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The investigation of cavities at two disused mines using soil gas geochemical and geophysical methods.

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The adaptation of soil gas geochemical analysis as an engineering geological investigation technique to detect cavities has been tested at two sites underlain by disused mineworkings. Geophysical surveys over the sites provided a useful comparison. The soil gas samples were analysed for oxygen, carbon dioxide, methane, radon, and helium concentrations. One site, a small metalliferous mine north of the Dartmoor Granite, is thought to consist of simple, limited workings. Soil gas and geophysical anomalies were detected associated with these workings. The second site over an extensive abandoned pillar-and-stall coalmine in South Wales showed a variation in soil gas concentrations relating to the depth of the workings. The results suggest that where fracturing has been enhanced around old mineworkings by partial collapse, equilibration with atmospheric air affects soil gas concentrations significantly, and can be contrasted with concentrations in areas not affected by the presence of cavities. The investigations to date suggest there is potential for using soil gas geochemistry in site investigations for cavities, integrated with standard geophysics and borehole probing.

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Introduction

Ground with cavities can prove to be a major hazard to engineering, as there are no methods available with a 100% success rate of cavity detection and delineation (Culshaw and Waltham 1987; Taylor 1968; Bell 1986). The best methods known to date are intensive trialpitting, boring and probing which are expensive, and geophysical techniques which can be misleading.

Any cavities in the ground above the water table (the vadose zone) are reservoirs for accumulation of gases and major pathways for their migration. The concentrations of soil gas above such cavities may reflect differences between cavity gases and atmospheric concentrations and may vary from background soil values. The adaptation of soil gas geochemical analysis as an engineering geological site investigation technique to detect underground cavities has been evaluated at two sites known to be underlain by disused mineworkings. This is part of a wider study (Sibley and Grainger 1988). The results of surveying at the same sites by the most useful of the geophysical methods for cavity location (Dearman *et al.* 1977; Jackson *et al.* 1986; McCann *et al.* 1987) are presented for comparison.

Soil gas geochemistry

Soil gas samples were collected from a depth of about 0.5m using a special probe, as described by Gregory and Durrance (1985a, b). The concentrations of carbon dioxide (CO_2), oxygen (O_2), methane (CH_4), helium (He) and radon (Rn) were analysed. The equipment used is described in detail elsewhere (Sibley and Grainger 1988).

CO_2, and O_2 may be considered together as factors affecting the concentration of one generally cause a complementary change in the other. The main source of O_2 in the soil is atmospheric air which contains 20.8% O_2 and only 0.035% CO_2. The factors affecting their concentrations can be divided into three categories (Gregory and Durrance 1985a; Lovell 1980; Lovell and Hale 1983):

a) Microbial oxidation and plant respiration can result in increases in CO_2 at the expense of O_2.

b) CH_4 and carbon monoxide (CO) migrating upwards to the surface, may similarly be oxidized to CO_2.

c) Oxidation of sulphides in the vadose zone may form sulphuric acid which then attacks nearby carbonate material to produce CO_2. A drop in the CO_2+O_2 concentration occurs as more O_2 is consumed than CO_2 produced. Transported acidic groundwater dissolving carbonates in limestone areas released CO_2 but without the corresponding drop in O_2.

Some CH_4 is thought to be produced inorganically at very large depth and migrates towards the surface via fractures. CH_4 is also a by-product of organic decay in reducing environments and high concentrations can be associated with coal, hydrocarbons or recent organic decay. In the atmosphere CH_4 is normally present only in trace quantities (1.6ppm, Rose *et al.* 1979). Its detection in the soil at higher concentrations suggests anomalous fracturing in the rock beneath, coal or hydrocarbons.

Helium may be primeval or is produced at depth within the Earth as a radioactive decay product (alpha particles) via several decay chains (Butt and Gole 1984). It also migrates to the surface via fractures (Dyck 1976) and the concentrations of soil gas He relative to atmospheric air (5.22ppm) give an indication of the location and characteristics of the fracturing in the rock beneath (Gregory *et al.* 1986).

Rn is a radioactive gas formed in the decay chains of the uranium and thorium series. Rn exists as three isotopes, two in measurable quantities, ^{222}Rn and ^{220}Rn, both with very short half lives; 3.82 days and 51 seconds respectively (Telford *et al.* 1976). These two isotopes can be differentiated by analysis over short time intervals (Smith *et al.* 1976). The concentration of Rn in atmospheric air can be considered as negligible and the detection of Rn in the soil in any quantities indicates a source close to the sample site and/or rapid transportation from the source to the soil. As with He, migration is via major fractures either in solution or as gas bubbles in rising groundwater.

Geophysical techniques

Geophysical data, together with information on the local geology, geomorphology and mine records, were used as a control with which to compare the soil gas geochemistry data. Two methods of geophysical investigation were used on each site: magnetic and electrical conductivity surveying. The magnetic surveying was carried out using a proton-precession magnetometer which measures the total magnetic field. It detects variations in natural iron content close to the surface, together with any artificial metallic objects or iron-rich material such as bricks lining old shafts (Hooper and McDowell 1977). The conductivity results were obtained using a non-contacting electromagnetic system (Geonics EM31) which measures the local ground conductivity (the inverse of resistivity) to a maximum depth of about 6m. The conductivity is a function of soil/rock moisture content, but high values are provided by other electrical conductors such as metalliferous ore bodies (Zalasiewicz *et al.* 1985).

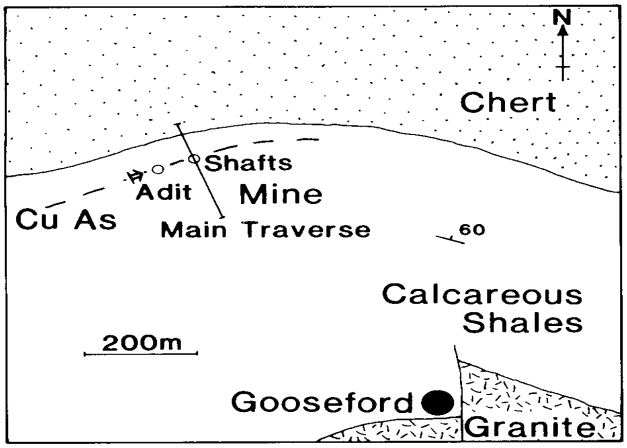

Figure 1. Site plan of Gooseford West Mine, Devon.

Gooseford

The first site, situated to the north of Dartmoor (SX 672925), is a small disused metalliferous mine (Gooseford West) which consists of two shafts and an adit along the strike of a stratiform Cu-As deposit in steeply dipping calcareous shales (Beer and Scrivener 1982) (Fig. I). A horizontal level at a depth of 10-15m is thought to connect the two shafts (Broughton 1964). Several traverses were carried out at the site but the only one considered here is trending roughly N-S across the eastern shaft (Fig. 1).

Geophysical work on the site consisted of conductivity and magnetic traverses along this line, with a coarse sampling interval of 10m over a 225m length. From the geophysical data the following points can be concluded (Fig. 2):

a) The area south of the mineworkings underlain by shale gave uniform values with very low conductivity.

b) The area of the mineralized zone and shaft has high conductivity values and a complex magnetic pattern. These could be due to the ore body or the workings or a combination of the two.

c) The area north of the workings has fairly constant high conductivity and magnetic values. The change of lithology to cherts is probably masked by the effect of artificial spoil spread over the area (Fig. 2). Soil gases investigated here were CO_2, O_2, He and CH_4 (Fig. 2). The results show the following features:

a) The area south of the mineralized zone has fairly constant gas concentrations for each of the gases, all differing from atmospheric values, indicating limited mixing with the air.

b) The readings taken over the infilled shaft show anomalously high O_2, together with anomalously low CO_2 and He values; all indicating near-atmospheric values and a high degree of equilibration with the air due to the permeability of material associated with the top of the shaft.

c) The boundary between the chert and shales is indicated by high CO_2 He, and CH_4, and low O_2 values, suggesting a fractured contact up which gases are migrating.

d) The rest of the area just north of the shaft has erratic soil gas concentrations, probably due to a covering of spoil observed at the surface.

A detailed traverse with 5m spacing was then conducted across the shaft to pinpoint the anomalies more precisely (Fig. 3). This survey investigated concentrations of CO_2, O_2 and Rn.

a) The low CO_2 and high O_2 values are confirmed and suggest considerable disturbance of the ground around the shaft, particularly on the north side.

b) An Rn traverse along the same line indicates three anomalously high Rn values, two of which, on either side of the shaft, possibly relate to the boundaries of the ore body. However directly over the shaft, soil gas Rn values are low suggesting equilibration with the air.

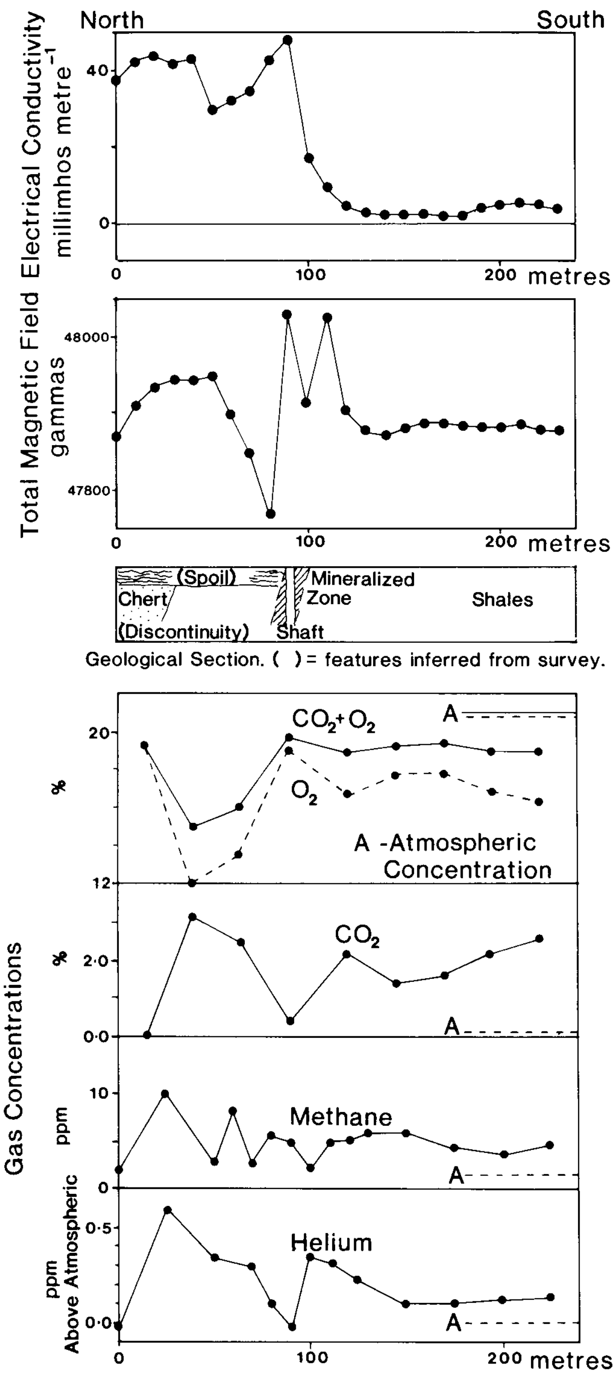

Figure 2. Results of geophysical and soil gas geochemical traverse at Gooseford West Mine.

c) The third high Rn value about 20m north of the shaft, which correlates with high CO_2 and low $_{02}$ values relative to atmospheric air, suggests the presence of a small but significant fracture here which could have been induced by the construction of the workings or could be associated with the mineralized zone.

Rhos-wen

The second site, Rhos-wen Colliery, is located in the eastern part of the South Wales coalfield near the village of Bedwellty (SO 172005). The colliery is an extensive disused pillar-and-stall mine which worked the Mynyddislwyn seam. This bed is a 1.6m coal deposit in the Upper Pennant Measures which in this locality are

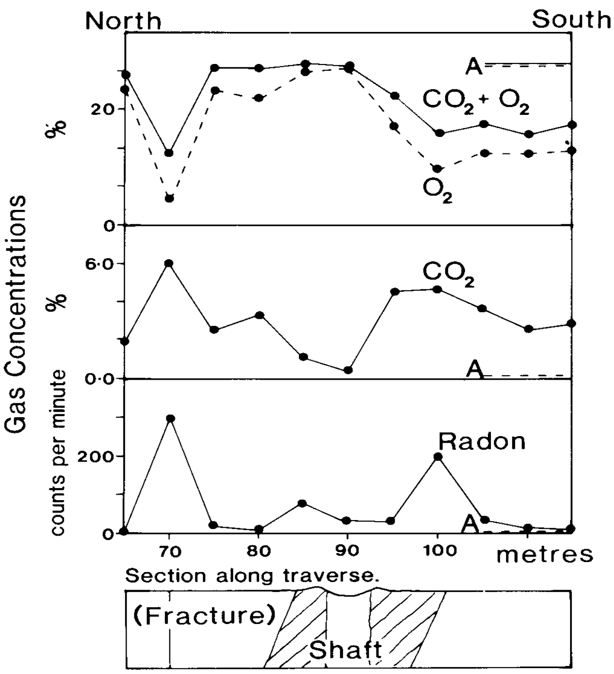

Figure 3. Detailed soil gas geochemical traverse over shaft at Gooseford.

virtually horizontal. About 30m above the Mynyddislwyn seam is the Small Rider, an unworked coal seam with ironstone and tonstein (Strahan 1909; Thewlis, pers. comm.) of about 0.8m thickness. The site chosen for fieldwork was a 100m by 150m grid close to Rhos-wen Farm (Fig. 4). According to disused mineworkings plans inspected at the British Coal Open-Cast Executive, South West Region, this site has no workings underlying its NW corner immediately adjacent to the farm (however absence of recorded old workings on plans does not necessarily prove that the seam has not been worked). The results from this corner are considered as a reference with which to compare values from the rest of the site which is underlain by workings.

The geophysical survey at Rhos-wen was done on a 10m grid over the whole of the site, the highlighted several areas of anomalous readings (Fig. 5):

a) A linear feature (A) trending approximately NW-SE in the SW

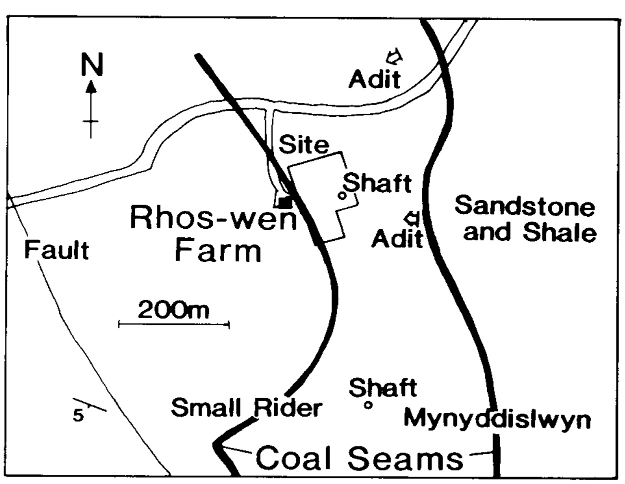

Figure 4. Map showing location of site over Rhos-wen disused colliery.

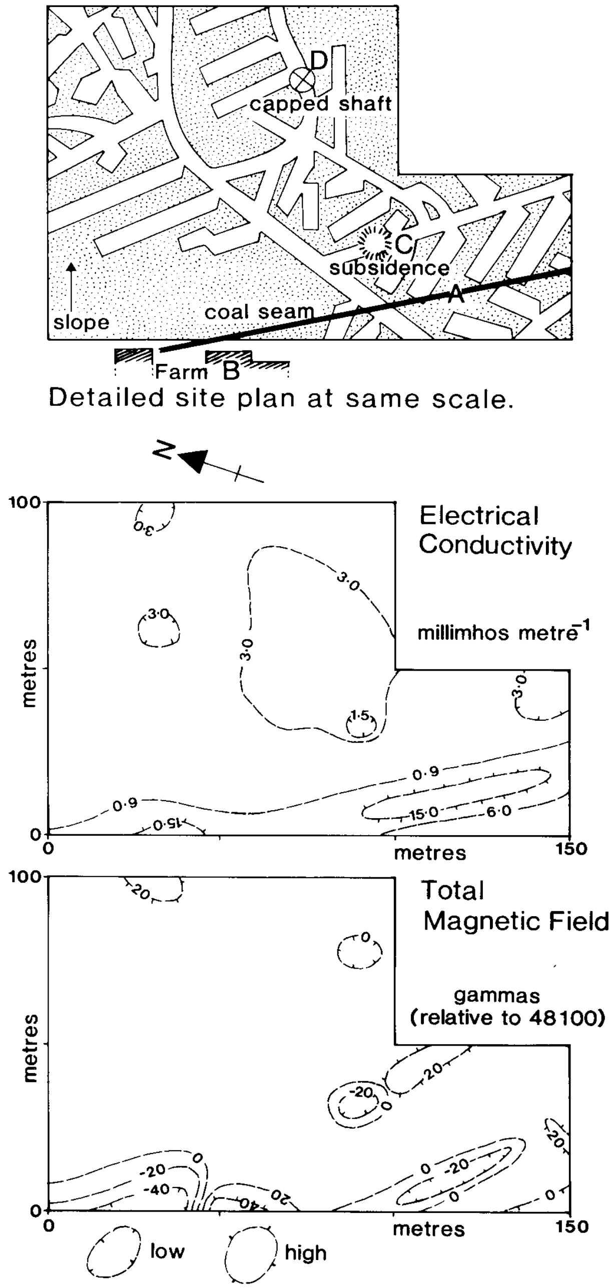

Figure 5. Site plan of the survey area at Rhos-wen and geophysical results.

area of the grid. This probably relates to the outcrop of the Small Rider coal seam.

b) The western edge of the grid near the location of the farm buildings (B). Artificial objects and interference are the cause of these anomalies.

c) From geomorphological mapping there is an area of subsidence (C) which has associated geophysical anomalies of low conductivity and a magnetic dipole. However a recently capped shaft (D) in the central part of the grid has no associated geophysical anomaly.

Soil gases investigated at Rhos-wen were CO_2, O_2, CH_4, He and Rn; sampling was conducted over the whole site on a grid spacing of 25m. The sampling points were so widely spaced because only the general trends of the soil gases were being investigated. More

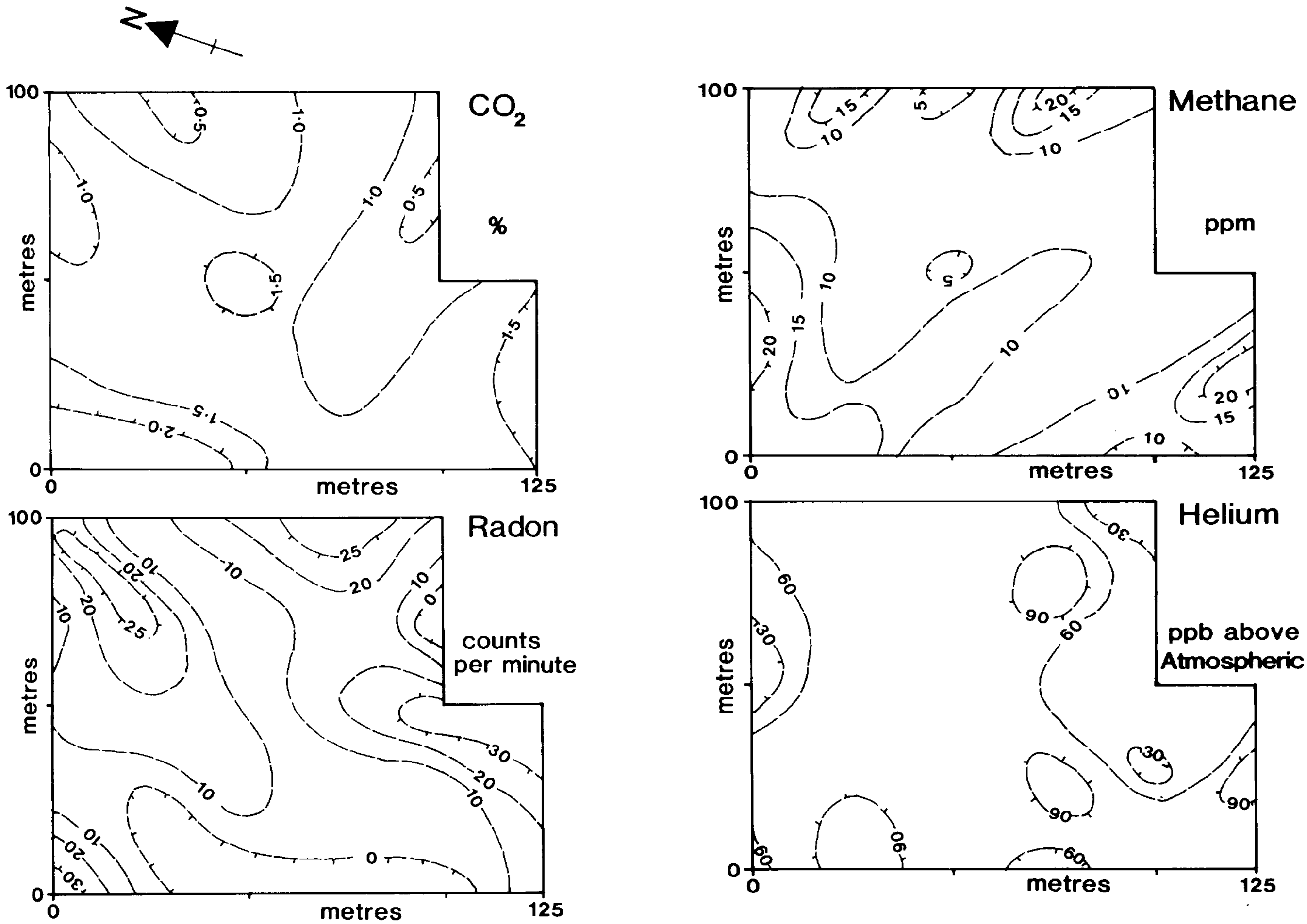

Figure 6. Soil gas geochemical results at Rhos-wen.

closely spaced sampling which was carried out over geophysical anomalies proved ineffective as the workings were so extensive. The soil gas results show the following features (Fig. 6):

a) The CO_2 values give very little correlation with geophysical results or when compared to old mine plans. However the NW corner of the grid, near the site of the farm buildings, which is thought not to be underlain by workings has substantially higher CO_2 concentrations than elsewhere. Also the O_2 concentrations (not shown) are lower in this area than elsewhere.

b) Rn shows anomalous values but with no relationship to the worked areas and probably reflects another aspect of the local geology such as the pattern of jointing or variation in the concentration of uranium in the coal measures.

c) CH_4 values over the whole site are higher than atmospheric due to the presence of coal. The location of the Small Rider coal seam is indicated by substantially higher CH_4 concentrations.

d) The area of subsidence at (C) (Fig. 5) has low He values when compared to the mean of the site, but around the recently capped shaft (D) values are fairly high. At this point He is the only gas showing an anomalous value. This is probably due to its mobility relative to other gases and the permeability of the capping to gas migration.

The geochemical results are of interest when compared to geophysical, geomorphological and geological data, however the extent of the workings under the grid is such that individual anomalies can only to a limited extent be related to specific features (e.g. subsidence). However as the workings are virtually horizontal and the field has a fairly consistent slope to the east, decreases from west to east from 30m to 15m. Therefore by averaging values along each N-S line an estimate of the variations of gas concentrations with the depth to workings can be gained by plotting these averages against W-E position (Fig. 7). These variations indicate that O_2 increases as the depth to workings decreases, while CO_2 and He both decrease. CH_4 values are highest over the outcrop of the Small Rider and increase again to the east as the Mynyddislwyn seam approaches the surface. Rn values tend to increase towards the east but are very erratic and possibly reflect natural or enhanced jointing on the site together with variable quantities of U associated with beds in the Coal Measures.

Conclusions

The results from Gooseford suggest that soil gas values over the shaft show an equilibration with atmospheric air, leading to an alteration of normal soil gas concentrations from values measured elsewhere on the site to values nearer atmospheric concentration. This is thought to be due to fracturing associated with the formation and presence of the artificial cavity, and with partial collapse of the filling material. This is shown with all the gases except CH_4. However the presence of remnants of the orebody at the location of the workings means that some variation could be due to the mineral body itself.

At Rhos-wen leakage of atmospheric air into adits east of the site appears to cause the soil gases to approach the concentrations of atmospheric air where the cavities are closer to the surface.

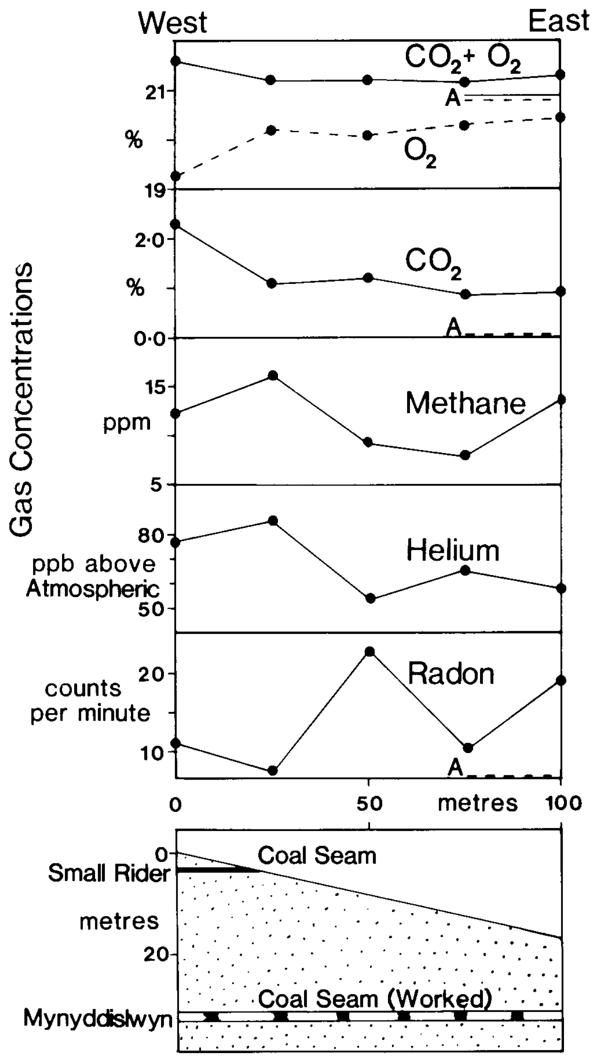

Figure 7. Averaged soil gas concentrations showing west-east trends relative to depth to mine workings at Rhos-wen.

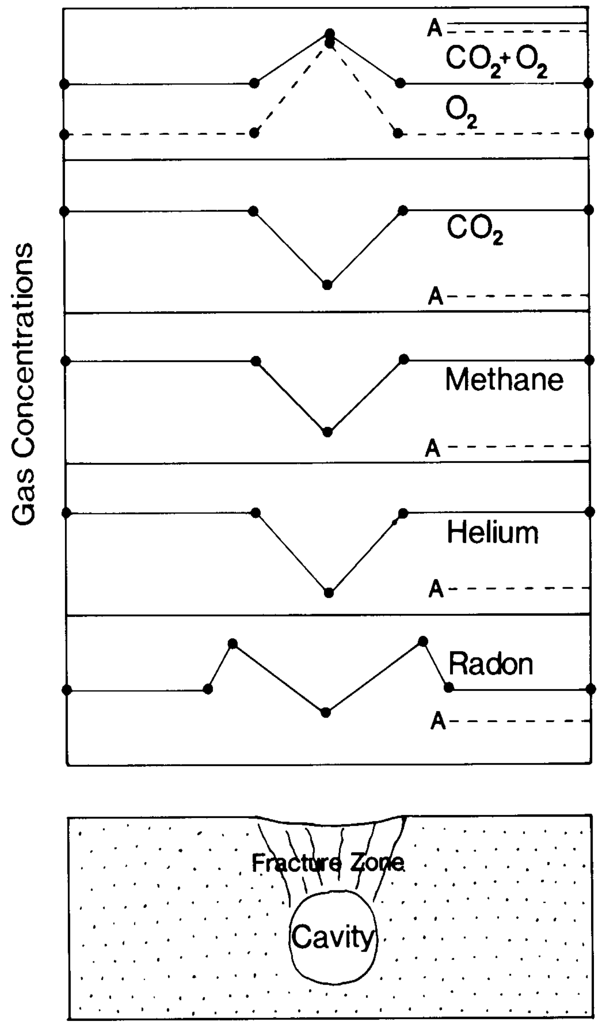

Figure 8. Idealised soil gas profiles over a near-surface cavity and associated zone of tension.

Fracturing associated with the construction and presence of the cavities exists in a zone surrounding them; where the cavities are nearer to the surface this fracture zone allows more rapid movement of gases and therefore more equilibration with atmospheric air.

The variations in soil gas concentrations related to the location of underground cavities at the two sites are shown in a simplified model (Fig. 8). This model shows idealised trends for soil gas concentrations over a cavity with no major discontinuities present in the immediate vicinity. The concentrations of CO_2, He and CH_4 all decrease from steady non-atmospheric values, characteristic of the local soil and rock formations, towards atmospheric values over the cavity. Helium can have a mean value below atmospheric, if the moisture content is high (Gregory et al. 1986). In this situation the He anomaly could be positive, negative or not apparent, depending on the absorption of He into the groundwater. CH_4 can have a positive or negative anomaly again dependent on the local geology and its CH_4 concentrations relative to atmospheric values. O_2 and (CO_2 + O_2) increase towards atmospheric values over the cavity as normal concentrations of the soil gas have lower O_2 values than the atmosphere.

Rn shows a curious anomaly over the cavity with normal soil gas concentrations being slightly higher than atmospheric. The intense fracturing over the cavity allows mixing with atmospheric air diluting the Rn to very low concentrations. However the fracturing each side of the cavity is not enough to allow much atmospheric mixing but allows Rn produced in the vicinity to migrate to the surface, enhancing normal values.

The model has been developed over known cavities at two sites by correlation with geophysical anomalies. Further work in progress will refine the model and evaluate the usefulness of soil gas geochemistry as a part of site investigation for cavities.

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