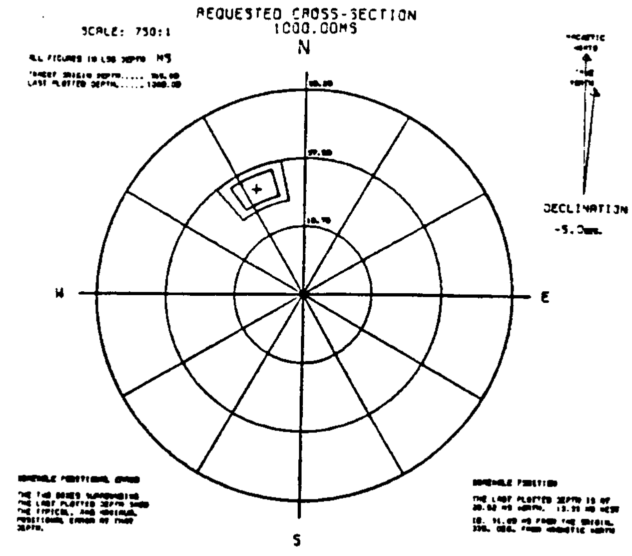


*Fig. 3d Requested Cross Section at any specified depth.*

```
                              Verticality Data Listing                         Date processed: 26-APR-83
                    All co-ordinates with respect to Magnetic North
    DEPTHS             BOREHOLE      AXIAL CO-ORDS.     POLAR              POLAR ERROR CO-ORDINATES (maximum & typical)
  log       true      tilt  AZI      North     East   brng radius        brng radius  brng radius  brng radius  brng radius

350.00     350.00     0.7   293.     0.03     -0.04   300.    0.05       300.    0.09  296.    0.01  300.    0.08  299.    0.02
355.00     355.00     0.7   293.     0.05     -0.10   297.    0.11       298.    0.20  295.    0.02  298.    0.17  297.    0.05
360.00     360.00     0.6   290.     0.08     -0.15   297.    0.17       297.    0.30  296.    0.04  297.    0.25  296.    0.08
365.00     365.00     0.7   300.     0.10     -0.20   296.    0.22       297.    0.40  296.    0.05  297.    0.34  296.    0.11
370.00     370.00     0.8   293.     0.12     -0.25   296.    0.28       296.    0.50  295.    0.07  296.    0.43  296.    0.14
375.00     375.00     0.7   292.     0.15     -0.31   295.    0.35       295.    0.61  294.    0.09  295.    0.52  295.    0.17
380.00     380.00     0.6   297.     0.17     -0.37   295.    0.41       295.    0.71  294.    0.11  295.    0.61  295.    0.21
385.00     385.00     0.6   306.     0.20     -0.42   296.    0.46       296.    0.81  295.    0.12  296.    0.70  295.    0.23
390.00     390.00     0.6   304.     0.23     -0.46   296.    0.51       296.    0.91  295.    0.12  296.    0.77  296.    0.25
395.00     395.00     0.7   302.     0.26     -0.52   297.    0.58       297.    1.01  296.    0.14  297.    0.87  297.    0.29
400.00     400.00     0.7   308.     0.30     -0.57   298.    0.64       298.    1.12  298.    0.17  298.    0.96  298.    0.33
```

*Fig. 3e Full Data Listings*

## APPLICATION SUMMARY:

**Hole surveying becomes particularly important in mine or production planning, where it is essential to understand the actual performance of any borehole as it relates to the real positions and true depths of intersection with specific horizons. The importance of such information increases with depth as borehole performance assumptions can become significantly and increasingly inaccurate.**

## REFERENCES:

**NB — The Verticality Sonde can be run alone or in conjunction with an attachable microresistivity/caliper section to create the Dipmeter Sonde. Here Verticality data continues to provide this full hole survey as well as enabling the measured strata dip to be referenced to the horizontal and it's direction orientated w.r.t. Magnetic or True North (see Leaflet Subsurface No. 9).**

**Further details of the Verticality service may be found in the following BPB publications available on request:**

1. **BPB Coal Interpretation Manual**
2. **Slimhole Dipmeter — R W Wroot**
3. **In-Truck Data Processing Techniques Applied to Slimline Logging — R W Wroot**

**SLIMLINE LOGGING**
**BPB**
**SERVICE MANUAL**

# DV1, DV2

## DIPMETER SONDES

*(INCLUDES THE VERTICALITY SONDE)*

**FIELD INSTRUMENTATIC**
**SUBSURFACE No. 9**

## MEASUREMENTS:

FORMATION DIP — MAGNITUDE
— AZIMUTH

HOLE VERTICALITY — output as per Verticality Sonde, see leaflet: Subsurface No. 8.

The Dipmeter Sonde is a 3 arm device designed to measure formation dip, and provide a complete hole survey, in nominally vertical or slightly deviated slimline boreholes. Two versions are offered: DV1 being the standard with DV2 a slightly larger version providing increased sidewall thrust for use at higher degrees of borehole tilt, at larger diameters or in more rugous boreholes.

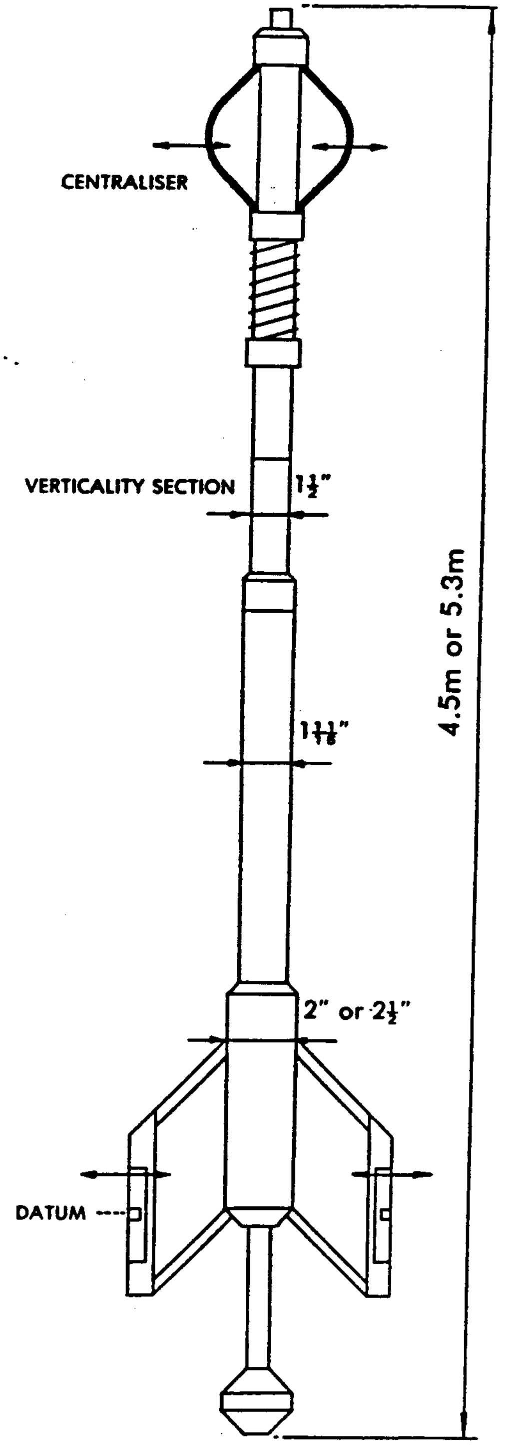
## GENERAL SPECIFICATIONS:

| | DV1 | DV2 |
|---|---|---|
| Length | — 4.5m (14.8') : | 5.3m (17.4') |
| Weight | — 24.5kg (54lbs) : | 36.0kg (79lbs) |
| Diameter | — 5.1cm (2") : | 6.4cm (2½") |
| Temperature | —up to 70°C (158°F) | |
| Pressure | —up to 210kg/cm² (3000 psi) | |

## OPERATING CONDITIONS:

Hole Depth — to a max. of approx. 2000m (6500')
Hole Diameter — open hole, DV1: 7.5 to 20cm (3 to 8")
DV2: 10.0 to 25cm (4 to 10")
Logging Speed — 4m/min (13'/min)
Logging Mode — centralized by the 3 caliper arms, aided in larger diameters by a passive guide system mounted on the upper section.

Formation dip can only be measured in open, fluid filled boreholes. Optimum results will be seen in small diameter boreholes (6" or less), with good caliper and with mud resistivities in the approximate range of 1 to 10 ohm metres. The DV1 Sonde will operate up to borehole tilts of approximately 15° and the DV2 to approximately 25°.



*DV1/2 SCHEMATIC*

## TECHNICAL INFORMATION:

The Dipmeter Sonde is designed to enable identification and measurement of offsets in the depths of features as seen by three detector pads, spaced around the borehole wall with 120° angular separation. Addition of pad direction and hole caliper data enables translation of these offsets into a measurement of 'Apparent' dip, i.e. dip with respect to the borehole. Conversion to 'True' dip may then be achieved by correcting for the effects of hole tilt, allowing presentation of Dip Magnitude w.r.t. the Horizontal and Dip Direction w.r.t. North.

The three circumferential measurements are made by caliper mounted microfocussed resistivity pads, assembled beneath an orientation sub section — the Verticality Sonde when run alone as a hole survey device. Sonde assembly aligns pad 1 into the x-axis of the verticality section (see leaflet No. 8) to allow orientation of the dip plane and presentation of True Dip, irrespective of hole tilt or sonde rotation, see ref. 2.

The caliper system is motor controlled, being held closed for borehole entry and activated into a spring loaded open position prior to the logging run. This provides both borehole diameter and pad pressure for sidewall resistivity measurement. The resistivity logs are recorded with ultra high vertical resolution (0.5cm sense electrode) and shallow investigation (hence the importance of minimising borehole caving), both essential for good dip measurements.

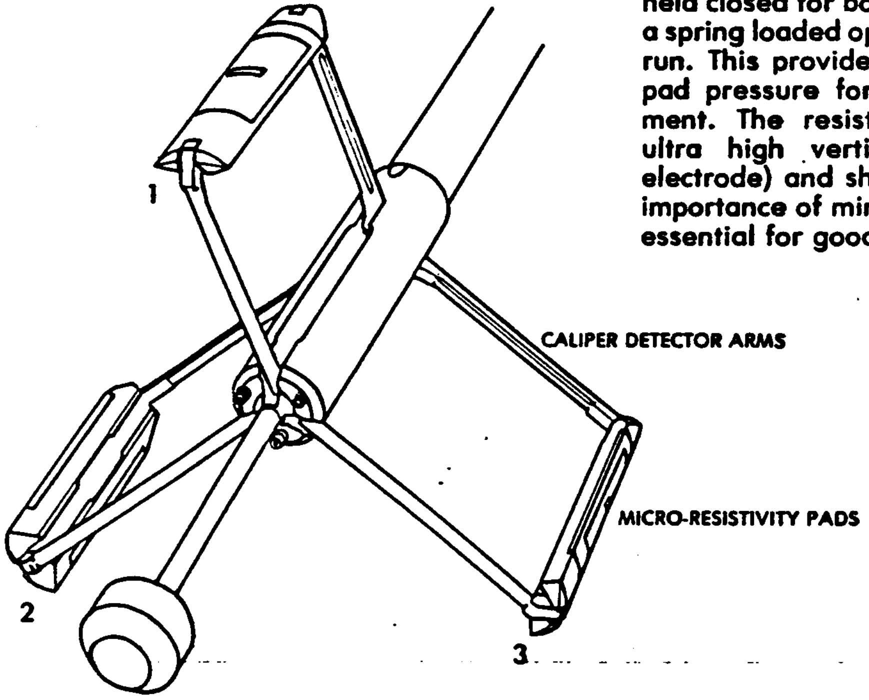


*Fig. 1 Pad and Arm Detail*

In operation the Dipmeter Sonde transmits 9 channels of data for surface recording on magnetic tape as continuous depth based logs.

In summary:

| | | |
|---|---|---|
| 3 × microfocussed resistivities | | Dipmeter Sonde |
| 1 × caliper | | |
| 2 × inclinometers | Verticality Sonde | |
| 3 × magnetometers | | |

Field presentation consists primarily of displaying the resistivity logs and monitoring all other data channels, to ensure that adequate quality data is available to the subsequent interpretation system. The quantity of data involved and the nature of the processing inevitably defines the need for a computer based approach to interpretation and result presentation.

## PRESENTATION:

Dipmeter logging offers all of the hole survey analysis options described in leaflet No. 8 in addition to the evaluation of formation dip illustrated below. Both Metric and Imperial data can be processed, with results available on a full variety of vertical scales.

Fig. 2 is an example of the final 'tadpole plot' output of the computer package, implementation of which requires the selection of certain interpretation parameters. The following notes summarize the process and describe the illustrated output, although comprehensive discussions are a little beyond the scope of this 'sonde' leaflet.

At the heart of the interpretation is computer matching of sections of the three resistivity curves, to determine offsets between pads 1—2 and 1—3. Such 'correlations' are graded up to a maximum value of 1.0, this grading remaining as a measure of confidence in the resulting calculation of dip at that depth.

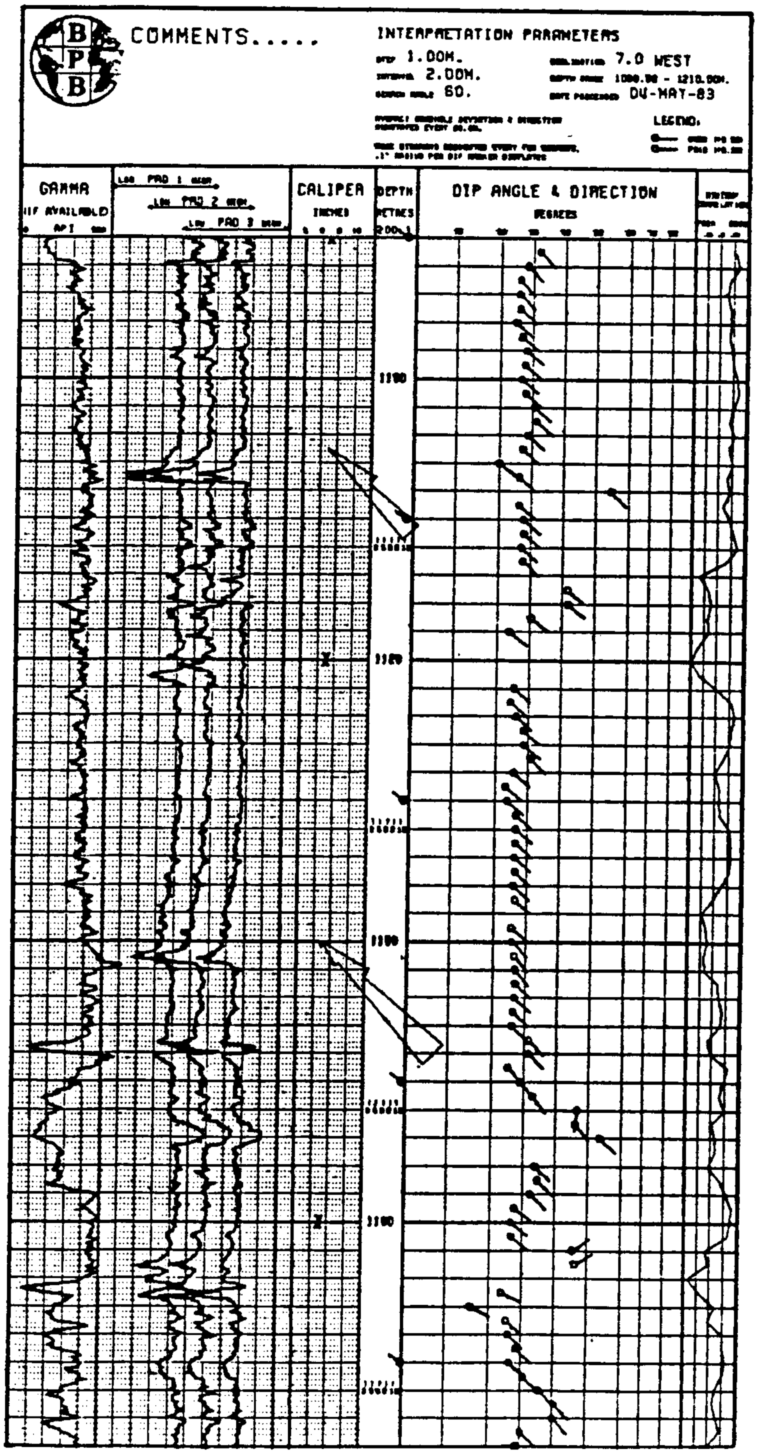


*Fig. 2 Dipmeter Interpretation, Standard Output*

**TRUE DIP MAGNITUDE**
— is indicated w.r.t. Horizontal by the position of the tadpole body.

**TRUE DIP DIRECTION**
— is indicated by the direction of the tail of the tadpole, True North being represented by a vertically upward pointing tail.

**BOREHOLE TILT**
— both tilt and its azimuth are indicated by slightly larger tadpoles, presenting averaged values periodically in the depth margin.

Step, Interval, Search Angle and Declination Angle are all selectable options defining the way in which interpretation is to proceed:

**STEP**
— is the distance between successive correlation depths.

**INTERVAL**
— is the length of Pad 1 curve used in each correlation.

**SEARCH ANGLE**
— is the maximum formation dip for which the program is allowed to search.

**DECLINATION ANGLE**
— is the local relationship between Magnetic and True North, input to allow presentation of directions w.r.t. True North.

A Gamma Ray log is plotted with the three resistivity curves to assist formation identification and correlation.

The Caliper log is presented as a monitor of hole condition.

'Rose Diagrams' or dip azimuth frequency plots are presented on a periodic basis through sections of the borehole as arrowed.

Minimum correlations are plotted to illustrate the value of the poorest of the two pad curve correlations (1—2 and 1—3) made for each dip calculation. The minimum correlation value also defines the presentation of dip according to the criteria listed in the legend:

Solid tadpoles represent 'good' or high confidence dips, and open tadpoles represent 'fair' or medium confidence dips, with 'poor' or low confidence dips left out of the final plot.

This criteria is determined during a preliminary phase (output not illustrated), during which all correlations are presented irrespective of quality.

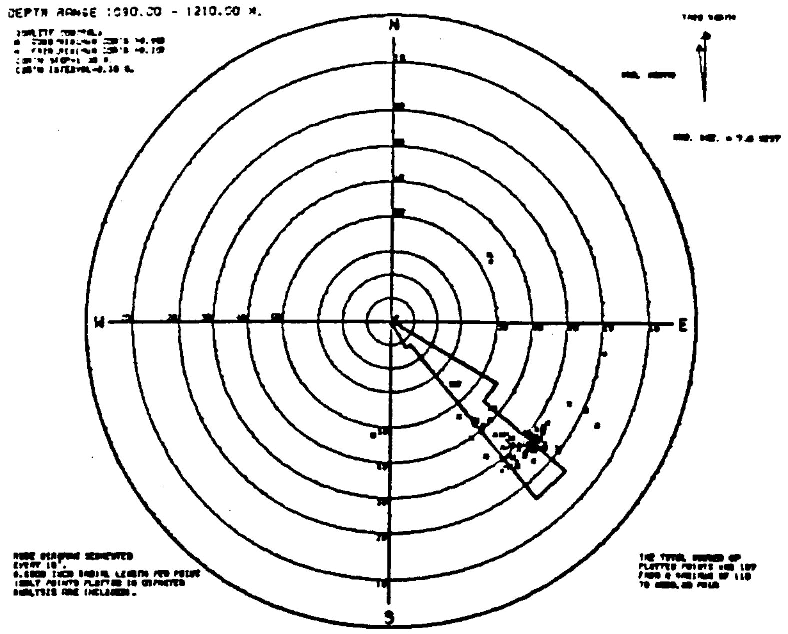


*Fig. 3*
*As an optional extra presentation this Dipmeter Point Distribution Analysis illustrates the frequency distribution of both dip magnitude and azimuth over any specified depth interval(s).*

```
                   Magnetic declination  7.00 degrees West of North                                                  04-MAY-83
                   Correlation step  1.00 metres ,interval  2.00 metres  Search angle 60. degrees                    PAGE    1

  DEPTH  CAL. BOREHOLE FORMATION  MIN.        DEPTH  CAL. BOREHOLE FORMATION  MIN.        DEPTH  CAL. BOREHOLE FORMATION  MIN.
 metres  ins. TILT AZI  DIP  AZI  COR.       metres  ins. TILT AZI  DIP  AZI  COR.       metres  ins. TILT AZI  DIP  AZI  COR.

1091.00  3.9   9.8 303. 32.4 138. 0.78      1092.00  3.9   9.8 303. 29.4 138. 0.85      1093.00  3.9   9.8 303. 26.0 140. 0.67
1094.00  3.9   9.8 303. 26.5 134. 0.63      1095.00  3.9   9.8 303. 26.8 132. 0.69      1096.00  3.9   9.9 303. 25.5 132. 0.70
1097.00  3.9   9.9 303. 27.5 130. 0.69      1098.00  4.0   9.9 303. 29.1 128. 0.73      1099.00  3.9   9.9 303. 28.6 129. 0.74
1100.00  3.9   9.9 303. 27.5 130. 0.83      1101.00  3.9   9.9 303. 28.8 129. 0.86      1102.00  3.9   9.9 303. 30.8 130. 0.76
1103.00  3.9   9.9 303. 31.5 131. 0.70      1104.00  3.9   9.9 303. 29.9 131. 0.78      1105.00  3.9  10.0 304. 28.3 131. 0.69
1106.00  3.9  10.0 304. 20.1 127. 0.77      1107.00  4.0  10.0 304. 27.1 131. 0.67      1108.00  4.0  10.1 304. 55.2 135. 0.71
1109.00  3.9  10.1 304. 27.2 130. 0.59      1110.00  3.9  10.1 304. 28.7 132. 0.71      1111.00  3.9  10.2 304. 28.9 131. 0.78
1112.00  3.9  10.2 304. 28.0 131. 0.87      1113.00  3.9  10.2 304. 28.7 135. 0.66      1114.00  3.9  10.2 304. 30.1 130. 0.17
1115.00  4.0  10.3 305. 41.9 129. 0.35      1116.00  3.9  10.3 305. 42.3 131. 0.40      1117.00  3.9  10.3 305. 30.6 129. 0.33
1118.00  4.0  10.4 305. 24.3 128. 0.35      1119.00  4.0  10.4 305. 23.1 135. 0.15      1120.00  4.0  10.4 305. 31.9 303. 0.01
1121.00  4.0  10.4 305. 26.8 130. 0.20      1122.00  4.0  10.4 305. 26.1 130. 0.53      1123.00  4.0  10.4 305. 25.1 131. 0.79
1124.00  4.0  10.4 305. 27.1 131. 0.84      1125.00  4.0  10.4 305. 29.5 129. 0.77      1126.00  4.0  10.5 305. 29.9 129. 0.76
1127.00  4.0  10.5 305. 31.2 136. 0.65      1128.00  4.0  10.5 305. 26.4 130. 0.50      1129.00  4.0  10.5 305. 23.6 129. 0.58
1130.00  4.0  10.5 305. 24.2 130. 0.58      1131.00  4.0  10.6 306. 27.4 131. 0.59      1132.00  4.0  10.6 306. 27.4 130. 0.77
1133.00  4.0  10.6 306. 27.4 130. 0.80      1134.00  4.0  10.6 306. 27.0 130. 0.79      1135.00  4.0  10.7 306. 27.2 132. 0.78
1136.00  4.0  10.7 306. 26.7 132. 0.62      1137.00  4.0  10.7 306. 27.3 132. 0.48      1138.00  4.0  10.7 306. 65.4 138. 0.28
1139.00  4.0  10.7 306. 26.2 129. 0.37      1140.00  4.0  10.7 307. 26.5 137. 0.40      1141.00  4.0  10.7 307. 27.3 143. 0.32
```

*Fig. 4*
*Comprehensive listings presented as part of the standard dipmeter interpretation package.*

## APPLICATIONS:

The Dipmeter provides structural information and enables apparent formation thicknesses to be corrected for the combined effects of formation dip and hole tilt.

Parameter selection, primarily of the interval, is all important and should be specified in accordance with the required application. Generally speaking long intervals will reveal structural dips whereas shorter intervals will be more suitable for the determination of finer details of dip associated with sedimentation studies. 1 to 2m intervals offer a good compromise and are usually used in the first instance.

Inspection of overall trends may often reveal faulting and other important geological features.

## REFERENCES:

Further information on the Slimline Dipmeter service may be found in the following BPB publications, available on request:

1. BPB Coal Interpretation Manual.
2. Slim Hole Dipmeter — R W Wroot.
3. Verticality Sonde — Leaflet Downhole No. 8.

# TT1 TEMPERATURE SONDE

## MEASUREMENTS:

ABSOLUTE TEMPERATURE
TEMPERATURE DIFFERENCE
TEMPERATURE DIFFERENTIAL

The TT1 Sonde provides an absolute temperature profile as a function of borehole depth, highlighting local anomalies through closer inspection of the temperature changes seen. For optimum results the borehole should be allowed to stand for 12-24 hours prior to temperature logging.

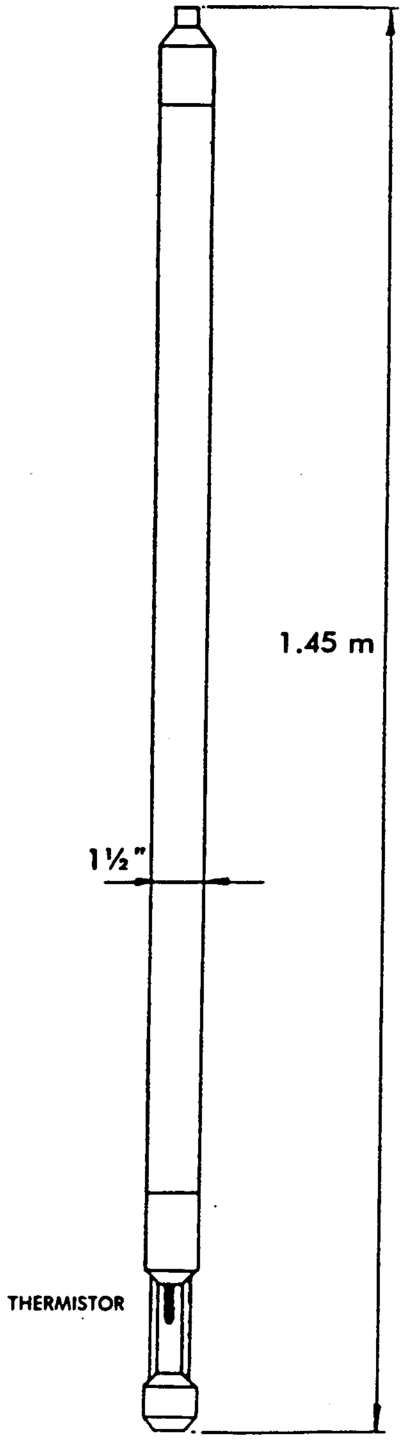
## GENERAL SPECIFICATIONS:

| | |
|---|---|
| Length | — 1.45 m (5.5′) |
| Weight | — 11 kg (24lb) |
| Diameter | — 3.8 cm (1½″) |
| Temperature | — up to 100°C (212°F) |
| Pressure | — up to 210 kg/cm² (3000 psi) |

## OPERATING CONDITIONS:

| | |
|---|---|
| Hole Depth | — to a max of approx. 2000 m (6500′) |
| Hole Diameter | — min. 6 cm (2.5″), no maximum |
| Logging Speed | — 9 m/min (30′/min) |
| Logging Mode | — free running, log recorded on entry into borehole |

Optimum logging requires that the formations and borehole fluid have been allowed to reach temperature stabilisation before logging begins. Furthermore for this same reason the temperature log should be the first tool into the borehole, and data should be recorded during the entry rather than exit run. The sonde will function in any borehole conditions although open, fluid filled conditions are needed to achieve the formation temperature monitoring usually required.



*TT1 SCHEMATIC*

## TECHNICAL INFORMATION:

All three log options are derived simultaneously from measurement of the electrical resistance of a single Thermistor, mounted in a protecting cage at the base of the sonde. Being a calibrated function of temperature this resistance measurement is presented as an absolute temperature log, with optional processing available to look more closely at the nature of the more rapid changes encountered. Specifically:

ABSOLUTE TEMPERATURE
— Borehole temperature seen by the sonde as a function of depth. This is the fundamental temperature log and is needed to properly evaluate any of the other options selected.

TEMPERATURE DIFFERENCE
— is an amplification of features seen on the Absolute log, with rapid changes stripped from the general background Temperature Gradient and presented on a more sensitive scale.

TEMPERATURE DIFFERENTIAL
— is a presentation of the Absolute log differentiated with respect to time. This can be related, through the constant logging speed, to the rate of change of temperature with depth.

## PRESENTATION:

Logs may be presented on a variety of metric or imperial vertical scales as required, with the following maximum sensitivities available for the display of each log:

(a) ABSOLUTE — 0.25°C/minor division
(b) DIFFERENCE — 0.25°C/minor division
(c) DIFFERENTIAL — 0.0025°C/sec/minor division

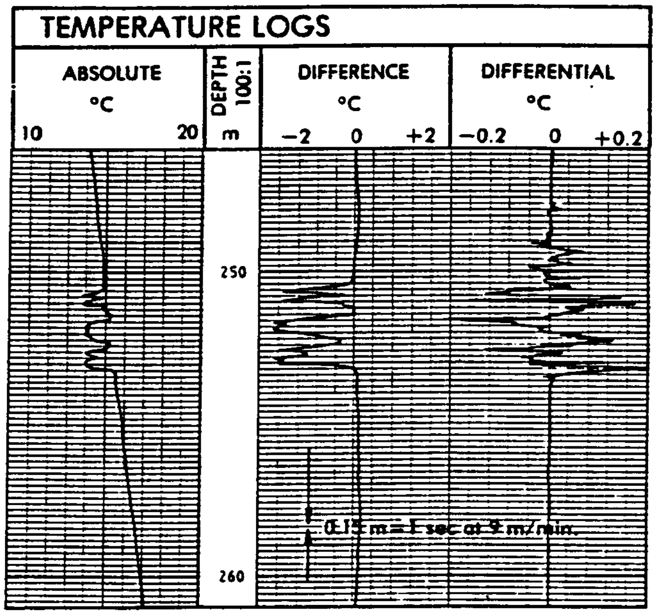


*Fig. 1 Presentation Example*

## APPLICATION SUMMARY:

Temperature logs are used for a variety of purposes, most commonly including:

ABSOLUTE LOGS — Formation temperature for underground-mine planning.
— As an aid to interpretation and correction of other logs, particularly resistivity logs.

DIFFERENTIAL — To identify and help quantify aquifers and fluid flows with the borehole.

NB: If only the Absolute Bottom Hole Temperature is required it may be more simply obtained by running a BHT insert in conjunction with any other sonde.

# SLIMLINE - DEPTHS OF PENETRATION AND VERTICAL RESOLUTION

| CURVE | PENETRATION | VERTICAL RESOLUTION |
|---|---|---|
| Gamma Ray | 0 - 31cm | 70cm |
| Bed Resolution Density | 0 - 5cm | 15cm |
| Long Spaced Density | 0 - 15cm | 48cm |
| Short Spaced Neutron | 0 - 13cm | 25cm |
| Long Spaced Neutron | 0 - 13cm | 45cm |
| Focussed Resistivity | 0 - 31cm | 10cm |

# STRUCTURAL GEOLOGY AND ITS APPLICATIONS TO COAL-BED METHANE RESERVOIRS

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Alberta Research Council

## INTRODUCTION

Coal-beds generate large quantities of dry gas (largely methane) as a by-product of coalification. In addition, coal plays an important role as reservoir rock for natural gas. This is evidenced by the capacity of coal to soak up large volumes of gas (even with low porosity). Coal reservoirs also allow flow of gas as indicated by their permeabilities (Levine, 1990).

Structural geology can play a role in explaining the tectonic setting of sedimentary basins and the resulting burial. This setting will predict the degree of coalification (rank) and resulting gas generation. In addition, structural geology can predict reservoir characteristics such as traps and permeability. In this paper tectonic influences on rank variation and reservoir characteristics of Alberta coals will be discussed, with special emphasis on coals from the Luscar Group of western Alberta.

## RANK VARIATION

The degree of coalification (rank) is governed primarily by rise of temperature during (sedimentary and tectonic) burial and the length of time during which this occurs. Near-surface coals in the Alberta plains occur in the Upper Cretaceous and Tertiary sediments of the Belly River Group, Horseshoe Canyon, Wapiti and Paskapoo formations. The coals range in rank from subbituminous C to high volatile bituminous C. The rank of these near-surface coals increases to the southwest (that is towards the mountains), related to (paleo) depth of burial. Progressively greater amounts of overburden existed in a direction toward the mountains at the time of coalification. Erosion since middle Tertiary time has removed between 900 and 1900 m of sediments; the greatest amount of removal is in the western area, where the highest rank coals are exposed (Nurkowski, 1985). Rank variation in the sub-surface coals of Alberta is insufficiently known and forms the subject of a present Alberta Geological Survey research project.

Major economic coal seams are present in the Mountains and Foothills in the Jurassic-Lower Cretaceous Kootenay Group, the Lower Cretaceous Luscar Group and the Paleocene Coalspur Formation. The Coalspur Formation coals are equivalent to the Ardley coals of the Plains and are of the same rank as the buried Ardley coals of the western-most plains (Macdonald et al., 1989). This suggest predeformational coalification for these coals. Coals at the base of the Kootenay Group in southern Alberta increase in rank from south to north, almost perpendicular to the trend of the mountains. This rank variation is not completely understood, but probably results from a combination of burial history (both sedimentary and tectonic) and paleo-geothermal history (Macdonald et al., 1989). Components of post-thrusting coalification for the Kootenay Group were documented by England and Bustin (1986). Data on coal rank of the Luscar Group of west cental Alberta suggest that the degree of coalification was largely achieved prior to deformation during burial in the foreland basin (Haquebard and Donaldson, 1974; Kalkreuth and McMechan, 1984 and 1988; Langenberg and Kalkreuth, 1989).

## LUSCAR GROUP

Coals from the Grande Cache Member of the Gates Formation, which forms part of the Luscar Group of the central and northern Foothills of western Alberta (figure 1),

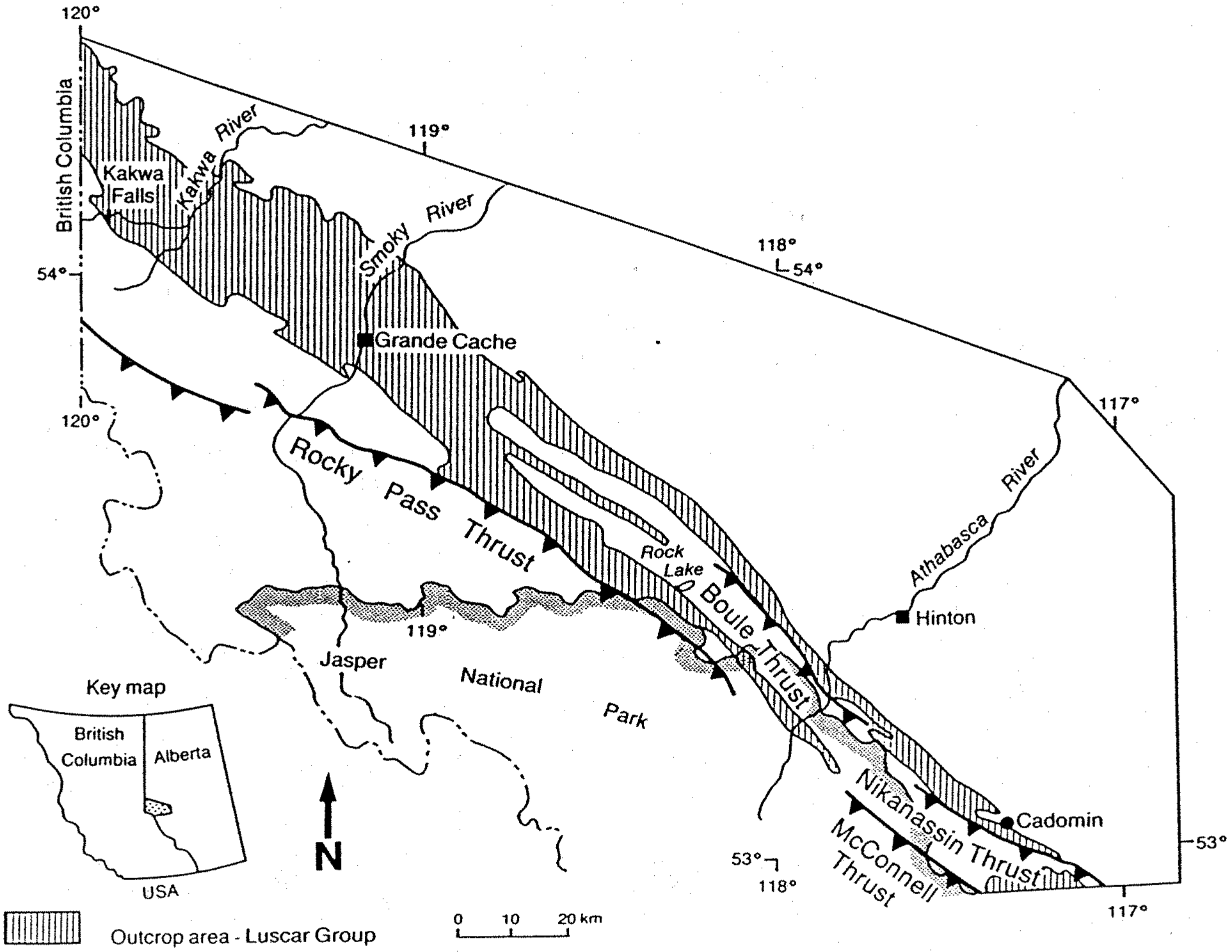

Figure 1. Map showing the outcrop area of the Luscar Group.

will be discussed in more detail. The Luscar Group is largely confined to the Inner Foothills, which consist of folded and faulted Lower Cretaceous rocks and are topographically higher than the Outer Foothills. In the Outer Foothills and in the Interior Plains the Luscar Group is at depth and information on rank pattern could be obtained from oil and gas wells. The boundary between Foothills and Mountains is formed by the McConnell Thrust in the south and by the Rocky Pass Thrust in the north (Figure 1). West of Hinton the boundary steps northeastward to the Boule Thrust and consequently the coal deposits of Rock Lake and Pocahontas (25 km west of Hinton) are situated in the Mountains.

The largely non-marine Gates Formation can be divided into three members, in ascending order: Torrens, Grande Cache and Mountain Park members. The age of the Gates Formation ranges from Early to Middle Albian. The basal Torrens Member, which is thin (about 30 m) compared with the other members, consists of sandstones deposited in a shoreface environment. The Grande Cache Member is characterized by coastal plain sandstones, shales and major economic coal seams. It grades into the Mountain Park Member, which consists of fluvial, fining-upward sandstones, shales and minor coal seams. Depositional environments of the Gates coals are discussed by Macdonald et al. (1988).

Strata in the region are complexly folded and cut by numerous thrust faults. Shortening ranges from 30 percent in the northwest to 50 percent in the southeast. Deformation in the Canadian Cordillera is thought to have proceeded from southwest to northeast and is estimated to have reached the area, which is now the Inner Foothills, during the Paleocene (see also Kalkreuth and McMechan, 1984).

## Regional coalification

Regional coalification patterns of the Luscar group are revealed by changes in volatile matter yields and vitrinite-reflectances. For the present discussion we concern ourselves only to those seams in the basal part of the Gates Formation, i.e. the Jewel Seam of the Cadomin area, the Kennedy Seam of the Mountain Park area, the No. 3 and 4 seams of the Grande Cache area, and equivalent seams of adjacent areas. The maximum vitrinite-reflectances for the base of the Grande Cache Member range from $R_{max}$ = 0.86 % (west of Rock Lake) to 1.97 % (from 2779 m depth in a well in the Outer Foothills). These reflectances indicate a rank range from high volatile A to low volatile bituminous, which are optimal for maximum gas generation during coalification (Rightmire, 1984). To produce the regional rank map shown in Figure 2, all vitrinite-reflectances were converted to dry ash free volatile matter contents (Langenberg and Kalkreuth,

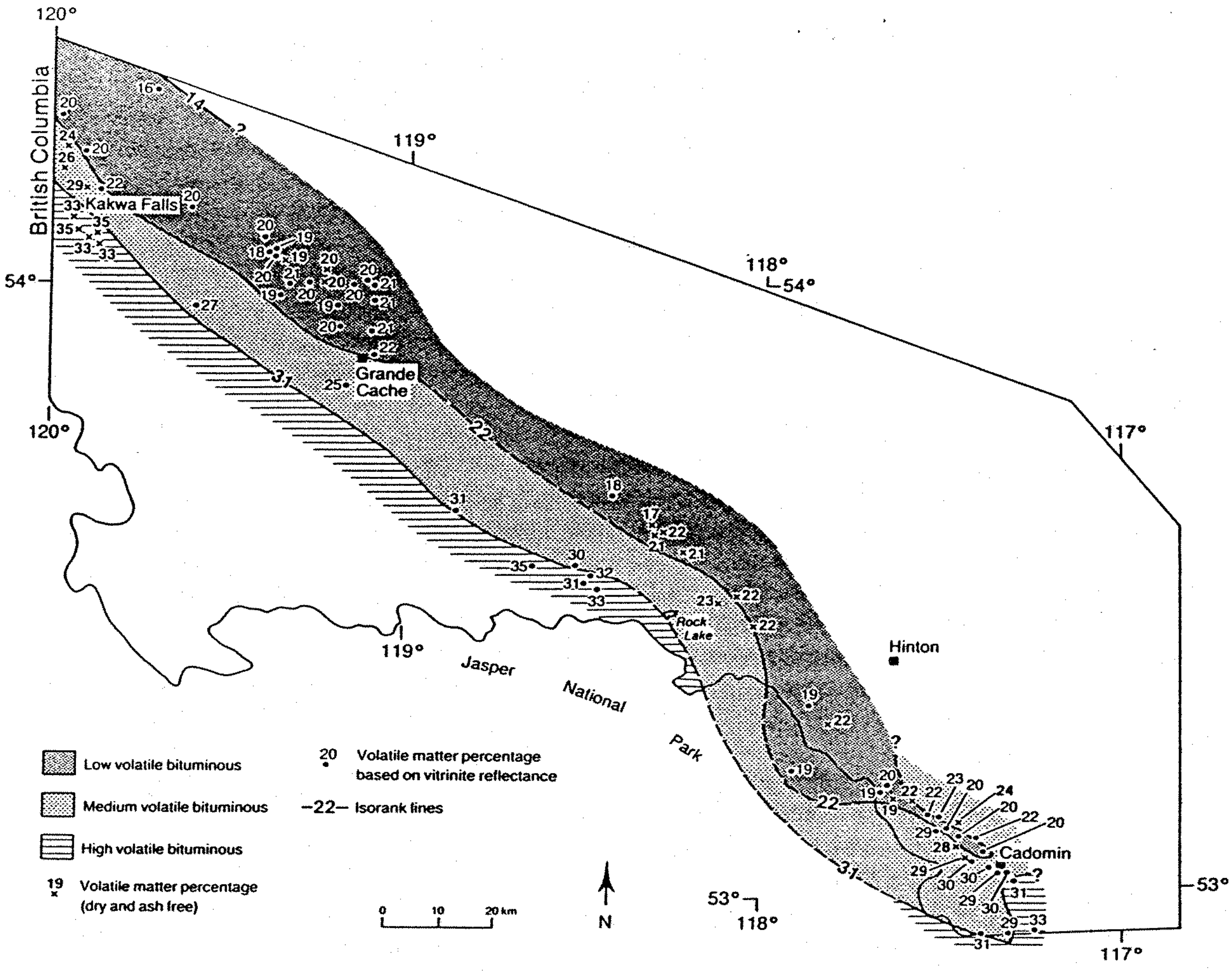

Figure 2. Coal rank variation at the base of the Grande Cache Member (from Langenberg and Kalkreuth, 1989).

1989). The contour map of Figure 2 shows a very consistent rank pattern, where the highest rank coals(low volatile bituminous) are present along the northeastern side and the lowest rank (high volatile A bituminous) are present along the southwestern side of the area. It should be noted that no sudden changes in rank across major thrust faults are observed.

The rank variation at the base of the Grande Cache Member (Figure 2) can be explained in three ways: 1) lateral variability in paleo-geothermal gradients, 2) variation in depth and duration of sedimentary burial, 3) variation in tectonic burial history, or by a combination of these factors (see also Kalkreuth and McMechan, 1988). No definite model for variation in paleo-geothermal gradients is available for the study area. Kalkreuth and McMechan (1988) found that paleo-geothermal gradients similar to the present day geothermal gradients give reasonable results in their time-depth (burial) curves for the area northwest of Grande Cache.

This may also apply for the present study area, implying a range of paleo-geothermal gradients of 20-30°C/km. However, the variation in geothermal gradients is quite different from the rank variation shown in Figure 2. Therefore, variation in sedimentary burial has to be considered.

Little information is available on the variation in depth of sedimentary burial because of extensive erosion. Based on stratigraphic arguments, one can assume about 5500 m of burial for the base of the Gates Formation (see Kalkreuth and McMechan, 1984). The isorank lines run largely parallel to the trend of the Foothills (Figure 2), suggesting that the degree of coalification is entirely related to sedimentary burial in a foreland basin. The broad areas of equal rank in the Kakwa Falls, Grande Cache and Rock Lake areas support this interpretation. This would imply that stratigraphic thicknesses of Late Cretaceous and Paleocene sequences are decreasing in southwesterly direction in the Foothills, indicating that this area was near the deformation front at that time. Significant rank changes over short distances in the Cadomin area (Figure 3) are more difficult to explain by sedimetary burial and may be related to tectonic burial (syn-deformational coalification).

### Syn-deformational coalification

In the Cadomin area maximum vitrinite-reflectance for the Jewel Seam ranges from 0.97 to 1.43 % (Figure 3). The highest rank is found in the central part of this area, with a decrease in rank both to the southwest and the northeast (Langenberg et al., 1989). Rather than coal rank maintaining a constant value across the folds, as would be the case if coalification preceded folding, the isorank surfaces intersect the folded Jewel Seam, as illustrated in Figure 3. This suggests that the central part of the area was buried somewhat deeper than the margins, resulting in the higher rank. This configuration of rank surfaces implies syn-deformational coalification. Consequently, coalification in the Cadomin area results partly from tectonic burial, whereby variation in burial results from the folding process.

The rank pattern in the Cadomin area (Figure 3) may be compared with the regional westward and eastward decrease in maturation of the Lower Cretaceous strata from a maximum near the edge of the deformed belt (Kalkreuth and McMechan, 1988). It is interesting to note that, in the Cadomin area, the maximum rank for the base of the Gates formation is exposed at the surface in the Foothills , while in the Grande Cache area the highest rank for the base of the Gates formation is present in the subsurface of the Interior Plains. Subsurface reflectance data from oil wells would verify if this decrease in rank eastward continues in the subsurface northeast of Cadomin.

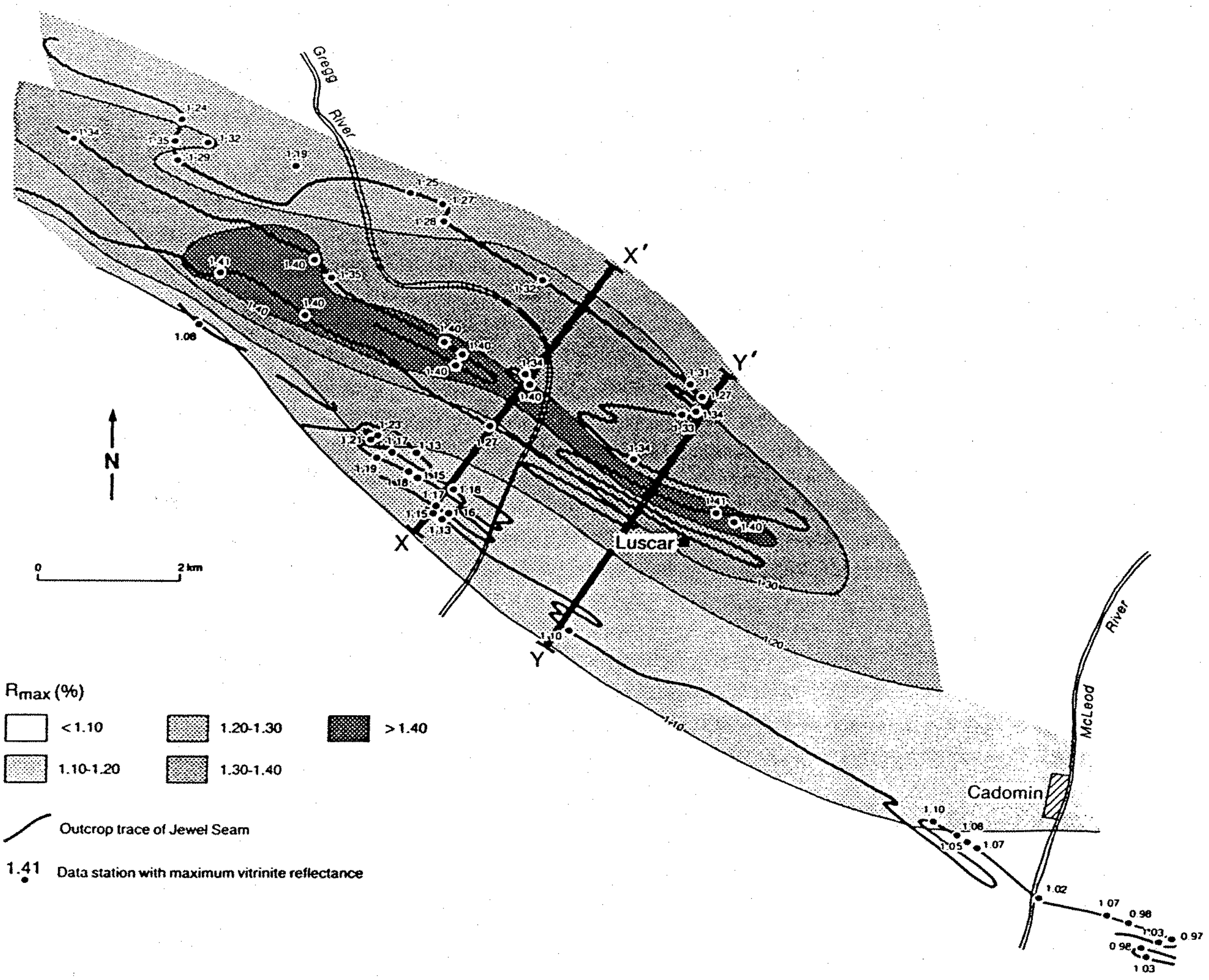

Figure 3. Vitrinite reflectance variation of the Jewel Seam in the Cadomin area (from Langenberg et al., 1989).

It is concluded that the rank variation shown on Figure 2 is largely controlled by sedimentary burial, with tectonic burial playing a lesser role. The amount of tectonic burial seems to increase from northwest to southeast, as indicated by the syn-deformational coalification of the Cadomin area. This conclusion is supported by structural cross sections, which show an increase in shortening (and consequently tectonic strain) from about 30 percent in the Grande Cache area (Langenberg et al., 1987) to about 50 percent in the Cadomin area (Langenberg et al., 1989).

## COAL RESERVOIR CHARCTERISTICS

One of the major tools in finding hydrocarbons (both petroleum and coal) has traditionally been understanding the geology of the area. The anticlinal theory of oil entrapment has been used for more than a century and up to the present day the quest for anticlines has been one of the most successful oil and gas exploration concepts (Selley, 1985).

Structural geology is also playing a major role in defining coal resources in deformed belts.

## STRUCTURAL TRAPS

Hydrocarbon traps are generally divided into: 1) structural traps, 2) diapiric traps, 3) stratigraphic traps, 4) hydrodynamic traps and 5) combination traps (Selley, 1985). For this discussion we will concern ourselves only with structural traps, which are those traps whose geometry was formed by tectonic processes after the deposition of the beds involved. Structural traps can be divided into fold and fault traps. The fold trap is synonymous with the traditionally successful anticlinal theory of oil entrapment. The Turner Valley oil and gas field is a classic example (Figure 4). It should be realized that faulting also plays a role in the Turner valley structure, because the reservoir is bounded on one side by a thrust fault. The anticline can be classified as a fault propagation fold (Suppe, 1985). Fault related traps are well known from the North Sea, although unconformities also play a major role.

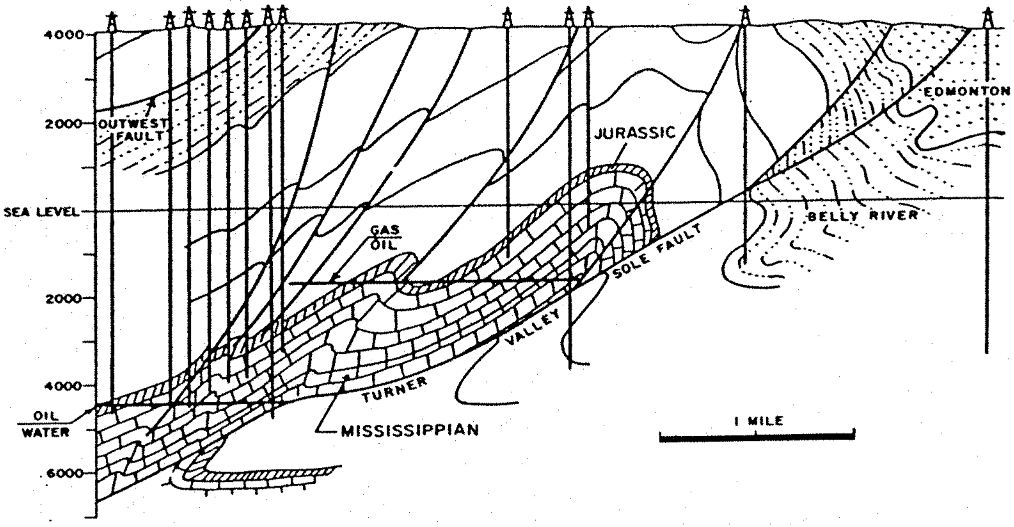

Figure 4. Turner Valley structure (from Gallup, 1975).

Almost certainly the same mechanisms that trap conventional oil and gas will also play a role in locating coal-bed methane. However, very little is known because of a lack of exploration. The main difference between a traditional oil and gas and a coal-bed methane reservoir seems to be the porosity. Coal generally has porosities of less than 5%, but because of the open molecular structure of coal it can accommodate far greater amounts of gas than conventional reservoirs. Consequently, volumes of coal (together with favorable rank) are possibly more important than trapping in locating coal-bed methane. One mechanism of increasing coal volumes locally is structural thickening of coal.

## STRUCTURALLY THICKENED COAL

Structurally thickened coal pods can be found in many places, where it forms important exploration targets for the development of open pit mines. Presently there are two structural positions identified where thickening occurs, in fold hinges resulting from dilation and in fold limbs resulting from duplex faulting. Coal pods along fold hinges have been known and explored for many years, while coal pods resulting from duplex thrusting have only been recognized recently. The prominent deformation process in this part of the Foothills was flexural slip folding, which resulted in chevron folds (Langenberg et al., 1987). Dilation took place at the fold hinges. The dilation zone can be filled in two ways, either by flow of incompetent material (such as coal) into the void or by hinge collapse. In the Foothills a combination of these two processes took place. Good examples of hinge dilations are exposed in open pits of the Grande Cache and Cadomin areas. One of these examples has been recently outlined in the South Pit area (Figure 5), which is located about 20 km north of the town of Grande Cache. If this structure was at depth it might imply enhanced volumes of gas present.

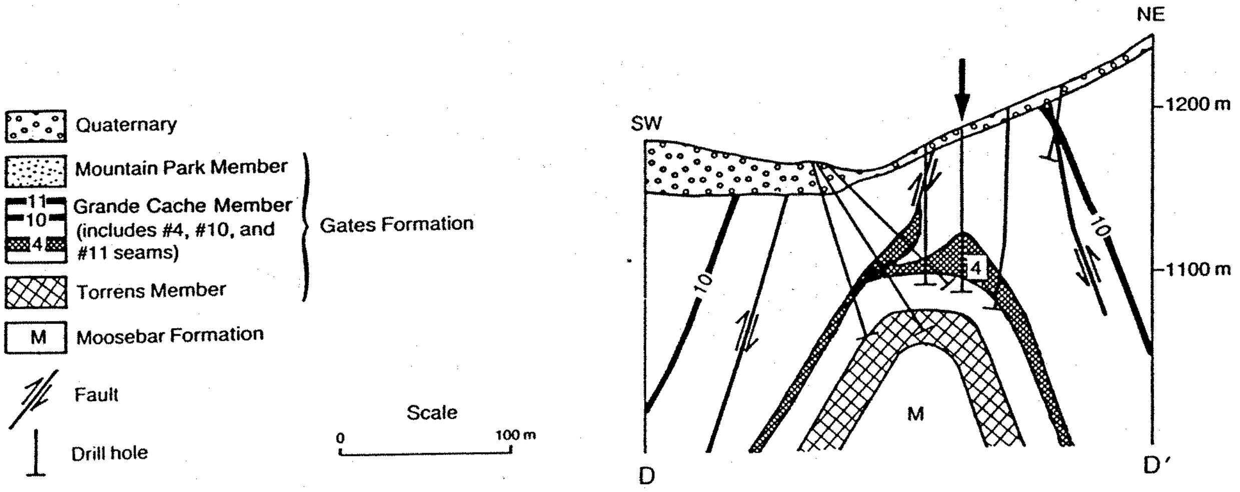

Figure 5. Structural thickening in the hinge of an anticline in the Grande Cache area.

A duplex is an imbricate thrust system where each subsidiary thrust joins two common thrusts, an upper roof thrust and a lower floor thrust. Charlesworth and Gagnon (1985) give an example of duplexes in a coal seam of the Outer Foothills at the Coal Valley Mine (southeast of Hinton) where the seam has been thickened 20 times the stratigraphic thickness. In the Grande Cache area duplexes are found in the limbs of macroscopic folds (Langenberg et al., 1987). A good example of a duplex in coal is present in the No. 12 Mine area (Figure 6) of the Grande Cache area. The volume of coal in the No. 12 mine area is significantly enhanced by the presence of the duplex and if this duplex was buried in the sub-surface it could mean larger volumes of gas being present.

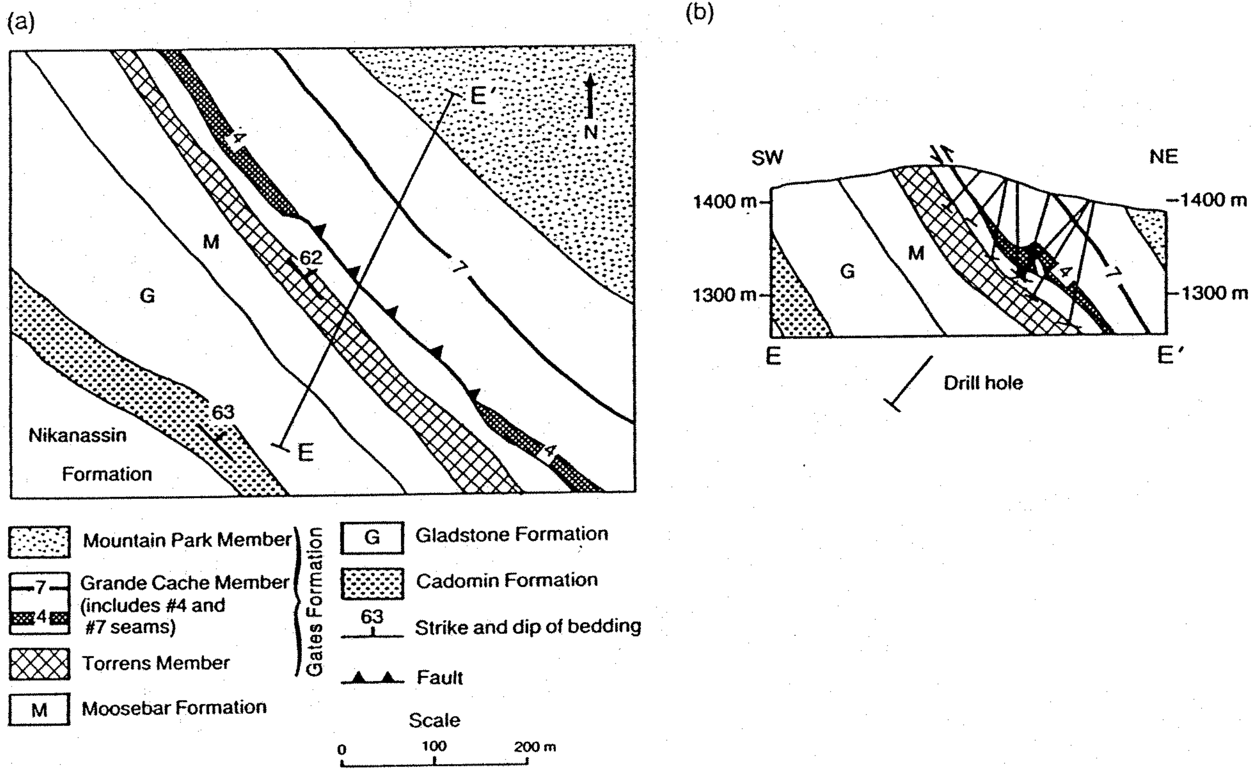

Figure 6. Duplex in the No. 12 Mine area (Grande Cache). (a) map (b) cross section.

## CLEATING

In coal-bed reservoirs flow is determined by permeability, which is primarily determined by fractures called cleats. Cleat is a miners' term for a natural system of fracture (also called joints) perpendicular to the coal-bed and present in most coals. Cleat spacing and orientation are important in reservoir flow. There are usually two cleat sets developed nearly perpendicular to each other. Face is the major cleat and may extend great distances. Butt cleat (also called end cleat) is perpendicular to the face cleat. In the Alberta Plains face cleat is generally perpendicular to the Rocky Mountain front (figure 7), indicating some relationship to orogenic forces and a northeast directed maximum principal stress (assuming extensional jointing). This is also reflected in the oval shape of drill holes (break-outs) elongated parallel to the mountain front (Bell and Babcock, 1986). In the Foothills and Mountains similar sets of cleats are present where the coal is not sheared. However, a large proportion of the coals in the deformed belt is strongly sheared and the cleats are no longer present.

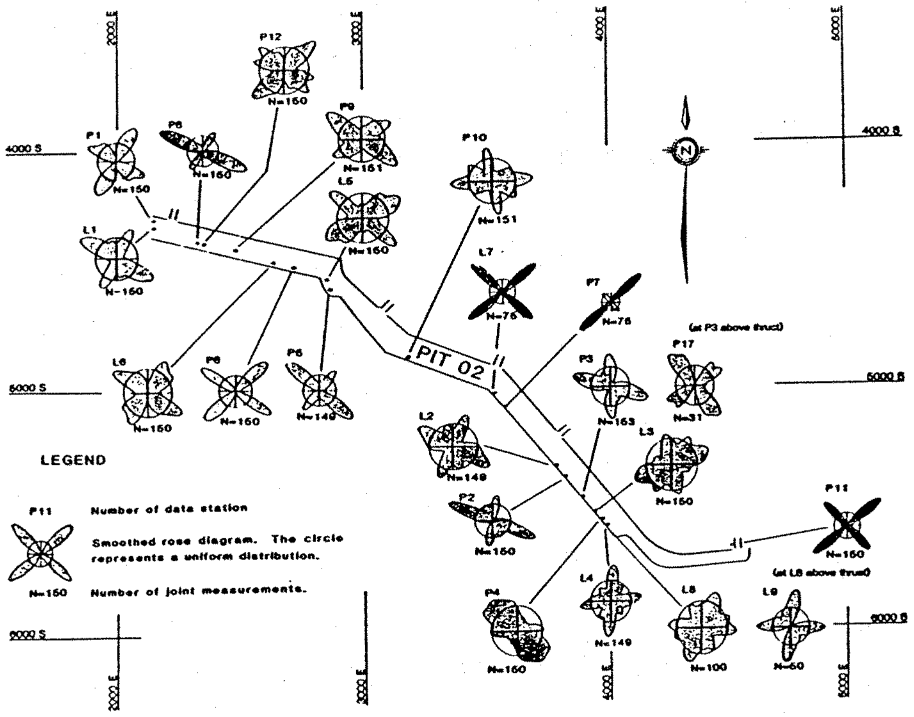

Figure 7. Smoothed rose diagrams of joints and cleats at Pit 2 of the Highvale Mine (near Lake Wabamun). Stations L7, P7 and P11 in coal (cleats); others are joints in clastic sediments (from Moell et al. 1985).

## SHEARING

Shearing of coal, that is related to faulting, has been observed in most areas of the deformed belt (e.g. Bustin, 1982). Figure 8 shows a section of the Jewel coal seam of the Cadomin-Luscar coal field. A shearing index was used, that describes the coal macroscopically as: undeformed, slightly deformed or strongly deformed (crushed). The hardgrove grindability is a laboratory test, which determines the ease whereby a coal can be ground to a fine powder. Coals with a high Grindability Index are relatively soft and easy to grind. Those with a low value (less than 50), are hard and much more difficult to make into pulverized fuel. Figure 8 shows that there is a good correlation between shearing and grindability. However, no work has been done yet to determine the effects of shearing on permeability of coal. Sheared coal might still have reasonable permeability, because shearing results in a tight network of fractures (Bustin, 1982). However, holes completed in sheared coal might have caving problems.

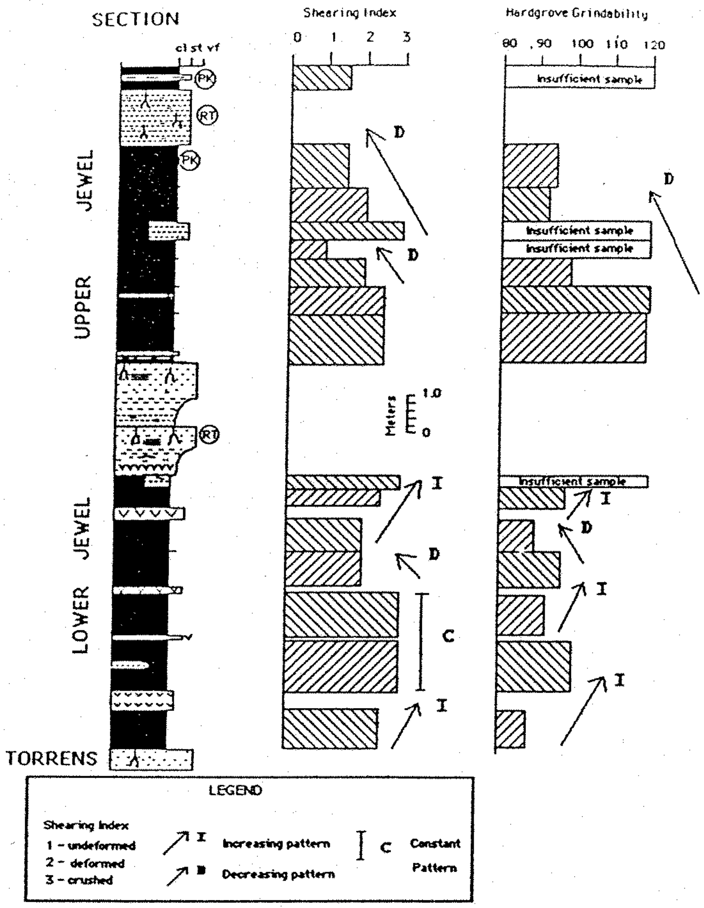

Figure 8. Section of the Jewel Seam (Cadomin area) with Shearing Index and Hardgrove Grindability profiles.

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# COAL SEAM SAMPLING AND GEOPHYSICAL LOG INTERPRETATION

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## INTRODUCTION

The two most important elements to be considered in the subsurface exploration of coal are the interpretation of seam and parting thicknesses and the chemical analyses that are conducted on the samples of these coal intersections. Systematic sampling procedures are required to ensure that the fundamental geological data collected and analyzed are accurate and representative.

The first consideration that must be addressed is WHAT IS THE PURPOSE OF DRILLING THE BOREHOLE?. Depending on the end usage of the sample, the methodology of sample reconciliation and handling will vary. For example, if the purpose of obtaining a sample is to determine an exact nature of seam quality characteristics, and overall coal zone or mining zone quality, a detailed sample profile must be undertaken. On the other hand, if a desorption value of gas is to be determined, speed of core recovery is of the upmost importance.

This workshop will examine the methodologies of geophysical log interpretation of coal seam profiles, detailed core description and subsequent reconciliation and sampling methodologies. The following course notes have been produced to provide guidelines for this seminar.

It must be remembered that the geological conditions are widely variable in the subsurface, even on close spaced drilling patterns. Utilization of geophysical logs to determine thickness data provides the fundamental tool for analyses, but a certain degree of geological interpretation may be required to determine the individual bed thicknesses. Individuals may determine thicknesses by slightly different methods, but the overall seam and parting thickness values should be the same. Geophysical logging of a borehole is the "Application of Technology" : Interpretation of the data has often been referred to as the "Application of Experience".

## I) SEAM AND PARTING THICKNESS DETERMINATION

### A) Geophysical Logs

Most geophysical logging companies will run a suite of logs ranging such as gamma ray, density (gamma gamma) resistivity, neutron, sonic, caliper and other special tools such as dipmeters. To determine seam and parting thickness only the following logs really need to be utilized.

- Gamma Ray
- Resistance or Resistivity
- Sidewall Density Log
- Caliper

Other logging devices may provide specialty data that will assist in the geological interpretation, but for this seminar, only the four listed above will be used. Presentation of these logs varies from company to company. For ease of analyses, we recommend the following combination formats: Gamma Resistance or Gamma Density Caliper, Focused Resistivity Log, Detailed Density Caliper Log. Both the Focused Electric and the Detailed Density should be run at an expanded scale (1:20). The smaller scale logs (1:100) can be utilized for lithologic interpretation and correlation, with the large scale profiles being used for seam thickness determination and sampling. Figure 1 illustrates a typical log presentation format for a coal borehole.

### B) Sidewall Density Log Interpretation Techniques

To determine the thickness of coal zones or seams from the geophysical log, a series of simple steps will be undertaken. For those of you who are not familiar with the chemical characteristics of coal, the relative bulk density of coal is much lower than that of "true rock". Varying amounts of high ash coal and carbonaceous shale will have bulk density values somewhere in between. The detailed density log presents the density contrast between the two, and can be compared to the caliper which was run over the same depth interval. The geophysical log response reflects the variations within the rock record of lower density carbonaceous material (or other low density material) and the higher density material of rock or partings. The transition between the two end values can be interpreted to determine the seam and parting thickness of the coal intervals.

Determine if any of the density responses are due to irregularities of the borehole diameter. Compare the caliper response with the density response (Figure 2) and make a note of these intervals. In many cases, a caved hole will give a lower bulk density response suggesting the presence of coal. The gamma ray/resistance log can also be utilized to determine lithology.

Mark the inflection points at each interface between rock and coal. The inflection point bounding the gradation curved line represents the presence of either true rock or coal. Measure the distance halfway between these two points to determine the roof and floor of each unit. The distance between the two midpoints is

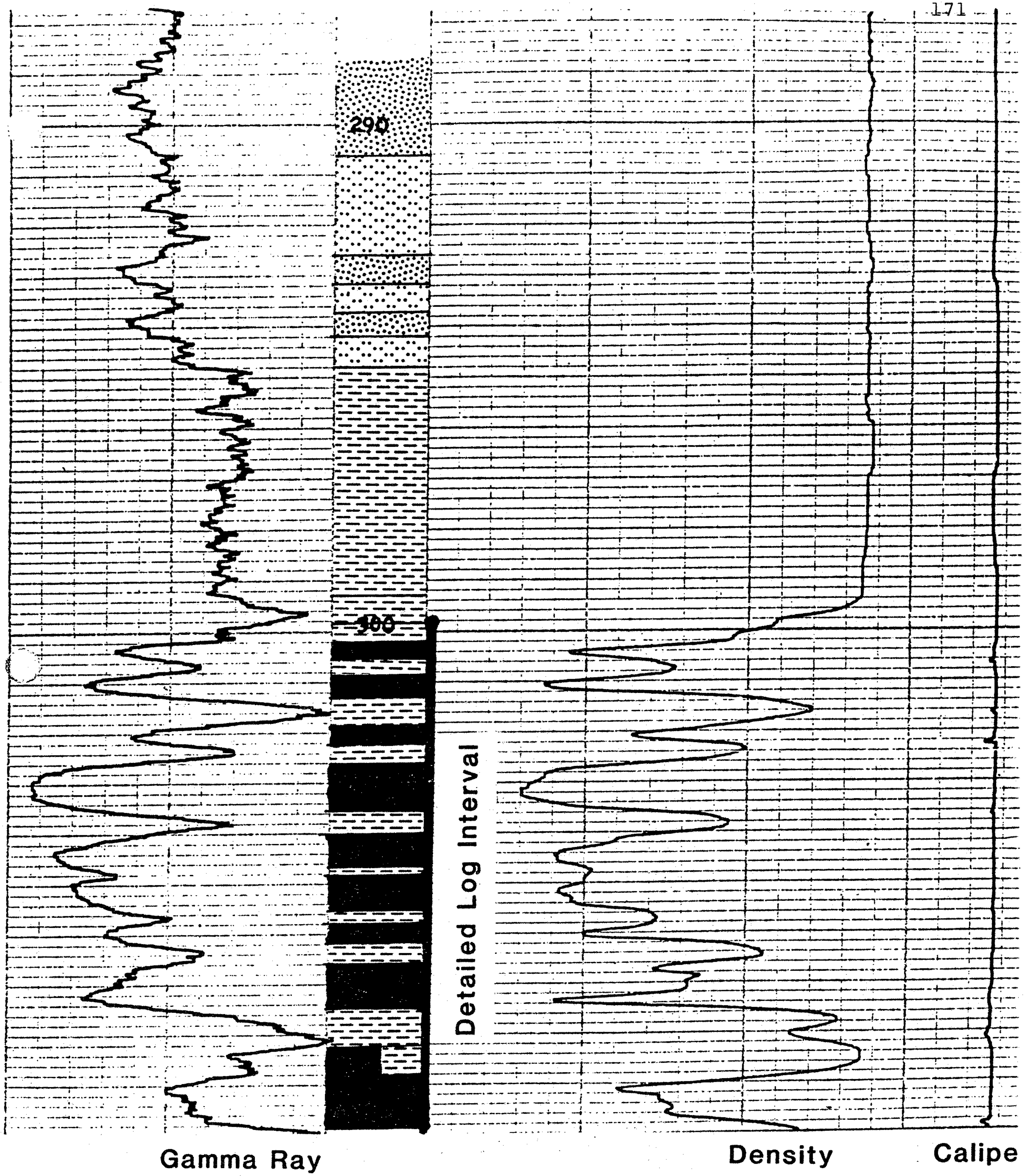


Fig. 1 Typical Geophysical Log Response

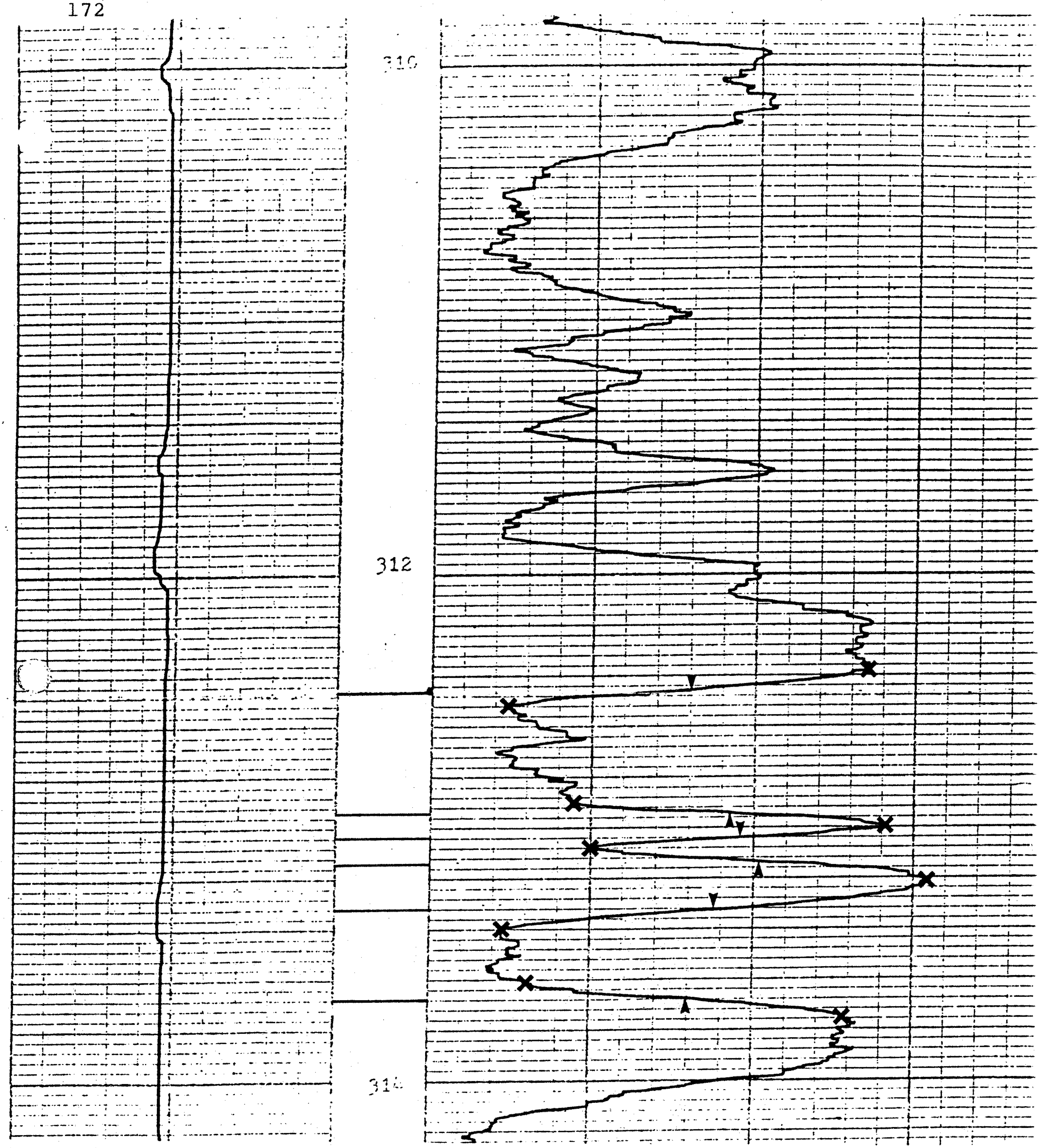


Fig. 2 Density Log Response and Thickness Determination

the thickness of the unit. Care must be taken when picking the inflection points and midpoints for areas of the log trace where the lithofacies contact between the units is gradational. In these instances it is often preferable to use the focused resistivity log response.

Zones of thin interbeds of coal and carbonaceous shale become difficult to interpret due to the source to detector spacing of the geophysical tool. Full resolution of the bulk density of these units cannot be achieved due to the influence of the bounding units. For thin rock partings the inflection points will indicate a bed of relatively low ash coal, even though the unit may have ash values of 60 to 70 percent. Similarly, a thin coal seam bounded by true rock partings will appear to have a higher ash content than the actual analyses indicates. As with the gradational horizons, a focused electric log trace often enables a better defined thickness and boundary.

### C) Focused Electric Log Interpretation Techniques

Seam thicknesses can be determined from the electric log in a similar method to the density log techniques. Coal/rock interfaces can be determined from the inflection points of the curves. For the focused electric log, the inflection point from true rock to true coal is determined. The interface contact is then placed at half the source/detector spacing (for a 20 cm tool, a correction of 10 cm) into the seam from the inflection point (figure 3). This is a general guideline that may vary dependent on the nature of the contact as well as the lithology of the parting material. Often if the parting material contains a gradational contact with the coal, the thickness of "true rock" is determined by the distance between the inflection points and the gradational zone by the correction factors.

Care must be taken in determining the "true rock" inflection point, as the resistivity tool is often sensitive to the presence of thin lenses of bright coal that may be present in the gradational roof or floor of the coal seam. These can produce a series of "hips" at the interface that may be confused with the true contact.

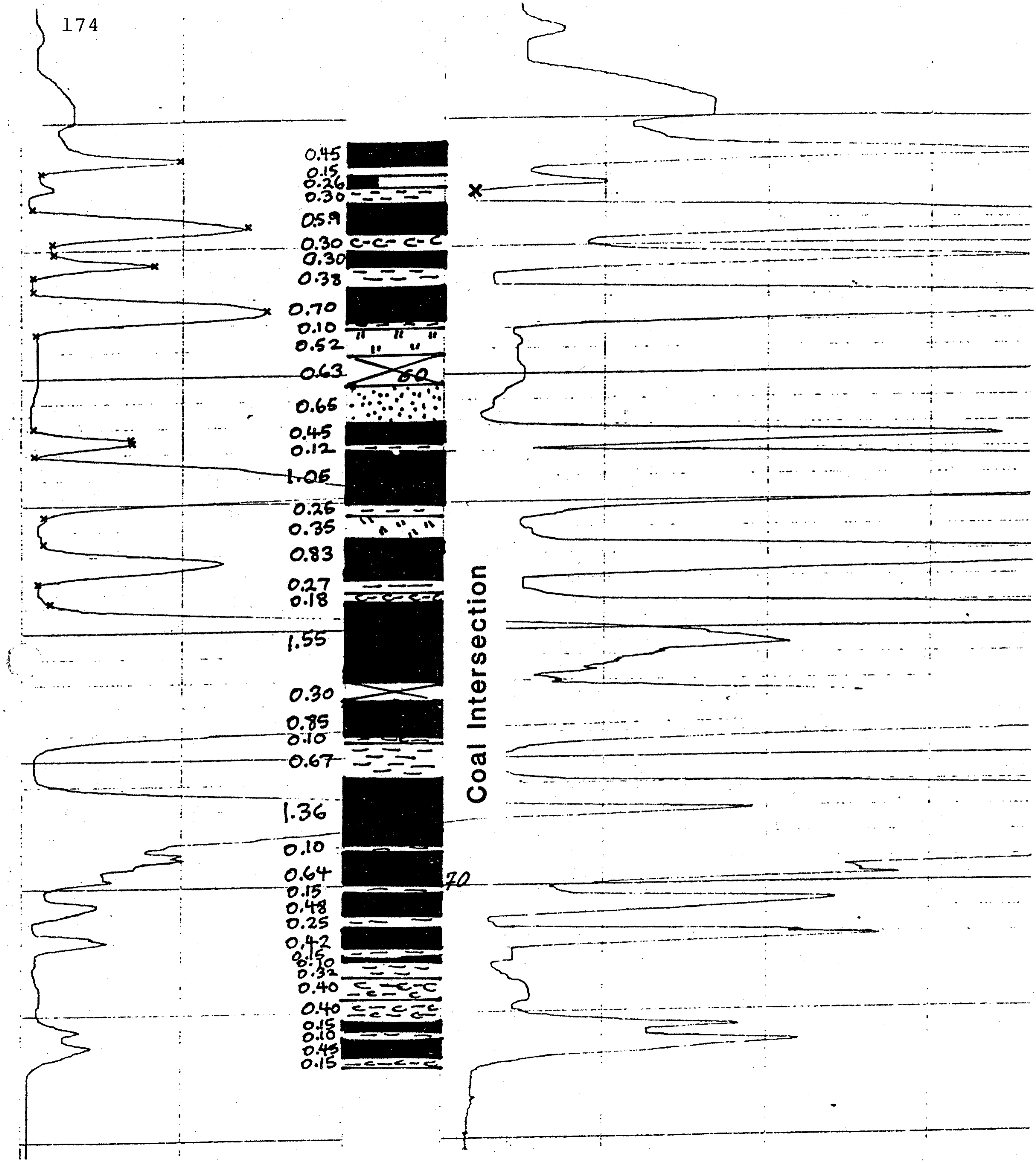


Fig. 3 Focussed Electric Log Response and Thickness Determination

## II) Core Description of Coal Samples

There are numerous types of coal samples that can be obtained from a subsurface exploration program. All techniques in obtaining these samples have both positive and negative aspects. Without dwelling on the elements of the other sampling methods, this seminar will address the description and sampling of core.

Upon completion of the coring run, the barrel is tripped out of the borehole and the geologist must then determine what is to be done with the core. Once the split tube or PVC tube is removed from the barrel, an assessment of the core recovery must be made. Simply by comparing the recovered core to the interval drilled will yield this information. In strata that contains swelling clays, core recovery of > 100 % is often obtained. In resistant units such as massive sandstones, < 100 % recovery may be obtained and then picked up on the next run, (ie. > 100 % ).

The geologist should make a descriptive log of the core recovered. This log can either be drawn directly on the geophysical log if there is a time delay in logging, or, it may be descriptively recorded and drawn up at a later time after the hole has been logged. When the core is logged, variations of lithotype should be recorded. It is important to note the nature of the contacts between the coal beds and non-coal partings. These interfaces will illustrate either sharp or gradational contacts with either complete core recovery or obvious core loss. The zones of obvious core loss may be due to faulting, grinding of coal/rock interfaces or at the beginning or end of the core run. Where the transition from coal to rock is complete, with no core loss, this position represents a marker that the reconciliation of the rest of the core recovery can be based upon. The geophysical log response for that interval should easily illustrate the same contact.

## III) Reconciliation of Core Recovery

Once the core has been adequately described, the lithotype description must be compared to the geophysical log response to determine the following:

--- exact depth of coal seam intersection
--- position of core recovery
--- sample intervals

The marker positions of core are marked on the log trace (expanded scale) and the depths accurately calculated. Remember that in many cases the driller's log depths are not accurate and the logged depths from the geophysical tools (resistance preferred) are much more accurate. The core thicknesses or intervals of either coal or rock from the marker positions to the next position are compared to the interpreted thickness from the geophysical log. In most cases there will be some form of core loss, especially if drilling in the foothills where the seams are more highly sheared. It is important to determine where the core loss (if any) is located, as this may affect the decision on the type of chemical analyses that are to be conducted on the core samples. The position of the core loss is determined by the best fit of the core descriptive interval to the calculated seam intersections. There is often sufficient evidence in the core to indicate where the core loss may occur.

## IV) Coal Seam Sampling Procedures

Upon completion of the reconciliation of the core to geophysical log trace, decisions must be made to the sample interval. Sample procedures for coal vary from company to company as well the projected end usage of the resource. Determination of a mining section for open cast mining is different than for a insitu or underground extraction method. Similarly the lithofacies component of the coal horizon is widely variable depending on the number and thickness of the coal and the partings. As a general rule, the sampling procedures should breakout lithologic differences into separate samples. They can always be composited back together after the analyses have been completed. As the sampling of the coal is probably the most important element of the exploration program, whatever methodology is chosen should be well documented. Figure 4 illustrates an example of a typical coal intersection and the various decisions made to determine the sample intervals and the mining horizon.

At first glance the sampling of coal for coalbed methane tests appears to be a relatively simple exercise. As the entire zone is the potential reservoir, a decision must be made as to how detailed the sample should be. Remember that the samples can be mathematically composited at a later time to represent the entire coal zone. Factors that should be considered however are the chemical and geotechnical variances that may exist within the individual plies of the coal zone. In addition, it is unknown at this stage, what influence the non-coal partings may have on the potential reservoir, be it fracture enhancement or the influence of swelling clays on permeability.

In summary, coal sampling and log reconciliation represent the most important phase of the exploration program. Methodologies to be employed must be well thought out and documented. The sampling of the coal is a destructive process and there are no second opportunites, save redrilling the borehole.

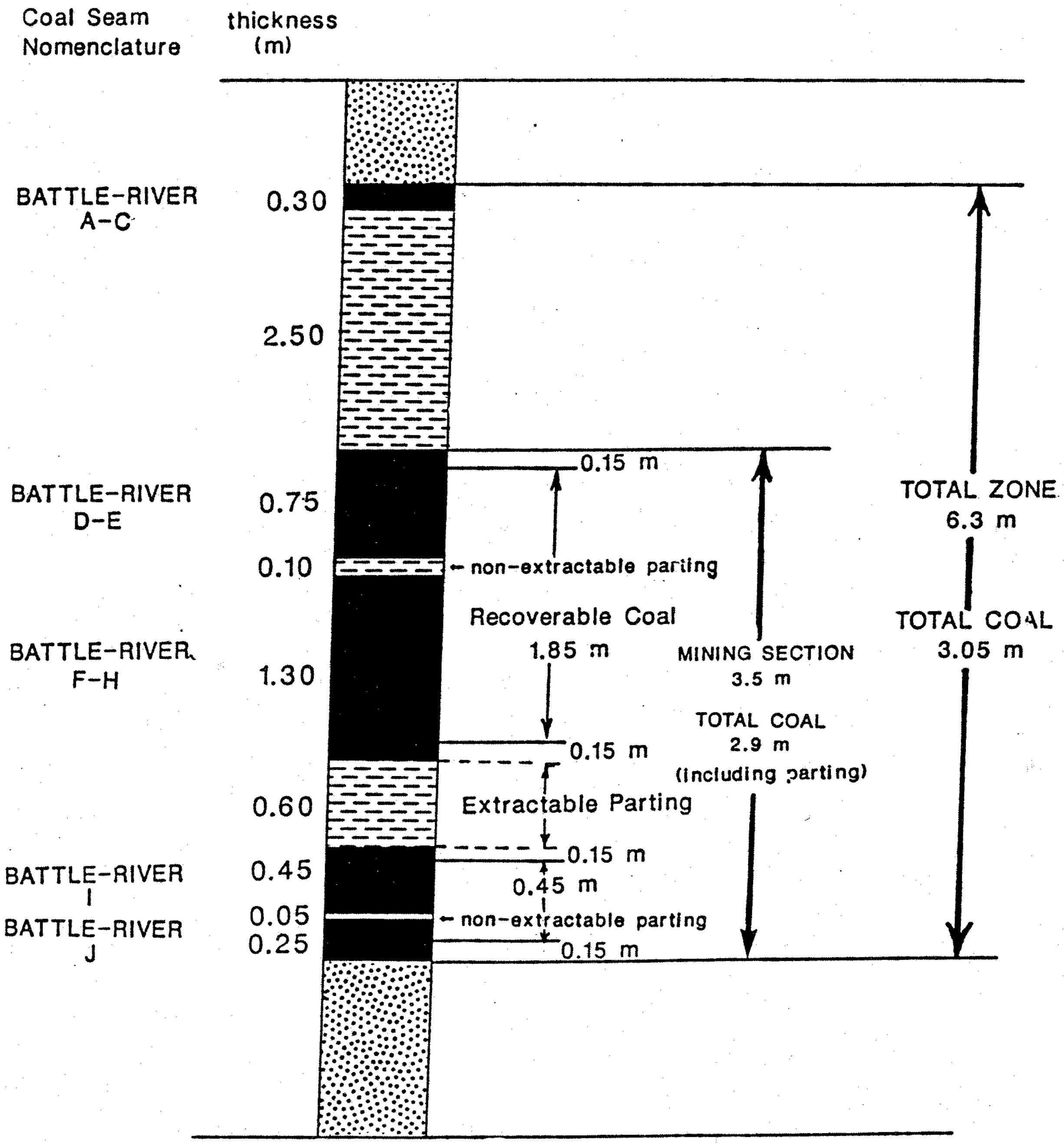


Fig. 4 Schematic Section Illustrating Total Coal Compared to Mineable Coal

*NOTE: Mining loss of 0.15 m of coal at coal/rock contact of extractable parting as well as roof and floor of mining section

# EQUIPMENT AND PROCEDURES FOR MEASURING METHANE CONTENT OF COAL USING THE USBM METHOD

## EQUIPMENT NEEDED

Figure A1 shows the equipment needed. This includes:

- Sufficient individually numbered canisters with needle valve and quick-connector nipple; tare weights are recorded.

- Two chain wrenches, plier type or otherwise.

- A graduated cylinder - 1000 ml; length between 0 and 1000 ml noted; and also between 1000 ml and a mark labeled "H20 Level".

- One to two meters of 1/8 to 1/4" (approximately 3 to 6 mm) hose, with quick connector, other end attached to cylinder with wire clip.

- A ring stand with clamp and clamp bracket.

- A note pad and raw data sheets.

- A timepiece.

- A thermometer;

- A pressure gauge attached to a quick-connector is optional but will give a good idea of how much gas each canister is likely to give off at each reading, and also lets the technician know if canisters need to be read sooner than scheduled, and also when not to open the valve if the pressure is negative on the gauge (attach gauge to the spare quick connector).

- A canister stand (see Figure A3).

- A water tub.

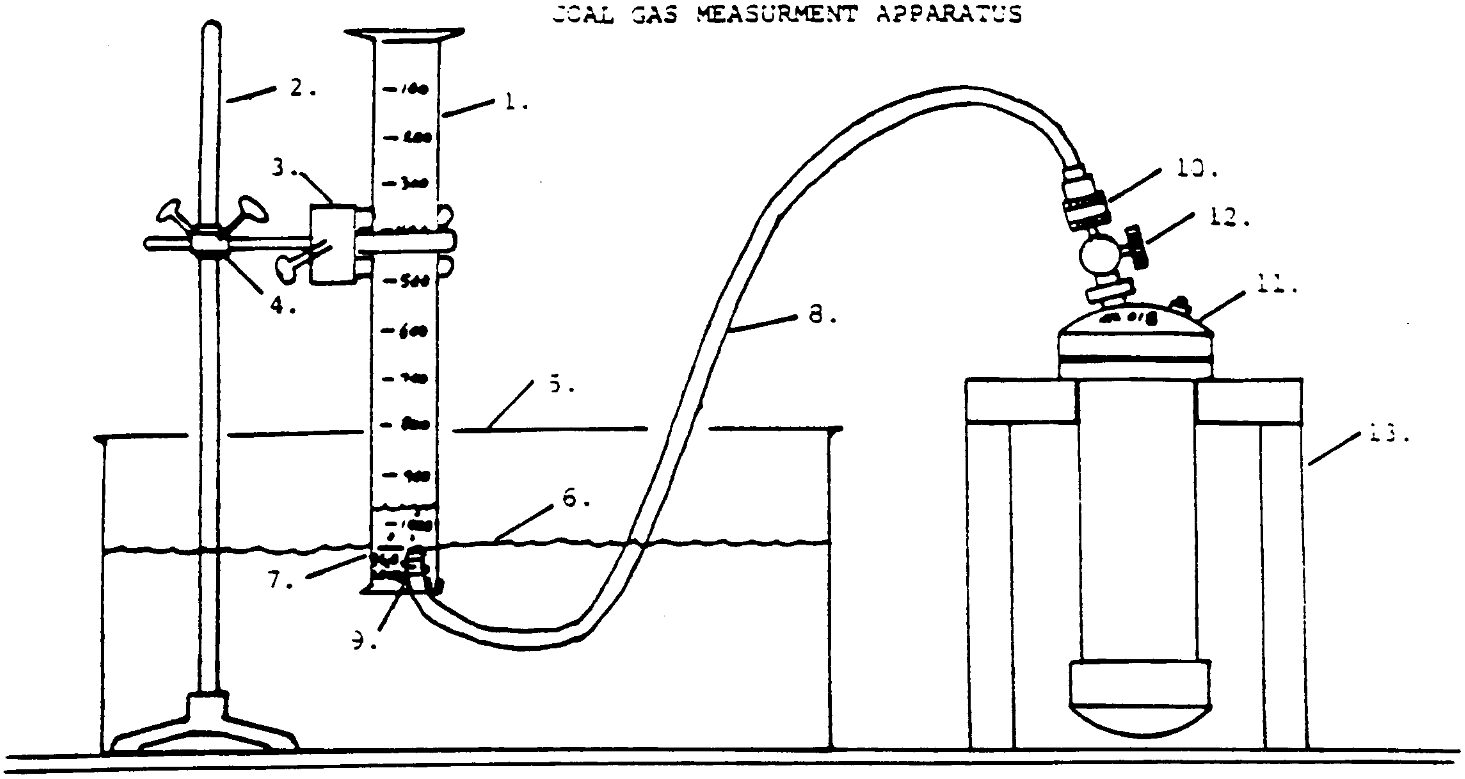
## COAL SAMPLING METHOD

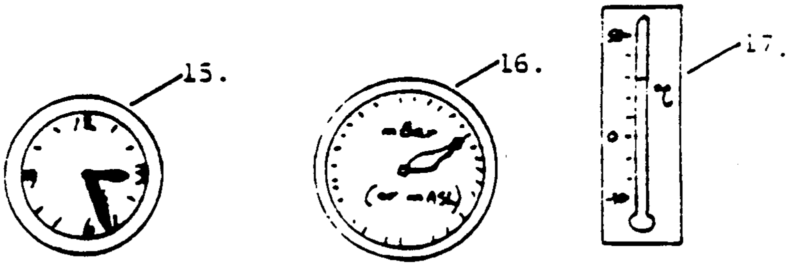
For chips (drill bit cuttings) or cores are, the sampling method is quite similar.

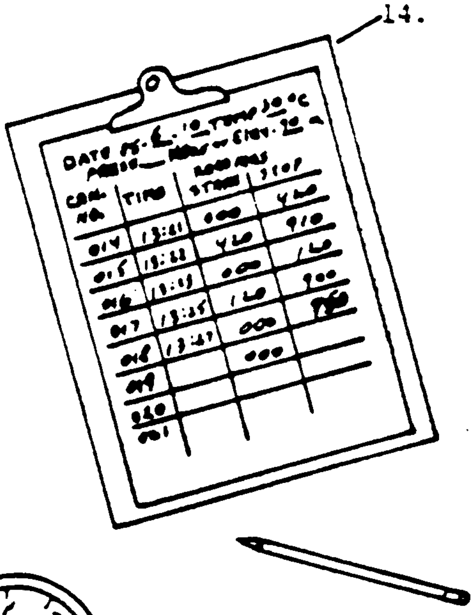
Sufficient desorption canisters are needed before drilling commences. The canisters need to be permanently and individually numbered (both tops and bottoms).

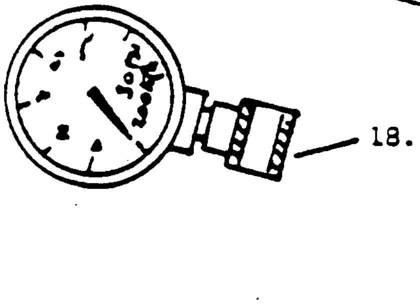
Figure A-1

COAL GAS MEASURMENT APPARATUS





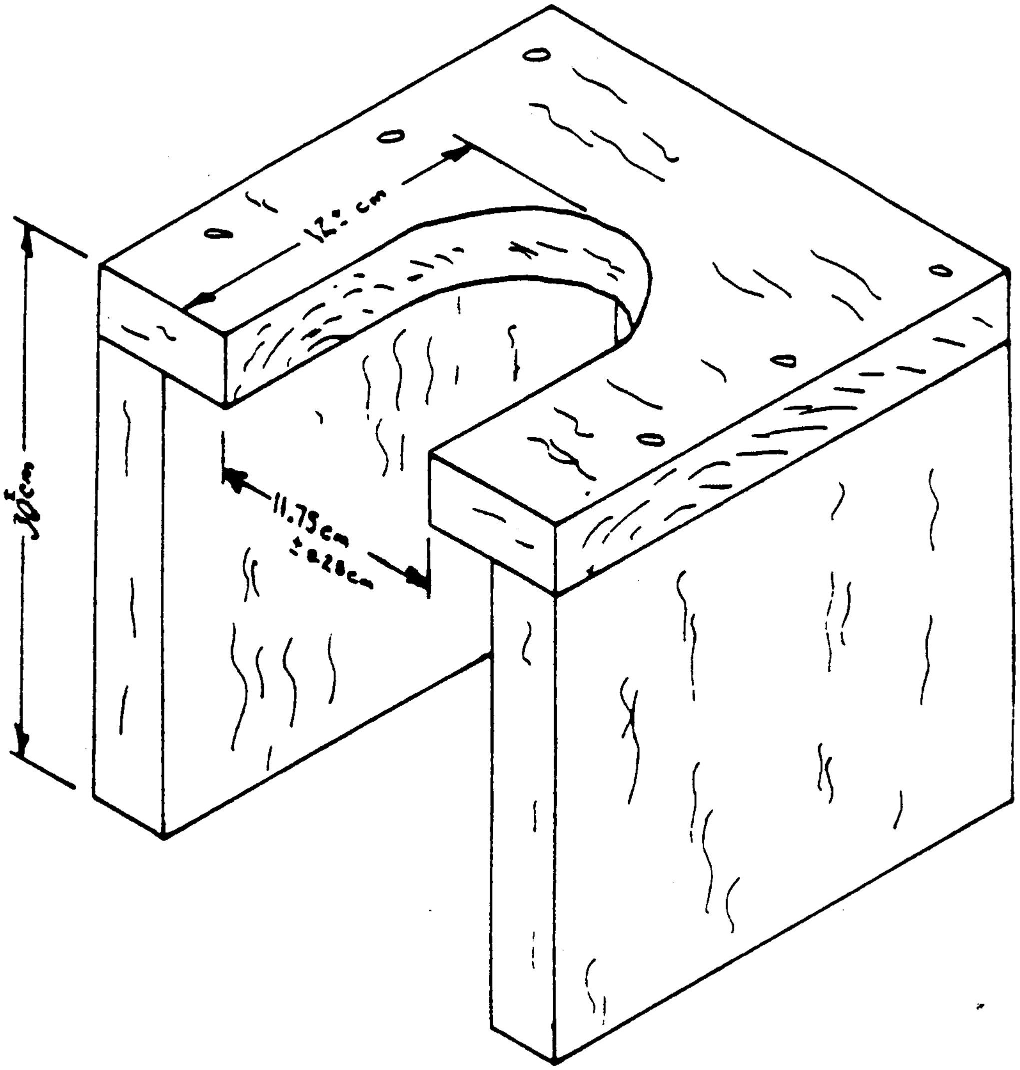




EQUIPMENT LIST

1. 1000 ml Graduated Cylinder
2. Ring Stand
3. Clamp
4. Clamp Holder Bracket
5. Water Tub
6. Water Level
7. Water Level Mark on Cylinder
8. Hose, ½"
9. Wire Clip, Holding Hose at Water Level
10. Quick Connecter, Ensure Positive Connection
11. Sample Canister
12. Valve, Ensure Well Tightened
13. Canister Stand
14. Clip Pad and Pencil
15. Time-piece
16. Atmospheric Pressure (Absolute)
17. Thermometer
18. Pressure Gauge with Quick Connecter, (OPTIONAL), ±30 PSI / ±200 kPa

Figure A-2



CANISTER STAND

Made from nominal 2" x 10" board, or any other material.

A number of drilling data need to be recorded. While drilling, the time that the coal sample is being cut is recorded. If chip samples are being collected then the lag time (or circulation time) to get the sample to the surface is recorded. the method of drilling (using air, water, foam, drill mud, etc.) is noted. Any delay time (i.e. pipe connection, pump shutdown, etc.) is also noted and included with lag time, but pipe connections should only, if possible, be made after the coal sample is recovered. The time the sample arrives at the surface is recorded.

For chips, a coarse screen, approximately 3 to 5 mm, should be used and the sample quickly washed of mud or foam, to remove the finer particles and clean the surfaces. If wire-line or standard coring is the method used to collect samples then the time that the core tube is started to be pulled is recorded. The time the tube arrives on the surface and if the tube is split, the time of opening, may also be recorded. The core is measured and a cursory log made as rapidly as is possible, a few minutes at the utmost.

The sample intervals are chosen and recorded and the samples immediately placed in canisters which are immediately closed (sealed) and the time of sealing recorded. This is recorded as Tc or "Time of Canistering", and from this time on no further gas is lost from the sample. If the canister is similar to the attached drawing, do not overtighten, but shut the cap against the O-ring using chain wrenches, plier type, or otherwise.

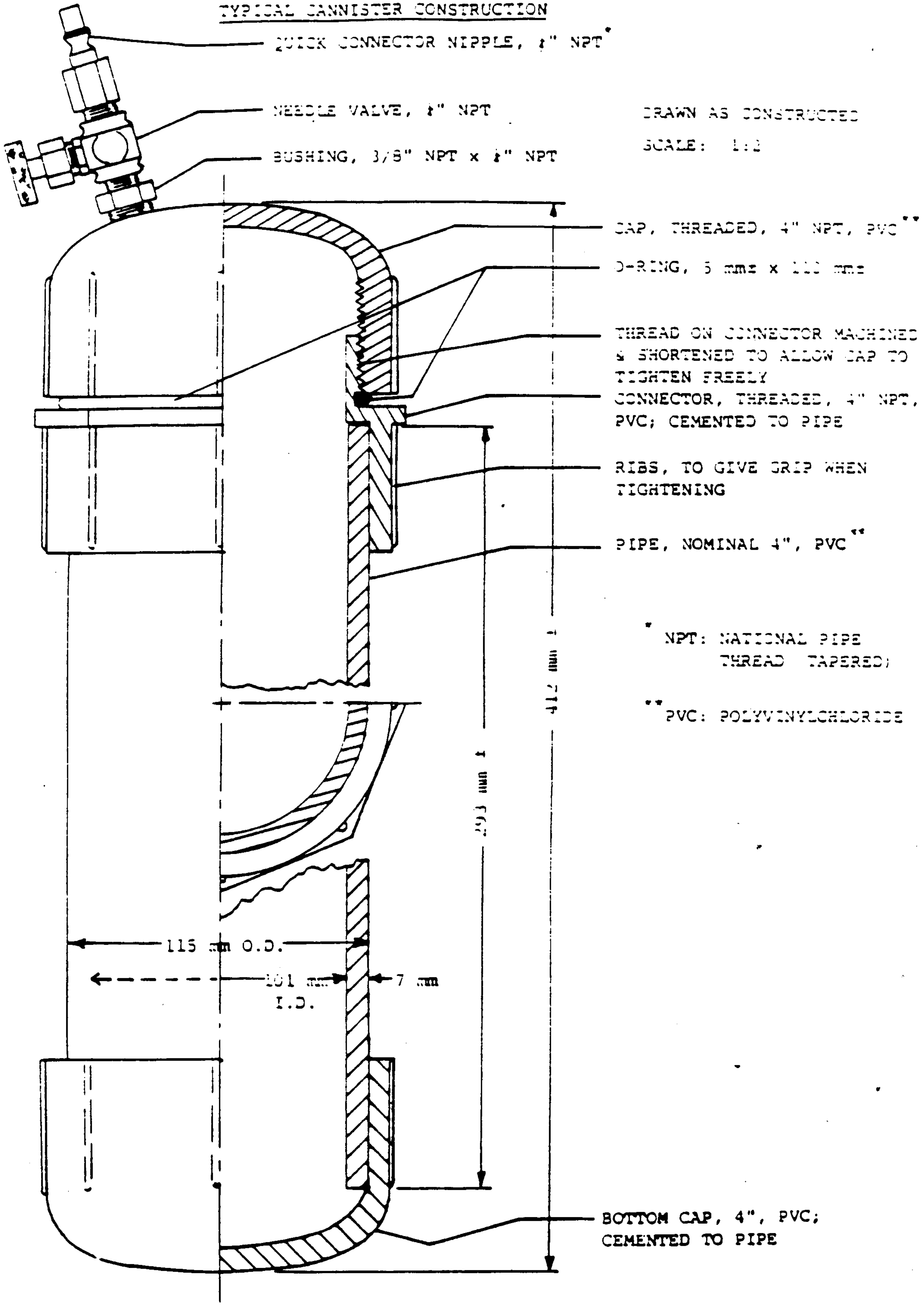
"Time Zero", or To, is the theoretical time that the confining pressure is released from the sample, normally the time of drilling when air drilling, or about half way or higher to surface with water drilling, or at surface if drilling with a mud. The time between To and Tc is the Lost Gas time.

Chip samples can be split so as to obtain a second set of samples referred to as "Grab Samples", on which proximate analyses can be done while the canister sample is desorbing. Chips from a coring bit can also be collected in this manner. These samples are drained, but not dried, and are securely tied up in plastic bags, or equivalent. These Grab Samples allow an early, rough calculation of the gas content of the coal.

The sample should not overfill the canister; about 2/3 full for chip samples and about 50 mm below the valve for core, (being about 300 mm of core for canisters of a size similar to the attached drawing - Figure A3). Canisters should not be placed in a position so as to allow the sample to contact the opening to the valve. This is to prevent the valve from plugging.

Figure A-3

TYPICAL CANNISTER CONSTRUCTION



DRAWN AS CONSTRUCTED

SCALE: 1:2

* NPT: NATIONAL PIPE THREAD (TAPERED)

** PVC: POLYVINYLCHLORIDE

When sampling is to commence, all materials and canisters should be placed neatly in order, and sufficient technicians on hand to record drilling data, collect and wash samples, fill and close canisters, and to record gas readings. Longer canisters than nominal 300 mm x 100 mm will result in a time and cost savings. for particularly thick seams canisters may, in fact, be 1000 mm x 100 mm.

Once the canister is sealed the first reading is due at Tc + 5 minutes.

## MEASURING TECHNIQUES

Measurement intervals are not haphazard, but are done as near as practical to the following schedule to allow for comparison to other coals around the world.

To is the time pressure released from the core (desorption starts) - approximate time of drilling if drilling by air, approximate time at surface if drilling with fluid; gas will be lost from To until Tc.

Tc is the time the canister is sealed; this is done as quickly as possible, no further gas is lost from this point;

Readings should be taken on a logarithmic scale with the first readings being close together and the subsequent readings being farther apart. It should be remembered that the early part of tthe desoption curve is very important so if an error in the frequency of the measurements has to be made it should be towards more measurements than too few. In any case if the pressure in the canister reaches about 5 psi or 35 kPa before the scheduled time for a measurement, then the canister should be read. This is because as the pressure builds up desorption slows. The readings of the first few hours are critical. Measurements are continued until the daily emission is less than 0.05 cu cm/gm per day for five consecutive days.

The line marked "H20 LEVEL" on the 1000 ml graduated cylinder is to be aligned at the water surface in the tub. (see Figure A1).

To aid in the accuracy of the calculations it helps to know how much the level of water in the water tub changes when the graduated cylinder is filled to 0 ml at the bottom of the meniscus. The cylinder need not be refilled for each reading if the volume of a reading is expected to be less than the remaining water volume. If a reading will exceed the 1000 ml capacity of the cylinder then close the valve, record the start/stop volumes (e.g. start: 100 ml, stop: 970 ml), refill the cylinder and repeat.

Filling of the graduated cylinder is most easily done by not releasing the clamp from the cylinder (once the "H20 mark is aligned with the water surface), and neither should the clamp bracket be released from the ring and use the cylinder clamp arm as a handle, returning it easily to the original position once refilled.

If any reading is in error by reason of the hose coming loose, or if a valve was not adequately tightened between readings then an estimate should be made in the field and the problem noted.

Readings can be made directly onto the data sheets or on to a sheet which lists all canisters being read at that particular time. Recorded are:

- Date.
- Temperature.
- For each canister:
  - the canister number.
  - time of reading.
  - canister pressure at start.
  - starting reading (ml).
  - stop reading (ml).

This information is transferred to each respective data sheet (one per canister). The gross weight of each canister (together with coal sample) is made to the nearest gram before opening, before desorption is completed. Once opened, the samples are sealed in plastic to prevent drying (the samples can be kept sealed in the canisters). the coal samples are sent to a analytical/assay laboratory to have proximate analyses done for each sample. The lab should also record weights to verify those recorded in the field. This information is recorded on the data sheets.

## CALCULATING GAS CONTENT FROM DESORPTION CANNISTERS DATA

The total gas content of the collected samples has three components:

1. Volume of the lost gas.
2. Volume of the measured gas in canister.
3. Volume of residual gas.

The measurement of the second component, the gas measured from the calculations explained in the previous section. Gas lost before the coal sample is placed in the canister (lost gas) is calculated and included in the total gas emission. The volume of the lost gas is proportional to the square root of the desorbed time (Figure A4).

When the daily emission has stabilized at less than 0.05 cubic metres per gram per day the coal sample is taken from the canister and sent to the laboratory for analysis. At this point the coal still contains residual gas. The amount depends on the nature and number of fractures of the coal sample. The volume of residual can be determined by grinding the coal sample to a 200- mesh size with a mechanical grinder inside a nitrogen filled contained. The residual methane desorbed from the fine coal is very rapid and is measured using gas chromatography as other methods.

Alternatively, a simpler method was developed, which although not as accurate, is adequate in the case of the Mecsek coalfield. The method is empirical based on plotting of residual gas versus desorbed gas plus lost gas for numerous samples analyzed by the gas chromatography procedure. These curves are used then, as standards for estimating the residual gas. Curves from many coals were found to fall into two types which reflect the friability of coals. Blockey coals tend to release their gas more slowly and thus have more residual gas than friable coals. Blockey coals retain about 40% of their total gas, whereas friable coals retain about 6%.

To evaluate the residual gas using Figure A5 the coal sample must first be classified as friable or blockey. Friable coals easily break into small pieces while blockey coals break into large lumps or square blocks. Friability appears to be related to a number of variables including the fixed carbon; the hardgrove grindability index, the depth of the coal seam, the degree of tectonic activity and cleat spacing. The fixed carbon percentage was found to be a good indicator of friability. All blockey coals tested had less than 57% fixed carbon. All friable coals had more than 57%.

The sum of lost gas; desorbed gas; and residual gas is the total gas content of a coal sample. by dividing the total gas by the weight of sample, the cubic centimetres of gas per gram of coal can be calculated.

For example, for a sample of friable coal:

| | |
|---|---|
| Weight of coal sample | 1,500 gm |
| Time to put sample into container | 25 min |
| Total gas released in the canister | 7,000 cc |
| Lost gas (from Figure A4) | 1,500 cc |
| Lost gas and measured gas | 8,500 cc |
| 6% retained gas in friable coal | 510 cc |
| TOTAL GAS | 9,010 cc |

9,010 cubic centimetres divided by 1,500 grams gives a gas content of 6.0 cubic centimetres/gram.

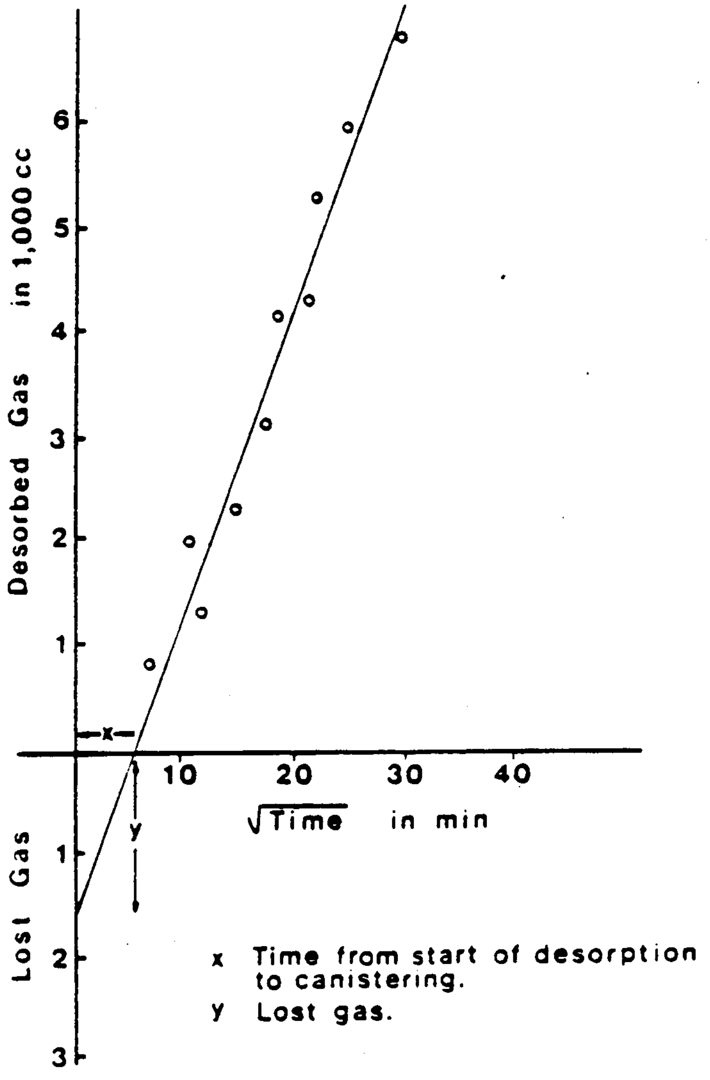


FIGURE A-4. Method of estimating lost gas. (After C. McCullock and W.P. Diamond U.S.B.M.)

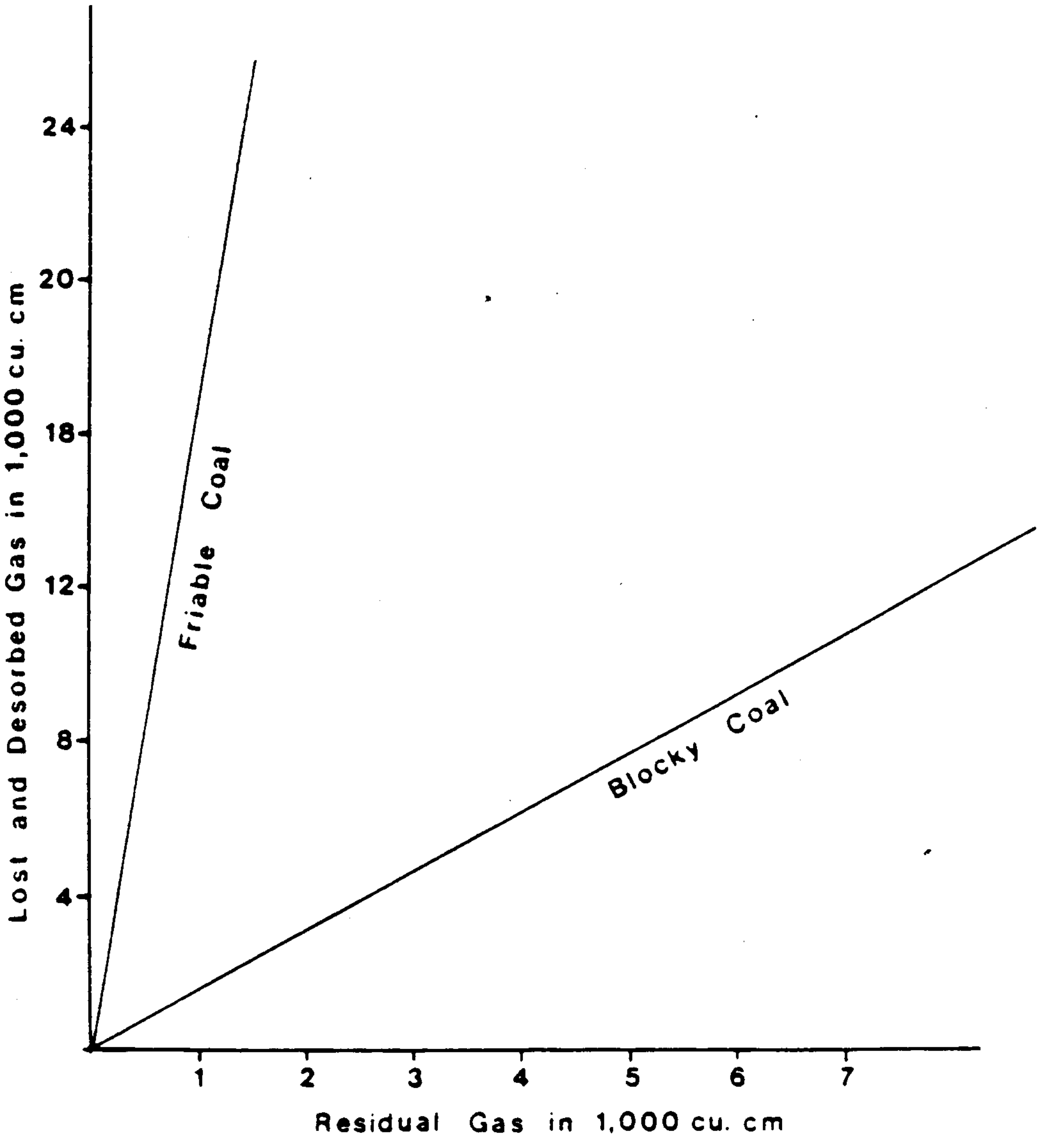


FIGURE A-5. Graph for estimating residual gas for blocky and friable coal. (After C. McCullock & W.P. Diamond U.S.B.M.)

# OUTCROP SAMPLING - METHODOLOGY AND ITS RELATION TO COAL BED METHANE RESERVOIR POTENTIAL

Field guide notes

Highvale Mine, Wababun Alberta

October 12, 1990

David Marchioni (Petro-Logic Services
Rudy Strobl (Alberta Research Council)

## HIGHVALE COAL MINE

The Highvale Mine in the Wabamun coal field is located 80 km west of Edmonton (Figure 1). Owned by TransAlta Utilities and operated by Manalta Coal Limited, Highvale produces more than 12 million tonnes of sub-bituminous B coal per year. The two thermal electric power plants, Keephills and Sundance in the Highvale Mine, the Wabamun thermal plant in the Whitewood Mine, and the Genessee plant in the Genessee Mine produce approximately 80% of Alberta's electrical needs.

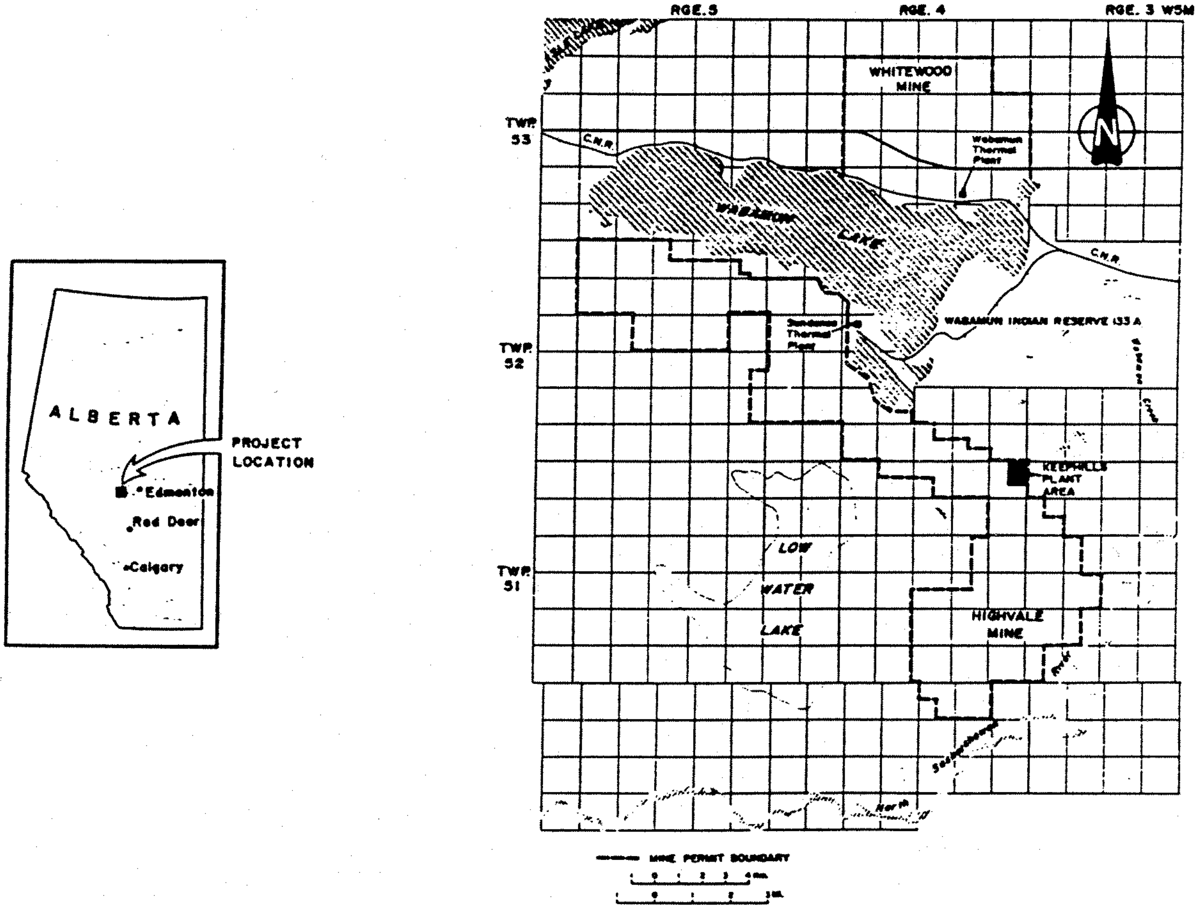


Figure 1. General location map of the Highvale Mine (modified from Lyons et al., 1987).

## Regional Geology

The coal being mined at Highvale, Whitewood and Genessee belongs to the Ardley Coal Zone. The Ardley zone occurs within the uppermost Scollard Formation and is underlain by the Battle Formation which is a distinctive stratigraphic marker in the central plains area of Alberta (Figure 2). These coals are lower Paleocene in age (Demchuk, in press) and the Cretaceous-Tertiary boundary is commonly at the base of the Ardley coal zone. In the Highvale mine, the Ardley coal zone is about 15 m thick, with 6 distinctive coal seams (Figure 3).

The Ardley coal zone is remarkably continuous and can be correlated with a high degree of geologic assurance from the foothills region to subcrop in the east (Figure 4). Regional correlation of individual coal seams, however, is often more difficult even over the relatively short distances from Highvale to Whitewood or Highvale to Genessee. Examples of regional correlation of coal seams will be discussed together with tectonic and depositional controls on coal development during the early Paleocene in Alberta. The overall distribution of Ardley coal development is shown in Figure 5. Note the thick accumulations of coal (12 m to 18 m) within the deeper portions of the basin. Assuming that appropriate coal rank and gas content are present, coal zones like the Ardley, offer prospective targets for coal bed methane.

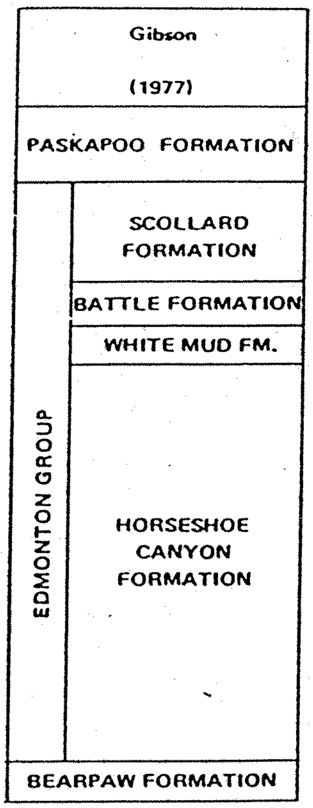


Figure 2. The Ardley coal zone in lower Paleocene in age, and occurs at the top of the Scollard Formation.

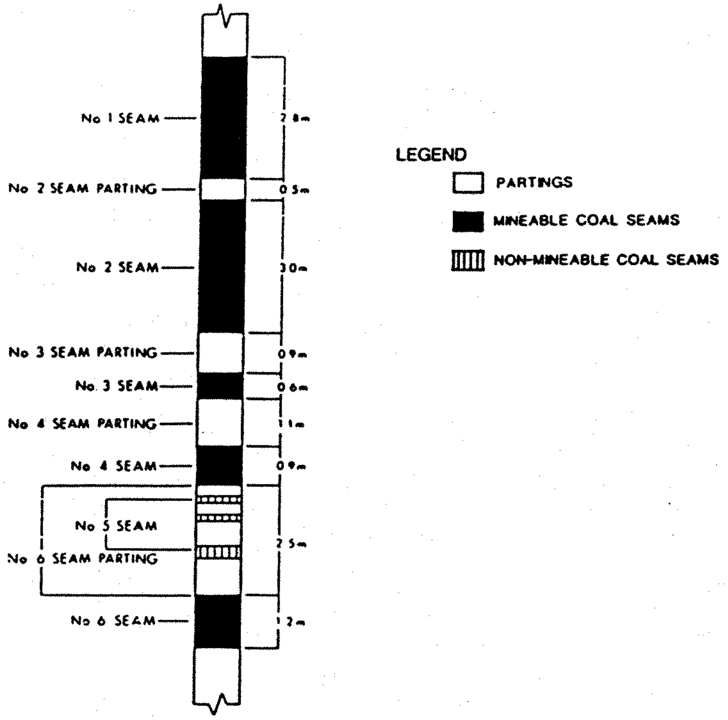


Figure 3. Numbering system of the Ardley coal seams in the Highvale Mine (after Taylor, 1985).

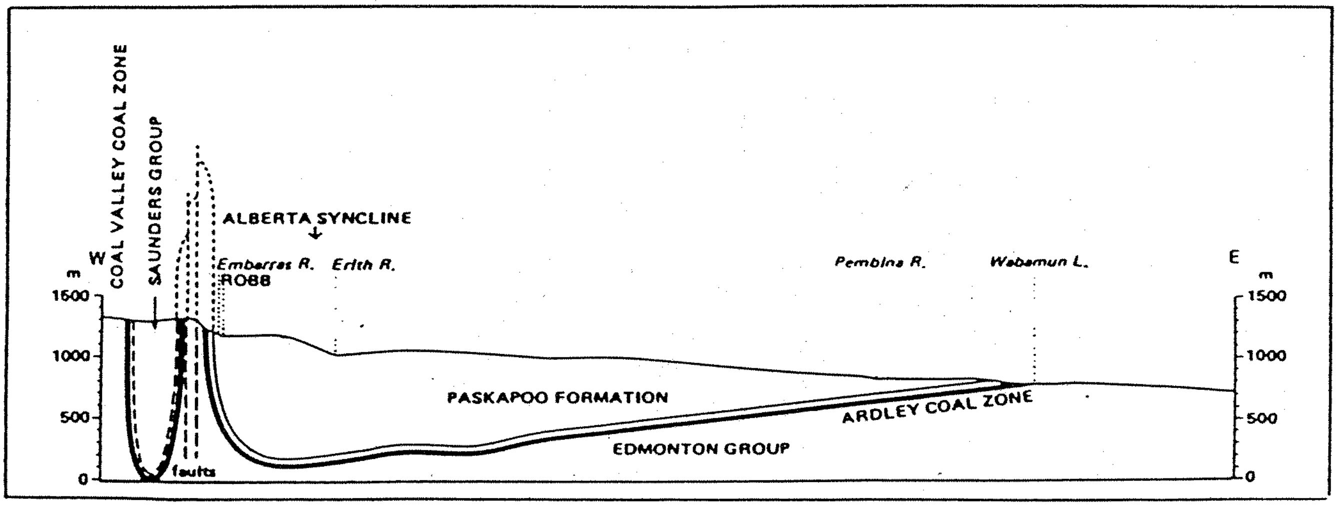


Figure 4. Generalized cross-section of the Ardley coal zone (from Horacek, 1986).

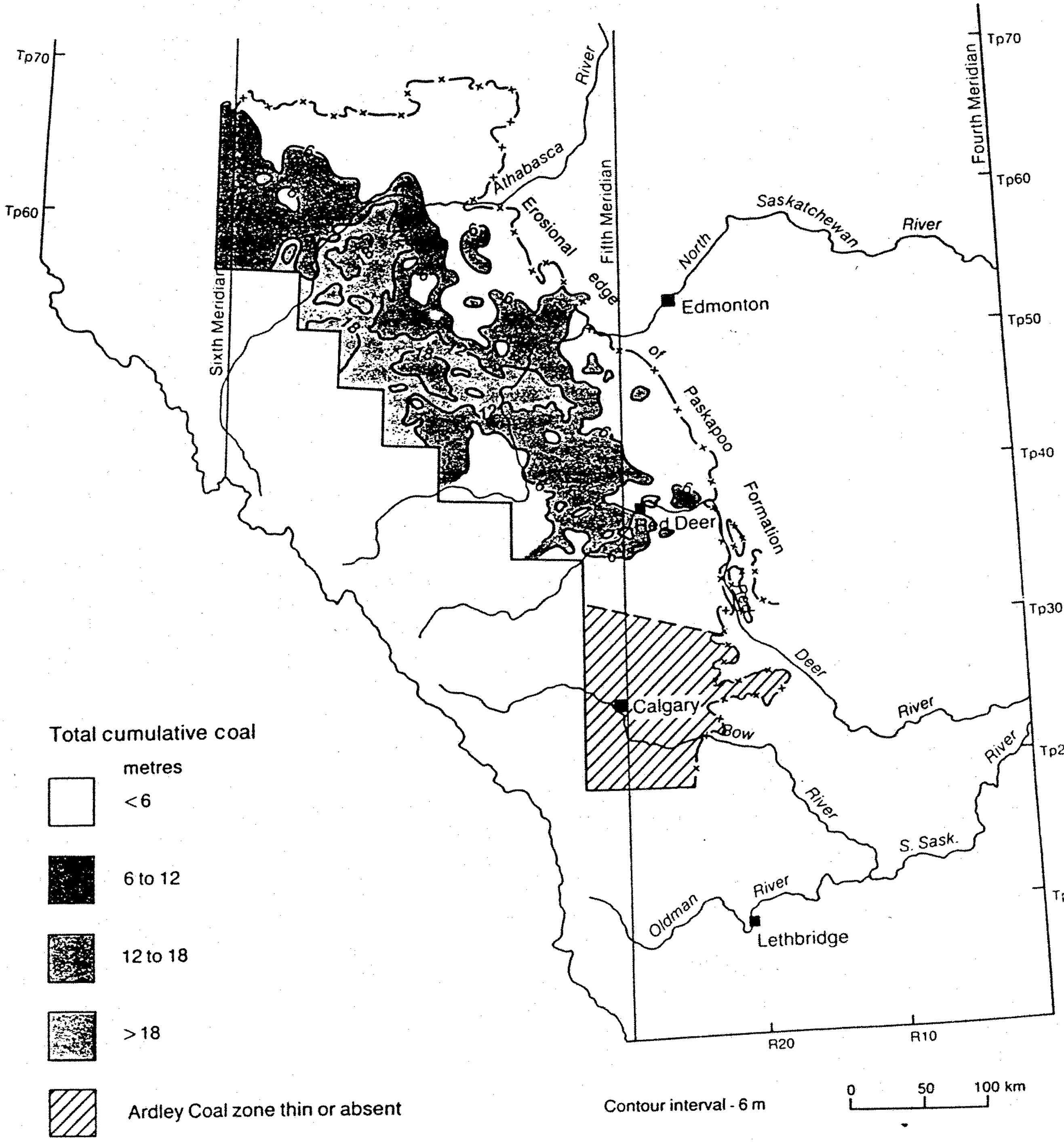


Figure 5. Cumulative coal thickness of the Ardley coal zone (from Richardson et al., 1988).

## STOP 1: HIGHVALE MINE (PIT 2, North) - ARDLEY COAL ZONE

**Objectives:**
(1) Overview of entire coal zone to show the lateral continuity of seams and rock partings on a deposit scale.
(2) Regional tectonic and geologic controls on coal development. Regional correlation of the Ardley coal zone.
(3) Discussion of coal quality variations between seams. Role of coal quality on gas content and reservoir behavior.

**Things to See:**

- Seams 1 to 6, numbered from top to bottom, respectively, are laterally continuous and easily correlated within the Highvale Mine area (Figure 6). Note the distinctive geophysical log signatures of each seam.

- Compare the bright/dull appearance of each coal seam. Seam 2 appears brighter (higher vitrinite content and lower ash content) than Seam 5 (higher inertinite content and higher ash content). Note differences in the frequency and spacing of cleats based on coal lithotypes.

- Measure the orientation of face (principal stress) and butt cleats. Compare with measurements at the second stop. Look for mineralization, usually calcite and pyrite, filling cleats which may affect local permeability.

- Coal is an extremely heterogeneous mixture of organic and inorganic constituents. Note the variation in coal quality between seams (Figure 7). Variations are noted within individual seams also, both vertically and horizontally. In seam 2, for example, the inertinite content increases at the expense of huminite from the base to the top of the seam. Ash content increases upwards and a change in the palynofloral assemblage from fern spores to Sphagnum moss occurs (Figure 8). Heterogeneities within coals must be recognized in much the same way as permeability barriers and heterogeneities are mapped for conventional reservoirs.

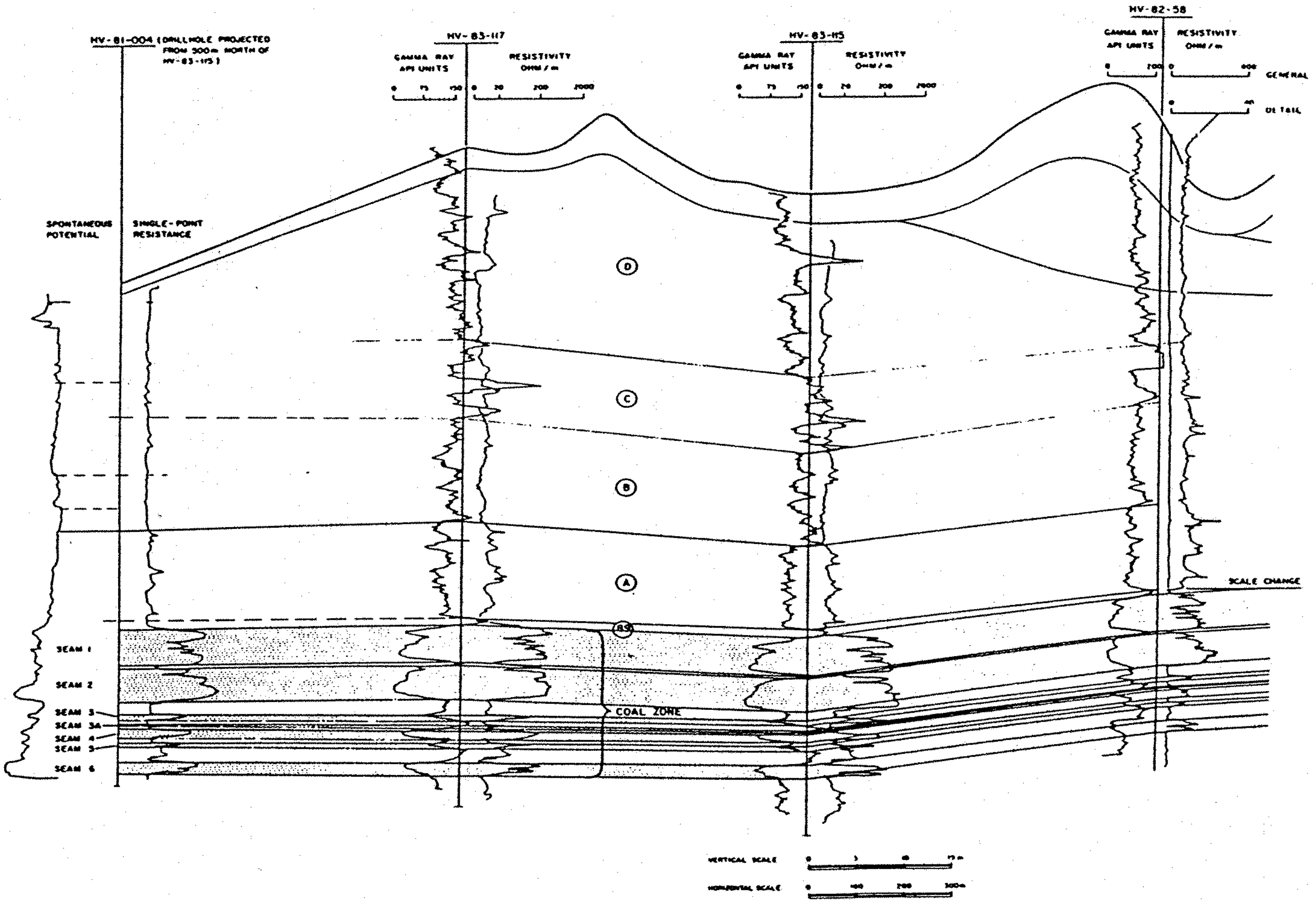


Figure 6. Generalized cross section showing the major seams in the Highvale Mine (from Lyons et al., 1987).

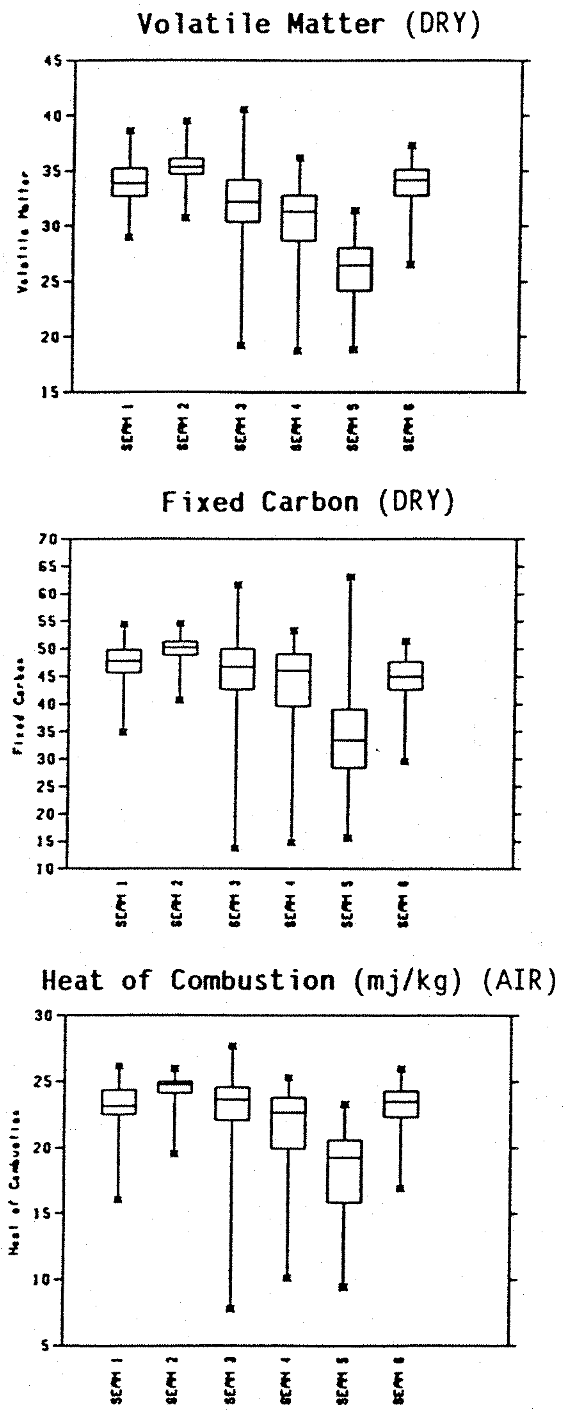


Figure 7. Box plots of coal quality - volatile matter, fixed carbon, calorific value, ash, and sulphur all on a dry basis, Highvale mine (from Strobl et al., 1989).

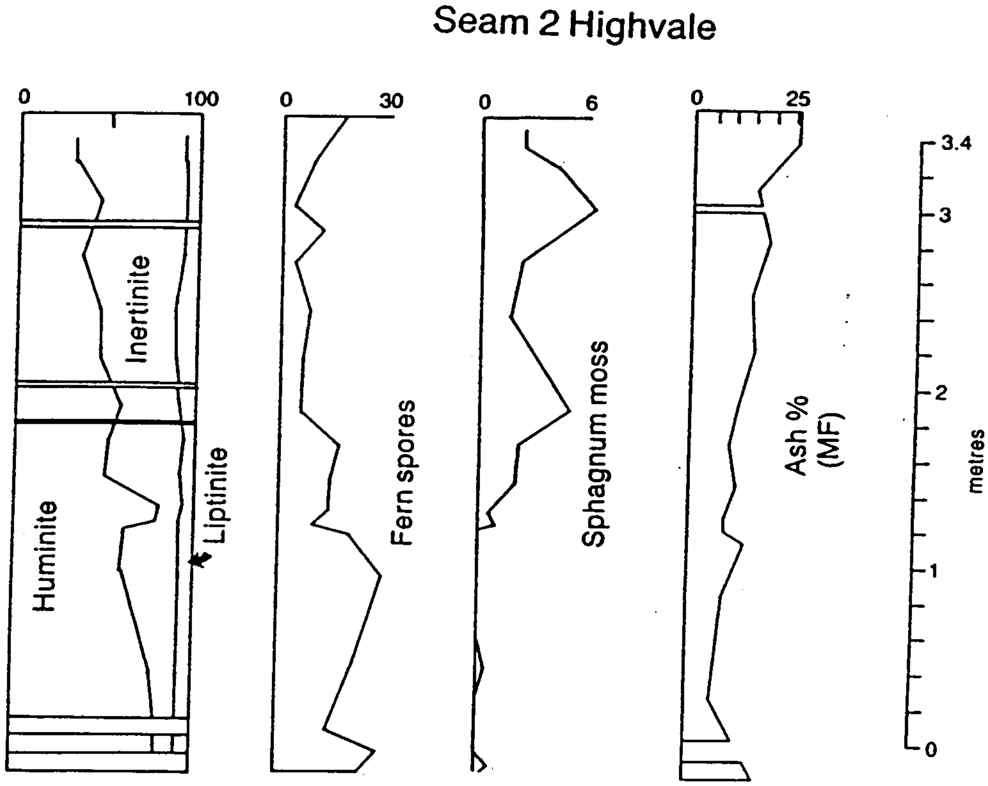


Figure 8. Vertical profile through Seam 2, at the Highvale Mine (modified from Demchuk and Strobl, 1989).

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Taylor, J., 1985, Highvale Mine in Coal in Canada, edited by T.H. Patching, Special Volume 31, Canadian Institute of Mining and Metallurgy, p. 164-167.

## STOP 2: HIGHVALE MINE (PIT 2, South) - ARDLEY COAL ZONE

**Objectives:** (1) Practice coal seam logging (Australian system) and sampling. Produce a standard coal seam profile as a basis for correlation and sampling.
(2) Compare a "core" view of a coal seam, using the slotted plywood, with the "outcrop" view provided by the highwall. Look for possible differences in interpretation.
(3) Consider the reservoir characteristics of a coal-bed methane well in this type of deposit. Cleat development and spacing, affects of lithotypes, ash content, presence of seals at the top or base of seams, and lateral continuity of seams are important aspects to study.

Things to See:

- Compare bright coal (with less than 10% dull components) with dull coal (with less than 10% bright components). Look for fusain layers (charcoal-like, fibrous coal).

- Compare the dominant cleat direction (face cleat) and subordinate cleat direction (butt cleat) between the two stops. The orientation of the dominant face cleats is commonly perpendicular to the mountain front, indicating northeast directed maximum stress (assuming extensional jointing). This is also reflected in the oval shape of drill holes (break-outs) elongated parallel to the mountain front (Bell and Babcock, 1986).

# COAL SEAM LOGGING AND SAMPLING IN OUTCROP

## INTRODUCTION

Coal seams vary both vertically and laterally in their macroscopic appearance and there are associated variations in physical and chemical properties. Coal geologists need a standardised means to describe seam profiles to serve as a basis for correlation, for sampling and for studies of vertical and lateral seam development.

## THE SEAM PROFILE

### Inorganic Beds (Partings)

The most obvious feature of a coal outcrop or core, is the presence of light coloured inorganic beds or partings, consisting of fine grained clastics, such as clays and silts, or authigenic minerals such as carbonates, phosphates and sulphides. Determining the position and thickness of such beds is often the starting point in logging a seam profile. Delineation of inorganic partings is important from both a geological and technological viewpoint. Peat swamps are very flat and so flood events, now represented as clastic partings, are often very extensive and readily correlated across wide areas (Fig. 1). Similarly, bands rich in authigenic minerals may have been deposited in response to regional variation in water table levels, or other widespread events and so are often important correlation units.

From a technological viewpoint, inorganic material is deleterious in most cases. For example, it is non-combustible and so contributes nothing to the heat value of a thermal coal. But often it must be mined and transported to a separation plant and removed at added expense. Where the mining method is able to remove the partings separately from the coal, it is important to be aware of their presence in order to acquire appropriate equipment and establish a mining sequence that maximises the volume of parting material removed and minimises the loss of underlying coal.

In methane evaluation, it should be noted that the partings do not generate gas and, due to their fine grained nature, are unlikely to retain significant volumes. Thus the proportion of inorganic material will influence the total generative/storage capacity of a seam. In addition, partings may act as barriers to the migration of gas between different horizons in the seam and may have significant influence on artificial fracturing of the seam to stimulate production.

Often, delineation of the inorganic beds is relatively simple as, due to their colour and thickness, they may be quite obvious. In many cases however, the boundary between coal and inorganic parting is gradational. The inorganic content of the coal increases gradationally into the parting and a boundary may be difficult to assess. A useful guide is to use a scratch test; coal has a black streak and high mineral content while the partings have a brown or lighter coloured streak.

A profile showing location, nature and thickness of partings and of the interbedded coal may be sufficient for many purposes (Fig. 1). In addition, if there are frequent partings, the interbedded coal units may be sufficiently thin for a channel sample of each sub-section to be readily obtained.

## Lithotypes

If a more detailed subdivision of the seam is required, perhaps for analytical or correlation purposes, or if coal beds between partings are too thick to permit consistent channel sampling, then it is necessary to utilise some form of standard scheme to visually subdivide the coal units.

It has long been recognised that bituminous coal displays a generally banded appearance, the banding being due to interbeds displaying variable lustre and fracture. Stopes (1919) first described "the four visible ingredients in banded bituminous coals" and Seyler (1954) introduced the term "lithotype" to designate these macroscopically recognisable bands. Lithotypes are essentially macropetrographic units which are distinguished and logged on the basis of features such as lustre, fracture pattern, colour, streak, texture and nature of stratification.

Due to the finely banded nature of coals in countries outside Europe, where the original definitions were proposed, many authors have found a need for a more detailed lithotype nomenclature. A descriptive system developed by Diessel (1965), and modified for use in Western Canada (Table I), subdivides coals on the basis of the proportion of dull and bright components. Bright coal, (with less than 10% dull components) and dull coal, (with less than 10% bright components) are assigned as end members of a gradational series. Between these two extremes, three more lithotypes are established and two additional lithotypes are defined. Fibrous coal is a relatively rare, but ubiquitous and distinctive lithology. Commonly in foothills coals, sections of the seam are sheared to such an extent that the coal is reduced to extremely fine fragments and and it is impossible to assign a brightness- based lithotype. For this reason it is necessary to create another lithotype called "sheared coal". Partings are generally described by standard clastic nomenclature (e.g. carbonaceous mudstone, siltstone).

In order to standardise lithotype analyses and retain compatibility between different analysts, it is necessary to specify a minimum thickness for lithotypes. Choosing different minimum thicknesses for a seam log would significantly affect the subsequent profile. When observing a fresh coal face, the analysts looks for coal units with relatively uniform proportions of banded components. As soon as an individual unit exceeds the chosen minimum thickness, it must be assigned to one of the lithotypes. Where a unit is less than the minimum thickness it must be included with adjoining units, the overall composition assessed, and a lithotype assigned. In this way the geologist works through the entire seam section.

The coal outcrop should be exposed to produce a fresh surface for examination and, as in any section description, the seam is logged along a line perpendicular to bedding. A minimum thickness is sometimes specified by National Standards for commercial analyses. Originally it was defined as 1cm and this is commonly used in Europe. For the finely banded Permian coals of Australia a standard is set at 5mm. For internal reports or research projects, the analyst usually decides on a minimum thickness based on the seam thickness, the thickness of the banded interbeds, the time available for creating the log and the level of detail required. All logs should specify the minimum thickness and it should be consistent within a study.

Some examples of lithotype logs are shown in Figs II and III from the Permian of eastern Australia and the Lower Cretaceous of western Canada respectively. In Fig II a minimum thickness of 5mm was used and in Fig III, 1cm. Note the differences in the frequency of clastic partings (or "bands"), differences in the typical level of brightness in each seam and differences in the pattern of vertical lithotypes succession (e.g. brightening up versus dulling up); features related to the development of the ecosystems forming the precursor peat swamps. For example, Seam 11 is dominated by banded coal and brighter lithotypes and typically displays oscillatory lithotype sequences while, Seam 10 has a dominance of banded coal and duller lithotypes and dulling upward sequences are common.

Although the method is rather subjective, conformity to a stated minimum thickness and to the chosen lithotype nomenclature can lead to general conformity of brightness logs between different analysts, especially once some "hands on" practice has been undertaken.

## Composition of Lithotypes

Variations in the macroscopic appearance of coal reflects significant variation in the coal type; i.e. the relative proportions of contained macerals and minerals. Numerous studies (e.g. Diessel 1965, Cameron 1968, Marchioni, 1980, Marchioni and Kalkreuth in press) have established that although there is no unique composition for each lithotype, and ranges of compositions for lithotypes overlap, there are well established trends in composition between the end members of the lithotype sequence. In general, inertinite and liptinite contents increase at the expense of vitrinite along the trend from bright to dull coal. Mineral content increases in the same sense.

The chemical and physical properties of the micro-components of coal vary and consequently, the composition of a coal seam and its response in technological processes are significantly influenced by coal type. An accurate seam profile is essential as the basis for any sampling program designed to elucidate the overall properties of a seam.

## SEAM SAMPLING AT OUTCROP OR MINE FACE

An exposure of a coal seam in a mine or outcrop is generally sampled along a line perpendicular to bedding. Due to the variations in physical and chemical properties of coal related to the variations in composition of coal lithotypes, it is essential that any sample taken to represent the properties of the whole seam should be obtained in a statistically sound manner as possible. It is essential that the volume of coal taken as a sample is representative of the bulk composition of the seam. If a single sample is taken to represent the whole seam, then it is essential that each section is represented in the same proportions as it occurs in the seam. Unless a seam is very thin this is very difficult to achieve in practice.

### Pillar and Channel Samples

In outcrop, two methods of sampling are practiced:

Pillar sampling - involves taking of a continuous prismatic block of coal from the top to the base and perpendicular to bedding. Although the pillar may be broken into several blocks, no part of the seam should be omitted and care must be taken to ensure constant dimensions for the prism. Such samples are very time consuming and are rarely used except for research oriented work

Strip or Channel Samples - involve cutting or digging a channel or groove into the coal face and collecting all of the pieces removed (Fig IV). Commonly this is done by spreading a sheet of plastic or a large bag at the bottom of the channel. Again, if only one sample is to be used to represent the properties of the seam, then it is essential that the channel has uniform dimensions so that each portion of the seam is represented statistically in the resulting sample. Unless the seam is quite thin this is difficult to achieve.

To provide a record of the macroscopic variations within the seam and to facilitate more accurate and often more useful analytical results, a macroscopic seam log is often used as the basis for sampling. This could be as simple as recording the thickness of the clastic partings and interbedded coal and sampling each sub-section so defined; or as detailed as sampling each individual lithotype and parting.

A channel sample is taken as described above, but each sub-section (or ply) would be retained as a separate sample. This will provide more information about the variations in properties within the seam and will also facilitate easier and more accurate sampling. It is not necessary that each ply be sampled in the same proportions, only that sampling within plies is consistent. The dimensions of the channel must remain consistent within each sampling unit but may vary between the units. The thinner the analysis unit, the easier this task becomes.

When the thickness of each subsection (determined during logging) and its specific gravity (measured in the lab) are known, then composite analytical data can be calculated for the whole seam or selected sub-units of the seam from the analyses of the individual plies. This "ply-by-ply" analytical approach will highlight portions of the seam with characteristic chemical and physical properties and facilitates calculation of bulk properties for the whole seam or for any selected sub-sections.

## Effects of Weathering

The processes of natural weathering resulting from exposure of a coal seam at outcrop or in a mine face will influence the chemical and physical properties of the coal. Typically, vitrinite reflectance, carbon and heat value are lower and oxygen and volatile matter contents are higher in weathered coals than in fresh coals. When sampling, reasonable efforts must be made to obtain coal that is as fresh and consequently as representative of the in-situ properties of the coal, as is possible. This will generally require digging a channel or pit into the outcrop to significant depths.

At outcrop, coal is usually very fine grained, friable and has a very dull and earthy appearance. With increasing freshness the coal becomes harder, more brittle, gains an increasingly bright lustre and fractures in a blocky fashion. In strip mines, a seam can often be followed from outcrop to a fresh face to observe the marked physical changes accompanying weathering.

Without excavation or drilling equipment, it is almost impossible to obtain truly "fresh" coal from a natural outcrop. Coal has been found to be effected by weathering at down-dip depths of up to 25 metres in the mountains and foothills and up to 11 metres in the prairies (Marchioni, 1983). The zone of strong weathering is much shallower, usually in the 5 to 10 metre range. Samples from the weathered zone will show physical and chemical properties different to the fresh coal, but if the degree of weathering can be estimated, then a compensating factor can be applied to the analyses to estimate the properties of the fresh coal (Marchioni, 1983).

In a freshly exposed mine face, the coal will have suffered only minor weathering effects, but it is still advisable to remove at least a thin layer of coal to obtain samples from the underlying unaffected zone. The different properties of coal show different sensitivities to the effects of weathering. Tests related to the fluidity of the coal and to oxygen and volatile matter contents usually show a high sensitivity. The most sensitive indicators are petrographic techniques that highlight the effects of oxidation at the microscopic level.

Natural outcrops and strip-mine exposures allow coal seam gas to escape to the atmosphere. Consequently samples will not provide useful information on the volume of contained gas. Such exposures may however, provide access to fresh coal by drilling down-dip from these convenient exposures.

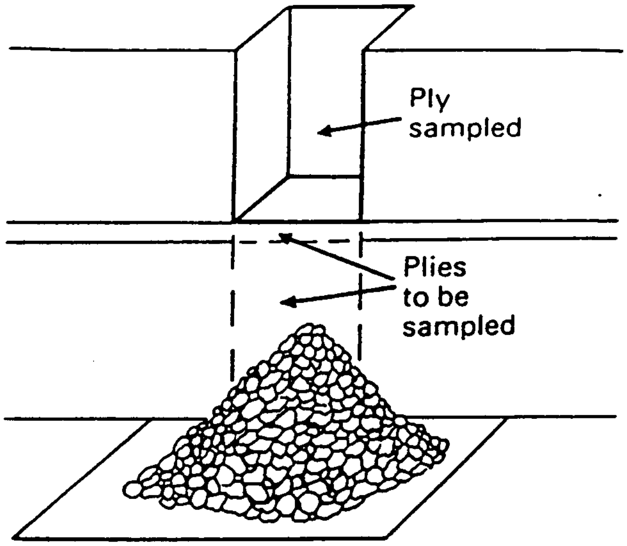

Fig. IV. Channel sample collection from a coal seam on a ply by ply basis. (From Ward, 1984)

| Division after Stopes | This Study | Description |
|---|---|---|
| Vitrain | Bright coal | Subvitreous to vitreous lustre, or conchoidal fracture<br>$<10$ per cent dull |
|  | Banded bright coal | Bright coal with some thin dull bands<br>10-40 per cent dull |
| Clarain | Banded coal | Bright and dull coal bands in equal proportion<br>40-60 per cent dull |
|  | Banded dull coal | Dull coal with some thin bright bands<br>10-40 per cent bright |
| Durain | Dull coal | Matt lustre, uneven fracture<br>$<10$ per cent bright |
| Fusain | Fibrous coal | Satin lustre, friable |
|  | Sheared coal | Variable lustre, disturbed bedding, numerous slip/slickenside surfaces, very brittle. |

Table I. Lithotype subdivisions modified after Diessel (1965)

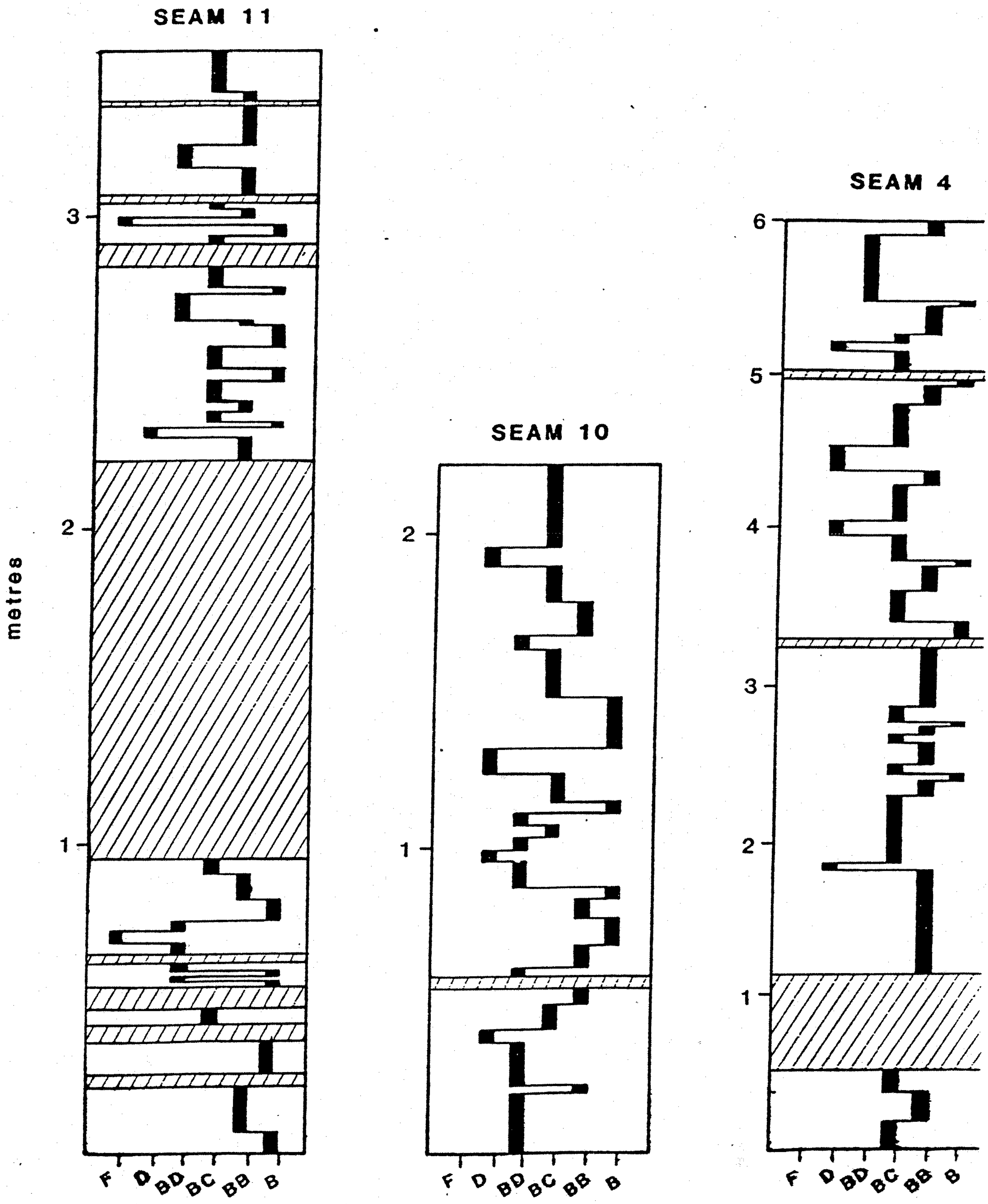

Fig. III. Lithotype profiles, Lower Cretaceous Gates Formation, Western Canada.

Minimum lithotype thickness 1 cm. Brightness increases from left to right, see Table I for lithotype nomenclature.

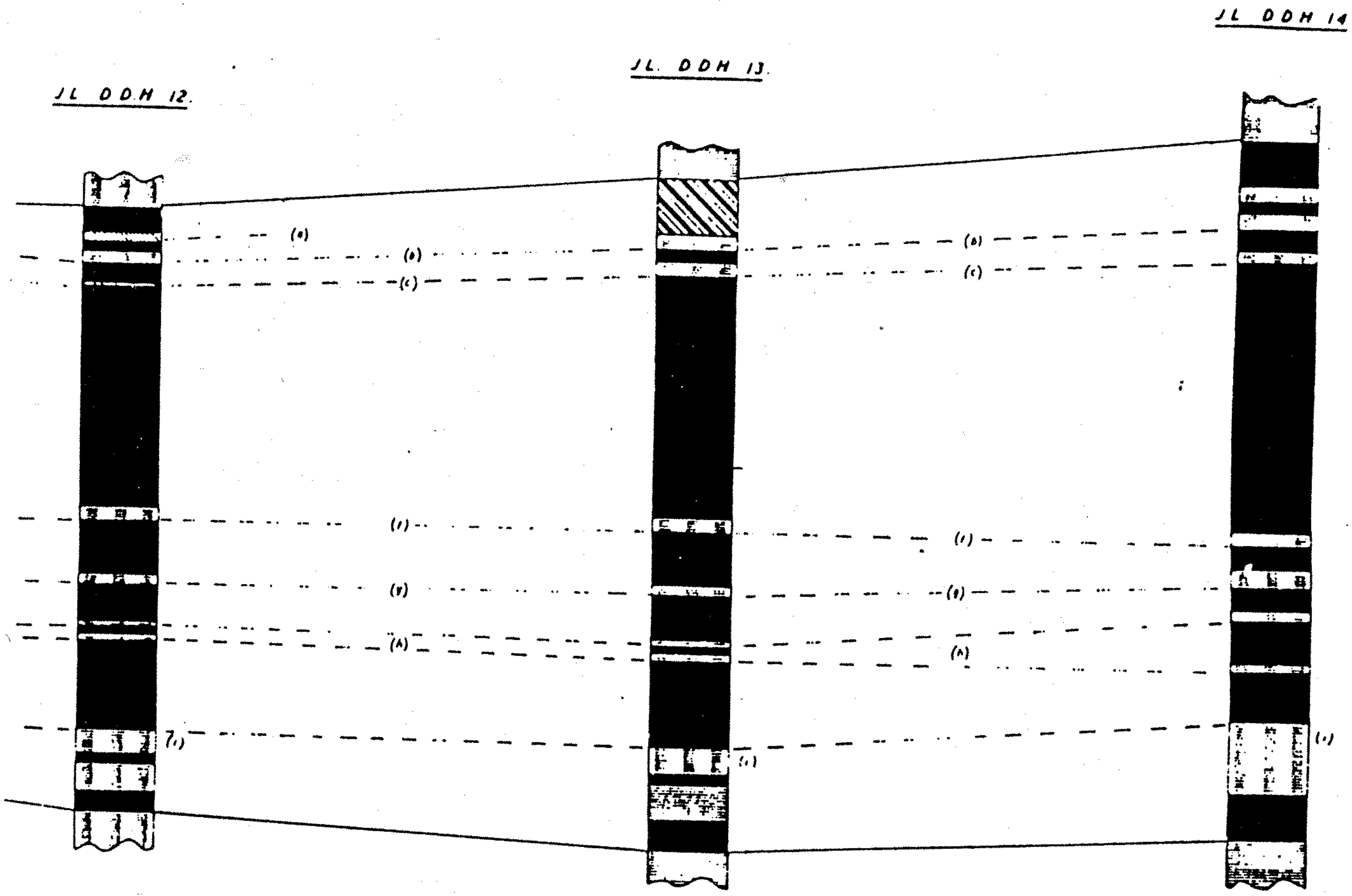

Fig. 1: Seam profiles without subdivision of coal, Permian Barrett Seam, Hunter Valley, Australia.

(Vertical Scale: 1cm=1m. Horizontal not to scale, distance between boreholes approx. 800m. From Marchioni, 1976)

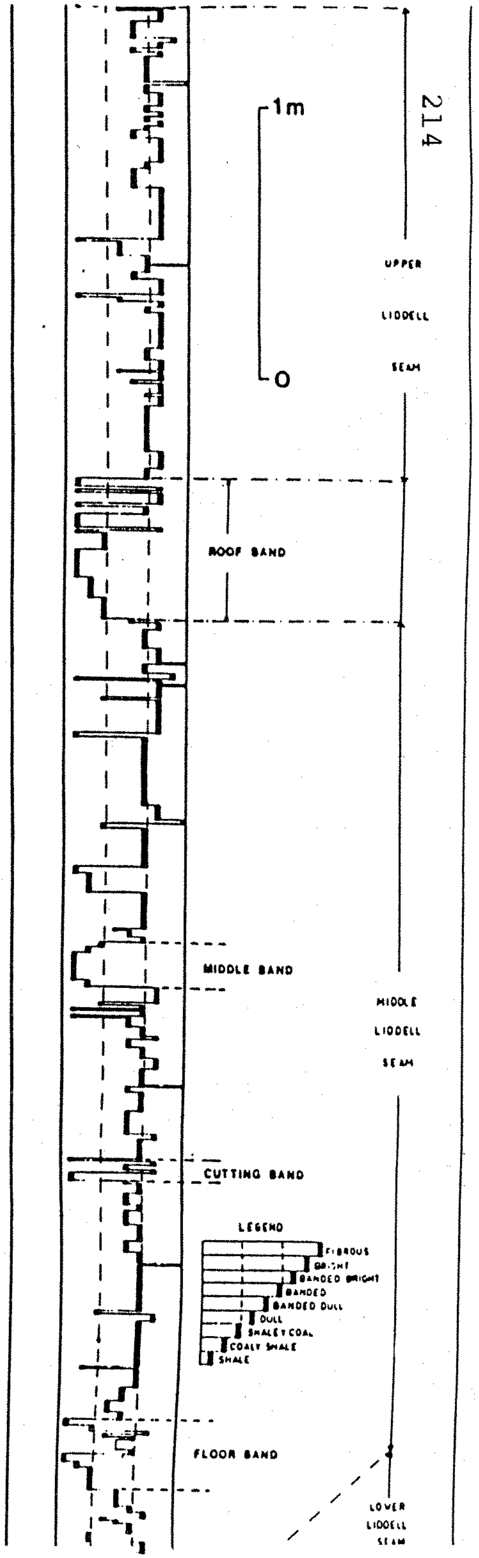

Fig. II. Lithotype profile, Permian Liddell Seam, Hunter Valley, Australia.

Minimum lithotype thickness 5mm (From Marchioni, 1980)

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# NOTES ON COAL CLEAT

Jointing in coal is commonly referred to in the mining industry as cleat. The term refers to a set of parallel fractures in the coal, usually oriented normal to bedding. The dominant set is called "face" cleat and is usually quite straight and persistent (up to several metres long). A second set, the "butt" cleat is commonly normal to face cleat and fractures are shorter, curved and often terminate against the face set. More than one pair of face and butt cleat may be present.

Cleat frequency is usually higher in coal than is the joint frequency in the overlying and underling sediments. Within the coal, different lithotypes also display different cleat spacing; density is usually highest in the brighter lithotypes and lowest in dull and shaley coal. Cleat spacing will influence the size of the fragments in the coal when mined or when artificially fractured. Dense spacing may lead to abundant fines which may result in well caving during drilling and excessive abrasion on down hole pumping equipment.

Cleat orientation often bears close relation to the joint pattern and this pattern may be used to predict cleat pattern at depth. Face cleat, in general, appears to be the result of extensional fracturing in the plane parallel to the maximum compressive paleostress in the region (Nickelsen and Hough, 1967; Hanes and Shepherd, 1981). Butt cleat origins are less well known and may be related to the depositional and early coalification history of the seams (Hanes and Shepherd, 1981).

Experience from the long history of underground coal mining has shown that coal is more permeable parallel to face cleat. Tunnels driven in this direction frequently experience higher rates of water seepage and gas emission. Experience in coalbed methane production also indicates that pressure depletion and production drawdown patterns around each well are elliptical, with the long axis parallel to face cleat.

Even in relatively undeformed basins there will be at least one cleat set. The pattern may become more complex in multipley deformed basins or in the vicinity of major structural features such as fault planes and fold axes. In some mines, changes in cleat patterns are used to predict the proximity of faults. The direction of maximum principal stress over much of the western part of the Western Canada Sedimentary Basin is, at present, normal to the mountain front (Fig. I) and, in view of the structural history of the basin, it might be expected that paleostress had a similar orientation. It could be expected that at least one set of face cleat is similarly oriented. Multiple deformation and secondary structures could be expected to generate additional sets or to influence the orientation of sets.

In the Alberta Plains, face cleat is generally perpendicular to the Rocky Mountain front indicating a relationship to northeast directed maximum principal stress. Fig II (fróm Moell et. al. 1985) shows cleat and joint orientations in the Highvale Mine

The basin has a history of thrusting deformation and this is particularly evident in coal seams which have acted as preferential paths for low angle movement. In the mountains and foothills it is very common to find extensive shearing in coal seams, often parallel to bedding over a clearly defined portion of the seam. In these zones, the coal is reduced to extremely fine particles and all lamination and cleat is obliterated. These zones are often assumed to be zones of high permeabilty but at the micro scale, some sheared coals display evidence of poor permeability. The range of grain sizes produced by the shearing is very gradational and extremely fine grains are often seen to be plugging larger fractures.

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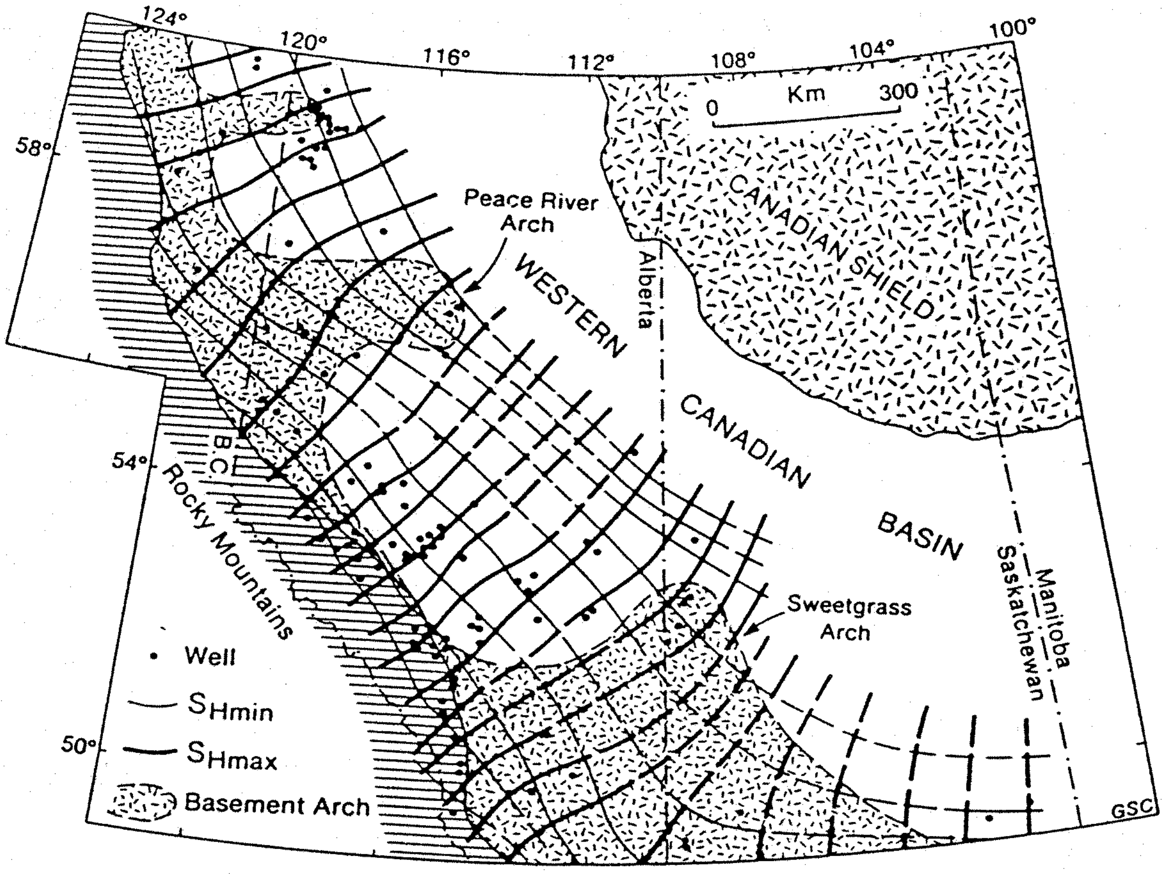

**Fig. 1. Possible stress trajectories in the Western Canadian Basin inferred from orientation of borehole breakouts. Note the deflections of principal horizontal stress directions around basement arches. (From Bell and Babcock, 1986)**

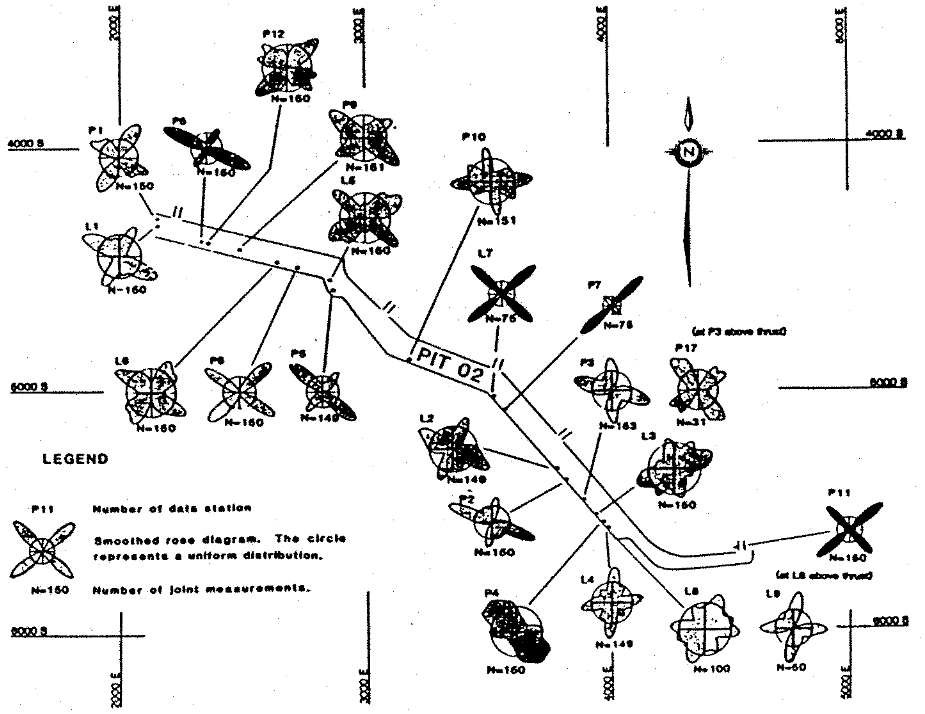

**Fig. 2. Smoothed rose diagrams of joints and cleats at Pit 2 of the Highvale Mine. Stations L7, P7 and P11 are cleats in coal and others are joints in clastic sediments (from Moell et al, 1985)**

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