SOIL GAS GEOCHEMISTRY AS AN INVESTIGATIVE TOOL IN SOUTH-WEST ENGLAND

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INTRODUCTION

The composition of pore gas in the unsaturated zone of soil profiles differs from that of the atmosphere due to biochemical and pedochemical reactions within the soil. Some of the gases present in the soil may have been generated at depth and give rise to anomalous areas following migration upwards via preferential pathways. Radon (^{222}Rn) is produced from the radioactive decay of uranium in rock-forming minerals, Helium (ΔHe) from alpha-particles and carbon dioxide CO_2 will result from dissolution and subsequent exsolution from groundwater moving within fault systems. Their measurement, therefore, has potential for revealing geological faults. The analytical techniques have been described previously in Duddridge *et al.* 1991 and Duddridge 1994.

To locate a fault it is possible to run a traverse across the area and the probability of detection is dependent on a close sample spacing or there being a lateral migration of gas within the soil horizon. A spatial survey will aid the determination of anomaly trends, but for practicality the sample spacing must increase. Does this mean that features will be missed on a spatial survey or will lateral migration of soil gas anomalies be sufficient to ensure that a significant number of anomalies will be resolved? What are the relative merits of each sampling technique? To help answer these questions the results of some surveys from Dorset and Devon are presented and discussed.

Traverses	A	B	C	D	E	F	G
Length	287.5	187.5	400	225	300	62.5	387.5
Sample points	22	16	32	19	25	6	31
Mean ^{222}Rn	0.3	0	0.2	0.5	0.2	0.3	0.7
Max ^{222}Rn	3	0.1	5	9.4	0.6	0.6	17.2
Standard deviation ^{222}Rn	0.6	0.1	0.9	2.2	0.3	0.2	3
Mean CO_2	0.28	0.15	0.36	0.55	0.8	0.32	0.28
Maximum CO_2	2.57	1.05	3.57	5.34	7.07	1.18	3.58
Standard deviation CO_2	0.66	0.29	0.82	1.47	1.89	0.39	0.82
Mean ΔHe	-3	3	19	nd	40	nd	18
Maximum ΔHe	43	34	65	nd	80	nd	245
Standard deviation ΔHe	32	19	28	nd	23	nd	51

Table 1. *Soil gas statistics from Westrow Survey (nd not determined)*

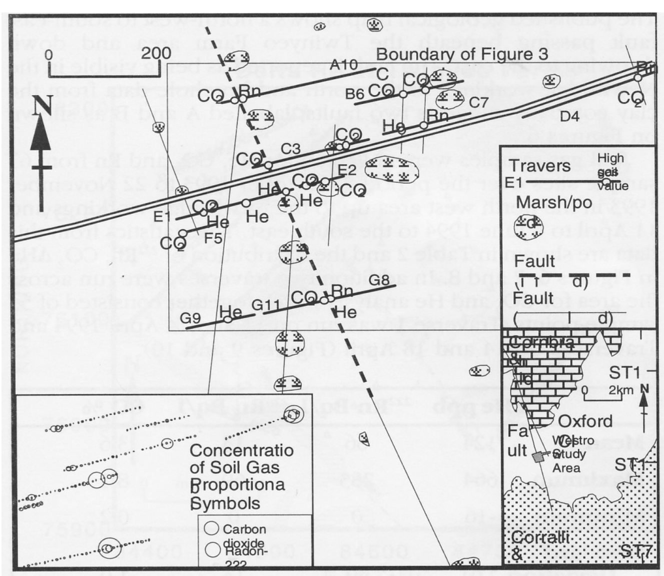

Figure 1: *The Westrow soil gas survey area showing location of traverse and soil gas anomalies.*

TRAVERSE SURVEYS

The 1970 edition of the Shaftesbury geological map showed a number of major faults. In the case of the Goat Hill-Westrow Fault and Crouch Hill Fault it is possible to project the fault lines from displaced horizons in the Jurassic Forest Marble and Cornbrash across the clay outcrop to further visible structures in the Corrallian to the south (Inset Figure 1). Accordingly it was this fault and its close neighbour, the Crouch Hill Fault, which were chosen for further study as discussed in Gregory and Duddridge (1991).

A survey of the land around the Westrow estate by the landowner Mr. Warty showed there to be a number of poorly drained areas of land thought to have a possible relation to faulting and fracturing. Their relationship could correspond to the outcrop of north-north-west to south-south-east faulting across the area and also minor fractures trending 5° east of north (Figure 1). A number of east-west trending soil gas survey lines were investigated by Gregory in the period from April to May 1988 and then additionally by Duddridge August to November. Sampling was carried out using conventional soil probe sampling techniques, analysing soil gas CO_2, O_2 and Rn on-site, with samples for ^4He returned to the laboratory for subsequent analysis. Table 1 shows the resulting statistics for the soil gas traverses.

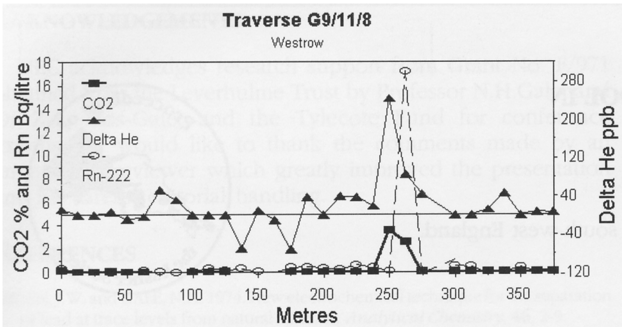

***Figure 2.** Soil Gas Traverse G from the Westrow Survey.*

A number of traverses detected soil gas anomalies which may have been fault related, the most significant being Traverse G with 245 ppb ΔHe, 3.58% CO_2 and 17.2Bq/l of ^{222}Rn where the anomalous area is clear at around 250 m (Figure 2). It seems likely that this feature resulted from the Goat Hill - Westrow Fault and it is possible to reconcile this feature to the north-north-west to south-south-east trend of the marshy areas (Figure 1). Traverse D on the east side of the study area gave the second highest maximum CO_2 and ^{222}Rn of the survey at 5.34% and 9.4Bq/l respectively. This traverse may have detected the Crouch Hill Fault. However, no other traverses recorded significant concentrations of ΔHe and many of the values recorded were within the 30 to 50 ppb error of the analysis. Furthermore the highest CO_2 value of 7.07% was recorded at the west end of Traverse E2 which would better fit with a fault trending 5° east of north and corresponding to the marshy areas to the south on this trend. If the relative values are plotted by proportional symbol (Inset Figure 1) it would also be possible to fit a trend at 55° east of north. It was concluded from the Westrow work that though the soil gas method detected what was believed to be the Goathill-Westrow Fault the technique was not conclusive. In practice a number of faults might be fitted to the pattern of soil gas anomalies and in the absence of the known structural trend much of the interpretation is speculative. Contouring the original CO_2 data from the Westrow survey shows that the technique reveals the north-north-west to south-south-east trending fault without reference to the marshy areas (Figure 3).

SPATIAL SURVEYS

The spatial survey offers an alternative to the traverse method and on a small scale survey the sampling points will normally be set out on a regular grid within one area of land such as a field. On larger surveys this may be impracticable due to buildings, roads and hedges. A compromise is to use the concept of the `random grid survey', where a controlled number of points can be placed anywhere within a given grid square, but the overall density of the survey is similar across the area.

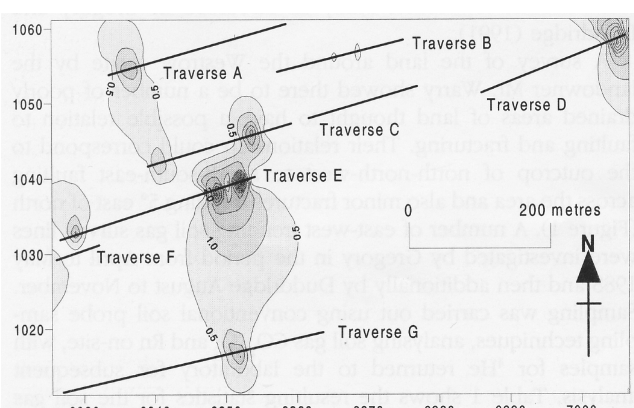

***Figure 3:** Contoured CO_2 data from the Westrow soil gas survey.*

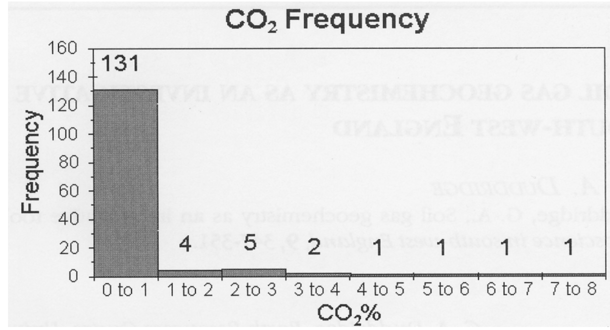

Figure 4: Carbon dioxide frequency data from the Westrow soil gas survey.

With only one sample site from the Westrow survey recording anomalous ΔHe and only 15 out of 146 sites recording CO_2 above the 1% level (Figure 4) it was considered that a sample spacing wider than 12.5 m was in danger of 'missing' the anomaly, yet this contradicts the concept of spatial regional scale surveys conducted by Italian researchers (Lombardi and Polizzano 1988), where sample density might consist of only 2 or 3 points/km^2. With a given number of sample sites the probability of missing a fault will increase as the sample density decreases, but by increasing the survey area the chances of detecting a deep fault with a high gas flux and lateral soil gas migration will be increased. Increasing the sample density improves the resolution of the survey and the advent of readily available computer based contouring packages from the 1990's has enabled data to be assessed during the course of a survey. This was practised during a soil gas survey over the Bovey Basin (Duddridge 1994) and it was found that some structural trends started to be resolved at a density of 1 sample/km^2 and by 2 samples/km^2 the north-west to south-east trend of the SticklepathLustleigh Fault was well shown by the contoured CO_2 data. Figure 5 shows the contoured data at 1, 1.5 and 2 samples /km^2

SPATIAL SURVEYS COMPARED WITH TRAVERSES

The Twinyeo Farm site is situated on the eastern side of the Bovey Basin within the area of economic clay working (Figure 6). The site is situated to the south of the English China Clay company's Newbridge workings, but the farm area is owned by Watts Blake and Bearne company who provided access to the area.

Geologically the area overlies the Southacre Clay and Lignite and both the Bovey and Teign valleys are filled with alluvium. The published geological map shows a north-west to south-east fault passing beneath the Twinyeo Farm area and down throwing to the east. The fault is reported as being visible in the Newbridge workings to the north and borehole data from the clay company suggests two faults, labelled A and B as shown on Figures 6.

Soil gas samples were collected for He, CO_2 and Rn from 67 sample sites over the period 23 October 1993 to 22 November 1993 in the north west area up to the Newbridge workings and 11 April to 6 June 1994 to the south east. The statistics from this data are shown in Table 2 and the distribution of ^{222}Rn, CO_2 ΔHe in Figures 6, 7 and 8. In addition two traverses were run across the area for CO_2 and He analysis which together consisted of 54 sample points. Traverse 1 was run on 11 and 14 April 1994 and Traverse 2 on 14 and 18 April (Figures 9 and 10).

	ΔHe ppb	^{222}Rn Bq/l	^{220}Rn Bq/l	CO_2%
Mean	124	66	13	3.6
Maximum	664	283	69	8.1
Minimum	-16	0	0	0.2
Standard Deviation	119	49	14	1.9

***Table 2.** Statistics from the 67 sample sites at Twinyeo Farm.*

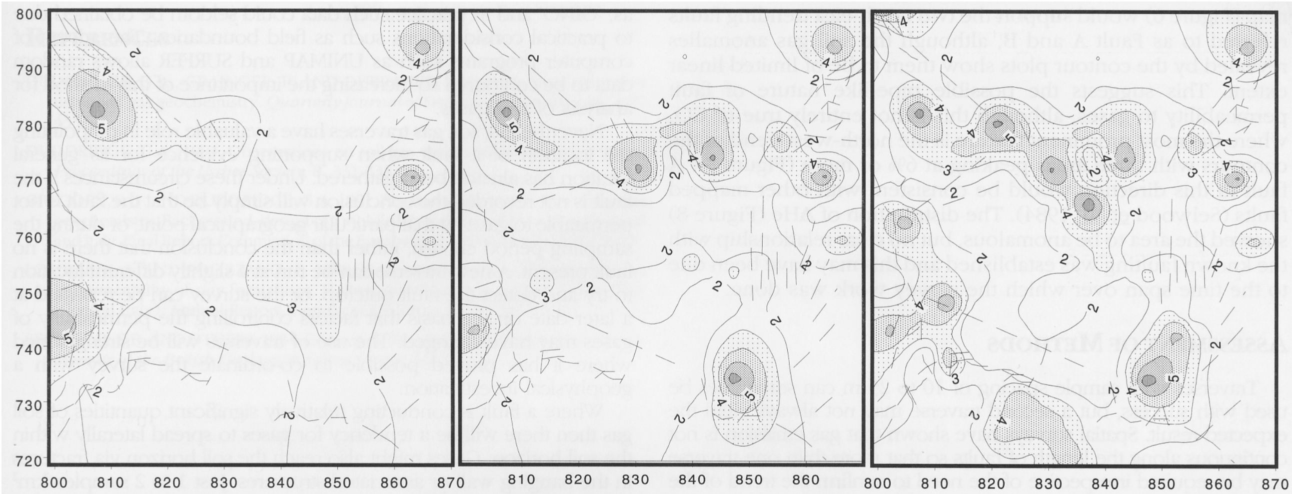

Figure 5: *Soil gas CO_2 data from the Bovey Basin survey plotted at 56, 84 and 113 levels of sampling (1, 5, and 2 samples/km²). Dashed lines indicate known faulting. Eastings and Northings are Nation Grid kilometre squares.*

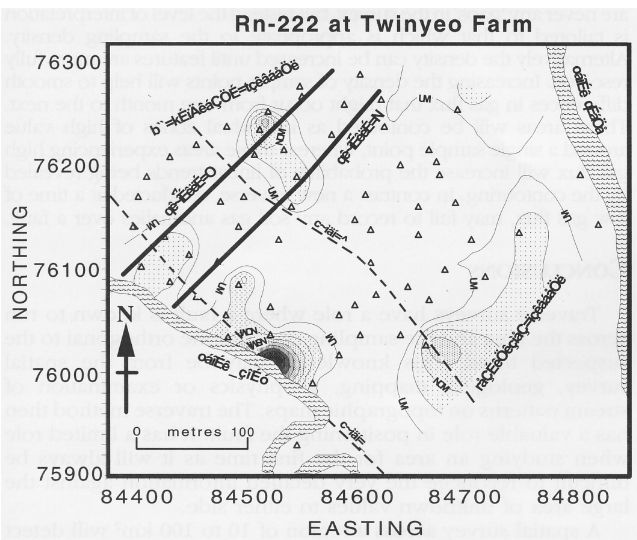

Figure 6: *Contoured ^{222}Rn data from the Twinyeo soil gas survey.*

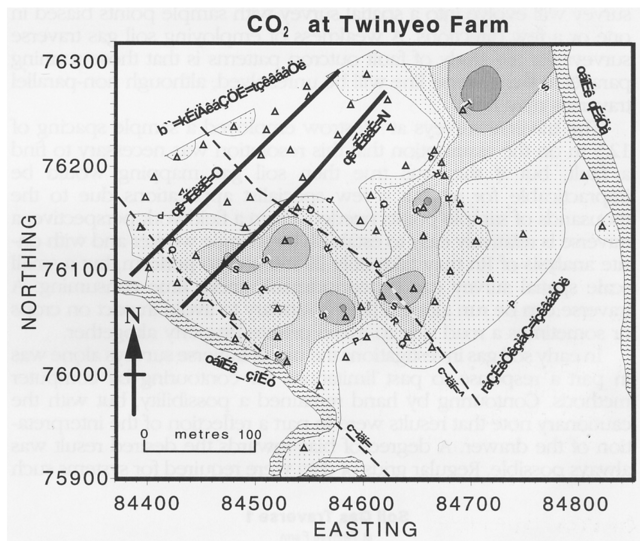

Figure 7: *Contoured CO_2 data from the Twinyeo soil gas survey.*

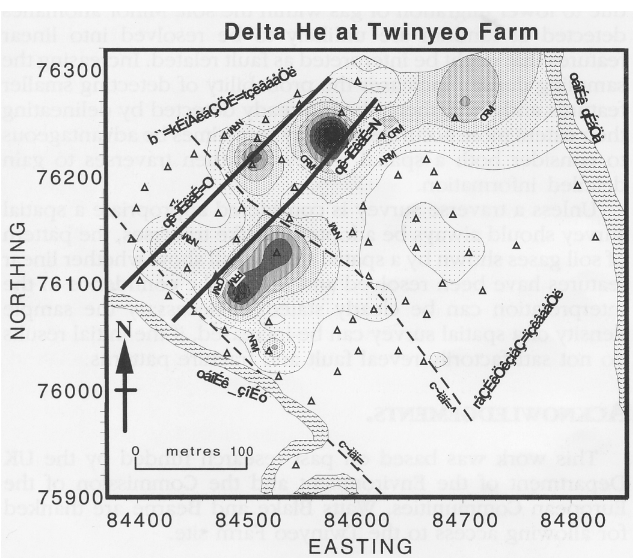

Figure 8: *Contoured ΔHe data from the Twinyeo soil gas survey.*

The soil gas concentrations found with Traverse 1 support the presence of faulting where ΔHe is anomalous over the fault, compared to adjacent background values of around 50 to 100 ppb. From 120 to 160 m ΔHe shows consecutive values of 213, 320, 352, 522 and 181 ppb. Carbon dioxide was also high at 5.57%, whilst O_2 and N_2 values recorded by the gas chromatography were 2.14% and 90.43% respectively. These gas values suggest that an oxidation event has depleted the soil gas atmosphere which under normal biogenic conditions would be restricted to O_2 values of about 17 to 20% and N_2 at around 79%. Such an oxidation might occur in the presence of methane, but the maximum recorded was 0.025% CH_4 at 167 m where the traverse intersected the field hedge. Upwelling of gases from a fault therefore seems a strong possibility. On Traverse 2 anomalies occur at 50 to 60 m and 200 to 220 m. The first corresponds closely to the outcrop of Fault B and here ΔHe reaches 208 ppb, CO_2 5.38%, O_2 a minimum of 11.46% and N_2 85.13%. The second anomaly does not correspond to any identified faults. Delta helium reaches 232 ppb, CO_2 7.64%, O_2 a minimum of 13.57% and N_2 83.76%.

The highest ^{222}Rn occurs in the Bovey Valley and may correspond to Fault B, but it may also be that there is much surface granite (uranium source) material in the valley. This contrasts with the Teign valley where no ^{222}Rn anomalies were recorded by the 2 samples taken there. The ^{222}Rn distribution map (Figure 6) would support the two north-east trending faults referred to as Fault A and B, although the soil gas anomalies revealed by the contour plots show them to be of limited linear extent. This suggests the possible pipe-like nature of fault permeability to gases, although this is not entirely true of CO_2 where the most prominent feature is the north-west trend of the contours with three areas peaking at 6% or more (Figure 7). A fault in this direction would be consistent with other mapped faults (Selwood et. al. 1984). The distribution of ΔHe (Figure 8) showed the area to be anomalous, but no clear relationship with the known faulting was established and this may have been due to the time span over which the survey work was done.

ASSESSMENT OF METHODS

Traverses with sample spacing of 10 to 25 m can sometimes be used with success, but a second traverse may not always yield the expected result. Spatial surveys have shown that gas emission is not continuous along the length of faults so that more than one traverse may be required irrespective of the need to confirm the trend of the fault. In many cases the absence of data between the traverses may limit the level of interpretation, despite there being a very detailed pattern of soil gas values along the sample line. To resolve unclear soil gas distributions it is possible to add more traverses, but ultimately the survey will evolve into a spatial survey with sample points biased in one or a few directions. A weakness of employing soil gas traverse surveys for the study of fault outcrop patterns is that those running parallel to the traverse line will be unresolved, although non-parallel traverses may help.

The traverse surveys at Westrow employed a sample spacing of 12.5 m on the assumption that this resolution was necessary to find a fault, but if this was true then soil gas mapping would be impracticable for all but a few specialist applications due to the thousands of sample points needed. From a fieldwork perspective, a traverse is relatively easy to establish by a single worker and with on-site analysis of Rn may take only 20 minutes to perform, but a small scale spatial survey can be considerably more time consuming. A traverse can be run along a field boundary to avoid impact on crops or sometimes a road side to avoid private property altogether.

In early soil gas investigations the use of traverse surveys alone was in part a response to past limitations for contouring by computer methods. Contouring by hand remained a possibility, but with the cautionary note that results were in part a reflection of the interpretation of the drawer. A degree of bias towards the desired result was always possible. Regular grids of data were required for systems such

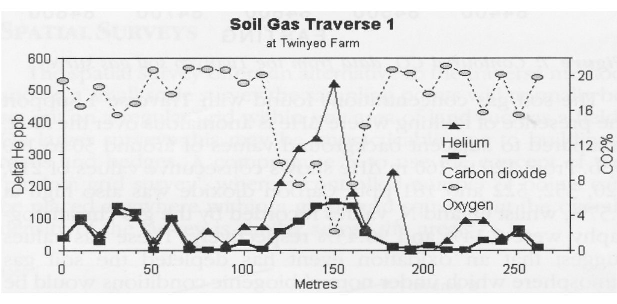

Figure 9: *Soil gas Traverse 1 from Twinyeo survey.*

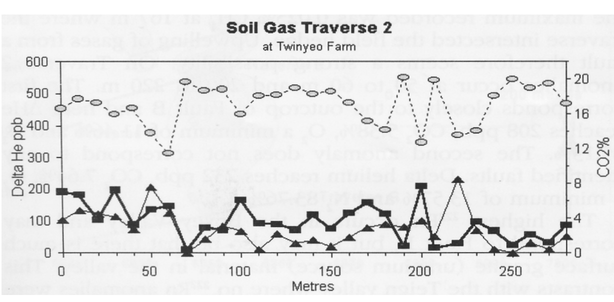

Figure 10: *Soil gas Traverse 2 from the Twinyeo survey.*

as, 'GINO' and in practice such data could seldom be obtained due to practical considerations such as field boundanes. The advent of computer programs such as UNIMAP and SURFER allows random data to be contoured so increasing the importance of this method for analysis of soil gases.

Nevertheless, soil gas traverses have a valuable role in pinpointing the location of a fault when supporting evidence for its general location has already been gathered. Under these circumstances if the fault is not recorded the conclusion will simply be that the fault is not permeable to gases at that particular geographical point, or during the sampling period chosen, rather than the conclusion that there is no fault present. A new traverse can be run at a slightly different location to try and detect the fault outcrop, or the survey can be repeated at a later date on the basis that factors controlling the permeability of gases may have changed. The use of traverses will be strengthened where it has proved possible to co-ordinate the survey with a geophysical investigation.

Where a fault is conducting relatively significant quantities of soil gas then there will be a tendency for gases to spread laterally within the soil horizon. Gases might also reach the soil horizon via fractures in the hanging wall or associated structures. Just 1 to 2 samples/km^2 on a spatial survey may start to resolve anomalies and contouring of the data may show linear features. Where anomalies are represented by just one sample point then they are likely to be the result of less significant structures beneath. The key to a spatial survey is that there are never any 'gaps' in the survey, but instead the level of interpretation is tailored to that which is appropriate to the sampling density. Alternatively the density can be increased until features are more fully resolved. Increasing the density of sample points will help to smooth differences in gas flux that might occur from one month to the next. These areas will be contoured as individual zones of high value around a single sample point, whereas those areas experiencing high gas flux will increase the probability of linear trends being revealed by the contouring. In contrast a new traverse, conducted at a time of low gas flux, may fail to record any soil gas anomalies over a fault.

CONCLUSIONS

Traverse surveys have a role where a fault is known to run across the area and the sampling can be done orthogonal to the suspected trend. This knowledge may be from the spatial survey, geological mapping, geophysics or examination of stream patterns on topographic maps. The traverse method then has a valuable role in positioning the fault. It has a limited role when studying an area for the first time as it will always be difficult to reconcile the very detailed information against the large area of unknown values to either side.

A spatial survey across a region of 10 to 100 km^2 will detect large features due to lateral migration of soil gas from faults with a high flux, but the probability of detecting minor features is low due to lower migration of gas within the soil. Minor anomalies detected at random are unlikely to be resolved into linear features that might be interpreted as fault related. Increasing the sampling density increases the probability of detecting smaller features and strengthens those already detected by delineating their extent more accurately. It may sometimes be advantageous to consider both a spatial survey and then traverses to gain detailed information.

Unless a traverse survey is considered appropriate a spatial survey should always be adopted. Unlike traverses, the pattern of soil gases shown by a spatial survey will show whether linear features have been resolved and in turn the confidence in the interpretation can be clearly stated. If necessary the sample density of a spatial survey can be increased, if the initial results do not satisfactorily reveal fault and fracture patterns.

ACKNOWLEDGEMENTS.

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