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Origin of mine water from interpretation of water analysis data

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Abstract

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Various techniques of interpreting mine water analysis data for a coal mining environment are briefly outlined. A brief review of the hydrochemical techniques indicates that an application of a triangular diagram method for identifying source characteristics seems to be very promising. This technique has been used to establish source characteristics in the North Derbyshire and the northeastern coalfields of England. Several case histories presented in the paper indicate that regular analyses of mine water can indicate the gradual dilution of the water from the source and may indicate the onset of an underground inundation. This technique has been applied to assess water danger in the undersea mine workings of Northeastern England.

Introduction

Underground mining operations below the groundwater table or the piezometric surface are associated with seepage or inflow of water and consequently the mine workings are likely to be wet. Under these circumstances, a range of control measures should be adopted in order to carry out mining operations in an efficient and safe manner. However, if an unexpected inflow of water is encountered, it is necessary to regularly monitor (1) the quantity of mine water inflow with time and (2) the chemistry of the mine water in order to determine its source.

If the source and quantity of water accumulation in relation to the size of mine is known and the rate of inflow can be estimated, the danger of inundation and the extent of water danger can be assessed. Regular monitoring of mine water seepage rates can give an indication of water danger and the chemical analysis of water may indicate the source of water or possible dilution of water from a large surface accumulation. Thus, by judiciously following the above mentioned two procedures, a mine operator can obtain the correct forecast for the water problem and adopt effective remedial measures. For example careful coal mining operations under large accumulations of surface water in the Sydney Basin in New South Wales, Australia anticipated a problem of leakage of dam water into the underlying workings: A method of chemical analysis of mine water was used to prove that the surface water was not leaking into the underground mine workings [1].

This paper deals with the method of data analysis, the presentation, and interpretation of water analysis results. The general water chemistry of the Coal Measures is described and is compared with the water chemistry of the surface accumulations of water endangering the mine. Methods of comparing water chemistry from various sources are discussed. By means of selected case histories, the paper illustrates the method of determining the origin of mine water.

General water chemistry

The most important chemical parameters of a water sample from the Coal Measures are as follows:

(1) Salinity: Total dissolved solids may vary between 0 and 300,000 mg/l. The chemical components present in water from underground coal mines include chlorides, sodium and a small amount potassium, calcium, magnesium and sulphate or barium.

(2) Insignificant components are carbonates, silicates, iron and manganese

Usually, sodium and potassium appear together in the chemical analysis results, as shown in Table 1.

TABLE 1

Water analysis results (mg/l)

Appearance	Slightly opaque
pH value	7.0
Suspended solids	–
Suspended Fe as Fe_2O_3	14
Total Fe as Fe_2O_3	6
Total hardness ($CaCO_3$)	4600
Calcium hardness ($CaCO_3$)	2000
Total alkalinity	200
Phonolphthalein alkalinity	–
Ca	800
Mg	630
Na	35690
Fe	1
Mn	1
Chlorides	57600
Sulphates	730
Nitrate	–
Ba	–
Sr	–
Total dissolved solids	95600
Ammonium	–

Sources of water

The purpose of geohydrochemical analysis is to isolate one of the following sources of water entering mine workings: underground aquifers or old surface or underground mine workings.

In order to interpret the water analysis results, firstly it is necessary to have some method of comparison. A brief review of some of the methods is presented in the following section.

Methods of comparison

The following methods are considered:

(1) Comparing chemical components (mg/l) as a percentage of the total dissolved solid.

(2) Kimpes method: In this method, water compositions are reported in milli-equivalents per litre and plotted as logarithmic values with the points joined to form a "hydrogram". This approach emphasizes the similarity of water samples rather than the differences, and therefore it is not suitable for identifying the onset of inundation.

(3) Comparison of the equivalent ratios of the related ions Na/Mg, Ca/Mg and Cl/SO_4: These parameters show a considerable overlap from different sources of water and a comparison between different samples from various sources is therefore difficult.

(4) Triangular graph method: The main problems of the interpretation of water analysis results using this method include identification of the various factors to be studied in the analysis, and data handling and manipulation, especially when a large number of results are available.

TABLE 2

Water sample data analysis (mg/l)

Total hardness ($CaCO_3$)	4600	
Calcium hardness ($CaCO_3$)	2000	
Total alkalinity	200	
pH	7	
Total Fe	14	
Ca, 800/20	40	(Ca + Mg 92.0)
Mg, 630/12.1	52	
Na, 35690/23	1551	
Fe, 1/18.62	0.05	
Mn, 1/27.47	0.036	
Ba, 1/68.67	0.01	
	1643.90 Total cation	
Cl, 57600/35.6	1622.53	
SO_4, 730/48.03	15.20	
	1637.73 + 6.17 Total anion	

Total dissolved solids, 95,600
Na/Cat, 1551.73/1643.89 = 0.94
Mg/(Mg + Ca), 52.0/92.06 = 0.56
Cl/SO_4, 1622.53/15.2 = 106.75

An analysis of earlier work has enabled the following conclusions to be made:

(1) No individual characteristics can unequivocally identify the source of water inflow.

(2) The interrelationship of proportions of the various components may be relevant in ascertaining the source of underground water. In this context, Na, Ca and Mg form 99% metals in solution (milliequivalents/l by dividing by equivalent weight) [3]. The active components of Na, Ca and Mg (mg/l) are converted to milliequivalents/l by dividing by equivalent weights obtained from chemical tables.

Table 1 shows a typical water analysis result obtained from a coal seam in an undersea working. The results are calculated as shown in Table 2 and the data are summarized as the Na/Cat. ratio, the Mg/(Mg + Ca) ratio, the pH level, total dissolved solids (TDS) and the Cl/SO_4 ratio. The calculated results can be plotted on a triangular graph. In order to use water analysis techniques for identifying the source of water, it is necessary to establish a database for defining source characteristics.

Establishing source characteristics

A meticulous sampling programme is necessary for collecting water samples from within coal seams, goaf samples from sources up to 60 m above the coal seam, borehole samples from various aquifers above the seam, and samples from old mine workings.

The interpretation of the water analysis results in order to identify the source of the water is difficult. However, in the past 15 years, several thousand water samples showing a wide range of qualities have been tested in underground coal mines in the U.K. [4]. It is now possible to identify recognizable quality patterns in water lying in undisturbed strata. The basic principles which are involved in identifying the source of water are as follows:

(1) Ratios of ionic concentration: A study of analytical data from water samples has revealed a common pattern of interrelationship between the ionic concentrations of the salts dissolved in the water [5]. A log/log plot of the ionic concentration of sodium, potassium, magnesium, calcium, barium and manganese

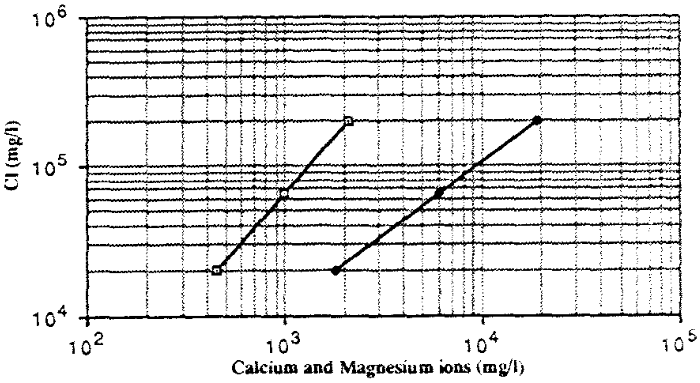

Fig. 1. Relationship between calcium and magnesium and chloride ions in the Harvey and Maudlin Seams, Northumberland [2].

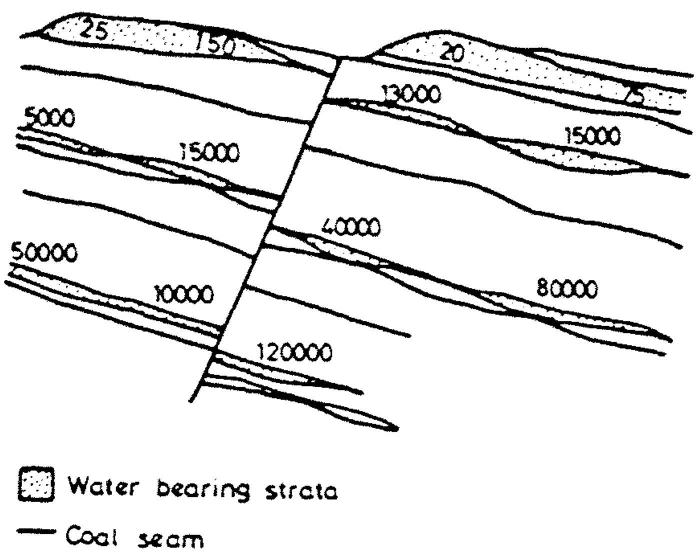

Fig. 2. Spatial distribution of chlorides in confined aquifers showing a gradual increase with depth and a stepwise variation over a fault [7].

against the concentration of ammonium, bicarbonate and chlorides shows a linear relationship. Figure 1, for example, shows the calcium and chloride relationship in water samples obtained from a confined aquifer.

(2) Spatial distribution of dissolved salts: It has been widely observed [2,5,6] that the chloride ion concentrations in water encountered in successively more deeply confined Coal Measures aquifers invariably increase with depth. This is also true of the cation concentrations illustrated in Fig. 2.

Establishment of water quality characteristics of the Coal Measures

Based on the above principles, water samples from confined Coal Measures aquifers, unconfined aquifers and abandoned underground coal workings have been known to have characteristic water quality features.

Water quality patterns of confined aquifers

The evidence suggests that dissolved salts are in geochemical equilibrium with the strata with which they are in contact, but are able to migrate freely over geological time between confined aquifers. A similarity in the water quality pattern has been observed in Coal Measures outcrops and in the concealed coalfields. In particular, pH values and oxidation potential are comparable in these two situations. It has been further observed that the increasing concentration of salts with depth may be attributed to a movement of salt-bearing water along bedding planes, with an associated vertical movement of brine across the bedding planes under artesian pressure [5].

Thus, water from confined Coal Measures aquifers will have the following chemical characteristics:

(i) Alkalinity of the groundwater initially increases, and then decreases with depth.

(ii) Salinity of groundwater increases with depth both in a single aquifer and in deeper aquifers.

(iii) The chloride, sodium, magnesium and calcium content of the water increases with depth.

(iv) Manganese, barium, strontium and ammonia were found in deeper Coal Measures aquifers and their concentrations increase with depth. Sulphate ions are absent, or only occur as traces.

Figure 2 shows the general relationship between ionic concentration and depth in the confined aquifers in a British coalfield. The quality changes in a confined aquifer along the bedding planes when the aquifer is a dipping aquifer, and stepwise quality changes occur when an aquifer is cut by a fault. Thus, it is possible to predict the presence of hydraulic discontinuities from the changes in the water quality results and also to interpolate the aquifer. Figure 2 also shows the variation in the chloride contents of an aquifer system in the British Coal Measures. It should be noted that there is a gradual increase in the chloride ion content in the aquifer with depth.

Water quality of unconfined aquifers

The chemical characteristics of groundwater in an unconfined aquifer will differ greatly depending on the type of aquifer—whether it is outcropping or "incropping". The groundwater in outcropping aquifers, which are normally 50–100 m deep, has a low chloride concentration (< 100 mg/l), is very hard (Ca = 100–500 mg/l), and has sulphate concentrations of 50–300 mg/l.

The groundwater characteristics of incropping aquifers occurring beneath overlying aquifers is intermediate between the typical Coal Measures and the overlying strata.

Water in flooded abandoned mines

The chemical characteristics of water in abandoned workings are essentially identical to the chemical properties of parent infiltrated water together with the oxidation products of pyrite. Thus, abandoned mine water contains iron and other sulphates, low concentrations of H_2S and dissolved sulphates remaining in the water indefinitely. Additionally, the pH value is stable between 5.3 and 6.8 and the oxidation potential is low.

Influence of carbon and chloride contents of coal on the chloride concentration of the aquifer water

Based on the geochemical analysis of brines in Coal Measures aquifers and on the chemical analysis of the adjoining coal seams, a relationship between the carbon content of the coal, the chloride content of the coal and the chloride content of the groundwater has been established in order to allow the prediction of the chloride content of the groundwater in a confined aquifer from the chemical analysis of coal.

In many coalfields, mine water may originate from one or a combination of several surface or underground water sources. It may, therefore, be necessary to ascertain the source horizon and recharge mechanism of the water in order to determine any danger of catastrophic inundation. This is particularly important in undersea mining where it is necessary to establish whether the water flowing into the mine workings has originated from one of the following sources: (1) from a discrete aquifer, (2) from an aquifer being recharged vertically from the seawater, (3) directly from old underground mine workings, or (4) from an aquifer which is being recharged by infiltration of surface water at the strata outcrop and which is percolating downdip along the plane of the aquifer.

Origin of mine water in the North Derbyshire Coalfield

The need for rapid identification of the source of mine water has been recognized by mining engineers since the Lofthouse inrush of 1973. Chemical analysis of water has been in use in the North Derbyshire and Nottinghamshire Coalfields since 1969, but the practice has been continued on a more regular basis since the appointment of a geologist in 1973. Since then, it has become a regular practice to identify the source of water as soon as it first appears in any of the underground workings.

A general geological description of the North Derbyshire Coalfield, which includes the site of investigation, is given in [9]. The exposed part of the coalfield including the E-dipping Coal Measures has also been discussed in [9]. Unconformable Permian beds are exposed towards the eastern side of the coalfield and the main structural feature of the coalfield is an anticline running approximately NW–SE. The coalfield is intersected by numerous faults. In total, there are fifteen coal seams, the deepest outcropping in the west and the shallowest outcropping in the east. The sandstone beds above the coal seams form the Coal Measures aquifers and present water seepage problems for the underground mine workings. Similar to the trend in other coalfields, the water problem gradually increases from west to east. The actual intensity of the water problem depends on the attitude of the strata, the method and sequence of working, the presence of faults, the accumulation of water in old workings, and the thickness of the protective barrier between the old workings and the current workings.

This section briefly presents a case example where the source of water was successfully identified with the help of chemical analysis.

Water percolation in the pit bottom area

The site concerned is a medium depth underground coal mine in the North Derbyshire area, U.K.

Access to the coal seams was obtained through a pair of circular shafts reaching the bottom of the Second Ell seam at a depth of 430 m. The water problem manifested itself in the form of a water seepage in the pit bottom area in the Second Ell Seam which completely saturated the silty mudstones surrounding the bottom section of the shaft, presenting a serious strata deterioration problem.

There are two well known sources of water in close proximity to No. 2 shaft in the Top Hard and Second St John seams. A programme of water sampling and analysis was initiated to determine the origin of the mine water. The main aim of the study was to confirm whether the water originated from either of the two known sources or whether it was a mixture of the two waters or had originated from a new, unidentifiable source.

Water samples were taken from locations A–F (Fig. 3). Sample A was taken at the inset to the Second St John seam 199 m above the pit bottom. Water in this inset originated only from one direction and was constantly replenished by the strata water. This water is normally piped to the water garland within the shaft from which it is transferred to the water lodgment at the lower levels. Samples from this source have been analyzed many times and the essential characteristics have been established.

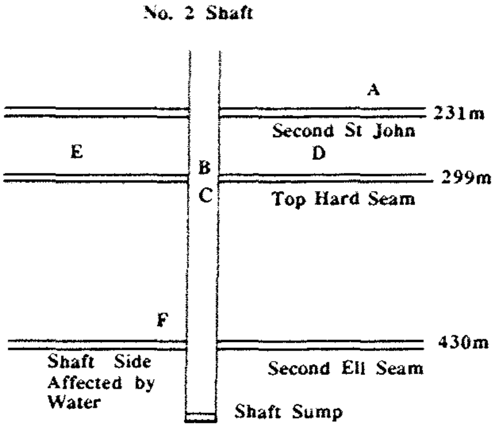

Fig. 3. Source of mine water causing deterioration of rock mass strength at the pit bottom (A–F are water sampling points).

Water samples B and C were taken from the water garland above and below the Top Hard inset in order to identify any source of dilution of the samples originating from sample point A. Water samples D and E were collected at either side of the shaft inset to the Top Hard seam 131 m above the pit bottom. Water at this inset is replenished from several known directions and sources. The chemical characteristics of this water have been established through chemical analyses over a period of 20 years. This water is disposed by siphoning down to the pit bottom sump from where it is pumped out of the mine.

Sample F was collected and analyzed at a site of strata deterioration at the pit bottom.

From Table 3 the following observations regarding the water chemistry may be made: (1) Samples A, B and F have the same range of total hardness, while samples D and E possess a similar range of total hardness; (2) the calcium contents of samples, A, B and F are all very similar whereas those for samples D and E are an order of magnitude less; and (3) the sulphate contents of samples E and F are much higher than those of A, B and D.

The cation contents of the samples were calculated in milliequivalents by dividing the

TABLE 3

Water analysis results (mg/l)

	Samples				
	A	B	D	E	F
Depth (m)	228	295	299	299	532
pH	6.8	7.7	7.4	7.8	6.8
Total hardness	5800	5400	1700	2450	6500
Alkalinity	4500	3400	600	1050	3700
Ca	1800	1900	240	280	1850
Sr	200	10	5	10	220
Mg	316	400	270	260	400
Ammonium	< 1	< 1	< 1	< 1	< 1
Ba	< 15	< 20	< 30	< 27	< 15
Mn	0.1	0.1	0.3	0.2	0.3
Na	11000	12000	11000	11000	11500
Sulphate	< 5	16	10	417	228
Chlorides	22700	21270	9400	10990	24820

See Fig. 3 for location of samples.

values expressed in milligrammes per litre by the equivalent weight of the ion under consideration. The chemical analyses of samples A, B, D, E and F are plotted in Fig. 4. It can be seen that A, B and F cluster together on the left-hand side of the diagram, while D and E

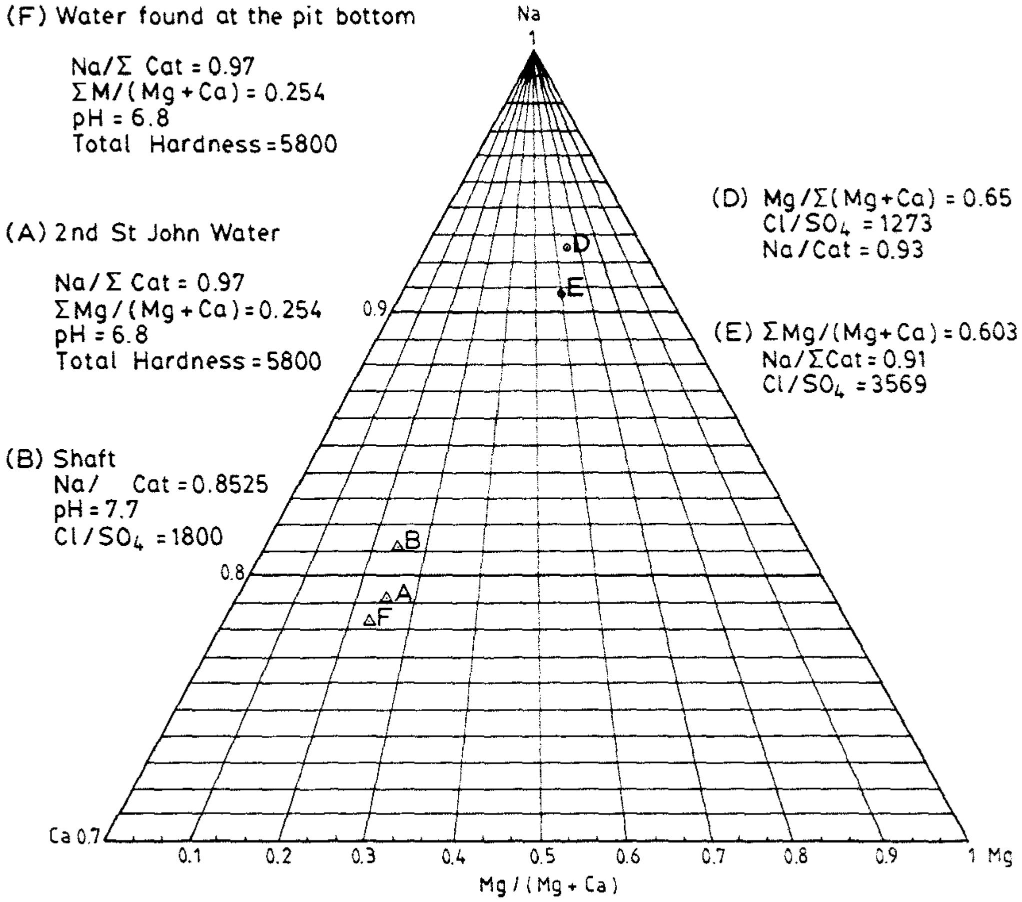

Fig. 4. Chemical analysis of water samples taken at points A–F (Fig. 3 and Table 3).

cluster together on the top right-hand side. This confirms that E and D are the water samples originating from the Top Hard seam and which form part of the same family of water.

It can also be concluded that sample F, representing the water which was the cause of concern, appears to be a sample of the Second St John water. Examination by the colliery staff revealed fractures in the water pipe at the Second St John's seam and that not all the water was being transferred down the shaft to the sump as intended. It was further observed that some water was finding its way down to the affected level through strata breaks. It may also be possible that the leakage water collected some sulphate on its way to the pit bottom.

Source of water entering mines beneath surface reservoirs

Coal mine workings below the surface reservoir in the Southern Coalfield of New South Wales, Australia have given cause for concern to the Dam Safety Committee regarding the integrity of the storage of water and loss of water to the underground coal mine workings [1]. The general stratigraphical sequence is shown in Fig. 5.

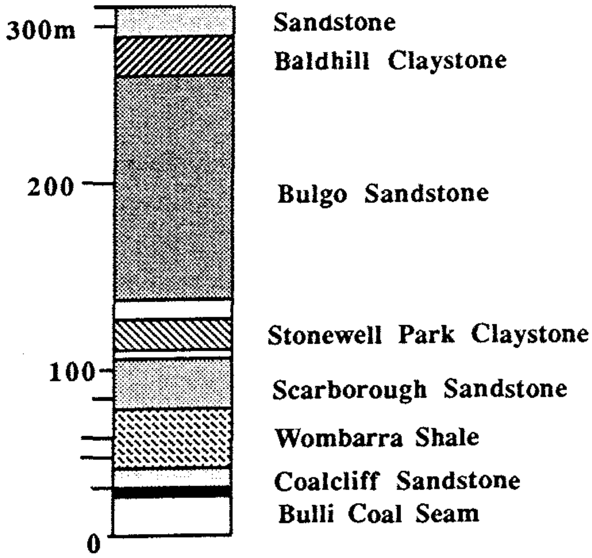

Fig. 5. Stratigraphic sequence of Bulli seam.

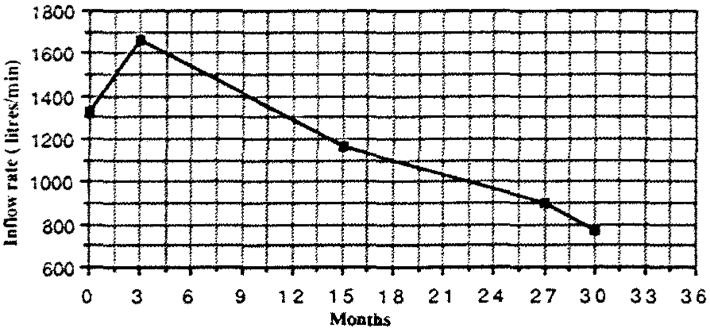

Fig. 6. Role of water seepage in Wongawilli seam workings in close proximity to the Avon Dam.

The coal seam concerned, the Bulli seam, is 10 m thick, and from this seam 3 m of coal are extracted from the bottom section by caving. The overlying strata are almost horizontal, but are intersected by many faults and dykes. The dominant overlying strata are sandstone with an undisturbed permeability of 10^{-10} m/s. Water seepage into the coal seam generally originates from the upper section of the Wongawilli seam. Full extraction of the coal seam causes only minor inflows to the workings, which continue over a short period before ceasing entirely. Geological discontinuities act as water barriers rather than as a flow path; faults and dykes were generally dry, but when wet they showed small seepages.

Figure 6 shows the mode of inflow into the coal seam. The maximum inflow was noticed

TABLE 4

Chemical analysis of water at Wongawilli Colliery and the Avon Reservoir

	Mine water	Reservoir water
pH	7.7	6.2
Cl	25, 0.7	19, 0.53
SO_4	< 2, 0.04	< 2, 0.04
Ca	24, 1.2	1, 0.05
Mg	11, 0.91	1, 0.08
Na + K	22, 0.96	6, 0.26
Alkalinity	135, –	5, –
TDS	190, –	33, –

Each component given in milligrammes per litre and milliequivalents, respectively. TDS—total dissolved solids.

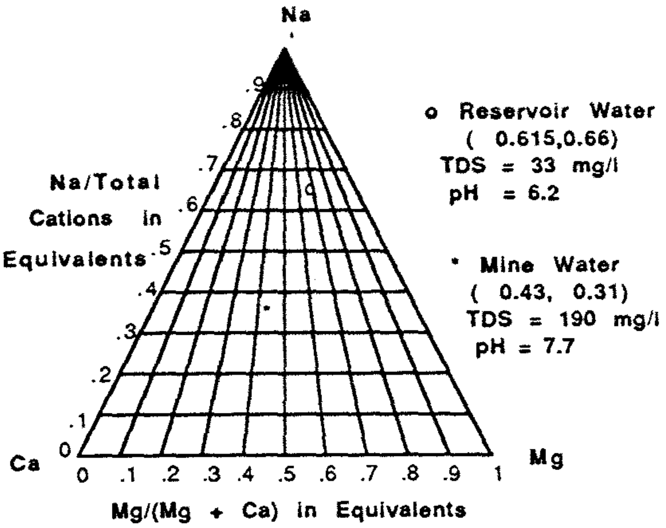

Fig. 7. The chemistry of the Avon Reservoir water and the Wongawilli Colliery water. TDS—total dissolved solids.

in the area where the coal seam has changed to cinder, which is highly permeable and porous. Table 4 shows the chemistry of the water sample at the colliery in 1982, and that of the Avon Reservoir.

The triangular diagram of the water analysis is shown in Fig. 7, indicating distinct water chemistries from two sources. Further chemical analysis of the water over a 5 year period has shown no significant change in the water chemistry. Thus, the dilution of groundwater due to inflow of the surface reservoir water has not taken place. The consistent chemical differences in the two waters suggest that the overlying rock mass is not acting as a flow path for the surface water.

Application of water analysis for the determination of the origin of water in undersea mine workings in Northeastern England

Introduction

Coal mining in Northeastern England, particularly in the South Durham undersea coalfield, presents special water problems of fairly large magnitude by British standards. For example, the amount of water pumped per tonne of coal raised in this area is 9.3 t as compared to the national average of 2.5 t. Past experience has shown that water problems in the area can be attributed to sea water, water from Permian aquifers, water from old mine workings and water from outcrops which is percolating into worked out coal seams.

One of the major concerns associated with working this coalfield safely is the need to ensure that the water from the first three sources does not enter the mine workings in catastrophic quantities. Experience has shown that there have been no incidents of seawater inrush into the mine workings. Most of the water problems accrue from the Permian water or from water from old workings. This section briefly shows how hydrochemical analysis can be used to evaluate water problems in the Northeastern England coalfield.

Geological environment

The areas of interest are the Coal Measures surrounding Blackhall, Horden, Dawdon and Westoe Collieries in the north of England. In this coalfield, the Coal Measures have a total thickness of 750 m. The coalfield can be divided into an exposed coalfield in the west and a concealed coalfield in the east (Fig. 8) [8]. A diagrammatic W–E crosssection is shown in Fig. 9. The Coal Measures in the east are overlain unconformably by Permian strata predominantly consisting of Magnesian Limestone. The Permian outcrops can be seen along the Coastline near Wearmouth in the north and at Hartlepool in the south (Fig. 10).

Stratigraphy

The sea near Blackhall Mine is about 50 m deep, gradually increasing, towards borehole No. 2 in the east (Fig. 9). The subsurface below the seabed comprises a variable thickness of Permian beds interbedded with anhydrites. The Permian strata are mainly

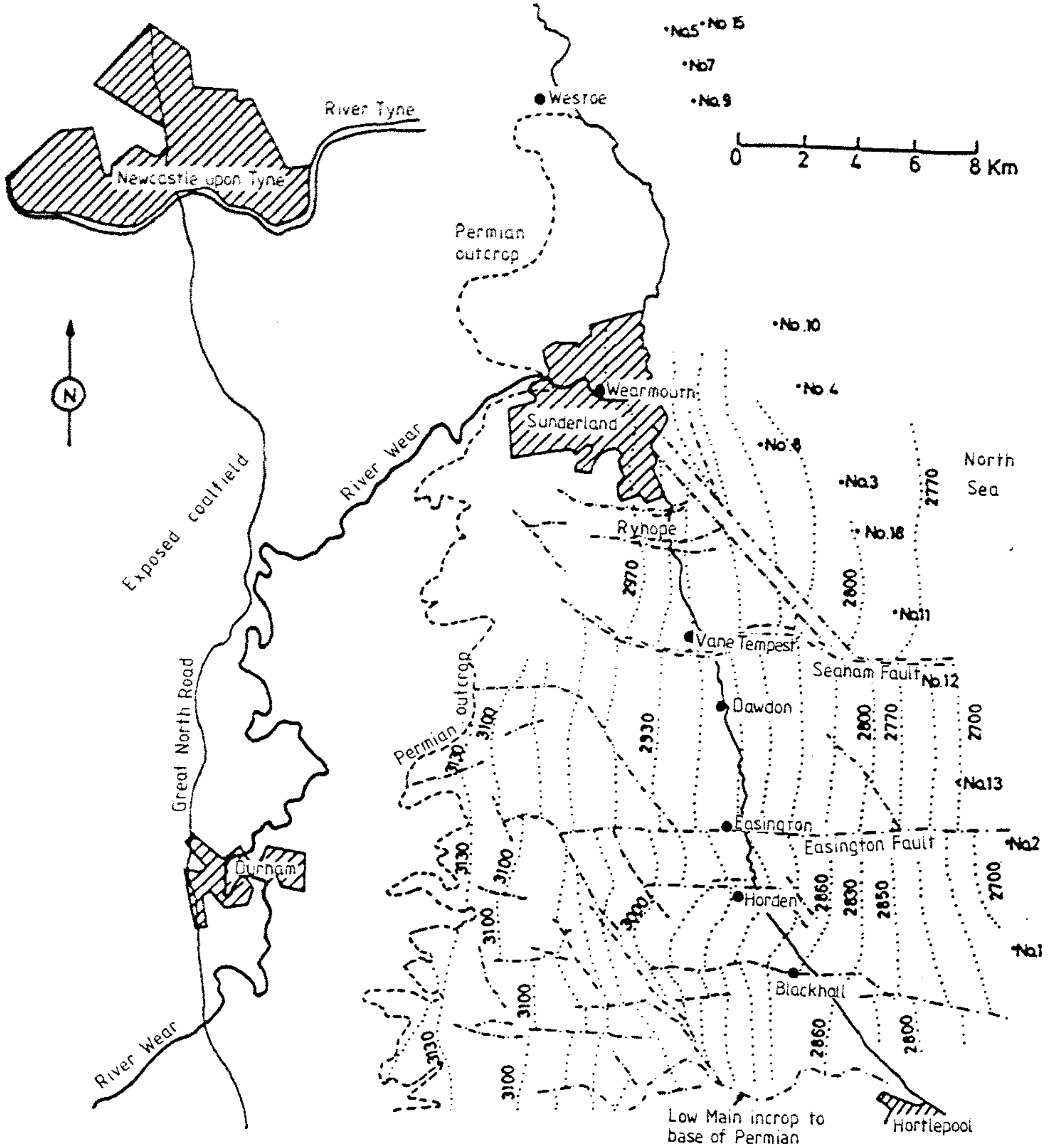

Fig 8. Geological map of Northeastern England.

Upper Magnesian Limestone, anhydrite and Lower Magnesian Limestone, all underlain by a variable thickness of yellow sand (unconsolidated sand, sandstone and breccia) which gradually decreases in thickness towards the east. This arenaceous layer lies unconformably over the Carboniferous and forms an important aquifer and source of water to the mine workings. The Coal Measures themselves comprise a variable thickness of interbedded mudstones, siltstone, seatearths and sandstones forming the Carboniferous cyclotherms [9].

Structures

The basin in which the Carboniferous has been deposited is irregular in shape with a general trend from northwest to southeast. The general dip of the Coal Measures is towards the east, ranging from 5° to 10°, with a pitching syncline as the main structural feature. Other major structural features are faults and dykes which may have a significant bearing on the water problem in the coalfields of the area. Two main fault systems strike NNE–WSW and NW–SE. A number of minor faults systems strike N–S and E–W.

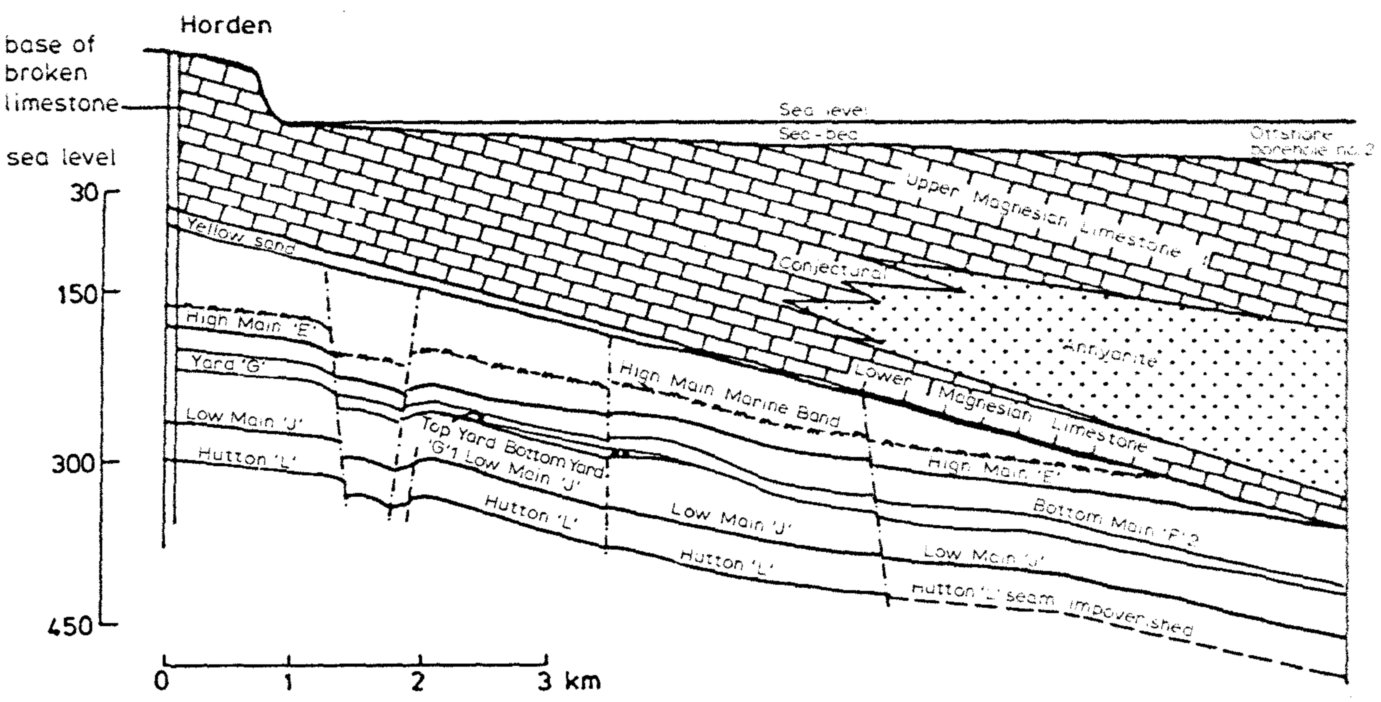

Fig. 9. Geological section from Horden Colliery to borehole No. 2 [8]. See Fig. 8 for orientation.

Two distinct dyke systems occur in the coalfields, one in the Coal Measures and other in the Tertiary. These dykes occur mainly in the coastal area and have been found in many of the coalfields in the Durham area. They contain many cavities interconnected by a system of well-developed fissures, and consequently they may form excellent aquifers if charged by water from the Permian strata.

Hydrogeology

The hydrogeology of the Northeastern England Coalfield is extremely complex, and the major hydrogeological features include aquifers, the interface between the Coal Measures and the Permian strata, aquicludes and aquitards, structural features acting as flow paths, and structural features acting as barriers to groundwater flow.

(1) Coal Measures aquifers: The Coal Measures consist of mudstone, siltstone, shale, coal and sandstone. Mudstone, siltstone and shale offer resistance to groundwater flow, whereas the sandstone beds facilitate this flow. Sandstone beds are highly capable of transmitting water through their interstices and

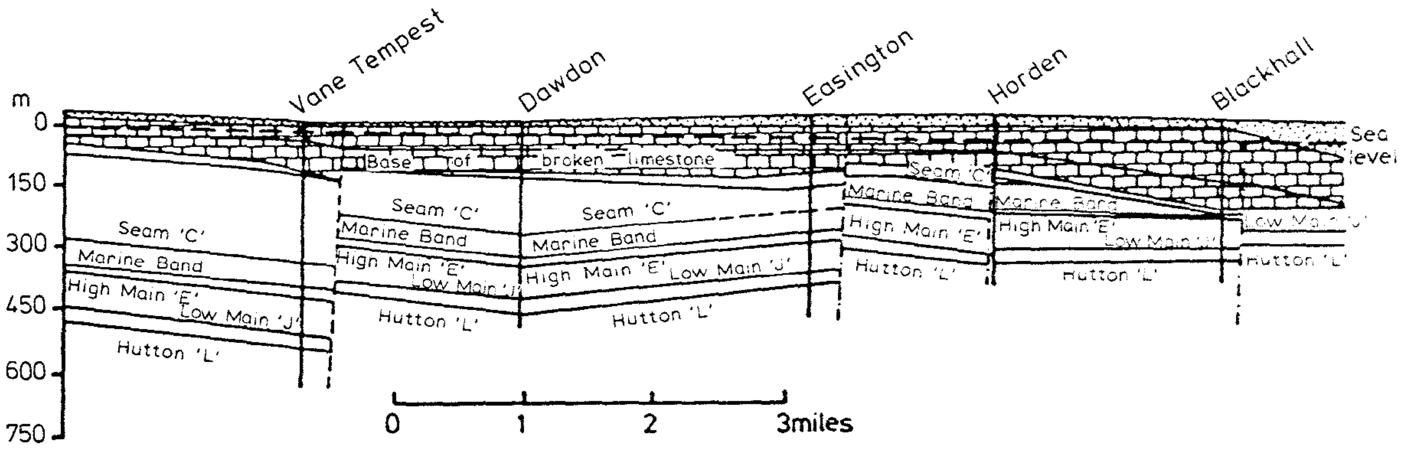

Fig. 10. Geological section along the Durham coast. See Fig. 8 for orientation.

can develop very high primary permeability and a very restricted specific yield. If they are recharged by a Permian aquifer from an unconformity, or from the sea, they may form very good secondary aquifers.

(2) Permian aquifers: Basal Permian sands display a very well established intergranular permeability but the variation in thickness and lithology affects the local flow regime. They generally form very good aquifer systems, providing excellent flow paths in both the vertical and lateral directions.

The Magnesian Limestone, when it outcrops at the seabed, may become completely saturated across its entire thickness, forming a major aquifer. It may also contain water under a very high hydraulic pressure head. Magnesian Limestone may also have a well-developed system of solution channels or cavities, providing very high secondary permeability. However, local variations in lithology can produce impermeable or semipermeable horizons, severely restricting the vertical and horizontal flows.

(3) Water at the Permo-Carboniferous interface: The amount of water at the Permo-Carboniferous interface above a coal seam in an undersea coalfield may be considered as equivalent to 1 m of rainfall per annum falling on the surface above an exposed onshore coalfield where the hydraulic pressure head is equal to that due to the depth from sea level. It is also important to note that many test boreholes to the basal sand have not encountered any heavy feeder of water [8]. Thus, it may be concluded that the Permo-Carboniferous interface may not necessarily be considered as the location of vast quantities of water.

(4) Aquicludes and aquitards: The Carboniferous mudstone and siltstone make very good aquicludes and aquitards capable of restricting the groundwater flow both in the vertical and horizontal directions, and Anhydrite beds in the Triassic also form good aquitards. Thus, the Carboniferous strata, under favourable conditions, have hydrogeologically healing characteristic: A sufficient thickness of carboniferous strata acting as a barrier between the source of water and the mine workings may be used as the main method of controlling the inflow of mine water.

(5) Structures acting as flow paths: Two fault systems occur in the Carboniferous and Permian strata. The minor fault system does not present any appreciable water problems in the undersea workings in Northeastern England. However, major faults can create a water problem by acting as conduits, and by bringing Permian strata close to permeable sandstone beds which may easily be recharged with water over geological time. Thus, secondary Coal Measures aquifer systems are formed in close proximity to the mining horizons.

Certain dykes having natural interstices or joint systems may also form very good aquifers.

(5) Structures acting as aquicludes: Faults and dykes may also act as barriers to groundwater inflow.

Site description and water problems

Site description

Blackhall Colliery is the southernmost colliery in the coastal region of the Durham Coalfield. The sinking of the shaft at Blackhall took place between 1909 and 1913, when a peak rate of inflow into the shaft of 70,000 l/min was recorded. Workings at Blackhall Colliery have been carried out extensively in the Low Main (J) seam and the farthest face has been worked 8 km from the shaft bottom. In the other seams, only a very limited amount of coal extraction has been carried out, the exception being the Lower Hutton seam (L), in which mining operations were mainly concentrated in the vicinity of the shaft bottom.

A major fault divides the take of the colliery into two distinct areas (Fig. 10). In the southern part, the Coal Measures occur in

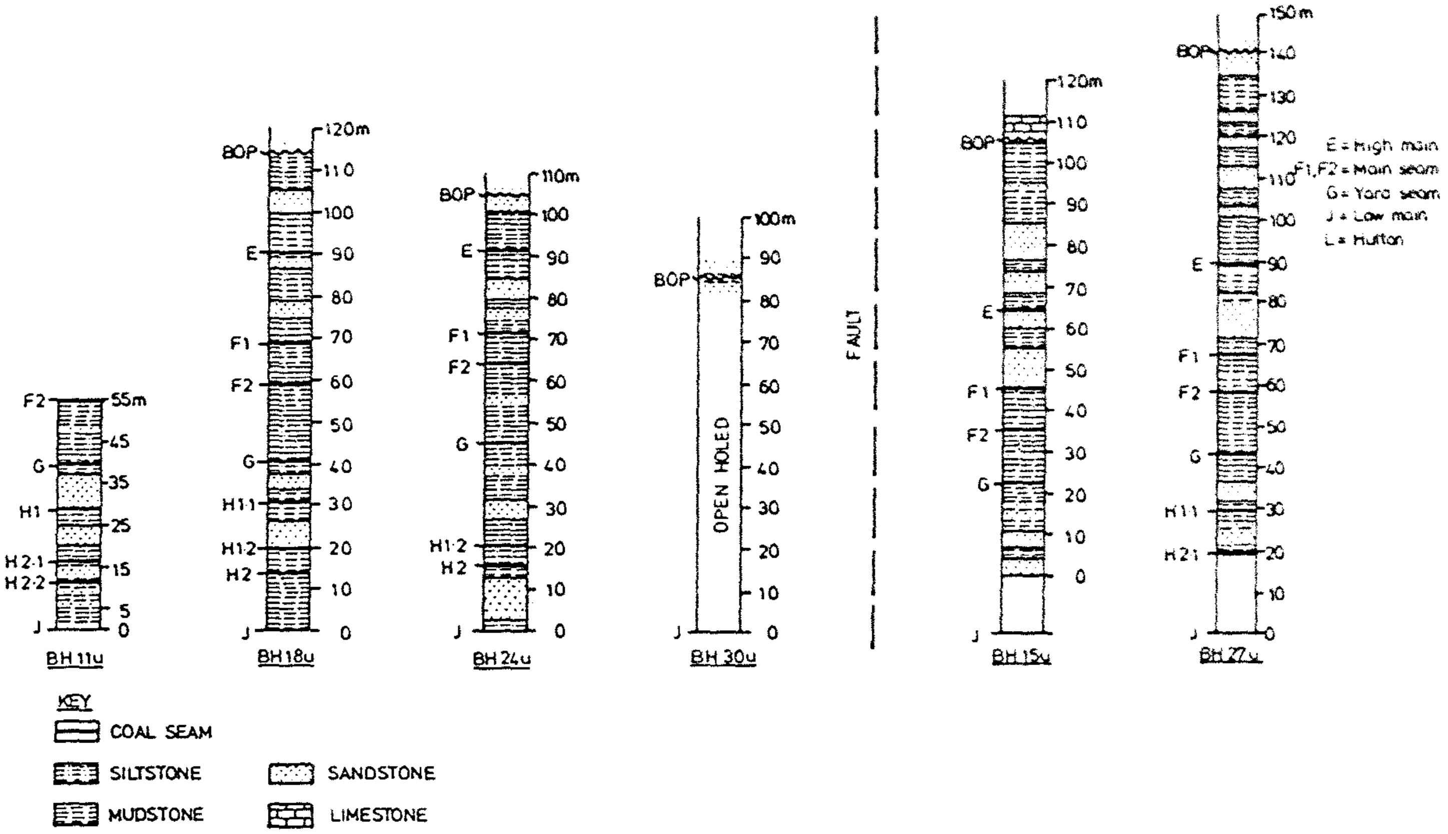

Fig. 11. Geological section through the Coal Measures on the north and south side of the Blackhall fault [10,11]. Boreholes to left of fault, see Fig. 12, to right of fault, see Fig. 13.

successively higher blocks so that there is a gradual reduction in the thickness of the Carboniferous cover above the Low Main coal seam. It may be seen in Fig. 10 that the High Main seam has been thrown out by the fault towards the southern end of the colliery boundary. The Low Main seam, which lies 80 m below the High Main seam, also approaches very close to the base of the Permian and causes an excessive make of water. Figure 11 shows various geological sections through the strata. In the southern area, the amount of cover between the Low Main seam (J) and the base of the Permian thins to the east and southeast. It may be seen that in borehole 18u, the required parting is 115 m, thinning down to 85 m in borehole 30u. In the area north of the major fault, the thickness of parting between the Low Main (J) coal seam and the base of the Permian increases abruptly towards the east: 105 m in borehole 15u, increasing to 140 m in borehole 27u. It has been suggested that the major fault shown in Fig. 12 is a hinge type, with its pivot situated at the left of face J13 and throw gradually increasing to 37 m eastwards across the workings [10]. Figure 13 illustrates the plan of the Low Main (J) coal seam workings in the northern sector of the mine.

Water problems and discussion of results

A distinction can be made between the mechanism of groundwater inflow in the southern and northern sectors of the Blackhall Colliery. In the southern sector of the mine, at the downthrow side of the major fault, about 51% of the faces have suffered water influx while 49% of the faces have remained dry. Five main points regarding the mechanism of flow have been considered: (1) The direction of face advance, (2) strain caused by longwall extraction at the base of

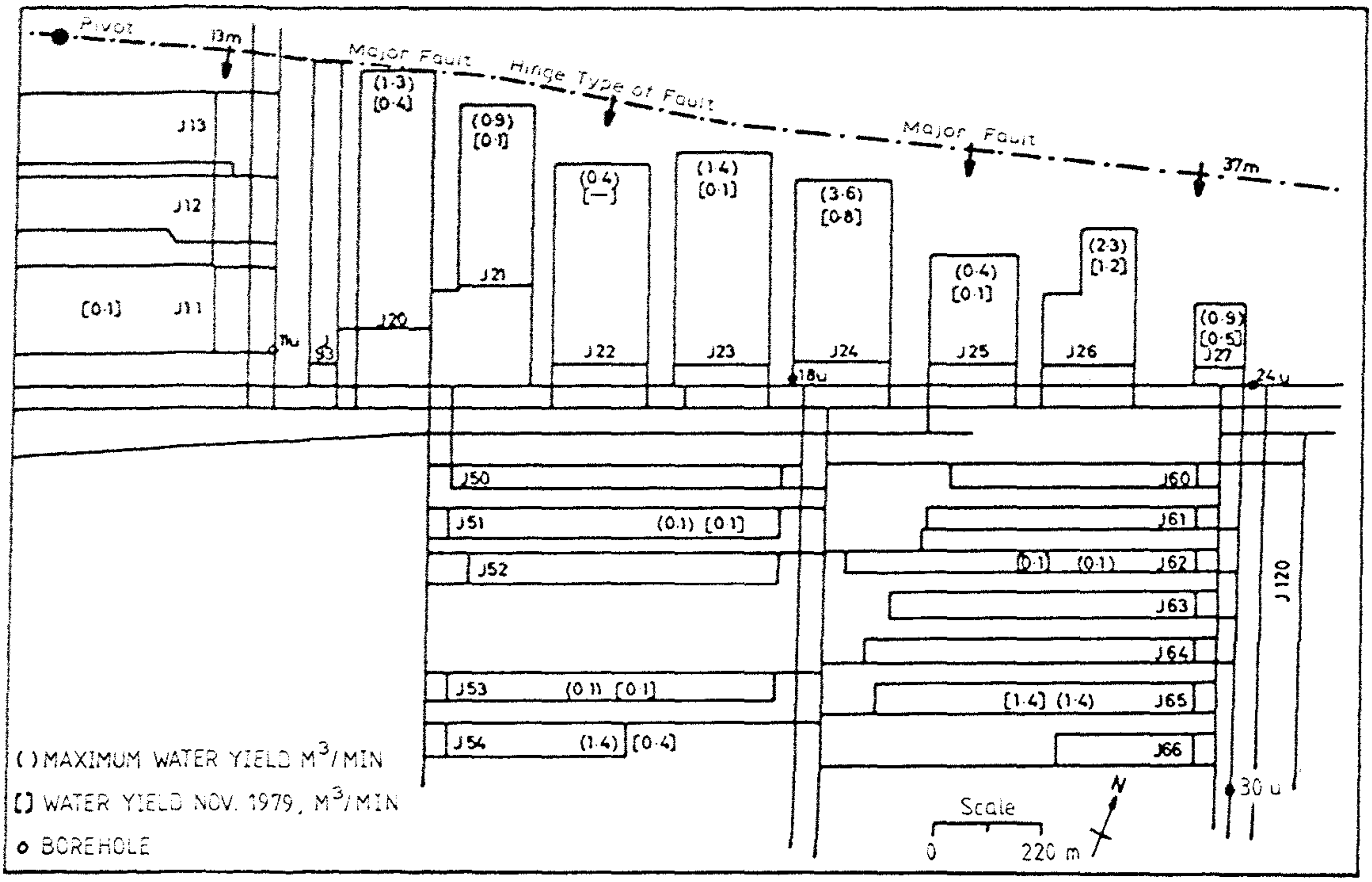

Fig. 12. Plan of workings in the Low Main seam (J), southern area of the Blackhall Colliery [10,11].

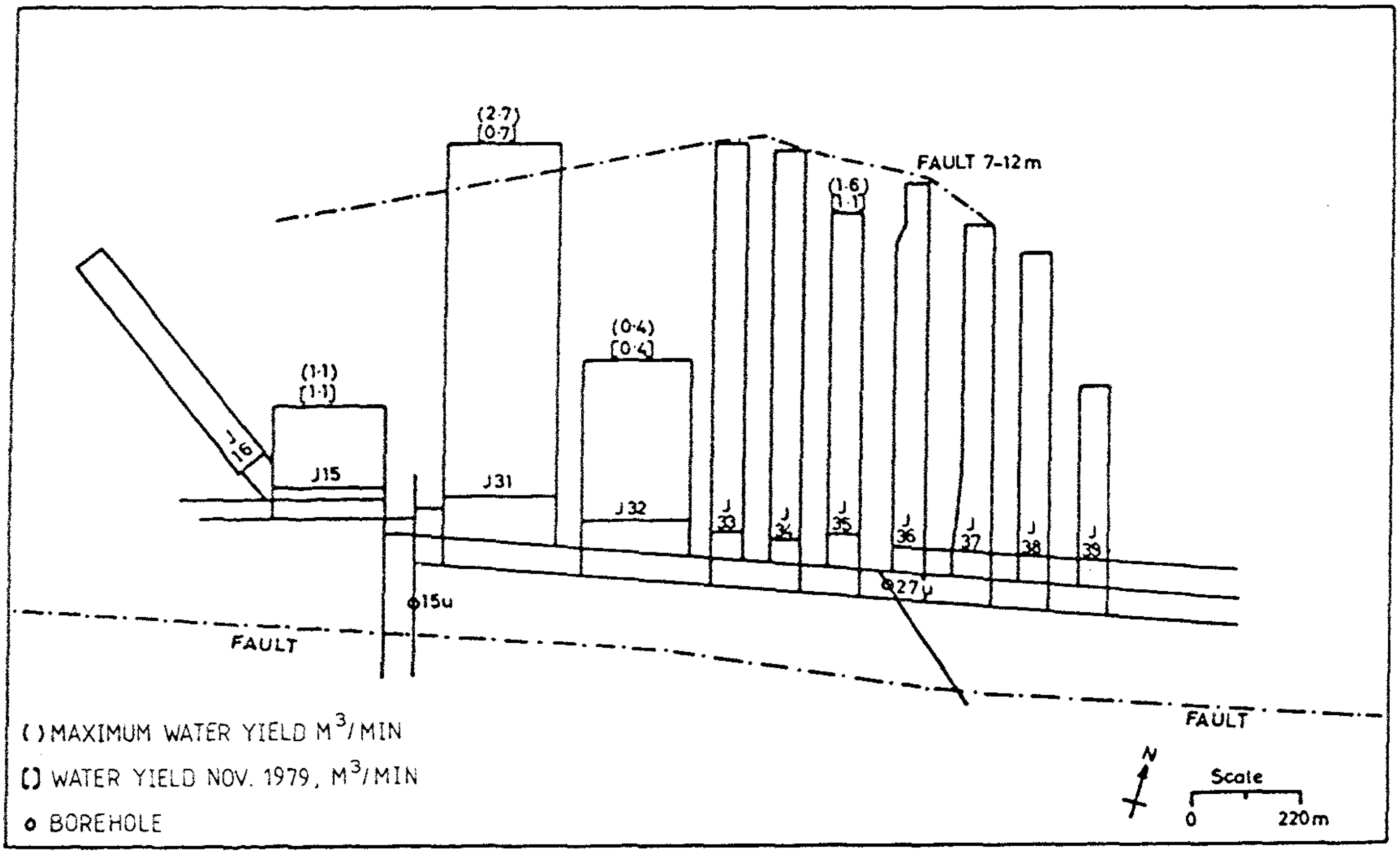

Fig. 13. Plan of workings in the Low Main seam (J), northern area of the Blackhall Colliery [10,11].

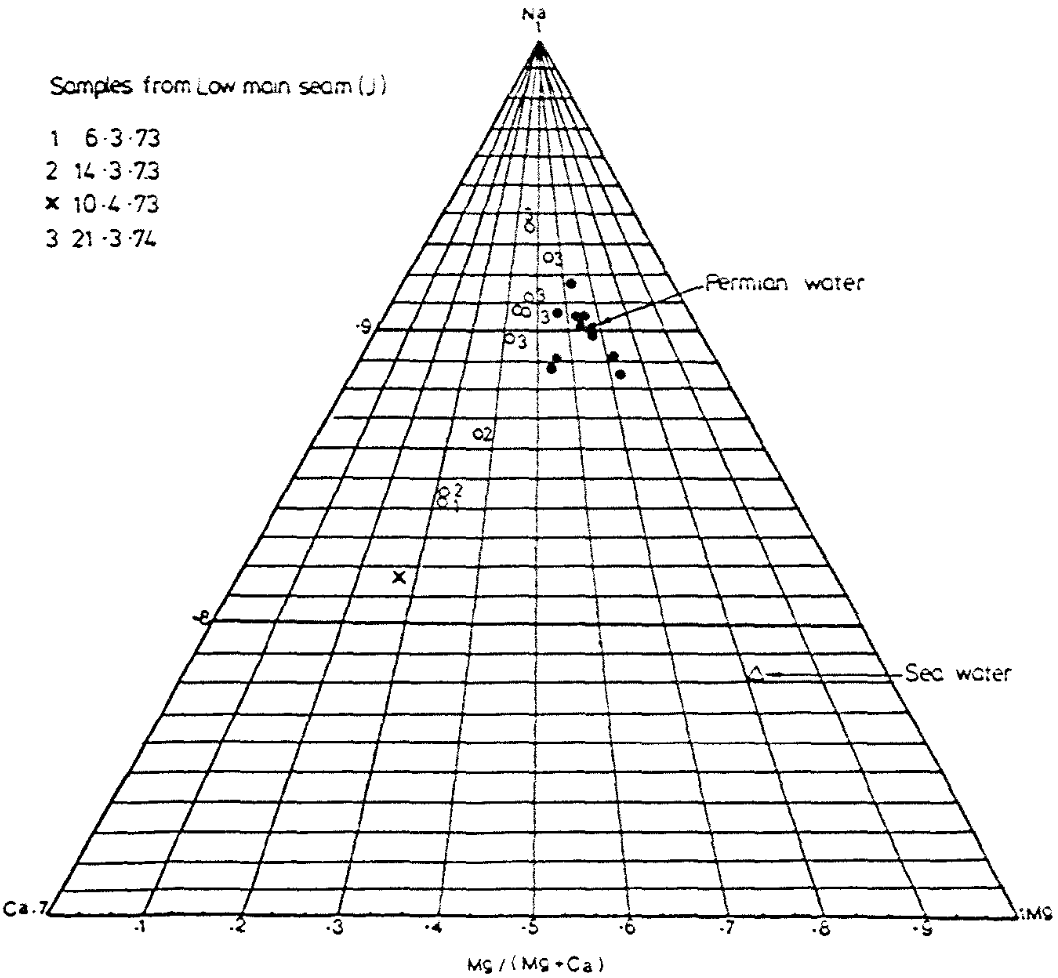

Fig. 14. Water samples taken at the maingate and tailgate at different locations and dates at J31 face, Blackhall Colliery.

the Permian, (3) the mode of inflow, (4) the width of extraction, and (5) primary, or secondary permeability.

The southern sector. *(1) Direction of face advance:* In the southern sector of the mine it has been noted that the coal faces advancing towards the major fault are 100% wet, with the exception of J93 face which is very narrow and therefore dry. The largest recorded inflow rate was 3600 l/min at J 24 face, followed by J26 face which had a maximum inflow rate of 2300 l/min. It may also be noted that when the orientation of faces was changed in such a way that the face advance was parallel to the main fault, the incidence of wet faces decreased to 40%.

(2) Mode of inflow: The mode of inflow experienced in the southern sector was similar to the situation where there is a sudden increase in inflow and an exponential decrease with time. For example, the peak inflow rate at J24 face was 3600 l/min with a base inflow rate of 800 l/min. The reduction in face width at J27 reduced the base rate of water inflow to 500 l/min. It was observed that the narrow face at J93 did not suffer any water influx.

(3) Predicted tensile strains: Predicted tensile strains were calculated in the manner suggested by Orchard [12]. The strains on the faces working at right angles to the direction of the major fault were 6–8 mm/m at the base of the Permian and 2 mm/m at the seabed. Similarly, the tensile strains of the reoriented faces parallel to the major faults ranged from 4 to 6 mm/m at the base of the Permian and were 1 mm/m at the seabed. Thus, the amount of water influx to the faces

in the southern sector can be correlated to the amount of strain at the base of the Permian and to the progressive thinning of the cover to this base.

(4) Width of workings: The width of longwall faces has a direct bearing on the amount of strain developed at the base of the Permian and at the seabed. It follows that for the same seam depth and thickness of extraction, the narrower face hs a lower strain than the wider faces, and consequently, a smaller inflow of water.

(5) Primary or secondary permeability: It has been suggested by Aston and Whittaker [10] that the overlying Coal Measures above the Low Main seam at Blackhall Colliery may contain discontinuity systems associated with structural and sedimentological features. Further, secondary aquifer systems in the sandstone units are probably formed by direct vertical recharge from the Permian.

It may seen in Fig. 12 that the average width of faces in the southern sector is between 120 and 140 m. In J26 face, the face length was reduced from 135 to 78 m and there was a reduction in the water inflow rate of 2300 l/min to 1200 l/min. A new face started near J26 had a width of 65 m, and the maximum rate of inflow recorded here was 900 l/min with a base flow rate of 500 l/min.

The northern sector. In the northern sector of the Blackhall colliery (Fig. 13), only four out of eleven faces encountered water. The rate of inflow at J31 face was initially 700 l/min gradually increasing to 2700 l/min as the face advanced towards the fault. Similarly, the rate of inflow to J35 face was 1100 l/min increasing to a flow rate of 1600 l/min as the face advanced towards the fault. In the other two wet faces, J15 and J32, the rate of

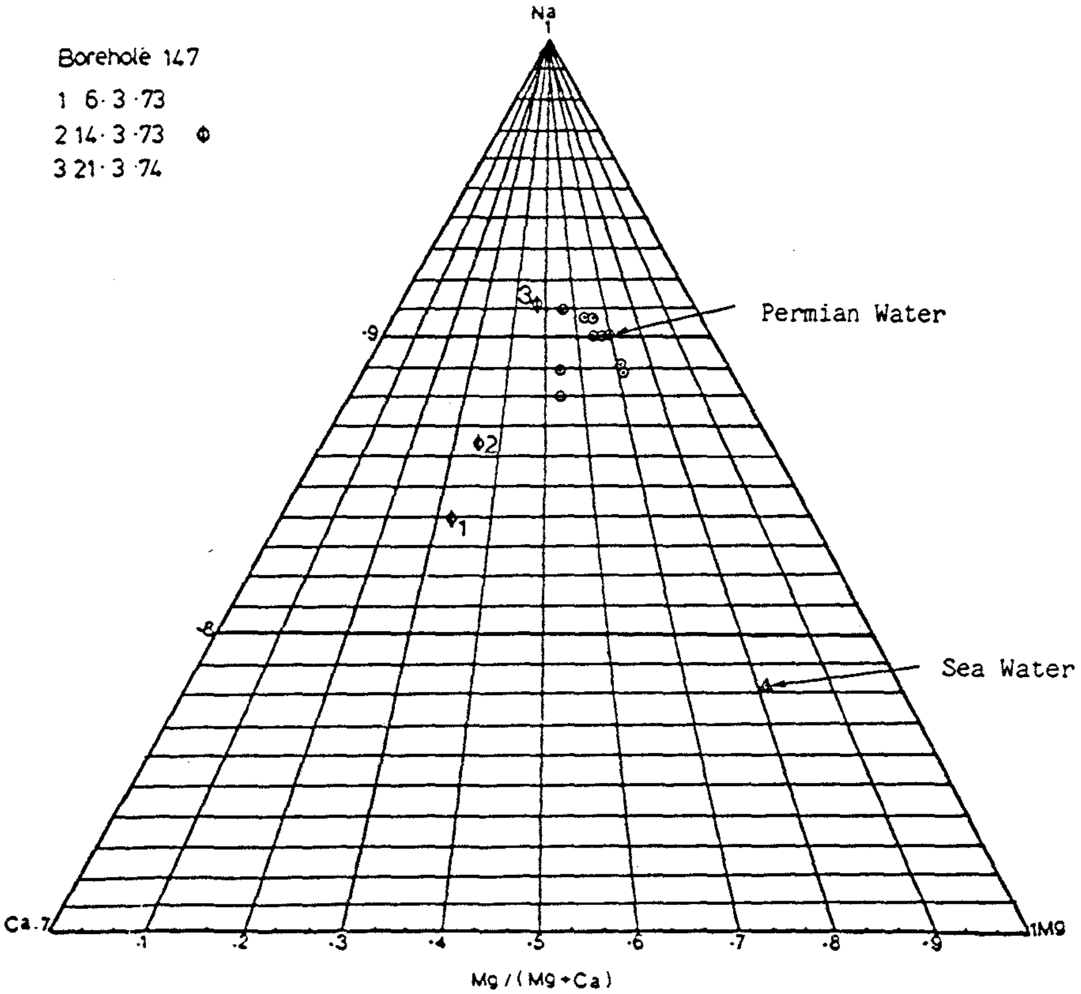

Fig. 15. Water seepage from the Permian at J31 face. Samples taken from borehole No. 147 as the face advanced towards the fault, Blackhall Colliery.

inflow remained constant at 100 and 400 l/min respectively.

(1) Direction of face advance: In this sector all but one face advanced at right angles to the major fault.

(2) Mode of inflow: The mode of inflow in the northern area has been observed as a seepage through the fault barrier.

(3) Tensile strain: It may be shown that three faces, J15, J31 and J32, developed ground strains at the base of the Permian of between 6 and 7 mm/m and ground strains of less than 2 mm/m at the seabed. The ground strains developed by the J35 face at the base of the Permian were 3 mm/m and those at the seabed were 2 mm/m. Ground strains calculated for the two adjoining faces can reach 7–9 mm/m at the base of the Permian and 2 mm/m at the seabed.

(4) Width of workings: Out of eleven faces, three were 155–165 m wide and the remainder were 45–50 m wide. Thus, it is believed that the narrower faces will develop low ground strains and will offer less inflow potential from secondary fissures which develop due to this ground strain.

(5) Primary or secondary permeability: In the northern area, the water problem on J31 and J35 can be related to the effect of the directions of longitudinal strain terminating against the major fault. No major fault occurs in the vicinity of these faces and the rate of water inflow is constant. Thus, the water inflow problem can be associated with the flow

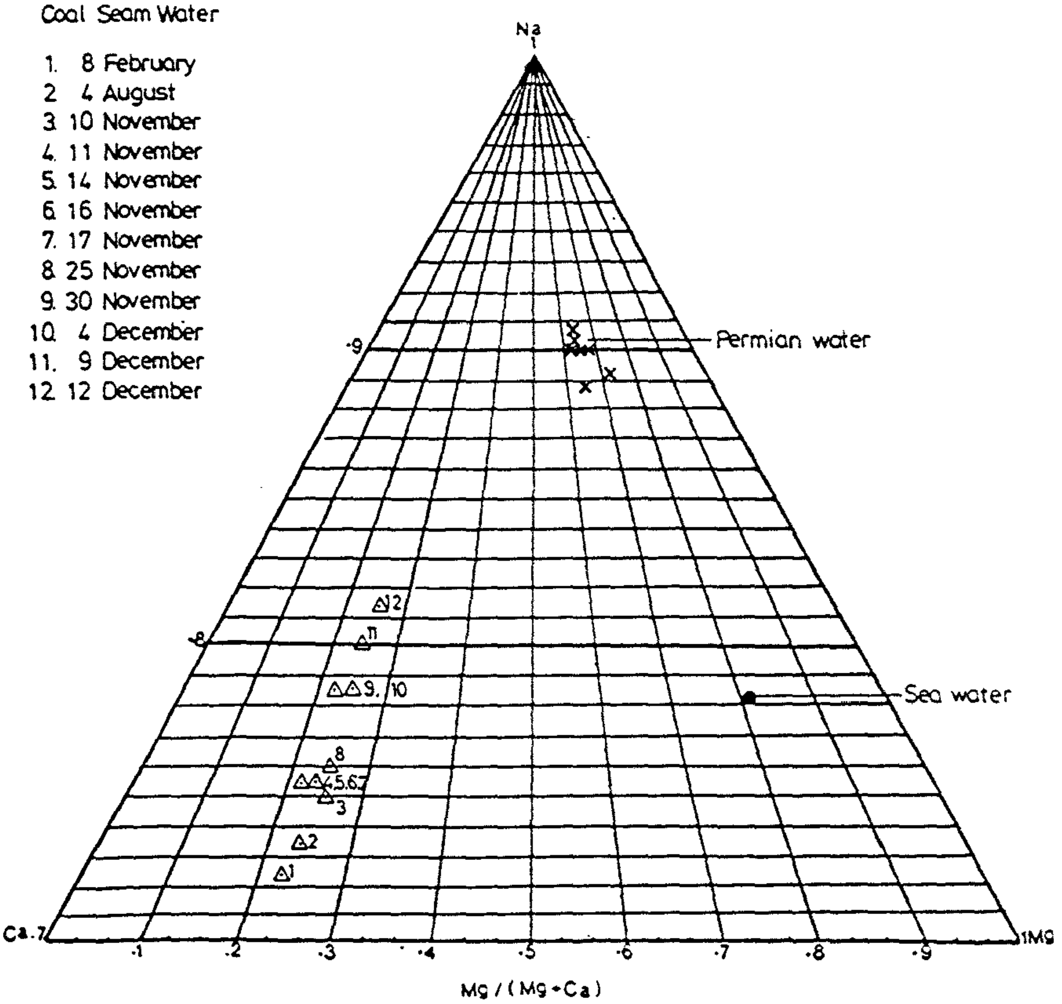

Fig. 16. Chemical analysis of water showing progressive influx of Permian water as J35 face advanced towards the fault, Blackhall Colliery.

regime related to mining induced ground strains.

Chemical analysis results. Figure 14 shows the chemical analysis of water samples collected in the area around J31 face at various sampling points and on different dates. Also marked on this graph are the results of chemical analyses of Permian water from an underground borehole intersecting the Permian aquifer. The results for seawater are also shown on the graph. Three different families of water showing different sources can be clearly seen in Fig. 14. Figure 15 shows water seepage in the area of J31 as recorded in borehole No. 147 at different dates as the face progresses towards the main fault. It may be seen that the chemistry of the water is gradually changing to that of Permian water as the Low Main seam water becomes progressively diluted by the Permian water, this indicates a free flow of water from the fault plane. Similarly, Fig. 16 shows the water analysis in the area of J35 where the water chemistry again gradually changes to that of Permian water as the face approaches the boundary fault.

Conclusion

Chemical analysis of water has indicated that there are characteristic groundwater zones in the Coal Measures: normal shallow water, deep confined aquifer water and water from old workings. The water in shallow unconfined aquifers is characterized by a high sulphate content (50–300 mg/l), low chloride content (< 100 mg/l) and significant hardness (Ca = 100–500 mg/l). The water from confined aquifers has high ionic contents of, sodium, calcium and magnesium. Deep confined aquifers contain manganese, barium and strontium, and the levels of these progressively increase with depth. The water from old workings is characteristic in having originated from a source modified by the presence of the oxidation products of pyrites. This water contains iron sulphate and traces of H_2S. The pH is 5.3–6.8.

Routine chemical analysis of groundwater can give an indication of the onset of inundation from a major aquifer or old workings. A case example of such an analysis has been shown in order to indicate the importance of this technique in determining the origin of mine water.

The main purpose of this paper was to present an appreciation of the geohydrochemical analysis technique for the determination of the origin of mine water. Indeed, this technique is particularly suitable for mines situated in areas of complex hydrology and hydrogeology which may have several sources of water posing a danger of inundation to mine workings.

The presentation of groundwater data on triangular diagrams has been used to determine the origin of mine water in the North Derbyshire Coalfield. It is possible to distinguish between water emanating from an aquifer and water emanating from old workings. A distinction can also be made between the waters entering a mine from two different aquifers.

The chemical analysis technique has also been applied to determine the origin of mine water in the undersea coalfield off Northeastern England where multiple sources of surface and underground water render the understanding of the mechanism of water inflow to the mines particularly difficult.

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