Some problems associated with past mining at a mine in the Witbank coalfield, South Africa

S. E. T Bullock · F. G. Bell

Abstract Mining in the Witbank Coalfield commenced at the turn of the century. Initially there was little environmental degradation associated with mining activities; however, in the late 1930s and early 1940s a pillar-robbing programme commenced. At one particular mine this has had marked effects on the environment. Primary effects include subsidence, the appearance of tension cracks at the surface and crownhole development. Secondary effects include spontaneous combustion of the coal worked, as air has been provided with ready access to the mine, accelerated subsidence due to the strength of many pillars being reduced by burning, and a marked deterioration in groundwater quality in the area. Spoil heaps also form blemishes on the landscape. These contain significant amounts of coal and have undergone spontaneous combustion. The deterioration in the water quality has led to the decimation of vegetation in some areas and the eradication of aquatic flora and fauna in a nearby stream.

Key words Pillar failure · Void migration · Burning coal seams · Spoil heaps · Acid mine drainage

Introduction

Coal mining unfortunately tends to make a notable effect on the environment, the impacts vary in severity depending on the age of the mine, mining techniques and the geological and geographical setting. This paper highlights the environmental degradation at one, now disused coal mine, in the Witbank coalfield, South Africa (Fig. 1). Mining operations at the mine concerned began in 1908, the coal being worked by the bord and pillar method. In the late 1930s and early 1940s pillars were robbed over an extensive area of the mine. This resulted in the formation of crownholes at the surface due to void migration as the collapse of bord areas occurred, and in discontinuous subsidence caused by multiple pillar failure. The subsidence resulted in extensive surface fracturing above the workings. In 1947 when the mine was being decommissioned, spontaneous combustion within the workings was noticed for the first time. Despite efforts to extinguish the fire, it is still burning, emitting noxious NO_x and SO_x into the atmosphere. The subsidence has had an impact on the groundwater. For example, recharge into the old workings from rainwater has been enhanced by extensive fracturing of the ground surface and the appearance of crownholes so that now more than 50% of the rain which falls infiltrates the ground over most of the mined area. To the east of the mine property, the groundwater issues from the mine in a number of small springs. This water, which is highly polluted, makes its way into a local stream. The polluted groundwater has a high total dissolved solids (TDS) concentration and a low pH value. As a consequence, plant life over an area of 3 ha where the seepage occurs has been decimated.

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Geology of the Witbank coalfield

The major coal bearing strata in South Africa are associated with the Karoo Basin and primarily occur on the southern and eastern flanks of the Kaapvaal Craton. The

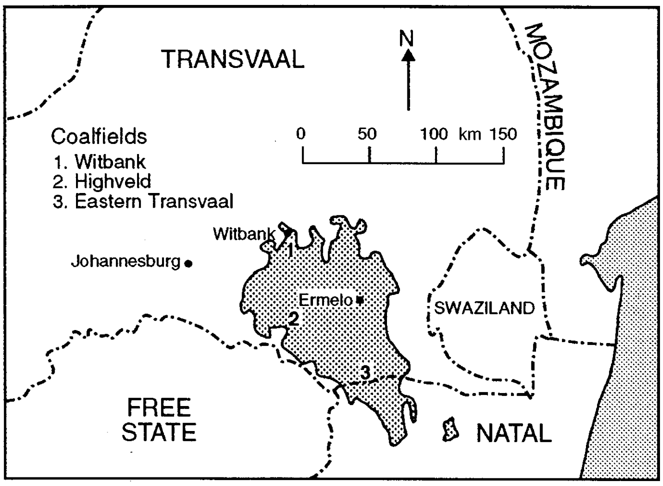

Fig. 1
Location of Witbank coalfield

strata range in age from Permian to mid-Triassic and occupy a wide range of structural and sedimentary settings. Unlike the Coal Measures of the northern hemisphere, which accumulated in low-lying swamps in hot humid climates, the Permian swamps of the southern hemisphere existed under cold to cool temperate climatic conditions associated with the waning of a massive ice age. The coal-bearing strata were deposited in relatively stable continental depressions. Two types of environment have been recognized in which the coal-bearing strata were formed, namely, the paraglacial environments and the epicontinental environments. The former developed in late Dwyka-Lower Ecca times around the north-west and northern side of the Karoo Basin, and are associated with the deposition of glaciolacustrine and fluvioglacial sediments on the moraine-covered surface of the Kaapvaal Craton.

The epicontinental environments subsequently formed across the north-eastern stable shelf area of the Karoo Basin. The associated strata continue southwards to the edge of the shelf area where they overlie and interdigitate with deeper water argillaceous sediments of the southern basin. This retrogressive wedge of deltaic sediments was deposited during Middle Ecca times and is characterized by several episodes of transgression and regression, the latter frequently closing with a coal seam. The cyclic sedimentation probably represents deposits which accumulated in alluvial plains, upper and lower deltas and associated shallow lagoon and coastal swamps.

The coal seams in the Witbank coalfield were formed in this epicontinental environment and occur within the Vryheid Formation. The Vryheid Formation forms the mid-part of the Ecca Group which, in turn, is part of the Karoo Supergroup. This formation consists of sediments deposited in shallow marine and fluvio-deltaic environments in which coal developed from peat which accumulated in swamps and marshes. The formation primarily consists of sandstones, siltstones, mudstones and shales. As the northern margin of the coalfield is approached, the sediments thin and the Vryheid Formation rest unconformably on the basement rocks, that is, the Transvaal Supergroup, the Waterberg Group and volcanic rocks associated with the Bushveld Igneous Complex. Minor dolerite dykes and sills are common. These have burned and devolatized the coal seams in certain areas. The five recognized coal seams in the Witbank area are numbered consecutively nos 1–5, the latter being the youngest. These seams occur within a succession some 70 m in thickness. At the mine, seam 1 is poorly developed. Seam 2, which was the only seam mined during the life of the mine, is found at a depth of approximately 18–23 m and ranges in thickness from 3.5 to 6 m (Fig. 2). A SSW-NNE trending anticlinal axis is present in the area. As a result, the coal seam dips to the west and to the east, on either side of the axis. The dip of this coal seam rarely exceeds 5°. In the east of the mine property, seam 2 crops out approximately 100 m west of a local stream. The Seams 3–5 have been removed in this area by post-Karoo erosion.

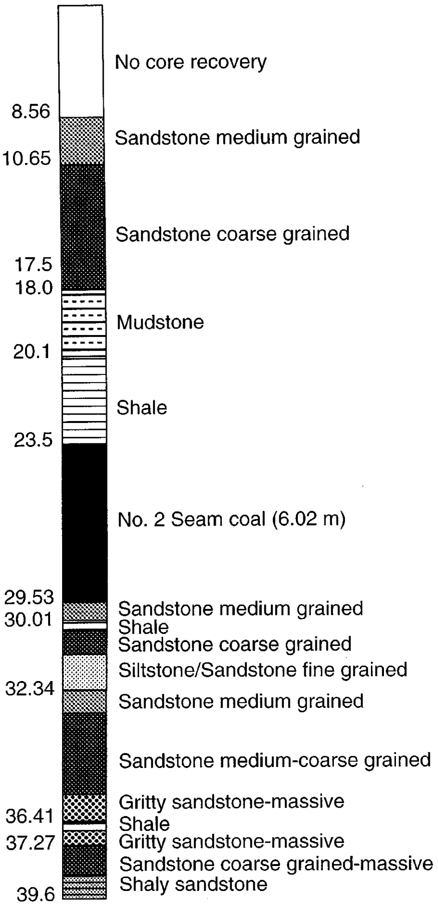

Fig. 2
Borehole log showing the sequence of strata in relation to No 2 coal seam

The unweathered strata overlying seam 2 consists of shale, fine-grained sandstone, interbedded sandstone and siltstone, and mudstone, and has an average thickness of 10–15 m (Fig. 2). The weathered zone varies in thickness, ranging between 5 and 10 m, and consists of weathered sandstones and shales with an abundance of ferricrete.

Mining history

Seam 2 was exploited using four different mining methods. These were bord and pillar, pillar robbing, stooping and opencast mining. Figure 3 shows the geographical distribution of the different mining methods within the mine property.

Bord and pillar mining started in 1908. The average pillar size left behind was 6 × 6 m and the average bord width was 7 m, so the extraction ratio was approximately 60%. The average mining depth was in the region of 18–20 m, with a mining height of 2.5 m. From 1908 to 1947, when operations at the mine ceased, a total area of some 1700 ha was undermined using the bord and pillar mining method.

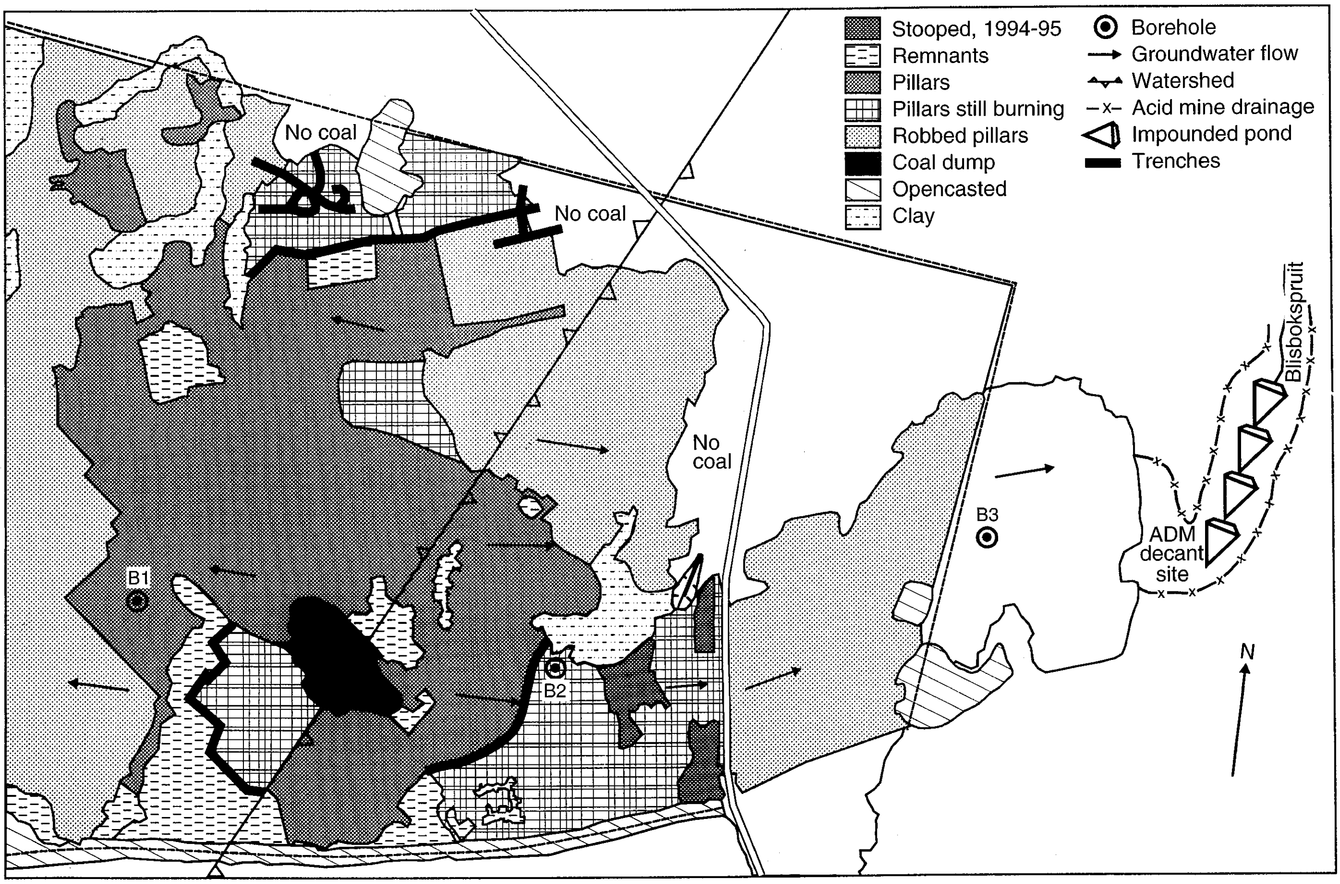

Fig. 3
Mining methods used at the mine site. Also shown are areas where underground fires still burn, the local watershed and the position of the polluted stream. Note that one of the spoil heaps is just off the map to immediate west

Pillar robbing started in the late 1930 and continued until 1946. The original 6 × 6-m pillars were quartered, leaving four smaller pillars at each corner. The remnant pillars comprised approximately 25% of the original pillar. This meant that the extraction ratio increased from 60% to about 90%. Any smaller pillars (4 × 4 m) were robbed on two sides, leaving approximately 33% of the original pillar intact. Pillar robbing occurred over an area of approximately 215 ha.

Stooping is a technique which entails removing 85% of the original pillar. On backward retreat, the hanging-wall caves into the goaf. Stooping was used in 1982 and 1983 over an area of 6 ha in order to ensure the long-term stability of a local municipal road, which was to be constructed, against subsidence damage and to protect it from the underground-burning coal.

Opencast mining of the boundary pillar of the mine began in 1991 and ceased in 1992. This operation was undertaken to prevent the spread of the underground fire into adjacent mines. In addition, a number of small coal remnants were mined by the opencast method, notably a sub-outcrop boundary pillar in the east of the mine property.

Environmental impacts

Impacts due to subsidence

In the pillar and bord method of mining, pillars of coal are left in place to support the roof. The pillars therefore have to sustain the redistributed load attributable to the overburden, which means that the strata immediately above and below the workings are subjected to added compression (Bell 1988). Stress concentrations tend to be located at the edges of pillars and intervening roof beds tend to sag. Surface subsidence may be an expression of either multiple pillar failure or bord collapse with accompanying void migration.

Slow deterioration and failure of pillars may take place after mining operations have ceased. This is particularly the case if pillars are robbed on retreat, that is, as the mine is coming to the end of its working life. Obviously, the stress on a pillar increases as the extraction ratio increases. The potential for failure also increases under strong roof rocks.

The roof rock in the bords may collapse with time. This leads to void migration, but the rocks which collapse bulk, so that void migration ultimately comes to an end. However, if seams are at shallow depth (e.g. less than about ten times the height of the workings), then void migration can give rise to the appearance of crownholes at the surface.

There is little evidence to suggest that the original mining method caused subsidence in the area. This is understandable, since mines with extraction ratios of up to 70% are often relatively stable and, as remarked, the extraction ratio was around 60%. Subsidence originated in the late 1930s when pillar robbing was practiced, the extraction ratio being increased substantially. Pillar robbing increased the load which the pillars had to carry by as much as one-third. Robbing also changed the shape of pillars by reducing their width significantly while the pillar height remained constant. This resulted in a reduction in pillar strength to the extent that many pillars could no longer support the overburden stress, failure occurring when the ratio of pillar strength to vertical stress became less than one.

The failure of a single pillar increases the stress on surrounding pillars, causing them to fail in domino fashion. The surface subsidences caused by multiple pillar failure are generally several hundred square metres in extent and the collapsed areas often are bounded by near vertical sides (Fig. 4a). Surface tension cracks around the outer edges of the collapsed areas are typically 200–800 mm in width and can extend in length for up to 100 m (Fig. 4b).

The roof strata at the mine are generally weak and incompetent shales, and are in tension between the pillars. Obviously, the length of the span between pillars and the strength of the rock beam are all important in terms of roof collapse. High compressive stresses acting in the vicinity of the pillars can cause failure of roof strata. Stresses tend to develop at an angle to the maximum compressive stress. In the incompetent roof strata this tends to be at a high angle (75°). These stress fractures combined with interpillar tensional areas have caused collapse, resulting in upward void migration through overlying strata, until the weathered zone is reached. Generally, the weathered material has subsided by 2 to 3 m, but in some cases the weathered material has collapsed totally into the old workings, leaving voids 15–20 m deep. The resultant crownholes at the surface have diameters between 5 and 10 m and are often regularly spaced (Fig. 5). Tension cracks, varying in width from 200 to 500 mm, are found around the perimeter of the crownholes.

Subsidence has led to flooding in places. However, the impact of subsidence on property has been minimal, as fortunately there is no major infrastructure in the area. Nonetheless, in the early 1980s a municipal road leading to the local airport was constructed over mine property. Stabilization of the area prior to road construction was necessary due to the high risk of surface subsidence and the spread of the underground fire. This was achieved by stooping the remaining pillars lying below the western side of the road, thus causing total collapse of the underground workings. Directly beneath and on the eastern side of the road, the bord areas were filled with a sand-cement grout mixture to provide additional support for the road foundation. These measures have been successful, as the road has not been affected by the subsidence which is common in the surrounding area.

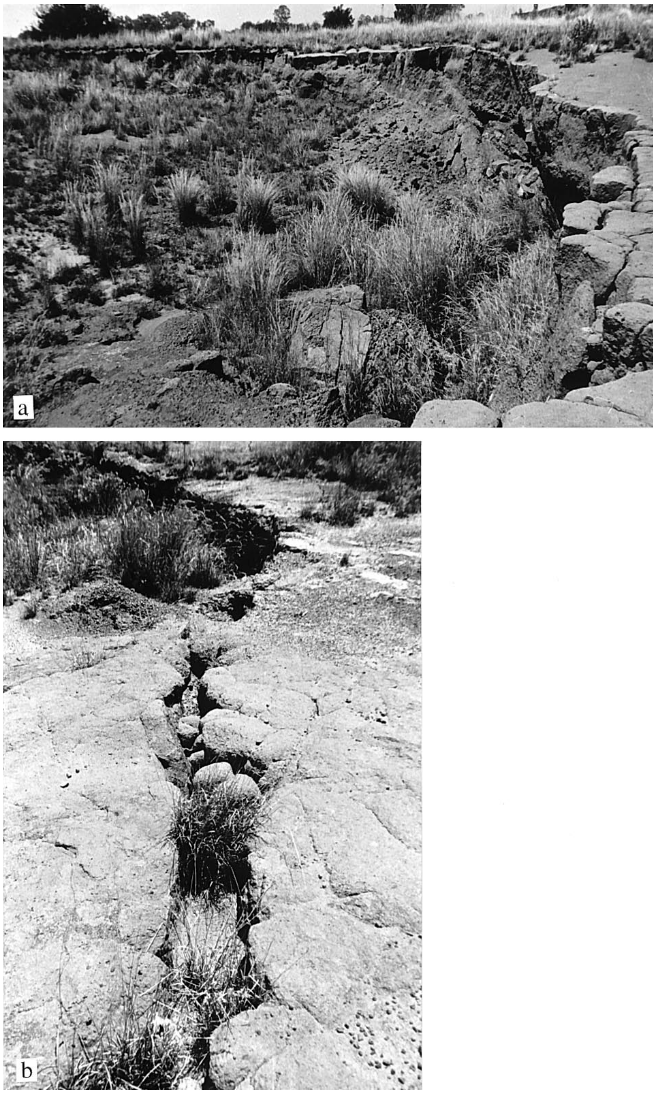

Fig. 4
a Subsidence due to pillar failure. **b** Tension crack developed as a result of subsidence

Fig. 5
Pattern of collapses at the surface due to void migration in bord areas

One of the few subsidence incidents to affect structures occurred in 1991 when a high-voltage-power-line pylon was affected by crownhole subsidence. The crownhole appeared after a period of heavy rain, directly beneath two limbs of the pylon. Remedial action included the placement of two horizontal struts beneath the pylon in order to spread the load on to more stable ground, together with the installation of a pulley system on the pylon to allow for overhead cable movement in the event of further subsidence.

Spontaneous combustion of the coal seam

All entries to the mine were sealed on closure in 1947. However, a shaft was opened for access when an area was mined by stooping in 1982-1983. This was sealed when stooping ceased. Hence, except for this limited period, air and water have not gained access to the mine by mine entrances. The coal in the mine has been undergoing spontaneous combustion for the last 40 years, and it is estimated that the area affected by burning is between 150 and 200 ha. The burning area is some 2 km from the nearest town.

The characteristics which affect the susceptibility of a particular coal to self-heating include temperature, rank, surface area exposed, moisture content and pyrite content. Obviously the rate of self-heating increases as the temperature increases, and so once ignited, the burning process can be self-sustaining if there is a continuous supply of oxygen. The tendency of coal to self-heat increases with decreasing rank of coal. According to Michalski and others (1990), as rank decreases the seam moisture content, oxygen content, internal surface area and air permeation tend to increase. An increase in the natural moisture content of coal can liberate heat, and greater surface area and air permeation have the same effect. If the pyrite content of coal exceeds 2%, then this also aids the self-heating process as oxidation of pyrite also is an exothermic reation.

Mining creates pathways through which air can be carried to coal. However, the retention of heat by the coal is largely dependent on the air flow, in that there is a critical velocity below which the coal is oxidized, but the air flow is not capable of removing the heat generated. Such conditions commonly exist in partially collapsed mines. Furthermore, in old abandoned workings, the sides of the pillars are normally fractured and fine coal is commonly strewn in the roadways. Hence, a large surface area of coal is available for oxidation and the exothermic reaction produces a rise in temperature which eventually becomes self-generating.

Most of the factors outlined here exist at this particular mine where spontaneous combustion of coal has occurred since around 1947. For example, surface subsidence has given rise to crownholes and tension cracks which extend to mine level. These allow free passage of air into the mine workings. In addition, the fracturing and collapse of pillars have provided a greater surface area of coal and air can permeate these fractures in coal pillars. Some burning pillars have collapsed and weakened the integrity of the remaining pillars, leading to further multiple pillar failure and related subsidence, thus further aggravating the problem. Table 1 indicates that these coals are low-rank bituminous coals. It also shows that the sulphide content, and therefore pyrite content, is frequently greater than 2%, and so presumably enhances the process of spontaneous combustion. Although the natural moisture content of the coal prior to the abandonment of the mine is unknown, it is assumed that it is now higher, since the mine is flooded or partially flooded in places. Certainly, sulphurous steam emanates from many crownholes almost continuously (Fig. 6) and from some tension cracks. The partially collapsed nature of the workings impedes the rapid flow of air, and so heat is not readily conducted away from hot spots. Indeed, the existing conditions appear almost ideal for the spontaneous combustion of coal.

Table 1a, b
Analysis of coal. **a** From opencast area and spoil heaps. **b** From the spoil heaps (* by XRF)

coal from spoil heap 1					coal from spoil heap 2					coal from opencast area				
sample	carbon content	ash content	sulphur content	moisture content	sample no.	carbon content	ash content	sulphur content	moisture content	sample no.	carbon content	ash content	sulphur content	moisture content
1	64.2	22.1	2.25	5.5	1	66.8	17.7	2.35	2.3	1	61.5	25.4	2.57	4.4
2	67.3	21.2	1.81	4.7	2	64.5	21.6	1.79	3.6	2	66.5	23.9	1.92	3.8
3	63.2	24.3	2.31	4.1	3	63.2	29.6	1.85	1.9	3	62.7	22.0	2.64	4.1

sample	carbon content	sulphur content	ash content	ash content							
				SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	TiO_2
1	64.5	2.79	26.9	52.9	43.3	0.59	–	0.11	0.25	0.76	1.65
2	62.7	3.77	28.5	40.6	35.7	1.99	0.06	10.2	0.23	0.35	1.75
3	61.4	1.26	31.2	58.6	38.1	0.22	0.05	–	0.27	0.21	1.93
4	58.4	2.76	24.0	52.8	43.4	1.48	0.12	0.09	0.12	0.33	1.01

Fig. 6
Gases (mostly steam) escaping from a crownhole

Fig. 7
Aerial view of one of the spoil heaps on the mine site. White patches are areas where spoil has been burnt

Various attempts have been made to control or extinguish the burning coal in the mine. These include construction of cut-off trenches, which were backfilled with earth, around burning zones (Fig. 3) and injection of water into the workings. In addition, the suggestion has been made to collapse the workings by subsurface explosions to try to inhibit the access of air. As this is just as likely to increase the access of air, the suggestion has not been put into effect. None of the efforts has had any real success. Burning appears to have bypassed many of the trenches simply because they were not long enough or wide enough and water injection has made no impression on the burning coal. The latter is probably because no barriers were placed to stop water draining away. In addition, water injection may take considerable time, sometimes years, to be successful. The programme was not continued for a long enough time, a matter of weeks being insufficient. In fact, there can be potential problems associated with water injection. First, carbon monoxide and hydrogen may be produced from watergas reactions with burning coal, and these would be emitted at the surface. Secondly, the release of heat of condensation causes the temperature to rise in the mine.

Spoil heaps

There are two spoil heaps on the site. One covers an area of approximately 56 250 m^2 and has a volume of 843 750 m^3, the respective figures for the other are 66 000 m^2 and 990 000 m^3. Spoil heaps are particularly conspicuous and can be difficult to rehabilitate into the landscape (Fig. 7). They are formed of coarse discard which consists of run-of-mine material and reflects the various rock types which are extracted during mining operations (Bell 1996). Such discard contains varying amounts of coal which have not been separated by the preparation process. The old spoil heaps on the mine area contain appreciable amounts of coal, in fact enough to consider reworking the dumps (i.e. approximately 20%–30%), and they are poorly compacted compared with their modern-day counterparts. Poor compaction of discard, which is associated with tipping, allows easier permation of air and water and so helps the spontaneous combustion process and the development of acid mine drainage.

The chemical composition of some samples of spoil material is given in Table 2. From this it can be seen that the two principal oxides are silica and alumina. Generally, the content of silica is lower and that of alumina is higher than in spoils in some of the coalfields in western Europe, notably Britain (Anonymous 1973). Calcium, magnesium, iron, sodium, potassium and titanium oxides are present in small concentrations. The sulphur content of these spoils averages approximately 1.5%.

The mineralogical composition of the shale material in the coarse discard, as determined by X-ray diffraction, consisted primarily of kaolinite (up to 76%), quartz (18%–29%) and mica (6%–21%). Other minerals present included aragonite, dolomite, gypsum and jarosite. Quartz, mullite and tridymite were the principal minerals present in the burnt shale. Minor minerals included rutile, anatase and alunite. Pyrite also occurs in the shales and coal of the spoil heaps. When pyrite weathers it gives rise to the formation of sulphuric acid, along with ferrous and ferric sulphates and ferric hydroxide, which gives rise to acidic conditions in the weathered spoil. Oxidation of pyrite within spoil-heap waste is governed by the access of oxygen, which in turn depends upon the particle size distribution, amount of water saturation and the degree of compaction. The poorly compacted nature of these spoil heaps aids the breakdown of pyrite. The resultant sulphates and sulphuric acid have reacted with clay and carbonate minerals to form secondary products including aluminium sulphates. Further reactions with these minerals have given rise to tertiary products such as calcium and magnesium sulphates. Such conditions do not promote the growth of vegetation. Indeed, spoil heaps may contain elements which are toxic to plant life. Some acidic water flows from the spoil heaps and infil-

Table 2
Analysis of spoil materials (1 = spoil heap 1; 2 = spoil heap 2)

	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	TiO_2	sulphur content
shale (1)	63.4	32.7	0.96	0.24	0.04	–	1.01	1.43	0.94
shale (1)	80.1	15.7	0.47	0.03	0.03	0.18	0.22	2.64	1.72
shale (2)	51.8	44.0	0.48	0.13	0.02	0.32	0.79	2.19	1.25
shale (2)	65.2	31.0	0.78	0.11	0.07	0.2	0.43	1.59	2.01
burnt shale (1)	52.8	43.4	1.48	0.12	0.09	0.12	0.33	1.01	0.78
burnt shale (1)	56.2	40.1	1.21	0.17	0.02	0.13	0.24	1.07	0.91
burnt shale (2)	51.9	44.6	0.82	0.09	0.05	0.27	0.16	1.93	0.87
burnt shale (2)	53.7	42.6	1.46	0.13	0.08	0.14	0.21	1.35	0.76
discard (1)	52.8	46.1	0.38	0.15	0.06	0.29	0.3	1.93	0.82
discard (1)	59.5	40.6	0.79	0.08	0.15	0.07	0.36	2.35	1.96
discard (2)	57.9	44.4	0.36	0.12	0.01	0.15	0.61	2.56	1.51
discard (2)	54.9	47.2	0.58	0.11	0.08	0.19	0.22	2.59	1.82

trates the ground. There are no small water courses near the spoils to suffer pollution from such runoff. As the spoil heaps on the mined-out area are not near any urban centre, no attempt has been made at restoration. Spontaneous combustion of carbonaceous material, aggravated by the oxidation of pyrite, is the most common cause of burning spoil (Beever 1982). Coal and carbonaceous materials may be oxidized in the presence of air at ordinary temperatures, below their ignition point. At relatively low temperatures an increase in free moisture, which occurs in poorly compacted spoil, increases the rate of spontaneous heating. Oxidation generally takes place very slowly at ambient temperatures, but as the temperature rises, oxidation increases rapidly. As already noted, the lower-rank coal in the spoil heaps is reactive and accordingly susceptible to self-heating. When heated, the oxidation of pyrite and organic sulphur in coal gives rise to the generation of sulphur dioxide. If there is not enough air for complete oxidation, then hydrogen sulphide is formed. Sulphur gases emanating from these spoil heaps can be readily detected by the nose, especially after rainfall. Noxious gases emitted from burning spoil include carbon monoxide and carbon dioxide.

Impact of mining on hydrogeology

The surface subsidence and the associated underground fire have had impacts on both groundwater and surface-water hydrology. These impacts include reduced surface runoff, increased groundwater recharge and deterioration of water quality. Surface runoff is reduced as rainfall collects in collapsed areas after heavy summer rains. The ponded water percolates through subsidence-related tension cracks and crownholes to the underground workings. Seam 2 workings act as an aquifer for the percolated water. Water collecting on the western side of the regional anticlinal axis flows to the west and dams up against the boundary pillar with the adjacent mine. However, water moving through the workings on the eastern side of the anticlinal axis flows towards the coal sub-outcrop in the vicinity of a nearby stream. Since 1991, after the coal sub-outcrop pillar along the eastern boundary of the working was mined, groundwater, which previously had been retained behind the pillar, began to seep from the workings. This seepage water flows overland in a series of springs, before merging to enter the nearby stream. A V-notch flume was installed to measure flow on the stream. Weekly flow readings were recorded for a 1-year period from December 1994 to November 1995. The total annual volume of water collecting over the mine site catchment area was derived from the rainfall data. The estimated recharge to the coal seam would appear to be around 50% of the volume of rain which falls (Table 3). Figure 8 suggests that there is a time-lag between the heaviest rainfall (January) and maximum flow over the V-notch (August).

Rainwater seeping into the old workings is affected by both the oxidation of pyrite and the presence of the underground fire. As a result there is a deterioration in water quality. Table 4 includes water quality analyses for a selection of water samples collected. Samples were obtained at the V-notch both during the summer (the wet season) and in winter (dry season), and are typical of the quality of water seeping from underground. A sample taken from a borehole (B1 see Fig. 3) sunk into seam 2 is provided for comparison, as are samples from an adjacent colliery, from the uppermost decantation pond and from the stream just below the lowermost decantation pond.

Inspection of the water quality data shows that both surface and underground water are highly polluted. The pH values are below the crisis limit recommended by the South African guidelines for domestic water (Anonymous 1993). At such values there is a danger to health due to dissolved metal ions. Low pH values can be attributed to the formation of sulphuric acid as a product of reactions involving the oxidation of pyrite with the production of acid mine drainage. This is supported by the sulphate content which in all the analyses is above the crisis limit guidelines, and in some instances is twice that limit. The high sulphate content is not unexpected when compared

Table 3
Rainfall and flow data

month	rainfall ($mm\ month^{-1}$)	total rainfall in catchment ($m^3\ month^{-1}$)	V-notch Reading (cm)	flow ($m^3\ month^{-1}$)
Dec	140	234 500	6.5	36 119
Jan	210	351 750	5.2	20 768
Feb	136	227 800	4.6	15 323
March	158	264 650	6.4	34 087
April	18	30 150	8.6	72 321
May	10	16 750	9.8	99 988
June	30	50 250	9.9	102 538
July	0	0	10.5	118 648
Aug	0	0	9.3	87 811
Sept	2	3 350	7.4	49 820
Oct	56	93 800	6.7	38 938
Nov	30	50 250	7	43 406
Total	790	1 323 250	91.8	719 770

Recharge = {flow/total rainfall in catchment} *100
= {719 770 ($m^3 month^{-1}$)/1 323 250 ($m^3\ month^{-1}$} *100
= 54%

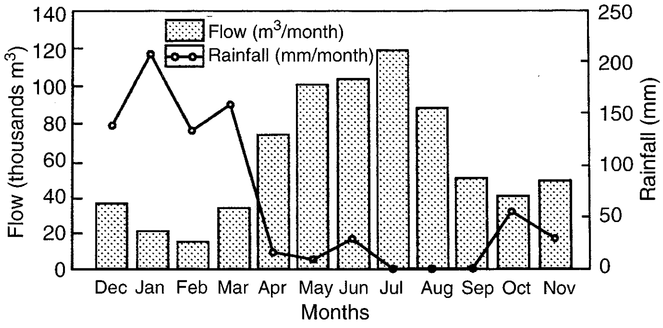

Fig. 8
Monthly rainfall figures compared with seepage flow over the V-notch

with the high sulphur content in the coal and associated shale (Tables 1 and 2). The character and rate of release of acid mine drainage is influenced by various chemical and biological reactions at the source of acid generation (Bell and Bullock 1996). Table 4 also shows that the salt concentrations of aluminium and iron far exceed the crisis limits for drinking water quality in South Africa. Most of the other constituents are around or exceed the maximum permissible limits.

It can be seen from Table 3 that there is a time-lag between the period of maximum rainfall and maximum runoff. Obviously this is due to the delay in the contribution made by seepage water from the mine workings. The effect of the time-lag between the period of maximum precipitation and maximum flow from the workings is reflected particularly in TDS concentrations. In other words, the salt concentrations for the wettest months, when flow is at its lowest, are generally greater than for the dry months, when flow is highest. For example, the relatively low TDS concentration (2 968 mg l^{-1}) for August 1996, coincides with the period of maximum flow from the workings. The increased volume of water therefore has a dilution effect on the concentration of dissolved salts in the water.

In an attempt to ameloriate the impact of underground water entering the stream, a series of four pollution control ponds was constructed (Fig. 3). A side-stream of the seepage water was directed into the upper reservoir, while the remaining flow entered the nearby stream below the ponds. Residence time in the ponds is not known but is likely to vary with season. Comparison of water quality data, especially of samples 13 and 14, shows that the effect of cascading part of the seepage water through the decantation ponds is negligible. There is even cause to suspect that aluminium is being leached from soil particles in the ponds as aluminium concentrations leaving the lowest pond are about double those of water at the V-notch flume.

Evaporation of acid mine drainage leads to the precipitation of various salts on and in the uppermost layers of the soil (Fig. 9). X-ray diffraction analysis of such salts indicated the presence of halite NaCl, soda-alum, $NaAl(SO_4)_2.12H_2O$, various members of the jarosite family of minerals (e.g. hydrojarosite, natrojarosite and possibly plumbojarosite), $KFe_3(SO_4)_2\ (OH)_6$, and a small amount of calcite, $CaCO_3$ (Fig. 10).

Impact of acid mine drainage on vegetation

The acidity of the seepage water and the high TDS concentration have affected vegetation locally. A denuded area of approximately 3 ha exists in the coal sub-outcrop area between the eastern boundary of the mine and the decantation ponds. In this area, almost all plant life has been killed (Fig. 11). Most plants cannot tolerate low pH

Table 4
Chemical composition of acid mine water and South African guidelines for drinking water quality (Anonymous 1993). Samples 1 to 12 taken from the V-notch; sample 13 taken from the uppermost decantation pond; sample 14 taken from the stream just below lowermost decantation pond; sample 15 taken from No. 2 coal seam level

Determinand (mg l^{-1})	sample 1 May 90	sample 2 June 90	sample 3 July 90	sample 4 Dec 90	sample 5 Jan 91	sample 6 Mar 91	sample 7 Dec 93	sample 8 Jan 94	sample 9 Feb 94	sample 10 Dec 95
TDS	2749	2575	2575	2843	2760	2082	3376	3038	3575	4844
Suspended solids										33
EC (mS/m)	283	327	465	421	379	298	424	463	418	471
pH value	2.3	2.4	3.0	1.8	1.9	2.0	2.8	66	2.8	1.9
Langelier S1										−8.2
Turbidity as NTU										5.5
Nitrate NO_3 as N	0.05						0.04	0.02	0.18	0.1
Chlorides as CI	91	84	186	120	106	124	179	174	170	310
Fluoride as F										0.6
Sulphate as SO_4	2361	2239	2697	2462	2330	1692	2722	2378	2897	3250
Total hardness										
Calcium hardness as $CaCO_3$										
Magnesium hardness as $CaCO_3$										
Calcium Ca	135	115	176	76	132	98	162	179	186	173.8
Magnesium as Mg	56	50	90	41	55	40	84	90	93	89.4
Sodium as Na	102	65	200	116	138	114	194	185	200	247.0
Potassium as K									9.4	7.3
Iron as Fe \			140						128	248.3
Manganese as Mn			18						15	17.9
Aluminium as Al			86						124	

Table 4. Continued

Determinand (mg l^{-1})	sample 11 Aug 96	sample 12 Aug 96	sample 13 Nov 96	sample 14 Nov 96	sample 15	adjacent coll Feb 95	adjacent coll Feb 95	recommended limit (no risk)	maximum permissible limit (insignificant risk)	crisis limit (max limit for low risk)
TDS	2968	3202	2490	3364	3604	3048	3354			
Suspended solids	10.4	12	10.0	7.6						
EC (mS/m)	430	443	377	404	340	389	403	70	300	400
pH value	2.4	2.95	2.9	2.3	2.8	2.65	2.7	6–9	5.5–9.5	>4 or <11
Langelier S1	−7.5	−6.9	−6.9	−7.7						
Turbidity as NTU	0.6	2.0	0.9	1.7				1	5	10
Nitrate NO_3 as N	0.1	0.1	0.1	0.1	0.1	0.2	0.29			
Chlorides as CI	431	406	324	353	611	411	989	250	600	1200
Fluoride as F	0.5	0.33	0.6	0.6	0.84			1	1.5	3
Sulphate as SO_4	1610	1730	1256	2124	1440	910	1306	20	600	1200
Total hardness	484	411	576	585	377					
Calcium hardness as $CaCO_3$	285	310	327	282		166	161	20–300	650	1300
Magnesium hardness as $CaCO_3$	199	101	249	305						
Calcium Ca	114.0	124	131	113	84	42	40	150	200	400
Magnesium as Mg	48.4	49.5	60.5	49.3	31	14.9	14.8	70	100	200
Sodium as Na	326.0	311	278	267	399	620	355	100	400	800
Potassium as K	9.4	8.9	6.4	3.8				200	400	800
Iron as Fe \	128	140	87	89.9	193	122	84	0.1	1	2
Manganese as Mn	15	9.9	13.4	13.9	9.3	5.9	3.9	0.05	1.0	2.0
Aluminium as Al	124		112	204	84	70	85	0.15	0.5	1.0

water because the high concentration of hydrogen ions causes inactivation of enzyme systems, restricting respiration and root uptake of mineral salts and water (Bradshaw and others 1992). Dissolved aluminium ions are regarded as a major cause of plant toxicity in acid soils. As the total aluminium concentration in the seepage water is over 100 mg l^{-1}, aluminium is likely to have played a role in the destruction of vegetation in this area. Other than

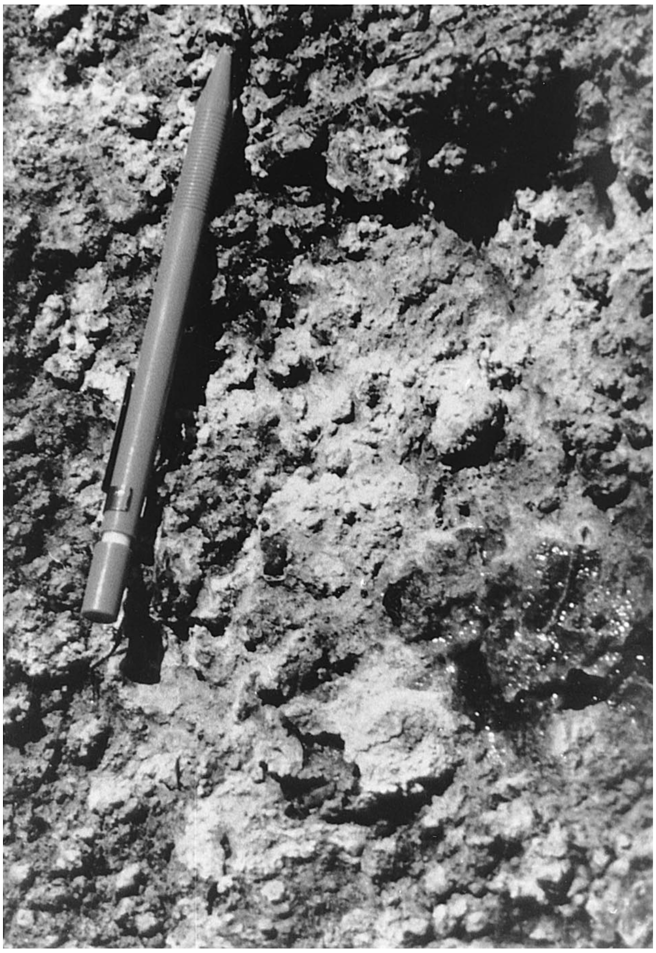

Fig. 9
Precipitation of salts from acid mine drainage water on the surface of the soil

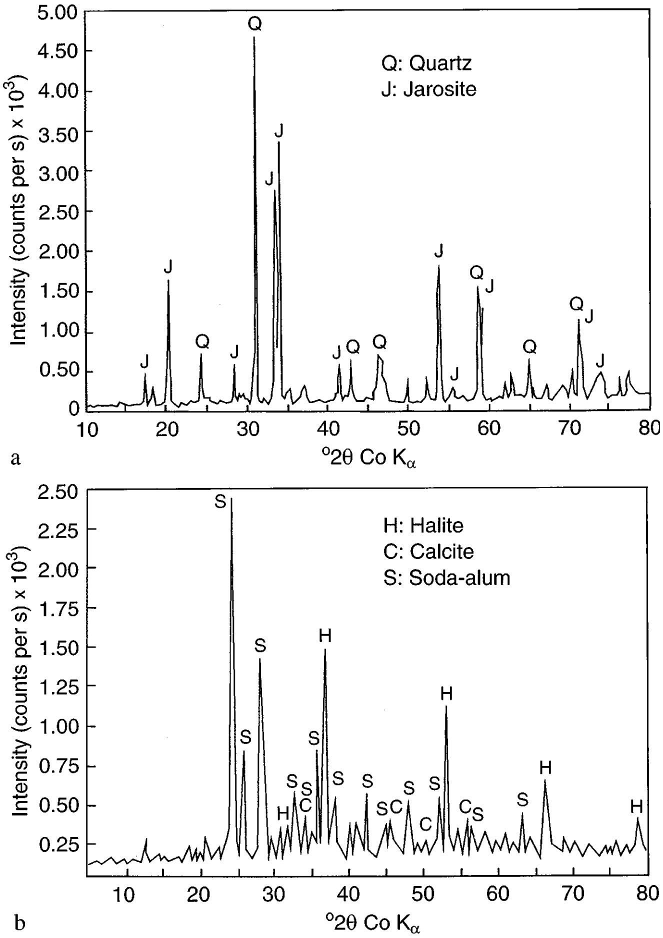

Fig. 10
X-ray diffractographs of salts precipitated from acid mine drainage water

species of red and green algae, no aquatic life appears to exist in the seepage area, in the pollution control ponds or in the stream.

Conclusion

Most of the environmental problems on the mine property can be attributed to the mining methods used in the 1930s and 1940s, notably the practice of pillar robbing. Pillar robbing has been responsible for the subsequent collapse of bords and of pillar failure. Subsidence has allowed continuous free entry of air into the workings, and this together with the heat generated by the oxidation of coal caused spontaneous combustion of many of the remaining coal pillars. Hence, underground burning has led to further subsidence as pillar strength is weakened. The formation of crownholes and deep tension cracks has increased recharge to the workings. The chemical composition of surface water percolating into the old mine workings is rapidly changed through contact with the pyrite which is oxidized, resulting in the formation of typical low pH and high TDS acid mine drainage water. After the removal of a sub-outcrop boundary pillar in 1991, acid mine drainage began to seep to the surface. There is

Fig. 11
Decimated vegetation killed by acid mine drainage water

a time-lag between the summer rainfall and the maximum seepage from the workings. Overland flow of this water towards a local water course is therefore strongest in the dry winter months, but the dissolved salt content is diluted. Nonetheless, the acid nature of the water has largely destroyed vegetation in a 3-ha area between the seepage points and the water course. Cascading the seepage water through decantation ponds situated along the water course is ineffective in terms of improving the quality of the water. Red and green algae are the only discernable forms of aquatic life in seepage water springs, in the ponds and in the stream. A minor contribution to the problem of acid mine drainage is made by the spoil heaps located on the mine site.

The problems outlined in this paper are not unique to this particular mine. Similar problems are found at other abandoned coal mines in this area and elsewhere in South Africa. Often a responsible ownership cannot be established and in these cases, responsibility for the mine has been taken over by the Department of Water Affairs and Forestry. In the case of the mine described, the last mining company to operate the site has assumed site responsibility. In fact, water quality is a problem that affects all coal mines in the area. Many local, often ephemeral, streams in this area eventually drain into the Loskop Reservoir and the Olifants River, as does the one in question. The Olifants River eventually flows through the Kruger National Park. The catchment area of the Olifants River is thus sensitive not only from the point of view of tourism and nature conservation but also because the lower and middle sections of the river are areas of intensive agricultural activity. Water quality management and any attempt at environmental remediation will need to be considered within a regional context and will require considerable cooperation between the various mining companies operating in the area, and with downstream users. It is likely that remedial measures or at least holding measures will be driven by water quality considerations.

South Africa is currently moving away from a uniform effluent standards approach to water quality management towards regulation based on water quality receiving objectives which take into account the assimilative capacity of the receiving water as well as the water quality requirements of the downstream user. These principles will be embodied in a new Water Act, which is likely to be introduced in 1997. All operating mines are now required to submit an Environmental Management Programme Report (EMPR). Sections of this report are legally binding and each mine is required to detail inter alia what the residual environmental impacts (including projected impact on water quality) of the mining activities will be, and to commit resources to minimize such impacts. It is this more holistic approach to mining which should mitigate against environmental degradation such as described in this paper, and ensure that mining activities and environmental protection are not mutually exclusive.

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